IDENTIFICATION OF LATE QUATERNARY SEDIMENT DEFORMATION AND ITS RELATION TO SEISMICITY IN THE ST. LAWRENCE LOWLAND, NEW YORK

Report to

NEW YORK STATE ATOMIC AND SPACE DEVELOPMENT AUTHORITY

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ABSTRACT

Although the relation of soft-sediment deformation to earthquakes has been debated many decades, recent work in correlating historic California earthquakes with distorted sediments provides a new dimension to the problem. The purpose of this reconnaissance study was to survey 2500 sq. mi. in the St. Lawrence Lowland of New York to determine: (1) if Quaternary sediments exhibit deformation structures similar to those in California, and (2) whether the deformation was related to possible seismic events. The New York region, however, is complicated because processes associated with glaciation have produced a wide range of deformed structures.

The St. Lawrence Lowland contains a vast array of soft-sediment deformation that includes faulting, folding, and décollement structures. These features occur in sediments of various thickness, areal extent, textures, and environments. The geometries of the deformed strata contain features similar to those reported as earthquake-induced in California. Limited visits were made to selected sites in other eastern regions. It is shown that the St. Lawrence structures are not unique, but the region contains an unusual concentration and variety of deformation. Criteria that can be used to differentiate glacial influences from other causes include: (1) diapirs, (2) horizontal continuity, (3) thixotropic features, (4) character of overburden, (5) environmental setting etc. The great majority of distorted units can be attributed to causes related to glaciation.

More than 200 sand and gravel pits were evaluated along with 100's of other sediment exposures. A literature search

provided information on more than 1600 relevant publications, and 600 are contained in the enclosed bibliography. Laboratory experiments with a shaking table have reproduced structures similar to those found in the field. When these studies are combined with the field criteria that can be used to exclude glacial deformation, localities near Malone, Canton, Gouverneur, and Alexandria Bay contain Quaternary structures with the greatest promise of being related to seismic events.

The regional framework has been determined for a Quaternary stratigraphy that also provides correlation of landforms and sedimentary environments. The deformed strata occur in materials associated with Ft. Covington glaciation, and with Lake Fort Ann and Champlain Sea events which have been bracketed by Carbon 14 dates that range from 12,300 to 10,300 yrs. B.P. Sedimentation rates of the deposits and evaluation of varve couplets aid to determine local time scales. When the character of the deformed units is placed into a combined regional and local chronology it can be inferred that the recurrence interval of possible earthquake events is less than 100 yrs.

The deformation of St. Lawrence Quaternary sediments is not unique in eastern United States. However, the exceptional abundance of the features, and their similarity with structures from other regions previously interpreted as seismic-induced, indicates the study approach used in this investigation is valid and can yield significant data for assessment of previous earthquake events.

CHAPTER I

INTRODUCTION

This report discusses Quaternary deformed sediments in the St. Lawrence Lowland of New York State. The principal objectives of the investigation have been to identify late Quaternary deformational structures and to evaluate the relation of soft-sediment changes with possible seismic events. To accomplish these goals it has been necessary to: (1) compile an extensive bibliography, (2) perform geological reconnaissance field work in a 2500 sq. mi. area, and (3) undertake laboratory analyses of specimens and experiment studies. Examination has been made of numerous field sites that contain deformed sediments and special attention has been placed on those structures that possess the greatest promise of being related to earthquake activity. Some additional work was done in glaciated aseismic terrane in eastern United States and Canada to serve as a basis for comparison of similar-appearing deformed structures in the St. Lawrence Lowland.

The work by J. D. Sims (1973, in Press) in relating deformed sediments in California to historic earthquakes served as a starting point for this report. Accordingly special effort has been made to compare structures that occur in soft-sediment deformed units in California with possible counterparts in the St. Lawrence Lowland. New York's Quaternary history and sedimentary deposits are much more complicated because of the large array of deformed features that can be caused by processes associated with glaciation. Thus, there is (1) a wider range of structures that include folding, faulting, and décollement, (2) a greater variety of sediment sizes from clay, silt, sand, gravel, cobbles, and boulders, (3) a more diverse environmental setting, and (4) less strata continuity with rapid changes both vertically and horizontally. Such complexities required evaluation of many diverse units without original prejudice for their ability to undergo liquefaction.

The processes that need consideration as possibilities for producing deformation structures in Quaternary sediments of the St. Lawrence Lowland include:

1. Glacial readvance over previously deposited stratified materials.
2. Collapse of sediments into a depression created by meltout of buried ice.
3. Gravitational sliding of sediments during disintegration of an ice margin.
4. Overburden loading pressure by water, ice, or other deposits.
5. Fluvial flooding and turbidity currents.

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6. Wave pulsations in water from seiches, iceberg calving, etc.
7. Water level changes in beach environment by winds and tides.
8. Sudden drop in water levels when lower base level outlets are used.
9. Impact of ice rafted boulders.
10. Isostatic rebound.
11. Earthquake shocks.

This report should not be interpreted as being the final word on the subject or on the localities that have been referenced. One of the purposes of this investigation was to form the background for more detailed work..."...recommend specific sediment sections for future intensive investigation of Quaternary deformational structures and seismic recurrence rates." Thus the conclusions of this report are stated at the end of the text along with a series of recommendations that should point the way for a more complete resolution of the problem.

REGIONAL SETTING

Physical Geography

The study region in the St. Lawrence Lowland comprises an area that extends from Lake Ontario on the west to Malone in the east, about 125 miles long, and from the St. Lawrence River on the north to the Tug Hill Plateau and Adirondack Upland on the south, about 20 miles wide. The major rivers are St. Lawrence tributaries and from west to east include (Plate 1) the Indian, Oswegatchie, Grass, Raquette, St. Regis, and Salmon Rivers. Although elevation ranges from 250 ft., at the St. Lawrence to 1000 ft. at the Adirondack foothills, the majority of the region is less than 500 ft. and local relief rarely exceeds 100-200 ft. Hill fabric shows dominant northeast-southwest orientation, regardless whether the hills are predominantly bedrock or unconsolidated deposits. Thus the topographic fabric consists of elongated hills with local swales that contain a variety of lakes, swamps, and streams.

Geology

Rocks of Precambrian age occur in many localities of the St. Lawrence Lowland and they constitute a wide range of igneous and metamorphic lithologies. Such rocks are dominant in: (1) the Adirondack Uplands (Plate 1), (2) along the Frontenac Arch which surfaces in the Thousand Island-Alexandria Bay area, (3) many outcrops in a trend from Potsdam to Gouveneur, (4) extensive exposures in the area surrounding Black Lake, and (5) much of the southwestern part of the study area where only thin drift mantles bedrock. The Precambrian rocks show major lineations and trend northeast-southwest throughout the entire region.

The remaining bedrock consists of Cambrian and Ordovician Paleozoic sedimentary deposits. These rocks have contributed much of the source material for the glacial deposits. The following formational units have been recognized: Potsdam sandstone (Cambrian), Ogdensburg and Theresa carbonates (Lower Ordovician), and Black River-Trenton limestones (mid to upper Ordovician). Although many of the Paleozoics are

essentially flat-lying with only slight dips, they occur in a series of northeast trending belts which have been block faulted and they contain some folded units (Dames & Moore, 1974, p. 2-15).

Quaternary events have caused some local features in the bedrock such as pop-ups in the Potsdam sandstone (Fig. 1-1). These structures may have resulted from a combination of isostatic rebound resulting from a 500 ft. of postglacial uplift, and removal of confining overburden pressure.

Glaciation

Although the St. Lawrence was glaciated several times during the Pleistocene, this study is largely confined to the most recent glaciations. These events occurred during late Wisconsinan time and represent the time interval of about 12,000 to 10,000 yrs. B.P. It has been traditional to refer to the older drift as "Malone" and the younger drift as "Fort Covington". The fabric of till shows southwest motion by Malone ice and south to southeast motion by Fort Covington ice. The directional changes are best explained by different ice responses during a single stade rather than two separate periods of glaciation. During the later stages of the Pleistocene a series of water bodies, both proglacial lakes and seas occupied parts of the area. These events have generally been related to Lake Iroquois, Lake Fort Ann, and Champlain Sea episodes.

The region contains an unusual variety of glacial deposts and landforms. Many different types of till occur such as lodgment, ablation, flow, and winnowed till. Stratified deposits include the full range of glaciofluvial, glaciolacustrine, glaciomarine, and glacioeolian sediments. Glacially-related landforms fall within such categories as kames, kame terraces, kame moraines kame deltas, drumlins, moraine ridges, outwash plains and deltas, and till plains.

The glacial sediment contains a wide gamut of deformational features in many scales and types. The major categories might be classed as folds, faults, diapirs, and décollement structures. They have been formed by several different processes, and it has been the purpose of part of this investigation to determine their origin mechanism.

TECTONIC SETTING

Tectonic studies of the St. Lawrence region have been a subject for extensive studies (Wynne-Edwards, 1972; Kay, 1975; Kumparelli, 1970). Some of the data (Wynne-Edwards, 1972; Kay, 1975) pertained to an earlier phase of tectonic activity and the faults may have already been "healed".

Field observation of faults has been difficult because of the overburden. Very significant though, are observations in bore holes (Berkey, 1945) and shafts, and zones of crustal basement rocks that are only partially filled by

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Tectonic Setting Prepared by Francis Wu

calcareous material. Such crushed zones have been seen at several points near the St. Lawrence valley and whether active faulting in this region is related to these zones is of interest.

The seismicity of the St. Lawrence Lowland is understood in a fairly rudimentary level. Several authors (Oliver, 1969; Sbar and Sykes, 1972) observed two trends in the historical seismicity of this region: one of them trending NE-SW along the St. Lawrence valley, the other trending NW-SE from Ottawa to Boston. The epicenter distribution in the region is actually rather diffused; this could result from inaccurate location of historical events but could also be inherent in the nature of continental seismicity. This latter possibility is well illustrated in China, where the level of activity is higher and even the post-1962 data shows a diffused pattern. The general interpretation is that the earthquake hypocenters are located on old weaknesses that have been reactivated in response to present-day tectonic stresses (Molnar, Fitch and Wu, 1973). It may be significant that based on ample historical seismicity data in China (Shih, et al, 1974) the recurrence frequency for destructive earthquakes in different seismic regions of eastern China, far away from island arc or mid-ocean ridges, ranges from one episode per 100 yrs. to one episode per 1000 yrs. Each episode may comprise one event or may include a series of events. Prediction of one destructive earthquake per 50 yrs. has been suggested (McGerrigle, 1966) as the recurrence rate for the St. Lawrence Region. However, without sufficient data for regionalization, his determination cannot be seriously employed for any particular section in the New York part.

The section of the St. Lawrence Lowland bordering New York State has had one known destructive earthquake, i.e., the Massena-Cornwall earthquake of September 5, 1944. This earthquake was investigated at some length by Berkey (1945), Hodgson (1945) among others. Combining the findings that the destruction was concentrated in an elliptical area with its major axis along a Massena-Cornwall line and that the tombstones tended to rotate one way north of the St. Lawrence or the other way south of the River, conclusions were drawn that the causative fault has an east-west strike. However, the destruction pattern may be controlled by the distribution of Massena clay (Berkey, 1945). The tombstone rotation pattern (counterclockwise on the Canadian side and clockwise on the American side) does seem to indicate a NE-SW strike.

It is of interest that the response of the Massena clay (Berkey, 1945) during the 1944 earthquake was widespread in the Massena-Cornwall area. The Massena clay (also known as the Leda Clay or Champlain Sea Clay) consists of marine clay and silty sands. Structures with foundations on the clay were more damaged than those on other types of sediments.

A review of previously published seismicity maps indicates the area between Massena and Lake Ontario is fairly free of activity. One may question again whether this section is truly quiescent or preparing for a future earthquake. The data

gathered by Lamont-Doherty Geological Observatory during 1974, shows this section is populated by small non-destructive earthquakes. That the Massena earthquake did not leave permanent surface traces is consistent with the focal depth of approximately 32 km. However, if the fault had been active for a long period of time, it could have reached the surface. On the other hand, the recurrence interval of surface faulting may be long enough so that the traces are obliterated by recent processes.

PROJECT DESIGN AND METHODOLOGY

The intrinsic nature of the problem of Quaternary deformed sediments and possible earthquake inducement require an interdiscipline approach within the geological sciences. The project was to perform a field reconnaissance of the 2500 sq. mi. area. This included the use of previously performed field work such as that by MacClintock and Stewart (1965), analysis of soil survey maps of the U. S. Department of Agriculture, and review of maps and aerial photographs to locate the most promising sites for deformed structures.

The first phase of field work was to initiate a rapid survey of all existing sand and gravel pits, more than 200 were located, and to evaluate their potential for containing deformed strata. The rationale for placing priority on these sites was that: (1) they were distributed throughout the entire region, and (2) many showed sediment sections of 40-50 ft., and (3) quickest benefits occurred from seeing 1000's of feet of lateral exposures. The second phase of the field work included locating riverbank outcrops, road-cuts, new cellar excavations, new drainage lines for sewer of power facilities, etc. The third phase was to obtain available drillers logs and to determine future sources of information where cores could be sampled from deeper drilling projects. One of the principal thrusts of the reconnaissance program was to locate several "type" localities that revealed various types of deformed strata for more intensive study and sampling by the sedimentologists. Other work that was included in reconnaissance mapping was to obtain information so that the general sedimentary environment and glacial history of the locality could be interpreted. Finally, the location was determined of sites that would prove most fruitful for future work.

The sedimentology group had two principal tasks: (1) a more detailed sediment analysis of fabric and composition of the material in situ, and (2) selection of those sediments that should undergo laboratory testing and analysis. These detailed studies included a variety of mineralogic analyses, scanning electron microscopy fabric analysis, and particle size determinations. In addition experimentation was performed using a shaking table to obtain deformed sediment analogs to those observed in the field.

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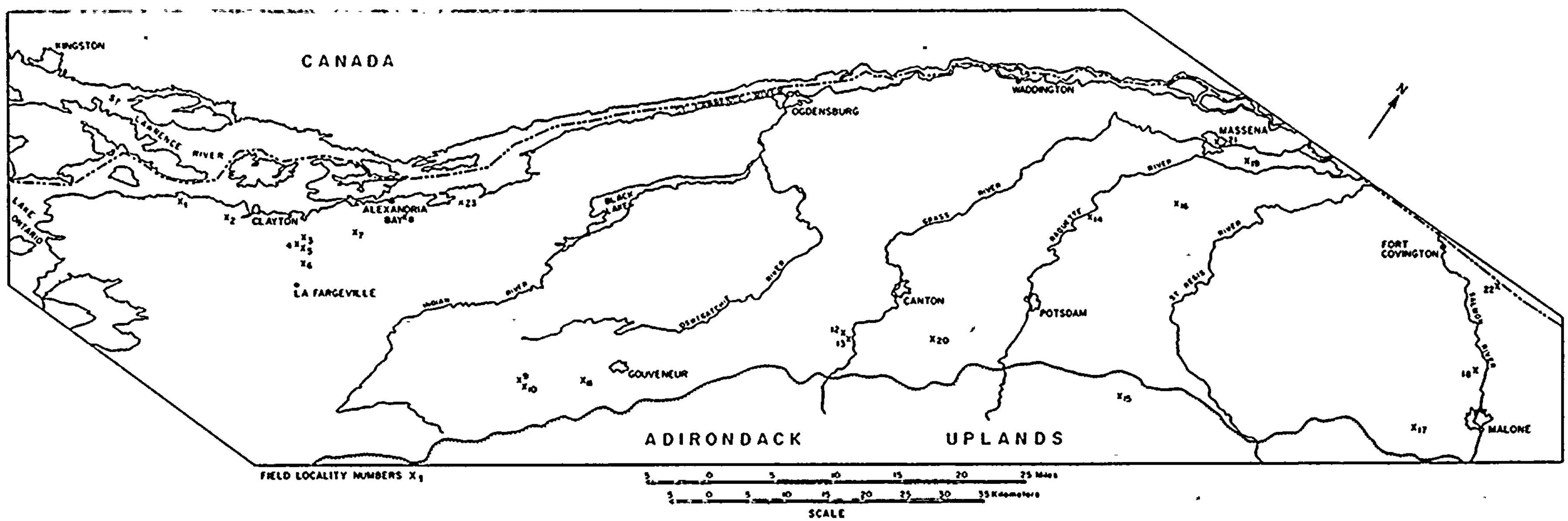

Plate 1. Location map of field sites and features of the St. Lawrence Lowland, New York.

Fig. 1-1. Pop-up in Potsdam sandstone near Alexandria Bay, N. Y. (locality 7). Probably caused by pressure release of overlying confining ice during postglacial time.

Fig. 1-1 (locality 23). Area of glacial and glaciofluvial erosion with extensive development of p-forms. Striae and other glacial movement indicators show ice direction was S 30° W. View looking northeast near Route 12.

Fig. 1-2 (locality 23). Small scale roche mountonnée with two generations of glacial erosion. Steep faces were plucked by ice and later were smoothed by fine-scale polish and abrasion. View looking northeast parallel to ice movement.

Fig. 1-3 (locality 23). Crescentic gouge features. Ice moved parallel and in direction Brunton compass is pointing.

I-4

I-1

I-3

CHAPTER 2

SOFT SEDIMENT DEFORMATION

INTRODUCTION

Phenomena of soft sediment deformation are widely reported and discussed in the geological literature. An extensive review would be superfluous in this report; the interested reader is referred to sedimentological texts which include lengthy references on this subject, some back to the mid-nineteenth century (Potter and Pettijohn, 1963; Dżulyński and Walton, 1965; Conybeare and Crook, 1968; Vassoyevich, 1960; Fairbridge, 1947; Shrock, 1948). Morphology and origin of soft sediment structures are variable and complex; the nomenclature and terminology that have developed over the years are even more so. Some of the terms result from attempts to produce a genetic classification, but much of the proliferation was created by the laudable efforts to steer away from genetic connotations and use non-committal descriptive terms. Literature abounds in terms such as pseudofolds, rheoglyphs, (Vassoyevich, 1960), convolute lamination (Kuenen, 1953), corrugated bedding (Shrock, 1948), prolapsed bedding (Wood and Smith, 1959), crumpled bedding, load folds (Sullwold, 1959), cusps and streamers (Selley et al., 1963), submarine disturbances (Bailey and Weir, 1933) recumbent cross stratification (Allen and Banks, 1972), deformed cross bedding (Jones, 1962), curved false bedding, puckering and overfolding of laminae etc. All these terms refer basically to features of sedimentary folding, the "contorted bedding" of McKee (1954).

Another group of terms includes pseudonodules (Macar, 1948), pillow structures, load pockets (Sullwold, 1959), flow rolls (Sorauf, 1965), roll structures (Cooper, 1943), rolled up pebbles (Hadding, 1931), and mammelones (Ashwin, 1957). All these structures refer to discoidal elliptical or rounded rock elements floating in or pressing into the underlying bed. Though the underlying bed usually is finer, these structures are by no means restricted to the sandstone/shale interface and occur also in apparently uniform sandstones.

In addition some genetic terms are in common usage, such as sandstone dikes, flowage structures, and "slump and slide" structures. The latter term now appears to be restricted to features displaying a distinct lateral translation.

Throughout the years, study of sediment deformation in glacial sediments has followed an independent and unrelated path, creating a separate set of terms, mainly genetic, such as ice wedges, cryoturbation, congeliflunction, solifluction, frost deformation, frost heave, involutions, and thurfurs. It is only recently that awareness has appeared in the glacial literature that some of these features may be produced by processes unrelated to frost (Butrym et al., 1964; Washburn, 1973).

Prepared by Iaakov Karcz and Paul Enos

GENERAL RELATIONS

The possible relationship between occurrence of soft sediment deformation and earthquakes has been widely reported and discussed in the geological and sedimentological literature. This assumption may be traced nearly two centuries back, to the early descriptions of major earthquakes and their related ground-deformation effects. In the 1860's De la Beche, Lyell (1883 and in earlier editions), Hobbs (1907) and Grabau (1913) were those who summarized accounts of seismically-induced deformation stressing ejection and injection structures such as sand cones, mud volcanoes, circular ponds and hollows, and sand dikes. Lawson (1908) discussed larger scale mass movements, recognizing earth-slumps, earth flows, earth avalanches etc.

A glance through the sedimentological literature indicates the majority of studies and reports of soft sediment deformation, published during the past hundred years, mention seismicity as the possible inducing source.

In some cases seismic interpretation of sediment deformation is presented as a tentative hypothesis along with other alternatives, and in many others as a fact. Thus for example Bailey et al. (1928) and Bailey and Weir (1933) discuss the record of "recurring tsunamis" in the Paleozoic of Quebec and Kimmeridgian in Scotland. Early accounts of the geology of Yorkshire in 1926 discuss sediment deformation under such headings as "Ancient Earthquakes". In numerous cases seismic shocks appear to represent almost a Deus ex machina invoked automatically at first sight of sedimentary disturbances. Studies of sediment deformation in glacial sediments are the exception in this respect, stressing the effects of frost, ice shear, ice melt and collapse with no recourse to seismicity, nor, for that matter to such processes as liquefaction. This perhaps is not surprising, because it may be argued that the glacial environment is sufficiently disturbed and tremorous and no special "need" for seismic shocks arises. Shrock (1948) wrote in his discussion of Shaler (1888):

"....myriads of miniature earthquakes occur during the periods of glacial advance, when the ice cracked upon surmounting prominences or sheared for other reasons, and the vibrations transmitted through the surficial or subaqueous sediments might well have caused the less stable upper part of the deposit to be deformed by folding or faulting, particularly if sediments lay on 2-3° slope".

In view of the massive literature relating soft sediment deformation and seismicity, it is hardly surprising that finally Sims (1973; in Press) has proposed to employ such sedimentary features in assessment of recurrence interval and regional seismic risk. There is no doubt that a major earthquake may destabilize a granular mass: the problem, however, is to distinguish the resulting deformation from that induced by other, aseismic processes.

In the course of this study we attempted to identify a number of critical questions which should be answered to make the usage of sediment deformation in assessment of seismic risk fully meaningful. These questions include the following:

(1). Assuming that sediment deformation occurs in response to a seismic shock, does it always signify a major event?

(2). What are the possible aseismic mechanisms that can lead to very similar features of deformation? Is distinction possible?

(3) Can the seismic events be dated according to the horizon in which they appear, (i.e., is it possible that the response to a seismic shock does not necessarily occur only close to the surface?) and is a recurrence study possible?

(4). What, if any, are reliable indicators of seismically-induced deformation?

Obviously, at the present moment we do not have more than indications of nature of answers to these questions, however, the material at hand demonstrates that the questions are not rhetorical but well founded in theory as well as in field evidence, and that the problems specified here, though difficult, are approachable.

Our presentation in this chapter is limited in its scope to structures of deformation identified in the field as unrelated to the glacial mechanisms. Chapter 3 discusses the implications when glaciation enters the picture. Thus, for example, we are not including here some of the structures interpreted by the glacial geomorphologists as caused by glacial events. To place the discussion in its proper context we need to recapitulate a number of concepts employed in engineering that assess seismic risk in terms of ground deformation.

(a). Terzaghi (1925, 1956) and Terzaghi and Peck (1967) defined the concept of metastable structure of saturated sediment. At this state the particles are supported at grain/grain point contacts, encompassing water filled voids. Such configurations are promoted by rapid deposition and admixtures of silt in sand, and may reach porosities in the 40-70% range. This structure may withstand static consolidation stresses but should a contact between grains be broken (by slip at grain contact), the hydrostatic pressure at depth will increase by an amount close to the submerged weight of the overlying sediment. In other words, the weight of the solid particles is transferred from points of contact to the pore water, and a spontaneous liquefaction occurs. The failure was observed to propagate through the sand and spread. As already indicated, in this metastable state the threshold for slip at a point of contact is low, and thus liquefaction may be induced also by less severe, causing aseismic disturbance.

Casagrande (1936, 1971) demonstrated the existence of a certain critical void-ratio, at which deformation takes place with no volume change. This void-ratio may be achieved through application of stress to a loose sand, which shows a decrease in volume; or to a dense sand which dilates strongly.

In an undrained saturated sand the strength is $S = (P - P_w) \tan \phi$. The application of stress results in densification with the corresponding rise in pore pressure, which leads to decrease in strength. When $P_w = P$ the strength is totally lost. In dense sand an opposite effect may be expected. It is obvious therefore that when the rate of increase in pore pressure exceeds rate of dissipation failure may be expected.

(b). It has been demonstrated in numerous works by Seed and his collaborators (Seed and Idriss, 1967, 1971; Seed and Lee, 1966; Seed and Peacock, 1971; and Castro, 1969), that application of cyclic loading to sands results in progressive decrease in volume and increase in pore pressure for each loading cycle. This effect occurs also in dense sands, which under unidirectional loading would normally dilate. If the incremental increase in pore pressure (Fig. 2-1) reaches a value equal to confining pressure, effective stress becomes zero, the strength is lost, and the sand is liquefied. Castro (1969) indicated this should be referred to as cyclic mobility rather than liquefaction in the sense of Casagrande (1936). The difference is that liquefaction deformation depends on the critical void ratio and takes place at constant volume and resistance, moreover the effective stress does not fall to zero. In cyclic loading, incremental deformations and related changes in void ratio occur.

(c). Simplified assessment of liquefaction potential (Seed and Idriss, 1971) consists of the following stages:

(1). Determination of the design earthquake and relevant properties of the soil material. These include: sediment type, mainly: <u>grain size</u> (Fig. 2-1), which suggests that maximum liquefaction potential is in the silt/fine silt range; <u>void ratio</u> - which shows that in cyclic loading, the incremental increase in pore pressure is greater for sands; <u>initial confining pressure</u> which indicates that contrary to slides, here an increase in confining pressure lowers the liquefaction potential, and the <u>intensity and duration</u> of ground shaking.

(2). Conversion of the assumed earthquake stress history into the equivalent number of stress cycles, and presentation of the equivalent cyclic stress level as a function of depth.

(3). Determination on the basis of laboratory tests of the cyclic stresses which would have to be developed at various depths in order to induce the liquefaction. Presentation for comparison with data obtained in the previous stage (Fig. 2-1).

Other authors suggested correlation between shear strength and penetration tests and the liquefaction potential of the soil.

There is no doubt that the application of the engineering reasoning and techniques to the geological problem of soft sediment deformation are very worthwhile, and will result in a feedback of sedimentological information highly pertinent in engineering research. Some difficulties arise however in this respect. <u>First</u>, the

procedures for assessment of liquefaction potential are simple to follow only in the case of homogenous, undrained noncohesive sediments. The first question that arises therefore involves the dissipation of pore pressure in stratified systems. In general the engineering technique stresses that because of the relatively rapid dissipation of pore pressure in sands, the rate of application of shear stress must be high, otherwise liquefaction does not occur. Silts and fine silts are believed to have a higher liquefaction potential, because of their lower permeability and resultant slow pore pressure dissipation. Work is now being carried out in a number of research laboratories to demonstrate the mechanisms of strain accumulations and pore pressure increases in clayey materials. This concept may prove to be quite critical in evaluation of evidence of soft sediment deformation. Assuming that clayey materials do show increment pore pressure increases under cyclic loading, then in view of their low dissipation rates, possibility exists for a gradual accumulation of pore pressures under repeated long term, but small magnitude, cyclic loading. It is known that any conspicuous wave system may be envisaged as representing a cyclic loading system. Therefore, when the accumulation rate of pore pressure exceeds the dissipation, liquefaction can be induced by any system of waves (especially storm systems oscillatory currents, and seiches). If these computations lead to realistic orders of magnitude as they well may, assessment of seismically induced soft sediment deformation may become even more difficult.

The second question involves the response and behaviour of stratified systems where discontinuities are present in porosity and permeability or in lithology; and where, therefore, pore pressure accumulation and dissipation occur at different rates. Under certain circumstances, the occluded layers such as a bed of sand underlaid and topped by thin layers of clay, may develop a different rate of instability than the rest of the system.

This may be easily demonstrated experimentally. Figures 2-2 to 2-6 show sequence of events recorded in a stratified system placed on a simple shaking table. The sealed layer seems to break into two main parts: lower one, which densifies and appears to behave like a solid, and the upper one which behaves like a fluid, pressing against the upper sealing layer and finally disrupting the layer and exploding upwards. Following the expulsion, the material shows a clear settlement and preservation of a folded structure. Figure 2-3 shows that if the upper seal is not pierced, cessation of shaking will result in a gradual settlement of the upper layer and an (load like) interface resembling a "load cast". In this particular case, the unusual interface suggests the loading by kaolinite (which maintains its coherence) into granular coarse sand. Similar response was observed in a fluidization experiment, where deformation took place first at the horizon with the greater voidage. Figure 2-3 shows diapiric features that resulted in experiments in which shaking was allowed

to continue until the increase in pore pressure was sufficient to induce penetration of the sealing layer. A full sequence of events is shown in Figure 2-4 which again demonstrates the appearance of the fluid layer, pressing and uparching the overlying seal, then bursting out, and finally entering the stage of collapse, or rather, settlement. Features of settlement are seen also in Figure 2-5 where a small graben-like collapse feature appears.

Two features shown in the experiments are significant in interpretation of recurrence intervals. First, it is obvious that deformation does not occur necessarily in the top layer. Apparently, the relative importance of "destabilizing" effects such as grain size and void ratio is greater than the "stabilizing" effect of increased confining pressure. Particularly important is the fact that Figure 2-5 shows that deformation may be occurring simultaneously in several horizons, whether interconnected or not.

Our inclination therefore is to assume that only the "truncated" anticlines, may be significant in assessment of recurrence interval. At the same time, it is the uppermost layer which is most prone to aseismic disturbances. Moreover, Figure 2-3 shows a small diapir which appears to indicate a truncated top, even though it did not reach the surface.

<u>Magnitude of an Earthquake</u>

The magnitude of an earthquake is expressed by Seed and Idriss (1971) in an equivalent number of equal stress cycles. Under natural conditions, however, the situation may be more complicated.

The occurrence of soft sediment deformation depends mainly on stability of the sediment (in terms of composition-especially in the finer sediments, and mechanical and physical properties) and on the nature, magnitude, and rate of the deforming stresses. Obviously, the less stable the sediment is, the less energy input is required to induce deformation. Close to the critical state, deformation may be induced almost instantaneously by any minor disturbance, and the work involved in deformation will be performed by the energy stored within the system itself. This concept is widely accepted and appears in somewhat different facets in considerations of all mechanisms of mass movement and failure. Dżulyński (1966) and Anketell et al (1970) discussed strata with inverse (unstable) density gradient in terms of trigger systems; Jackson (1968) summarized the instability of fluidized systems to disturbances, and of course Terzaghi's original concept of liquefaction relies on disturbance-prone "metastable" structure of the granular mass. The more unstable the system, the smaller the required triggering disturbance and thus the more chance of its being produced by a source other than a major earthquake. The question therefore becomes not so much whether a deforming stress, or trigger is available, but rather whether and how the sediment can reach such an unstable state.

From what has been previously mentioned about the general behaviour of fine grained sediments, i.e., the chances of gradual accumulation of strain and increase

in instability, and about the stratified systems, it is evident that the disturbance triggering the soft sediment deformation does not necessarily have to represent a major event. This point will be emphasized again while discussing some other mechanisms of sediment deformation. At this stage it is pertinent to point out a number of writers, especially Oulianoff (1951), suggested that some effects of deformation may be due to a persistent microseismic activity. In this context it may well have to be indicated, that the Quaternary lacustrine sediments exposed along the Dead Sea-Jordan Rift Valley, where seismic activity is taking place (Wu, et al., 1973), about in spectacular features of soft sediment deformation.

ASEISMIC PROCESSES OF SEDIMENT DEFORMATION

Numerous mechanisms have been proposed in sedimentological literature to explain the occurrence of soft sediment deformation. In most cases they were presented as possible alternatives to seismic disturbances or were presented to account for the presence of instability activated by a seismic trigger. Several good comprehensive reviews are available (Pettijohn and Potter, 1964; Dżulyński, 1966; Anketell et al., 1970; McKee and Goldberg, 1969; Selley, 1969; Allen and Banks, 1972 and others), so that this presentation will be brief and oriented mostly towards structures unrelated to glacial effects recorded in the field.

A number of processes discussed below involve virtually the same parameters and stresses and the mechanisms are interrelated, so that the grouping seems somewhat artificial and arbitrary.

The general order of presentation (Karcz, 1963) is: Syndepositional effects, including effects of settling (also compression stage of settling) and flow shear; Syndepositional or postdepositional deformation, induced by unstable density stratification; Postdepositional effects of consolidation and fluidication; Sliding and groundwater flows.

Syndepositional Effects of Settling and Flow

(1). Settling

With increase in concentration, settling velocity of a suspension diminishes and deviates from Stokes Law according to

$V_c = V_o\ (1-c)^3/10c$ or $V_c = V_o\ (1-c)^n = 3.5$

V_c settling velocity of suspension

V_o settling velocity Stokes Law

c solid fraction

This decline in settling velocity, known to engineers as retarded, hindered or batch settling, is attributed to the effect of upward moving fluid displaced from below by the settling particles. Settling velocity may be expressed as the negative superficial velocity of fluid displaced upwards due

to difference in hydrostatic head of the bulk suspension and the clear fluid. Retarded settling may therefore be regarded as reverse equivalent of fluidization.

At concentrations of about 10% or lower, suspension breaks into a number of zones: accumulating bottom sediment, irregular zone (not always present), suspension, and clear supernatant fluid at the top. When the upper interface between the fluid and suspension (referred to as sludge line, mud line, disturbance, shock) meets on its descent the ascending sediment interface, suspension is stated to enter the stage of "compression" (or compaction).

Kuenen (1965, 1968) reported on the effect of the upward moving fluids, describing settling convection as well as formation of small vertical veinlets or channels cutting across the compressing sediment zone, and suggested that they are the small scale analogs of sand volcanoes (Gill and Kuenen, 1958).

Presence of this upward flow led Kuenen to doubt the existence of "scaffold" or "house-of-cards" architecture in clayey deposits. Our observations indicate however, that the fluid moves through the compressed zone in fairly well defined small channels not affecting the fabric in between.

In a number of shaking table experiments, some of the small scale channels provided outlet for the fluid expelled from an occluded layer and led to development of diapirs. Some small veinlets and channels were also observed in the field. In principle, the compression stage of settling represents a transition stage between fluidization and consolidation. Material behaves essentially as a fixed bed (in fluidization terminology) through which fluids are moving according to laws of flow in porous media.

In addition, complex physicochemical processes operate within the settling suspensions of clay, or mixed with clay. The interparticle forces operating within the suspension and the compression zone, depend on the mineralogical and colloidal properties of the suspended material and on the composition of the interstitial fluids. These control the formation of links, and determine the nature of flocculation, aggregation, thixotropy and architecture of the fabric, which in turn determine other properties of the freshly deposited sediment. Thus for example, face/face clay contacts result in lower viscosity, and the edge/face and edge/edge contacts in a higher viscosity. The appearance of some definite structure within the fine grained sediment resembles the metastable sediment structure of Terzaghi (1925); however some disagreement appears to exist as to the actual nature of this framework and processes leading to its collapse. It is clear however that this sediment is thixotropic, i.e., possesses a certain strength, which may be destroyed in remolding, but is gradually restored after the remolding. It has been shown by several workers that small admixtures of clay can provide thixotropic properties to coarser sand. The same apparently is true with respect to numerous mixtures of silt, sand, and gravel with clay. It is not surprising therefore to find that some of the coarser sediments of the St. Lawrence region display excellent flowage properties due to the presence of clay.

Fabrics and links and thus the general behaviour of the clayey materials depends also to a large extent on the electrolytes present. Thus for example, the Norwegian quick clays show a strong correlation with the salt content, and increase in sensitivity with the leaching of salt. A number of research laboratories are now attempting to develop similar relationships for the Leda Clay, however until now no concrete results are available. It is possible, that the total chemical analysis of interstitial waters could provide some indication as to the rheological properties of the sediment. The deformation of clay beds appears to follow the deformation of sand, often the clayey layers representing the sealing of small occluded systems. As already indicated, the cohesive properties of the clay result in its greater coherence in deformation.

(2). Flow

Numerous investigators considered the possible effect of flow drag on deformation of soft sediment. The frequent occurrence of deformation in a close association with ripple drift, leading to oversteepened, drawn out or sheared units led Kuenen (1953; 1968a; 1968b) to suggest that the deformation results from pressure difference between the ripple crest and trough as predicted by the Bernoulli relationship. These supposedly lead to an upward suction on the crests and formation of folds. Sanders (1960) suggested that convolute lamination represents the response of slightly cohesive sediment to fluid shear, i.e., counterparts of ripples. McKee et al. (1962a; 1962b) suggested that fluid drag combined with the drag of the overriding mass of sediments exerts sufficient shear to induce deformation of the soft sediment. Cline (1966) suggested that deformation occurs at some critical high velocity. A recent study by Allen and Banks (1972) of recumbently folded cross stratification maintains however that the shear stress expected from a moving fluid will not be high enough to induce the deformation, and propose a rather complex combination of seismic and fluid shear.

In the present context, however, evidence suggestive of flow-induced deformation implies that such structures must be disregarded as possible indicators of seismicity. Therefore care must be taken to distinguish between the "drawn out" convolute laminations associated with ripple drift, and a situation in which a rippled bed is uparched and penetrated by a diapir from below.

Another example of such elimination is the treatment of ripple load shown in Figure 2-7. It was shown by Dżulyński and Kotlarczyk (1962), and others, that ripples advancing along a muddy bottom may sink. The fluid shear is sufficient to incise them still further, with ensuing rotation and incision of the next ripple ridge. At the same time, it is known to geologists (Kuenen, 1958) that a seismic shock will lead to loss of strength in the mud and the sinking of the overlying rippled bed. As no way to determine which process was operative appears to exist, the evidence was recorded but can not be used for the present purpose.

However, two comments should be made. First, experimental stressing of fresh deposited mud by flow of clear water indicated, after a fairly long period, that consolidation and expulsion of fluid (and occasionally also sediment) is taking place. The resulting mounds and craters are definitely analogous to mud volcanoes described in the literature (Karcz and Shanmugam, 1974). The second comment is related to the behaviour of the bed in response to the passing wave. It has already been pointed out that a series of storm waves may be treated in terms of cyclic stresses, in an analogous way to the earthquake stresses. In principle however it is possible to show also that the pressure gradients induced by a wave within the streambed leads to vertical flow force, which in turn may induce liquefaction in the upper layer. Such effects have not been investigated thoroughly, because previously most of the attention in hydraulics was focussed on the damping effect of the porous bed on the wave. Nevertheless, this effect may be real and should be considered while analyzing sediment deformation. It should perhaps be mentioned, just as a visual reminder, that in flume experiments with silty material, very often the internal bed geometry will become distorted when the flow is shut off too rapidly and a back wave is running to the upstream.

Inverse Density Stratification

In a series of papers Dżulyński and his collaborators (e.g. Dżulyński, 1966; Anketell and Dżulyński, 1968a; 1968b; Anketell et al., 1970) presented a comprehensive treatment of various features of sediment deformation in terms of instability induced by inverse density stratification.

It is well known that inverse density stratification, i.e., in which the heavier density material overlies the lower density material, is unstable. The best known illustration is a fluid heated from below and cooled from above. When a certain critical parameter (either Rayleigh Number, or Richardson Number) is exceeded a convection pattern sets in. The pattern, known also as the Benard pattern consists of polygonal (hexagonal) cells along a vertical axis, along which the fluid is circulating. In presence of lateral shear this convection pattern will be transformed into a pattern of flow rolls aligned parallel to the direction of shear.

Inverse density stratification may be achieved in a number of ways, either through difference in lithology or through difference in porosity. This is particularly important, because the intergranular relationships change not only in the course of deformation but also through compaction. It is possible therefore that no trace will be left of the original difference in porosity between two adjoining beds. Moreover, the onset of deformation requires that a certain threshold is overcome, otherwise the system may persist in its initial stage. In other words, it is possible to induce deformation through a certain triggering event. Furthermore it is obvious that this mechanism starts operating without need for initial loading to take place, i.e., various types of penetrative and injection structures can form in the complete absence of loading or lateral motions. The actual geometry of the individual structures would

depend on the sediment properties of the composing material, and their continuity.

Geometrical patterns produced by this mechanism (Figs. 2-5 and 2-8) are not unlike the spectacular deformational features near Malone, and LaFargeville (see Chapter 4, localities 3, 4, 5, 18). It may be argued however, that the field exposures show repeated deformations at different levels and uneven penetration. The previous authors indicate however, that when deformation takes place at a certain level, it may affect the stability of the neighboring horizons. In recent years, Dżulyński and his collaborators applied this theory to interpretation of numerous periglacial structures, and demonstrated that results are fairly convincing both in terms of experiment and field evidence.

Consolidation and Fluidization

The compression stage of settling heralds the transition to consolidation regime, i.e., a process of reduction in sediment-volume with the accompanying expulsion of fluids. Processes of consolidation were widely investigated and described in the soil mechanics literature as well as in sedimentological and marine technology studies. Extensive reviews are presented in Rubey and Hubbert (1959), Terzaghi and Peck (1967), Richards (1967) and Rieke and Chilingarian (1974). It would be presumptuous to include in this section more than three "reminders". First, we are dealing with a stratified system and thus different responses may be expected in layers of different voidage and different lithological interfaces. Second, liquefaction may obviously occur here in response to the monotonically increasing deforming force, provided of course that the increment in stress exceeds the rate of pressure dissipation and expulsion of fluid. Related to this process are the widely reported phenomena of rapid dewatering in zones of accelerated deposition. Third, the significance of consolidation in context of sediment deformation may be in the history of upward (and perhaps also lateral) movement of the expelled fluids, i.e., possible occurrence of fluidization. Our decision to focus on the fluidization features was prompted by the fact that relatively little attention has been paid to fluidization in the past few years (Karcz, 1963; Allen and Banks, 1972).

Migration of the fluids expelled during volume reduction may be gradual, obeying the laws of flow in a porous medium, and may proceed at a low rate. In this case movement may be expressed in terms of movement of fluid through a bed of particles, without affecting the particles themselves. This corresponds therefore to a migration of fluid through a "fixed" bed, in fluidization terminology. When the velocity of fluid is increased (occasionally the fluidizing force is expressed in terms of <u>mass</u> velocity, or in terms of pressure drop), to a point that it balances the weight of the particles, the bed starts expanding. Particles are not supported by the fluid and any increase in fluid velocity will result in further expansion. In other words when the frictional pressure drop is equal to the buoyant weight of the solid bed

particles, any further increase in fluid velocity must result in a slight upward movement of particles. Particles are reoriented and rearranged so that the resistance to fluid will decrease and the bed voidage will increase. At this point the bed is fluidized, and the fluid velocity is referred to as the minimum fluidizing velocity.

Several brief comments, pertinent in the present context should be made at this stage:

(1). Unlike air or gas fluidized systems which show bubbling and discontinuities (aggregative fluidization) the liquid-fluidized systems are reasonably uniform (particulate fluidization). At the same time it should be realized that the process is not completely regular, especially if envisaged to occur under natural conditions. First, some bed expansion occurs before the point of fluidization is reached, (especially in highly consolidated or randomly packed beds). Second, at the point of incipient fluidization a somewhat greater velocity is required to set the process in motion, than computed from the weight of the particles. This represents the effect of interparticle bridging and interlocking. Furthermore, the various nonuniformities in bed properties imply that the minimum fluidization velocity is not a sacred value, and that a situation may arise in which fluidized and nonfluidized regions will coexist within the domains of the same bed. In some systems, extensive channeling may occur, in which the fluidized motions are restricted to channels within the bed. When a channel of this type is wide enough to affect the particles around it so that a circulation pattern sets in, the bed is referred to as "spouted" bed. Local circulation patterns may also arise when the drag exerted along the boundaries of the fluidized zone starts affecting the upward movement.

(2). Prediction of the minimum, threshold fluidization velocity can be expressed in terms of equations derived mostly on the basis of Carman Kozeny equation and leading to expressions such as

$$U = 0.00059\ d^2\ (\rho_s - \rho_f)\ g/\mu$$

ρ_s solid density

ρ_f fluid density

μ viscosity

which was developed for fine spherical particles at 0.4 voidage. Obviously the velocity at threshold will depend on the voidage. Variation of fluidizing velocity with voidage are given in terms of $U/U_t = c^n$ where U and U_t are the fluid and settling velocity c is the voidage and n is a constant depending on the settling Reynolds Number.

(3). It is extremely important to realize that a state of uniform fluidization is unstable. Stability of the fluidized state has been investigated by numerous authors (see Jackson, 1971). This study of hydrodynamic instability proceeded as usual by application of the small perturbation method and demonstrated that in this state one wavelength always exists for which the disturbance is amplified more rapidly than for all others. This study is important in the present context

for a number of reasons. First, usually it is assumed that instabilities are restricted to the gas-fluidized system where high density difference exists between the particles and the fluid. However, it has been shown that the same instability mechanism operates in the water-fluidized system, though the growth and propagation of disturbances are about a hundred times slower than in the gas-fluidized system. As might be expected instability is promoted by high voidages.

From what has been said above it appears that soft sediment deformation may occur when rapidly expelled fluids reach the mass velocity required to start fluidization - along selected zones within only certain horizons within the consolidating column. The fluidized system is unstable and thus disturbances grow rapidly probably assuming a certain geometrical configuration. It is important however, that close to the unstable stage deformation may be induced by a triggering disturbance.

It appears also that the natural system of consolidated sediments may lead to a variety of combinations between compaction, liquefaction and fluidization. The former two are responsible essentially for mobilization and expulsion of the fluid, whereas fluidization is the process that occurs in the sediment as a result of this expulsion.

A series of preliminary experiments was conducted in a vertical pyrex tube infilled with laminated sediments, and connected to a water pipe. The flow was allowed to enter into a mixing chamber from which it proceeded through screen and glass wool baffles into the sediment. The entry was fairly smooth, but unfortunately our flow gauge was not sensitive enough to monitor the developing pressures.

The nature of deformation is shown in Figure 2-5 which demonstrates a number of successive stages in the development of diapir folding between the strata. There is no doubt that the process will be controlled by the porosity differences between the different layers. It is clear however that the disturbance is not related to the top horizon of the sequence, and that it is penetrative, occurring probably at the same time at different levels.

Fluidization may also be induced through mechanisms other than simple consolidation. Thus for example lateral changes in porosity, the so-called "spring mechanisms" have been discussed by Williams (1960) and by Selley (1969). Such effects may be particularly appropriate for the St. Lawrence Quaternary sediments, which abound in lateral changes and discontinuities. The exposures examined were not sufficiently extensive or our work sufficiently detailed to determine whether any such fluidizing spring mechanisms or secondary water horizons were present or not.

In addition to the spring mechanisms, a further way of producing fluidization would be through oscillations of the water table in a poorly consolidated sedimentary column. This is especially true under ephemeral conditions or in coastal zones. Features of sediment deformation related to such effects were described by numerous investigators (e.g., Emery, 1950, and others).

RECURRENCE INTERVALS

If the time intervals between repetitions of seismic events, or any other event causing soft sediment deformation, are to be deciphered from study of the stratigraphic record then we must be able to recognize discrete deformational events. The simplest case, and that most amenable to conventional stratigraphic analysis, would be if the deformation were confined to the surface layer. This condition was implicit, although not specifically stated, in Sims' (1973) analysis of seismicity in the Van Norman Reservoir where he identified deformation of the surface layer with the most recent seismic event and deformation of deeper horizons with successively earlier events. We saw however, that as a result of the discontinuities, and changes in porosity, permeability and grain size, the response to a shock may occur at different levels, depending presumably on the degree of cementation and on the magnitude of the confining pressure. It is possible through extension of the existing methods (Figs. 2-6, 2-7, 2-8) to develop a technique of assessment of the maximum possible thickness of sediment to be affected by a single event. The first approximation calculations performed here indicate that the problem is approachable.

Recognition of surface deformation in the sedimentary record is possible, but care must be taken to distinguish the possibly seismically induced deformation from other sources of deformation, whether syndepositional or postdepositional. Truncation of deformational structures such as diapirs at an overlying bedding surface is suggestive of deformation at the surface. Other possibilities for causing truncation are erosion of an interval sufficient to decapitate structures and possibly the formation of "secondary layering" during deformation. Erosion might be recognizable by the nature of the overlying bed, e.g., channel forms, unusually high energy deposits, or reworking of coherent fragments of the underlying bed. If "secondary bedding" is formed, e.g., by reworking of fluidized sediment during deformation, it might be inferred by noting unusual relationships to primary bedding.

From experiments conducted in this study and from reports of clouding of lakes near earthquake epicenters, it appears that copious mud is commonly thrown into suspension, at least if shock-induced liquefaction produces eruptions at the sediment surface. If the point of eruption is exposed, a distinct cone of sediment may be recognizable in cross section. In shallow water such a cone would be readily removed by currents. Even in the absence of a cone, the suspension of sediment might be recognized by the formation of a thin, relatively fine-grained micrograded layer overlying a zone of deformation.

If deformation produces surface relief in a current-dominated regime, interaction between the deformational relief and the current might be a criterion for deformation at the surface. Such interaction could include decapitation of positive relief and deposition of sediment, possibly cross laminated, in negative relief. If shear produced by the current were sufficient to induce orientation of the structures, it might become impossible to determine whether the structures were produced solely by current shear (cf. Sanders, 1967) or by other external causes.

In the St. Lawrence Lowland only a few cases were observed in which deformation could reasonably be inferred to have involved the surface layer because of truncation of structures in the absence of significant erosion. In no case was an eruptive cone or a fine layer of sediment possibly formed by settle-out following eruption identified. On the other hand, thick intervals or sequences of beds in which deformation was simultaneous throughout were encountered, most convincingly in the Malone road cut (locality 18). This implies that the interval between recurrences of deformational episodes will be difficult, if not impossible to determine.

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Fig. 2-2 to 2-5. are photographs showing a series of sediment changes created during shaking table experiments. These tests were made to simulate the deformational features observed in the St. Lawrence Lowland. Different textures and colors of sand were formed into discrete strata with a layer of kaolinite at the top.

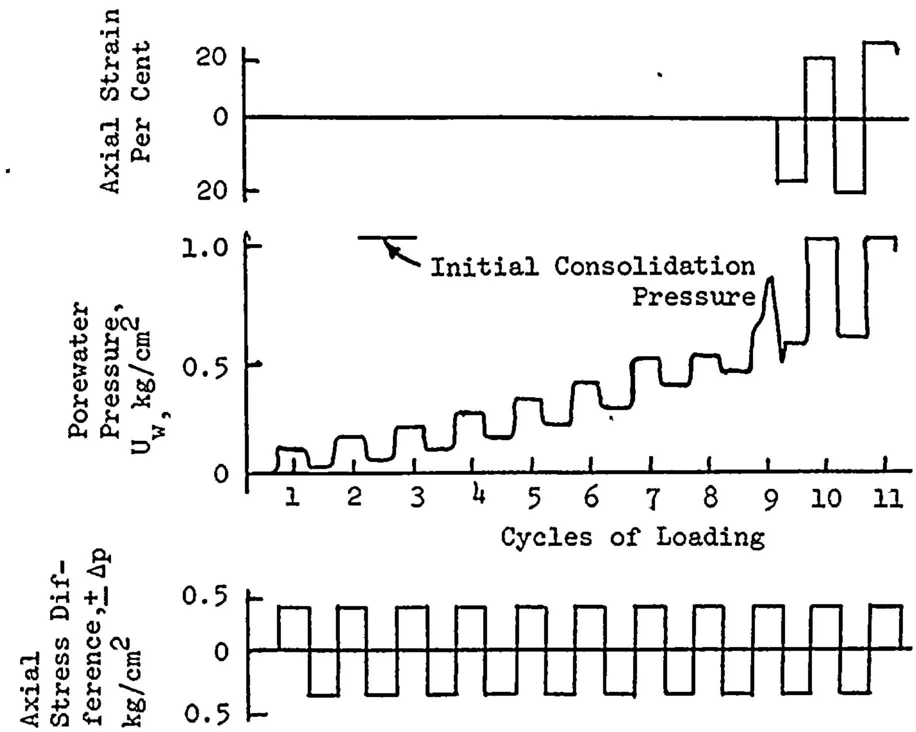
Fig. 2-2. Formation of a fluid layer, penetration of the kaolinite, with ejection and settlement.

Fig. 2-3 a and b show formation of a liquid layer and adjustment after dissipation. b. Diapirs with flat tops have developed.

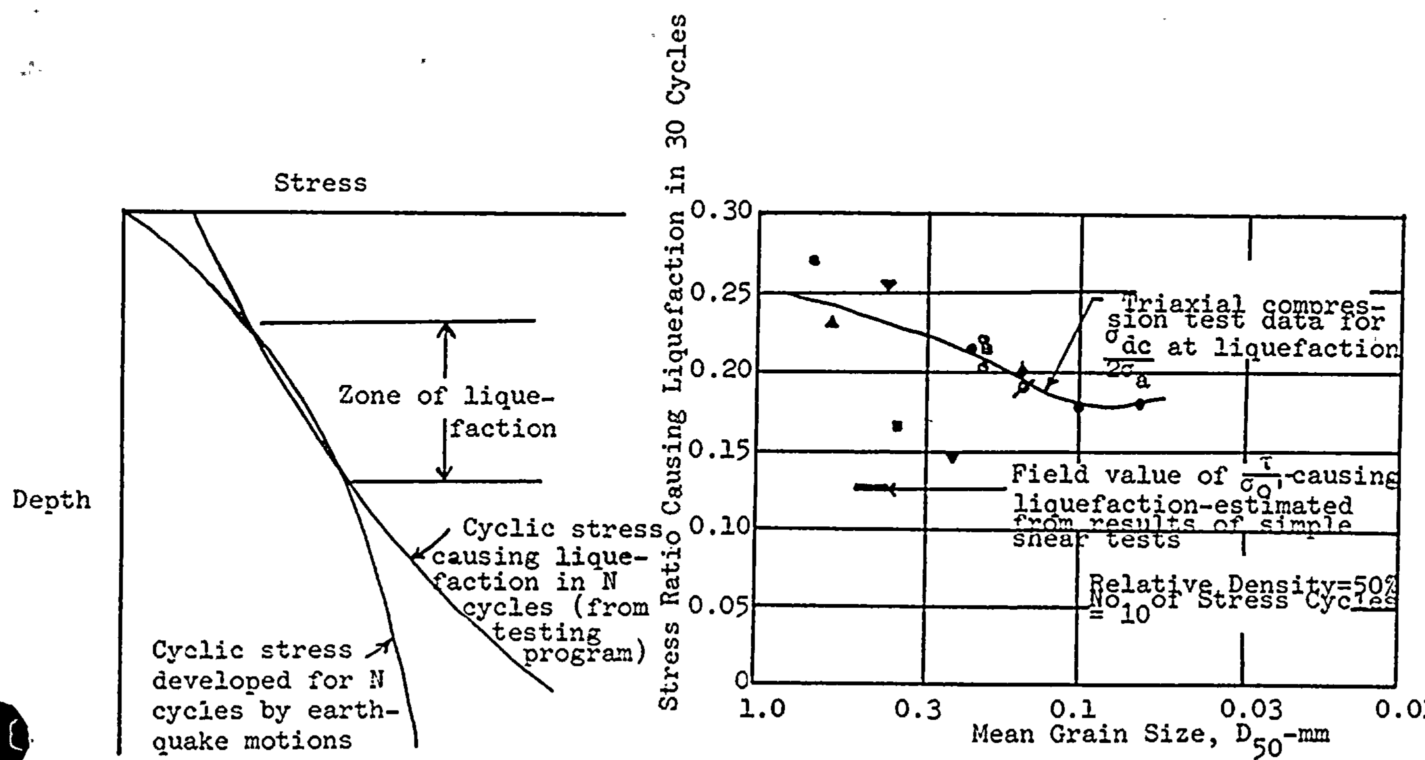
Fig. 2-4 Formation of a liquid layer and uparching, ejection, and subsidence.

Fig. 2-5. Multiple deformations that include uparching, diapirism, and faulting. For example see graben and subsidence in photograph c.

Fig. 2-6. Fluidization experiments with development of contorted bedding and diapirs.



a. Results of undrained triaxial test on loose saturated sand wherein axial stress alternates between 1 ± 0.39 kg/cm^2 while cell pressure is maintained at equivalent of 1 kg/cm^2.

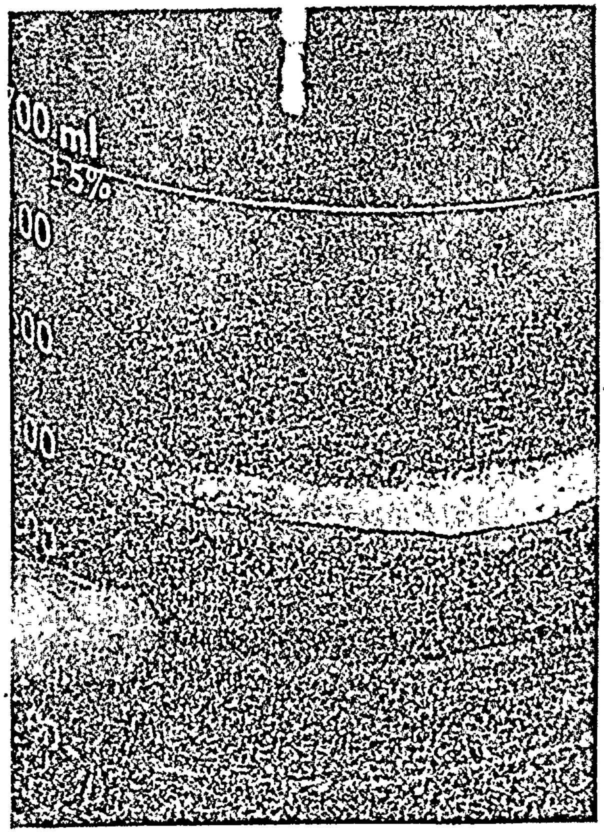


-METHOD OF EVALUATING LIQUEFACTION POTENTIAL

-STRESS CONDITIONS CAUSING LIQUEFACTION OF SANDS IN 30 CYCLES

b.

Fig. 2-1. a. Increase in pore pressure in cyclic loading (Seed and Lee, 1966)
b. Assessment of liquefaction potential (Seed and Idriss, 1971)



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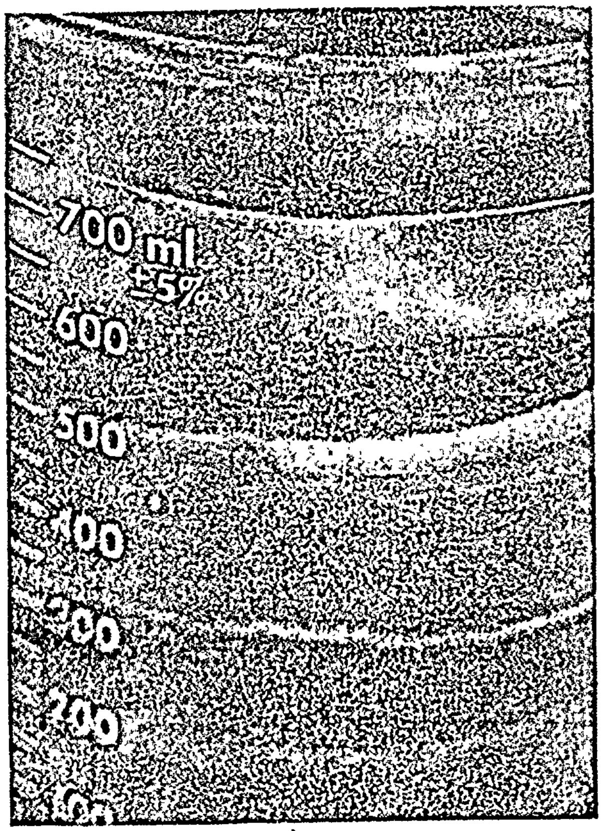

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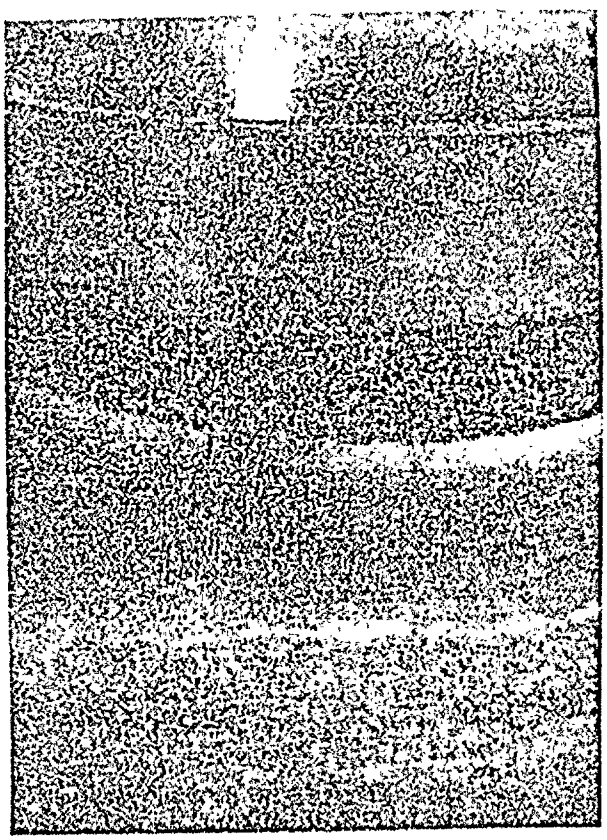

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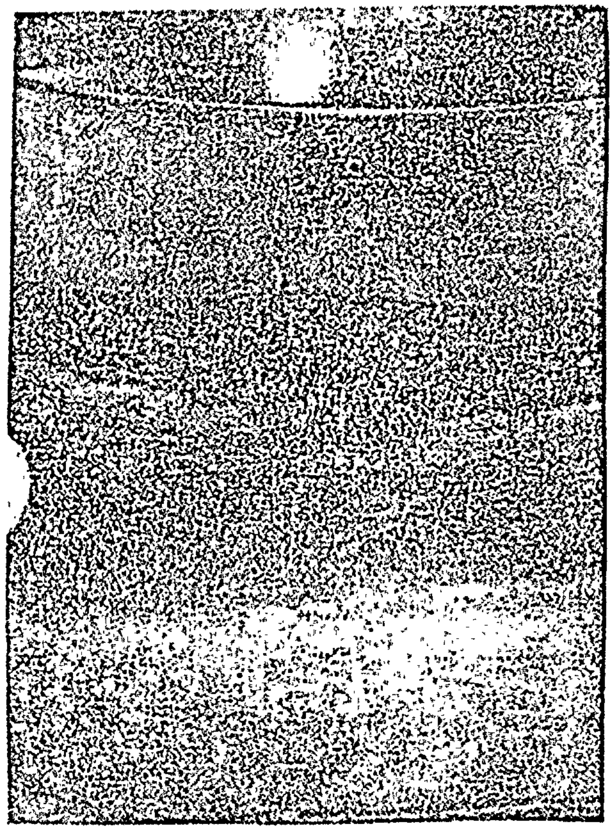

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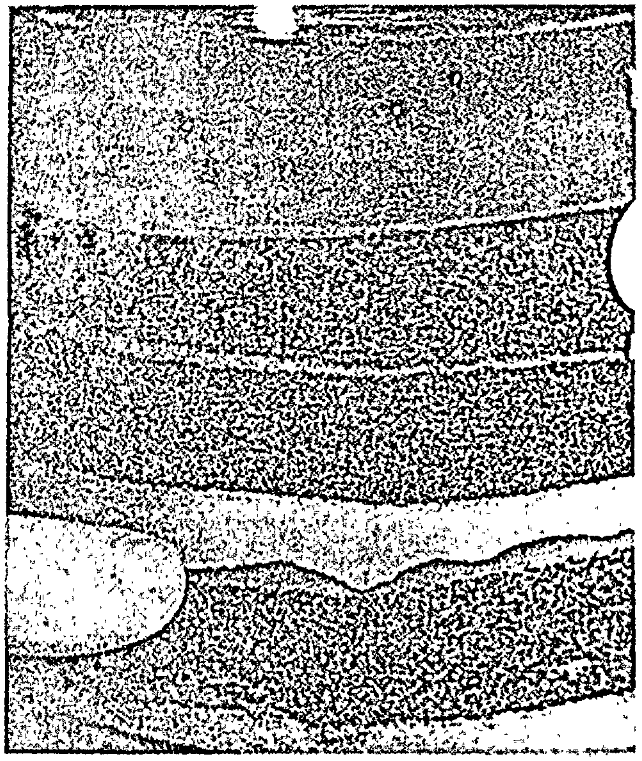

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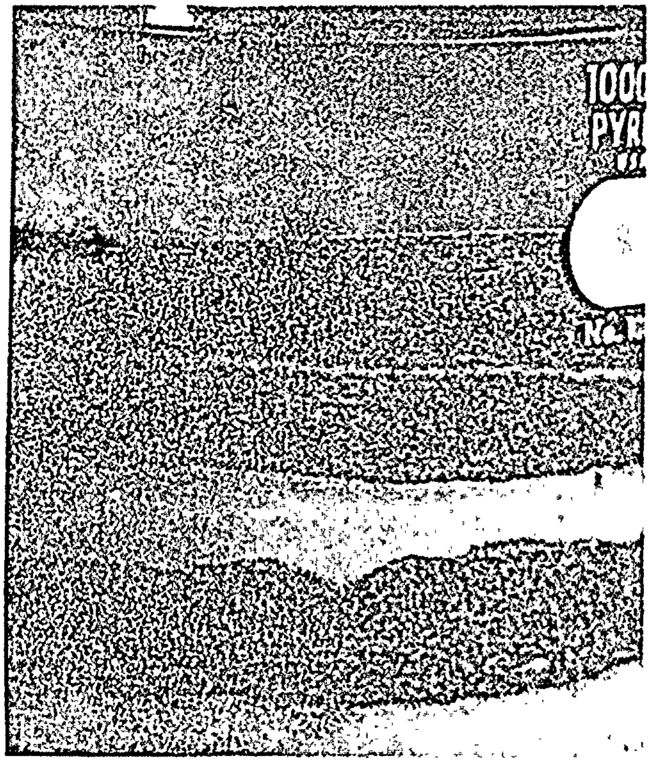

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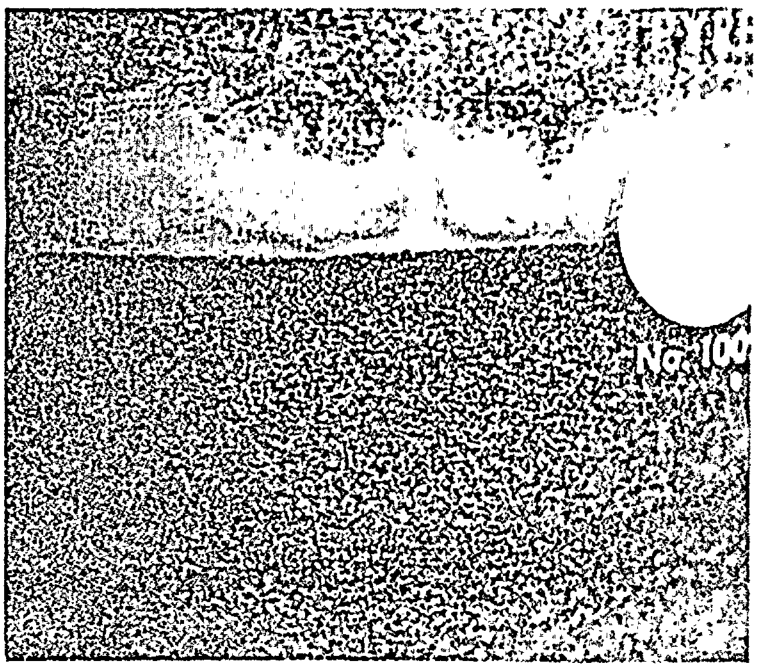

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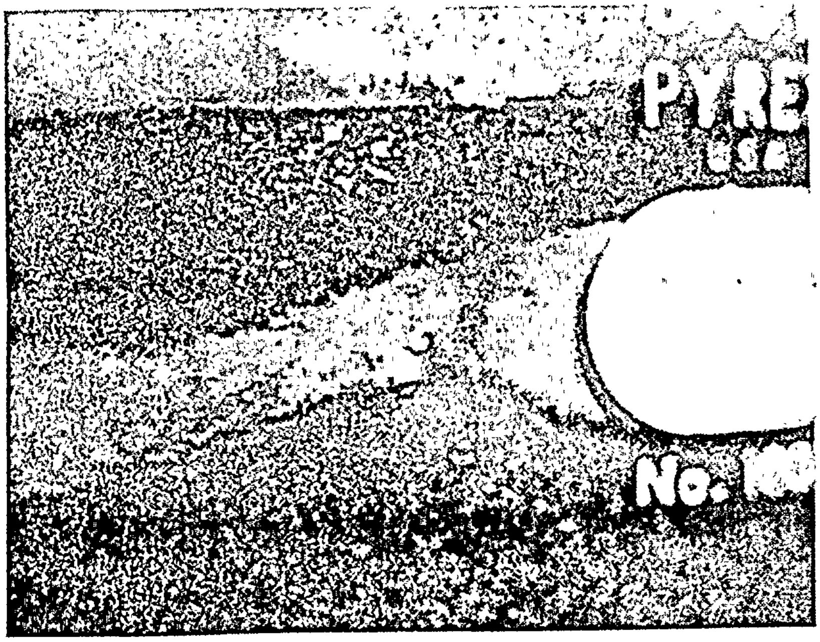

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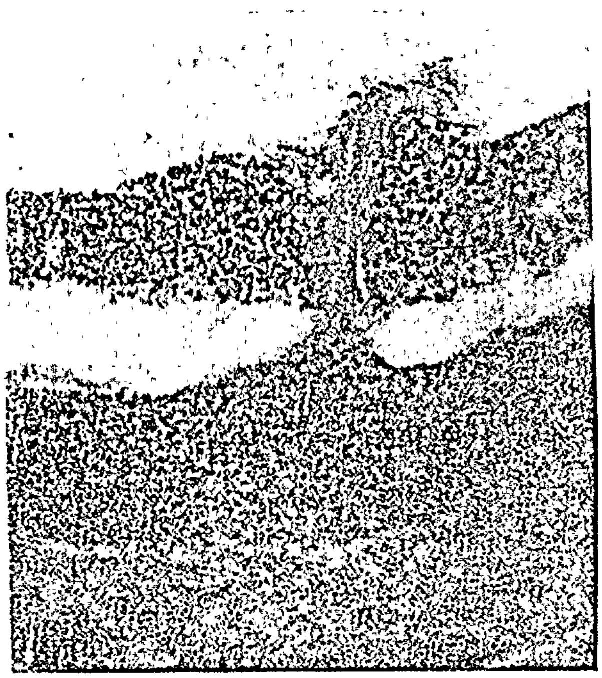

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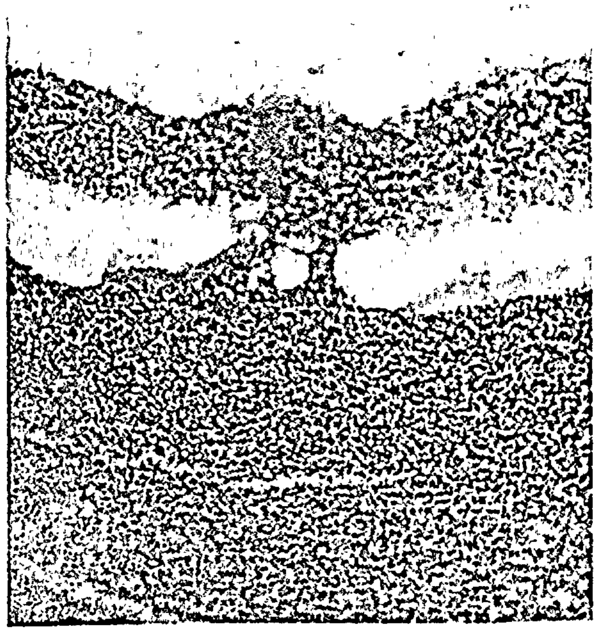

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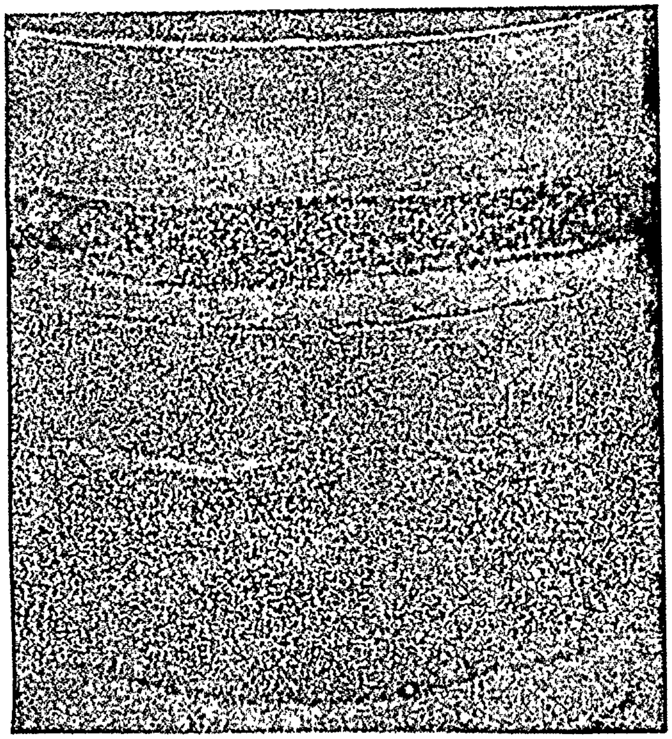

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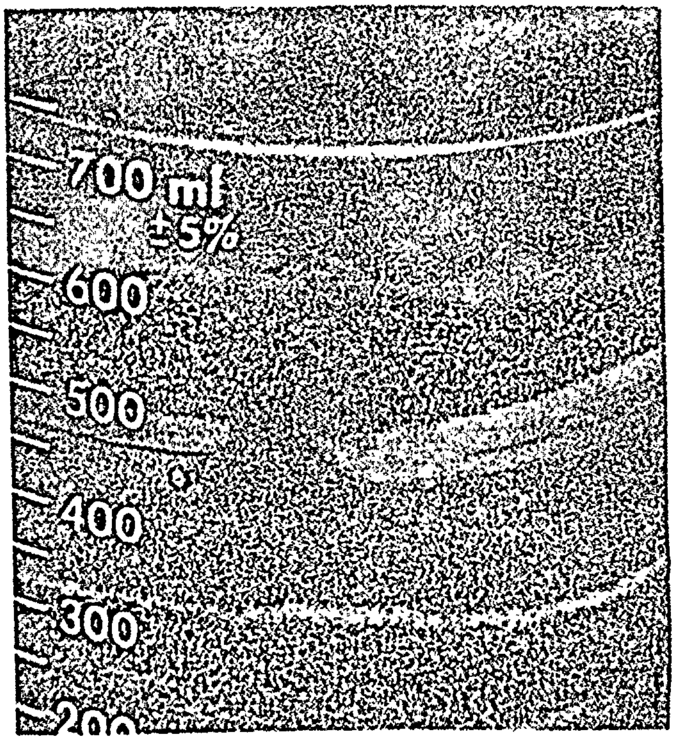

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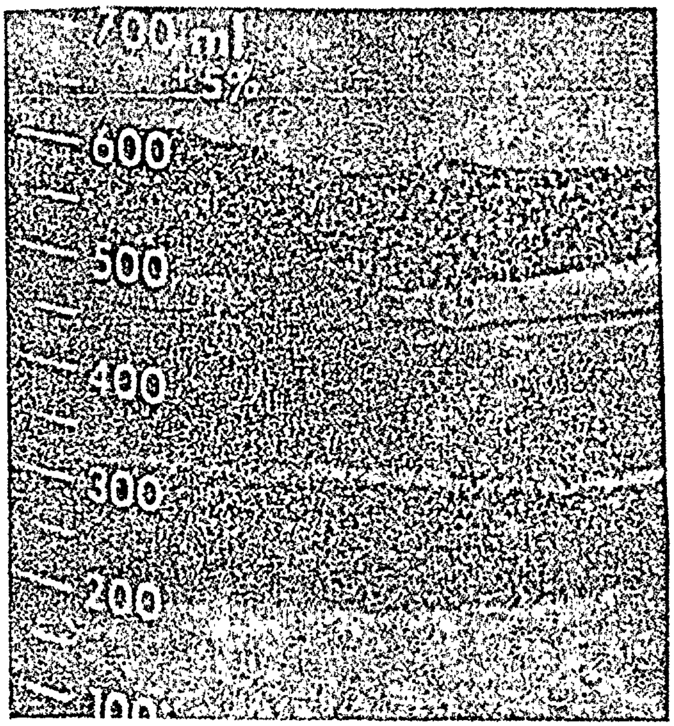

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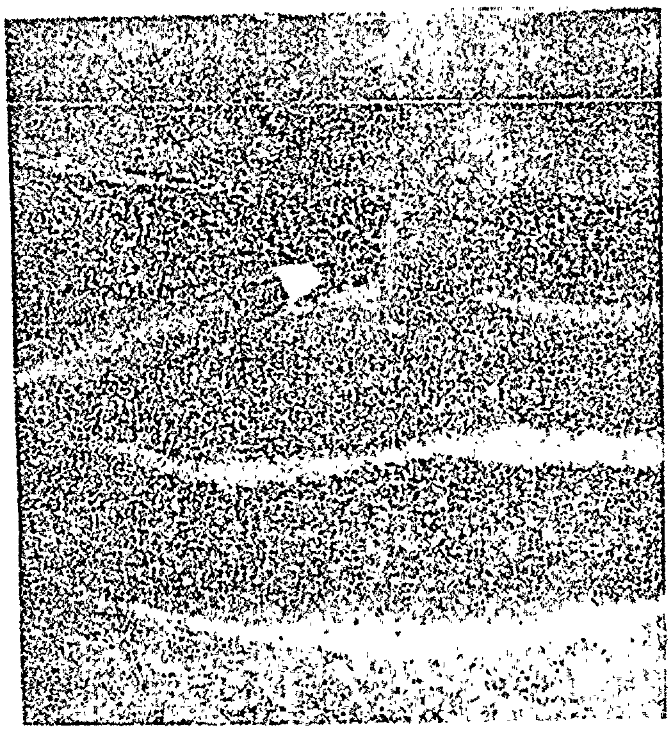

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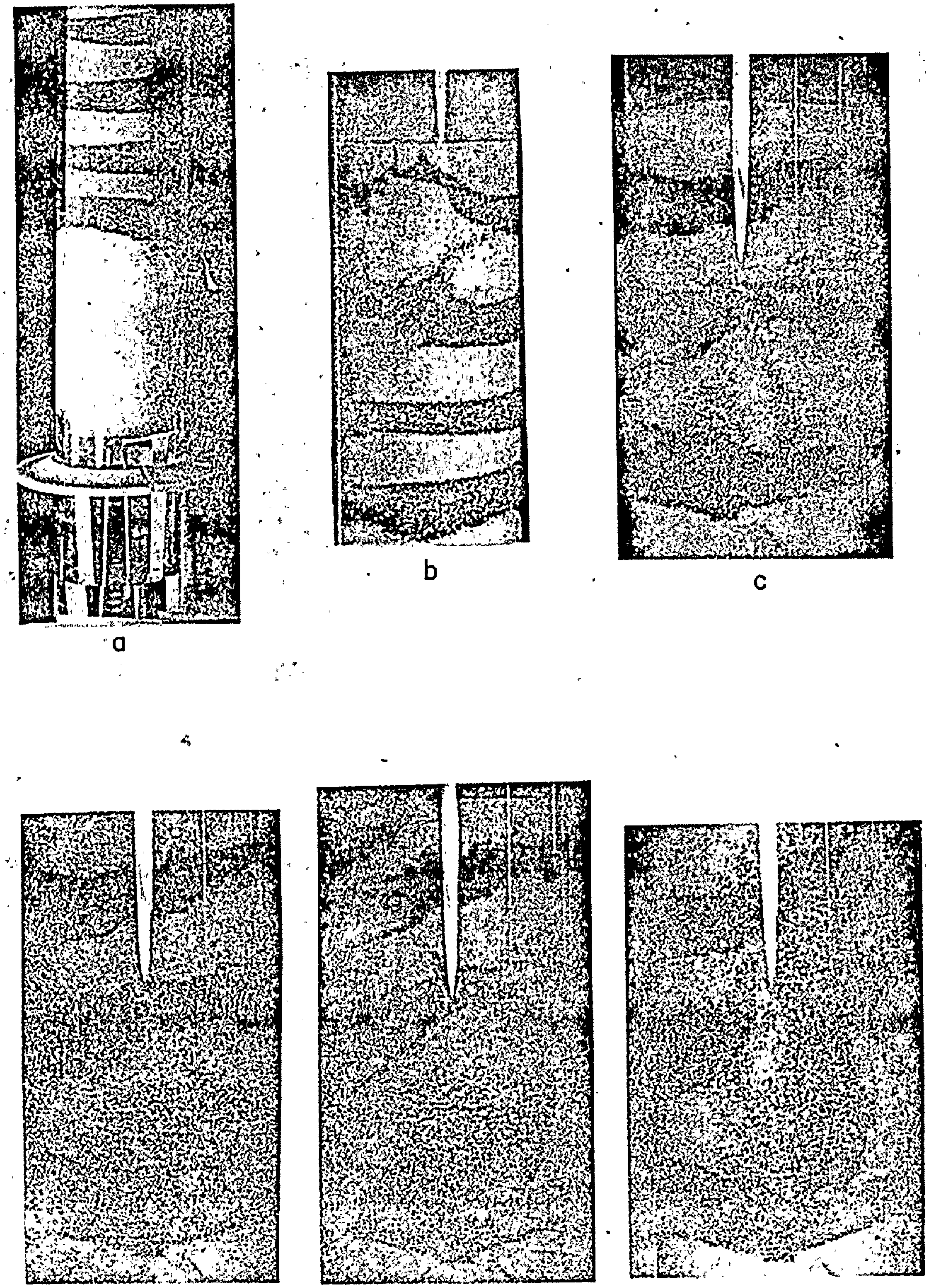

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appearing features from other regions. An elemental classification system is provided as a tool for easy reference, comparison, and discussion. The Law of Equifinality must be borne in mind at all times, however....that structures that visually appear to be almost identical may have been formed by different processes.. The selection of unique solutions and mechanisms to produce the features can be very elusive.

The following discussion of specific deformed structures is a distillation of viewing of more than 200 sand and gravel pits and 100's of sediment exposures throughout the St. Lawrence Lowland. Such features as herein described, however, are not ubiquitous in the region. Examples of faulted and folded deposits are much more common, for example, than are the occurrences of proved thixotropy and localities where diapir-type structures are present.

COMPLEXITY OF GLACIAL DEPOSITS

Of all the surficial processes that produce sedimentary deposits, the most complex are those processes associated with the glacial environment. Unravelling the history and genesis of specific sediments or structures is complicated by the vast phantasmagoria of events that comprise glaciation episodes. Some of the factors that contribute to these interpretative difficulties include:

1. Deposition agents. These may consist of ice meltout, basal lodgment, fluvial, lacustrine, marine, gravity, and eolian processes.

2. Sediment size. There is an entire gamut from clay and clay-silt size rock flour to boulders with every conceivable gradation and distribution of silt, sand, cobbles, etc.

3. Composition. Because glaciers can override drainage divides, exotic materials can be incorporated with all other lithologies over which the glacier moves.

4. Stratification. A complete range of bedding relations occurs from well-stratified units with horizontal and/or vertical continuity to those that change chaotically in all directions.

5. Sorting. Deposits may be completely and randomly unsorted, may be unsorted but with clast fabric, or may be well sorted with predictable grain sizing.

6. Depositional direction. Sediments formed in a previous glaciated terrane may have bedding attitudes as diverse as the compass azimuths. This occurs because glaciers may advance and "retreat" over the same area many times. Isolated stagnant ice remnants often remain, after the main glacier mass has left the area, and contribute their own unique brand of diverse deposits.

7. Depositional time scale. Some thick sediments may form in a matter of minutes or hours as in jökulhlaups, or even some surges, whereas others....as in true varves....may take 6 months or more to form a laminae that is 1-2 mm thick. See Mickelson, 1971, 1973 and Goldthwait, 1974, for rates of formation of different glacial units.

CHAPTER 3

GLACIATION AND DEFORMED SEDIMENTS

INTRODUCTION

An understanding of the general history of glacial sediments and their environmental setting is of paramount importance in the resolution of the problem for possible links of deformed strata with seismic events. The entire St. Lawrence Lowland has been repeatedly glaciated and is now covered with various thicknesses of Quaternary deposits. These materials, (1) consist of the entire range of sediment sizes, (2) have been deposited by vastly contrasting physical processes, and (3) possess an unusually large and complex array of deformed structures.

The purpose of this chapter is to provide the regional glacial framework for what comprise deformed units in Quaternary sediments of the St. Lawrence Lowland. This generalized aspect is intended to be only a first-order approximation. These concepts and tentative conclusions are those reached through glacial-type study of the features and sites. Such ideas are consistent with comparisons of other regions and constitute the types of interpretations that have been used for decades by glacial geologists throughout the world. It must be pointed out, however, that rarely have glacial geologists tested such features with the hypothesis that they might represent the results of an earthquake event. This certainly is one of the side benefits of this investigation....to provide a new stimulus and direction for study of Quaternary sediments that can give new insights into earth history.

It has become conventional practice for glacial geologists to attribute a wide spectrum of deformed glacial sediments to causation by processes connected with glaciation. Indeed such distortions have been taken for granted and only rarely have non-glacial processes been considered as possibly contributing to such features. No publications treat the entire scope of glacially-related deformation. Furthermore detailed quantitative field studies are lacking as are laboratory and experimental data on the topic. In recent years the number of field observations on modern glaciers has greatly increased, however, and results of these studies support the general view that glaciers cause a great variety of deformed structures in glacial sediments. There is still a paucity of publications in the glacial literature that treat the creation of distorted beds by liquefaction processes.

A principal focus of this chapter is to provide a reference frame so that the reader can visually identify the vast number of different types of Quaternary deformed sediments in the St. Lawrence Lowland. Comparison is made with similar-

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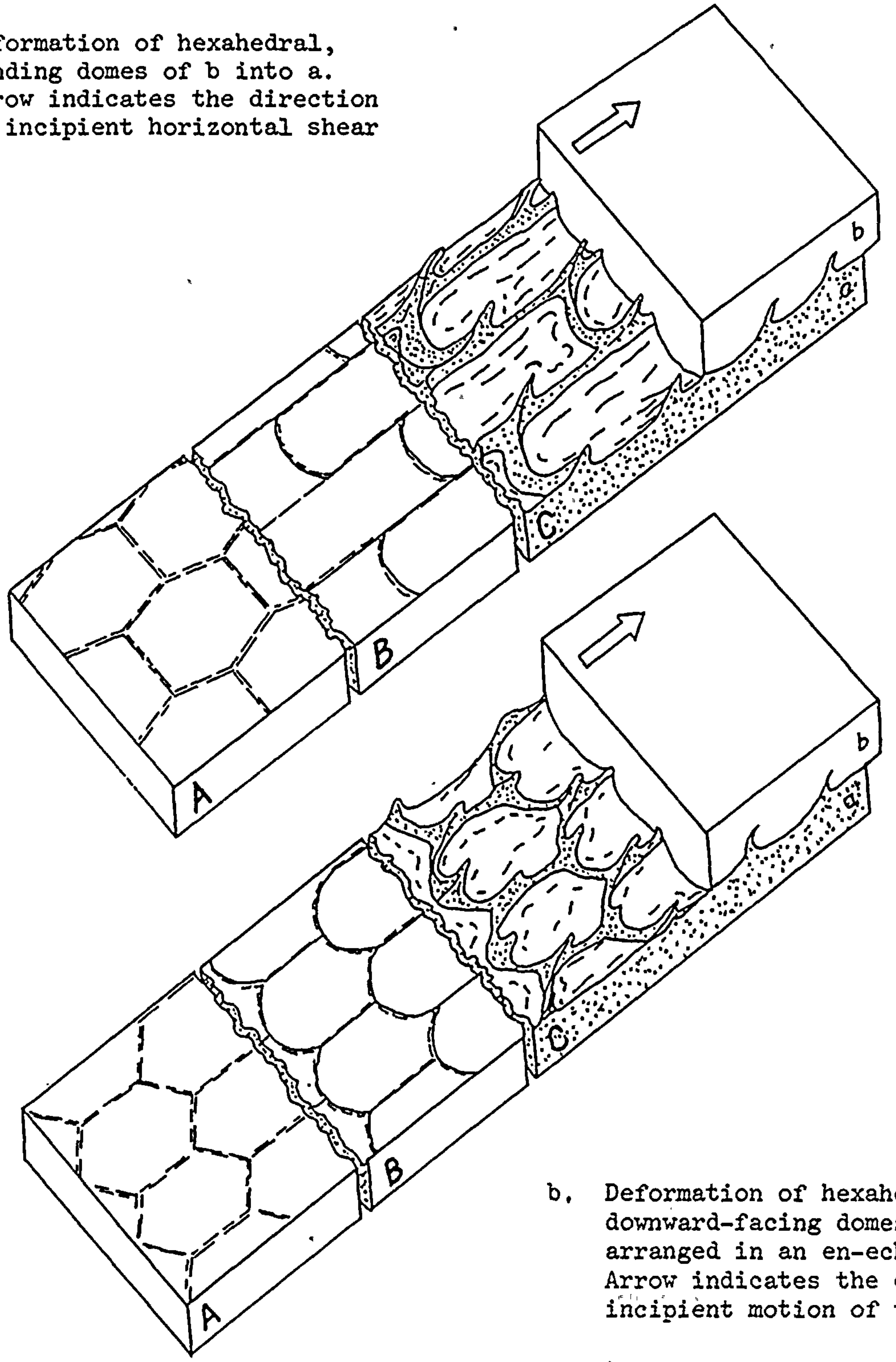
Prepared by Donald R. Coates and James T. Kirkland

a. Deformation of hexahedral, pending domes of b into a. Arrow indicates the direction of incipient horizontal shear



b, Deformation of hexahedral, downward-facing domes of b into a. arranged in an en-echelon pattern Arrow indicates the direction of incipient motion of the member b

Fig. 2-7. Structures of inverse density stratification (Anketell et al. 1970)

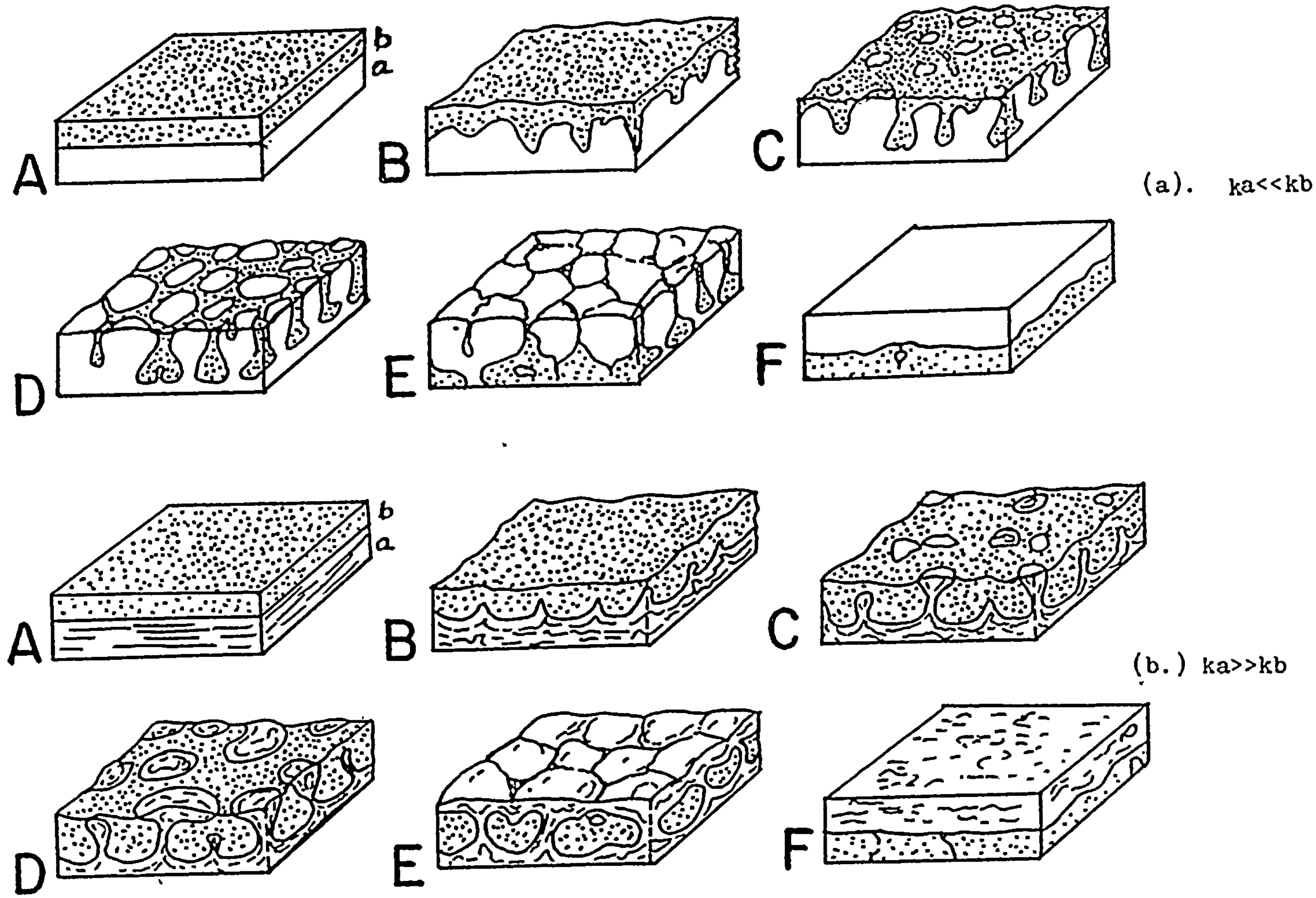


Fig. 2-8. Deformational stages in non-mobile systems (after Anketell et al, 1970)

Glacial Mechanisms that Deform Sediments

This section discusses traditional causes cited in the glacial literature to explain distorted sediments. The terminology used to describe the features is not consistent, so there is not a universally accepted nomenclature. Glacialists have used such terms as glacial tectonics, load casts, diapir, décollement, folds, thrusts, faults etc. Bibliographic indexes (viz. Geomorphological Abstracts) now reference these structures as deformed, convolutions, and involutions. Such sedimentologic terms as flame structures, ball and pillow, flow rolls etc. are rarely used in the glacial literature.

The power of glaciers to deform underlying sedimentary rocks is reported by Sardeson (1905, 1906), and Bluemle (1966), so it is not surprising that ice also transforms nonconsolidated strata. Slater (1926) provides an early review of glacially distorted deposits, and other reviews occur in Flint (1971) and Moran (1971). There is an unbelievably wide gamut of types, and scale of features usually attributed to glacial processes. The timing of the deformation ranges from being nearly simultaneous with deposition, to penecontemporaneous, to immediately postglacial. Thus, it is important to consider many possibilities when dealing with Quaternary sediment deformation and their diagenesis.

The following classification and description represents traditional glacial concepts and ideas that have been used to decipher the genesis of deformed strata in glaciated terrane. As in any study, one does not know what is normal and expectable until it is compared with other regions. This forms the basis of part of the entire investigation. Therefore, it was felt necessary to compare the St. Lawrence Lowland with, (1) California sediments that seem to have been deformed by seismic events (Sims, 1973 and in Press), and (2) Olympic Peninsula, Washington glacial sediments that may have been deformed by earthquakes. (See Appendices C and E). Another basis of comparison as provided in this chapter is also fruitful, namely, to compare St. Lawrence features with those glaciated areas in eastern United States that are not as seismicly active as the St. Lawrence. Many possible glacial methods for deformation of strata needed to be evaluated for this study. The following processes were used as guideposts and comparisons for the St. Lawrence Lowland.

1. Ice push. Sediments in front of the glacier can be shoved in snowplow fashion (Rutten, 1960; Deliwig and Baldwin, 1965; MacClintock and Stewart, 1965, p. 50-51; Embleton and King, 1968, p. 355-356).

2. Ice thrust. In the distal margin of the glacier debris is transported from the base upward along shear lines and thrust planes. When the ice melts the thrust sheets subside, assume shallower gradients, may deform internally, and develop imbricate structures (Mackay, 1959; Slater 1927a, 1927b, 1927c, 1927d; Clayton and Moran, 1974; Kaye, in Press; Mackay and Stager, 1966).

3. Glacier overriding. This process causes readjustment of sediments previously deposited over which the ice moves. The type and degree of contortions that are produced are highly variable and are dependent upon such factors as characteristics of the sediments, ice velocity, and temperature differentials. Thermal gradients are very important because they determine whether the sediments are frozen, and whether the basal ice is frozen to the ground. Thus the ability of the glacier to incorporate, or to deform basal sediment in place is a function of whether ice is at the pressure melting point or below. When sediments are frozen the high viscosity of the materials can cause them to deform but still maintain their internal integrity. If sediments have incorporated water, their fluidity is enhanced and the deformed fabric loses much of its original coherence. Examples of such deformation is provided by Hansen and others (1961), Banham (1965), and Flint (1971, p. 121-124). Figure 3-1 illustrates deformation in outwash beds by ice readvance over the deposit.

4. Static loading and compaction. This phenomenon is also referred to as "ice pressing" and involves the deformation of lower and older strata by the pressure of overburden materials. The additional weight of the overlying materials, which may be water, ice, or sediments, may cause sufficient force to disrupt the stability of the original strata. When this threshold is exceeded the sediments must readjust. Mobility of the units is enhanced when (1) the beds have a slight inclination, (2) there are differentials in overlying pressures, (3) the strata have layers of differing viscosity, and (4) sediments have abundant free pore water. Literature references to such types of deformation include, Harrison (1958), Hansen (1961), Watson (1965), Okku (1967), Stankowski (1969), and Leeder (1972). They present discussions with pictures that show thixotropy of the sediments plays an important role in the resulting structures, which consist of load casts, and diapirs. Figures 3-2 to 3-6 have previously been described in earlier works and illustrate structures formed by these processes.

5. Collapse by ice meltout. Probably the best known, documented, and most common examples of glacially deformed strata are those associated with ice contact deposits. In this environment blocks of ice can be buried, as in kames or in pitted outwash plains, by the superposition of younger sediments. Although such deposits act as insulation for awhile (in cases many hundreds of years), eventually the ice mass melts and the overlying beds subside and drape into the vacated depression. Such subsidence causes a steepening of dips, and results in such features as folds, faults, shearing, and sliding. Dionne (1970), Flint (1971, p. 185, 212-214), and Brown (1933) provide a few of the examples that occur in a rather large literature on the topic. Figures 3-7 to 3-10 illustrate deformation features such as folds and faults, in a well-documented case of a pitted outwash and ice contract complex at Binghamton, N. Y. (Coates, 1973).

6. Free-standing ice margin. When sediments are deposited against an ice wall another group of structures can form when the ice melts and the beds can no longer maintain a supported steep face. The units gradually adjust and move by gravity

toward the former ice face. Thus original dips are shifted in opposite direction and processes of solifluction and earthslides activate the sediments. Such depositional types occur in crevasses and depressions in the ice, and at the terminus of the glacier.

7. Frozen ground phenomena. Terms used in the literature to describe the variety of forms that result from this process include, periglacial, permafrost, perennially frozen ground, cryogenic features, cryoturbation etc. Books have been written on the topic (Péwé, 1969) and there are journals devoted entirely to the subject, such as the Biuletyn Peryglacjalny. Deformed sediments caused by these processes are produced by the thaw-freeze cycle, and can contain a great range of distorted shapes. References that are especially relevant to the St. Lawrence situation include publications of Mathews and Mackay (1960), Johnson (1962), Watson (1965), Péwé (1969), Hails and White (1970), and Leeder (1972).

CLASSIFICATION AND CHARACTERISTICS OF QUATERNARY DEFORMED SEDIMENTS

The great complexity of deformational features in surficial materials of the St. Lawrence Lowland make it difficult to classify precisely a coherent and consistent framework. Since the distorted strata show great scale and geometric pattern differences, it is felt that the most useful classification system would be one that is descriptive and non-genetic. This method avoids an initial bias for causation of the deformation and the features can be easily compared and contrasted with those of other regions. Correlation has always been a cornerstone of geology. Thus, St. Lawrence deformed sediments should not be discussed in isolation but instead should be cross-referenced with somewhat similar appearing features from other regions and terranes. By comparison with other parts of eastern United States, with Sims' localities in the West, and with examples from other publications a more comprehensive picture can be painted for the part that glacial processes may, or may not, play in the development of Quaternary deformed sediments.

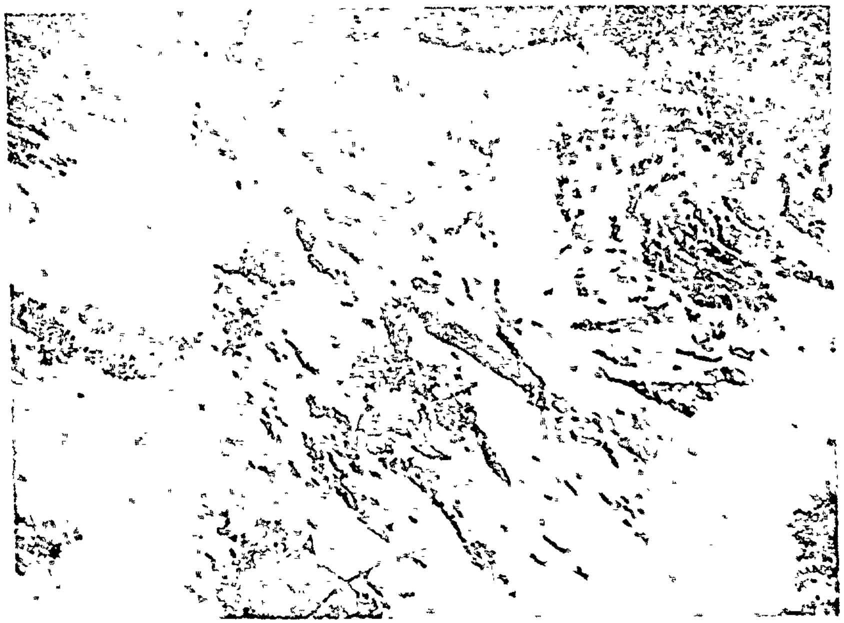
The following descriptive geometric classification scheme is adopted because of its simplicity and non-genetic flavor. Six major families of distorted strata are identified, but it should be understood that various suborders of units can occur within each of these categories. Indeed there is a continuous series of forms within each group, as well as transitional forms that cross the boundaries of the classes. For example, there is a large range of deformational features that vary in size from microscopic to those that are many feet. Folds and faults occur in every conceivable type of bedding condition but nothing is gained to have a classification system that contains only a single class. The major emphasis of the discussion is placed on a glacial appraisal of the features, whereas the detailed sedimentological analysis of specific forms at type localities is treated in Chapter 4.

Fig. 3-1. Kame delta and outwash sands near Dutch Plains, Long Island, New York. The sediments are associated with Montauk drift events. Reports of the New York State Geological Association 40th Annual Meeting, May 1968, stated the deformed units resulted from ice readvance.

Fig. 3-2. Kame delta near Toronto, Canada. Reports at the Friends of the Pleistocene 38th Annual Meeting May, 1974, interpreted the deformed structures as developing from a type of gravitational sliding induced by the unstable glacial environment.

Fig. 3-3. Kame delta near Stroudsburg, Pennsylvania. Picture taken during Friends of the Pleistocene 39th Annual Meeting, May 1975. The sands in the delta were overridden by glacial ice which deposited till on top. The contorted layers were interpreted as resulting from processes connected with the dynamic glacial environment.

Fig. 3-4. Kame delta built into Glacial Lake Hitchcock. Locality near Lebanon, New Hampshire, east side of Connecticut River. Deformed sands caused by gravity sliding on underlying varved clays. Initiating mechanism reported as associated with unequal loading.



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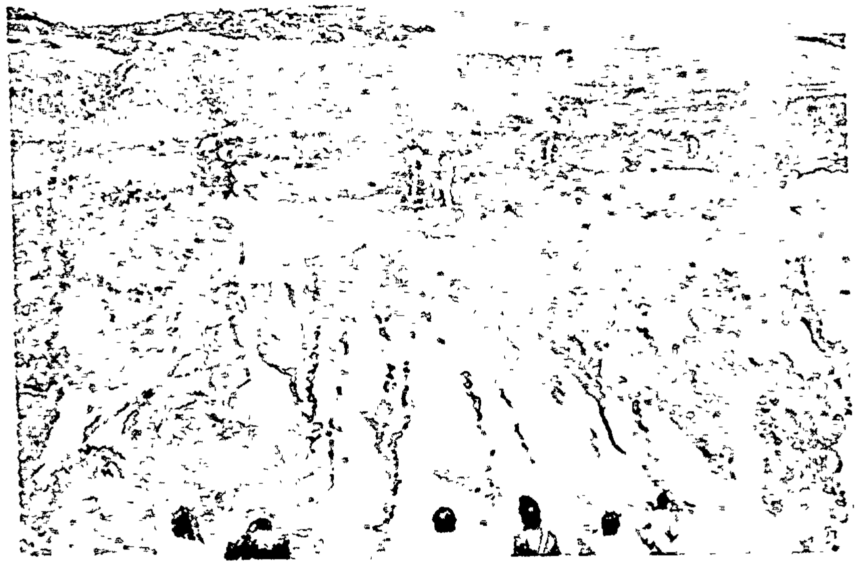

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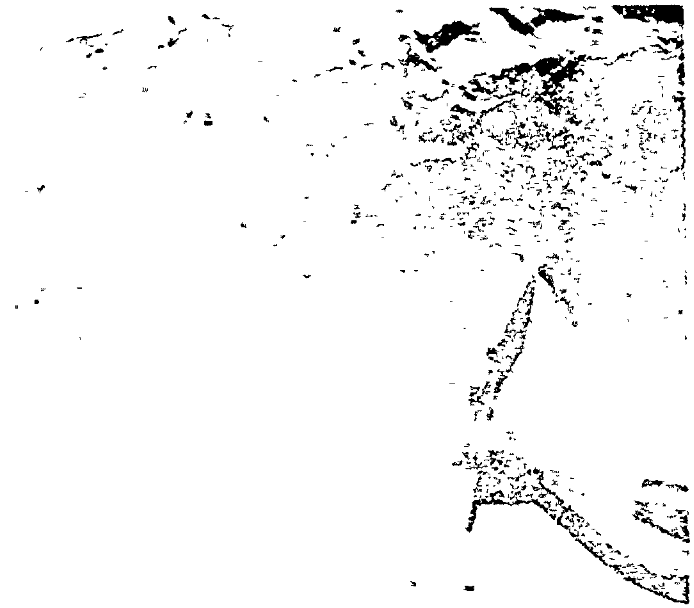

3 - 3

3 - 4

Figs. 3-5, 3-6, 3-7. Complex pitted valley train outwash at Van Pit, Corbisello Quarries, Binghamton, New York. Figures 3-5 and 3-6 show deformed sediments at a contiguous outcrop in sands, silts and clays. The structures developed under conditions of thixotropy and the deformation was initiated by pressure of overlying units being deposited while sediments were in a low state of viscosity. Figure 3-7 shows folds and faults in varved sediments. Nearby relations of adjacent units shows the structures were caused by meltout of ice block to the right of the photo.

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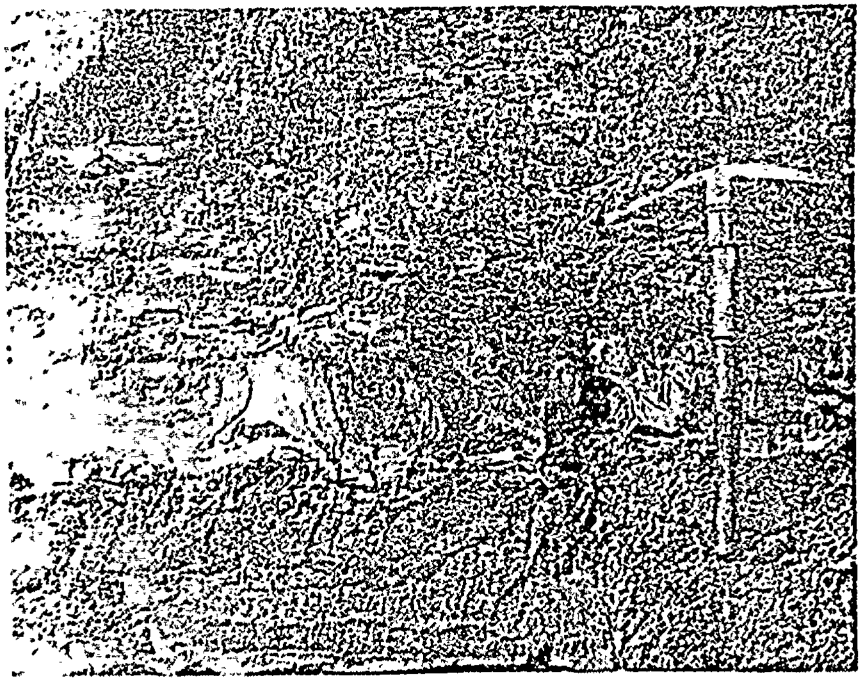

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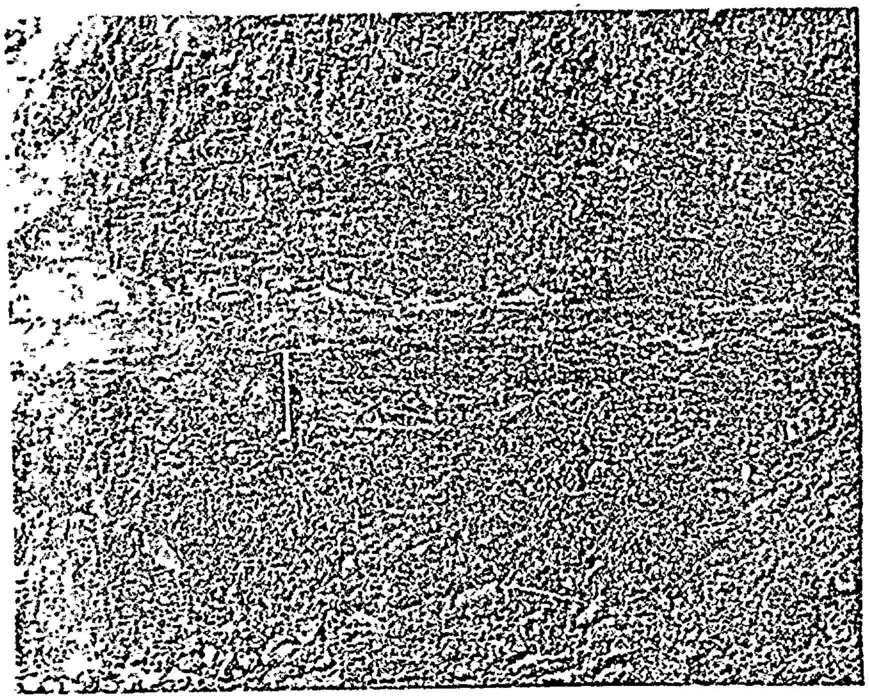
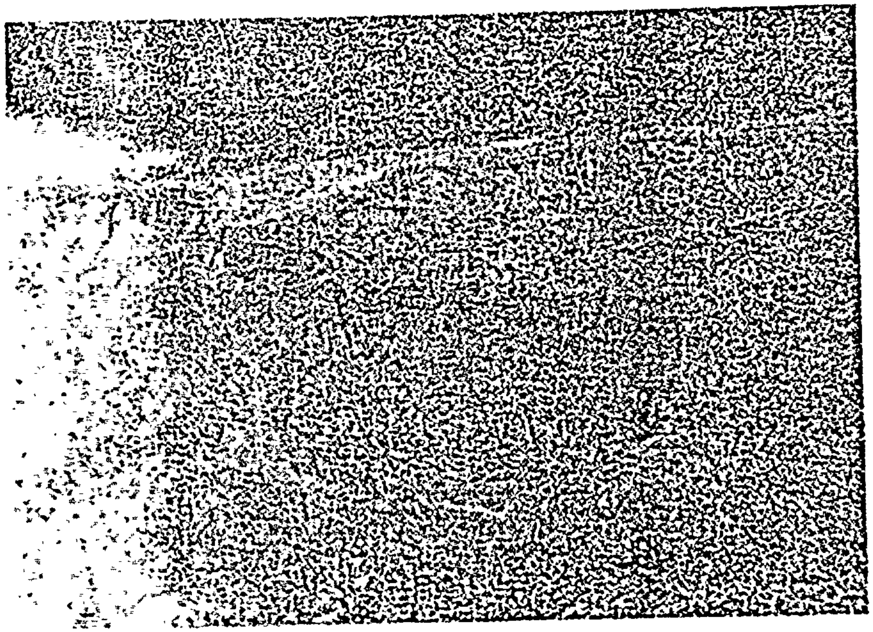
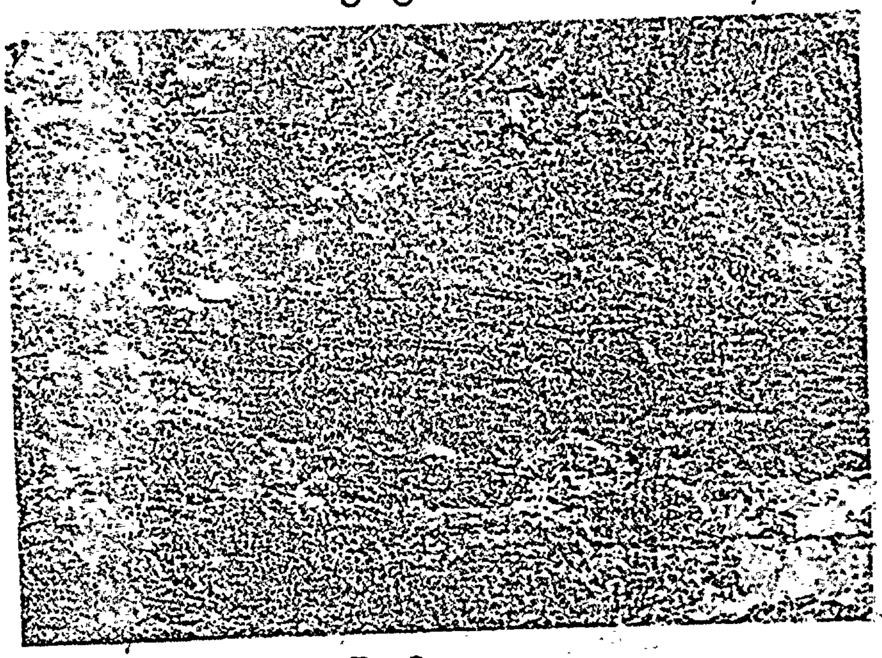



3-7

Figs. 3-8 - 3-10. Van Pit, Binghamton, New York, Figure 3-8, shows faulting that was caused by moderate collapse of units into a melted out ice block. Folded structures of Figure 3-9 are in varved sediments caused by loading pressure from overlying units. Figure 3-10 shows detail of overturned fold in varved sediments. Feature developed by loading and slippage of units. To the left of photograph, ice block meltout caused varved sediments to assume steep dips, and the sliding and adjustment between varved units of differing viscosity produced a feedback mechanism that also affected and deformed some contiguous strata.



3-8



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3-10

Classification of Deformed Sediments

The following classification is provided as a handy reference frame so the reader can easily visualize and compare various geometric sets of deformed Quaternary deposits in the St. Lawrence Lowland. By using such a system it becomes vividly apparent that there is wealth and variety of deformed structures, and the way is paved for their detailed analysis in Chapter 4.

1. Small scale deformation. This class is reserved for those sedimentary features where the deformed unit is restricted to the confining stratum and is > 1 ft. These forms are best observed in laminated clays and the type of structure invariably consists of folds and/or faults. Figures 3-11 to 3-16 illustrates this classification, and such photographs should be compared with Figures 3-9 and 3-10 which represent structures in aseismic terrane. Such features are usually explained by loading stresses caused by subsequent deposition of overlying materials. The units generally do not involve thixotropy, although when thicker and also when closely associated with other units they may grade into deformation patterns that involve liquefaction. See upper strata in Figures 3-11 and 3-16, and middle stratum in Figure 3-6. The resemblance of such small-scale diapiric structures in both the St. Lawrence Lowland and the nonseismic Binghamton area, suggest they were both created by the more usual process of loading phenomena during glaciation, than from seismic events.

2. Folds and faults in dipping strata. These structures occur where the confining stratum has pronounced dips which are considerably greater than the original depositional bedding attitude (Figs. 3-17, 3-18). Thus, strata may possess dips that greatly exceed the normal angle of repose for such materials. Fault planes may also severely contort the units. The principal cause is generally conceived to be the meltout from a preexisting ice block over which the sediments were deposited. This mechanism leads to the ultimate collapse and subsidence of sediments into the vacated space, resulting in an entire range of deformed features including slides, folds, and faults. Deformed sediments in this class can usually be assigned a glacial origin with little controversy about the stress source. In some situations, however, the mechanism for the distortion needs more careful evaluation. Ice contact forms of the St. Lawrence are not greatly different than those from other regions. For example compare with Figures 3-7 and 3-8.

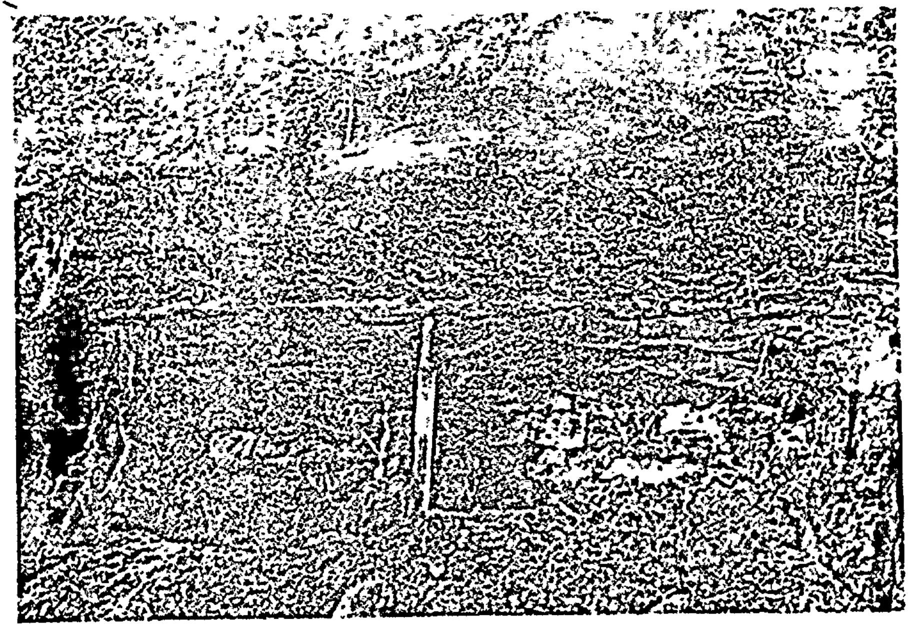
3. Folds and faults in horizontal strata. Deformed sediments in this group possess a wide range of structures, grade into several other classes, and were not formed by a single process. One of the subsets within this category are those folds that have maintained their coherence and continuity with well-ordered fold axes that exhibit a preferred direction of strain. Such structures developed by a differential sliding pressure which could be initiated by ice readvance or by differential loading that permitted sliding in a direction of lesser stress. Compare Figures 3-19 and D-3 and D-4. Rotational faulting is illustrated in Figure 3-20 within a stratum that contains confining horizontal beds, and Figure 3-21 illustrates a fault plane within flat-lying units but shows evidence for multiple deformation events.

The initiating mechanism for this gravitational slide is obscure, but it was not a meltout phenomenon. Figures 3-22 to 3-25 depict transitional forms that contain more complex relations. Figure 3-22 occurs in a continuous outcrop with Figure 3-19. The faulted structures along with the small-scale anticlinorium overlying the asymmetrical folds were most likely caused by unequal loading stress when the materials had rather low viscosity, but still were sufficiently rigid to shear and maintain coherence. Figures 3-22, 3-24 and 3-25 provide a range of other anticlinal properties and may all have been formed by different processes. Figure 3-23 shows vertical mobilization of materials in the anticline core that assisted in the arching process. When this feature is considered in the total context of the outcrop (see Figure 3-34) many of the sediments possessed thixotropic properties which were set in motion by overburden pressure of confining strata. The overturned anticline in Figure 3-24 may have formed when ice overrode the sediments. This interpretation is consistent with the kame moraine setting of the deposit. Note the similarity with Figure 3-36. A slightly different structure is illustrated by Figure 3-25. This feature was also formed by processes associated with glaciation, but the most plausible cause was by ice shove directly into the deformed unit.

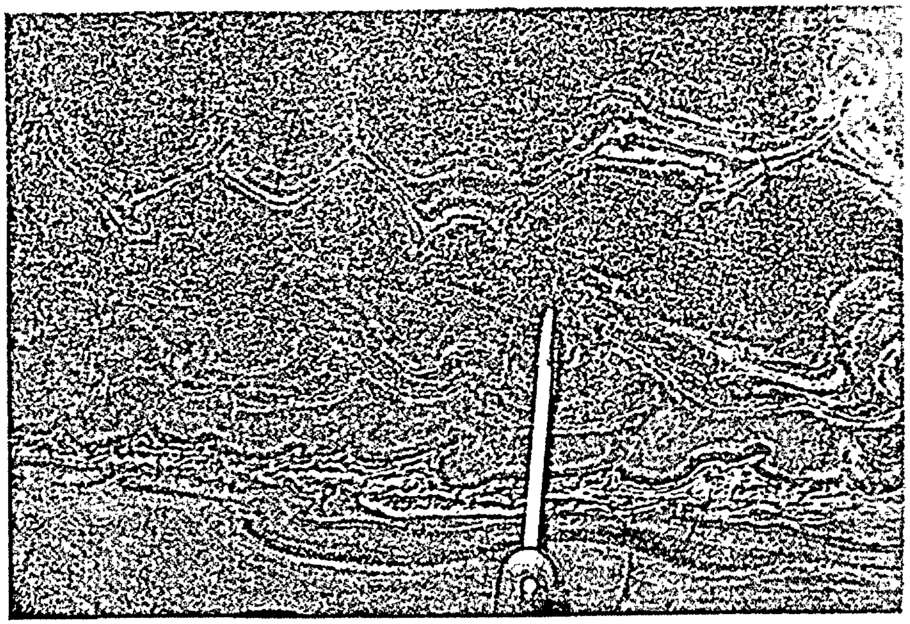
4. Recumbent folds. This class is reserved for those folds with axes that are nearly horizontal. Figures 3-26 to 3-29 illustrate that deformed beds in this class show a wide range in materials, size, and shape. The mechanics of maintaining continuity in clays is understood and reasonable but the problem enters when granular and friable materials retain their coherence. Figure 3-26 shows axial plane thickening indicating some flowage in the sediments during the time of their deformation. The photos of sand and gravel folds in Figures 3-27 and 3-28 indicate remarkable continuity but Figure 3-29 is a special enigma. The regional setting of these deposits is helpful in giving additional insight into the possible stress mechanisms. All deposits occur in kame delta settings with evidence that the ice margin was pulsating. Glacial override is a reasonable hypothesis for similar type deposits (compare with Fig. 3-1). In order for the granular materials to maintain sharp boundaries they were probably partly frozen during the folding episode.

5. Diapirs. Although detailed discussion of these features is contained in Chapter 4, the environmental flavor, regional setting, and comparison of these structures must first be placed in proper perspective. Features included in this class have a diverse nomenclature such as flame structures, sand dikes, ball and pillow, flow rolls, etc. The elements they have in common include cross cutting of confining strata, evidence that pressure release was primarily vertical, the minimal development of faults, and the existence of some state of thixotropy. The photographs used to depict these structures were all taken of exposures of deltas and invariably the diapirs are best developed in bottom-set

Figs. 3-11 - 3-14 are all taken of the same face in a kame delta. This exposure is located 1 mi. west of the village of Worcester, New York, near Route 7 in the Schenevus River valley. All views are looking east. The deformed strata are sands and silts which are capped by coarse gravels that are poorly sorted. Figure 3-12 is closeup of Figure 3-11, and Figure 3-14 is closeup of Figure 3-13. Under the deformed strata are ripple drift sequences of sand, and these have also been folded. There is a relation to fold wavelengths and the ripple drift. The folding and faulting show very low order of thixotropy, and the deformation was probably not associated with seismic events. Instead the presence of thick coarse grained gravels above, and of till (Fig. 3-33) in the overburden of nearby deposits indicates a dynamic ice margin with a pulsating glacier front created by readvance. Compare these photographs with Figures 3-19 and 3-22 of somewhat similar sites and conditions in the St. Lawrence.



3-11



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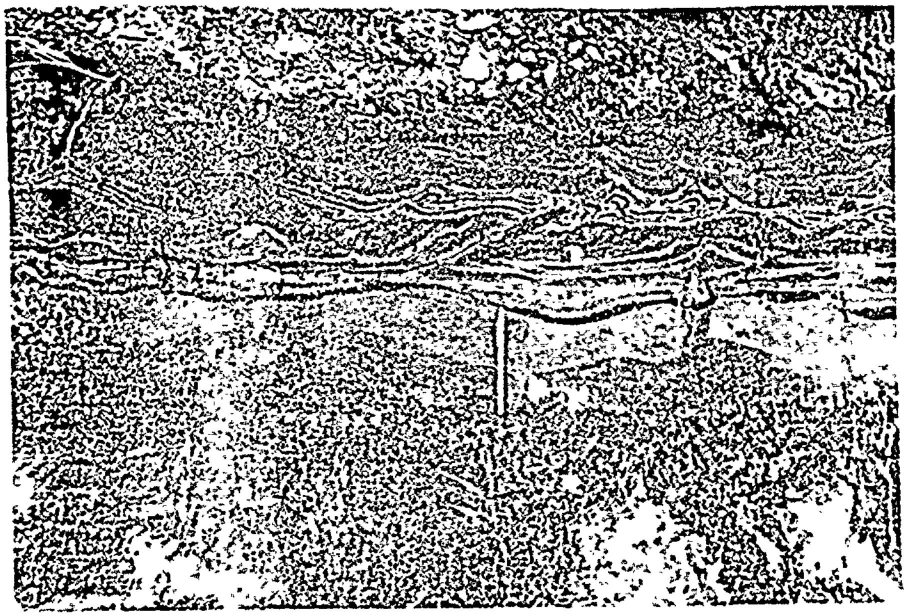

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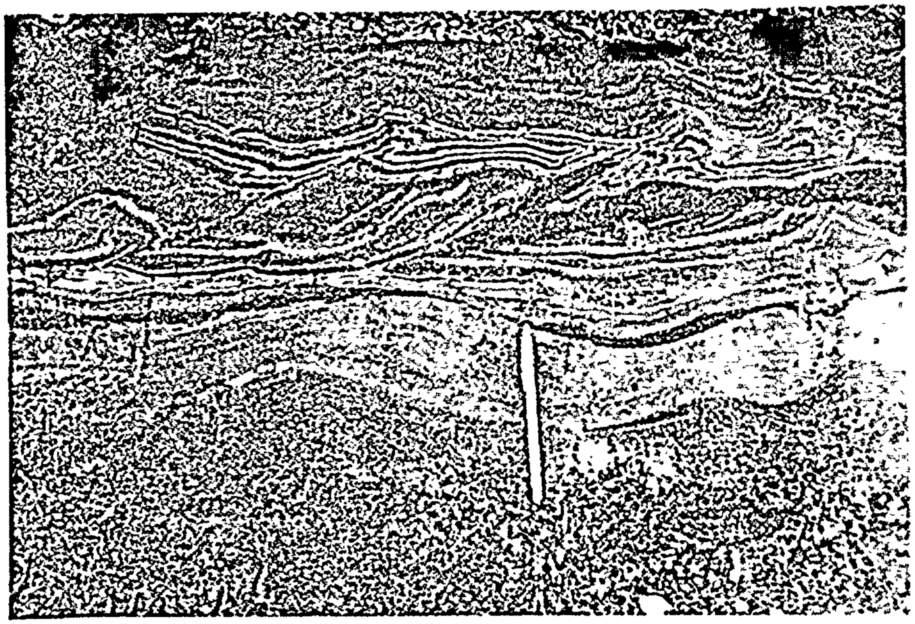


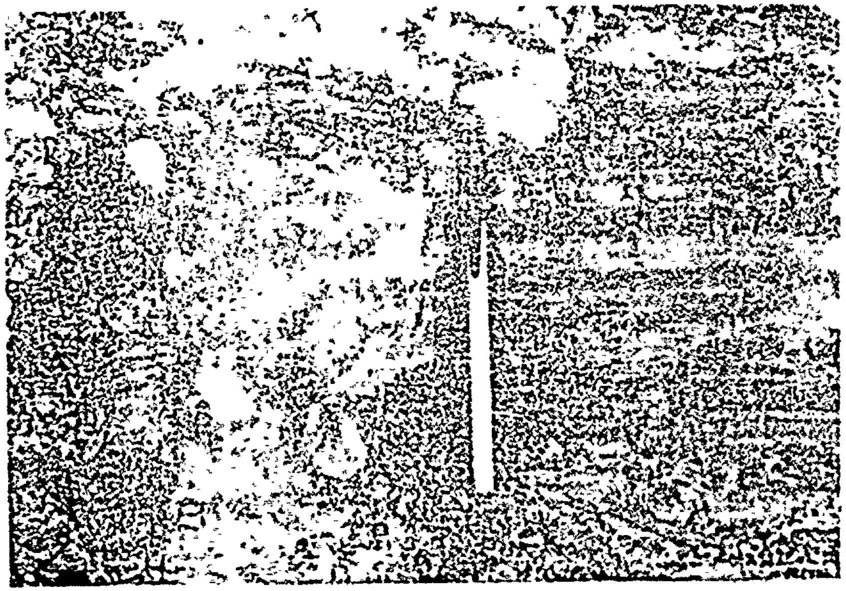
3-14

Fig. 3-15. (locality 8). Champlain Sea rhythmites on north side of sand pit. Small scale folds and faults are most common type of deformation and were probably caused by non-uniform overburden pressure.

Fig. 3-16. (locality 8). Another view of laminated sediments near Figure 3-15. Middle units are folded and faulted, and an upper unit shows major displacement of thixotropic units.

Fig. 3-17. (locality 11). Downward displacement of strata caused by meltout of ice block in kame. Collapse of enclosing sediments filled the depression. Light-colored sand unit in center shows folds and faults in stratum whose dip exceeds angle of repose of materials.

Fig. 3-18. (locality 9). Kame delta deposit in the Marion Construction Co. pit. Severely deformed sand and gravel units are faulted and contorted into depression created by ice meltout blocks.



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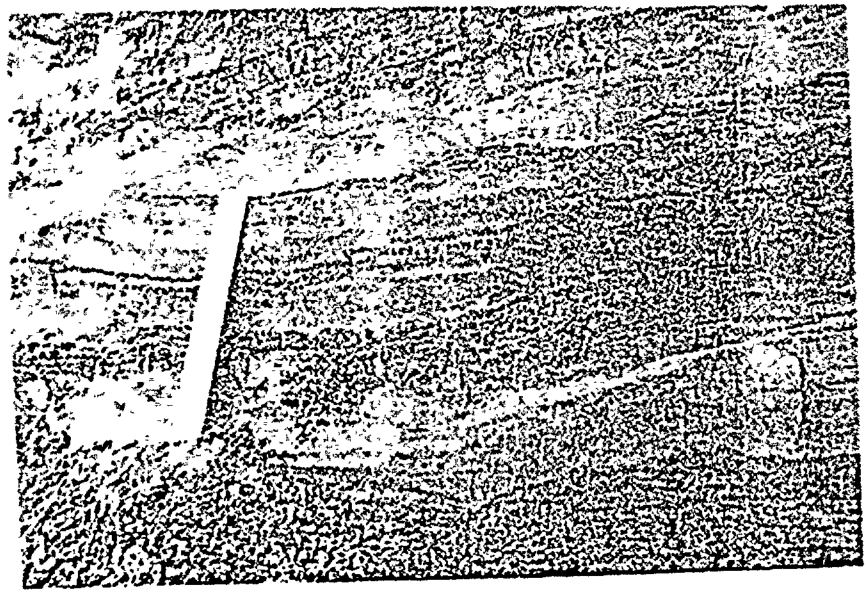

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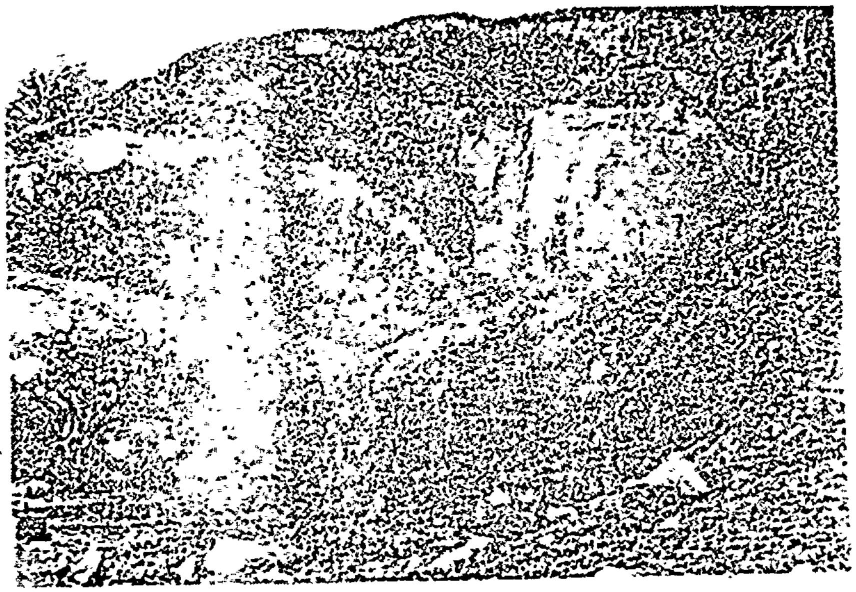

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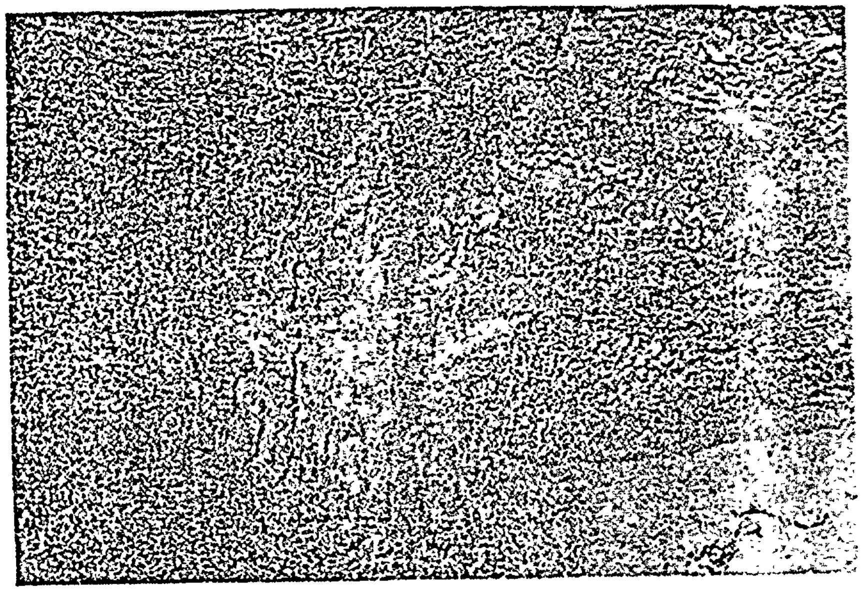


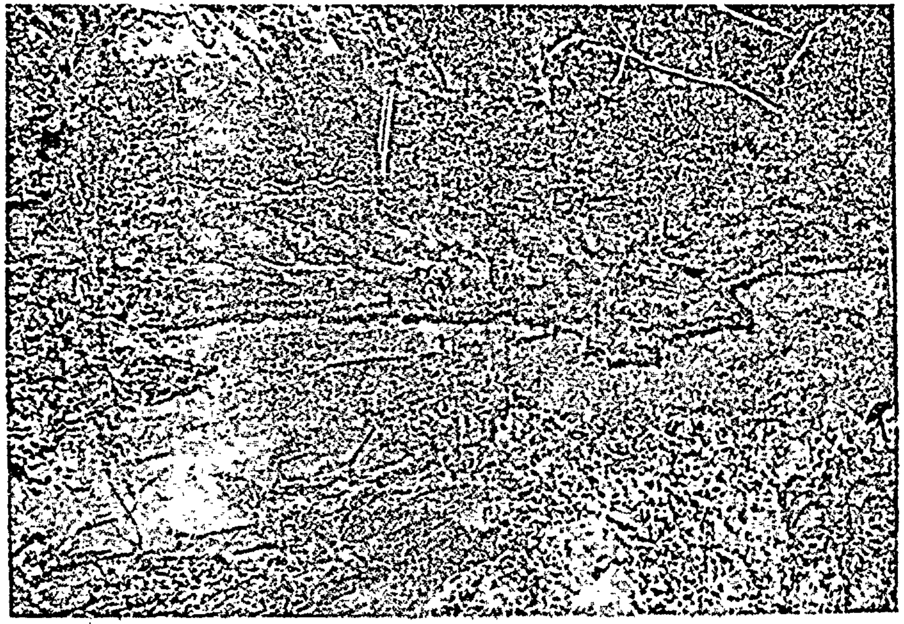
3-18

Fig. 3-19. (locality 17). Asymmetrical folds created by shearing and sliding from right to left. Sediments are fine sands and silts. Bottom unit contains diapir development. Kame delta sequence deposited during ice margin pulsations. Structure formed by ice readvance or differential loading that proceeded from right to left.

Fig. 3-20. (locality 3). Rotational block faulting in a horizontal sandy stratum. This site is part of a complex kame moraine-kame delta sequence that contains many other deformational types as in Figure 3-37.

Fig. 3-21. (locality 12). Shallow dipping fault plane in essentially horizontal sand beds. Several generations of deformation are indicated. The contorted breccia blocks in the hanging wall were deformed before the faulting event. Outcrop is in a sand pit of deposits formed into the Champlain Sea. Deformation is not associated with ice margin.

Fig. 3-22. (locality 17). This outcrop is contiguous with Figure 3-19 but illustrates an advanced state of folding and faulting.



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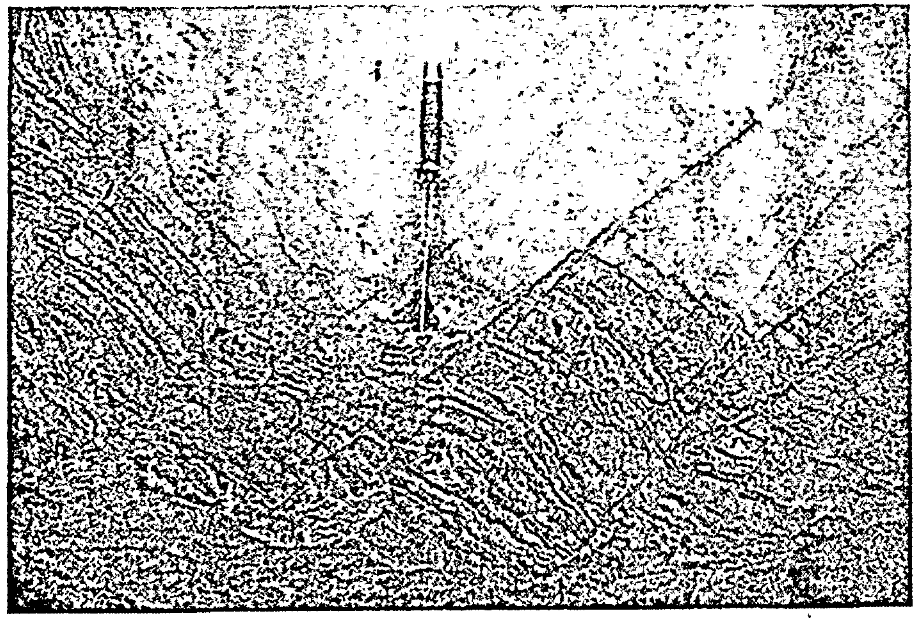

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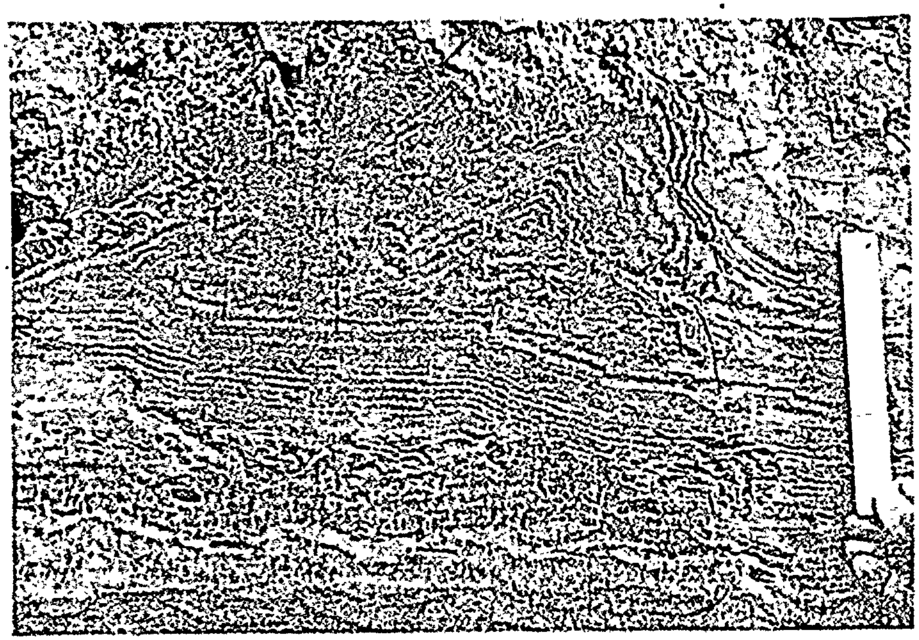


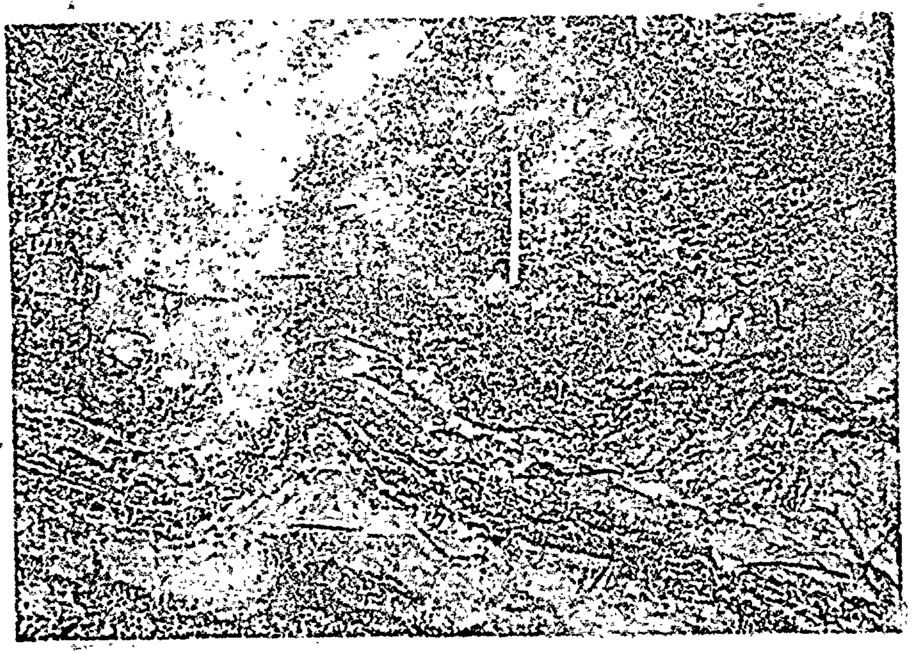
3-22

Fig. 3-23. (locality 10). Temporary outcrop in roadcut during widening construction of Route 11. Bedrock is just below lowermost exposed sediments. Anticline with diapiric intrusions are present in the lower center of photograph. Light materials are sandy and dark materials are silts and clays.

Fig. 3-24. (locality 2). Kame moraine and delta. View west in sand and gravel pit on a large northeast trending ridge. Till and other morainic indications occur north of outcrop. The deformed sands in middle of photo probably developed from ice overriding, moving from right to left in picture.

Fig. 3-25. (locality 2). This is in the same general area as Figure 3-24, but the deformed units in right center may have resulted from direct ice shove from the right. An alternate explanation is that the feature is part of a mudflow (flowtill) sliding off the distal margin of the ice.

Fig. 3-26. (locality 6). Recumbent fold in silts, clays, and gravels in a kame delta. The margin of what might be termed the "LaFargeville moraine" passes through this vicinity. View is east and the structure resulted from ice deformation.



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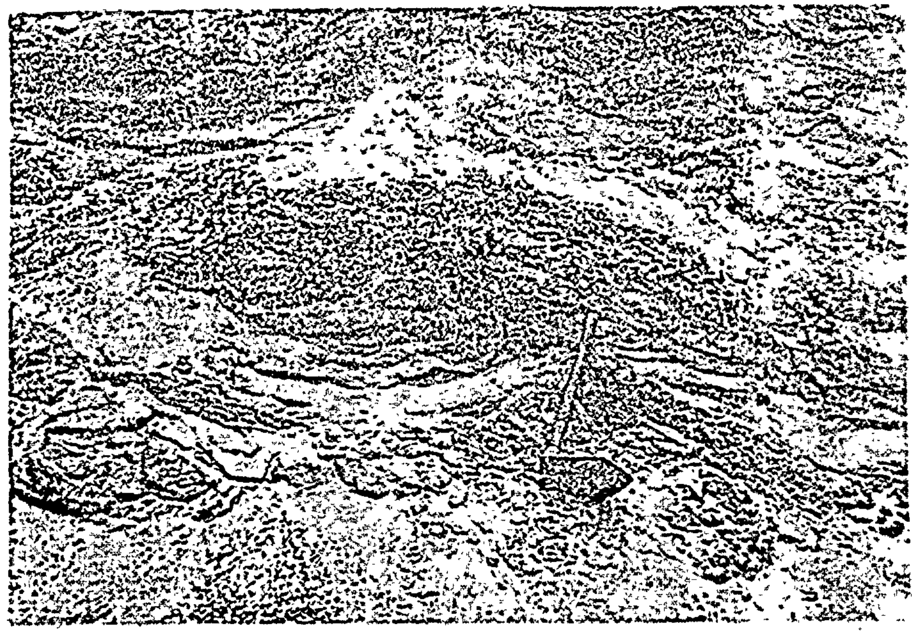

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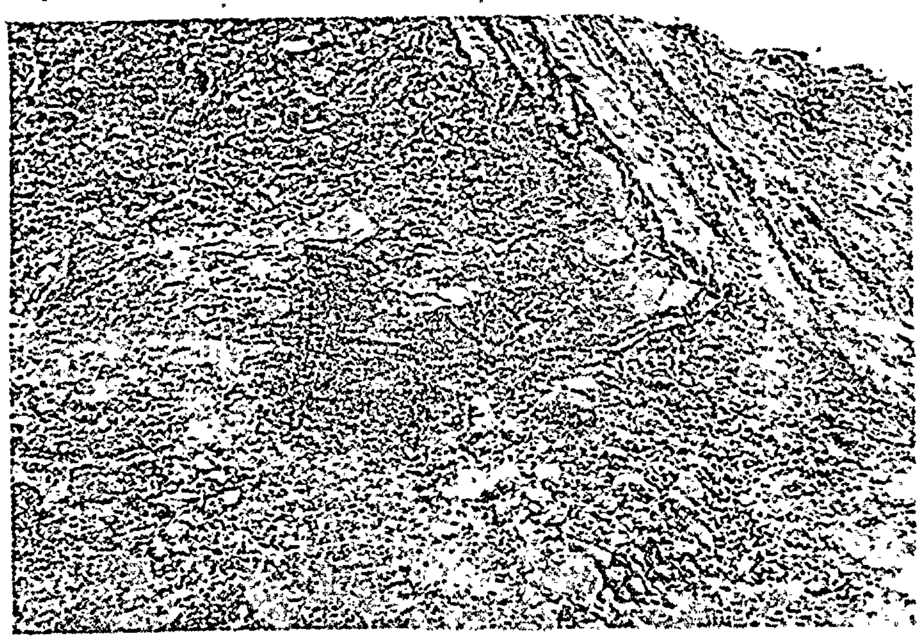
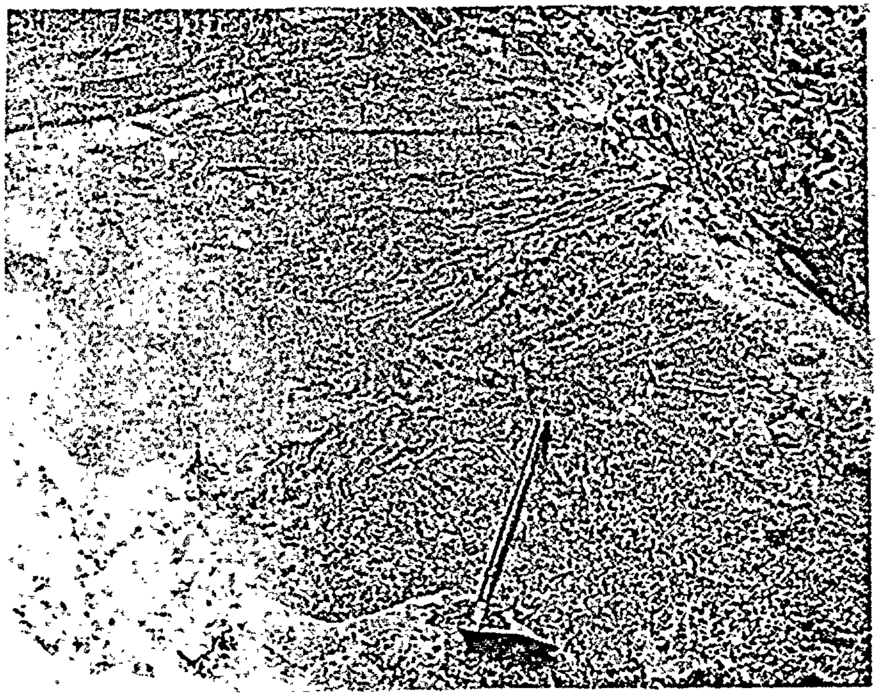


3-26

Fig. 3-27. (locality 17). Recumbent folds in sand. The sands occur in a deltaic sequence that formed with a nearby ice margin. Such structures can be developed by many different processes, but the contiguous character of the ice suggests glacial causes.

Fig. 3-28. (locality 11). Contorted and recumbent folds in sand. This ripple drift sequence occurs in the lacustrine part of a kame delta. Deformation and instability of the sands is attributed to processes associated with the ice margin.

Fig. 3-29. (locality 9). Recumbent and isoclinal folds in gravel and cobble strata. Exposure is looking south in large gravel pit of Marion Construction Co. The structure was probably frozen during its deformational emplacement. The kame delta environment with ice margin contiguous to this outcrop suggests a glacial origin.



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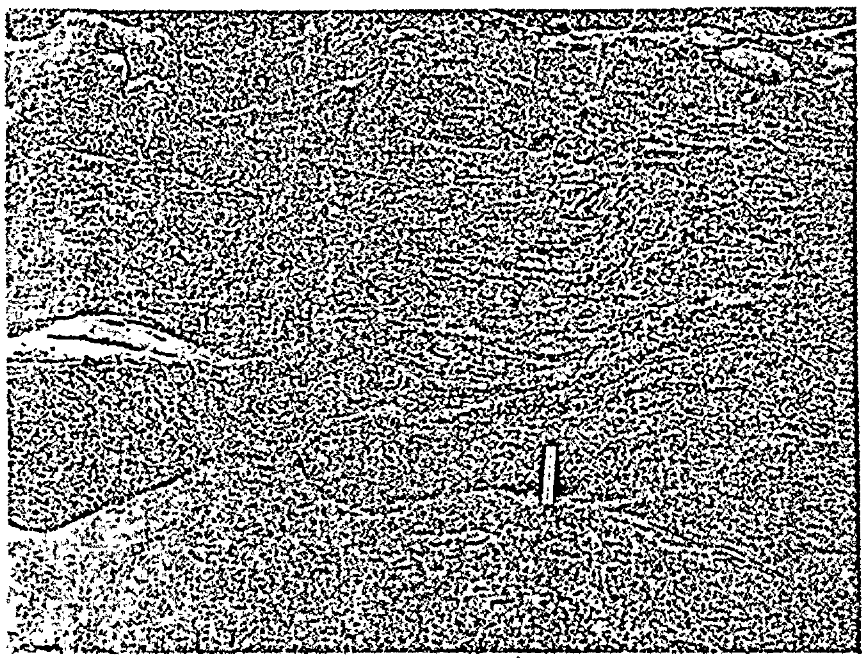

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3-29

beds. Legget (1962, p. 118-119) provides a general statement of conditions that pertains to such materials:

"During the settling of the fine particles in the fresh water of glacial lakes, the particles came together in such a way that interparticle attraction led to what can best be described as a 'honecomb structure' of the solid particles. Excess water is therefore held between the particles and gives the resulting soil an artificially high moisture content. When the soil is in its natural position, this unusual condition is of no moment and may be unsuspected. When such soils are disturbed, however (as they can be by engineering operations), the excess water may be released, thus quickly converting what had previously been a solid-looking material into a viscous liquid that will flow readily on low slopes until the excess moisture is lost and the soil 'solidifies' and has a new moisture content".

These structures have almost universally been interpreted by glacial geologists as resulting from the pressure of overlying material (water, sediment, and/or ice). The critical stability threshold of the buried sediments is exceeded and they behave in a thixotropic manner. Several variations of the structures are shown in Figs. 3-30-3-37. In most localities sand intrudes other sediments. The structures also range from simple to complex, show diversity in sizes, and are commonly multiple. Refolding and other complications may occur (Figs. 3-37, 3-38). Several of the St. Lawrence diapirs strongly resemble those from seismic regions (See Chapter 4 and Appendix D). Several St. Lawrence localities such as Figs. 4-13, 3-23 contain deformed sediments that are similar to those in Pennsylvania (Fig. 3-3) and at the Van Pit, Binghamton, N. Y. (Figs. 3-5 and 3-6).

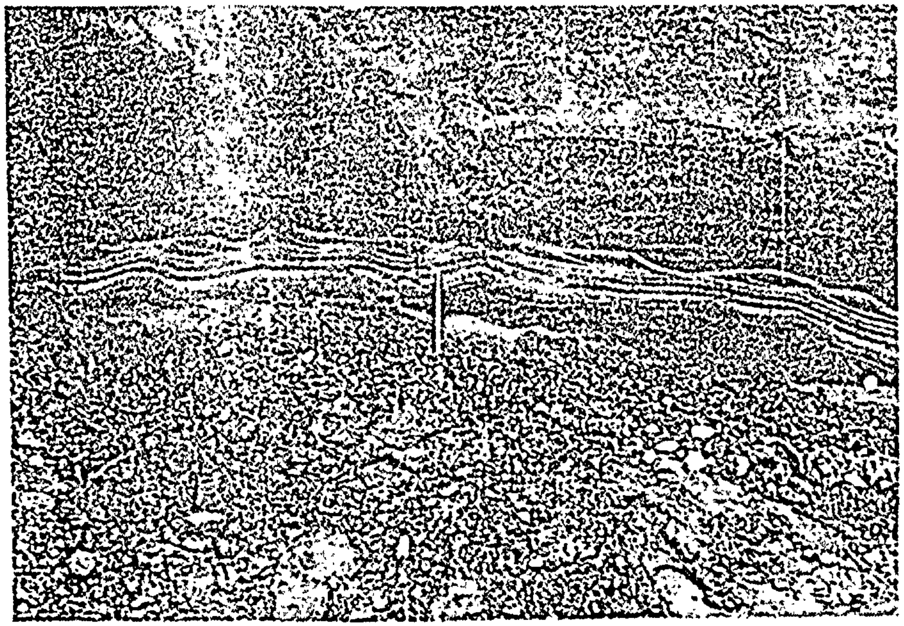
The conclusion that might be drawn from such visual comparisons is that the St. Lawrence diapirs also occur in other regions....some of which have a record of seismicity and others that are aseismic. The reconnaissance in the St. Lawrence Lowland has also indicated that diapir structures are largely related to deltas that are mostly fine grained; however, there are many similar type deltas that do not contain the structures. In similar fashion many deltas in other regions that have similarities with those in the St. Lawrence contain no diapirs or structures that behave in thixotropic manner. Since the ice margin was far removed from the sedimentation sites in the St. Lawrence cases, ice was not a contributing cause to the deformation. Thus, it would be presumptuous to rule out the possibility that seismic events could have provided a force for the initiation of the deformed units.

6. Complex structures. This class is dependent upon sets of structures that are so confused that reconstruction of the sense of movement can not be determined. The structures depicted in Figures 3-39 and 3-44 are representative of this class in which the movement and differential displacement occurs. The materials behave differently because of unequal motion caused by variations in their viscosities when stressed. It is a situation that resembles the movement of oil slicks on

water. They are the glacial equivalent of ptygmatic folds. These features occur in thixotropic-prone media and have slurried in a fashion that indicates they were highly mobilized. Their mode of formation has usually been explained as being caused by differential pressures of overburden that exceeds the critical stable limit for the interbedded silts and clays. Glacial geologists have generally not attributed such features to earthquake shocks.

Figs. 3-30 to 3-33 are photographs in different parts of the same sand and gravel pit illustrated in Figures 3-11 to 3-14. (Schenevus River valley near Worcester, N. Y.) Figures 3-31 and 3-32 are closeups of Figure 3-30. The laminated clay-silt-sand units show both gentle folding and diapirs. The folds are somewhat harmonic with ripple drift bedding. Thixotropy can be seen of the single diapir in upper center of Figure 3-31, and small scale diapirs occur in fine-grained stratum above and to the right of the quarter.

Fig. 3-33. This photograph shows coarse grained gravels overlain by till in the western part of the pit. These units are stratigraphically younger than strata in Figures 3-11 to 3-14, and 3-30 and 3-32. This locality is very significant in the glacial history of the region and shows the presence of live ice and glacial readvance soon after deposition of some of the kame deposits.



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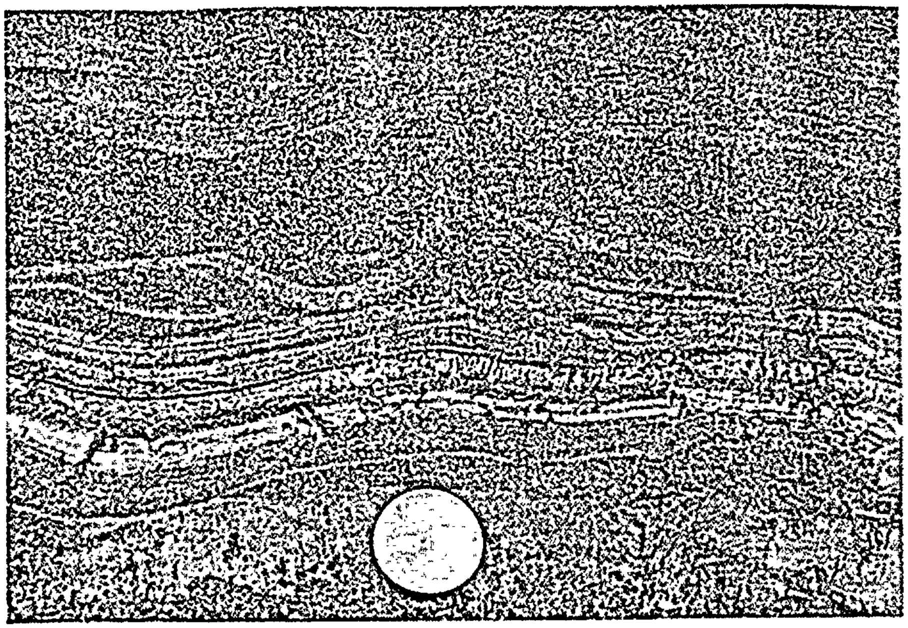

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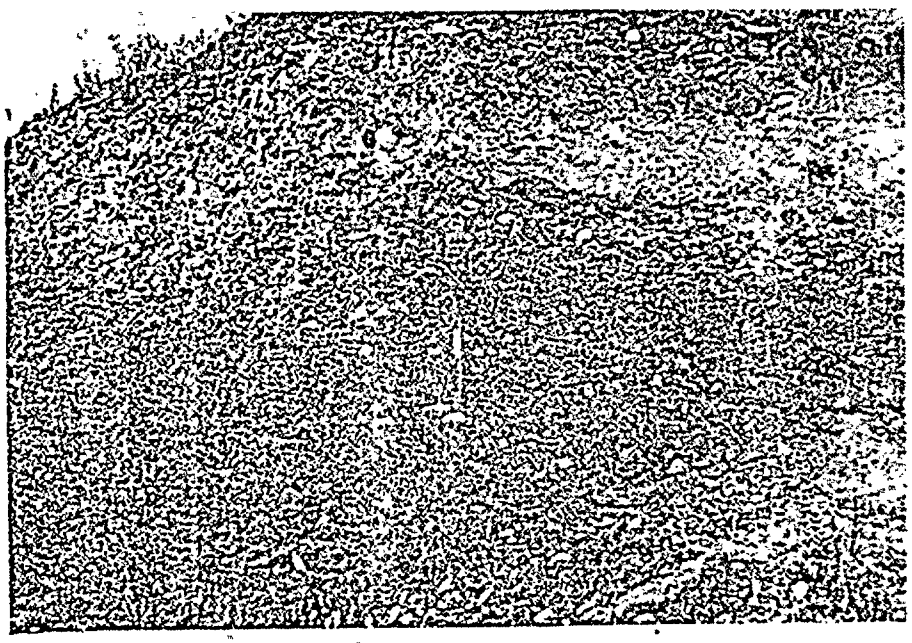


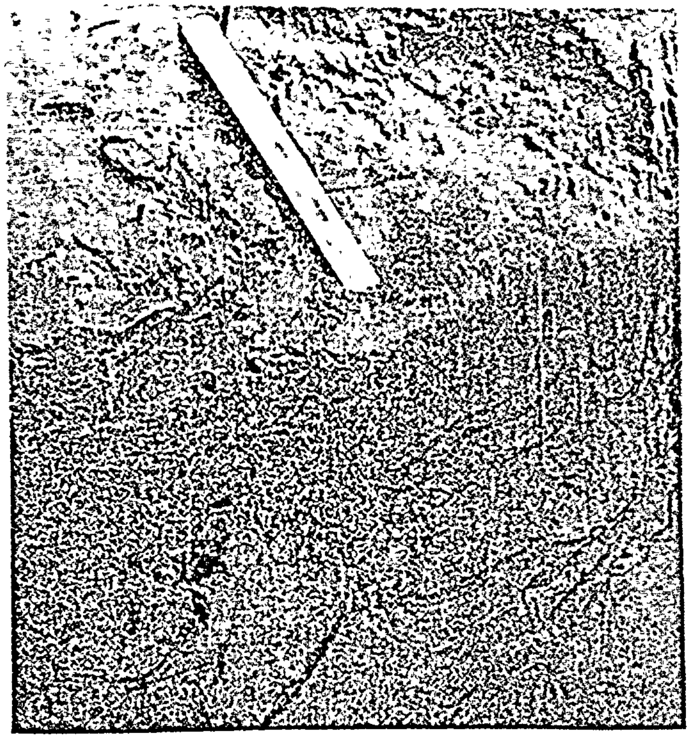
3-33

Fig. 3-34. (locality 10). Diapirs in sand and clay units along a new road cut for Route 11. This site is contiguous to a kame delta. See also Figure 3-23 at this location.

Fig. 3-35. (locality 12). Diapirs in sand pit of large delta built into the Champlain Sea. See Chapter 4 for further explanation of this environment.

Fig. 3-36. (locality 4). Folded sediments and diapir development in sands and clays of kame delta. The LaFargeville moraine passes through the site. Bouldery till rests on top of the sequence. Deformation was associated with glacial processes. The contorted unit is 4-6 ft. thick.

Fig. 3-37. (locality 5). Same general area as Figure 3-20. Photo shows a different size and type of diapir development in which deformed unit is also a décollement.



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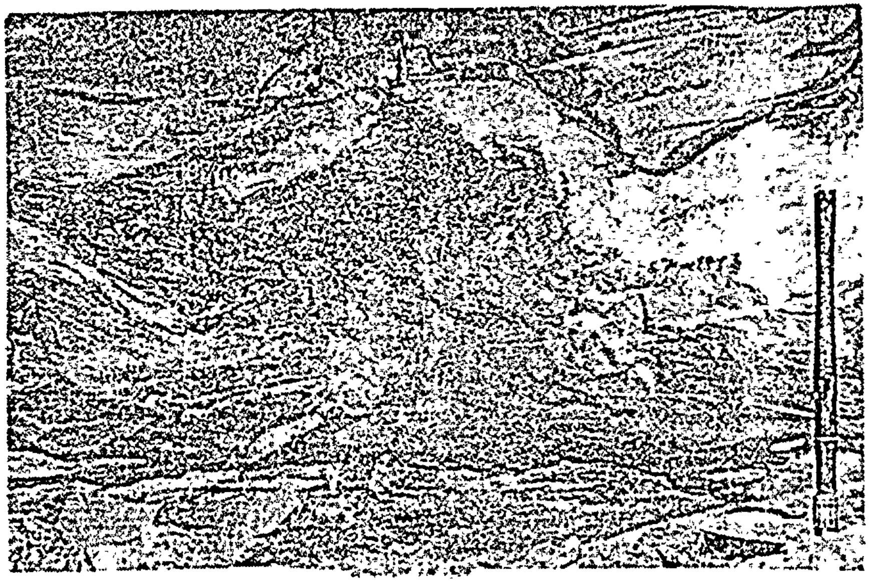
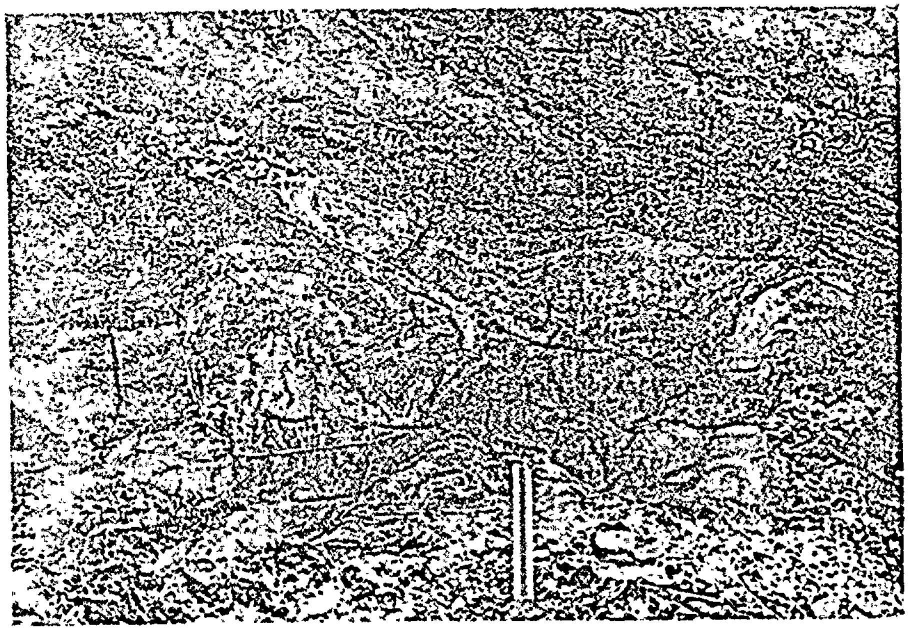


3-37

Fig. 3-38. (locality 17). Thixotropically deformed sands and silts overlie asymmetrical folds. This site is contiguous with a kame delta and deformation is related to fluctuations of the ice margin.

Fig. 3-39. (locality 12). Highly deformed unit near same outcrop as Figure 3-35. See Chapter 4 for further description.

Fig. 3-40. (locality 12). Thixotropically deformed sand strata in the same general site as Figures 3-35 and 3-39.



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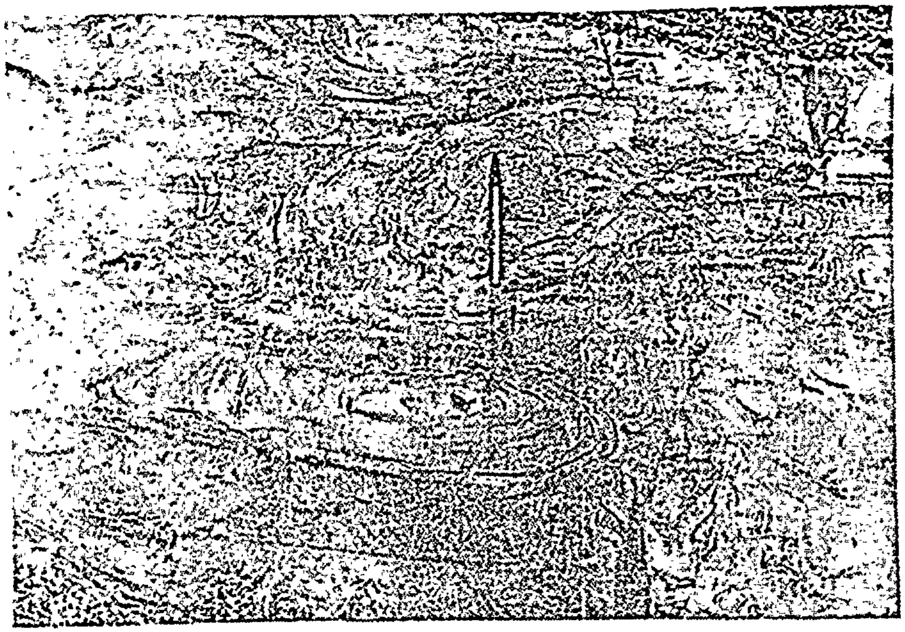

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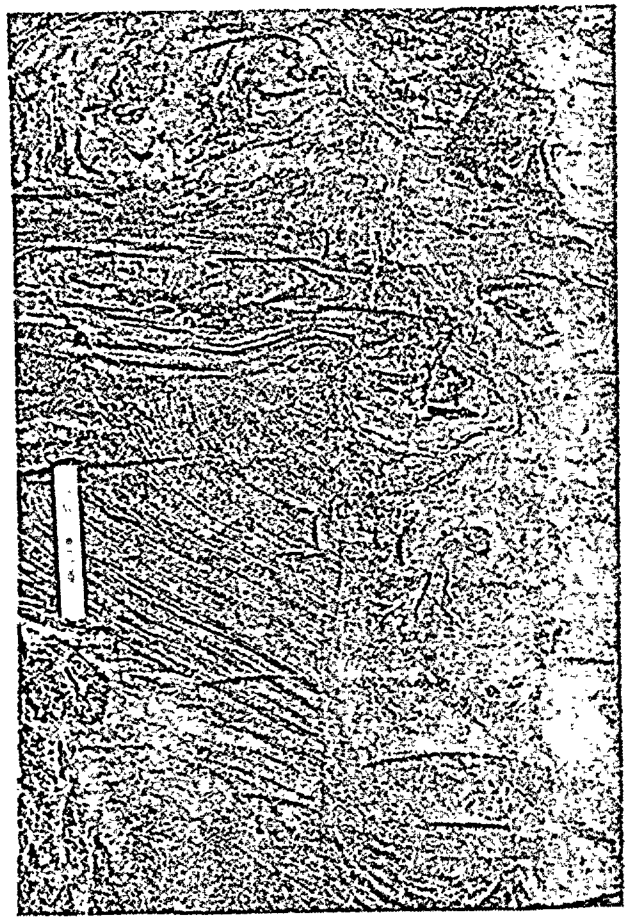

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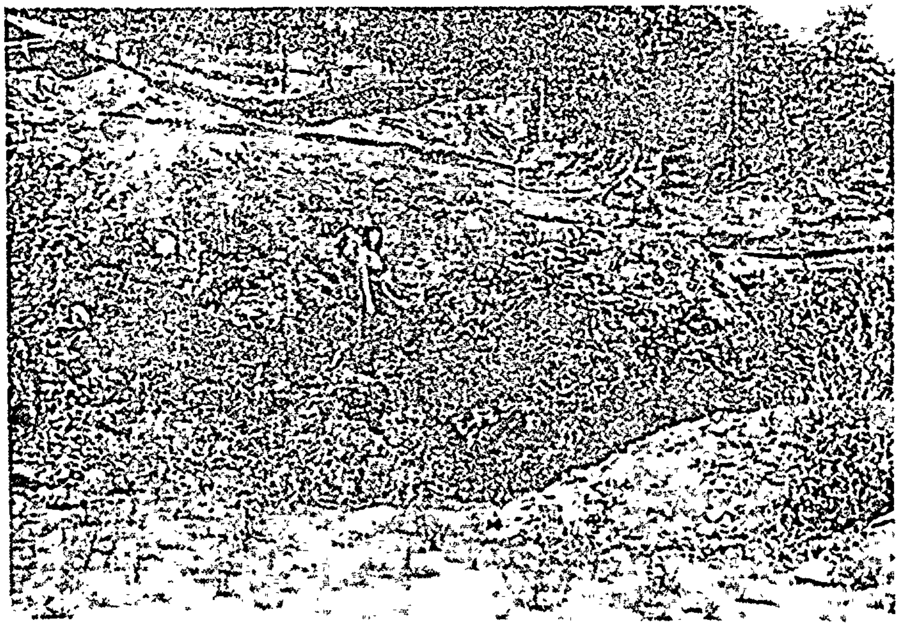
Figs. 3-41 to 3-44 are photographs of Quaternary sediments in abandoned pit immediately west of village of Worcester, New York, on Route 7. The deposits are all fine-grained and contain a wide range of thixotropically deformed features that include diapirs, pillows, and load casts. Compare Figure 3-41 with 3-2, 3-3, and 3-36. Also compare Figures 3-42 and 3-43 with Figures 3-39 and E-8, and Figure 3-44 with Figure 3-40. These structures in this reportedly aseismic area of the Glaciated Appalachian Plateau are visually similar and identical with those in the St. Lawrence, other glaciated areas of the east, and with deformed sediments in California. At this site in the Schenevus Valley the sediments formed in a proglacial lake but there is no evidence of ice readvance after formation of the strata. A glacial cause for the origin of the structures is very unlikely. Detailed work in this area is necessary to assess probable genesis of the deformation.



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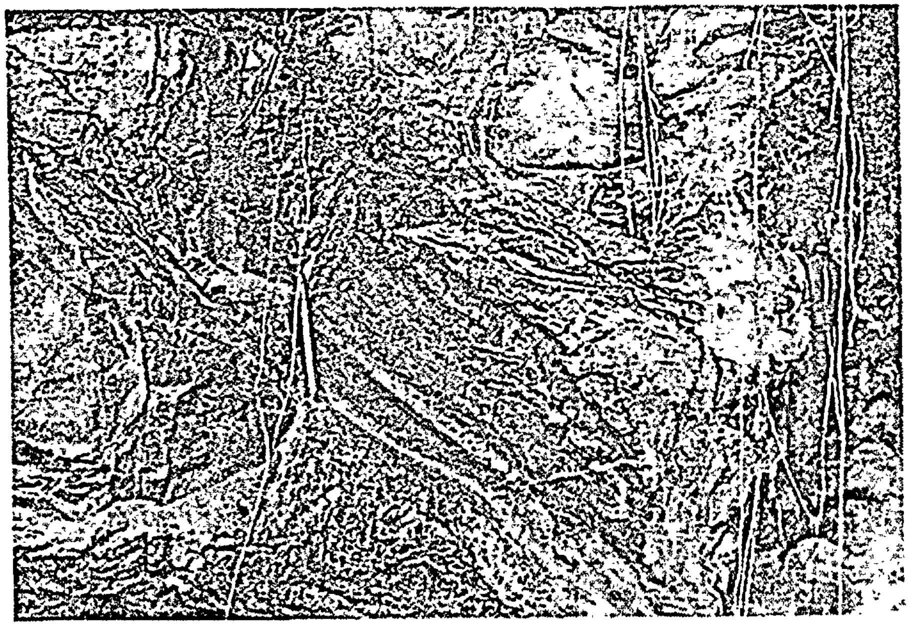

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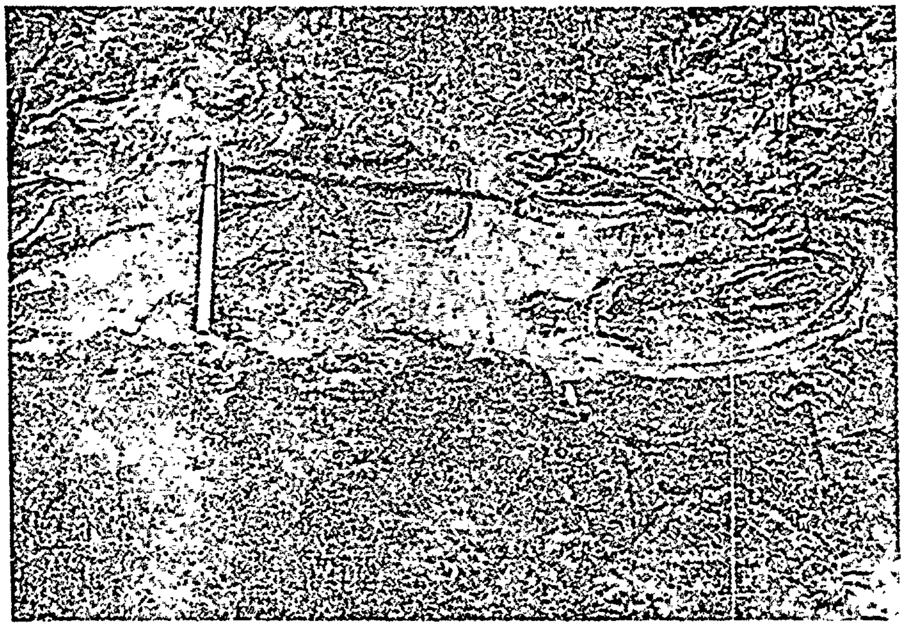

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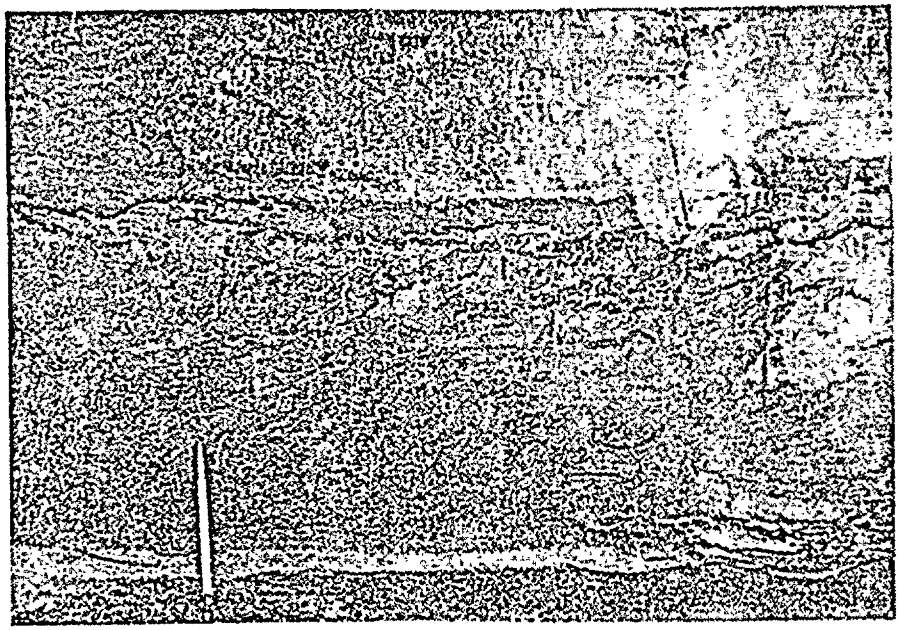

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CHAPTER 4.

DEFORMED SEDIMENTS OF SELECTED LOCALITIES

This chapter consists of detailed descriptions of the types of soft-sediment deformation in the St. Lawrence Lowland and analysis of several type localities. An attempt is made to interpret the sedimentary environment at each locality and to place the suites of deformed structures in a depositional context.

To avoid genetic implications which permeate most terminology for soft-sediment deformation, the terminology used here is purely geometric and based on conventions used in structural geology. This procedure is, predictably easier in theory than in practice. While simple structures may be readily described, e.g., synclines and anticlines, more intense deformation leads to disruption of bedding and injection. Thus, there is a continuum from sharp-crested anticlines, through diapirs, to dikes. Synclines in which the flanks are ruptured become "pillows" or "pseudo-nodules". In lithified rocks, monoclinal folds commonly grade into high angle faults and recumbent folds occasionally grade into thrust faults. In unlithified sediments the distinction is blurred further because many faults are not sharp edged. Finally, there are the chaotic exposures which have resulted in usages such as "melange" or "chaotic terrain" for the structural geology analogs.

The field deformed features can be grouped into four broad categories: (1) faults; (2) contorted bedding, including all features of folded and contorted strata; (3) sag and load structures for all features with dominantly vertical movement, whether continuity with the parent bed is preserved or the structures in question are detached, and; (4) slump structures for all features in which lateral motion is dominant. The main merit, perhaps the only one, of this usage, is its simplicity in communication in the field. Since the groups grade into each other the mechanisms invoked in interpreting their origin may be very much the same. For detailed description of the various structures observed in the field, geometric terms were employed - again for purpose of description and not classification. Moreover, attention was paid to a number of features (i.e., injection, truncation, collapse, rotation, etc.) which seem pertinent to the mechanism of origin.

It should perhaps be pointed out that despite the voluminous literature relating soft sediment deformation to seismicity, no clear morphological criteria exist for the recognition of seismically triggered disturbances. Many of the criteria cited in the past as suggestive of ancient seismic disturbances are not morphological, and involve parameters such as assumed or known proximity to the highly seismic zones, and extensive lateral continuity of the disturbed horizons. Other criteria, citing similarity to experimentally-produced structures or occurrence of structures suggestive of liquefaction, are somewhat conjectural, and assume for example that structures can be produced experimentally only in one way, that liquefaction must be related to

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Prepared by Iaakov Karcz, Donald Coates, Paul Enos, and James Kirkland

a major earthquake, and that lithostructural evidence of liquefaction is unambiguous.

Two sources should be mentioned in connection with this project. One is the research conducted by Sims (1973, in Press) in California. Summary of information obtained from Dr. Sims and his study area are presented in Appendix E. The second source was a few comments included in the Dames and Moore (1974) report to NYASDA. In a number of localities in Quebec, visited under the guidance of Dr. LaSalle of the Quebec Ministry of National Resources, they concluded seismically induced deformation of the Quaternary sediments may be a viable possibility. A visit to the Quebec exposures was undertaken under the kind guidance of Dr. LaSalle. The structures were briefly examined and some sediment samples of the disturbed and undisturbed beds were collected. In both our opinion and that of Dr. LaSalle, none of the outcrops visited in Quebec necessarily implies a seismic origin of the deformation. In each case a reasonably strong case can be made for an aseismic origin.

DESCRIPTIVE TERMINOLOGY

The simplest fold geometries encountered in soft sediment deformation of the St. Lawrence Lowland are not ordinarily simple sine waves. The anticlines are normally sharp crested and the synclines relatively broad with flat bottoms (Fig. 4-27). Such folds are formed in sediments ranging in grain size from clays (relatively rare) through gravelly sand, but were not observed in coarse gravel or diamictons*. The amplitude of the folds observed was generally a few cm. or tens of m., but locally may reach two meters.

Fold geometry varies with sediment size; this is most readily apparent with the interbedded contrasting sediments. Folds are sharper and bedding thickness more constant in finer grained interbeds, normally silts or clayey silts, whereas sands thicken in the fold crests and compensate any disharmony between adjacent finer-grained beds. This contrasts with concentric tectonic folding in lithified rocks where the coarser-grained beds are typically more "competent" deforming without significant differential volume changes, and finer-grained beds deform more plasticaly. The difference in the St.Lawrence soft-sediment fold geometries probably arises from the greater cohesiveness of finer-grained sediments which renders them relatively more competent. The intergranular forces in sand are negligible in comparison to grain mass so they deform by "flowing", as a cohesionless granular fluid.

Diapirs are anticlinal structures in which the overlying layers have been pierced or ruptured. Clayey silt beds commonly protrude into sand, apparently acting as a cohesive element which pierces the adjacent beds

*Diamicton is an unsorted terrigenous sediment (or rock) containing a wide range of particle sizes, regardless of genesis (Flint, 1971, p. 154).

(Fig. 4-26). Sand-in-sand diapirs were also observed, however, (Fig. 4-38). Digging into a few small diapirs indicated that they were elongate, i.e. diapiric anticlines, not piercement domes, but elongation may be slight (Fig. 4-23). The amplitude of the largest diapir observed was 1-2 m.

Truncated folds is a term coined to describe a geometry in which folded layers abut against the plane surface of an overlying layer (Fig. 4-38, 4-39). This would be an angular unconformity in lithified rocks and generally has the same significance - the fold was formed and truncated before deposition of the overlying bed. Before leaping to the important conclusion that the fold was formed immediately at the surface of deposition, two alternative hypotheses must be considered. First, can an apparent truncation be formed within a sediment without disrupting an overlying bed? Second, did significant erosion occur which may have stripped down to a contorted interlayer?

If two limbs of a truncated structure are exposed, original fold geometry may usually be inferred, although it may not be possible to distinguish between a simple sharp-crested anticline, or diapir, and a structure which may have broken the surface as a "volcano" to form a lump of sand or mud. If only one limb is exposed, care must be taken to distinguish between a truncated monocline (or incompletely exposed anticline) and a simple truncated cross bed set.

Synclines in unlithified sediments may be no more than flat portions of a layer left behind as sharp-crested anticlines or diapirs moved upward. In other cases they may represent the active element which moved down, displacing underlying sediment (Fig. 4-28). These cases are normally called "load casts", although the term is etymologically improper (Potter and Pettijohn, 1963, p. 145) and in some cases genetically questionable. Where the syncline is the active element, the amplitude is usually small (10-1 - 10^1 cm) and the layer displaced downward is sand, coarser than the sediment underlying. This is generally the relative grain size relationship with "load casts" reported in the literature, although exceptions were encountered in the St. Lawrence region.

Pillow is the conventional name for irregular, but generally smooth-sided, isolated masses of sediment (or rock). They differ from "load casts" in being somewhat isolated from the parent layer or lens, which may be broken up partially or totally into pillows, and commonly in being somewhat larger (Fig. 4-40). Approximate synonyms are "ball-and-pillow structure", "hassock structures", "pseudonodules", "flow rolls", "storm rollers", etc. (Potter and Pettijohn, 1963, p. 148). Pillows reported in the literature are sandstone or siltstone isolated in shale beds or by shale films. Many of the pillows examined in this study were internally bounded by the finest-grained sediment in the sequence, typically a clayey silt, and surrounded by sand. Some pillows appear to have been isolated by the eruption of diapirs which have totally disrupted the sediment layers around them. In these cases they would be passive elements analogous to the broad synclines.

Monoclines are generally small structures (10^0 - 10^1 cm) which form sharp steps in a bed or series of beds. Some of them involve considerable elongation of the steep limb, which may actually be overturned or pass into a fault. If a number of layers are involved, the folding geometry is parallel. As with other types of soft-sediment folds, the flexures are sharpest in finer-grained layers and may die out entirely by volume changes in sand layers. Recumbent folds are also common in pits of the St. Lawrence Lowland (See Chapter 2).

Rotational structures is used as a "waste-basket" term for structures akin to folds but lacking the simple geometry and symmetry. On a large scale (several meters) they involve irregular draping of sediment packages over other masses of sediment (Fig. 4-33).

Small scale rotation is involved in some types of deformation of cross beds and ripple drift cross lamination. "Oversteepening" is the rotation of cross laminae beyond the normal angle of repose for cohesionless grains (30-40°). This can occur from current drag during deposition which may produce recognizable interaction between the deformation and continuing deposition. Excessive oversteepening of cross laminae, by syn-depositional current drag or any other mechanism, may lead to microfolding with fairly simple geometry and finally to intense crumpling which is one form of "convolute lamination". The deformation of some cross laminae examined in this study appears to involve reordering the fabric so that the original lamination was blurred to the point of disappearance. Clearly, more than simple rotation is involved in these examples: the sediment lost cohesion and/or dilated to allow repacking.

Faults in soft sediments can be described by ordinary structural terminology, although they may lack sharp fault planes and appreciable continuity. High-angle normal faults and reverse faults are the most common (Fig. 4-10). Reverse faults have rarely been described from unconsolidated sediment. Low angle reverse faults or thrusts are associated with recumbent folds (Figs. 4-4, 4-11). All faults involve small displacement (10^{-1} to 10^1 cm). High angle faults occur in sediments ranging in size from clay to coarse sand, but low angle faults appear to be confined to silts and fine sand.

Sedimentary dikes are rare and obscure in the sediments of the St. Lawrence Lowlands. Narrow, fairly straightsided dikes of muddy silt were observed cutting thin layers of fine sand (Fig. 4-29), reversing the textural contrasts reported in the literature on sandstone dikes. In another occurrence small dikes of silt cut clay layers (Fig. 4-8). The margins of the dikes are ptygmatically folded indicating that the dikes were emplaced before appreciable compaction of the surrounding clay.

TYPE LOCALITIES

The field work of this project was strictly of a reconnaissance nature

with the objective of determining what areas in the St. Lawrence Lowland deserved detailed study at some future time. However, during the progress of the project it became clear that certain areas needed more interpretative work because of their complexities. The following six localities were selected as representing many of the Quaternary deformed sediment features, and extra attention was focussed to provide preliminary conclusions on their environment and genesis.

Gouverneur Town/County Gravel Pit (Locality 11)

This is an actively worked sand and gravel pit that is located in a large kame and kame delta complex. Figure 3-17 shows an overview of the sediments and typical structures of ice collapse features. Figure 4-1 illustrates the various pit faces and Figures 4-2 to 4-9 provide details of the deformation.

A great variety of sediment types and structures are present in this pit. In the short time available it was not feasible to correlate the units encountered in complex juxtaposition on each of the three faces. The uppermost unit of the pit was a moderately sorted fine gravel overlying laminated ("varved") clays which interfingered very abruptly with inclined layers of muddy gravel. Underlying the clays were lenticular units of ripple-drift cross-laminated fine to medium sand, silty to sandy gravels, and well sorted cross-bedded sands. Most sediment units showed some type of large scale deformation, rapid changes in character, and abrupt, in some cases steep, contacts.

The laminated clays formed in a lake; their interfingering with inclined beds of gravel indicates the lake margin received influxes of poorly sorted sediment, in the form of a small delta built by a high energy, sediment-choked stream. The other units also suggest current deposition by high gradient, overloaded streams, ending in small, coalescing deltas. Diamictons in the basal units of the central and southwest faces (unit 1 in Fig. 4-1A and B) consist of till. The draping, deformation, and steep contacts of sedimentary units were caused by the melting of isolated blocks of glacial ice buried within the sediment.

The most intensely deformed unit is no. 7 on the north face (Fig. 4-1C). It contains small open folds, recumbent folds, (Figs. 4-3, 4-4), sharp monoclines associated with reverse faults, and low angle thrust faults (Fig. 4-5). The southwest face (Fig. 4-1B) displays a flat-topped anticline with both limbs overturned, a truncated fold(?), and several oversteepened cross bed sets. The center face has very small, high angle faults (Fig. 4-1A) and small ptygmatic dikes in the clay interval (Fig. 4-8, 4-9). A large probable diapir in clay is poorly expressed at the far right of Figure 4-1A. Parallel sets of high-angle reverse faults cut a spectacular set of ripple-drift cross laminae and an underlying silty layer (Fig. 4-1A, unit 3; Fig. 4-6).

There is a wide range of structures in Quaternary sediments of the area, and in the pit as revealed in the exposures of the working faces, but there is no evidence that the deformed sediments were earthquake induced. The absence of thixotropy, the lack of structural continuity, and the dissimilarity of features with those at the

Van Norman Reservoir and Brawley sites in California (Appendix E figures) suggest a non-seismic origin. Indeed all features in the pit can be explained by the traditional disturbances related to glaciation. The dynamic setting of the complex kame and kame delta environment that produced extensive ice meltout with collapse, subsidence, and lateral displacement of sediment units, plus the oscillating margin of some of the live ice, were sufficient to cause all observed distortions in the sediments.

Fig. 4-1. Field sketches of pit faces. Vertical scales approximate; drawn with some vertical exaggeration

A. Central face, units indicated are :

1. Sandy gravel.
2. Gravelly sand gradational to unit 3.
3. Fine sand; cross bedded and ripple drift cross-laminated (upper left).
4. Laminated clay with silty interbeds.
5. Brown muddy gravel.
6. Well sorted, fine gravel.
7. Rusty brown silt with calcareous concretions.

B. Southwest face. Units:

1. Sandy gravel; virtually unstratified.
2. Coarse sand, few pebbles.
3. Sandy gravel.
4. Medium sand.
5. Pebbly brown silt.

C. North face. Units:

1. Open work gravel, graded.
2. Imbricated sandy gravel.
3. Pebbly sand to well sorted lower medium sand*, laminated and cross-laminated.
4. Sandy gravel.
5. Moderately sorted lower medium sand with some granules interlaminated with well sorted upper very fine sand.*
6. Silty sandy gravel; cobble to boulder size clasts.
7. Sandy unit (well sorted lower medium sand*) with fine-grained layers of muddy silt to well sorted very fine sand (black in sketch) and lenses of cobbles.
8. Unstratified brown silty sand; pebbles and cobbles at base.
9. Micaceous clay rich silty, sandy gravel (diamicton)

*Detailed estimates of size and sorting from field use of grain size comparator

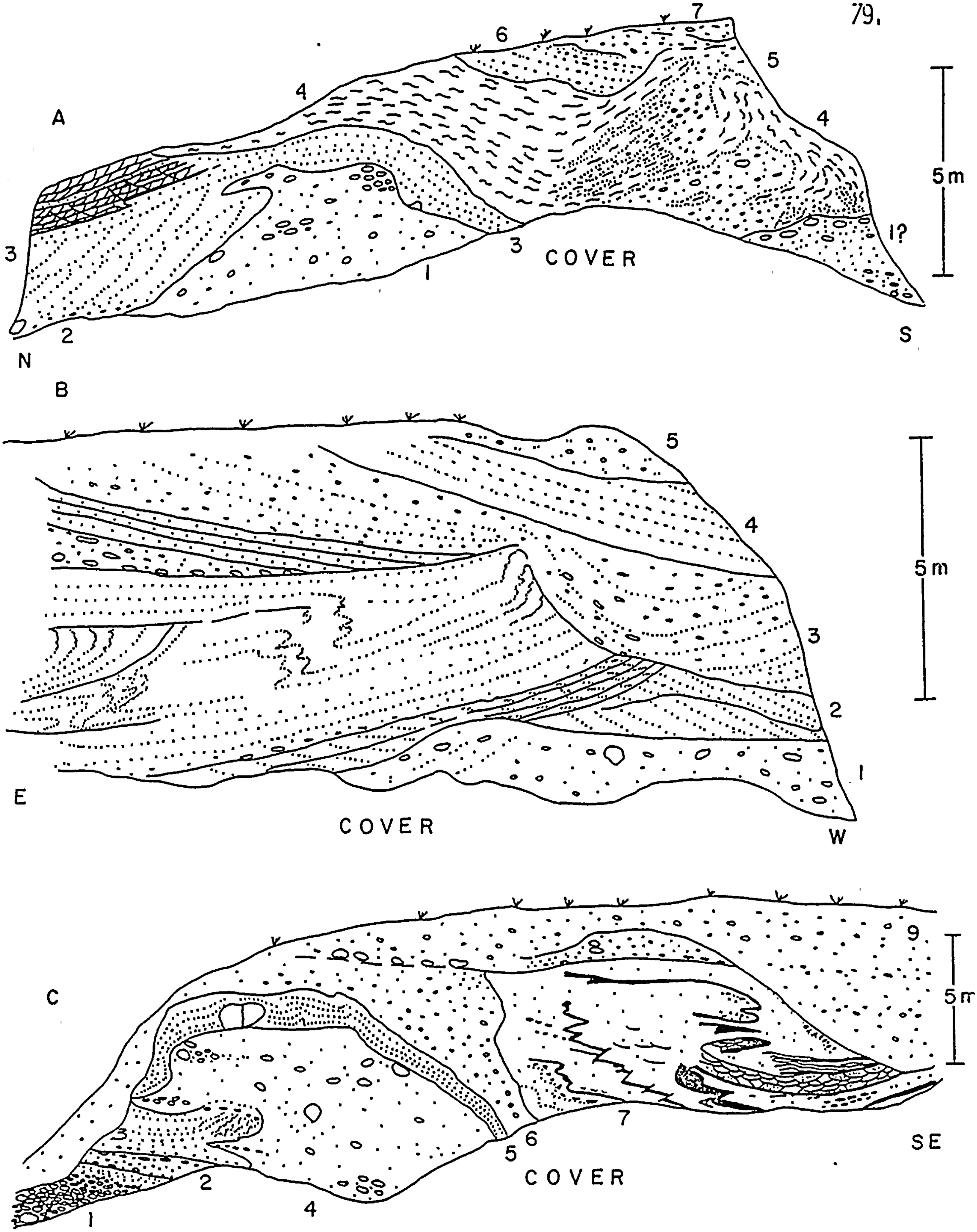

A
1 2 3 4 5 6 7 1?
COVER
N
S
5 m
B
1 2 3 4 5
E
W
COVER
5 m
C
1 2 3 4 5 6 7 8 9
COVER
SW
SE
5 m

Fig. 4-1

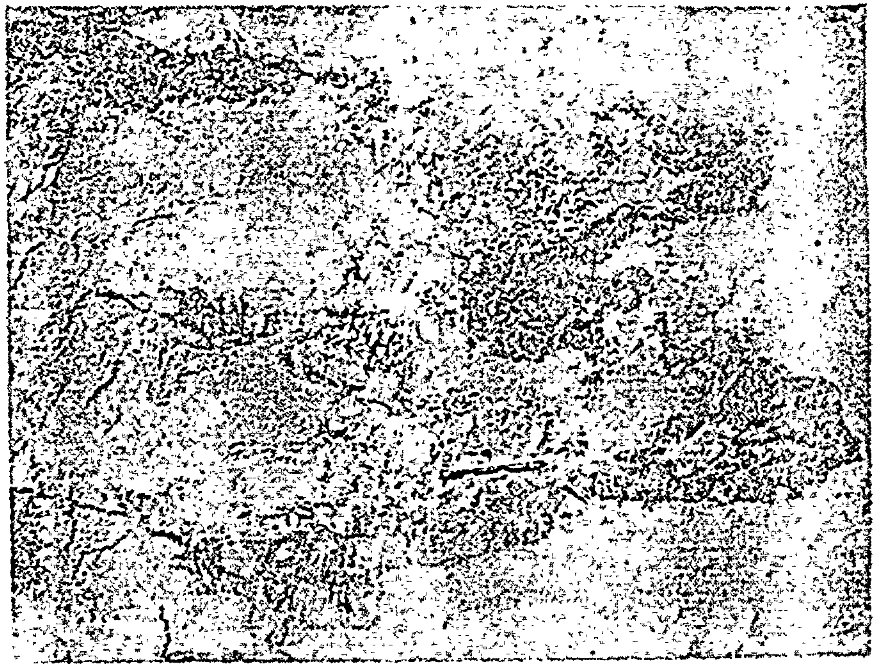
Fig. 4-2. Drape; note sandy unit. North face (Fig. 4-1C).

Fig. 4-3. Recumbent fold. North face, unit 7 (Fig. 4-1C).

Fig. 4-4. Recumbent silts and clays in the kame delta. The features were caused by the somewhat chaotic conditions of glaciation in this dynamic and changing environment.

Fig. 4-5. Highly deformed silts and fine grained sands near Fig. 4-4. Deformation was glacially induced.

4-2



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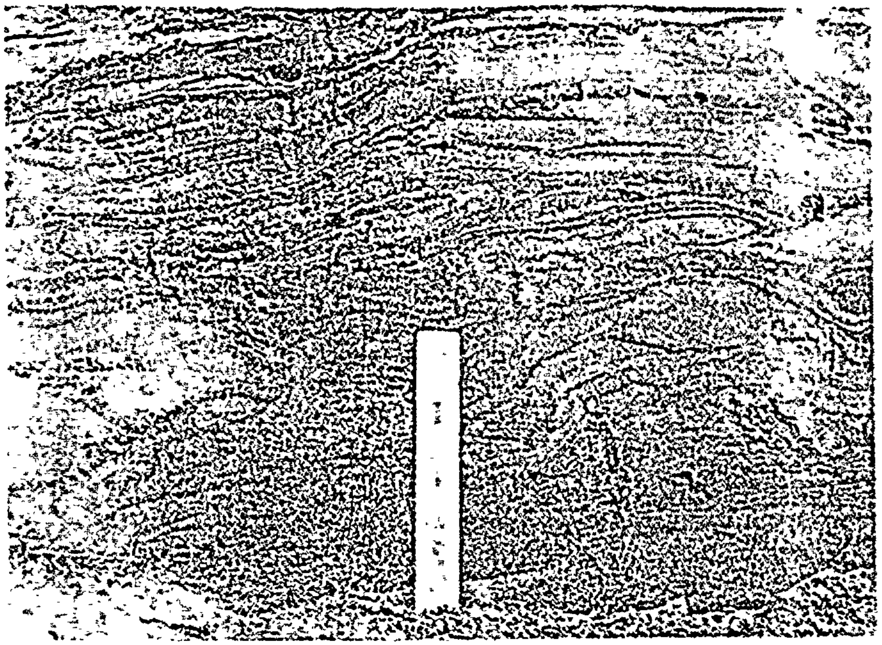
4-4



4-5

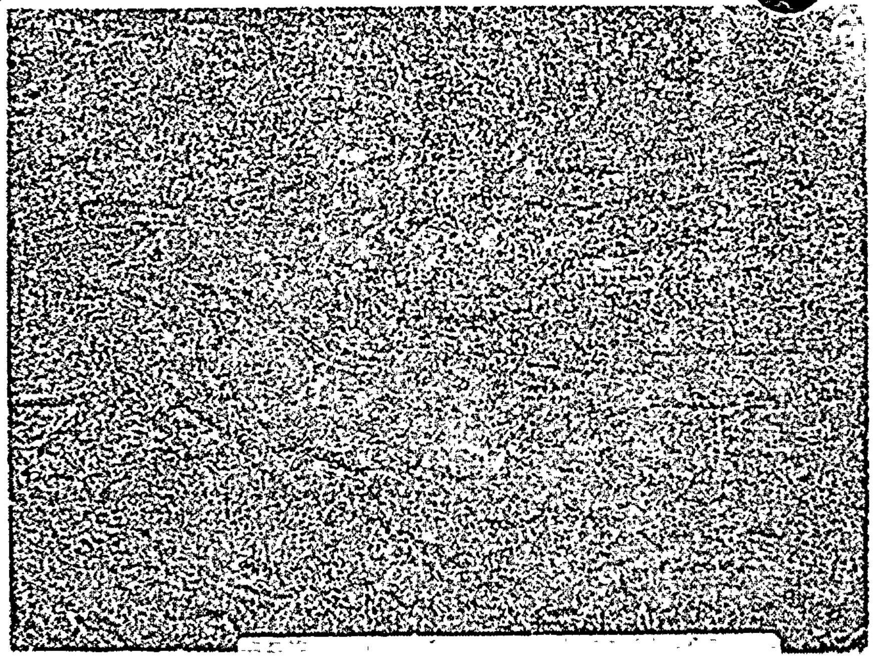
Fig. 4-6. Parallel faults cutting ripple-drift cross laminae. Center face, unit 3 (Fig. 4-1A).

Fig. 4-7. Asymmetric and overturned folds with high angle faulting. Interbedded sand and silt on north face, unit 7. Width of photo is 10 in.

Fig. 4-8. Dikes with ptygmatic boundaries (Center, above 0 and 7 cm. marks on rule). Fine silt injects clay, center face, unit 4 (Fig. 4-1A). The feature above the 10 cm mark is not a dike; it is a surficial feature produced by drying along a crack.

Fig. 4-9. Continuation of Figure 4-8, showing additional high angle faulting in laminated silts and clays.


4-6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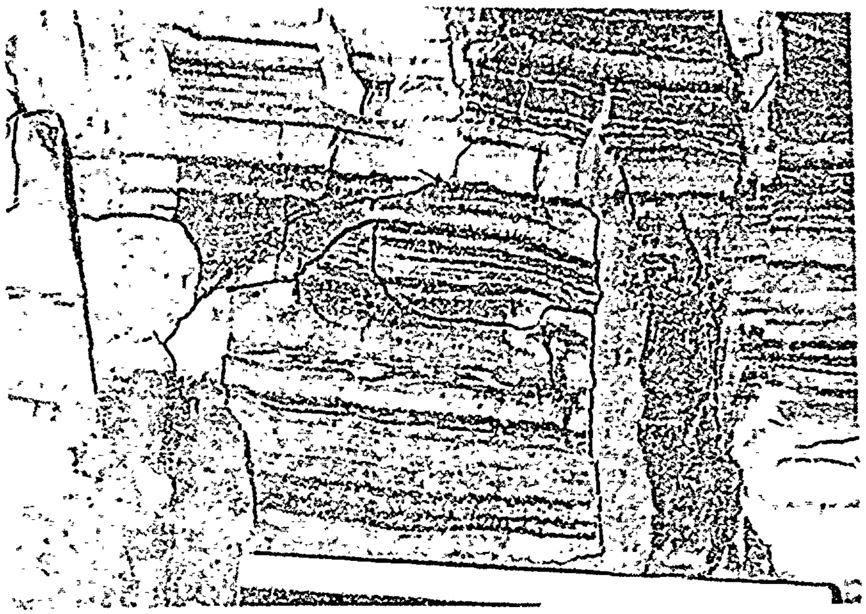
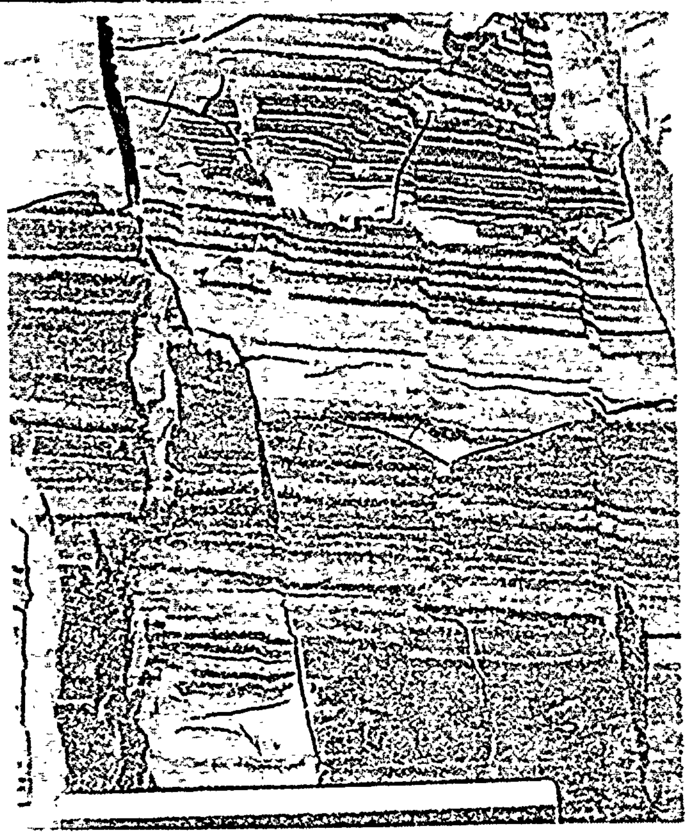

4-8


4-9

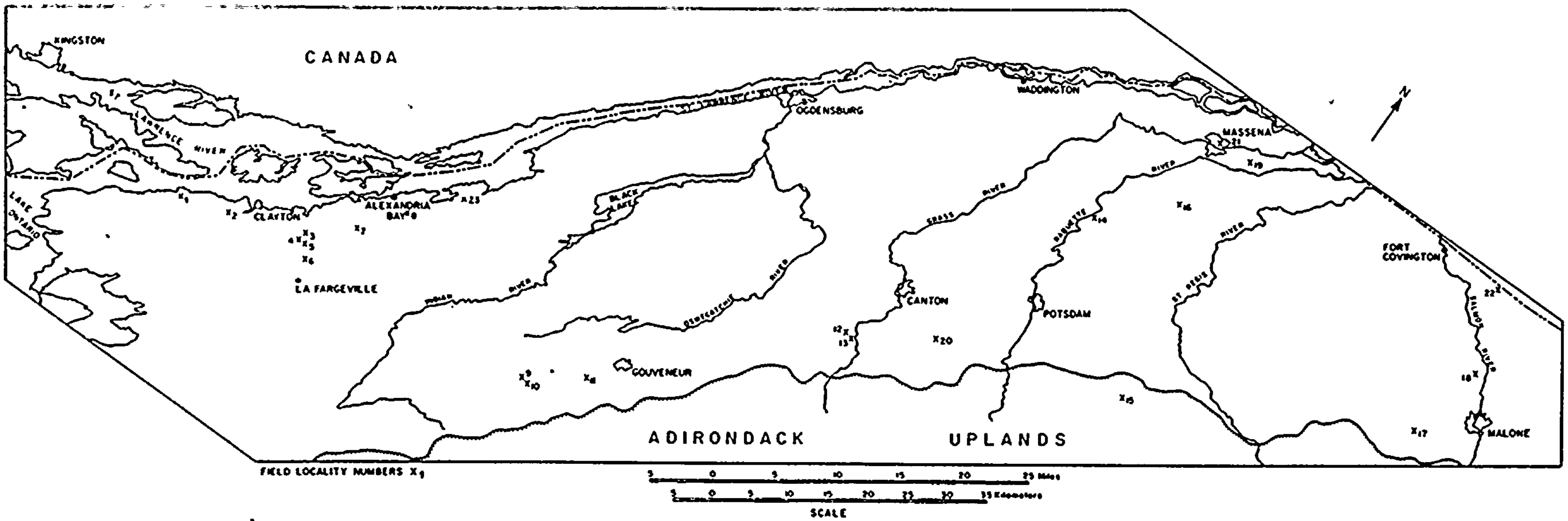


Plate 1. Location map of field sites and features of the St. Lawrence Lowland, New York.

LaFargeville Area (localities 3, 4, and 5)

This area and its northwest extension to the St. Lawrence River is also described from a Pleistocene stratigraphy viewpoint in Appendix D. MacClintock and Stewart (1965, p. 123) describe sediments in the area as constituting the LaFargeville kame moraine. A wide range of deposits and structures occur in three pits that are immediately west of De LaFarge Corners. The lower units are cross-laminated sands, in festoons or ripple drift, with interbeds of nearly structureless silts. When deformed these units can be vertically faulted or thrust faulted (Fig. 4-10, 4-11), or can undergo thixotropy. Diapirs occur in several different scales (Fig. 3-36, 3-37, 4-12, and 4-13). They are present in both the middle units and the upper units. The large sand-in-sand diapir of Figures 3-36 and its closeup in Figure 4-12, appears truncated and probably erupted at or near the surface when it formed. Rotational faulting is also present throughout the area (Fig. 3-20).

The deformed structures in these localities were developed in the active and dynamic setting of the glacier environment. The similarity of such forms as shown in Figures 3-36 and 4-12 with those in Figures 3-2 and 3-4 is remarkable. The latter features have previously been described by other workers as being caused by aseismic processes under deltaic conditions. The presence of till that overlies, and in some cases interfingers, the stratified deposits provides proof of the oscillating nature of the ice margin and indicates a high energy and changing sedimentation regime for the deposits. The numerous faults of different type and magnitude which often occur in close association with thixotropic deformations is another indication that seismic shock was probably not the cause of the distortions. This lack of continuity of deformed types within some of the more homogeneous sand strata shows that the forces that created the features did not act ubiquitously or uniformly throughout the area. This is such a complex area, however, that additional work and analysis of other exposures in the region should be done.

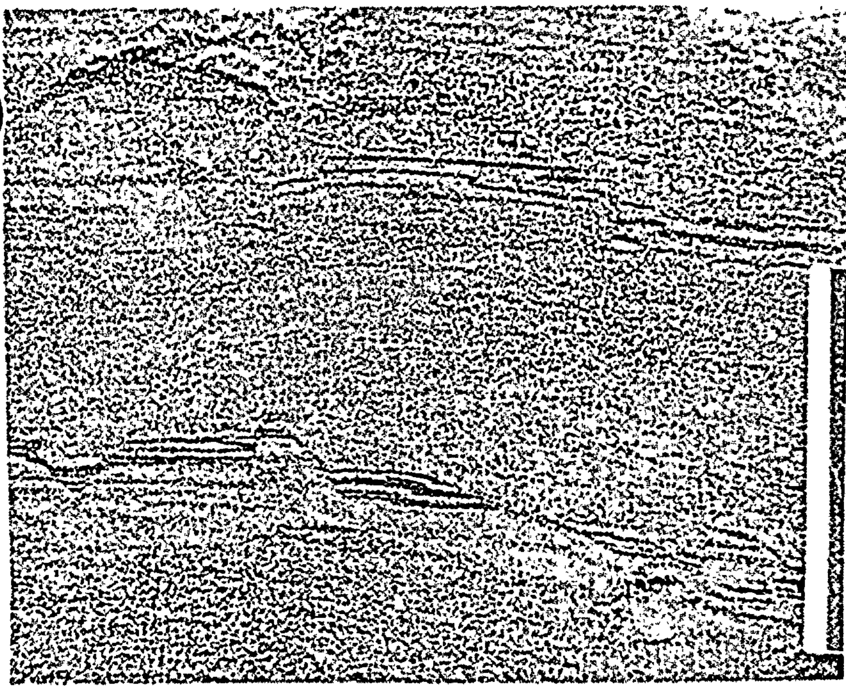
Fig. 4-10. Small scale vertical faulting in sands. Locality 5.

Fig. 4-11. Thrust faults in fine sands and silt. Locality 4.

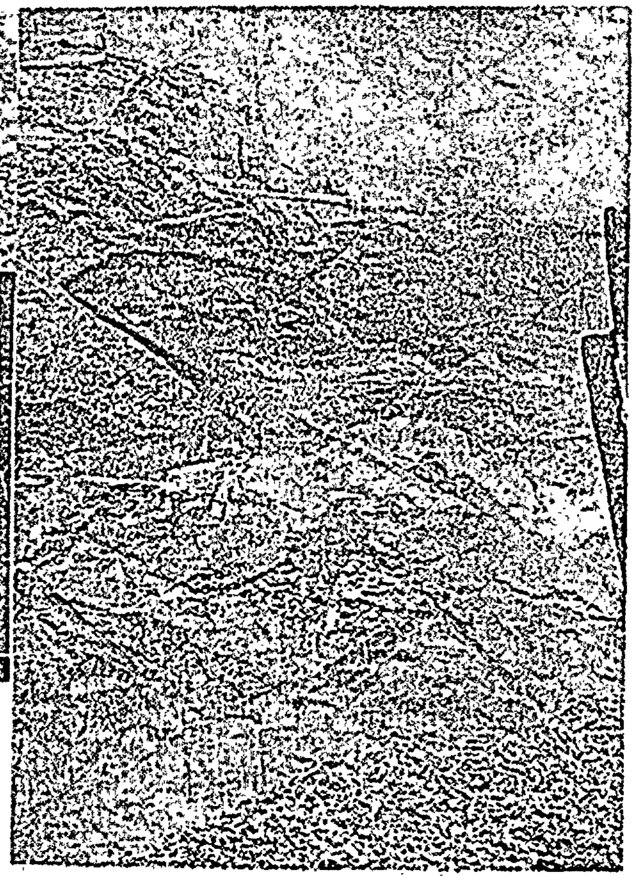
Fig. 4-12. Closeup view of large diapir in sands and silts at Locality 3. See also Figures 3-36 and 3-37 for comparison and general setting.

Fig. 4-13. Highly contorted thixotropically-deformed fine-grained sandy and silty units. Near center of photograph the light colored coarse grained units intrude as diapiric structures into the darker finer grained strata. The strata are capped by till at the top. Locality 5.

4-10



4-11



4-12

4-13

Alexandria Bay - Newberry Sand Pit (locality 8)

Three different sedimentary units comprise materials in the pit. The texture of the strata fines upwards (Fig. 4-14) with gravels (unit 1) at the bottom, and overlain by the middle sandy beds, (unit 2), and capped by the laminated silts and clays (unit 37). The gravels in this deposit are interpreted as part of a small steep-fronted delta, probably fed by a channel incised into the bedrock. The sands occur both on top of some gravel and also grade laterally into coarse materials. The silts and clays are lake-floor deposits in the proglacial lake and overlap the delta. They are thicker between the two delta lobes that occur within the pit area.

The poorly sorted gravels are in contrast to the clean sands with silt that occur in the ripple drift sequences. Furthermore the laminated silts and clay grade upward into rather pure clays. The northeast part of the pit, adjacent to the rock outcrops, contains coarse sand with lenses of angular and of well-rounded boulders which dip steeply to the west and southwest.

Deformation is confined to the laminated silts and clays (Figs. 4-15 to 4-20). The contorted units exhibit several different types of features that include: (1) distortion from dropstone impact (Fig. 4-16); (2) pillows (Fig. 4-15); (3) faults (Fig. 4-15); (4) diapirs (Fig. 4-15, 4-19, 4-20); and, (5) complexly folded units (Fig. 4-17, 4-18).

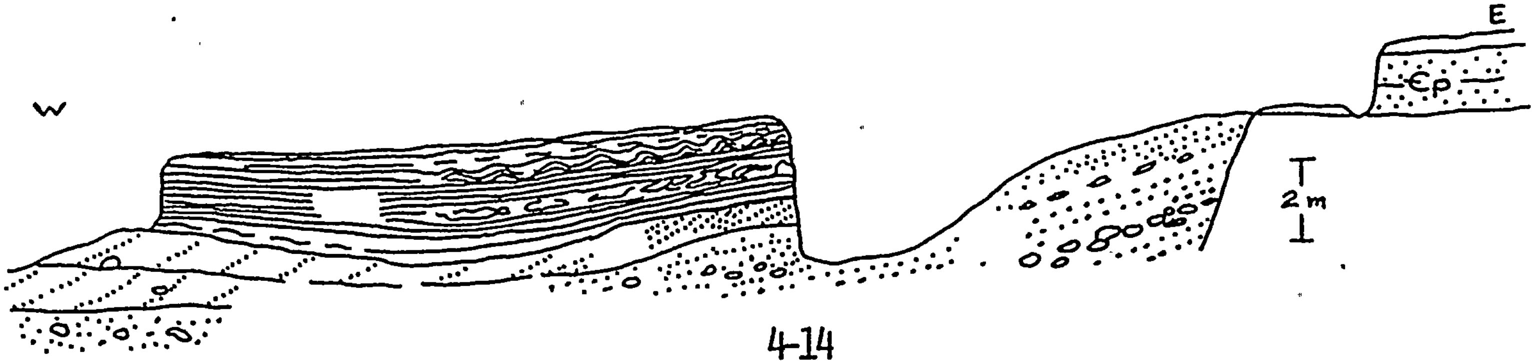
This area contains the maximum number of deformed structures that were observed in laminated silts and clays in the St. Lawrence Lowland. Their complexity and the somewhat unusual circumstances of this environmental setting deserve detailed study. Except for the dropstone features, the cause of the deformed strata cannot be attributed to processes closely associated with direct glacial processes. The magnitude of the deformation and its continuity must be considered seriously in any theory that attempts an explanation for these features. The presence of wide-spread thixotropy, diapirism of many units, and form similarities with structures in the seismic-active areas in California (see photographs in Appendix D) is strongly suggestive that earthquake-triggered events provides a reasonable hypothesis for their development.

Fig. 4-14. Diagrammatic cross section of general relations in pit and adjacent terrain. Potsdam sandstone crops out east of highway. Three different Quaternary units comprise materials in the pit.

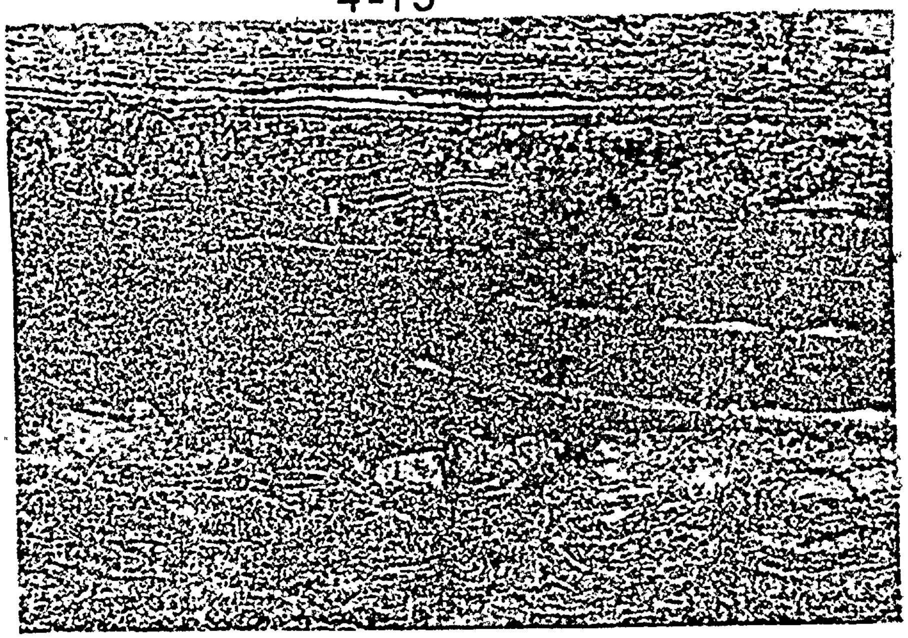
Fig. 4-15. Laminated lacustrine silts and clays. Bottom unit below the dropstone and shovel head shows thixotropic deformation with pillow structures and small scale diapirs. Middle unit contains folds and reverse faults. Upper unit is undeformed.

Fig. 4-16. View showing deformation resulting from impact into the sediments when ice-rafted boulder melted from iceberg.

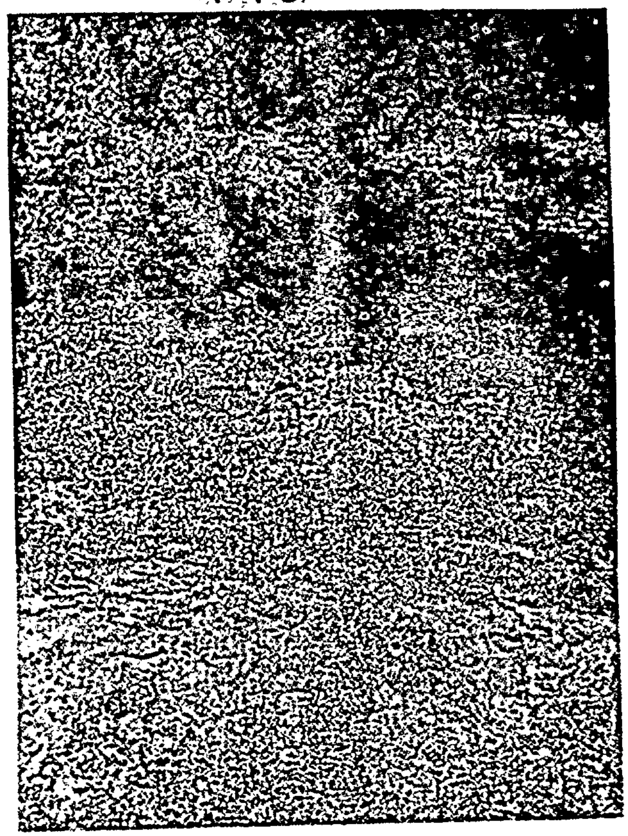
4-14



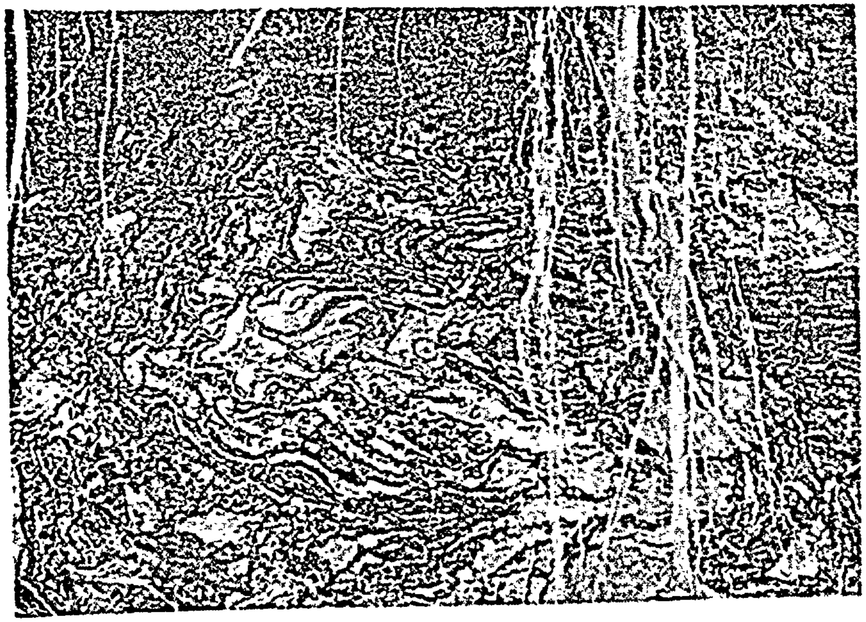
4-15



4-16



Figs. 4-17 to 4-20. Photographs of the middle deformed unit 3 in Figure 4-14. The laminated fine-grained sediments have been severely contorted and show a wide range of folded structures in Figures 4-17 and 4-18, and diapiric structures in Figures 4-19 and 4-20. Figure 4-20 is a closeup of Figure 4-19. Note truncation of diapirs in left of Figure 4-20 and at the position of the pen. The strata immediately above those shown in Figures 4-19 and 4-20 are undeformed.



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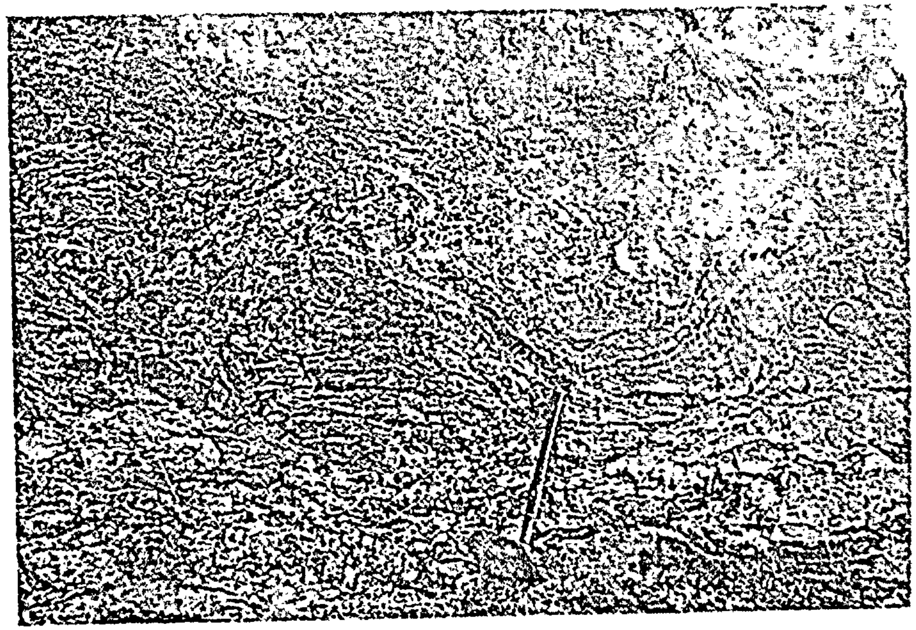
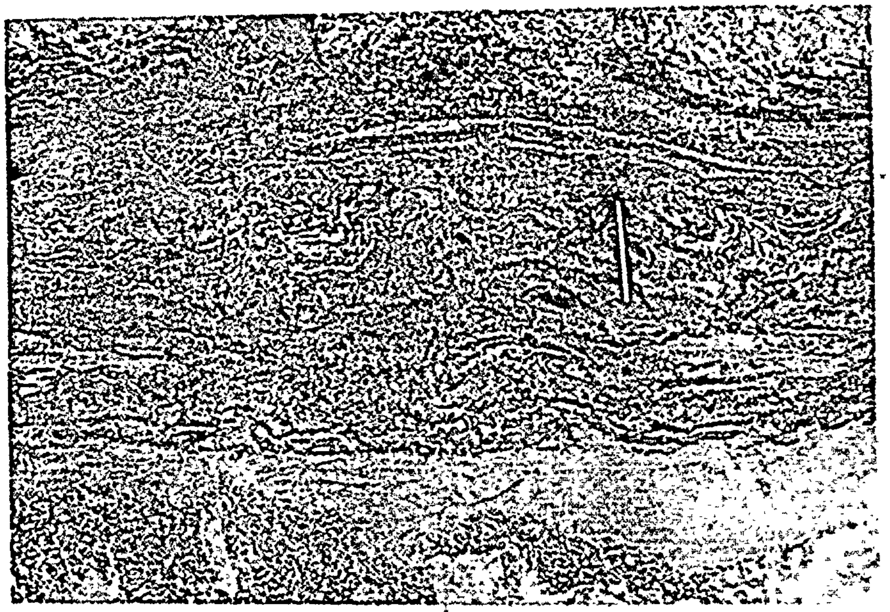


4-18



4-19

4-20

Malone-Constable Area (locality 18)

Two different delta systems occur in the general area of Malone. Both are associated with fluvial deposition by the Salmon and Trout Rivers, transporting debris from the south. The higher delta is located in Malone, is called the "Malone delta" and consists of a "wave washed flat-topped, pebbly sand deposit with a steep lobate northward-facing outer slope" (MacClintock and Stewart, 1965, p. 69). The delta top elevation ranges from 700-730 ft. and correlates with the Fort Ann stage of Lake Vermont in the Champlain Valley. The lower feature is the "Constable delta" and it occurs north of Malone (locality 18). The cut elevation of 440 ft. (Fig. 4-21A) and the occurrence of Hiatella and Macoma shells correlate it with the Champlain Sea event.

In May, 1975 a large area between the two deltas near the Fay community between Malone and Constable was exposed by construction of a new segment of Route 37 and provided about 1500 ft. of outcrops. Additional data of this area is contained in boring and auger logs which were graciously donated by the Watertown District Office, New York State Department of Transportation. A total of a 130 ft. vertical section was able to be reconstructed. This composite section contains 15 ft. of medium to fine sand with a few pebbles overlying about 35 ft. of fine sand and silt. Beneath is 10-20 ft. of clay exposed in a streambed, and silty clay that grades into a very clay-rich gray till. The till clasts are somewhat rounded, from 1-2 in. in diameter, and incorporated in a matrix of plastic gray clay. The section just described represents mainly bottomset units of the deltaic sequence. The upper 15 ft. sand units (Figs. 4-21A and B) consist of deltaic materials that were reworked by shore processes during the Champlain Sea stage. Below this unit is the sandy strata that were largely involved in the formation of the Quaternary deformed sediments (Figs. 4-21 to 4-32).

The sediments shown in Figures 4-21 to 4-32 of the cut are part of a flat-topped wedge-shaped sand body with a steep, lobate, north-facing escarpment in the valley of the Salmon River. The clays, exposed in the cut are lake-floor deposits. Lowermost flat-bedded sands and silts near the cut could also be lake floor deposits or even delta-top deposits. Since they represent a major input of sand, were current swept to produce ripples, and are cut by channels in the overlying sand, a delta-top environment is indicated. The coarse grained, channelled sands in the upper part of the cut suggest that the delta filled up to water level and became an extension of the river or distributary system. Coarsening up sequences are common in deposits of medium and large-scale deltas.

Along the actively worked road cut, maximum vertical exposure at any one face is about 12 ft. (Fig. 4-21B). The sediments form a subtle coarsening-up sequence (Fig. 4-21B). The lowermost exposures contain numerous clayey silt layers interbedded with well-sorted fine sand. Sand increases in abundance upward. The upper sediments are medium sand to coarse sand with pebbly lenses. Some fine sand is interbedded. The sequence exposed in the cut is underlain by still finer sediments.

Bedding in the lower units of the cut is flat and continuous, except where disrupted by soft-sediment deformation. Individual beds of fine sand generally show ripple-drift cross lamination. Some silt layers show ripple forms although internal lamination is not visible. Medium scale, planar cross beds with some channel forms (Figs. 4-21B, 4-24) is the norm in the upper, coarser sand layers. Ripple-drift cross lamination is ubiquitous in the finer sand innerbeds.

The most prominent structures in the cut are numerous small diapirs of silty units injected into sandy beds (Fig. 4-22). Pillows are associated with the diapirs. Smaller pillows of fine sand in clayey silt (Fig. 4-30) bear a striking resemblance to those experimentally produced by Kuenen (1958, Pl. 2; widely reproduced by other authors, cf. Pettijohn, Potter, and Siever, 1973, p. 371). A contact between rippled fine sand overlying clayey silt (unit 2 in Fig. 4-21A) is deformed by relative sinking of the sand, but with little bodily deformation of laminations in the sand so that the synclinal structure is not apparent (Fig. 4-25). Slight rotation may be involved in the internal deformation of some of these structures. The structures are elongate parallel to ripple trough axes (parallel to flow direction) in the sandy layer (Figs. 4-31, 4-32). They may also parallel ripple crests in the underlying silt; deformation and lack of visible lamination in the silt preclude a definite statement. Other structures are oversteepened cross bedding in sand (unit 8, Fig. 4-21A); distorted, blurred ripple-drift cross lamination in fine sand (units between silts 2-6 in Fig. 4-21A; and small, fairly straight-sided dikes of clayey silt (Fig. 4-29).

The Malone road cut is one of the few exposures in the area with sufficient lateral extent and bedding continuity to allow observations on continuity of deformation. Deformation is concentrated in distinct horizons, namely the clayey silt layers and adjacent fine sand beds. The prominent deformed horizons, particularly units 3-5, (Fig. 4-21A) showed some deformation everywhere they could be observed in the cut, over a distance of about 80 m. The degree of deformation is far from constant, however. The most highly deformed exposure passes laterally into practically undeformed beds within several meters (Fig. 4-24).

This cut also provided an opportunity to observe time relationships of deformation among various beds. Referring to Figure 4-21A, it appears that units 3-5 were deformed simultaneously because diapirs from the lower two beds penetrate at least as high as unit 5 (point A on the reference grid in Fig. 4-21A). The diapirs from each bed are also very similar in size, orientation, and appearance, although this depends much more on similar physical parameters than temporal factors. There is no conclusive evidence of a time link between the deformation of units 1-2 and 3-5 nor even between the diapir of unit 2 (at point A) and the pillows within 1 and 2 or the deformed upper

boundary of unit 2. The assumption that all deformation in unit 2 was a single event is reasonable, because prior deformation normally leaves a bed with more stable packing (reduced pore space) and so less susceptible to future deformation. There is a suggestion that the deformation which formed the diapir in unit 2 extended through the intervening fine sand bed to unit 3 because ripple-drift cross stratification in the sand bed is almost totally destroyed adjacent to and above the diapir, whereas it is prominent elsewhere in the bed. Similar evidence links the deformation of units 3-5 with that of units 6 and 7. Ripple drift cross lamination is destroyed within the base of the sand unit 5 to 6 between B and C (Fig. 4-21A), although it is intact at the top of the bed; it is destroyed at the top of the bed but not at the base at D; and apparently throughout the bed and into the overlying bed at A. Units 5 and 6 were deformed simultaneously if interpenetration of diapirs (at C) and parallel rotation (at E) are acceptable evidence. Diapirs from these units penetrate the base of the overlying channel sand (unit 8) at C. D. and possibly E. It is not clear whether the rotation leading to oversteepening of cross bedding in unit 8 is related to current drag during deposition or to deformation of the underlying units. Thus, there is reasonable, although not conclusive, evidence that deformation of units 1-8 was a single simultaneous event or at most 3 events involving units 1-2, 3-5, and 6-8. "Simultaneous" in this context means occurring throughout the same time span whether it be seconds or years in duration. A short span appears more likely. No evidence exists that any of the structures reached the depositional interface, except for the truncation of oversteepened cross beds in unit 8 which may be an unrelated event. If 3 episodes of deformation were the favored hypothesis, then by definition the lower levels of disruption in each (units 1, 3-4, and 6-7) were not at the surface.

The deformation mechanism that affected the strata in this roadcut at locality 18 was not associated with direct glacial processes, because the sediments were deposited in an environment far removed from the ice margin....there is even a lack of ice-rafted materials. As pointed out in Chapter 2 there is a large variety of other processes that can create thixotropically deformed sediments. For example note the similarities of photographs of Figures 4-27, 4-28, 4-31, and 4-32 with the drawings in Figure 2-8. The photographs, however, lack a lateral asymmetry as depicted in drawings of Figure 2-7. There is furthermore a resemblance of several of the deformed features, such as depicted in Figure 4-27, with the contorted sediments of California (see for example Fig. D-8). In many of the outcrops of locality 18 remarkable thixotropy occurred and the deformation was always directed vertically and the resulting features were able to be reproduced experimentally with shaking table techniques (compare with Figs. 2-2, 2-3, 2-4, 2-5, and 2-6). The only evidence mitigating an earthquake explanation for creation of the deformation is the lack of continuity in some units throughout the entire outcrop area (compare Figs. 4-22 and 4-24). Until further detailed work is done however, a seismic origin for these deformed sediments cannot be dismissed.

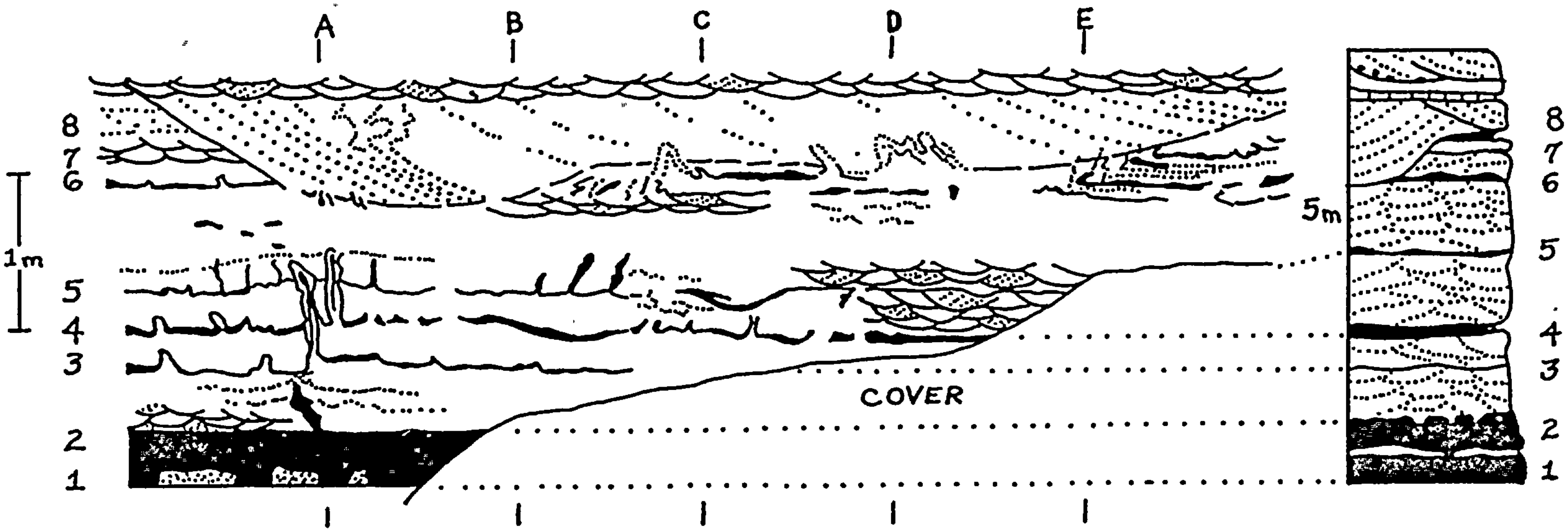


Fig. 4-21A

Field sketch of new road cut excavation along Route 37
northwest of Malone near Fay. Locality 18.

Fig. 4-21B. Upward coarsening of grain size. Lower unit is fine-grained, sandy, and contains thixotropic deformed structures. Middle and upper units are non-deformed and show current direction from left to right.

Fig. 4-22. Diapirs in fine-grained sands. These structures range from knife-edged intrusions to open forms that are as wide as their vertical dimension.

Fig. 4-23. Diapir in three dimensions. The penny lies on a horizontal surface. Diapir shapes come in a variety of forms from those that are pencil and cone-like, to those that are tabular.

Fig. 4-24. This photograph is 6 ft. to the right of Figure 4-22, thus showing the lateral changes in deformed and non-deformed sections. The section shown is depicted as units 3-5 in Figure 4-21A. Units 4 and 5 display ripple sequences. Photo height is 18 in.

-21B

4-22

4-23

4-24

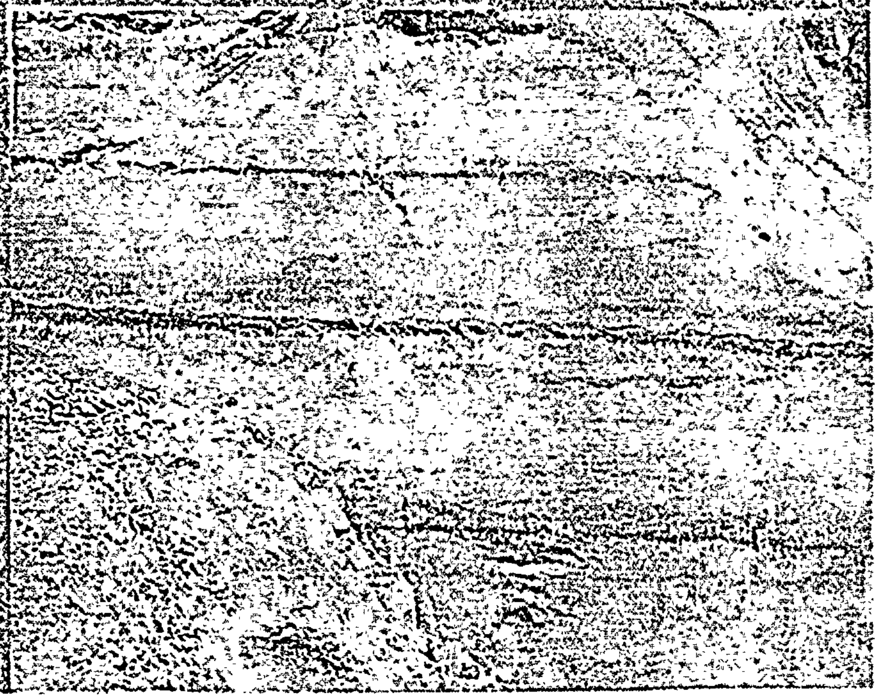


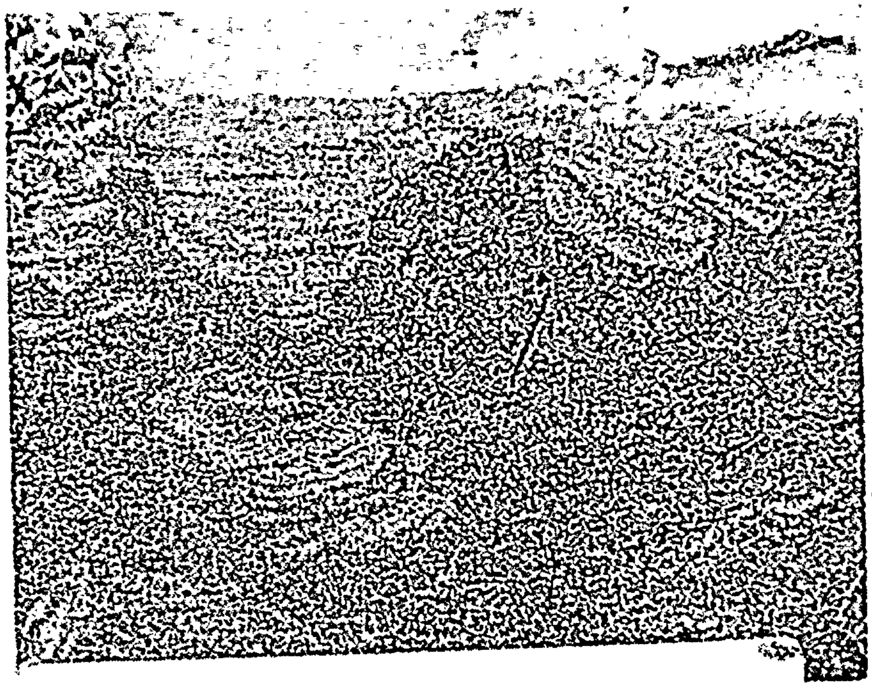
Fig. 4-25. Load casts of sand unit into clayey silt. Note slight rotation of laminae. Width of field is 5 in.

Fig. 4-26. This is an unusually large diapir for this locality. Note the entire section contains deformed units with complex structures that all exhibit extreme thixotropy.

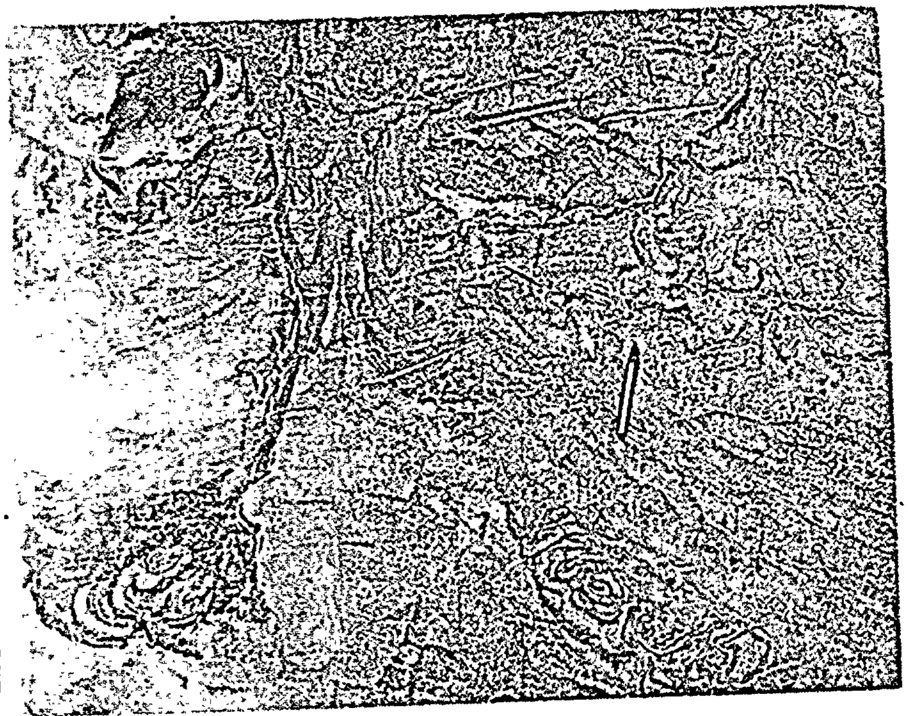
Fig. 4-27. Soft sediment folds. Note broad, flat synclines and sharp anticline crests, which become diapiric at higher levels.

Fig. 4-28. Syncline produced by load cast occurs in layer above the scale. Contrast the diapirs at the upper boundary of dark and light sediments with those in Figures 4-22, 4-26, and 4-27.

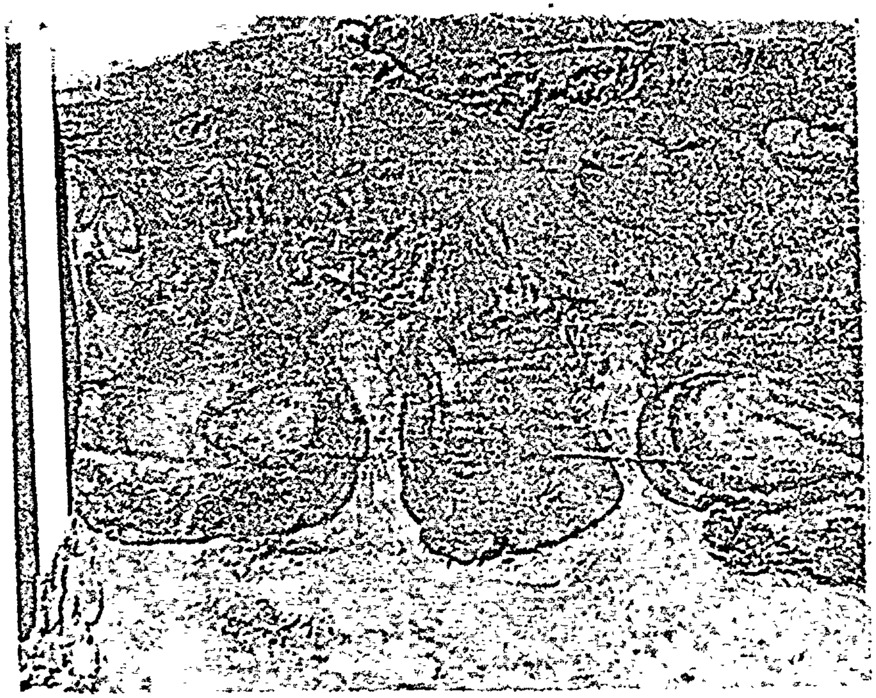
4-25



4-26



4-27



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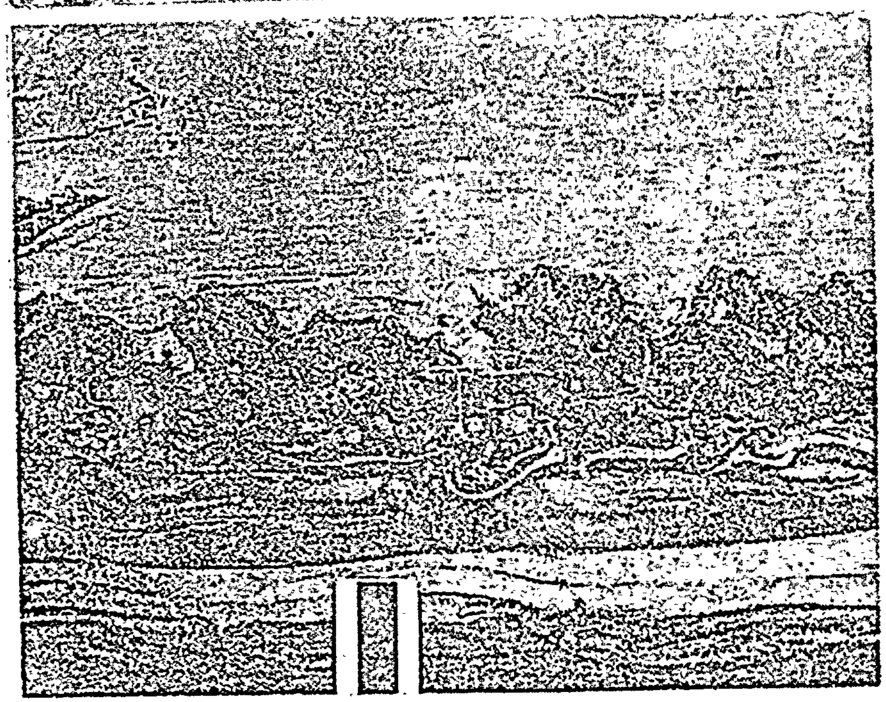


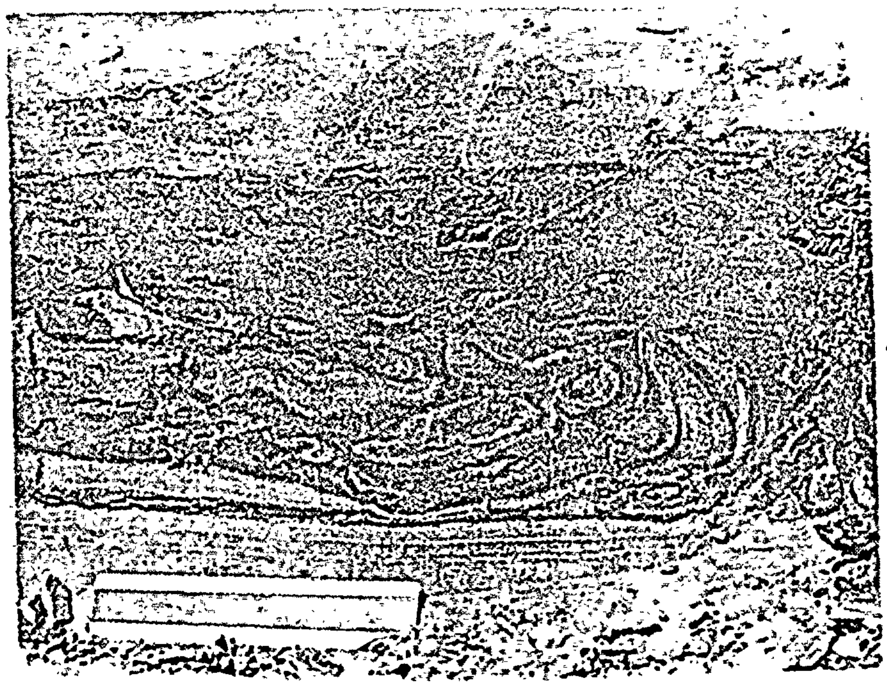
Fig. 4-29. Dikes and diapirs in fine-grained sediments. The muddy silt injects fine sand. Section is 15 in. long.

Fig. 4-30. Pillows (center) and load casts (above) of sandy unit into clayey silt.

Fig. 4-31. Three-dimensional view of load casts in Figure 4-25. The scale is lying on a small step separating a vertical face below and a horizontal face above. Note orientation and shape of load casts when the vertical features are related to the horizontal structures.

Fig. 4-32. This is a small-scale map view of the horizontal surface that cuts the load casts which is shown in Figure 4-31.

4-29



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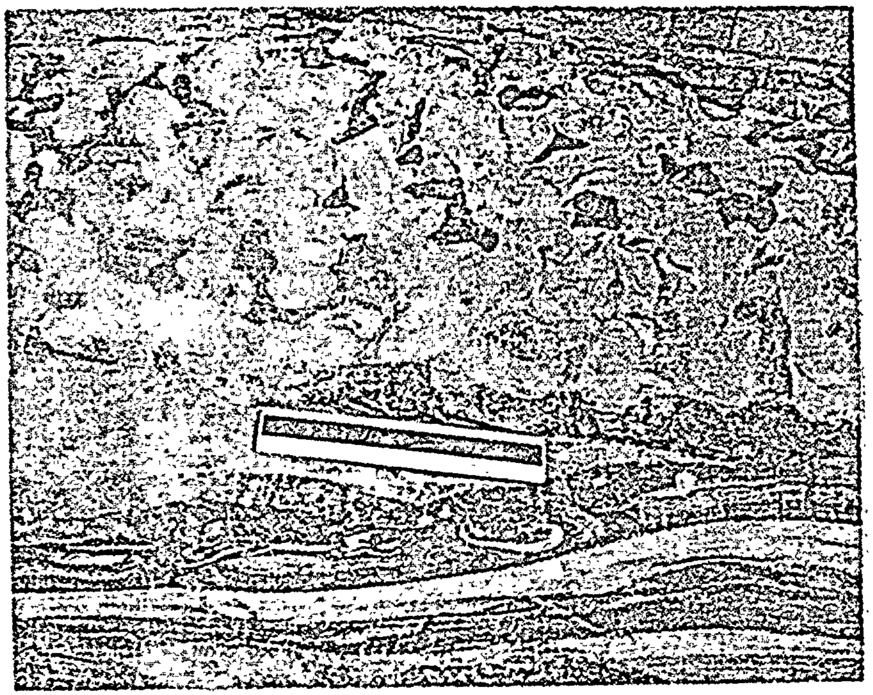

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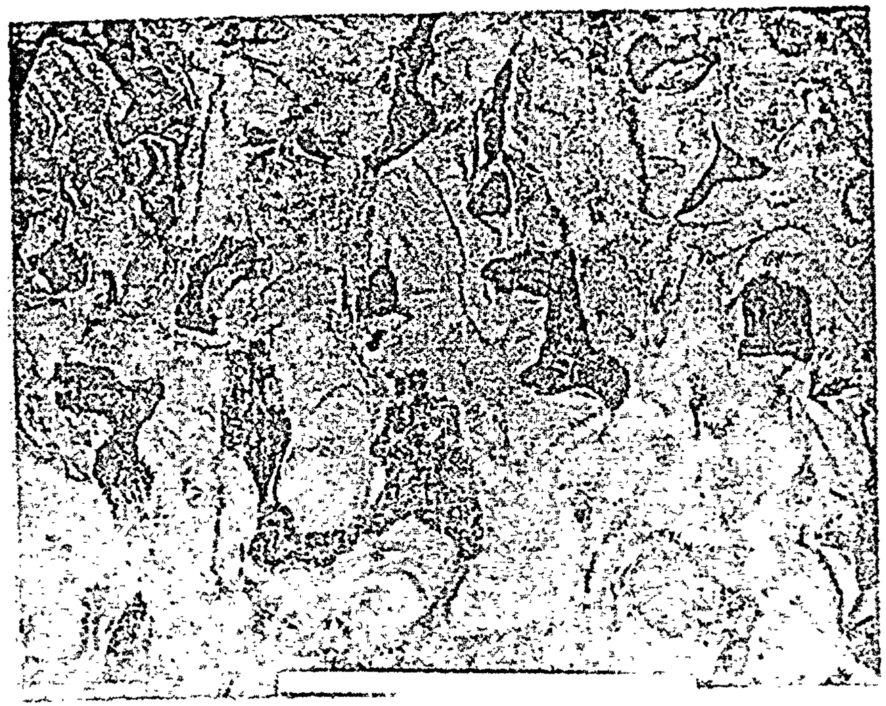


4-32

Canton Sanitary Landfill Area (localities 12 and 13)

The Quaternary sediments in this area comprise part of a broad belt of sand along the north side of the Adirondack uplands mapped as "shoreline sands" of the Champlain Sea by MacClintock and Stewart (1965, Pl. 1B). They further identified sandy deltaic deposits near the community of Pyrites, about 0.7 mi. ESE of this site. Extensive sand deposits occur in an area that exceeds 1 $mi.^2$ in contiguous lands to localities 12 and 13. These sediments were formed by north-flowing rivers into the Champlain Sea, and the Grass and Harrison Rivers are the modern day locations of the earlier drainage. Strandlines were developed in the area and beach and dune deposits also occur extensively, with the secondary development of an erg-environment in nearby exposures. Similar deposits occur throughout the St. Lawrence region and have their counterparts in places as localities 15 and 18.

Location 13 contains the greatest variety of deformational features seen at a single site in the entire St. Lawrence Lowland. Here excavation of the north face of the facility has revealed a system of four different levels of deformation in a 25 ft. exposure. Figure 4-33 provides an overview of a part of the outcrop, and Figures 4-34 to 4-36 show closeups of several types of deformation. Diapirs are the most common type of structures. Their size and perfection is dependent upon the nature of the material in the stratum, its thickness, and characteristics of the confining units. An important element in this locality is the lateral continuity of the deformed units. Although some of the individual beds have interruptions in the deformed patterns this entire outcrop of deformation can be traced more than 1500 ft. Furthermore similar style deformations occur throughout a much larger contiguous region of > 1 $mi.^2$. Another important consideration is the vertical array of the deformed sediments. It is significant that four different strata have been involved in these patterns, and each unit has its own particular blend of contorted features.

Locality 12 occurs in a 5 acre sand pit where deposits are exposed in 50 ft. sections. Figures 4-38 to 4-41 are typical of deformed units at this site. The lowermost sediments exposed in this pit are well sorted fine sand to very fine sand with some layers of silty sand and lenses of medium sand. Medium scale cross bed sets occur in the coarser sediments; ripple drift cross lamination is common in the finer ones. The upper part of this unit, at least on the well-exposed east face, is arranged in large sets (1-2 m) of low-angle inclined beds with rather variable dip angles (average 5-10°) and some variations in dip azimuth from the average SW direction. On the south and southwest faces, the lowermost unit is incised by channel forms filled with medium-to coarse-grained sand with low angle festoon cross beds (Fig. 4-37). A thin topmost unit of brown, fine-grained, pebbly sand with poorly defined inclined layering grades up into soil.

The lower part of the lowermost unit with many silty layers and lenses of contrasting grain size, the overlying festooned channels of coarser sand, and the pebbly fine sand do not permit a beach or beach dune interpretation for the rest of the

sequence. The lowermost unit probably represents subaqueous deposits, perhaps a low-relief delta or offshore bar which built up into the shore zone (east face) and was then channeled by streams or distributaries emptying into the water.

Deformation is confined to the lowermost unit and to its contacts with the channel sands. The most spectacular structures are diapirs and related pillows (Figs. 4-38 - 4/41). These structures usually involve the finest layers in the sequence, but since those are silty sand, the structures are essentially sand-in-sand. Some nonpiercing sharp anticlines are also present as well as several truncated structures. A small syncline or load cast of fine sand into medium sand is shown in Figure 4-39. A high-angle fault with some 10 cm of offset appears to extend into the base of a superjacent channel (Fig. 4-41). This suggests that the fault may have originally extended to the depositional surface. The possibility of eroding as much as a meter of the lowermost unit with formation of the channel to exhume a buried fault should also be considered.

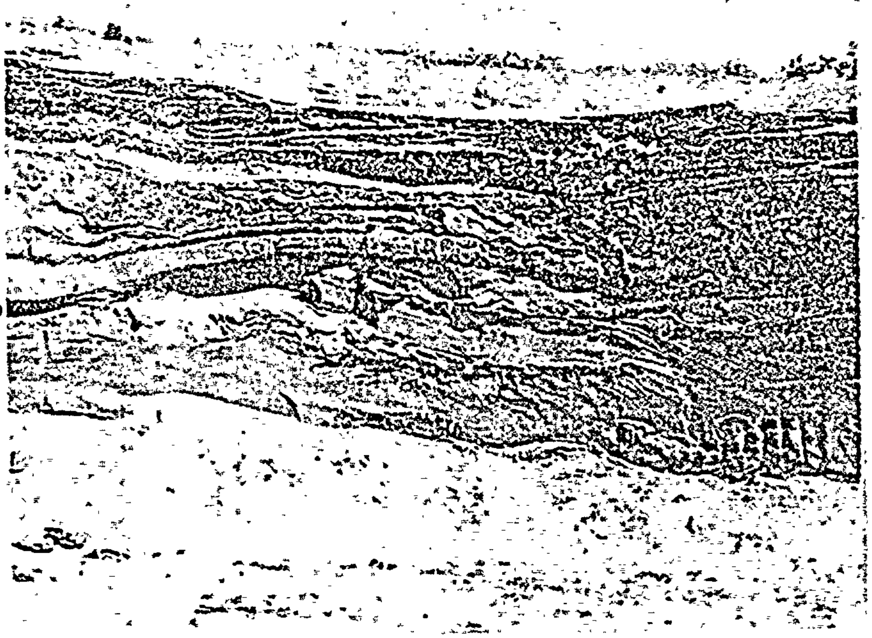
The Quaternary deformed sediments at the Canton Sanitary Landfill site when compared with all other St. Lawrence areas that were visited, have the greatest possibility of having originated from earthquake shocks. This area contains all of the features that have been described by Sims (1973, in Press) in California as requisities for being seismic-related. The deformational scale of the features in localities 12 and 13 is consistent with those from California, and the diapiric and pillow structures are very similar. The truncation of diapirs and the vertical-induced thixotropic features as shown in Figures 4-33 to 4-41 all have their counterparts in the structures that were created during laboratory experimentation in this project (Figs. 2-2, 2-3, 2-4, 2-5, and 2-6). One of the strongest evidences for a possible seismic source for deformation is the large-scale continuity of several of the strata. Deformed structures in several members can be traced for 100's of ft. in many instances. Much additional work needs to be done at these localities and in the entire surrounding area.

Fig. 4-33. The four photographs of this plate were taken of the working face at the Canton Sanitary Landfill site (locality 13). Figure 4-33 provides an overview of one of the sections and the other photographs are closeups that depict greater detail in some of the sediments. At this site sands cover 50 acres, and similar sands are found in contiguous lands. At least four different deformed units can be identified in this vertical 25 ft. section. These are marine sands deposited into the Champlain Sea.

Fig. 4-34. Three deformed horizons occur in this photograph. The lower unit contains diapirs with some having truncations. The middle unit shows folding within the sands, and the axes seem to have developed in accentuated form from the ripple drift sequence. The upper unit contains diapirs and flow structures in a thixotropic sand-clay member.

Fig. 4-35. There are four deformed units visible in this photograph. The most prominent contains extensive development of pillows and load casts in the darker colored fine-grained sands and silts.

Fig. 4-36. Detail of sand-in-sand diapirs.



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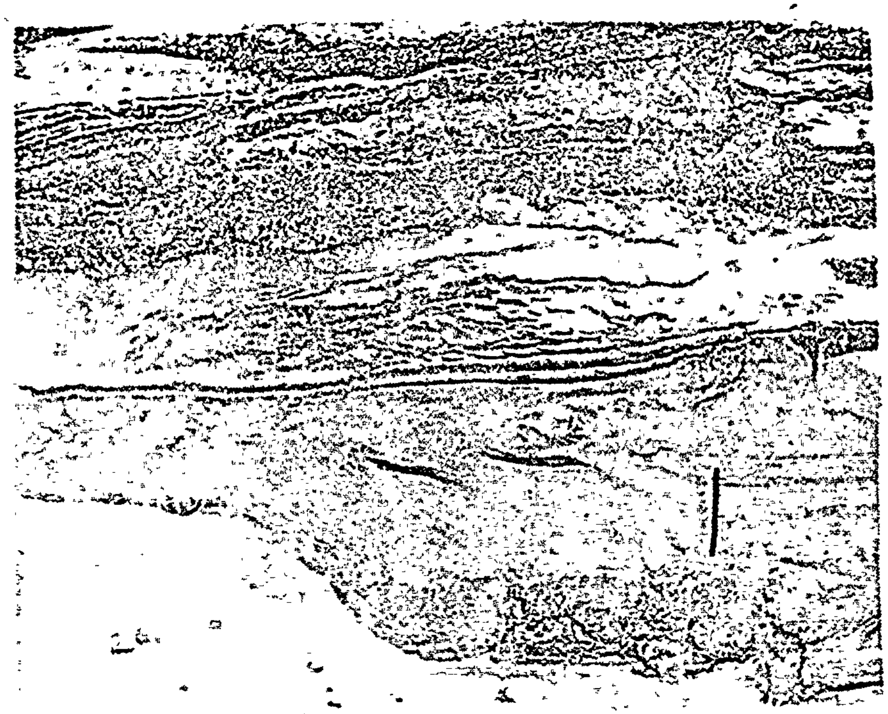

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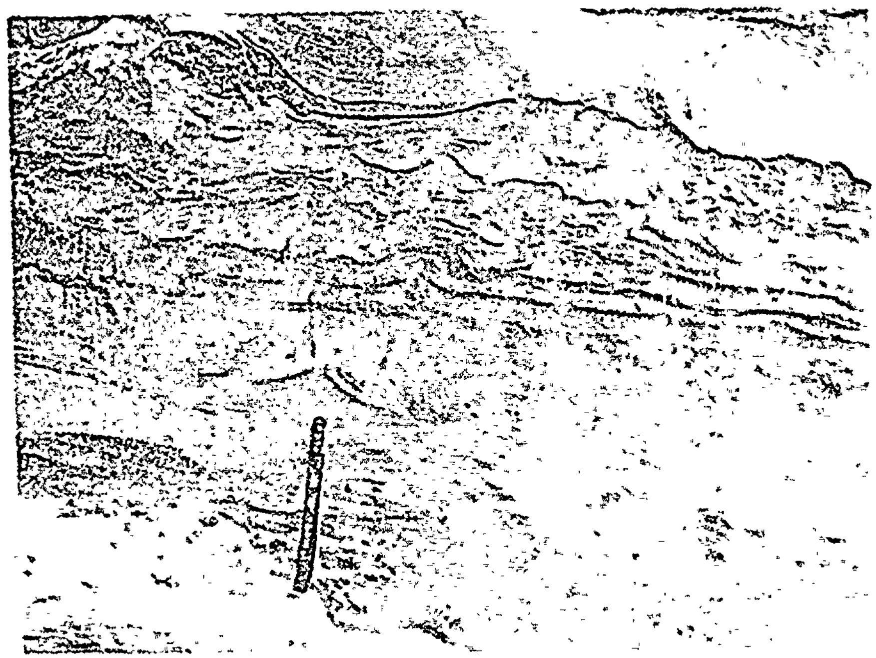

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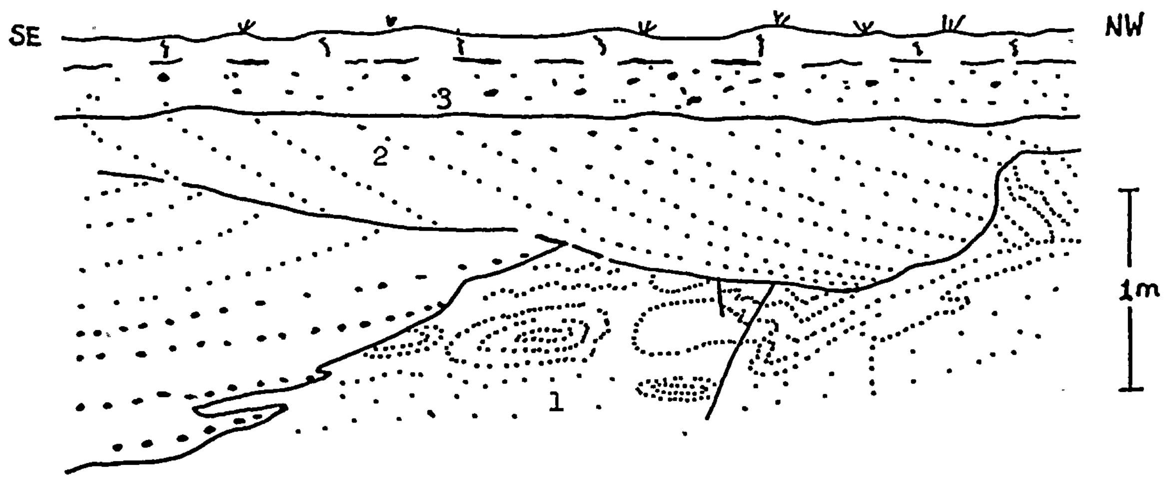


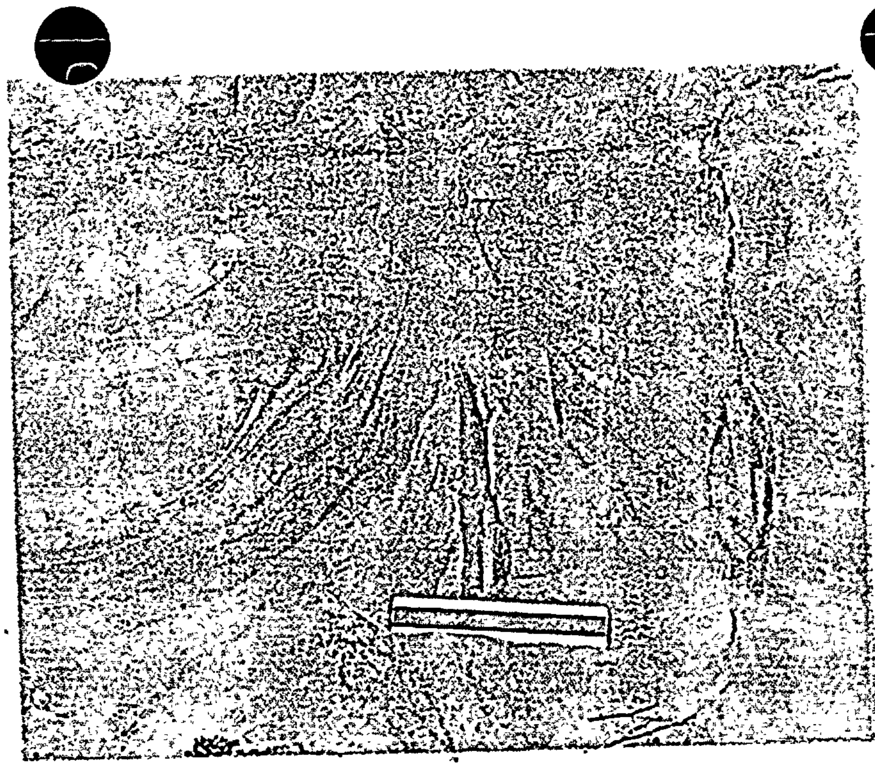
Fig. 4-37. Field sketch of Southwest Face of Pit (locality 12).

Fig. 4-38. The four photographs of this plate were taken in an abandoned sand pit (locality 12) on the opposite side of a small ridge separating this site and the exposures at the Canton Sanitary Landfill. This picture shows a sand-in-sand diapir. Figures 4-38 to 4-40 occur in same stratum of the pit (unit 1).

Fig. 4-39. Syncline produced by a load cast.

Fig. 4-40. Pillow structure.

Fig. 4-41. Small faults extending to base of the channel fill gravels in top of photograph.



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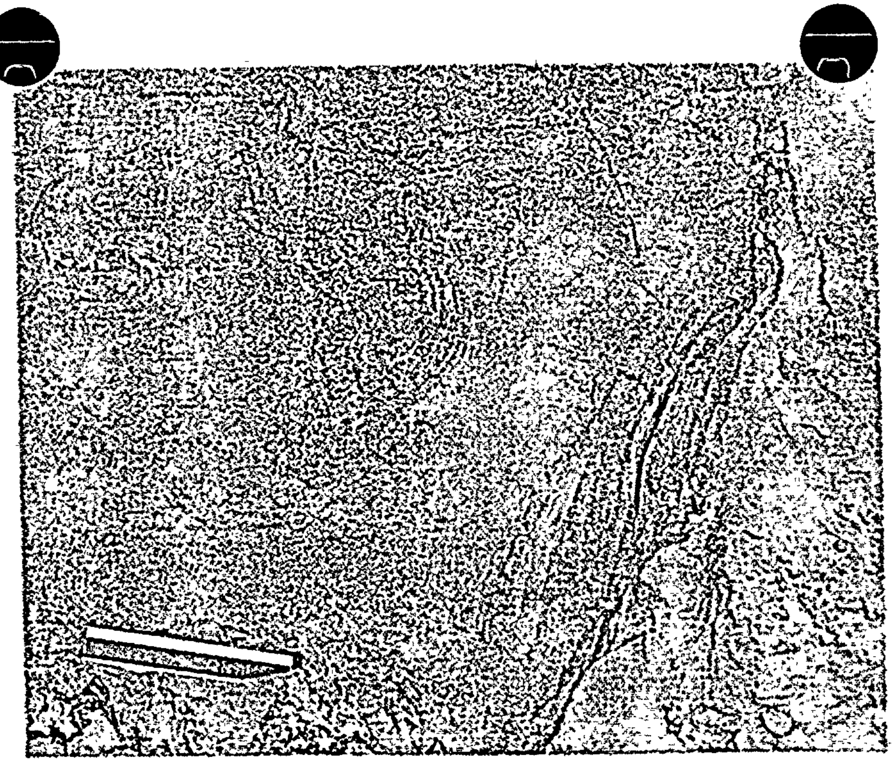

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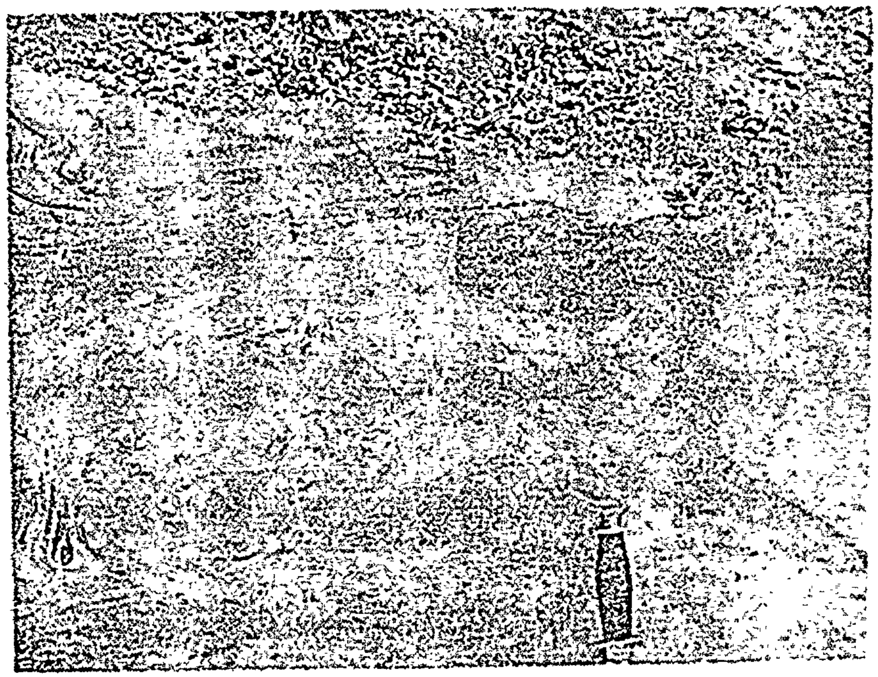

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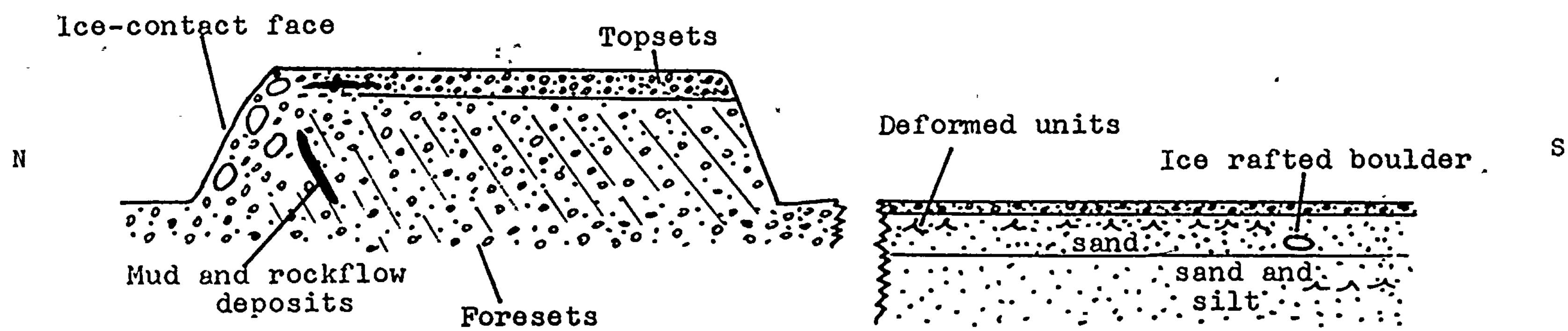


Fig. 4-42. Diagrammatic relations of sedimentary units.

Colwell Gravel Pit - Watertown, N. Y.

The Colwell Brothers Gravel Pit is located 2 mi. south of Watertown, N. Y. on the east side of Route 12. Although this area was considered outside of the principal study region, a brief account is now made of this site for comparison purposes with the previously-mentioned type localities. At the Colwell Gravel Pit 200 acres of sand and gravel have been extensively mined, and excellent exposures occur throughout the pit. This is the largest working sand and gravel pit in the region, and is situated on the west side of a northwest trending bedrock ridge. Figure 4-42 provides a diagrammatic overview of the setting and materials of the pit. The sediments formed in an exceptionally large kame delta, with fining of materials southward. The glacier margin and ice blocks occurred to the north of the pit and meltout left in the immediate vicinity left a range of deposits that include mud and rockflows, foreset beds which eventually give way to topset beds (Fig. 4-42). This section is about 50 ft. thick and the coarse-grained sands and gravels of the deltaic units predominate.

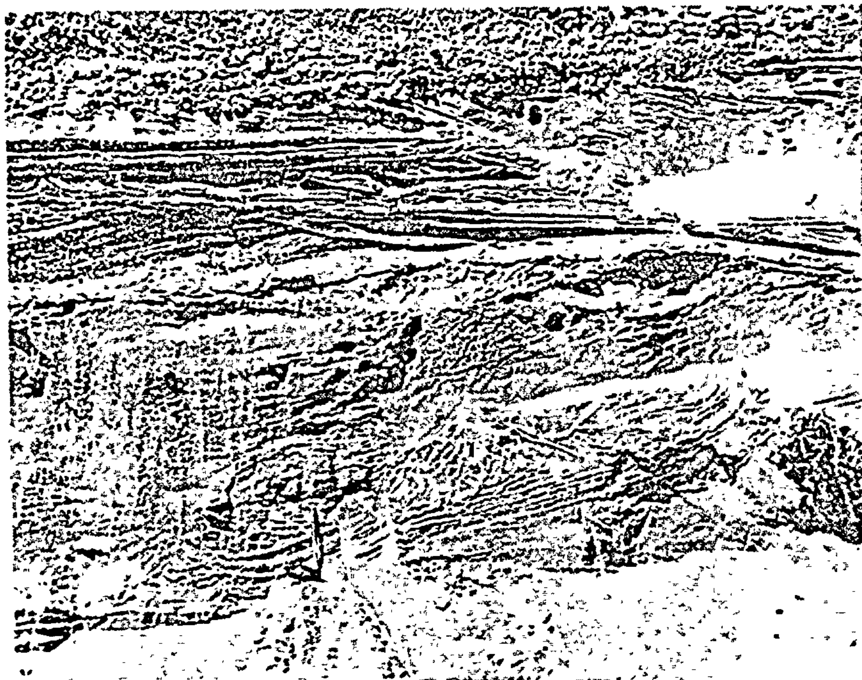
The lower level of the delta (Fig. 4-42) is about 2,000 ft. south of the principal ice-contact face. The fine-grained sediments are essentially flat-lying in exposed sections of 30 ft. thickness. Figures 4-43 to 4-46 show the character of the materials and their structures. The sands exhibit well developed crossbedding with abundant ripple drift sequences and ice rafted boulders up to 2 ft. in size. These sediments also contain a variety of deformed features that include truncated diapirs. A much siltier phase of deposition occurs at depths 12 ft. below the sands. These are bottomset beds in the proglacial lake and they contain thixotropically deformed sediments that can be traced for 100's of ft. Since the ice margin was about 2,000 ft. away, such deformation cannot be linked directly to a glacial cause. However, the rapid superposition of coarser grained topset beds may have occurred before the bottomset units had reached sedimentary stability. The weight of overlying materials may have been sufficient to initiate thixotropy that led to the diapirs and pillow structures. Much additional work must be done to determine whether seismic events also contributed to the deformation.

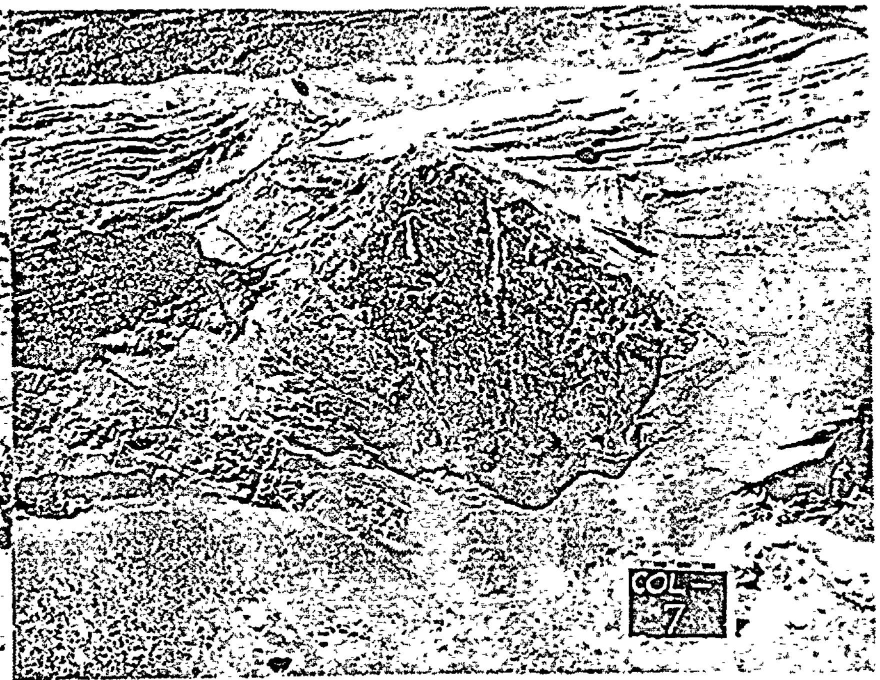
Fig. 4-43. View near south part of pit looking south. 12 ft. of sands are overlain by cobbles. Several zones of deformed strata occur, with other sedimentary structures. Truncated diapirs can be seen below horizontal sand stratum in upper left of photograph. Ice rafted boulder with deformed strata in lower right.

Fig. 4-44. Closeup of ice rafted boulder in Figure 4-43. The rock is amply striated and its impact distorted adjacent sands.

Fig. 4-45. Fine-grained sediments with pillow structures. This thixotropically deformed unit is stratigraphically older than the sands in Figures 4-43, but the photograph shows an outcrop 600 ft. away.

4-43





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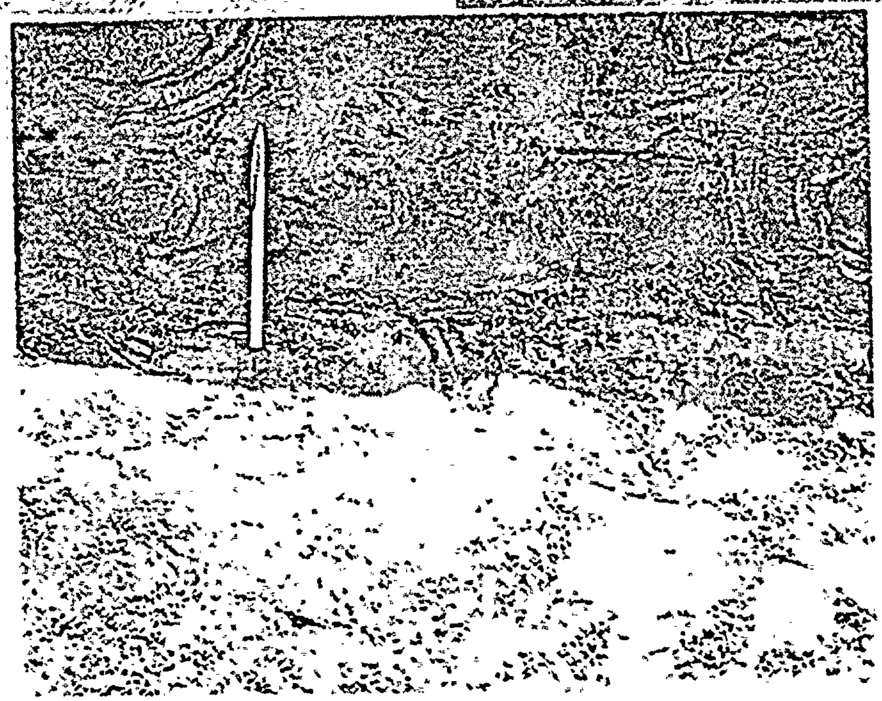

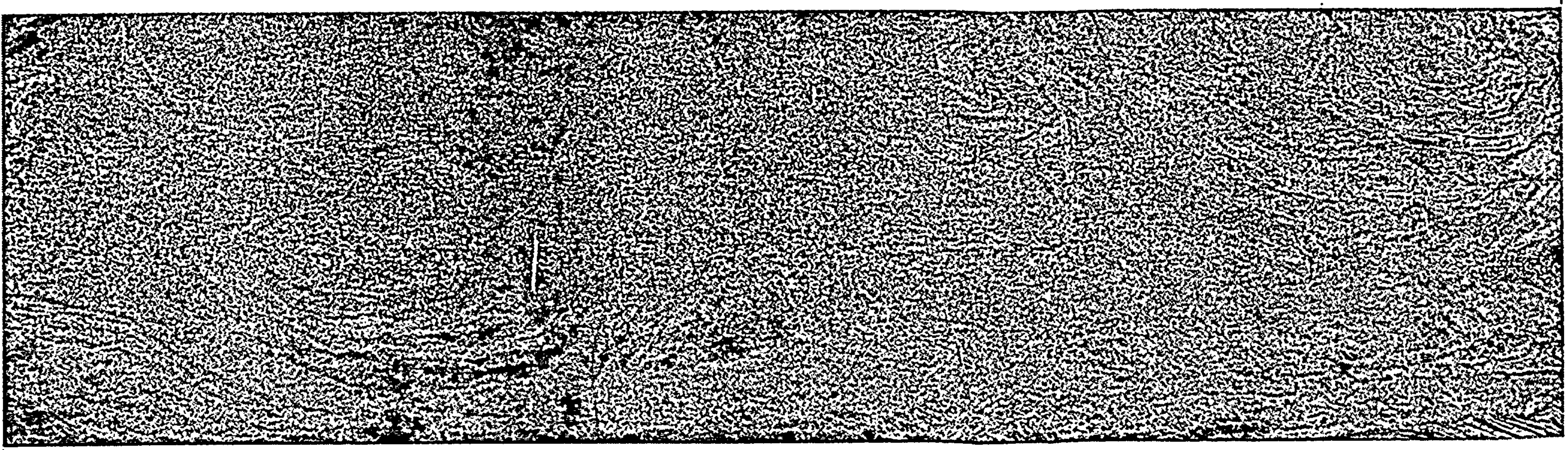

4-46

Fig. 4-46. Small-scale panorama of pillows and diapirs in bottomset beds. This site is in the same stratigraphic horizon as Figure 4-45 but is 500 ft. away. Sediments are mostly silts and fine-grained sands.

Quebec, Canada Pleistocene Sediments

In order to better understand the nature of Quaternary deformed sediments in the St. Lawrence Lowland of New York, a number of other field localities were visited and evaluated. Some of these are mentioned in Chapter 3. Dr. Palmer studied both the California and the St. Lawrence sediments (Appendix E), and we also viewed glacial deposits in Canada.

Following up a brief comment on the possible seismic origin of soft sediment deformation in the Quaternary deposits of Quebec, included in the Dames and Moore (1974), a field trip was arranged to visit the critical exposures. Dr. LaSalle, a Pleistocene research geologist from the Quebec Ministry of Natural Resources, who provided helpful assistance to the Dames and Moore team, kindly agreed to guide us through the critical exposures. Five main localities were visited in the area within easy reach from Quebec City, and the principal findings are briefly summarized below:

1. St. Jean Chrysostome. This exposure is located in a small sand and gravel pit in glaciofluvial deposits aligned parallel to the Highland Moraine system. The uppermost part of the cut consists of a 100-150 cm thick gravel bed, underlain by a medium to coarse sand with occasional beds of clayey silt. Deformation features include:

a. A larger scale (150 cm across) relatively open fold with a horizontal axial plane.

b. Smaller (5-15 cm across) somewhat irregular folds with changing axial plane and an occasional orthorombic (conjugate) symmetry.

c. Small scale normal faults in the lowermost part of the cut. Displacement ranges from several cm to 1 m. Occasionally the faults are closely spaced and a "reticular" pattern appears. The structures are interpreted by LaSalle in terms of ice collapse (cf. the faults) and possibly an ice or gravel push (cf. the fold elements).

2. St. Romuald. The pit shows a sequence of marine clays about 10,500 yrs. B.P. interbedded with thin layered sand , believed to represent a distal part of the Chaudriere River paleodelta. The fresh cut examined consists of sand beds 3-6 cm thick interbedded with layers of clay 1-4 cm thick. The sand is fine to medium grained and abounds in ripple drift cross lamination. Features of scour and loading appear at the sand/clay interface. However, they are not continuous laterally. This type of structure is very common in sedimentary sequences along clay-sand interfaces, and is not a mechanism which must be triggered by a shock.

3. Collieres. This large sand quarry in a thick sequence represents a part of the Montmorency Delta System. The sequence includes large scale channels up to 5 m wide (and probably more). Numerous bands of contorted beds have structures from 2-25 cm in amplitude. The geometry is variable, from gentle anticlines to overturned and recumbent folds. Diapiric, injection structures

are common, but in numerous places truncated folds were observed. Some horizons of contorted bedding may be traced laterally for 50 to 100 m. In a number of places the contortions appear within the channels and seem to decrease in size and terminate at a channel bank (or possibly along a rotational slide at the bank). These structures represent the classical sedimentary folding in sand as described in numerous places, and in principle are somewhat analogous to the structures described from Malone and Canton. Contorted bedding of this type have been reported from other deltaic deposits, and have previously been believed to indicate a rapid deposition, presumably in a metastable, disturbance-prone state. Their possible seismic relationship needs a complete evaluation.

4. Lac St. Charles. Extensive pits in a coarse sand, grit and gravel sequence in a moraine. A striking kettle dominates the exposure. On the northern side of the kettle are prominent normal faults, on the south abundant small scale reverse faults. Several larger scale , somewhat irregular folds appear on the north, close to the top of the exposed sequence. Both folds and faults are interpreted by LaSalle to collapse over melting ice.

5. Duberger-Charlesbourg. Glacial marine clays (Leda Clay) with remnants of fauna (Portlandia artica) show a local intense deformation with folds up to 40 cm across. The folds vary in size and shape, but usually are tight and may be refolded. The deformed zone appears to terminate against a small reverse fault. LaSalle interprets the exposure in terms of glacial readvance or a mobile ice front, at times floating and at times grounded, causing the observed faulting and contortions.

CHAPTER 5

SUMMATION

The objectives of this project have been to identify Quaternary sediments that meet the criteria for earthquake-induced structures and to evaluate the applicability to the St. Lawrence Lowland of studying the deformed features as a means of better defining earthquake recurrence rates. To accomplish these aims a four month reconnaissance study was done by an interdisciplinary team of geoscientists representing the specialties of glacial geology, sedimentology, neotectonics, and geophysics.

CONCLUSIONS

1. A 2500 mi.^{2} area in the St. Lawrence Lowland of New York was studied by geologic methods. This included aerial photograph analysis, visits to more than 200 sand and gravel pits, sampling of 100's of outcrops, study of soil surveys, evaluation of published surficial geology maps, and analysis of drillers logs. In addition, 1600 published reports were referenced for relevancy to the project and the 600 most appropriate have been included in the bibliography.

2. A set of criteria have been developed that are suggestive of seismic-induced deformation in soft sediments and include: (1) diapirs, especially when truncated, (2) horizontal continuity of deformed units, (3) presence of thixotropic features, (4) vertically-directed distortion, (5) absence of glacial processes, and (6) character of overburden. For example thick and coarse-grained sediments atop deformed strata might infer dynamic events with rapid sedimentation prior to bottom units reaching stability. The total nature of the environmental setting must also be considered, as should the character of faults when present. Most faulting types are not compatible with thixotropically deformed sediments.

3. St. Lawrence Quaternary strata possess deformation in a wide range of types, sizes, distribution, and environments. Deformed units occur in all textures of sediments, but are most common in silts and fine sands. Deformation occurs in kames, kame deltas, shorelines, and lake and marine floor sediments. The majority of deformation was caused by events associated with glaciation.

4. There are several areas in the St. Lawrence Lowland that require intensive detailed studies. Sites that hold the greatest promise for containing deformed sediments that could be caused by seismic events (see Chapter 4) include the localities of Canton (12, 13), Malone (18), Gouverneur (10), Alexandria Bay (8), and the Colwell Gravel Pit at Watertown. Preliminary study at these localities shows they contain distorted Quaternary sediments that meet the criteria established as being suggestive of seismic-induced deformation (see Conclusion #2). Other areas that have well developed sediment deformation and need additional work, include the Clayton-LaFargeville sites (1,2,3,4,5).

5. A regional time scale was developed to provide a chronologic framework for assessment of recurrent seismic events. The following Quaternary stratigraphic conclusions are (see Chapter 3, and Appendix D):

(1). Fort Covington drift represents a retreatal phase of the same stade associated with the older Malone drift, and dates from about 12,600 yrs. B.P.

(2). New Carbon 14 dates have been obtained for representative areas and events and include dates of 12,000 ± 200 yrs. B.P. for Champlain Sea varve clays at Massena, 11,000 ± 150 yrs. B.P. for strandline-related silts near Norfolk, and 10,340 ± 130 yrs. B.P. for fine sands of the Champlain Sea near Fort Covington.

(3). Deformation events occurred repeatedly during a 2,000 yr. period (about 12,300 to 10,300 yrs. B.P.).

6. A local time scale for chronology of depositional sequences can be inferred from thickness, extent, size, type, and distribution of the Quaternary sediments. If the rhythmites are true varve deposits, and if the fine-grained sands were deposited at rates that have analogs in present-day glacial regions, then time spans of several hundred years are represented by such sediment sequences as those at Canton (12, 13), Malone (18), and Alexandria Bay (8).

7. If the deformed sediments that bear the greatest resemblance to seismic-induced structures were indeed formed by earthquakes, then the recurrence interval for such events operated on a scale of 100 yrs. or less.

8. Mineralogy of deformed sediments is not significantly different from undeformed sediments (Appendix C). The scanning electron microscope provides a useful tool for study of fabrics of whole clays on freshly broken surfaces. It can aid the determination of metastable fabrics from those that have undergone liquefaction. Shaking table experiments were performed that duplicated the critical types of thixotropically deformed sediments, such as the development of different types of diapirs.

9. Holocene sediments show little promise for use in determining a linkage between deformational structures and seismic events (Appendix D.).

10. This preliminary reconnaissance study has shown that methods for evaluation of Quaternary deformed sediments can add an important dimension in the determination of possible earthquake recurrence intervals. Detailed studies (see below) are now needed before the problem can be completely resolved. Greater precision is needed in dating the sediment record and the amount of time represented by the sediments at any given site. Thus final conclusions are limited by the accuracy of the dating techniques. Success can be enhanced by careful attention to the environmental setting of each deposit with identical sediments presently forming in glacial terrane.

RECOMMENDATIONS

If unlimited funds were available for the resolvement of the general problem of possible linkage of Quaternary deformed sediments with earthquake events and recurrence intervals, then a full scale program for a comprehensive unified field, laboratory, and experimental investigation should be launched. Ingredients for this program would be the complete integration of many of the subdisciplines in the geosciences with soil and sediment mechanics. With more limited funds, however, several projects could be inaugurated that would yield especially high investment returns. The following enumeration of suggestions for future work is presented in order of priority.

1. A detailed and intensive field study of such areas as Constable-Malone, Canton, Gouverneur, Alexandria Bay, Clayton-LaFargeville, Massena, and the Colwell Gravel Pit. This includes localities 1, 2, 3, 4, 5, 8, 10, 11, 12, 13, 18, and 21. Such an investigation could easily build upon the foundations of this report which has documented the feasibility for studying these areas in much greater scope. These localities contain the most readily available sites that can yield significant results in analysis of proved sites of seismic-appearing deformed sediments.

2. Perform detailed analysis of silt and clay sediments. Unfortunately, such deposits are generally not important ingredients in sand and gravel pits, so specimens must be obtained by other means. Therefore, a program should be initiated that will involve: (1) trenching in critical areas, and (2) examination of boring cores now held by such companies as Atlantic Testing Laboratory, Canton, N. Y. Study of varved sediments and rhythmites should prove extremely valuable. This report has shown that varved sediments occur at many localities, that the silt and clay sediments are fossiliferous, and that reliable Carbon 14 dates can be obtained. Since some of these deposits contain deformed units (Alexandria Bay, locality 8), it should be possible to obtain a chronology based on Carbon 14 and couplet correlations that will yield higher levels of precision for determination of possible earthquake recurrence intervals.

3. A mapping study that utilizes geomorphic criteria for evidence of faulting should be initiated. Such an investigation was beyond the scope of the present report, but it was established that the St. Lawrence Lowland contains many linear elements that need careful field examination. Other types of geomorphic clues that have proved their value in other regions include evaluation of knickpoints, gradient changes in rivers, precise levelling of strandline positions, and determination of possible landform offsets such as beach ridges, terraces, floodplains, deltas etc. Although exact time scales cannot be determined by such studies, identification of faulting by these methods would generally assure that the earthquake was more recent than 12,000 yrs.

4. Piston coring of lake bottom sediments should be attempted to a depth of 10-15 m. with preparation of radiographs of the cores. Although preliminary work and considerations in the present study indicate low probability of success, a very short feasibility field project could determine this and provide the insurance necessary to adopt or reject an expanded program. If the cores show deformed zones that can be differentiated from bioturbation effects, and if they can be correlated from several different localities this would then open a new door for additional studies.

5. The implementation of a comprehensive laboratory - experimental investigation would measurably enhance understandings of the relation of thixotropic sediments to seismic events. The very preliminary work done in this report documents that experiments done with the shaking table can duplicate many of the structures found in the field. The work should be aimed to seek quantification of such factors as the relation of earthquake magnitude to the deformed strata, the number of separate sedimentary strata that can become deformed in seismic events of varying magnitude, and the relation of earthquake distance to deformed strata. Such work should be combined with determination of stability in terms of liquefaction potential and internal fabrics. It has been shown in this report that the scanning electron microscope can be a powerful tool in aiding to decipher the degree of thixotropy in sediments. The assumption would be that a highly unstable configuration would have been destroyed in a major earthquake. This study should also be combined with a systematic examination of porosity, permeability, orientation, and distribution of the sediments and their structures. A 3-week geophysics investigation near Massena indicates the possible occurrence of small seismic sources in the area. Additional work is needed to document this.

6. Further work is necessary in eastern United States that will yield a more detailed comparison of the St. Lawrence region with other glacial environments that provide analog conditions of sedimentation but which are located in stable areas. Some of this work has already been done and it has been demonstrated this is a very fruitful investigative technique. Such studies are essential to prove any type of uniqueness factors that may be associated with seismic shocked sediments.

7. A cooperative and integrated project should be initiated with other workers and agencies interested in problems of relations of deformed sediments to seismic events. Such jointly-sponsored programs could be united with the ongoing research of such workers as J. D. Sims (U. S. Geological Survey). It would be useful to have an entire team of investigators, representing several different subdisciplines in geology, compare and study in detail the western areas of known earthquake-prone areas with eastern United States. For example the description of Van Norman reservoir conditions, poses some questions as to

the possible operation of additional mechanisms. For example, what is the possible effect of surges, associated with the seasonal flooding and infilling of the reservoir? The water depth curves for the reservoir indicate profound changes in depth and in the aerial extent of the waters in the reservoir. It is known that convolute lamination can be generated by seasonal floods. A further question concerns the possible loading of the sediment by the reservoir waves which could perhaps lead to accumulation of strain comparable to that required for liquefaction. Such study should also include evaluation of sites in the Olympic Peninsula, Washington. This region has the virtue of being in a glaciated region and containing varve deposits....thus comparing favorably with the St. Lawrence region. Such a comparison would provide a useful parameter for analyzing seismic-sensitive sediments in glaciated terrane in contrast to the non-glaciated California region.

CHAPTER 6

BIBLIOGRAPHY

The publications that are listed represent a selected bibliography of references that are considered the most pertinent on topics related to the relation of Quaternary deformed sediments with possible seismic events. Also included in the bibliography are those publications that were cited as background material in previous chapters. A total listing of 1500 references were compiled for this report, and those that are not included have been retained on index cards for use by interested parties.

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APPENDIX A

EVALUATION OF RECENT VERTICAL CRUSTAL MOVEMENTS

Introduction

A search for the connection between soft sediment deformation and earthquake occurence must take into account the effects of regional crustal activity. Differential subsidence and tilting will affect the stability of slopes, and in addition, develop local stresses, which during earthquakes (or other cyclic loading) will promote the occurrence of liquefaction (in the sense of Casagrande, 1940, 1971 and Castro, 1969, 1975). Moreover, it is known that the magnitude, trend, and pattern of secular crustal movements reflect the stress accumulation in the crust, and may be used in assessment of the regional seismic risk (e.g. Dambara, 1966; Fuji, 1969; Whitten, 1966, 1968).

The longer-term trends of secular activity, involving periods from 10^2 to 10^5 years, may be derived from Quaternary, geomorphological and archeological studies (e.g. IUGG, 1962, 1966, 1971). Information pertinent to the St. Lawrence region is therefore presented in Chapters 1-4. This section deals with the more detailed estimates of activity (i.e. on the scale of 10^1-10^2 years), based on the results of repeated precise leveling carried out by the U.S. Coast and Geodetic Survey along the geodetic network in New York.

Data and techniques of study

Precise leveling is the measurement in increments of differences in elevation (ΔH) between consecutive monumented benchmarks located 1-2 km apart along the geodetic network-polygons. To control the leveling accuracy, measurements are repeated forwards and backwards. The discrepancy between the two should not exceed $4\sqrt{D}$ mm (D= leveled distance in km). If the leveling is repeated after n years, the difference between the old and new ΔH values ($d\Delta H = \Delta H_1 - \Delta H_2$) is assumed to represent an estimate of the net vertical movement that took place between the levelings, and

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exceed 1mm/km. The question arises however, whether the estimate of operational errors may ignore the effects of benchmark construction and monumentation. Bomford (1971) states quite clearly, that the only benchmarks to be used in studies of recent crustal movements are those anchored in rock (preferably cut in a rock face). The percentage of rock-anchored benchmarks in the present case is rather low (38% in St. Lawrence traverse, 13% in the Hudson traverse, and 25% in the (Fig. A-1) Saratoga Springs traverse). The Hudson and Saratoga Springs lines run along major railway tracks, and the benchmarks are anchored in various structures ranging from platforms, and station buildings, to bases of signals, warning signs, culverts and bridge constructions. The actual description of the benchmarks and field observations do not inspire great confidence in benchmark stability.

To assess the possible effect of benchmark construction, the benchmarks were grouped in five major monumentation groups and the mean $\underline{d\Delta H}$ values were computed. In view of the differences in construction and condition within each group, and in view of the fact that the $\underline{d\Delta H}$ values are always based on <u>two</u> benchmarks (so that it is not always clear which one is responsible for the movement), additional measures of stability were employed. First was the distribution of stable benchmarks (i.e. where $\underline{d\Delta H} = \pm$ 1mm), second were the mean values for the pairs of adjoining benchmarks of the same monumentation type, and the third involved the distribution of identical reversals. Identical reversal is the result of the appearance of nearly equal, but opposite in sign $\underline{d\Delta H}$ values on adjoining benchmarks, and is marked by a sharp peak on the cummulative $\underline{d\Delta H}$ curve. Such reversal may be produced when an unstable benchmark sinks or rises with respect to its two neighbors.

The results presented in Figures A-1,2,3,4, demonstrate correlation between the $\underline{d\Delta H}$ values and the monumentation. The mean $\underline{d\Delta H}$ values increase in the following order: rock/walls/buildings/bridges and culverts/concrete posts, signs and platforms. Percentage

of stable benchmarks in rocks, walls and building is higher than expected; and is lower than expected in bridge structures and concrete. The reverse is true of the percentages of identical reversals (Fig. A-5).

It appears that in some traverses the difference between the <u>dΔH</u> values for rock-anchored and concrete-anchored benchmarks may be ten-fold, indicating that benchmark instability may overshadow and obscure the pattern of geological control of vertical crustal movements in this region. This effect must be kept in mind while assessing the significance of results presented in the next paragraph.

Results

The St. Lawrence traverse (Fig. A-6) shows data for 40 twice leveled benchmarks (1941-1969). The magnitude of movement is rather low, with mean <u>dΔH</u> of 2mm/km. The traverse cuts across the Massena area, but does not show any indication of intense ground deformation. The cumulative curve shows a gentle differential rise of the Chippewa Bay-Morristown segment relative to the neighboring segments on the east and west. The evidence is too limited to allow speculation on the possible relation of this uplift to the uparching of the Adirondacks suggested by Isachsen (1975).

The Hudson traverse (Fig.A-7) shows 268 twice leveled benchmarks (1934 and 1955). The <u>dΔH</u> values are higher than in the St. Lawrence traverse, however, no meaningful mean <u>dΔH</u> value can be computed as the traverse abounds in identical reversals ranging from 100 to 1100 mm, at least some of which represent damage or relocation of benchmarks, or errors in benchmark identification.

The traverse may be divided into a number of segments, according to the general nature of the <u>dΔH</u> values. The first segment, between Manhattan and Tarrytown shows a generally even uplift relative to Manhattan, with an average <u>dΔH</u> between 50 and 60mm. At Tarrytown, the cumulative <u>dΔH</u> curve shows a rapid

subsidence towards the structurally complicated Peekskill-Dutchess County region, where the average <u>dΔH</u> ranges from 10mm to -10mm. Following a somewhat moderate rise to about 40mm the <u>dΔH</u> curve for the segment between Dutchess County and Tivoli is fairly even. From Tivoli to Cattleton on Hudson the curve is uneven and fluctuates, but in general the trend appears to be toward subsidence, followed by a "horst-like" feature (<u>dΔH</u> = 70-80 mm) between Cattleton and East Greenbush. From East Greenbush to Whitehall, numerous thrusts and faults cut across the traverse at a low angle, and the curve displays a number of reversals. It appears that the values of <u>dΔH</u> rise to about 100mm. The numerous reversals of high magnitude, and relatively sparse distribution of benchmarks between Whitehall and Valcour Island make generalizations difficult. However, between Valcour Island and West Chazy the curve is fairly even, with dΔH between 180 and 200mm. From West Chazy the curve descends towards Rouses Point.

The Saratoga Springs traverse (Fig. A-8) includes 213 benchmarks leveled in 1955 and 1973, and overlaps numerous benchmarks of the Hudson traverse. The <u>dΔH</u> values are on the average 6.2 to 8.7 mm/km.

Isachsen (1975) interpreted the cumulative <u>dΔH</u> curve for this traverse in terms of a gentle uparching with an apex at Ticonderoga, presumably related to the uparching of the Adirondacks.

The visual comparison of the overlapping parts of the Hudson and Saratoga Springs traverse suggests some general similarity (Figs.A-7,A-8). However in view of doubts regarding the reliability of numerous benchmarks of the first releveling a more quantitative assessment is not possible.

<u>Summary</u>

The results of repeated precise leveling in New York suggest the occurrence of low velocity secular vertical movements of the

$d\Delta H/n$ is assumed to represent the velocity of the movement. Obviously, such assumptions are justified only when the operational errors are known to be small and unrelated to the $d\Delta H$ values. Most studies of recent crustal movements follow the geodetic procedure of expressing the leveling operational error in terms of discrepancies and polygon-closures (e.g. IUGG, 1962, 1966, 1971 and Gerasimov, 1967). Relatively little attention has so far been paid to other effects, especially benchmark construction and stability.

Examination of the leveling operations carried out by the Coast and Geodetic Survey throughout the past 20 years revealed three major twice-leveled traverses in northern New York. The first, is parallel to the St. Lawrence River, higher than St. Regis and Cape Vincent. The second extends along the Hudson, from Manhattan, to Rouses Point on the Canadian border. The third overlaps a part of the Hudson traverse and extends from Saratoga Springs to Rouses Point. The first was leveled in 1941 and 1969, the second in 1934 and 1955 and the third in 1955 and 1973.

The relevant data (differences in elevation, topographic elevations, distances and description of location and construction of the individual benchmarks) have been extracted from files and description pamphlets of the C&GS. The computed $d\Delta H$ values were plotted in cross-section and on geological maps (Figs. A-6,7,8). Each cross-section shows the $d\Delta H$ values for individual benchmarks, and a cumulative $d\Delta H$ curve showing the movement relative to the starting point of the traverse. At present, there is no way to relate the St. Lawrence and Hudson traverses to each other or to the sea level.

Before proceeding to the analysis of the three traverses comment should be made on the reliability and significance of data. The standards of leveling quoted by the C&GS conform to the specifications of first order precise leveling (Rappleye, 1948; Bomford, 1971) and the combined mean error does not

crust. Along the shores of St. Lawrence the rate of movement is considerably lower than along the Hudson line, and no evidence related to the Massena earthquake was detected.

The variability in benchmark stability, and the absence of closed releveling loops do not allow evaluation of the possible geological controls of movement. As a whole, though the reversal in sign of <u>dΔH</u> across faults and thrusts is more common than expected (60% and 70% along the Hudson and Saratoga Springs traverse respectively) the movements appear considerably smaller than reported from areas of high seismic risk.

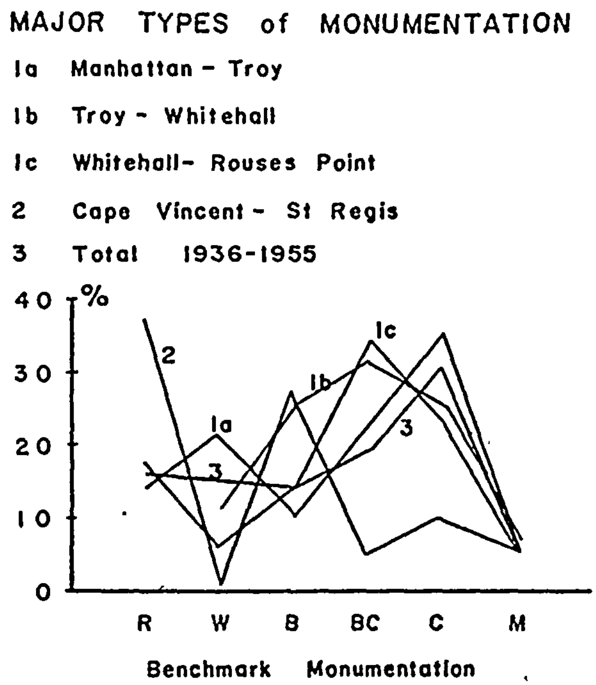

MAJOR TYPES of MONUMENTATION
Ia Manhattan - Troy
Ib Troy - Whitehall
Ic Whitehall- Rouses Point
2 Cape Vincent - St Regis
3 Total 1936-1955
%
40
30
20
10
0
2
Ia
Ib
Ic
3
R
W
B
BC
C
M
Benchmark Monumentation

Fig. A-1

Fig. A-2

MEAN dΔH VALUES for MAJOR TYPES of BENCHMARK MONUMENTATION

1a Manhattan - Troy

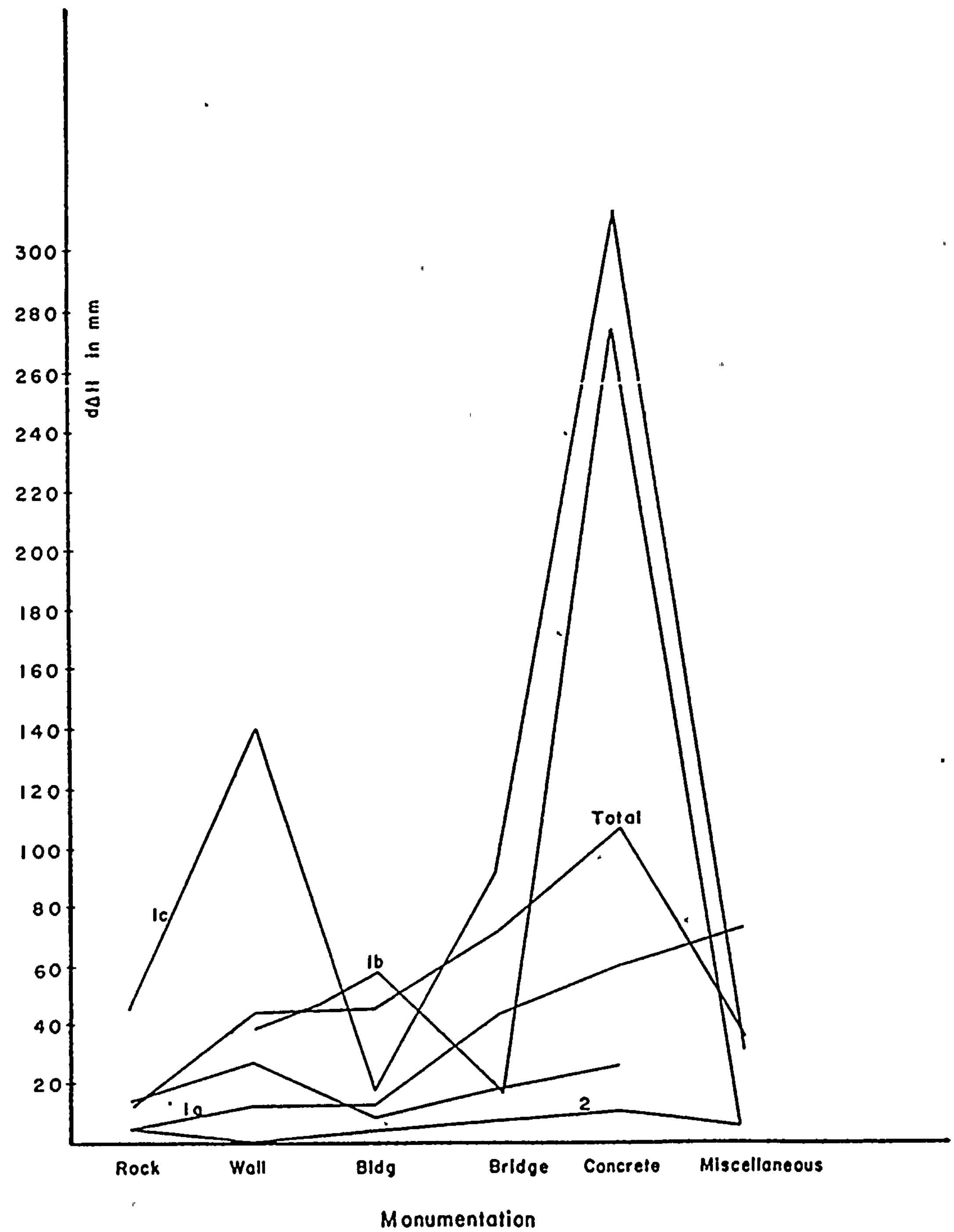
1b Troy - Whitehall

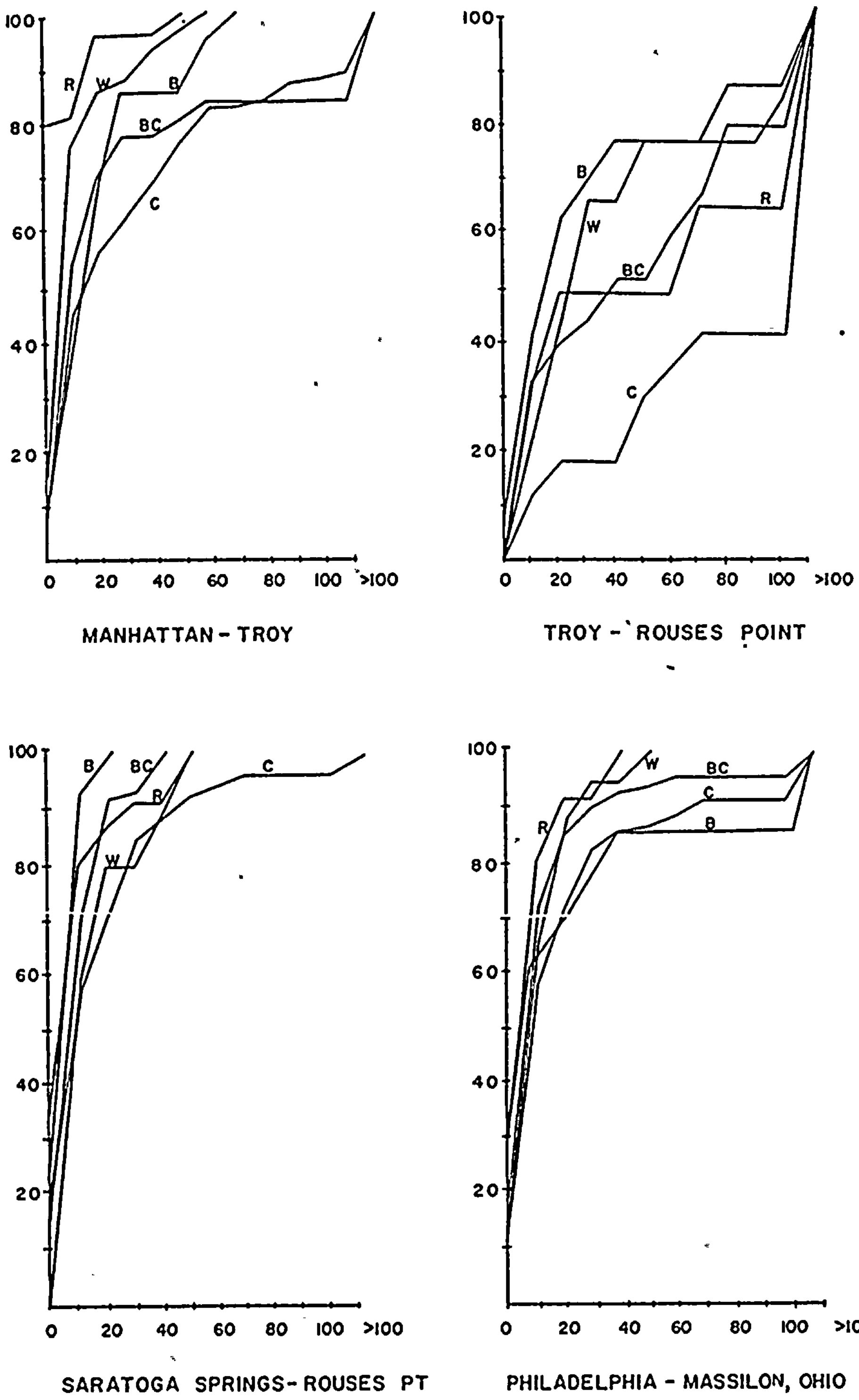
1c Whitehall - Rouses Point

2 Cape Vincent - St Regis

3 Total 1a,b,c

4 Saratoga Springs





.DISTRIBUTION of dΔH VALUES ACCORDING to BENCHMARK MONUMENTATION

R - Rock Wall
W - Wall
B - Building
BC - Bridge and Culvert
C - Concrete

Fig. A-3

MEAN ΔH VALUES for MAJOR TYPES of BENCHMARK MONUMENTATION (Excluding Identical Reversals)

Ia Manhattan - Troy

Ib Troy - Whitehall

Ic Whitehall - Rouses Point

2 Cape Vincent - St Regis

3 Total Ia,b,c

4 Saratoga Springs - Rouses Point

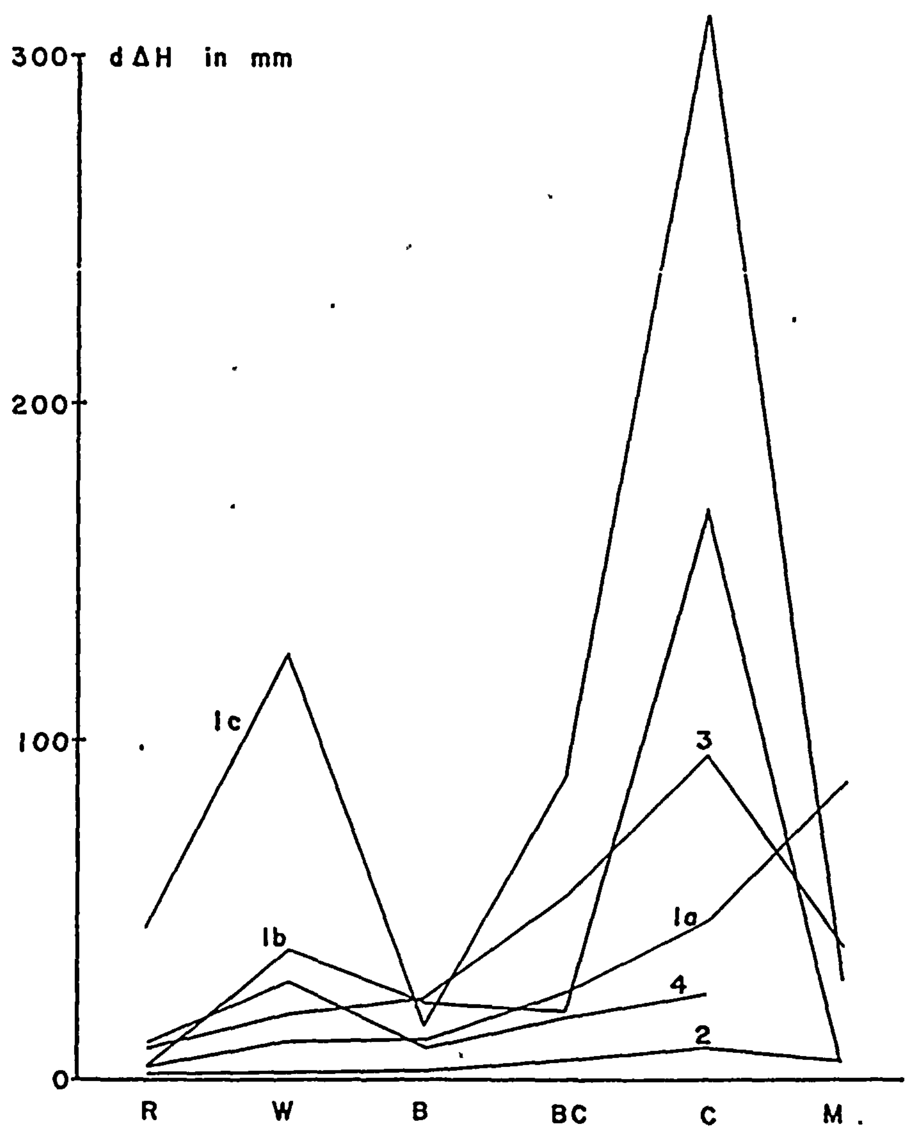


Fig. A-4

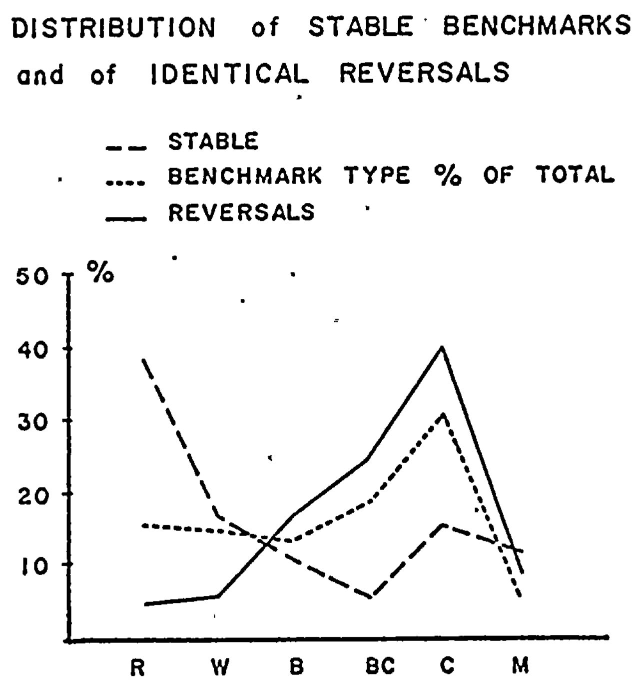
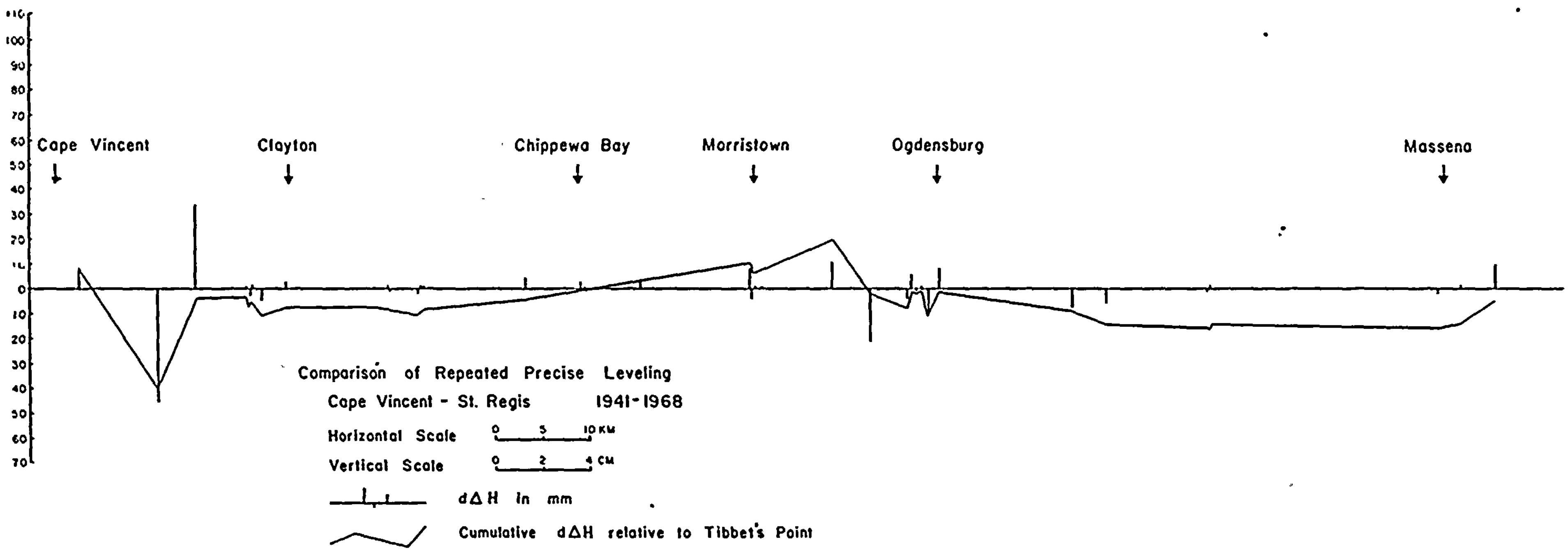

DISTRIBUTION of STABLE BENCHMARKS
and of IDENTICAL REVERSALS
STABLE
BENCHMARK TYPE % OF TOTAL
REVERSALS
%
50
40
30
20
10
R
W
B
BC
C
M

Fig. A-5



Cape Vincent
Clayton
Chippewa Bay
Morristown
Ogdensburg
Massena
Comparison of Repeated Precise Leveling
Cape Vincent - St. Regis 1941-1968
Horizontal Scale 0 5 10 KM
Vertical Scale 0 2 4 CM
dΔH in mm
Cumulative dΔH relative to Tibbet's Point

Fig. A-6

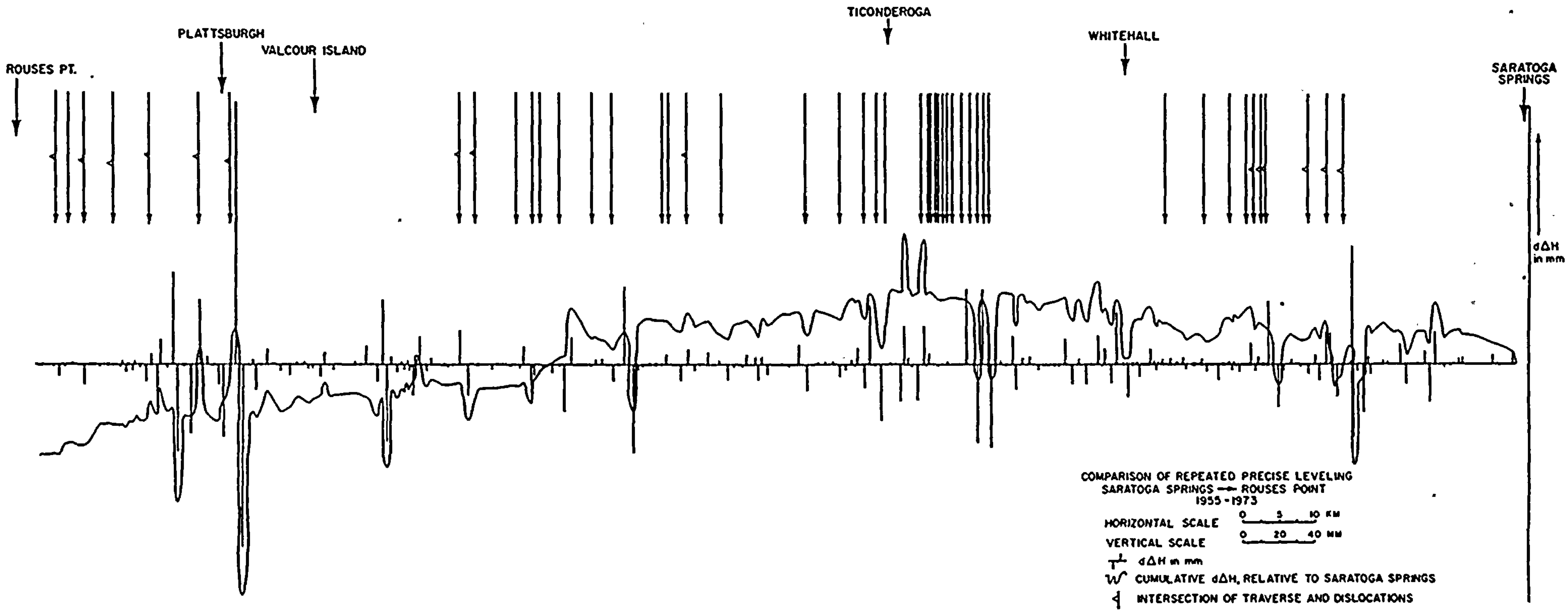

ROUSES PT.
PLATTSBURGH
VALCOUR ISLAND
TICONDEROGA
WHITEHALL
SARATOGA SPRINGS
dΔH in mm
COMPARISON OF REPEATED PRECISE LEVELING
SARATOGA SPRINGS → ROUSES POINT
1955-1973
HORIZONTAL SCALE 0 5 10 KM
VERTICAL SCALE 0 20 40 MM
dΔH in mm
CUMULATIVE dΔH, RELATIVE TO SARATOGA SPRINGS
INTERSECTION OF TRAVERSE AND DISLOCATIONS

Fig. A-8

APPENDIX B

PHOTOGRAPHIC INTERPRETATION OF LINEAMENTS

Seismic events commonly produce a variety of effects on the surface of the earth. It is important to recognize such features in the geologic record of faulting since these supply one method of evaluating earthquake hazards and indicate field study sites.

Topographic features resulting from earthquakes can often be traced. Displacement of the earth's surface may form a geomorphic feature which is recognizable on air photographs, topographic maps or in the field. Landforms used as criteria for earthquake events include lineaments, drainage features, offsets, and miscellaneous associated landforms.

(1.) Lineaments. Straight, linear features often result from faulting due to earthquakes. Such lineaments may form a mountain or ridge front or a valley or even a linear cross-cutting feature. Freshly formed surface ruptures or displacements called scarps are easily recognized because they show offset of the ground and generally lack vegetation. Scarps, however, are quickly altered by rain, mass movements and erosion and become hard to recognize. It should be kept in mind that small scarps can also be formed by landslides, erosion and other geologic processes.

Lineaments may often be seen, however, even after the original scarp has been modified and vegetated. This is especially true when two different rock types are in contact along the fault. One rock type may be more easily eroded or promote different vegetation, making the lineament visible. Other kinds of linear features may result from jointing, strike valleys, erosional escarpments, etc. Thus lineaments in themselves are not conclusive evidence of earthquake faulting but are simply an indication that faulting may have taken place and that the lineaments (and the region) should be investigated further.

(2.) Drainage features. Streams are extremely sensitive to the surface over which they flow, tending to seek out the easiest path for their channels. Hence, linearity of a stream course indicates a weakness along a line which may be a fault, joint or softer layer. A change in texture of drainage shows that the stream flows over different rock types which may be a result of faulting (or may not).

Faulting may cause a scarp or broaded uplift of an area which can be reflected in rivers. A scarp may cut across a stream forming a knickpoint, or falls or rapids. These, of course, disappear with time but may persist for long periods if in bedrock. Broad uplift of a region by faulting can cause rivers to downcut and incise their channels. These features may be formed in

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Prepared by Marie Morisawa

other ways than faulting but are an indication that earthquakes may have taken place.

Anomalous drainage features such as springs (particularly a line of springs or hot springs), sag ponds, linear lakes or offset of stream courses should be investigated for possible faulting.

(3.) Offsets. Offsets or breaks in stream courses, ridges, lakes or other topographic features are suspect as far as faulting is concerned and should be investigated. Offsets of geologic rock types should be pinpointed to verify faulting.

(4.) Associated features. Other types of features which may be associated with faulting and earthquake tremors are landslides and sand spouts. Although both may be created by processes other than seismic events, finding of such features in association with topographic forms already mentioned adds to the evidence for evaluating earthquake hazards.

Photo-interpretation - ERTS imagery

Using ERTS imagery lineaments were traced. Figure B-1 is an example of one of the ERTS photographs used in the determination of linears. Five ERTS photographs (019,237,272,035,051) were used to examine for the area between the St. Lawrence River and the Adirondack foothills. Lineaments from these high altitude photographs are shown in Figure B-2.

Most of the high altitude lineaments are oriented northeast, but a number have a northwest direction of alignment. The lineaments are in part stream valleys, ridges and vegetative. Some may be manmade drainage channels or roads. In order to further interpret these low altitude air photographs and topographic maps were examined.

Map and Photo-interpretation (low altitude)

Figure B-3 is a map of stream courses south of the St. Lawrence River as determined from air photographs (low altitude). It shows a predominantly northeasterly direction of flow. Not only are stream courses aligned in this direction over most of their flow, individually, but any stream chosen is seen to be aligned with the direction of flow of other stream systems. The overall pattern is parallel in a northeasterly direction.

Numerous lineaments are obvious on the low altitude air photographs and the topographic maps. These are shown in Figure B-3. These are primarily ridge lineaments although some coincide with stream drainage lines. Again the overall pattern is one of a northeast orientation.

Analysis of Lineaments

The linear and parallel arrangement of both ridges and stream courses is a result of two factors, structural and glacial. The regional strike of the bedrock

underlying the glacial material is in a northeast-southwest direction with a gentle northwestward dip. The Ordovician limestones offer layers which are easily eroded and supply an easy path for stream channels to develop. The Grenville structural trend is N 45°E which is close to the overall trend of both stream and ridge lineaments. Thus many streams may be flowing in pre-glacial strike valleys which were widened and deepened by the ice and reoccupied by rivers after glaciation.

Some stream courses may follow, in part, along joints. There are several systems of joints in the study area. Those coinciding with lineament orientation are aligned N 70°E, EW, N 40°E. The northwest trending joints do not seem to have influenced drainage lineaments or ridge trends.

Glaciation has also affected drainages in the St. Lawrence Lowland. Glacial landforms have influenced the orientation of postglacial streams, and some of this fabric appears to be northeast-southwest. Other streams flow northwest and developed as extended consequents upon the surface slope of upraised beaches and old lake bottoms. Such segments produce a cross-cutting and choppy pattern.

Dames and Moore (1974, p. 3-45) describe N 30°E linears as the dominant ones in the region. However, our evaluation of ERTS imagery indicates that a N 50°E direction, with variations, is the most common lineament orientation. Many stream courses flow in this direction. In the northeast part of the region there is a strong tendency for drainage to develop in a northwest direction off the Adirondack uplands.

Conclusions

There are many strong lineaments present in the study area. These are visible on high altitude ERTS photographs, on low altitude air photographs, and on topographic maps. Although the present pattern of lineaments may be a development from the deposits left by glaciation, many landforms were greatly influenced by the preglacial topography which was structurally determined. There were, however, no definite topographic evidences of Quaternary tectonic movements. Further examination of the lineaments is needed to establish this.

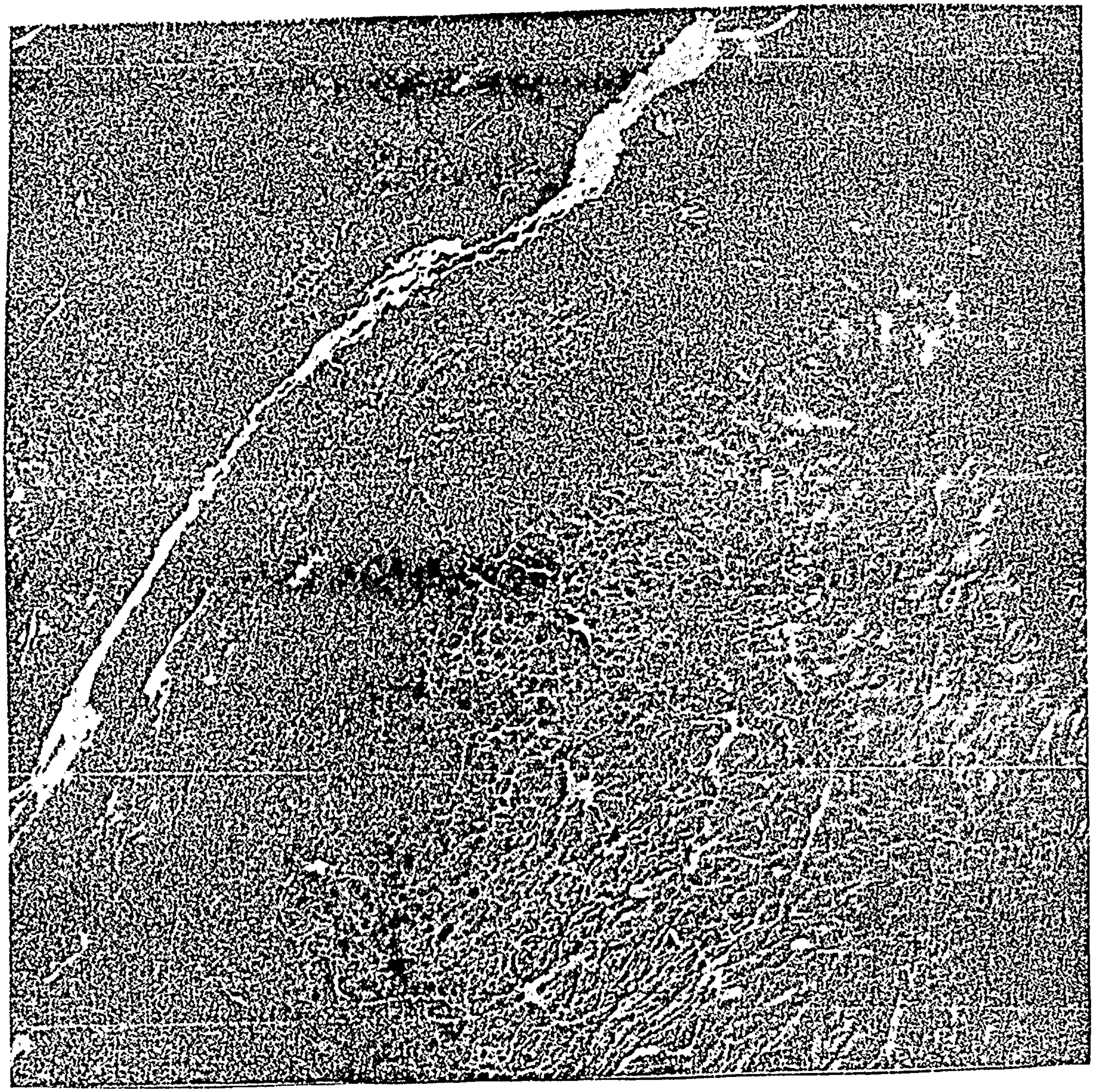

Fig. 8-1. ERTS Photograph 035. This is one of six photographs used to determine lineaments as revealed by high altitude photography.

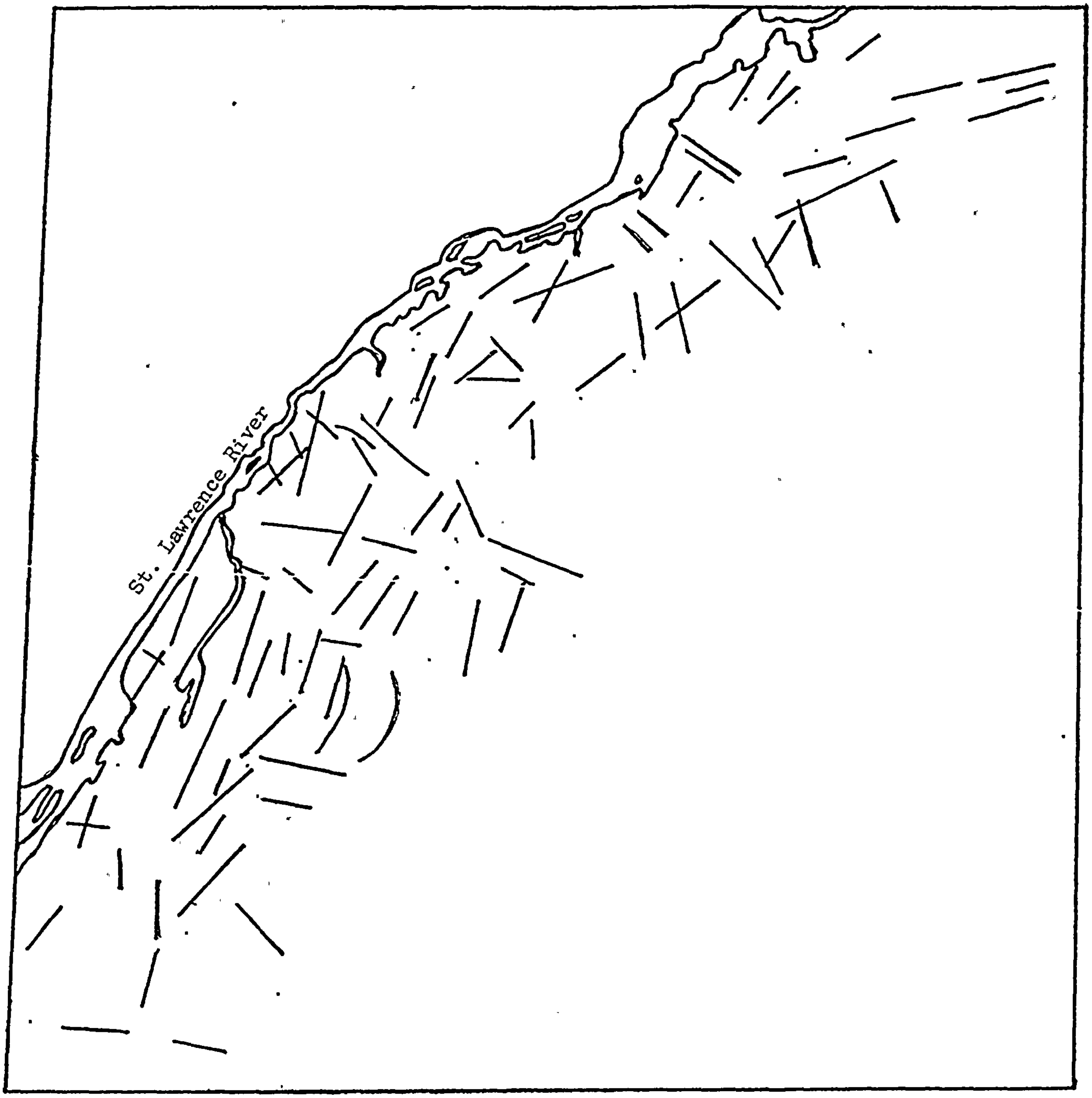

Fig. B-2. Lineaments as seen and traced from ERTS photographs.

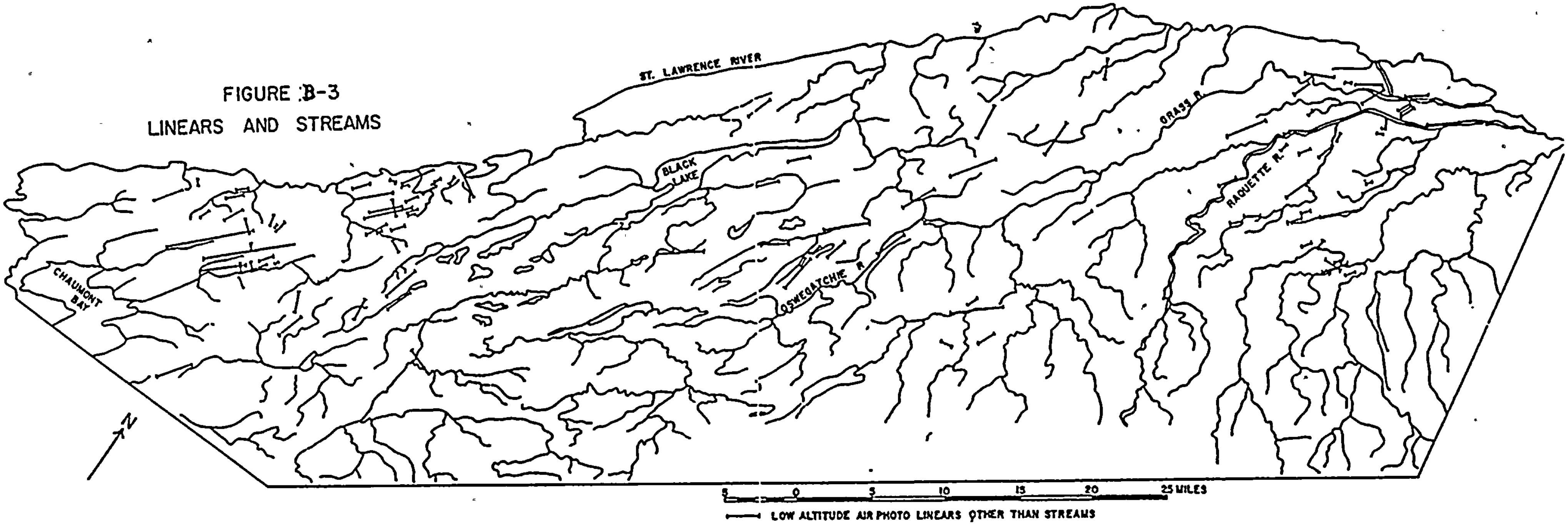

Fig. B-3. Drainage in the study area, showing the pattern of stream courses. Lineaments traced from low altitude air photographs and topographic maps.

APPENDIX C

SEDIMENT PROPERTIES

Within the framework of a short-term feasibility study it was impossible to conduct a complete and systematic sampling and analysis of all sediments that occur in this highly variable and diverse depositional environment. It was decided therefore to emphasize fine-grained sediments rather than coarser materials. In the latter the deformative processes such as liquefaction and fluidization are controlled largely by the representative grain diameter and by the relative density (e.g. Seed and Idriss, 1971; Castro, 1969, 1975; Leva, 1958; Davidson and Harrison, 1971). Assessment of the deformation potential followed in earthquake engineering is therefore relatively simple. In fine grained cohesive sediments the situation is more complex (e.g. Skempton, 1964; Gilliot, 1968; Bjerrum, 1967; etc.) and the identity and role of the controlling material properties is not clear, nor, for that matter, is the nature of the mechanism operating in deformation. From the various factors suggested in the literature, four were selected not only to portray the sediment characteristics, but also to test their potential applicability in further study of deformation. These include mineralogy, size distribution, viscosity and internal fabrics.

Most samples were collected at representative outcrops of the St. Lawrence Quaternary deposits at locations with and without features of soft sediment deformation. In each case attempts were made to determine what, if any, differences exist between samples from deformed and undeformed beds. A number of samples were collected during a field work trip in Quebec under the guidance of Dr. P. LaSalle. This trip was undertaken following a number of paragraphs in the Dames and Moore (1974) report submitted to NYASDA, in which reference was made to the possibly tectonically induced features of soft sediment deformation in Quebec.

Selected samples from Quebec (Canada), the St. Lawrence valley (New York), Brawley (California), and the Van Norman reservoir (San Fernando, California) were chosen for size analysis and mineral identification (see Table C-1). The clay/silt samples in this group were also used in the viscosity measurements. The procedure used in the size analysis was modified from Folk (1968). Sediment samples for X-ray analysis were decanted from stable sediment suspensions (Krumbein and Pettijohn, 1938). The procedure followed in the size and mineral analyses is shown in Figure C-1, but it should be noted that the samples used in the X-ray analysis were prepared from the decanted samples.

The mineralogical analysis of the clay and silt fractions was done with the aid of a Norelco X-ray diffractometer. The diffractometer was equipped with a Cu tube and a Ni filter. The instrument was operated at 40 KV and 20 ma with a scanning speed of 1° 2θ/minute and a chart speed of 1 inch/minute. The minerals in each sample were

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Prepared by James Sorauf and David Kersey

identified by their characteristic X-ray diffraction patterns as described by Smith and Yoder (1956), Weaver (1958), Brown (1961), Malloy and Kerr (1961), Biscaye (1965), Grim (1968), and Carroll (1970). Clay minerals were broadly grouped into four groups: Kaolinite, "mica" (micas plus illite), montmorillonite, and chlorite. Also identified by X-ray diffraction are quartz, plagioclase, K-spar, calcite, dolomite, ilmenite, and amphiboles. The viscosity measurements were done with a Contraves Rheomatic 15.

Mineralogy

X-ray analysis of 26 samples shows mineralogical composition changes little from sample to sample (Table C-2). All samples, except K-5 and Malone, contain montmorillonite. All samples have chlorite, "micas", amphiboles, quartz, and feldspar. Calcite, dolomite, and ilmenite are present in some samples. The mineralogy of the silt and clay fractions are basically the same. The presence of montmorillonite in the silt fraction indicates some of the clay probably flocculated during separation of the silt and clay fractions. However, the presence of quartz, amphiboles, and feldspar in the clay size fraction in the New York and Canadian samples indicates that the fine fraction is presumably glacial flour. The presence of quartz, amphiboles, and feldspar in the clay fraction of the California samples may be a result of the semi-arid climate and sedimentary source rocks. The sedimentary source rocks can provide large amounts of fine size material that formed in earlier weathering and transportation processes. The semi-arid climate results in a minimum of chemical weathering and consequently the fine-grained material can consist of relatively unstable minerals.

The peak area ratios generally show greater amount of montmorillonite, chlorite and "mica" in the clay fraction compared to the silt fraction. The silt fraction is enriched in amphiboles, plagioclase and quartz compared to the clay fraction (Table C-3).

Size Analysis

Size fractionation of 28 samples shows a range in sand content from over 75% sand to less than 1%. The clay content ranged from less than 1% to more than 60%. The percentage silt varied from 18.6% to over 81% (Table C-4).

Viscosity

Viscosity measurements were made on 14 samples (Table C-5). Two different types of flow behavior were observed. In the first type (samples: K-1, Norfolk/Adams, K-3, K-10, K-11, K-11a, K-11b, K-14, and Massena/Top), the viscosities were measurable only at relatively high instrument settings (11-12). Also, the measured apparent viscosities are low, with a range of 2-4 poises. Generally, the measured apparent viscosities are the same, within the precision of measurement and are time independent. The measured apparent viscosities increase with increasing speed of the bob and decrease with decreasing speed. This is indicative of non-Newtonian

flow, and the increase in apparent viscosity with increasing shear is a property of dilatant flow. Whether there is a yield point associated with these samples can not be determined because the initial viscosities are close to the lower limit of the instruments sensitivity.

The second type of flow (samples: Norfolk/Barrett, K-7, K-8, K-26, and Massena) show a decrease of apparent viscosity with increasing shear rate. Samples Norfolk/Barrett, K-7, K-8 and Massena have different apparent viscosities, for the same instrument setting. Thus, the behavior of the samples is dependent upon the previous history of the sample. These time dependent samples show a decrease in apparent viscosity with increasing shear stress, hence, they are thixotropic. Sample K-16 shows a decrease in apparent viscosity with increasing shear stress but seems to be time independent. Flow of this type is referred to as non-linear flow with a yield stress.

Discussion

The viscosity of a fluid, more properly -- a suspension, is a function of the mineralogy, size parameters, fabric, fluid content, and chemical nature of the material in suspension and the viscosity of the fluid medium. Sample preparation alters or destroys the original fabric of the sample and the initial fabric of the sample may play a controlling role in determining the behavior of the suspension. The sample preparation technique used in this study destroyed the original fabric and consequently it is only possible to discuss the influence of the mineralogy, sorting, and possibly the fabric that develops during the sample preparation on the rheological behavior of the samples.

Nine of the samples show dilatant behavior and five (including K-16, which shows a decrease of viscosity with increasing shear) show thixotropic behavior (Table C-5). The explanation proposed to explain dilatant flow is that as a result of shearing stresses, the packing structure of the particles in the flow changes from a closely packed material to a more open material. This increase in pore space results in some of the pores being incompletely filled with fluid. The resultant lack of "lubrication" creates an increase of resistence to shear (Skelland, 1967).

Clays that were deposited in a deflocculated condition sometimes show dilatancy (Gillott, 1968, p. 136). When deposited, the clays form a close packed system which, when sheared, is destroyed. The apparent viscosity increases with increasing shear due to the physical interactions between the clay particles as they move to form a more open packing system.

Thixotropic behavior has been explained as resulting from the parallel orientation of the platy particles in the fluid during shear. At zero shear, the particles form a "structure" which is broken during shear. The "structure" can reform when the shearing stresses are removed (Skelland, 1967; Govier and Aziz, 1972). Flocculated systems are often, but not always, thixotropic.

Flocculation can occur when clays come in contact with polymers, divalent ions, etc. In the St. Lawrence Lowland, flocculation could have happened when a river flowed

into ocean or brackish water. Clays deposited in fresh water lakes would not have flocculated as much.

The explanations of dilatant and thixotropic behavior consider the fabric of the mixture to be very important in determining the "fluid" behavior. It is not clear why the two types of rheological behavior are found in the St. Lawrence and Canadian samples because the sample preparation would tend to homogenize the structures. One possible explanation might be that during the last stages of the sample preparation, the concentration of particles in the water changed such that the concentration of particles was different in the dilatant suspensions compared to the thixotropic suspensions. Metzner and Whitlock (1958) demonstrate that dilatant flow is restricted to high concentration of particles in the fluid and high rates of shear. At lower or higher concentrations, the fluid can exhibit pseudo-plastic (viscosity decreases with increasing shear), yield pseudo-plastic (viscosity decreases with increasing shear after an initial yield strength), and Bingham plastic (viscosity is constant after initial yield strength) behavior. However, the size parameters of the thixotropic and dilatant samples in this study are not different (Table C-4), so it is not clear if sorting could bring about any differences in the concentrations between the two sample groups.

The mineralogical composition of the two sample groups is about the same (Table C-6). Difference between the "mica" contents of the two samples is significant at the 90% level. There is more "mica" in both the clay and silt fractions of the thixotropic samples, and this "mica" could affect the strength of the material because its platy shape would tend to align parallel to the flow. If the "mica" were randomly oriented, resistence could be initially high, and as the "micas" progressively orient parallel to one another the strength would decrease.

The mineralogy of the deformed samples (2-2, 3-1, 3-2, K-4, K-5, K-6, K-7, K-8, and K-17) is not significantly different than the mineralogy of the undeformed samples (2-1, 3, K-1, Norfolk/Adams, K-3, Norfolk/Barrett's, K-10, K-11, K-11a, K-11b, K-14, K-16, Massena, Massena/Top, and Malone). The percentage of clay or sand does not seem to affect the behavior of the sample as there seems to be no difference between the deformed and undeformed samples with respect to the size parameters.

Most studies on the strength and rheology of clays have been done with suspension of one mineral type and with one grain size. It is not possible to directly apply the conclusions of these studies to the St. Lawrence and Canadian samples because the samples have varied size and sorting parameters and contain six or more minerals.

In pure clay suspensions, viscosity is a function of the type of bonding between the clay minerals. Depending on the type and extent of bonding, a clay suspension can be deflocculated - dispersed, deflocculated (edge to surface contacts between the clays), flocculated dispersed (face to face contacts between clays forming "books"), and flocculated (face to face contacts between clays forming "books" and these "books" in turn are in edge to face contact with one another) (Rieke and Chilingarian, 1974, p. 9-10).

The presence of other minerals, such as quartz, feldspar, etc., in the suspension can alter the type of bonding and consequently the structure of the clay. Clay size particles of these non-clay minerals have a different shape, and most importantly, a different distribution of ionic charges than the clay minerals. One result of the presence of these clay size non-clay minerals could be the formation of disordered clay "books" (face to face bonding). A quartz particle between illite flakes might distort the illite "books" or make the edges of the "book" ragged. As a flocculated clay depends upon the edge to face bonds for its strength, the presence of ragged edges or impurities on the edges of the "books" will alter the strength of the suspension (Ingles, 1968). The strength of a clay is not just a function of the mineralogy and resultant texture, but it also depends on the water content and chemical composition of the interstitial fluids. Clays that show a marked difference in strength before and after remolding, that is a marked loss of strength after shear, are called "quick clays". Some quick clays regain some of their strength after being remolded, in other words, they are thixotropic. The degree of regain in strength seems to depend somewhat on the mineralogy of the suspension. The maximum regain of strength is found in montmorillonite-rich clays. The regain is moderate for illite-rich clays and very low for kaolinite-rich clays. Other clays do not regain strength after remolding, but there seems to be no correlation between the mineralogy or grain size distribution of the clays and the degree of loss of strength. However, many of the

clays that do not regain strength have a large component of silt size particles (Skempton and Northy, 1952).

The behavior of the Scandinavian quick clays has been attributed to the colloid chemical properties of the clays. Scandinavian researchers feel the quickness of the clays results from the clays being deposited in a flocculated state. Subsequent chemical changes alter the double layer, either by the leaching of electrolyte (cations) or the addition of anions. The inital flocculated structure (edge to face bonding of the clay "books"), is unstable (Rosenqvist, 1966). Pusch (1966) gave support to this hypothesis when he found no difference between the structure of leached and unleached Scandinavian clays. However, the sensitivity of the quick clays of eastern Canada, primarily the Leda Clay, which were deposited in an environment similar to that of the Scandinavian clays, is independent of the salt content (Penner, 1963).

Porosity and permeability are two properties of a suspension or sediment that can affect the strength and rheology of the suspension or sediment. These two properties are affected by the mineralogy and size parameters of the clay. At a given overburden pressure, the porosity increases with decreasing grain size. The permeability is affected by the mineralogy; the addition of 10% mica to quartz sand will decrease the permeability by an order of magnitude. If montmorillonite is present instead of mica, the permeability is decreased by another order of magnitude. The replacement of montmorillonite by kaolinite will reduce the permeability by another 1/2 order of magnitude (Grim, 1962, p. 241). Experiments with illite and kaolinite (Obrien, 1963; Martin, 1965) show that pressures as low as a few Kg/cm^2 will produce a marked preferred orientation of these minerals. Pressures of around 100 Kg/cm^2 will produce preferred orientation with any clay. The preferred orientation will markedly affect the permeability and porosity of the clay.

FABRIC

Sampling

Samples chosen for scanning electron microscopy come from two general areas, Quebec (St. Romuald and Charlesbourg) and the St. Lawrence Lowland, New York.

The samples from the Quebec area were selected, each to form part of a coupled pair of one undeformed and one or more deformed clays. In the case of the clay collected at St. Romuald d'Echemain on the St. Lawrence River, the unit sampled is the "Leda Clay", with a date of 10,500 yrs. B.P. and marine fossils providing clear indication of its environment of origin. One sample of laminated, apparently undeformed clay from this locality has been examined, as well as samples of clay interlayered with load deformed sand, where it was assumed that the clay is likewise somewhat deformed. A second set of samples were collected from the Quebec area, near the town of Charlesbourg, northeast of Quebec city.

These are from marine sediments dated at approximately 13,600 yrs. B.P. and include a sample from the unit of laminated fine silt or clay in a sandpit where it is not deformed, and a sample from an area where it is disturbed and folded. This folding (LaSalle, 1972, p. 42) resulted from push by advancing ice on sediments in the marginal marine environment.

Clay samples from the Massena-Malone and Norfolk area of the St. Lawrence Lowland are all from units of "Leda Clay", several of which are without visible deformation at the outcrop. Those originating from localities without apparent deformation are from Barrett's Quarry near Norfolk and from Massena. The sample from Malone comes from within a sequence showing what are apparently two stages of load-associated deformation. A sample from Adams Street in Norfolk is from a structureless clay in which there is no ready means of determining if the unit is deformed.

<u>Method</u>

The method of preparation of samples was consciously kept simple. As Pusch (1970, p. 40) has noted, the investigator looking at a broken surface, regardless of choice of presently available preparation methods, will necessarily be looking at a plane of failure. Thus, artifacts induced during preparation impose limits on the method of investigation.

It has been here assumed that moist clay or fine silt, collected in the field in this condition and thus maintained at constant contained moisture by wrapping in plastic and occasionally gently wetting, will provide the best specimen for study. This moist clay or fine silt was parted or broken to provide a surface for study. When the material is moist, breaking is easiest and it is thought, fewest artifacts are created by the process. As a control, several samples were allowed to dry and then were broken; this affects the outcome very little in reality.

The clay sample was broken in a moist condition to form three observation surfaces, mutually perpendicular to one another. These have been called (Fig. C-2), for convenience, A-, parallel to bedding, B-, perpendicular to bedding and C-, perpendicular to both the A- and B-sections.

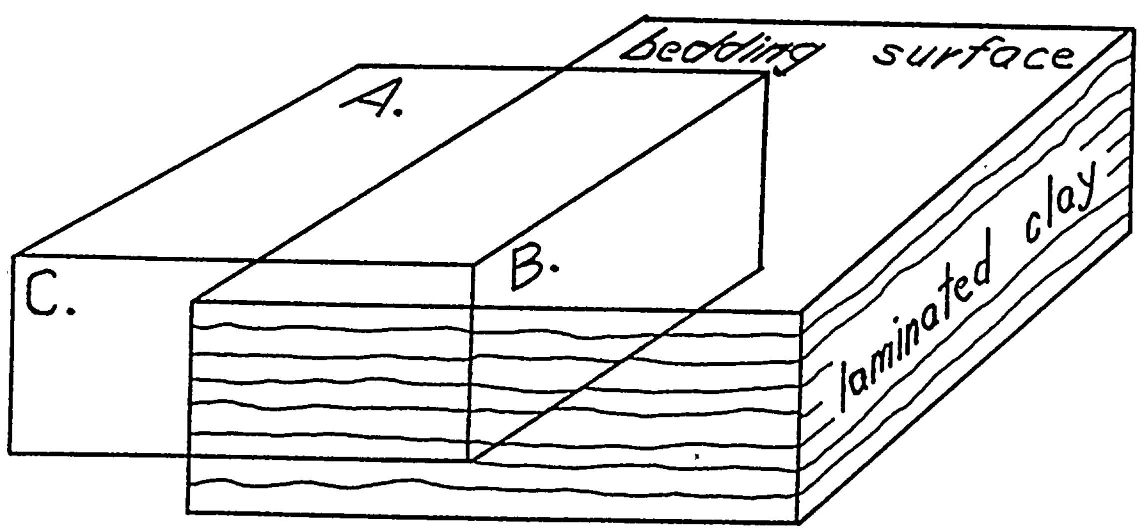


Fig. C-2 Clay fabric designators

TYPE LOCALITIES

QUEBEC AREA, CANADA

Charlesbourg Northeast locality (Samples 3, 3-1, 3-2, X-ray analysis) - this locality shows deformation (Pl. C1-1) due to ice pushing on the marine clays in their environment of deposition (according to LaSalle, 1970, p. 40). The marine "clay" noted here is fine silt, largely rock flour, both in the clay fraction and the silt fraction. The latter observation is further substantiated by surface microarchitecture (Pl. C2-4) noted on flat surfaces which show no effects of transportation, but possess fracture patterns on their surface.

1. Undeformed. Most striking in this sample is the rather random orientation of large, flat detrital grains, whether seen from top (Pl. C-3-3) or from the side, normal to bedding (Pl. C-3-2). Striking preferred orientation is noted in one sample, Plate C-3-3, where an inclined fabric is obvious.
2. Deformed. This specimen was taken from the underside of the small fold illustrated in (Pl.C-1-1). The vertical direction is still at the top of the scanning micrograph (Pl. C-3-4). One is immediately struck by several aspects of this sample, as well as those of other contorted clays of this locality. The "clay" is silt, mostly fine silt with some large grains. The angularity of these grains and their mineralogy argues for their origin in large part as rock flour. There is very little if any preferred orientation; grains are randomly oriented (Pl. C-4-1). There is a rather close packing of grains caused by the silty nature of the sediment and its extreme poor sorting rather than by collapse under deformational stress. However, it must be understood that water saturated silt will be "quicker" than sand or perhaps even clay.

Summary: The 13,600 yrs. B.P. marine "clay" of LaSalle (1972, p. 42) is in reality silt. The S.E.M. is of great use in determining grain size and shape and differentiating fine detrital sediments from true clay minerals. At Charlesbourg no differences were noted between deformed and non-deformed marine silt.

St. Romuald d'Etchemain (Samples 2-1, 2-2, X-ray analysis)

1. Undeformed - This is apparently undeformed, laminated marine clay. The fabric as seen in B- and C-sections shows a definite predominance of platy fragments and most have a rounded or subrounded appearance (Pl. C-1-2), but it is also noted that the inter-granular spaces are largely filled by "smeared-on" very fine material (Pl. C-1-3). Preferred orientation of platy or elongate grains is difficult to ascertain, but there is a hint of such in Plate C-1-3.

2. Deformed. The deformed sample is of laminated clay with load deformation visible in interstratified laminae of sand. We thus assume some degree of modification of interstratified clay at that time of load deformation. It is of considerable interest to compare this with the undeformed material from the same locality. First, it is striking that elongate particles are commonly in a subvertical position (Pl. C-2-1, 2). In at least one micrograph can be noted a preferred orientation at approximately 45° to bedding (Pl. C-2-3).

Summary: 1. Little pore space remains in this clay, as finer matrix seems to fill pores, while some has most likely been lost by packing various sized particles.

2. Preferred orientation, as compared between the undeformed sequence and the intermittently, load deformed sequence give little to choose between. It is rather surprising that neither shows marked orientation directions, and the suspected deformed sample has a large number of subvertical elements.

3. Compared with other localities (discussed below) this clay is much less silty than most, or else there is enough clay plastered on the silt that larger grains are not visible. The latter is inconsistent with findings discussed below.

ST. LAWRENCE LOWLAND, NEW YORK

Malone-Massena-Norfolk Area

1. Malone. The samples examined from the Malone locality came from within a folded sequence, and in fact, from within a small individual fold. The material is fine to coarse silt, somewhat more spherical than the silt from other localities, and lacking any apparent preferred orientation of grains. The third point most likely hinges on the first two. Typical Malone material is illustrated in Plate C-4-2.
2. Massena. The samples taken for study at Massena come from a well-laminated thixotropic clay sequence without visible disruption of stratification. In both B- and C-sections, Plate C-4-3,4, there is a weak horizontal internal stratification, or orientation of planar or elongate grains. Clay flakes are also rather abundant, scattered among and between larger grains (Pl. C-4-3, 4). In a very fine pair of micrographs, Plate C-5-1,2, pore support is noted where platy grains are aggregated to form "arch" supports over pores, right side of Plate C-5-2. Apparent "pore" spaces could have been formed during sample preparation by plucking of silt-sized grains from these spaces. However, the "edge to edge" and "edge to face" arrangement of clay flakes as shown in Plate C-5-2 is thought to be of considerable importance in retaining pore space, and indicating that this

clay has not undergone major deformation at this locality.

3. Norfolk - Barrett's Quarry. The samples examined from Barrett's Quarry near Norfolk are from "Leda Clay", here overlying Fort Covington till which lies directly on Ordovician limestones. The clay sequence is laminated at the 1/2 cm scale, apparently undeformed and thixotropic.

It is readily apparent in micrographs that this clay is much less silty than the average for the "Leda". In both B- and C-sections (Pl. C-5-3 and Pl. C-5-4), a generally inclined stratification is noted, resulting from the preferred orientation of clay flakes. These are not thought to be artifacts because of the "flat surface" of the flakes noted in A-section (Pl. C-6-1). In this type of clay, there are many "edge-to-edge" supports, and it is considered as providing a porosity-retention structure, noted widely in the literature as "house-of-cards" (Pl. C-6-2).

This thixotropic clay at the Barrett's Quarry locality is purer than most noted to date, has edge to flake or edge to edge aggregates lumped under the "house-of-cards" term, and rather good orientation of clay flakes, although this clay has all the appearances of clearly being undeformed.

4. Norfolk - Adams Street. This specimen was collected from an apparently structureless and undeformed clay. As seen in Plate C-6-3, this clay has a structure that appears to be rather massive, with somewhat solid aggregates of clays, and without the clear appearance of individual flakes except where noted with a "plastered on" appearance. It is suspected that, either this clay has been deformed without leaving a trace other than collapsed internal structure, or that its depositional environment is such that the clay is markedly different in appearance from others observed in this study.

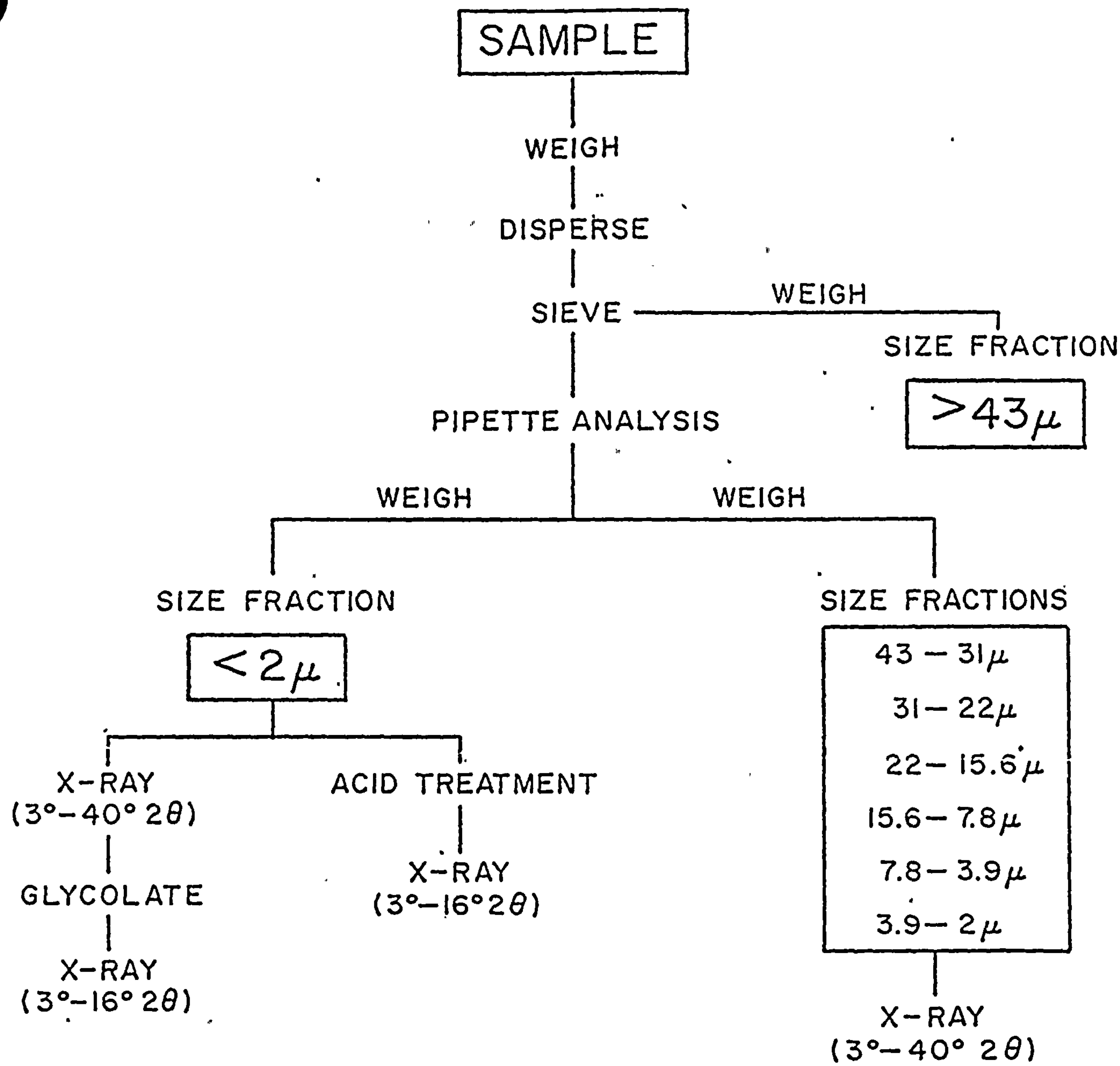
Summary: 1. In the Quebec area, there was little difference in the marine clays where interlayered with load-deformed sands with undisturbed sequences.

2. The ice-deformed "clays" as seen at Charlesbourg, near Quebec City, are fine silt, and the assumption is that much of the fine silt and clay fraction seen is glacial rock flour.

3. In undeformed clays from Massena, what are apparently arches support pore spaces. The presence of such structures are regarded as a clear indication that deformation accompanied by liquefaction has not taken place.

4. Where the "house-of-cards" structure is well-preserved, as in the clay at Barrett's Quarry near Norfolk, deformation involving liquefaction is likewise unlikely.

5. Where a rather solid, lumpy appearance is present in structureless clay, as at the Adams Street locality in Norfolk, there is a definite suggestion that either the depositional or post-depositional history is responsible for the clay structure and fabric. More data would be necessary to make more authoritative interpretations of this "collapsed" or clotted fabric.



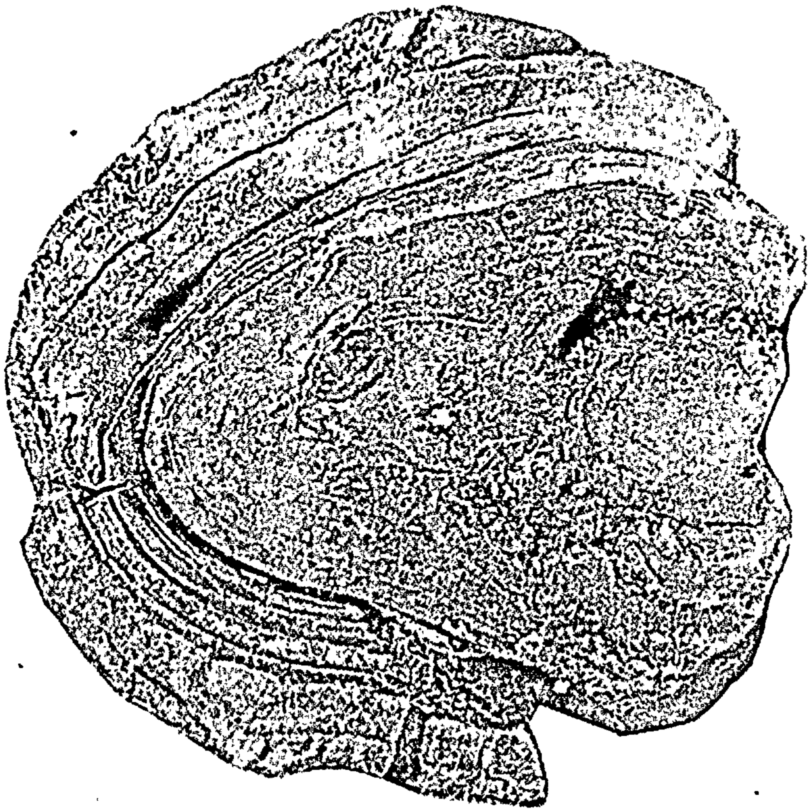
FLOW CHART: SIZE ANALYSIS AND X-RAY IDENTIFICATION

FIG. C-1.

PLATE C-1

Fig. 1. Photograph of sample of folded marine sediment (13,600 yrs. B.P.) collected from the locality northeast of Charlesbourg, near Quebec City, x1.

Figs. 2-3. Scanning electron micrographs; 2, subrounded platy fragments in undeformed marine clays (10,500 yrs. B.P.) from St. Romuald d'Etchemain, Quebec, b-section, x11,000. 3, Slightly apparent preferred orientation sloping slightly toward left, same sample, b-section, x 5.500.



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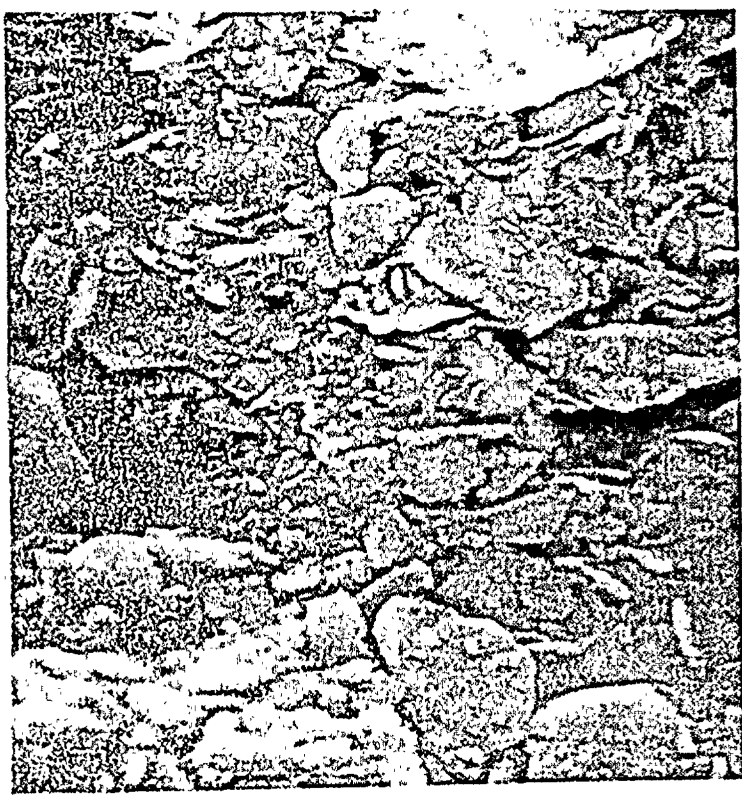

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PLATE C-2

All figures are scanning electron micrographs; top of micrograph is top of sample.

Fig. 1. Sample of marine clay with interbedded load-deformed sand, St. Romuald d'Etchemain, a-section, x 5,500.

Fig. 2. Same sample, with abundant subvertical particles, b-section, x 5,500.

Fig. 3. Same sample, weak preferred orientation sloping to left, c-section, x 5,500.

Fig. 4. Surface microarchitecture an angular silt grain; marine sediment collected N. E. of Charlesbourg, near the city of Quebec, c-section, x 2,200.

1

2

3

4

PLATE C-3

All figures are scanning electron micrographs; top of micrograph is top of sample.

Fig. 1. Sample of undeformed marine silt from N. E. of Charlesbourg, near the city of Quebec, with subrandom orientation of grains, a-section, x 550.

Fig. 2. Same sample, seen normal to bedding, b-section, x 2,200.

Fig. 3. Same sample with good orientation of grains, b-section, x 550.

Fig. 4. Sample of deformed marine sediment, taken from fold shown in Plate 7, Fig. 1, c-section, x 550.

1

2

2

3

PLATE C-4

All figures are scanning electron micrographs; top of micrograph is top of sample.

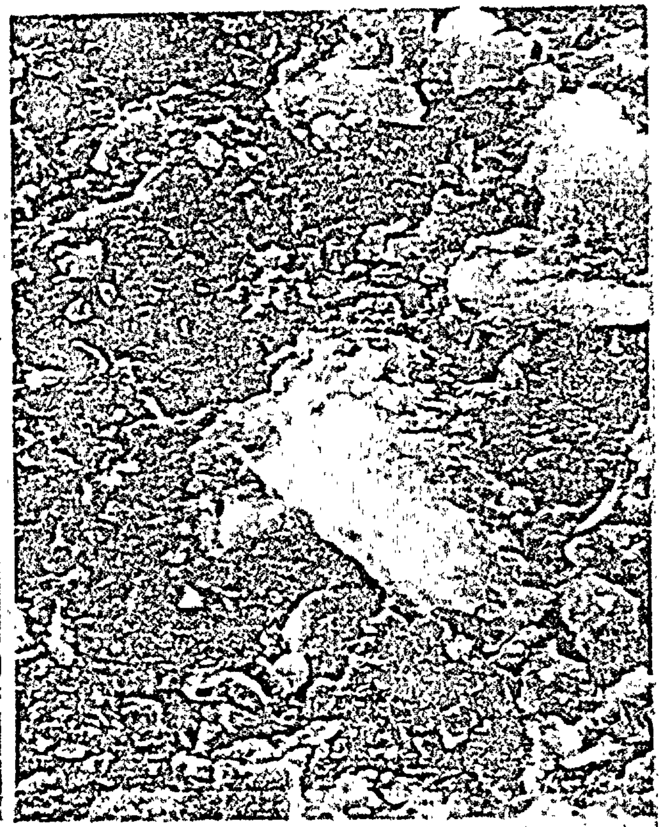
Fig. 1. Sample of deformed marine silt from N. E. of Charlesbourg, near city of Quebec, with angular fragments (rock flour?), c-section, x 550.

Fig. 2. Sample of deformed silt from Malone, New York, with no apparent orientation, c-section, x 220.

Fig. 3. Sample from undeformed laminated clay at Massena, New York, with abundant subhorizontal clay flakes, c-section, x 5,500.

Fig. 4. Same sample, b-section, x 2,200.

1



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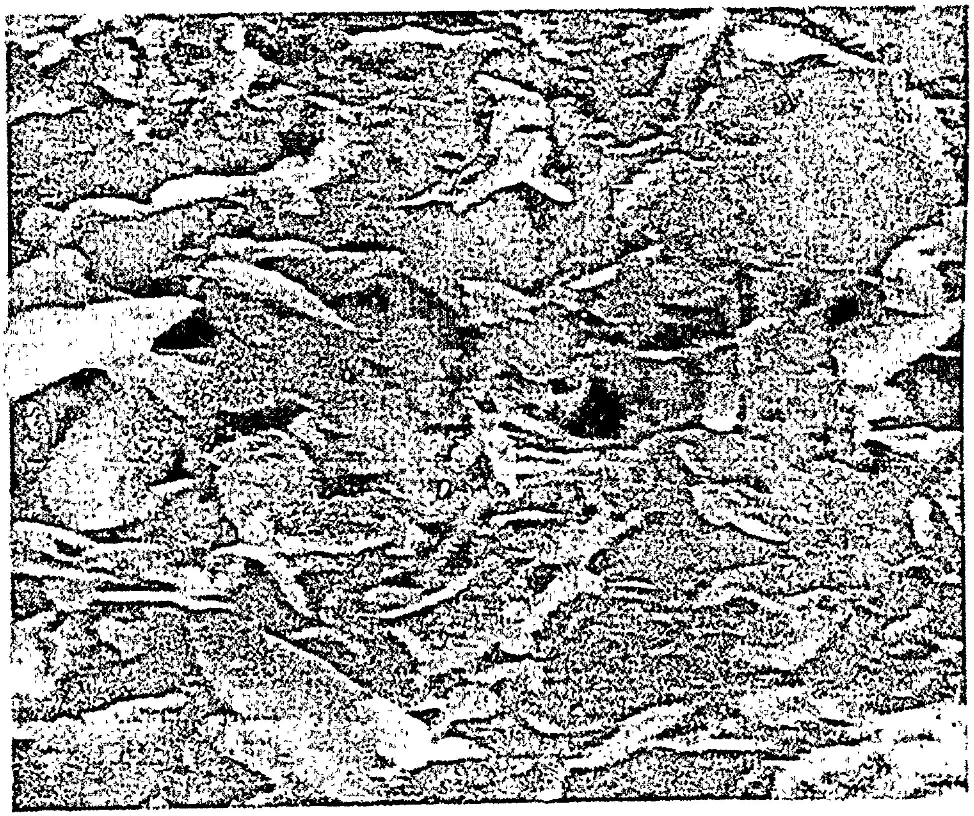

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PLATE C-5

All figures are scanning electron micrographs; top of micrograph is top of sample.

Fig. 1. Sample of undeformed, laminated clay from Massena, New York, with pore-support arches, c-section, x 2,200.

Fig. 2. Same sample, area of Fig. 1 enlarged to show arch of clay flakes at right side of micrograph, c-section, x 5,500.

Fig. 3. Sample of laminated undeformed clay from Barrett's Quarry near Norfolk, New York, with internal stratification shown by orientation of clay flakes, b-section, x 2,200.

Fig. 4. Same sample, c-section, x 2,200.

PLATE C-6

All figures are scanning electron micrographs.

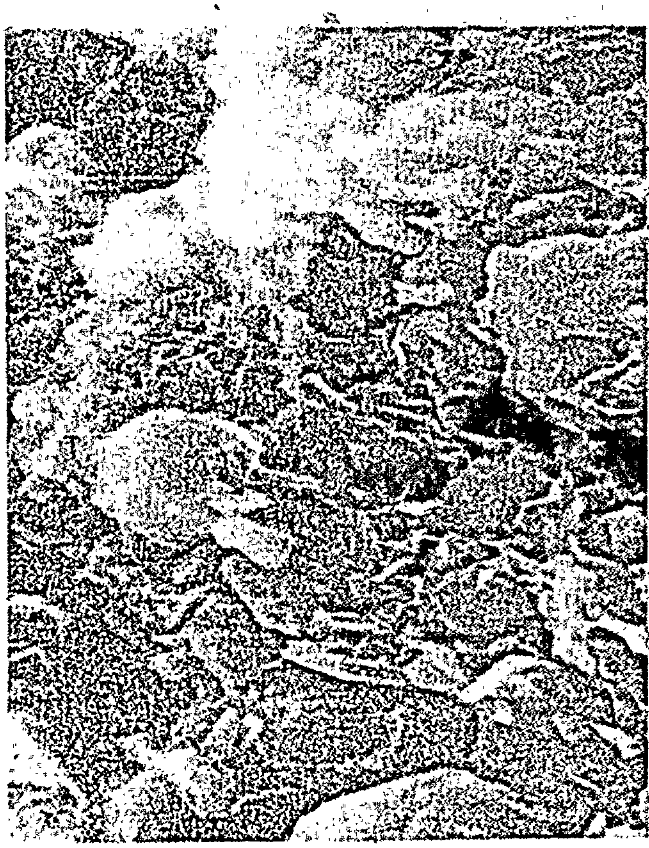
Fig. 1. Lamination-plane view of sample from Barrett's Quarry near Norfolk, New York, a-section, x 2,200.

Fig. 2. "House of Cards" structure in sample from Barrett's Quarry, c-section, x 11,000.

Fig. 3. Apparently collapsed structure in sample from Adams Street in Norfolk, New York, b-section, x 5,500.

1

2



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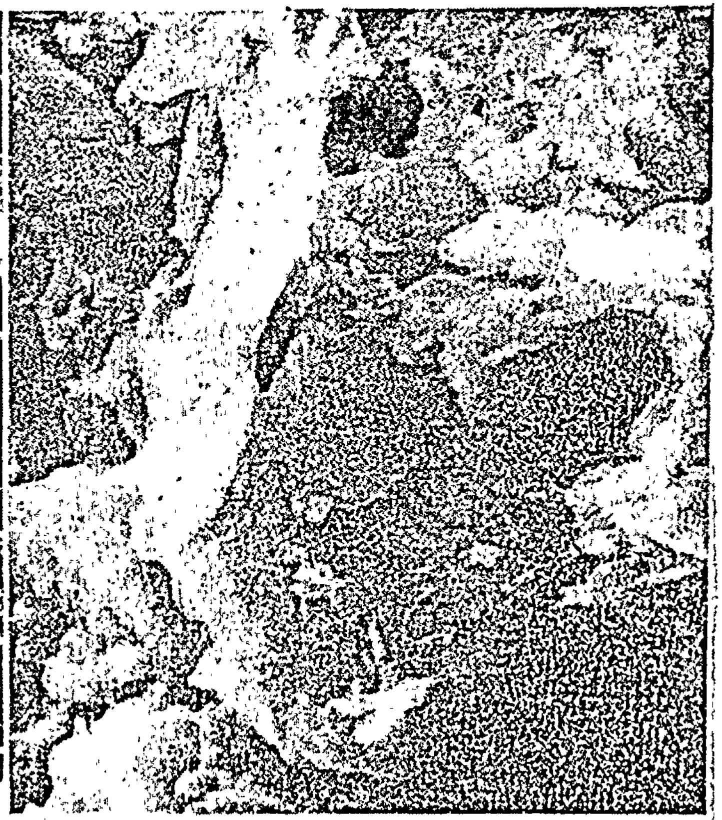

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TABLE C-1

SAMPLE LOCATIONS: X-RAY ANALYSIS, SIZE AND VISCOSITY MEASUREMENTS

Sample Number	Field Description	Location
2-1	"Leda clay"	St. Romuald 'd'Etchemain Quebec City, Quebec, Canada. Rhymites of sand and clay. Sample taken from undeformed clay unit.
2-2	"Leda clay"	Same location as 2-1. Sample taken from clay unit 10 m south of 2-1 from a deformed clay unit.
3	"Leda clay"	Charlesbourg, Quebec City, Quebec, Canada. Sample taken from undeformed clay bed.
3-1	"Leda clay"	Same location as 3. Sample taken from deformed clay unit 15 m west of sample 3.
3-2	"Leda clay"	Same location as 3. Sample taken 3 m west of 3-1 from a deformed clay unit.
K-1	"Leda clay"	Norfolk Quad. Adams St. (house foundation). Sample taken 10 cm below contact between "Leda clay" and overlying crossbedded sand. They clay unit appears to be undeformed.
Norfolk Adams St.	"Leda clay"	Same location as K-1. Sample taken 1.2 m below contact between "Leda dlay" and overlying crossbedded sand. Sample taken from an apparently undeformed unit.
K-3	"Leda clay"	Norfolk Quad., Barrett Quarry. "Leda clay" overlies till. Sample taken form clay about 30 cm below soil horizon. The clay is a laminated. undeformed unit.
Norfolk, Barrett's Quarry	"Leda clay"	Same location as K-3. Sample taken 1 m below K-3 in a varved clay. The clay unit shows no deformation.
K-4	clay	Canton Quarry. Sample taken from clay linina in deformed sand unit.
K-5	clay	Natural Dam and Gouveneur Clay sample taken from deformed sand unit.
K-6	clay/silt	Same location as K-5. Sample taken from fine matrix of the conglomerate overlying deformed sand of K-5

TABLE C-1 (cont.)

Sample Number	Field Description	Location
K-7	clay	Same location as K-5. Sample from highly contorted clay unit.
K-8	clay	Same location as K-5. Sample from highly contorted clay unit about 50 m from K-7.
K-10	clay	Same location as K-5. Sample from undeformed clay unit about 5 m below sample K-8.
K-11	sand/silt/ clay	Massena, South Gross River Road, house foundation. Sample taken from crossbedded sand 20 cm below contact with soil.
K-11a	clay	Same location as K-11. Sample taken from clay lamina in crossbedded sand, about 20 cm below sample K-11.
K-11b	"Leda clay"	Same location as K-11. Sample taken 20 cm below contact between "Leda clay" and overlying crossbedded sand. Clay unit is undeformed.
K-14	clay	Gouvernour, Route 11, Gravel pit. Sample taken from massive clay unit. Clay appears to be undeformed.
K-16	"Leda clay"	Massena, Howerstock Rd., Sample taken form river bank.
Massena	silt	Massena, Sample taken from undeformed silt unit.
Massena (Top of exposure)	silt	Massena, Sample taken from undeformed silt unit.
K-17	clay	Alexandria Bay, Newberry Sand and Gravel Quarry. Sample taken from laminated, deformed clay unit.
Malone (Top of exposure)	silt	Malone. Sample taken from deformed silt unit
Brawley	silt	Brawley, California. Sample taken from deformed silt unit.
Van Norman 1	silt	Van Norman Reservoir, Calif. Sample taken form deformed unit 10 cm below surface.
Van Norman 2	silt	Same location as Van Norman 1 Sample taken 30 cm below surface in undeformed layer
Van Norman 3	silt	Same location as Van Norman 1 Sample taken 5 cm below Van Norman 2 in a slightly deformed unit.

TABLE C-2.

PEAK AREAS (cm^2) (WEIGHTED)
(C = clay S = silt)

Sample	2-1 C	2-1 S	2-2 C	2-2 S
Montmorillonite	5.08	2.43	7.56	3.90
Chlorite	16.40	8.93	17.38	9.88
"Micas"	25.40	7.36	26.68	17.00
Amphibole	2.19	1.68	1.88	1.68
Quartz	8.26	14.45	13.44	9.94
Plagioclase	2.60	9.18	4.24	2.70
Potassium Feldspar	9.02	3.90	9.44	7.13
Total Feldspar	11.62	13.08	13.68	9.82
Kaolinite				
Calcite				
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.62	0.17	0.56	0.39
Chlorite/Quartz	1.99	0.62	1.29	0.99
"Micas"/Quartz	3.12	0.51	1.99	1.71
Amphibole/ Quartz	0.27	0.12	0.14	0.17
Plagioclase/ Quartz	0.31	0.64	0.32	0.27
Potassium Feldspar/ Quartz	1.09	0.27	0.70	0.72
Total Feldspar/ Quartz				
Kaolinite/ Quartz				
Calcite/Quartz				
Dolomite/ Quartz				
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	3-C	3-S	3-1 C	3-1 S
Montmorillonite	2.94		4.92	1.28
Chlorite	6.28	4.60	1.80	0.75
"Micas"	26.40	28.50	144.90	49.40
Amphibole	1.58	1.75	2.63	2.67
Quartz	8.25	14.50	30.80	19.62
Plagioclase	2.73	5.79	9.07	10.38
Potassium Feldspar	5.60	27.75	24.31	17.64
Total Feldspar	8.33	33.54	33.38	28.02
Kaolinite				
Calcite				
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.36		0.16	0.07
Chlorite/Quartz	0.76	0.32	0.06	0.04
"Micas"/Quartz	3.20	1.97	4.70	2.52
Amphibole/Quartz	0.19	0.12	0.09	0.13
Plagioclase/ Quartz	0.33	0.40	0.29	0.53
Potassium Feldspar/ Quartz	0.68	1.91	0.79	0.90
Total Feldspar/ Quartz	1.00	2.31	1.08	1.43
Kaolinite/Quartz				
Calcite/Quartz				0.03
Dolomite/Quartz				
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	3-2 C	3-2 S	K-1 C	K-1 S
Montmorillonite	2.13	2.13	6.60	3.60
Chlorite	3.15	3.15	8.74	5.25
"Micas"	32.40	23.75	70.04	34.80
Amphibole	1.30	0.72	0.93	1.37
Quartz	11.20	4.40	13.32	13.97
Plagioclase	15.75	1.28	6.08	3.64
Potassium Feldspar	1.65	1.52	0.91	7.92
Total Feldspar	17.40	2.80	6.99	11.56
Kaolinite				
Calcite				
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.19	0.48	0.49	0.25
Chlorite/Quartz	0.28	0.72	0.66	0.38
"Micas"/Quartz	2.89	5.40	5.26	2.49
Amphibole/Quartz	0.12	0.16	0.07	0.10
Plagioclase/ Quartz	1.40	0.29	0.46	0.26
Potassium Feldspar/ Quartz	0.15	0.35	0.07	0.57
Total Feldspar/ Quartz	1.55	0.64	0.52	0.83
Kaolinite/Quartz				
Calcite/Quartz				
Dolomite/Quartz				
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	Norfolk/ Adams St. C	Norfolk/ Adams St. S	K-3 C	K-3 S
Montmorillonite	4.26	1.75	6.72	6.11
Chlorite	9.24	3.12	7.54	3.80
"Micas"	46.72	21.48	48.00	12.39
Amphibole	0.99	0.94	0.83	1.40
Quartz	8.60	11.62	9.44	23.94
Plagioclase	4.42	1.44	1.60	3.76
Potassium Feldspar	3.71	4.22	3.01	7.23
Total Feldspar	8.13	5.66	4.61	10.99
Kaolinite				
Calcite				
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.49	0.15	0.71	0.26
Chlorite/Quartz	1.07	0.27	0.80	0.16
"Micas"/Quartz	5.43	1.85	5.05	0.52
Amphibole/Quartz	0.12	0.08	0.09	0.06
Plagioclase/ Quartz	0.51	0.12	0.17	0.16
Potassium Feldspar/ Quartz	0.43	0.36	0.32	0.30
Total Feldspar/ Quartz	0.95	0.49	0.49	0.46
Kaolinite/Quartz				
Calcite/Quartz		0.21		
Dolomite/Quartz		0.31		
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	Norfolk/ Barretts Quarry C	Norfolk/ Barretts Quarry S
Montmorillonite	4.50	2.95
Chlorite	7.02	6.67
"Micas"	40.50	24.18
Amphibole	0.91	1.45
Quartz	4.51	13.90
Plagioclase	0.55	3.00
Potassium Feldspar	1.37	4.13
Total Feldspar	1.92	7.13
Kaolinite		
Calcite		0.15
Dolomite		2.31
Ilmenite		
Montmorillonite/ Quartz	1.00	0.21
Chlorite/Quartz	1.56	0.48
"Micas"/Quartz	8.89	1.74
Amphibole/Quartz	0.20	0.10
Plagioclase/ Quartz	0.12	0.22
Potassium Feldspar/ Quartz	0.30	0.30
Total Feldspar/ Quartz	0.42	0.51
Kaolinite/Quartz		
Calcite/Quartz		0.01
Dolomite/Quartz		0.17
Ilmenite/Quartz		

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	K-4 C	K-4 S	K-5 C	K-5 S
Montmorillonite	3.68	1.32		
Chlorite	0.76	0.91	9.00	5.28
"Micas"	3.72	4.92	31.80	16.72
Amphibole	1.30	1.52	0.78	0.98
Quartz	36.42	39.95	13.32	39.18
Plagioclase	12.62	11.41	1.92	4.44
Potassium Feldspar	15.90	14.02	3.33	8.75
Total Feldspar	28.52	25.42	5.25	13.19
Kaolinite				
Calcite				
Dolomite			0.90	6.70
Ilmenite				
Montmorillonite/Quartz			0.28	0.03
Chlorite/Quartz	0.02	0.02	0.68	0.13
"Micas"/Quartz	0.10	0.12	2.39	0.43
Amphibole/Quartz	0.04	0.04	0.06	0.02
Plagioclase/Quartz	0.35	0.28	0.14	0.11
Potassium Feldspar/Quartz	0.44	0.35	0.25	0.22
Total Feldspar/Quartz	0.78	0.64	0.39	0.34
Kaolinite/Quartz				
Calcite/Quartz			0.07	0.17
Dolomite/Quartz				
Ilmenite/Quartz				

TABLE C-2 (cont.)

PEAK AREAS (WEIGHTED)

Sample	K-6 C	K-6 S	K-7 C	K-7 S
Montmorillonite	4.03	2.10	3.78	2.00
Chlorite	8.37	1.12	8.52	1.34
"Micas"	64.24	52.36	69.24	49.52
Amphibole	0.50	3.68	0.71	4.10
Quartz	7.66	14.90	8.99	13.70
Plagioclase	0.38	24.18	8.33	23.10
Potassium Feldspar				
Total Feldspar				
Kaolinite				
Calcite				
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.53	0.14	0.42	0.15
Chlorite/Quartz	1.09	0.08	0.95	0.10
"Micas"/Quartz	8.38	3.51	7.70	3.61
Amphibole/Quartz	0.07	0.25	0.08	0.30
Plagioclase/ Quartz	0.05	0.54	0.04	0.51
Potassium Feldspar/ Quartz		1.08	0.89	1.18
Total Feldspar/ Quartz	0.05	1.62	0.93	1.69
Kaolinite/Quartz				
Calcite/Quartz				
Dolomite/Quartz				
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREA (WEIGHTED)

Sample	K-8 C	K-8 S	K-10 C	K-10 S	K-11 C	K-11 S
Montmorillonite	4.11	3.00	6.66	3.75	2.70	1.05
Chlorite	8.31	2.21	10.12	9.46	7.30	2.60
"Micas"	57.20	52.01	65.60	47.76	6.00	11.50
Amphibole	0.65	6.20	0.85	0.61		0.60
Quartz	9.43	15.01	14.18	23.70	7.30	12.78
Plagioclase	0.16	8.31	2.28	4.20	0.81	2.58
Potassium Feldspar	7.29	16.85	3.08	6.48	0.90	0.28
Total Feldspar	7.45	25.26	5.36	10.68	1.71	2.86
Kaolinite						
Calcite						
Dolomite						
Ilmenite						
Montmorillonite/ Quartz	0.44	0.19	0.47	0.16	0.37	0.08
Chlorite/Quartz	0.88	0.14	0.71	0.40	0.45	0.20
"Micas"/Quartz	6.07	3.27	4.63	2.02	0.82	0.90
Amphibole/Quartz	0.07	0.39	0.06	0.03		0.05
Plagioclase/ Quartz	0.02	0.52	2.28	4.20	0.81	2.58
Potassium Feldspar/ Quartz	0.77	1.06	0.22	0.27	0.12	0.02
Total Feldspar/ Quartz	0.79	1.59	0.38	0.45	0.23	0.22
Kaolinite/Quartz						
Calcite/Quartz						
Dolomite/Quartz						
Ilmenite/Quartz						

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	K-14 C	K-14 S	K-16 C	K-16 S
Montmorillonite	3.60	6.60	4.16	3.50
Chlorite	3.60	7.48	7.24	30.50
"Micas"	72.40	82.80	47.36	31.00
Amphibole	0.80	1.20	1.20	0.99
Quartz	9.10	20.24	9.16	12.70
Plagioclase	1.10	3.28	0.77	1.45
Potassium Feldspar	1.40	3.97	3.37	4.80
Total Feldspar	2.50	7.25	4.14	6.25
Kaolinite				
Calcite			1.12	1.85
Dolomite			0.96	2.47
Ilmenite				
Montmorillonite/ Quartz	0.40	0.33	0.45	0.28
Chlorite/Quartz	0.40	0.37	0.79	2.40
"Micas"/Quartz	7.96	4.09	5.17	2.44
Amphibole/Quartz	0.09	0.06	0.13	0.08
Plagioclase/ Quartz	0.12	0.16	0.08	0.11
Potassium Feldspar/ Quartz	0.15	0.20	0.37	0.38
Total Feldspar/ Quartz	0.27	0.36	0.45	0.49
Kaolinite/Quartz				
Calcite/Quartz			0.12	0.15
Dolomite/Quartz			0.10	0.19
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	Massena C	Massena S	Massena Top C	Massena Top S
Montmorillonite	3.20	2.40	7.17	3.79
Chlorite	3.96	3.78	6.74	3.78
"Micas"	31.86	21.84	48.16	21.60
Amphibole	0.41	1.32	1.49	1.30
Quartz	4.16	11.15	7.97	14.30
Plagioclase	0.46	0.90	1.10	1.35
Potassium Feldspar	1.56	3.30	2.28	5.13
Total Feldspar	2.02	4.20	3.38	6.48
Kaolinite				
Calcite	0.66	2.34		1.22
Dolomite	0.66	4.40		4.40
Ilmenite				
Montmorillonite/ Quartz	0.77	0.22	0.90	0.26
Chlorite/Quartz	0.95	0.34	0.85	0.26
"Micas"/Quartz	7.66	1.96	6.04	1.51
Amphibole/Quartz	0.10	0.12	0.19	0.09
Plagioclase/ Quartz	0.11	0.08	0.14	0.09
Potassium Feldspar/ Quartz	0.38	0.30	0.29	0.36
Total Feldspar/ Quartz	0.49	0.38	0.43	0.45
Kaolinite/Quartz				
Calcite/Quartz	0.16	0.21		0.08
Dolomite/Quartz	0.16	0.39		0.31
Ilmenite/Quartz				

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	K-17 C	K-17 S	MAL C	MAL S	Brawley C	Brawley S
Montmorillonite	2.99	3.64			35.04	7.75
Chlorite	5.13	4.32	2.91	2.86	6.97	1.89
"Micas"	11.21	9.72	10.21	9.72	30.68	7.00
Amphibole	1.22	1.02	0.76	0.96		
Quartz	14.20	13.80	26.50	26.92	15.96	18.00
Plagioclase	6.21	5.95	4.71	5.00	1.95	1.35
Potassium Feldspar	0.75	0.95	11.32	10.26	1.15	3.32
Total Feldspar	6.96	6.90	16.03	15.26	3.10	4.67
Kaolinite					3.21	0.91
Calcite					3.57	3.75
Dolomite	6.31	5.55			1.74	5.55
Ilmenite						
Halloysite						0.70
Montmorillonite/ Quartz	0.21	0.26			2.20	0.43
Chlorite/Quartz	0.36	0.31	0.11	0.11	0.41	0.11
"Micas"/Quartz	0.79	0.70	0.39	0.36	1.90	0.39
Amphibole/Quartz	0.09	0.07	0.03	0.04		
Plagioclase/ Quartz	0.44	0.43	0.18	0.19	0.12	0.07
Potassium Feldspar/ Quartz	0.05	0.07	0.43	0.38	0.07	0.18
Total Feldspar/ Quartz	0.49	0.50	0.61	0.57	0.19	0.26
Kaolinite/Quartz					0.20	0.05
Calcite/Quartz					3.57	3.75
Dolomite/Quartz	0.44	0.40			0.11	0.31
Ilmenite/Quartz						
Halloysite/ Quartz						0.03

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	VN-1 C	VN-1 S	VN-2 C	VN-2 S
Montmorillonite	4.32	5.67	8.56	11.93
Chlorite	3.50	3.80	1.77	2.22
"Micas"	13.21	14.56	13.92	14.56
Amphibole				
Quartz	5.62	6.82	6.02	6.65
Plagioclase	3.99	6.75	0.99	1.43
Potassium Feldspar	2.21	1.17	5.72	5.82
Total Feldspar	6.20	7.92	6.71	7.25
Kaolinite	0.40	0.42	0.20	0.22
Calcite				
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.77	0.83	1.42	1.79
Chlorite/Quartz	0.62	0.55	0.29	0.33
"Micas"/Quartz	2.35	21.3	2.31	2.19
Amphibole/Quartz				
Plagioclase/ Quartz	0.71	0.99	0.16	0.22
Potassium Feldspar/ Quartz	0.39	0.17	0.95	0.88
Total Feldspar/ Quartz	1.10	1.16	1.11	1.09
Kaolinite/Quartz	0.07	0.06	0.03	0.03
Calcite/Quartz				
Dolomite/Quartz				
Ilmenite/Quartz				

TABLE C-3 (cont'd.)
MINERALOGY (greater than 63 microns)

Sample	K-11A	K-11B	K-14	K-16
% present				
quartz + K-spar	70	80	70	60
plagioclase	tr.	tr.	tr.	--
heavy minerals	10	10	5	5
micas	20	10	20	35
mafics	tr.	tr.	5	--

Sample	Massena	Massena/top	K-17	Malone
% present				
quartz + K-spar	50	50	40	80
plagioclase	--	--	--	tr.
heavy minerals	tr.	tr.	tr.	10
micas	45	50	55	10
mafics	5	tr.	5	tr.

Sample	V.N.	V.N. 1	V.N. 2	V.N. 3
% present				
quartz + K-spar	65	50	40	50
plagioclase	tr.	5	tr.	tr.
heavy minerals	25	5	tr.	5
micas	tr.	35	55	40
mafics	10	5	5	5

TABLE C-4
GRAIN SIZE ANALYSES

Sample Size: % greater than (μ)	2-1	2-2	3	3-1
62.5	---	---	---	---
44.0	43.6	15.0	21.56	26.92
31.0	53.0	20.0	42.7	42.2
22.1	56.1	22.5	---	49.9
15.6	57.0	24.9	53.2	58.1
7.8	60.6	28.9	73.7	78.9
3.9	61.7	34.0	80.7	90.0
2.0	62.2	38.0	90.1	93.7

Sample Size: % greater than (μ)	3-2	K-1	Norfolk/ Adams St.	K-3
62.5	46.42	22.00	31.11	9.96
44.0	62.99	39.52	40.86	13.66
31.0	68.30	45.62	48.80	16.53
22.1	70.95	48.67	52.77	17.97
15.6	73.99	51.64	56.51	20.22
7.8	77.78	56.90	63.88	24.00
3.9	83.85	62.86	71.36	29.95
2.0	92.26	72.31	79.13	43.57

Sample Size: % greater than (μ)	Norfolk/ Barrett's Quarry	K-4	K-5	K-6
62.5	22.67	52.51	22.99	61.21
44.0	31.32	71.90	46.64	63.18
31.0	36.44	83.32	57.72	71.73
22.1	39.00	89.03	63.27	76.01
15.6	41.40	92.40	69.04	80.71
7.8	48.01	96.42	82.90	92.14
3.9	57.42	97.63	91.45	95.21
2.0	68.69	98.38	96.52	96.15

TABLE C-2 (cont.)
PEAK AREAS (WEIGHTED)

Sample	K-11A C	K-11A S	K-11B C	K-11B S
Montmorillonite	1.24	2.03	5.41	3.00
Chlorite	4.50	4.18	4.38	3.30
"Micas"	5.12	5.20	122.00	44.40
Amphibole	1.10	2.25	0.60	1.44
Quartz	6.30	26.39	15.39	28.29
Plagioclase	0.67	5.40	2.48	7.20
Potassium Feldspar	0.52	9.56	2.04	12.04
Total Feldspar	1.19	14.96	4.52	19.24
Kaolinite				
Calcite				0.65
Dolomite				
Ilmenite				
Montmorillonite/ Quartz	0.20	0.08	0.35	0.11
Chlorite/Quartz	0.71	0.16	0.28	0.12
"Micas"/Quartz	0.81	0.20	7.93	1.57
Amphibole/Quartz	0.17	0.09	0.04	0.05
Plagioclase/ Quartz	0.11	0.20	0.16	0.25
Potassium Feldspar/ Quartz	0.08	0.36	0.13	0.42
Total Feldspar/ Quartz	0.19	0.57	0.29	0.68
Kaolinite/Quartz				
Calcite/Quartz				0.02
Dolomite/Quartz				
Ilmenite/Quartz				

TABLE C-3
MINERALOGY (greater than 63 microns)

Sample % present	2-1	2-2	3	3-1
quartz + K-spar	54	70	80	80
plagioclase	tr.	5	tr.	tr.
heavy minerals	14	15	7	10
micas	30	10	12	9
mafics	2	--	tr.	tr.

Sample % present	3-2	K-1	Norfolk/ Adams St.	K-3
quartz + K-spar	75	80	60	30
plagioclase	1	--	tr.	--
heavy minerals	12	5	5	5
micas	12	15	35	65
mafics	tr.	tr.	tr.	tr.

Sample % present	Norfolk/ Barrett's Quarry	K-4	K-5	K-6
quartz + K-spar	25	75	85	40
plagioclase	--	--	tr.	--
heavy minerals	5	10	5	tr.
micas	70	14	9	60
mafics	tr.	1	tr.	tr.

Sample % present	K-7	K-8	K-10	K-11
quartz + K-spar	75	80	30	73
plagioclase	5	--	--	--
heavy minerals	5	5	tr.	25
micas	10	10	70	1
mafics	tr.	tr.	tr.	1

TABLE C-4 (cont'd.)
GRAIN SIZE ANALYSES

Sample Size: % greater than (μ)	K-11A	K-11B	K-14	K-16
62.5	75.49	2.19	---	33.85
44.0	86.59	4.72	---	41.48
31.0	90.50	14.81	6.98	50.52
22.1	92.46	19.85	10.48	55.05
15.6	93.97	26.43	16.32	59.49
7.8	96.05	46.92	24.35	66.70
3.9	97.49	63.55	31.86	74.49
2.0	99.32	82.45	40.25	79.56

Sample Size: % greater than (μ)	Massena	Massena/top	K-17	Malone
62.5	18.40	0.86	23.28	46.99
44.0	35.18	2.12	25.25	70.28
31.0	40.00	7.73	32.10	82.26
22.1	42.42	10.53	35.53	88.26
15.6	45.44	15.16	39.83	91.91
7.8	54.27	33.24	48.59	94.69
3.9	64.29	52.51	58.66	97.15
2.0	77.08	66.61	68.86	---

Sample Size: % greater than (μ)	Brawley	Van Norman 1	Van Norman 2	Van Norman 3
62.5	40.88	11.69	42.84	12.04
44.0	73.77	28.49	49.78	31.54
31.0	83.60	31.82	54.78	42.57
22.1	88.52	35.14	57.29	48.10
15.6	91.52	40.98	64.70	54.78
7.8	94.47	57.34	79.99	71.02
3.9	95.92	77.94	94.38	84.83
2.0	97.34	93.67	97.81	90.56

TABLE C-5
MEASURED VISCOSITY (POISES)

Sample Setting (RPM)	K-1	Norfolk/ Adams St.	K-3	Norfolk/ Barretts Quarry
1 (5.595)				101.96
2 (7.513)				89.01
3 (9.885)				49.75
4 (13.19)				47.72
5 (17.40)				31.65
6 (25.08)				23.53
7 (33.67)				14.31
8 (44.31)				15.10
9 (59.11)				11.98
10 (77.98)				9.33
11 (113.2)		3.13		7.12
12 (152.0)	2.07	3.30	2.20	6.34
13 (200.0)	3.05	3.44	2.87	5.80
14 (266.8)	4.43	4.72	2.95	5.83
15 (352.0)	4.47	5.42	3.80	7.10
14 (266.8)	4.43	4.57	2.95	6.42
13 (200.0)	2.95	5.90	2.87	5.80
12 (152.0)	2.07	3.62	2.20	6.21
11 (113.2)		3.65		6.95
10 (77.98)				8.32
9 (59.11)				9.15
8 (44.31)				12.21
7 (33.67)				14.02
6 (25.08)				18.82
5 (17.40)				23.74
4 (13.19)				31.32

TABLE C-5 (cont.)
MEASURED VISCOSITY (POISES)

Sample Setting (RPM)	K-1	Norfolk/ Adams St.	K-3	Norfolk/ Barretts Quarry
3 (9.885)				41.79
2 (7.513)				54.98
1 (5.595)				73.84

TABLE C-5 (cont.)
MEASURED VISCOSITY (POISES)

Sample Setting (RPM)	K-7	K-8	K-10	K-11	K-11A
1 (5.595)	232.06	193.38			
2 (7.513)	172.79	162.32			
3 (9.885)	131.32	97.50			
4 (13.19)	98.42	74.56			
5 (17.40)	74,61	56.52			
6 (25.08)	53.33	39.99			
7 (33.67)	38.56	29.79			
8 (44.31)	30,19	27.20			
9 (59.11)	23.30	17.64			
10 (77.98)	18.41	14.12			
11 (113.2)	13.90	10.77	2.87		
12 (152.0)	11.39	9.12	2.26		2.07
13 (200.0)	9.64	7.77	3.00		1.57
14 (266.8)	7.89	7.74	4.06	1.99	2.36
15 (352.0)	8.61	8.05	4.81	2.99	3.30
14 (266.8)	8.11	7.74	3.98	1.99	2.29
13 (200.0)	9.54	7.97	2.95		1.17
12 (152.0)	11.13	9.32	2.07		2.07
11 (113.2)	13.55	11.12			
10 (77.98)	17.65	13.87			
9 (59.11)	22.30	16.97			
8 (44.31)	28.86	20.42			
7 (33.67)	37.97	26.87			
6 (25.08)	50.58	35.30			
5 (17.40)	73.48	49.74			
4 (13.19)	95.44	67.10			

TABLE C-5 (cont.)

MEASURED VISCOSITY (POISES)

Sample Setting (RPM)	K-7	K-8	K-10	K-11	K-11A
3 (9.885)	127.35	87.55			
2 (7.513)	164.93	112.57			
1 (5.595)	221.51	154.70			

TABLE C-5 (cont.)
MEASURED VISCOSITY (POISES)

Sample Setting (RPM)	K-11B	K-14	K-16	Massena (Top)	Massena
1 (5.595)			196.91		172.28
2 (7.513)			154.42		120.43
3 (9.885)			115.80		81.58
4 (13.19)			89.51		59.65
5 (17.40)			66.77		46.35
6 (25.08)			45.56		30.58
7 (33.67)			34.51		22.78
8 (44.31)			26.69		17.76
9 (59.11)			20.33		13.64
10 (77.98)	4.79		16.67		11.35
11 (113.2)	5.21	2.95	12.31		8.86
12 (152.0)	5.69	2.98	9.06	2.72	7.63
13 (200.0)	5.61	3.15	8.56	3.44	6.93
14 (266.8)	6.12	4.28	7.74	4.65	6.34
15 (352.0)	6.71	5.09	8.49	6.04	7.32
14 (266.8)	5.97	4.13	8.85	5.02	6.27
13 (200.0)	5.70	3.15	10.08	3.54	6.69
12 (152.0)	5.82	2.72	11.38	2.20	7.51
11 (113.2)	6.08	2.95	13.90		8.69
10 (77.98)	6.56		17.65		11.10
9 (59.11)	7.32		21.63		13.64
8 (44.31)	7.55		27.08		17.76
7 (33.67)			35.05		25.12
6 (25.08)			45.48		35.29
5 (17.40)			63.30		46.35
4 (13.19)			83.51		56.67
3			113.42		79.59

TABLE C-5 (cont.)
MEASURED VISCOSITY (POISES)

Sample Setting (RPM)	K-11B	K-14	K-16	Massena (Top)	Massena
(9.885)					
2			154.46		103.41
(7.513)					
1			200.41		144.16
(5.595)					

TABLE C-6

Average Peak Area Ratios

	Dilatant (9 samples)		Thixotropic (5 samples including K-16	
	Clay	Silt	Clay	Silt
Montmorillonite/ Quartz	.49	.19	.61	.21
Chlorite/Quartz	.66	.26	1.03	.69
"Mica"/Quartz	4.88	2.19	7.12	2.60
Amphiboles/ Quartz	.09	.07	.12	.20
Plagioclase/ Quartz	.52	.89	.07	.29
K-Spar/Quartz	.20	.32	.54	.64
Total Feldspar/ Quartz	.72	1.21	.61	.93

Average Peak Areas Ratios

	Undeformed		Deformed	
	Clay	Silt	Clay	Silt
Montmorillonite/ Quartz	.51	.17	.31	.20
Chlorite/Quartz	.81	.44	.63	.28
"Mica"/Quartz	4.83	1.60	3.89	2.37
Amphiboles/ Quartz	.12	.08	.08	.17
Plagioclase/ Quartz	.39	.64	.34	.39
K-Spar/Quartz	.34	.43	.44	.66
Total Feldspar/ Quartz	.54	.64	.78	1.05

APPENDIX D

QUATERNARY SEDIMENTS AND STRATIGRAPHY

PLEISTOCENE SEDIMENTS

Unstratified Deposits

Till is the major unstratified sediment and exists in a wide range of textures, composition, particle sizes, genesis, and degree of stratification. Malone till (Fig. D-1, D-2) is invariably buried by younger Ft. Covington till, but the tills where present in a continuous stratigraphic section often show intervening beds of stratified deposits. The Malone till may be reddish, although color is highly dependent on local lithology. It contains a clay-rich matrix with striated clasts and boulders that may exceed 2 ft. Ft. Covington till contains a wider variety of facies than Malone because it is more surficially expressed. The till fabric, composition, and other sediment properties reflect the special environmental conditions and mode of deposition from the ice. The many different types of tills and their complex relationship to stratified sediments are significantly determined by the subaerial and the aqueous conditions. Many of the St. Lawrence tills formed under water. Till variety also occurs because some formed during active glaciation whereas other tills developed from disintegrating ice masses. The following types of till are all present in the study region.

1. Lodgment till. These deposits formed from basal drift in active ice that is grounded (Fig. D-1). The till is usually compact, angular, and may contain a variety of clasts that contain striae.

2. Ablation till. This sediment formed by drift filtering down through the ice along crevassed and melted paths having vertical components. The original position of rocks was englacial or supraglacial and the rocks may show rounding and have minimum retention of striae. Such deposits are more porous than lodgment till and may possess crude stratification. These materials grade into other till varieties, as in moraines where several till families can occur (Fig. D-2).

3. Flow till. This sediment formed by moving off the ice laterally, by processes akin to mudflows and landsliding. Such deposits retain some continuity but are found in complex sequences and may be contorted (Figs. D-4, D-5).

4. Marine/proglacial lake till. These tills form from active ice that is not grounded (Fig. D-6). The glacier may be a few hundred ft. thick and the sediments move downward through the water and accumulate on the basin floor. All gradations occur from these deposits which may be several feet thick to thinner deposits and isolated dropstones, or rafted boulders (Fig. D-7) that may locally deform the enclosing sediments. The source of these materials may

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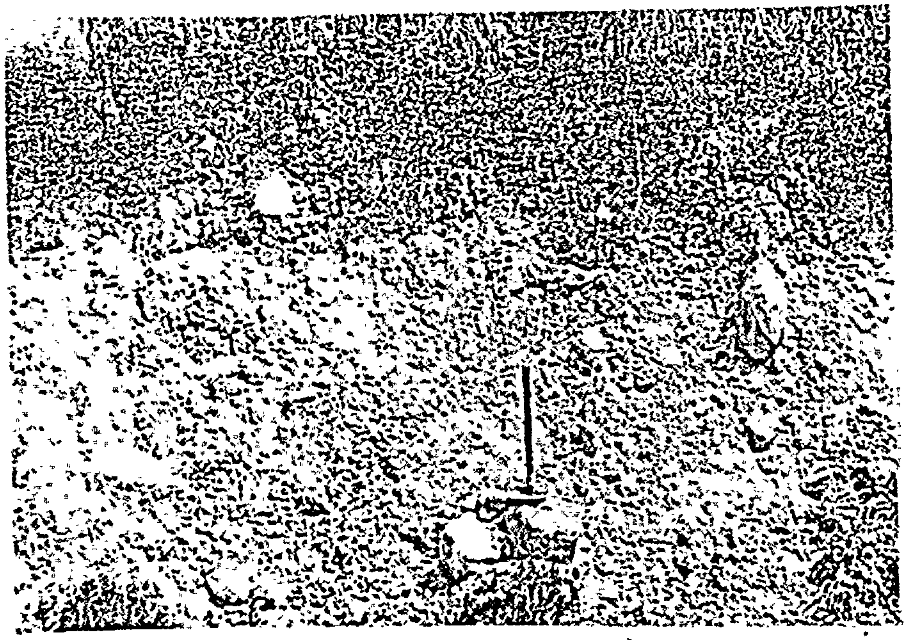
Fig. D-1 (locality 20). Malone till. Slightly reddish color with silt-clay matrix and boulders about 2 ft. long.

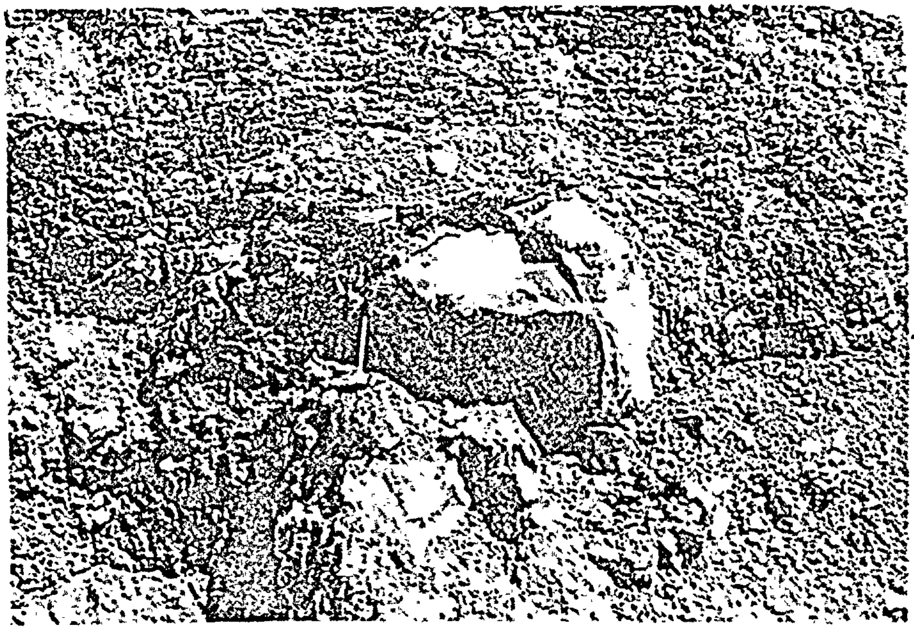
Fig. D-2 (locality 14). Champlain Sea varved sediments overlying Fort Covington Till. Boulder is at top of the till with sediments draped over forming a supratenuous fold. Compare with Fig. 4-12 which shows varved sediment laminations after weathered surface has been scraped off.

Fig. D-3 (locality 3). Fort Covington till in the LaFargeville moraine. Till is very gravelly and coarse, showing evidence of large scale but poorly defined bedding units. Part of a kame moraine-kame delta complex.

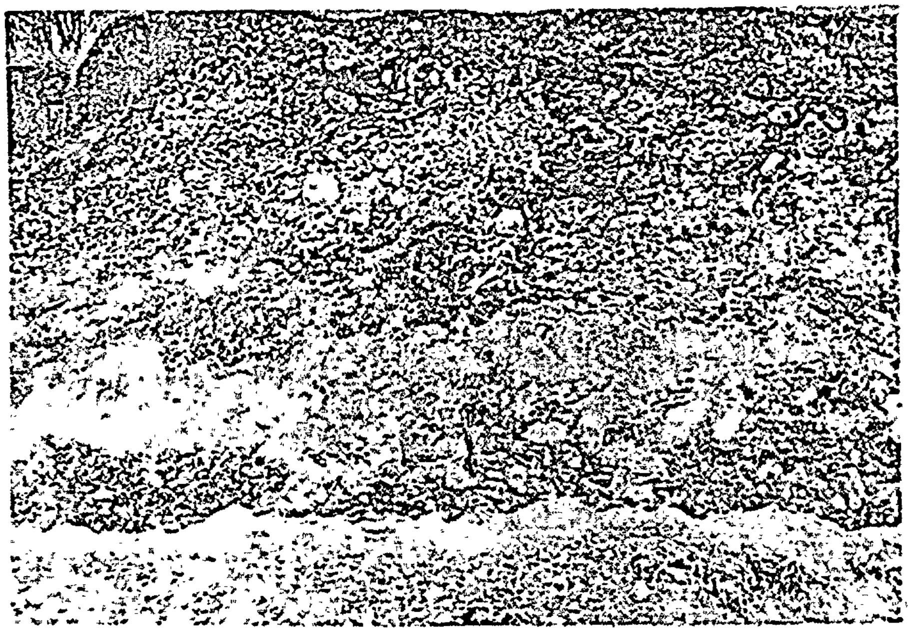
Fig. D-4 (locality 17). Fort Covington till overlying poorly sorted gravels. Part of a kame delta sequence with oscillating ice margin.



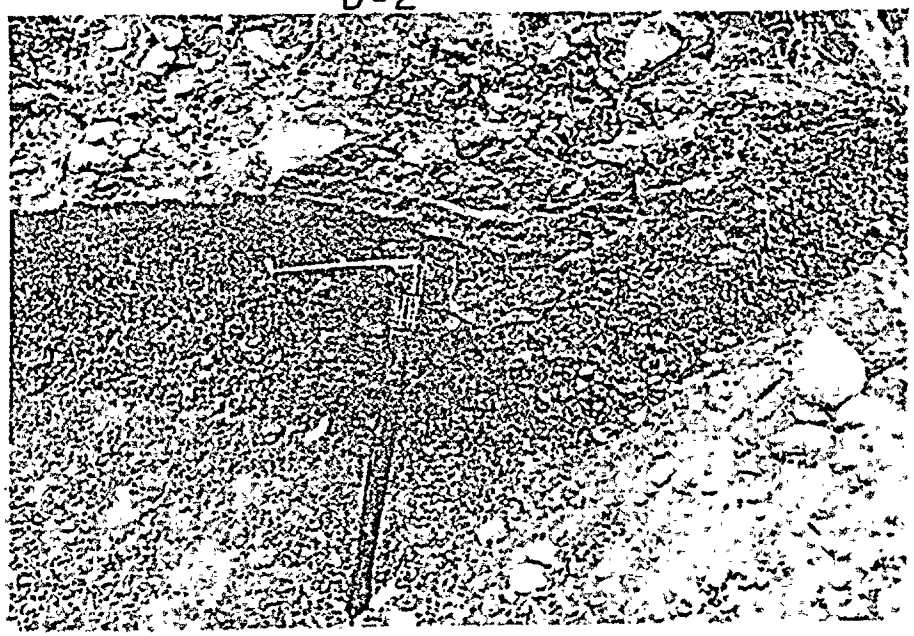
D-1



D-2



D-3



D-4

also occur from iceberg calving where deposits occur near the glacier, or by drift ice that melts far from the parental glacier.

5. Reworked till. Many of the original tills in the St. Lawrence have been subsequently changed by other processes. One of the most common transformations is what MacClintock and Stewart (1965) refer to as "winnowed till". These materials were changed by water both during their formation and by later lake and/or marine waters. Some of these tills are nearly indistinguishable from stratified deposits into which they grade. The lag gravels have been sufficiently concentrated at many localities throughout the St. Lawrence so they have been successfully mined for aggregate.

Stratified Deposits

The St. Lawrence Lowland contains a textbook in multiple variations and types of sedimentary strata. The deposits formed both by single and joint processes associated with glaciers, river, lakes, seas, gravity, and wind. Thus there are primary and secondary glaciofluvial, glaciolacustrine, glacioeolian and glaciomarine strata. There are also associated deposits from non-glacial sources such as those originating from the south which were transported northward to mingle with the glacial meterials. Such permutation of processes operating within the same locality and sedimentary regime caused unusually complicated bedding sequences. Many examples of the following stratified types occur throughout the region.

1. Ice contact deposits. These are essentially layered units that formed at or near the contact of a disintegrating block of ice. Because the materials have not been water-transported for long distances, the bedding changes rapidly both vertically and horizontally. Till may be present in a variety of forms and locations within the drift. Many gradations in stratification occur from chaotic to uniform, horizontal, and well sorted units. A study of the bedding structure, fabric, and sediment size plus analysis of landform characteristics reveals whether the deposits formed in a kame, kame moraine, kame terrace, kame delta, or esker....all of which occur in the St. Lawrence Lowland.

2. Outwash deposits. These are materials that have been fluvially transported by meltwaters away from the glacier margin. They are recognized by well ordered sedimentary sequences that are well sorted and stratified. Bedding is usually nearly horizontal with individual units being continuous over large areas. Such deposits form outwash plains or aprons where they spread laterally and create such features as sandurs, or in valley trains when confined by hillslopes of the sides of a river valley. Such materials may grade into other groups of deposits....such as those that are deltaic.

3. Delta deposits. The standard deltaic model consists of three sedimentary facies....topset, foreset, and bottomset beds. When only limited exposures occur, foreset beds are the most diagnostic. Some extensive deltas, such as at Canton (Locality 12, 13) and Malone (Locality 18) formed as a result of northflowing streams depositing their load in proglacial lakes and marine waters. Some materials may have

been derived from residual ice masses in the Adirondacks.

4. Beach deposits. Shoreline features and the effects of waves and wind at strandline positions of lakes and seas locally abound in the St. Lawrence Lowland. Some hills were eroded and/or truncated by such bodies of water and extensive sand plains are now residual in many areas such as the erg at Locality 15 (Fig. D-8). Here winds have piled sand into dunes that occur in a 250 acre desert-type terrain. Wind-faceted rocks occur in many shapes with ventifacts and dreikanters in abundance. Loess has blown into surrounding areas where it is incorporated into soil horizons.

5. Clay deposits. These sediments deserve special treatment because of their widespread occurrence and testimony they provide on the Quaternary evolution of the region. Rock flour-silts are also included in this grouping of sediments, because they are often mixed and interbedded with the "clays". This is especially true of the extensive "varved clays" or rhythmites.

There are several different types of clays....for example marine and fresh water, varved, rhythmites, laminated, and massive units. Proglacial lake and marine clays occur in many of the region's sand and gravel pits and quarries (Figs. D-9 and D-10). In several pits the thickness of varved sediments is 5 ft. or more, and if these rhythmites are truly seasonal by counting the couplets of dark and light lamina they indicate more than 100 years of depositional record. On exposed surfaces many of the clays are thoroughly jointed and crumbly (Fig. D-10).

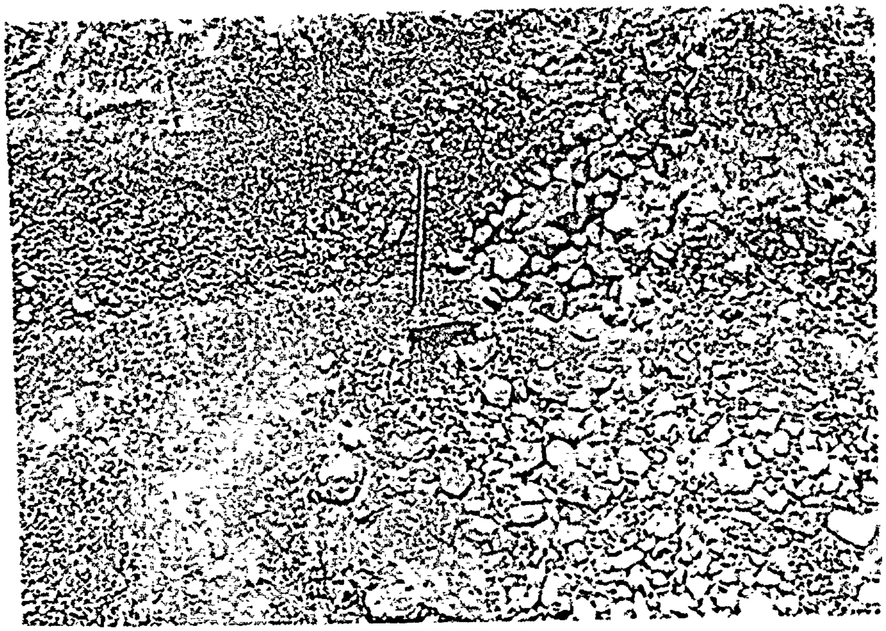
The Leda Clay is a more ubiquitous sediment and occurs extensively in the northwestern part of the region. By definition these sediments are of marine origin which formed in the waters of the Champlain Sea. Recent workers such as N. C. Gadd and others suggest that the terms "Leda Clay" should be restricted in usage to imply a type of material whose physical and mechanical properties are being evaluated for soil mechanics and engineering purposes. When discussing the geologic history of the sediments they should be called "Champlain Sea Clay". These materials reach thicknesses in excess of 100 ft. and are restricted to elevations below 525 ft. Continuous outcrops occur for several miles along the St. Lawrence River east of Waddington, and they are also common throughout the Massena area and along the Raquette and Grass Rivers. J. Thew (Personal Communication, June 1975) reports thicknesses of more than 20 ft. are common in bore holes between Massena and Ft. Covington, and that more than 60 ft. of clay was encountered in extensive boring sites near Ogdensubrg. Recent evidence on dating Champlain Sea clays (Gadd, 1975) indicates the marine transgression occurred as early as 12,800 $\pm$ 220 yrs. B.P., and the termination of saline waters occurred at 10,200 $\pm$ 90 yrs. B.P. These clays are notoriously landlside prone, and have created numerous slides on both sides of the St. Lawrence River (Fig. D-11). Most slides are initiated by river undercutting

Fig. D-5 (locality 17). Deposition of glaciofluvial strata associated with Fort Covington event. The cobbles on right are set in a clay matrix and relations indicate the till in Figs. D-4 and D-5 are probably of the mudflow "flow till" family of glacially - associated sediments.

Fig. D-6 (locality 1). Photograph shows two Fort Covington tills separated by 2-3 ft. silt bed. The tills formed in a proglacial lake environment and provide evidence for a pulsating ice margin. The silt was deposited as rock flour in the lake while the lake was still deep. As the lake drained and shallowed the sediments became varved in units higher in this sequence.

Fig. D-7 (locality 8). Dropstone (ice rafted rock) in varved sediments. Note the deformation of light-colored silty units that occurs in both sides of the rock. The shock waves of the impact contributed to some of the deformed features.

Fig. D-8 (locality 15). View of small part of "erg" that covers several hundred acres. Numerous ventifacts occur in rocks of all lithologies. When falling proglacial lake waters revealed sandy plains they were formed into dunes during immediate postglacial episodes.



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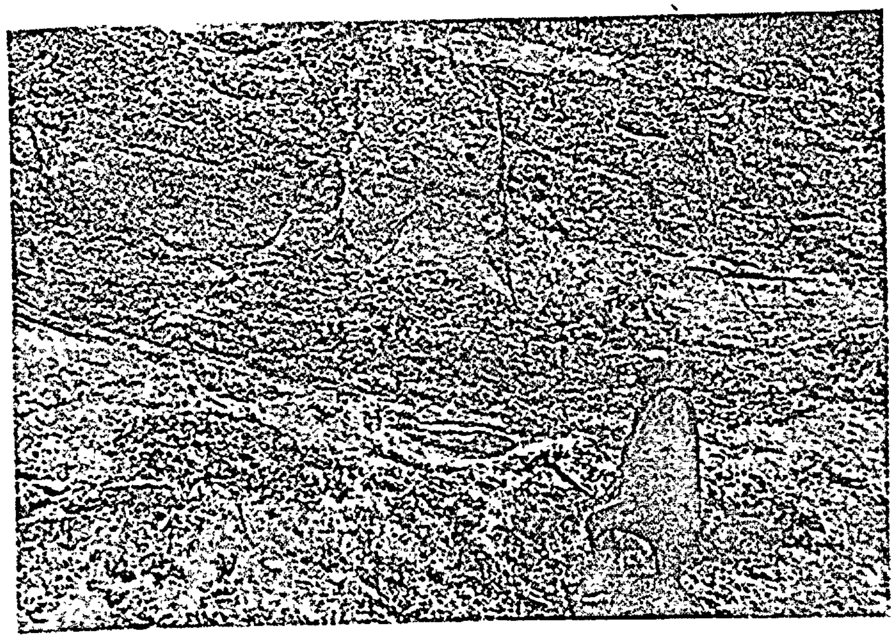

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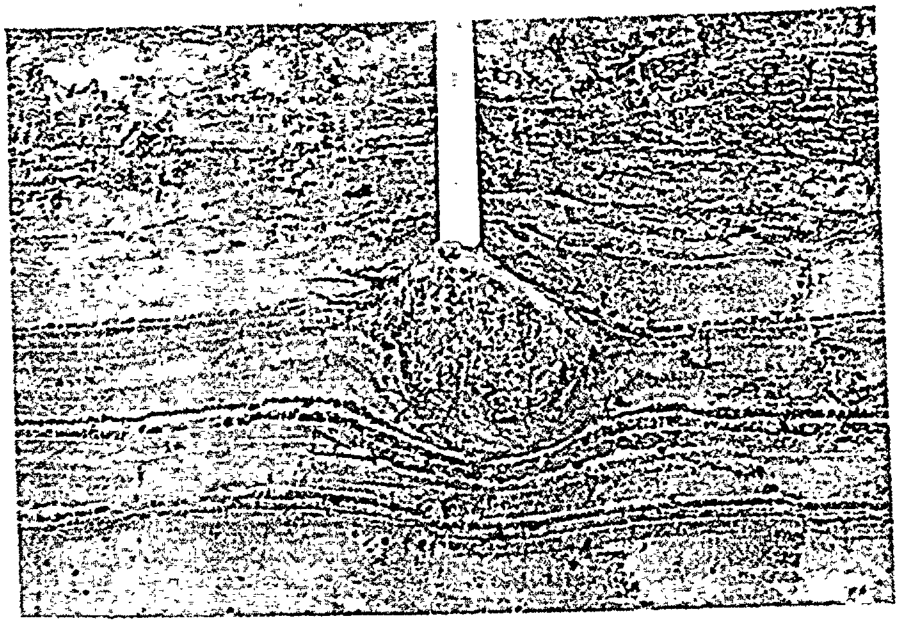


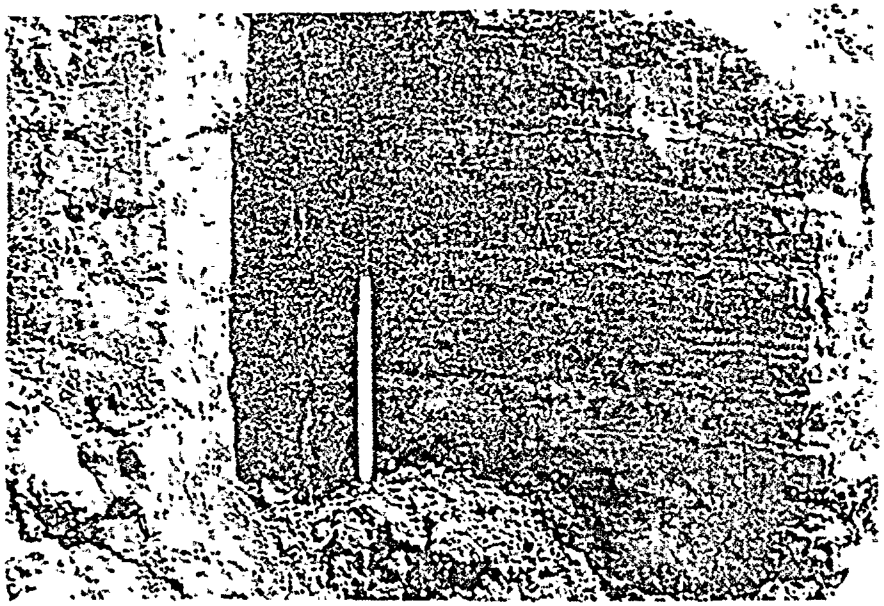
D-7

D-8

Fig. D- 9 (locality 14). Varved sediments in the Barrett Quarry. Laminae show small scale deformation. Total thickness of this varved section is 8 ft. which rests on Fort Covington till (Fig. D-2).

Fig. D-10 (locality 1). Weathered surface of varved sediments that occur near top of 25 ft. section of proglacial lake beds formed during Fort Covington time. See also Figure D-6. Light colored clasts are rock flour units that were incorporated as distinct masses.

Fig. D-11 (locality 19). Landslide scars adjacent to Grass River near Massena. They formed by river undercutting the base of the Champlain Sea Clays which constitute the rotational blocks.



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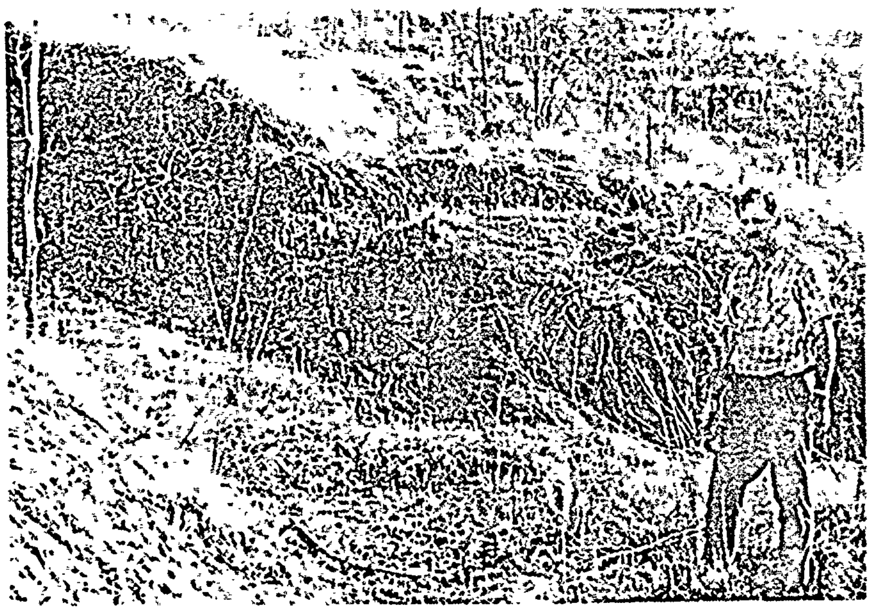

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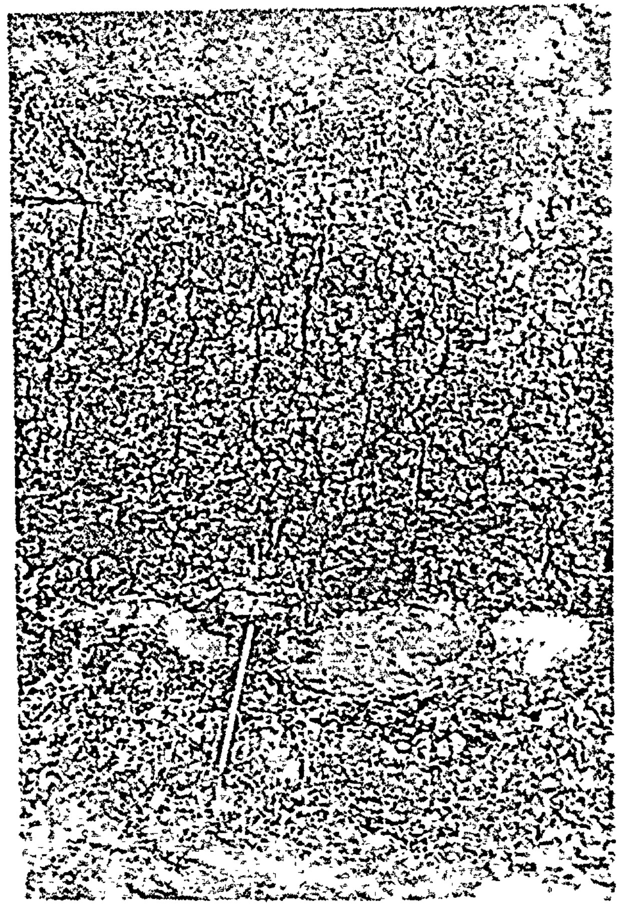


D-10

at the toe of the slope (Harrison and Misiaszek, 1971). Many have continued to occur since the Massena earthquake of 1944, and there appears to have been no earthquake triggering in the last 31 years.

PLEISTOCENE STRATIGRAPHY

This part is an integrated analysis of our St. Lawrence work and previous reports, and provides a regional view of glacial events during late Wisconsinan time. It has been necessary to develop this synthesis so that a chronological framework could be placed on observed deformational events.

The St. Lawrence Lowland has been studied in varying degrees for more than 70 years in both the United States and Canada. Only since the advent of radiocarbon dating has absolute chronology been possible. Utilizing the results of the present study and those of previous workers, both locally and in Canada, a fairly detailed model for the deglaciation of the upper St. Lawrence valley has been constructed. This model contains many complex events that include variations in lake levels, and position changes of the ice margin. It also accounts rather simply for directional changes in ice movement and for variations in till fabric and composition.

Three general physiographic sections (Fig. D-12) are involved in the development of this model. They include the Southwest Tablelands, the Frontenac Axis Precambrian region, and the Winnowed Till or oriented till ridges of MacClintock and Stewart (1965).

With retreat of ice away from the Adirondack Upland, ice ceased to be channeled southwest down the St. Lawrence Lowland. This permitted a glacial flow pattern from the north, which corresponds with the outflow centers suggested by Flint (1959). We interpret the Malone drift and striae directions reported by MacClintock and Stewart (1965), and substantiated by our work, to the channeling of ice around the northern Adirondacks. The Fort Covington glaciation then becomes an event associated with the subsequent northward retreat of ice during the same glacial stade, instead of a separate glaciation. Thus, the Fort Covington border of MacClintock and Stewart (1965) represents a zone of ice direction shift instead of a new readvance position. This interpretation is consistent with field evidence and the regional flow patterns indicated by McDonald and Shilts (1971) and Flint (1959).

Gadd (1971) suggests that the middle St. Lawrence Lowland was covered by ice for a 40,000 to 50,000 yr. period, from 12,000 to 65,000 yrs. B.P. He refers to this as the Gentilly Stade and considers the formation of the Drummondville and St. Narcisse moraines in Canada, along with the associated flooding of the St. Lawrence Lowland, to represent closing phases of the Gentilly Stade. Although several interstades may have occurred in the upper St. Lawrence Lowland during Gadd's Gentilly interval, no direct evidence to confirm or disprove has been observed. In fact the same negative evidence used by Gadd to support his contention of a long time span of ice coverage also applies to the upper St. Lawrence valley. Gadd (1971) believes

Gentilly ice advanced into proglacial Lake Deschaillons some 60,000 yrs. B.P. This makes it likely that the Malone ice, a Gentilly equivalent, also advanced into some form of proglacial lake, most probably a continuation of Lake Deschaillons. This could help explain many of the features described by MacClintock and Stewart (1965) in their Malone till sections.

The Champlain Sea

MacClintock and Stewart (1965) report three major lake levels in the upper St. Lawrence valley: (1) a 1,000 ft. level corresponding to the Covey Hill gap (which they interpret as Lake Iroquis); (2) a 700-730 ft. Lake Fort Ann level; and (3) a 500-530 ft. Champlain Sea level.

Other than a few deltas and some high level drainages, little evidence can be mustered to support the 1,000 ft. level as representing any more than a short-lived phenomenon when the ice stood at the Highland Front Moraine and abutted against Covey Hill.

The 700-730 ft. Lake Fort Ann level of MacClintock and Stewart (1965) can not be correlated west of the upper St. Lawrence Valley at this time. If as Connally (unpublished manuscript) suggests, that the ice margin responsible for the Highland Front Moraine occurred at the north end of the Champlain Valley, then Lake Fort Ann was confined to the Champlain Valley as originally defined by Chapman. This makes the Lake Fort Ann of Stewart and MacClintock an early local lake or possibly correlative with an early pre-Iroquois level and the overflow at Covey Hill gap a spillway into Lake Fort Ann in the Champlain Valley as originally suggested by Chapman (1937).

Karrow, Clark, and Terasmae (1961) believe Lake Iroquois to be short-lived and report dates from Lake Iroquois sediments of 12,600 ± 400 and 12,080 ± 300 yrs. B.P. to the west. When compared to Gadd's (1975) 12,800 to 10,200 yrs. B.P. span for inundation of the St. Lawrence valley by marine Champlain Sea waters (Fig. D-13), this makes the Lake Iroquois of Fairchild (1918) and Karrow, Clark, and Terasmae (1961) time equivalent with the Champlain Sea. A re-evaluation of Fairchild's (1918) and the MacClintock and Stewart (1965) lake level data as well as additional information from Chapman (1937) and Elson (1968) supports this conclusion (Fig. D-14).

With the retreat of ice away from the Highland Front Moraine the Champlain Sea was formed by a marine inundation of the lowland. A variety of evidence supports the presence of the ice margin as forming the northern margin of the lake during at least part of the life of the Champlain Sea (Elson 1969; Karrow, Clark, and Terasmae 1961, Gadd 1975; this study). With retreat of Gentilly ice front (Fort Covington phase) the Champlain Sea expanded westward into Lake Iroquois. Both the Drummondville and St. Narcisse moraines to the northeast and the winnowed till ridges in the upper St. Lawrence valley were built into

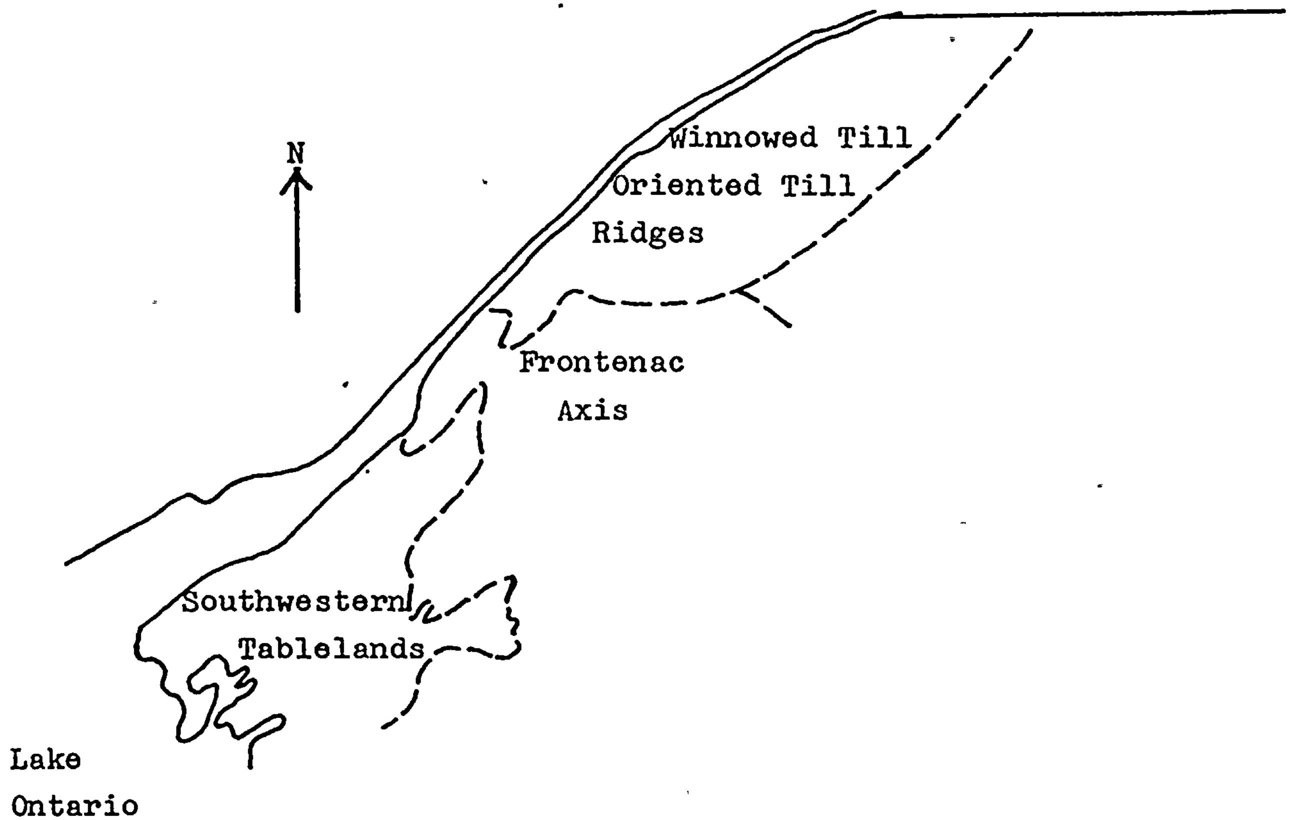


Figure D-12. Index map of the physiographic subsections.
Modified from MacClintock and Stewart 1965.

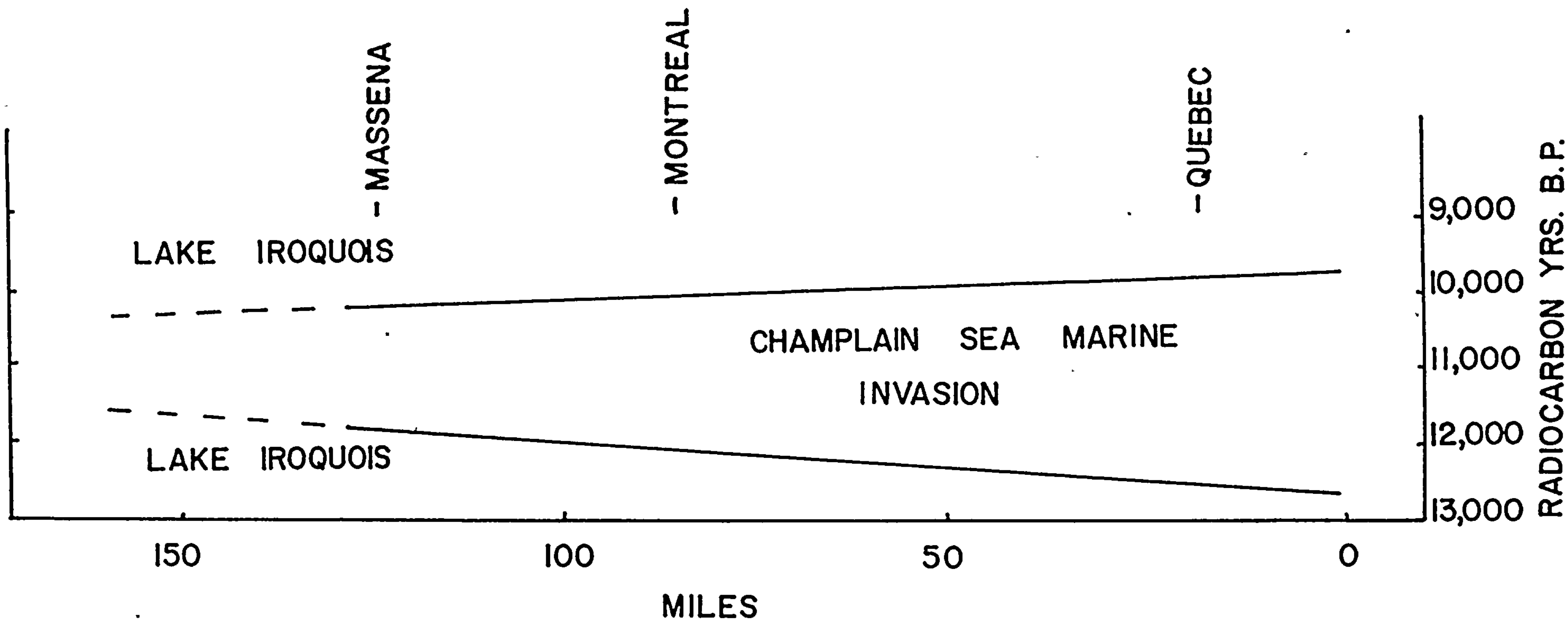


Fig. D-13. Time-transgression diagram of the Champlain Sea marine waters into Lake Iroquois.

this expanding lake-sea environment. The maximum extent of the invasion in the study area is unknown but fossil evidence (this report), places it as far west as the Potsdam-Norfolk area and possibly as far west as Alexandria Bay (J. S. Street, personal communication).

We suggest that the lowering of the lake level from 730 ft. to 500 ft. took place during the retreat of the ice from the upper St. Lawrence valley approximately 12,800 yrs. B.P. The marine invasion took place in the upper St. Lawrence valley between 10,000 and 12,000 yrs. ago as indicated by dates on marine shells of 10,340 ± 130 yrs. B.P. east of Fort Covington, 12,000 ± 200 yrs. B.P. from Champlain Sea Clay in downtown Massena (Locality 21) and 11,000 ± 160 yrs. B.P. from reworked sands overlying winnowed till northeast of Norfolk (Locality 16).

TYPE LOCALITIES

The following locations were selected for further study so as to compare differences in the style and process of glaciation in the eastern or winnowed till section with the southwest tablelands section. These two areas are separated by the Precambrian Frontenac Axis.

Clayton-LaFargeville Area

The area extending from Clayton to LaFargeville is typical of the southwest tablelands. Here numerous exposures of kame deltas contain deformed structures in their sandy units (Chapter 2). These exposures also show a wide variety of till types including small units of angular till incorporated in the drift, subangular to subround flow tills, and subround to round ablation tills. Three types or modes of origin for these deposits are proposed: (1) the more angular and smaller bodies of till incorporated within the drift were formed either by deposition from floating icebergs or from off the base of floating shelf ice, (2) the subangular to subround "flow tills" were deposited by gravity flow off the front of the ice margin, and (3) the subround to round upper tills by ablation of overriding shelf ice. We suggest that the glacier in this area was less active than in the Ogdensburg-Massena winnowed till area to the east, and that it was fronted by considerable amounts of shelf ice.

MacClintock and Stewart (1965) describe this region as one of ice retreat by calving. They use this to justify the general lack of large till bodies, large exposures of bedrock, close relationship between surface and bedrock topography, and the predominance of lacustrine deposits lying directly on bedrock. While they may be partly correct, the lack of deposits in this region is also due to the paucity of easily erodable materials. This region is just southwest of the Frontenac Axis crystallines which offer resistance to easy ice erodability thus fewer materials were incorporated into the glacier for possible later deposition in the southwestern area. Even so the small angular till units incorporated in some of the gravels, such as those found in gravel pits west of Clayton, (Locality 1), contain a high percentage of crystallines that were probably derived locally at the base of the ice sheet.

Our suggestion for floating active ice in this region indicates a higher lake level during this phase of retreat than farther to the east. We believe this to be the 700-730 ft. level of MacClintock and Stewart (1965). With terrain elevations of 250 to 400 ft. this provides for thickness of floating ice of about 350 to 500 ft. if a 1.00/.9 ratio for the specific gravity of water to ice is used. This would be sufficiently ample to produce the observed sediment features in this region.

Norfolk Winnowed Till Ridge

Numerous sections were examined in the northeast part of the Norfolk quadrangle (USGS 1:24,000) to determine the mode of deposition of winnowed till and its relationship to overlying sands. Location 16 was chosen due to the large number of exposures, their continuity, and the availability of subsurface information provided by gravel pit owner-operator Gerald Michaud. The Norfolk winnowed till ridge was particularly useful due to the abundance of marine fossils associated with the reworked sand unit (Fig. D-15).

The ridge is oriented about N 75°E or roughly perpendicular to the flow of Fort Covington ice. The ridge is typical of such ridges in an 18 mile belt between Ogdensburg and Malone. MacClintock and Stewart (1965) considered these ridges to be morainal in character and that the tops had been lowered some 30-40 ft. during the winnowing process. Since these ridges are composed of Fort Covington drift, it is reasonable to assume that, (1) they were deposited by the retreating Fort Covington glacier, and (2) they were deposited against some type of bedrock topographic high as occur in other parts of the upper St. Lawrence Lowland. Although a bedrock core was not seen in this particular case it is common for the location of such moraines to be topographically controlled.

The ice that formed the winnowed till ridges was of a different character than that which formed the deposits in the Clayton-LaFargeville area. That it was grounded, and not floating, is suggested by the type of deposit and by the presence of p-forms, subglacially formed fluvially scoured bedrock forms, on the Frontenac Arch. The most logical method for lowering the ice at the glacial terminus into contact with the bedrock is to have a lake level drop. A drop from 700-730 to 500-550 ft. would accomplish this, grounding all ice more than 220-250 ft. thick.

The winnowed till in the Norfolk region is poorly sorted ranging from boulders 2 ft. across to pebbles and cobbles (Fig. D-16). It displays a general lack of fines and sometimes displays some semblance of stratification. Striations are common on boulders within the winnowed till. The till grades southward into stratified gravels and then into a light brown sand (Fig. D-15). The sand overlies a more silty unit which in turn overlies varved clays. Taken as a total sequence the winnowed till ridge shows the effects of two processes: (1) winnowing of the till during deposition by wave and current action, and (2) the redistri-

bution of the winnowed fines by both wave and wind action (Figs. D-15, D-17). A date of 11,000 ± 160 yrs. B.P. was obtained on marine shells associated with the reworked sands indicating that much of the reworking took place during the Champlain Sea episode. It should be noted, however, that light brown sands abundantly occur throughout the upper St. Lawrence Lowland and can have many modes of origin other than from the winnowing of till, and can be of nonglacial origin. They possess in common a reworking by both wave and wind action.

The winnowed till region represents a series of moraines deposited into Lake Iroquois waters and are time equivalent or intermediate to the formation of the Highland Front and St. Narcisse moraines deposited into transgressing marine waters to the northeast in Canada.

HOLOCENE SEDIMENTS

The major types of Holocene sediments found in the St. Lawrence Lowland are, (1) wetland deposits (bogs, marshes, lakes) which invariably have high organic content, and (2) alluvium which includes channel fill and overbank sediments. Wetland deposits are probably not suitable indicators for seismic events because of the difficulty in attempting to separate contortions caused by bioturbation and normal sedimentary processes for possible seismic-induced deformation. Alluvial deposits have been examined for many years by members of the investigative team, and the consensus reached is that they hold little promise for determination of earthquake-related thixotropy events. For example Kirkland (in a present ongoing joint geological-archeological study in the Susquehanna River) has shown deposits of this type do not retain their original bedding configurations. Various types of bioturbation, soil-forming processes, and flooding phenomena conspire to alter surface materials.

The St. Lawrence Lowland does not have the type of man-made reservoirs or recently formed lakes, as in California, which can supply a record of late Quaternary history.

STRATIGRAPHIC SYNTHESIS

It is impossible and presumptuous in the limited time and scope of the present project to solve problems of chronology that previous workers during a 70-year period could not resolve. Therefore the following observations must be viewed in the context of presenting reconnaissance field observations that may give promise for development of a time scale of events.

1. The Malone and Fort Covington drifts represent phases of Gadd's (1964, 1971) Gentilly stade.

2. The Fort Covington readvance of MacClintock and Stewart (1965) represents a retreatal phase of the Gentilly stade.

3. The western end of the study area can be characterized by a higher lake level permitting the construction of many large complex kame deltas containing a wide

variety of ice-contact and till features such as found at the Clayton, LaFargeville, and Watertown sites. (The Colwell Delta also stands at the 700-730 ft. level, see Chapter 4).

4. The lowering of lake level in the upper St. Lawrence Lowland to 500 ft. occurred when the ice margin was in the vicinity of the Frontenac Arch.

5. As the ice retreated away from the Highland Front moraine, marine waters transgressed into the St. Lawrence Lowland beginning about 12,800 yrs. ago, and terminating about 10,000 yrs. ago.

6. The winnowed till ridges in the Ogdensburg-Massena area form a sequence of moraines created by retreating Gentilly, (Fort Covington), ice. They constitute a series of moraines intermediate between the Highland Front and St. Narcisse moraines to the northeast in Canada.

7. Two important shoreline positions have been established for the region, a 700-730 ft. Lake Fort Ann level, and a 500-530 ft. Champlain Sea level.

8. The Lake Iroquois level of about 1,000 ft. reported by MacClintock and Stewart is incorrect. Instead the Lake Iroquois event is more closely associated with the Champlain Sea episode.

9. Deformed sections that occur in the Watertown (Colwell Pit) Gouveneur (localities 9, 10, 11) and Clayton-LaFargeville (localities 1, 2, 3, 4, 5, 6) are associated with the Fort Covington phase of ice retreat and probably date about 12,500 yrs. B.P.

10. Deformed sections located in the bottomset part of the Constable delta (locality 18) belong to the Fort Ann Lake stage of MacClintock and Stewart (1965).

11. The deformed structures located in the Canton delta are found near the delta front and can be interpreted to have formed near the close of deltaic sedimentation into the Champlain-Iroquois 500-530 ft. level.

12. The varve sediments overlying Fort Covington till in the Barrett Quarry (locality 14) are Champlain Sea equivalent as demonstrated by the presence of marine fossils. They probably date about 12,000 yrs. B.P. by correlation with the Massena clay section.

13. Analysis of varve sediments may aid in developing a chronology if the sediment couplets can be proved to represent annual deposition. The use of field localities such as 8 and 14 as well as study of boring cores in the Ogdensburg and Massena-Fort Covington areas (such cores are available at the Atlantic Testing Laboratory, Canton, N. Y.) might provide significant correlations of deformed units. Some of the cores penetrate as much as 60 ft. of varved sediments and many show thicknesses more than 20 ft. If couplets indeed represent yearly cycles then a detailed chronology of many hundred of years can be obtained.

14. Sediments in localities 2, 3, 4, 5, 6, 9, 10, 11 and 18 were all deposited into the 700-730 ft. lake level of the Lake Fort Ann episode and thus predate the formation of the Champlain Sea (locality 12, 13) which occurs at the 500-530 ft. level. These events are separated by a 2,000 yr. time span, thus providing an indicator for measurements of recurrence intervals. In addition the Colwell Pit at Watertown displays deformational structures at several levels, as do those in the Canton area. Small-scale deformities occur in varve clays and many of these show couplet contortions that are possibly separated by only several years. Additional work must be done to determine if the varves are annual and if the deformities are normal sedimentologic structures. If rate of sedimentation can be determined in some of the large exposures, then another tool can be added to aid in calculation of times between deformational events. For example at least four different deformed sequences occur in several areas, such as locality 13.

The main question that still remains is the separation of those contorted sediments that were formed by glacial and ice-related processes, and those that are not glacially related. A further question concerns whether the nonglacial deformed sediments were caused by processes other than earthquake shocks. Interpretation of the evidence presented in Chapters 3 and 4 suggests that the majority of deformed sediments <u>can</u> be attributed to glacially related events. The principal problems now remaining are concerned with detailed investigations to determine (1) criteria that are necessary for separation of glacially and tectonically induced events, and (2) if particular important deformational structures noted in this report are found in non-tectonically-active glaciated areas.

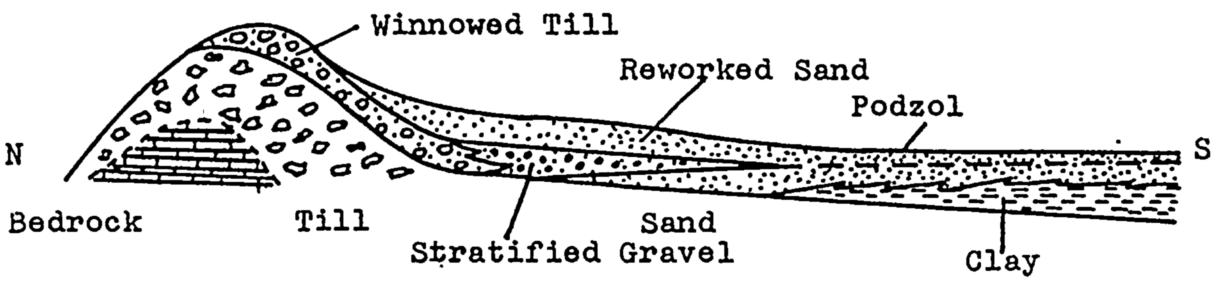
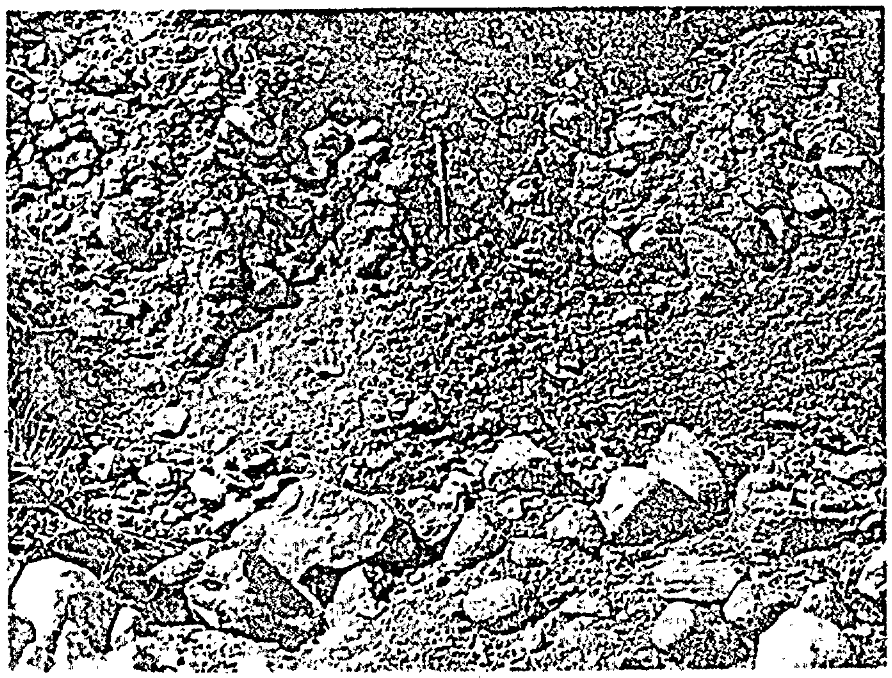


Figure D-15. Diagrammatic cross section of winnowed till ridge Locality 16

Figure D-16. Winnowed till exposure in the Norfolk winnowed till ridge (locality 16.)

Figure D-17. Winnowed till with overlying reworked sands.

D-16



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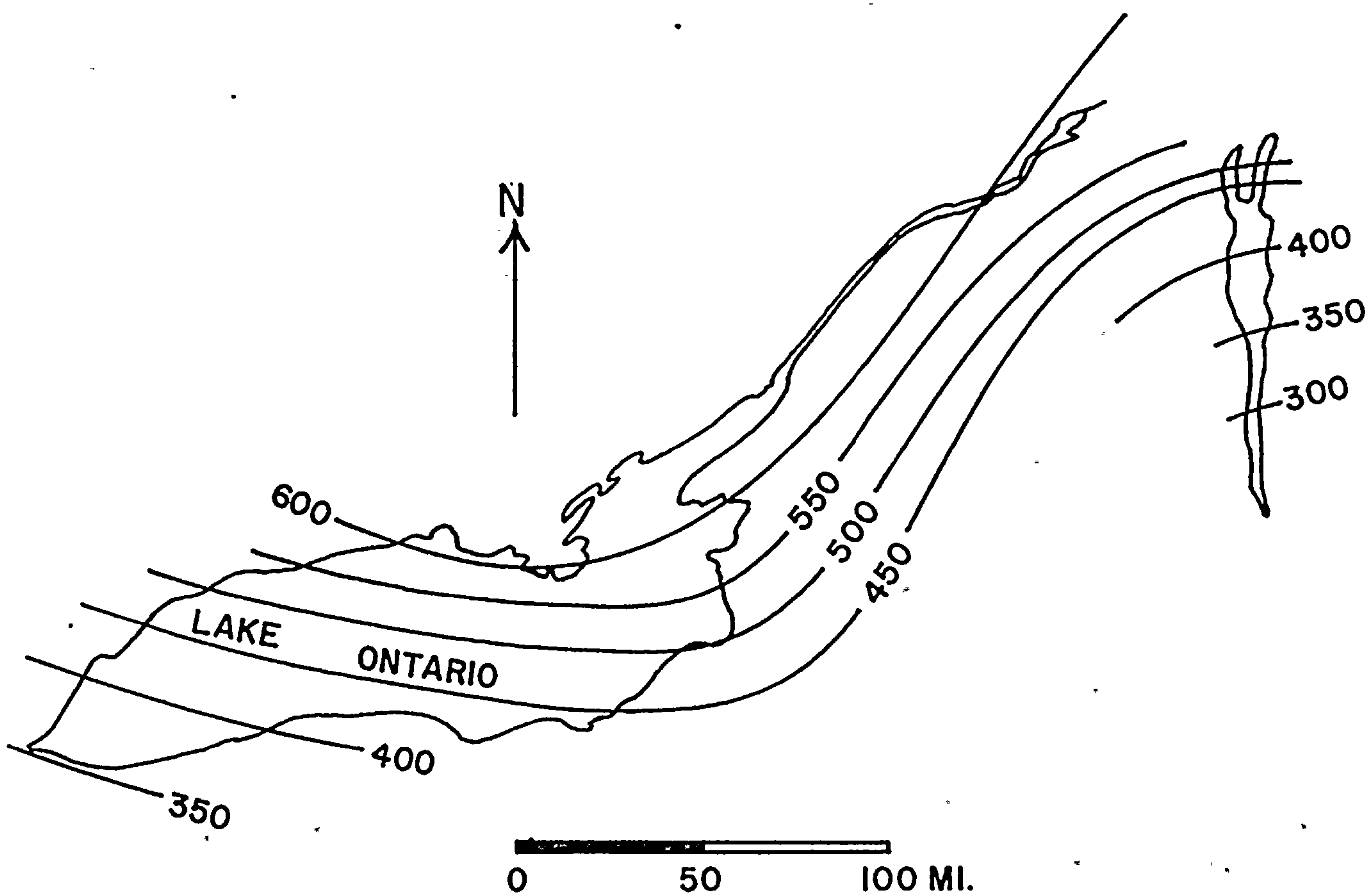

Figure D-14. Isobases of the northern New York region drawn on the upwarped surface of Lake Iroquois and the Champlain sea.

APPENDIX E

REPORT ON ST. LAWRENCE PROJECT[1]

INTRODUCTION AND CONCEPTS

Project Has Met Its Objectives

The purpose of this project to identify deformational structures in the St. Lawrence River Valley and their relation to seismic events has been well served by location of numerous deformational structures and development of criteria to determine their origin from seismic or non-seismic causes.

Multidisciplinary Approach Justified

The complexity of differentiating seismic from other origins for deformed sedimentary structures has also been confirmed, and the need for multidisciplinary analysis has been justified. Geomorphic definition of the environmental settings, stratigraphic interrelations with deposits over and under deformed units, and detailed analysis of the deformational structures appear to be the three essential ingredients in analysis of the deformational origins.

Contrast to California Sediment Deformation Sites

Another important variable that was recognized in the proposal and has been most significant, is the contrast in sedimentary environments between California and New York. The western desert mountain and basin terrane has produced circumstances different from the temperature climate, low relief glacial terrain of New York. Though finer grained silt beds may yet be located in New York through further field work, the sediments available for evaluation through this quick reconnaissance are more coarse, and much more complex for lateral correlation than those of California.

---

[1] Prepared by Dr. Leonard Palmer, Consulting Geologist, Portland State University, Portland, Oregon

No glacial generated complexity was present in the sites I visited at San Fernando and the Salton Sea. In the environment of the California localities there were: (1) no sudden water level changes, (2) no ice lens melting, (3) no glacial pushing, (4) no rapid water velocity currents, (5) no contrast in sediment strata composition, (6) no great changes in depositional environment, (7) no temperature contrasts over freezing temperature of water.

On the other hand, the California sites do have well documented seismicity in the area of deposition. It was exceptionally useful for me to be able to visit both the California and New York localities for first hand comparison. Many environmental and physical characterisitcs needed to be determined so that similarities and dissimilarities of distorted Quaternary sediments could be more adequately evaluated.

Comparative Sedimentary and Physical Principles

Though the environment in New York contrasts considerably from that of California, and a little from that of the Olympic Peninsula --- the factors controlling sediment deformation can be compared.

Universality of measurable physical characteristics and physical response of sediments provides a way for comparing the criteria of one area with another.

The response of sediment particles to the conditions in the depositional environment can be evaluated and compared. Factors which can be recognized or measured and used for comparison include: (1) particle characteristics within sedimentary units, (2) sedimentary structures, (3) interretations of the various units or beds, (4) characteristics of the environmental unit in which the deposit occurs (i.e., delta, kame, lake beds).

The particles display various characteristics such as size, shape, texture and mineralogy which determine other physical properties of the deposit such as:

(1) porosity
(2) permeability
(3) shear strength
(4) liquefaction response to applied forces
(5) thixotropy
(6) density
(7) fabric-texture

The genetic origin of a given deformed unit can be studied by determining the characteristics of the (1) environment of deposition, (2) interrelation of units and their physical distribution and size, (3) the sedimentary structures within individual units and (4) the particle characteristics. Characteristic features can be used to define the possible origins, or at least to exclude possible origins incompatible with the evidence.

SEDIMENT DEFORMATION

Types of Sedimentary Deformation

Deformation of Quaternary sediments, can result from several different processes including: (1) collapse (ice melt), (2) compaction, (3) glacial push (or overriding), (4) density (load deformation), (5) hydraulic forces (differential pore water pressure), (6) seismic, (7) current drag (surface water currents), (8) gravitational downslope movement, and (9) air entrapment. Recognition of the type of deformation may be best performed by experienced sedimentologists. Some fabrics are easily recognized with minimal examination, but others have characteristics which do not exclude genesis by several different processes.

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SEDIMENT DEFORMATION

Types of Sedimentary Deformation

Deformation of Quaternary sediments, can result from several different processed including: (1) collapse (ice melt), (2) compaction, (3) glacial push (or overriding), (4) density (load deformation), (5) hydraulic forces (differential pore water pressure), (6) seismic, (7) current drag (surface water currents), (8) gravitational downslope movement, and (9) air entrapment. Recognition of the type of deformation may be best performed by experienced sedimentologists. Some fabrics are easily recognized with minimal examination, but others have characteristics which do not exclude genesis by several different processes.

Criteria for Determining the Originating Mechanism

I think the mechanism which has caused sediments to deform may be recognized by characteristics of the following: (1) environment of deposition, (2) adjacent bedding characteristics, (3) sedimentary structures, (4) sediment particle characteristics. It should be possible to determine the origin of most sediment deformation if the above characteristics are known. There may be other clues known to experienced sedimentologists, but most of the deformation seen in New York and California presented characteristics which seemed to me to eliminate most of the ambiguities.

Data Needed

Although a fair identification of mechanism for deformation can now be made, it would be much better in future work to be able to derive the amount of force needed to produce the various forms. The environment could then be evaluated to see if there is enough driving force in factors such as: - hydraulic head differential between beds - dip-or depositional slope - shear strength of sediments - density contrasts of sediments - texture and grain packing - seismic acceleration, etc.

It is not enough to say a given mechanism can or could cause the deformation of sediment without determining whether adequate forces are plausible for field conditions at a given site. Table 1 provides a check list matrix that might serve as a guide for indexing and relating probabilities for determination of sediment deformation origins.

SUMMARY OF INTERVIEW WITH JOHN D. SIMS

The following statements provide my synopsis of discussions I held with Dr. John D. Sims, U.S. Geological Survey, at Menlo Park, California on March 24, 1975.

Question 1. What kind of sediment records earthquake shaking structure?

A. (1) Fine-grained sediments are very important indicators.

(2) The sediment should be saturated at time of shaking.

(3) Silt is best to keep scale of sedimentary structures small enough to recognize and less distortion is generated than with sand.

Example: The 1906 San Francisco earthquake produced large scale structure (6 to 8 feet) in which spreading wipes out the event record, produces dikes and sills and cross cutting features too gross to show individual events.

(4) Fine silt with a bit of clay layers less than 10% to 15% is best. Clay helps hold the structure, or helps display the structure--but will not fail (liquefy) except with very strong event.

(5) Anticipated shaking response of silt can be extrapolated from the response of sand (as shown by the publications such as by Seed at Berkeley).

Question 2. What is the relation of the size and distance of an earthquake to the disturbance of sediment?

A. (1) Sediment structures provide a very conservative record of seismicity.

a. earthquake must be close--(less than 20 mi.- 30 mi.)

b. quake must be large--greater than intensity 6 modified Mercalli.

c. earthquake events closer than 10 year interval will obscure the record

d. sedimentation must be fast enough to provide a time record of events.

Example: Long Beach earthquake of 1933 was not preserved in Van Norman Reservoir (magnitude 6.5, distance 50 miles) perhaps by distance or by masking by 1930 earthquake structure.

e. if seismic record is found in sediment, it will be a minimum seismic history for engineering design.

(2) The style of sedimentary structure may change with the intensity of shaking.

Question 3. What type of lake and what drainage basin characteristics will produce sediment with potential for recording earthwuake shaking?

A. (1) For early results, lake bottom sediments may give a low return on effort invested.

(2) A record of continuous sedimentation is desirable for a time scale of seismic events.

(3) The size of sediment should be appropriately fine grained.

(4) Temperature is best cold to reduce organism stirring of sediment.

(5) Depth of water is best deep. Shallow water may have more sediment disturbance.

(6) Exposed varve sedimentation in outcrops with silty deposits should yield the best results, most quickly.

(7) Plants and animals can stir the bottom and destroy the seismic structures in the sediments.

Example: Clear Lake was a poor choice of seismic structure investigation because of the depth and temperature and organic activity. (The study was instigated

exploration but now could be recognized as a poor site.)

Puget Sound with its glacial lakes is a good location for investigation because of the cooler climate, varved silty sediments and earthquake history.

The logistics of drilling are very time consuming for the amount of material that can be observed. Lake drilling should be done in later stages of a project when time is not critical.

(8) Examination of stream sediment sizes and rate of contribution to a lake might help locate proper continuity and size of sedimentation. (This may be part Palmer idea, not Sims?)

Question 4. What study techniques of sediments in the field?

A. (1) Do detailed sediment descriptions from outcrops first.

(2) Use careful description of structures as by sedimentologists--(glacial stratigraphers work too fast with regional view for unit origin). Should spend several hours at an outcrop.

(3) Sims:

a. cut a block of sediment

b. pack for shipment to lab

c. saw with a carpenter's hand saw into slab

d. impregnate with Elmer's glue + 50% water

e. dry about 1 day (California dry air time?)

f. x-ray slabs 1 cm or less thick

(4) Reference on sediment description methods, use a system such as described by Sloss and Dapples.

(5) Sims did complete surficial mapping of Van Norman Reservoir.

Question 5. What laboratory techniques used?

A. (1) See Bouma, Arnold H. (1969), Methods of the Study of Sedimentary Structures, Wiley Interscience.

(2) Kuenen's experiments were good, but were not treated seriously by Kuenen. (1958) "Experiments in Geology," Geol. Mag., Vol. 23, pp. 1-28.

(3) Some reproduction of seismic structures might be profitable in the lab for comparison of style of deformation under varying shaking. (This comment by Palmer).

FIELD WORK IN CALIFORNIA AND WASHINGTON

March 26-31, 1975, I studied, photographed, and collected specimens from sites in California which J.D. Sims had used to document his interpretation that sediment deformation could be linked to seismic events.

1. Van Norman Reservoir, San Fernando, California.

The San Fernando earthquake of February 9, 1971 deformed the sediments of the reservoir floor. These were examined a year later by Sims and were found to contain the deformed layers of three earthquake events. See Figures E-1,2,5 which show the typical type of structures used in interpreting that this type of thixotropy resulted from seismic vibrations. Although the sediments were more contorted in some areas than others, deformation seemed to occur throughout a large and widespread area.

2. Salton Sea area, Brawley, California.

Sediments in this area were sampled from a locality about 5 miles southwest of Brawley. The deposits formed in ancient Lake Cahuilla and the deformed units were discovered by Professor Robert Sharp and have been described by Sims in his recent unpublished paper (given as a talk at Zurich). These

sediments have less shrinkage (see Figures E-6-8for general setting and sedimentary features) and less dry strength than those in the Van Norman Reservoir. This is due in part to the absence of higher percentages of clay or clay layers. Thus the Salton Sea sediments were composed of more uniform silt-size materials with minor parting surfaces. No contrasting bedding resistance was apparent.

3. Similarity of Olympic Peninsula and New York.

It may be useful to mention one other field locality used by Sims in his work, the Puget Sound area, Washington. Although I had previously visited the region, I was unable to revisit the area because of time restrictions of the present project. The glacial setting of the site makes it more attractive as comparison to the potential sites for possible seismic deformation in New York. Because of the similarity in structure to some observed in the St. Lawrence Lowland, I include pictures which Dr. Sims kindly permitted me to copy (Figs.E -3-4).

The Olympic Peninsula glacial lacustrine varve deposits described by Sims in his unpublished manuscript has produced the best record of seismic recurrence yet known. Though I have not examined Sims localities I am familiar with the glacial deposits there, and feel that they are enough like New York deposits to warrant an expectation that seismic recurrence history for New York areas may well be definable with an expanded and detailed future project.

The Olympic Peninsula similarities to New York include: (1) how relief glaciated terrain, (2) recessional ice lake present, (3) comparable climatic conditions, (4) sediment grain size ranges are comparable (many clay sands and gravels), (5) ice contact features are common. The contrasting environmental conditions include such features as the presence of adjacent high mountains (6000'-8000') in Puget Sound.

ASSESSMENT OF DEFORMED SEDIMENTS IN NEW YORK

Selected field localities in the St. Lawrence area were examined June 5-6, 1975, under the leadership of Donald R. Coates. The field party also included Paul Enos, Iaakov Karcz, James Kirkland, Robert LaFleur, William Lilly, and Warren Prell. Eleven localities were studied in pits, quarries, and outcrops, and they displayed an exceptionally large range of different types of deformation features. Although exceptions occur, New York sediments can be compared with California deformed sediments in the following general terms:

1. Most localities visited had only one major deformed unit. Although multiple distorted strata occur, they did not seem so common in New York.

2. The majority of the deformed units appeared to be at or near the present surface in New York.

3. The most commonly deformed strata were those of sand size material in New York, whereas in California finer-grained units were the rule.

4. The scale of deformed units in New York was larger than those in California by a factor of 5 to 10.

5. Deformation in New York sediments showed a much wider range of distortion types than in California.

6. There is ample evidence that in several of the New York localities thixotropy was a very important part of the deformed fabric. Determining the initiating mechanism, however, is much more complicated because effects produced by glacial processes must be sorted out from those caused by seismic influence.

Of the localities that were visited those in the Malone road cut (No. 18), west of Clayton (No. 1), and south of Canton (No.12) showed structures that contained the greatest similarity to those in California. Because of torrential

rains the large kame south of Clayton (No. 2) received only cursory study; however, it appeared that some of the features also had resemblance to California deformed sediments. In spite of strong glacial action in these sites, the possibility that some of the deformation was seismically induced cannot be ruled out.

SUGGESTIONS FOR FUTURE INVESTIGATIONS

Although there is a vast literature on liquefaction it is not clear that sufficient data is at hand to translate other studies of thixotropy and its relation to earthquakes to the smaller localized glacial landforms such as kames or local deltas. Thus it would be exceedingly important to know:

1. The relation of the magnitude of the earthquake with the distance to which liquefaction can occur. As part of this exercise a sliding scale might be developed for the force to cause thixotropy in sand is different than for silt or gravel.

2. The depth to which thixotropy can be anticipated when related to earthquake magnitude, and particle size would be another important factor to determine.

Additional St. Lawrence Studies

Other studies that might well prove useful to evaluate deformation or displacement in the St. Lawrence region include: (1) Additional search for lacustrine fine sands and silts with a continuity of time of deposition and of lateral extent. These might require extensive drilling, trenching, and lake bottom sampling and coring. (2) Vertical displacment of shoreline features across the St. Lawrence - preferably a well-defined level - perhaps from deltaic deposits related to a correlatable beach. (3) Pre-Pleistocene rocks should be searched for piercing points (J.C. Crowell, pub.) to define "displacement" [not just "offset"] along the St. Lawrence

in bedrock units. One should search for axes of folds, intersecting planes, unique lithologic units (intrusion?) offset by the St. Lawrence.

(Editor's Note: Dr. Palmer also included in his work: (1) a series of references, (2) Field notes, and (3) specimens of California sediments. These materials have been incorporated into the total framework of the project.)

Figs. E-1 to E-4. These photographs were generously donated by Dr. John D. Sims, U. S. Geological Survey, Menlo Park, California. Figures A-1 to A-3 occur in his preprint (Sims, in Press).

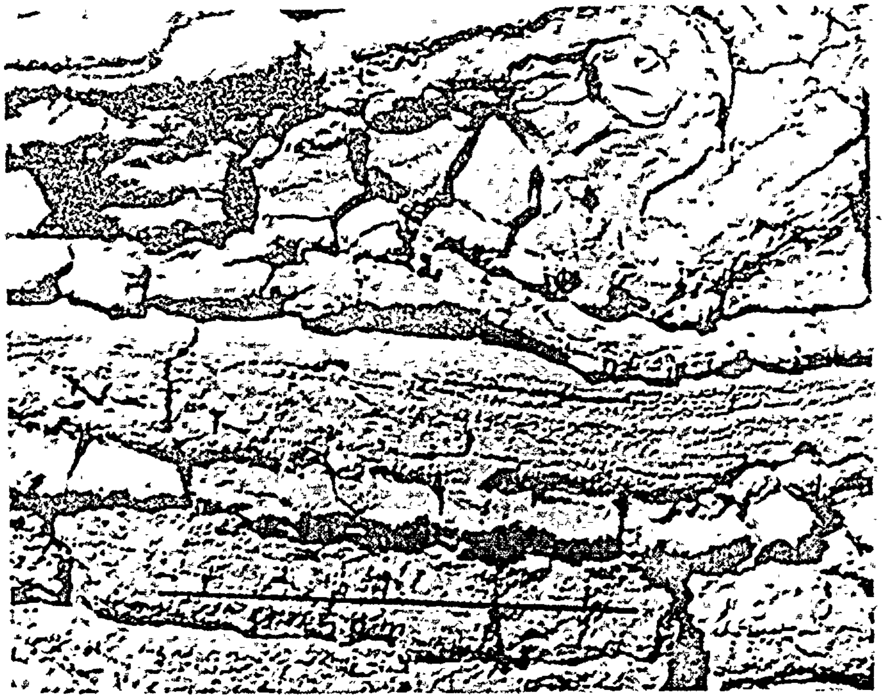
Fig. E-1. This is Sims' Figure 2B and carries the caption "Earthquake-induced deformational structures in sediments of Van Norman Lake, attributed to the 9 February 1971 earthquake. Small-scale recumbent fold".

Fig. E-2. This is Sims' Figure 3A and carries the caption "Earthquake-induced deformational structures in sediments of Van Norman Lake associated with the 21 July 1952 Kern County, California earthquake. Arrows show thickness of the zone. The triangual load case (1) is a deformed laminated mass that contains more clay than the host material (2)".

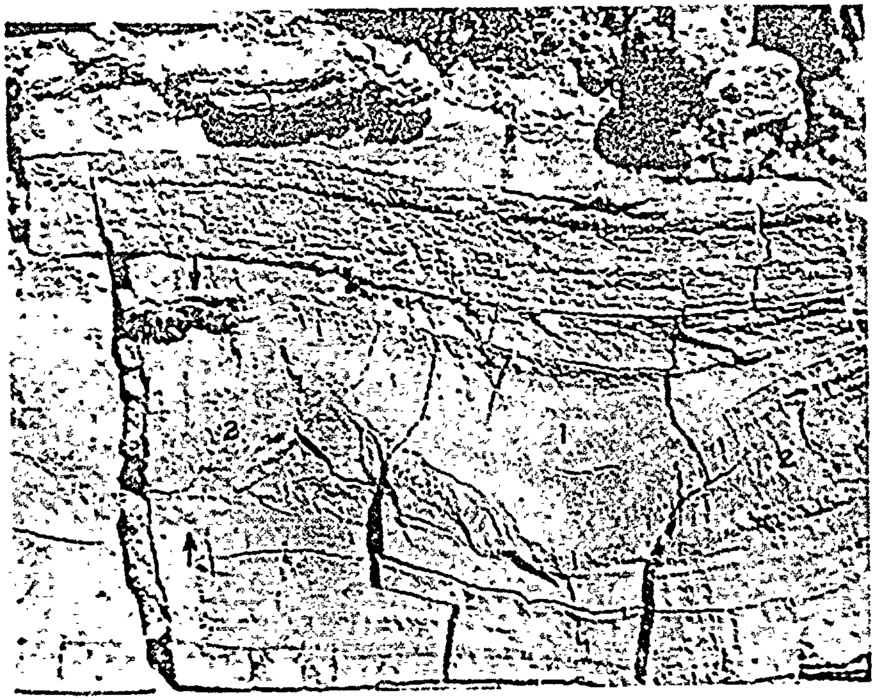
Fig. E-3. This is Sims' Figure 12 and the caption reads "Slope-failure structures in varved glaciolacustrine sediments along the Hood Canal (Olympic Peninsula, Washington). The slope along which these sediments slumped can be seen in outcrop and the structures easily interpreted at this locality".

Fig. E-4. This photograph was taken by Sims near the same locality as Fig. E-3.

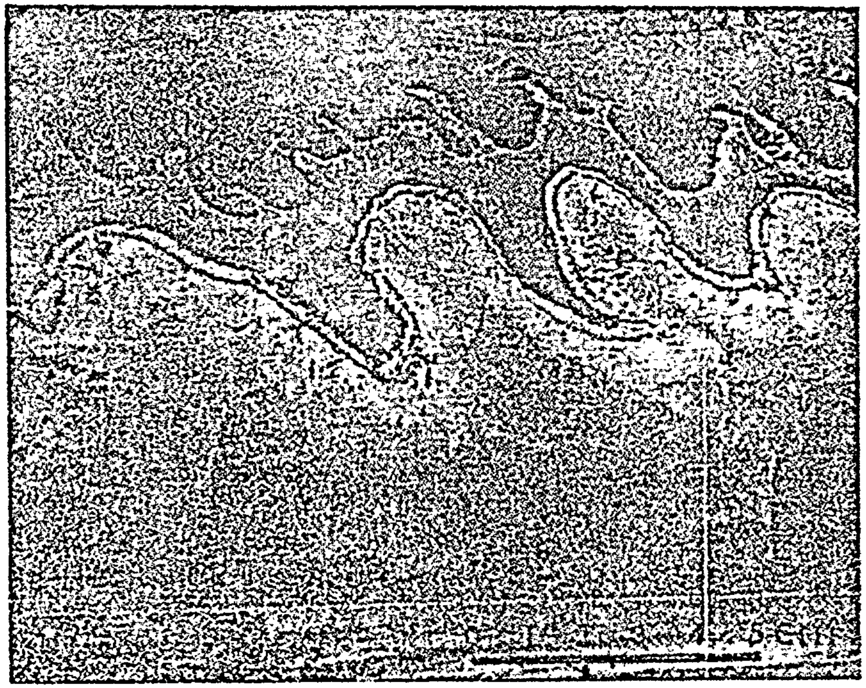
E - 1



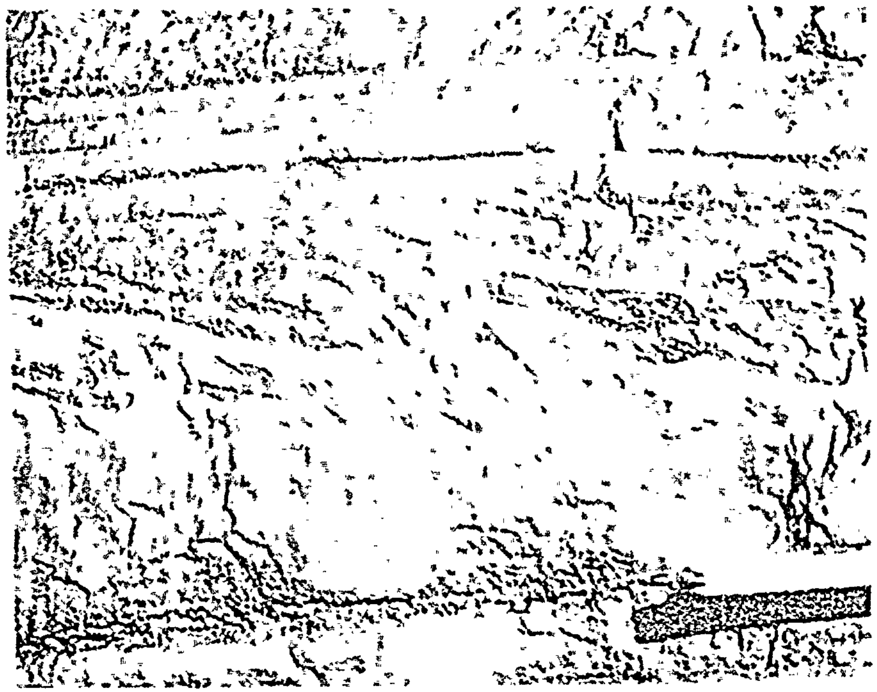
E - 2



E - 3



E - 4



Figs. E-5 to E-8. These photographs were taken by Leonard Palmer on March 25-31, 1975.

Fig. E-5. Van Norman Reservoir, California. Photograph shows severe dessication of the sediments with large mudcracks. The sections reveal highly deformed units interpreted as resulting from the San Fernando earthquake of 9 February 1971.

Figs. E-6 to E-8. They were all taken in the Brawley locality, California. Several zones of what have been interpreted by Sims as containing deformed sediments from earthquake events occur at this Imperial Valley site. The sediments were deposited into ancient Lake Cahuilla.

Fig. E-6. Shows ball and pillow structures with diapiric-developments. Long bar of ice axe is 1 in.

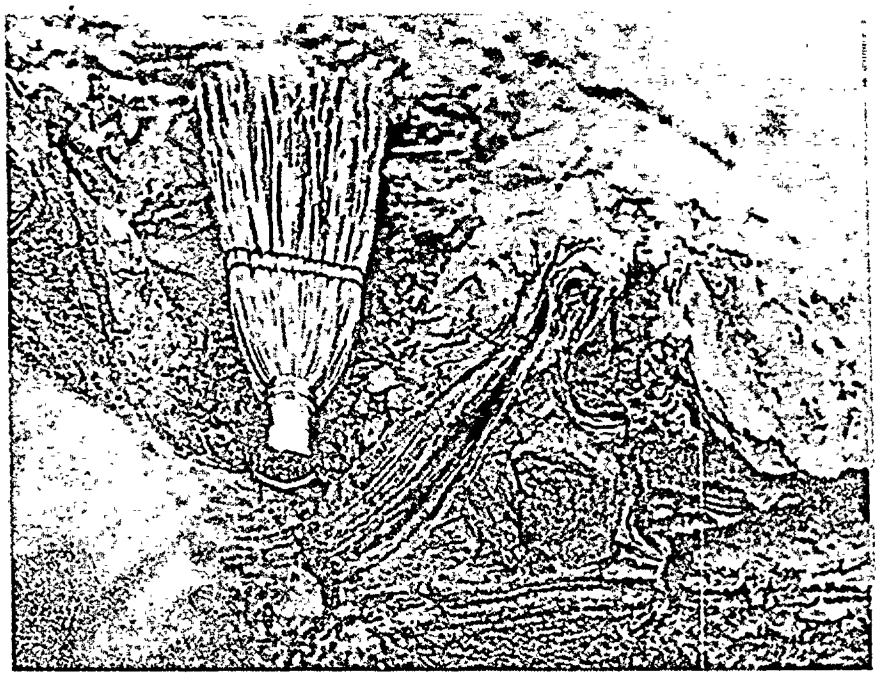
Fig. E-7. Shows antiformal structure in adjacent beds.

Fig. E-8. Shows structures similar to flow rolls and also contains a major diapir on left side of the middle contorted unit.

E-5

E-6

E-7



E-8

Table 1: SEDIMENT DEFORMATION PARAMETERS AND POTENTIAL CAUSATIONS

	Mechanical			Hydraulic Air Entrapment			Liquefaction	
	compaction	glacial push	collapse	compaction	gravity (down-slope flow)	current drag	local	seismic
Sediment Structure								
a. slow (plastically deformed clay, faulted sand)								
b. fast (liquefaction of sand, broken clay)								
c. hydraulic eruption (air, water, "volcano", density)								
d. orientation: good								
some								
none								
e. local								
f. wide lateral extent								
Adjacent Bedding								
a. density: contrast								
uniform								
b. grain size: high variation								
uniform								
c. permeability: high contrast								
uniform								
d. lateral variations: high								
low								
Environment								
a. ice contact								
b. fluvial								
c. deltoic								
d. lacustrine/moraine								
e. beach								

APPENDIX F

LISTING OF PROJECT PERSONNEL

1. The following people are on the professional staff of the Department of Geological Sciences, State University of New York at Binghamton. They were responsible for the field work, the laboratory analyses, and writing the report.

Dr. Donald R. Coates
Dr. Paul Enos
Dr. Iaakov Karcz
Dr. David Kersey
Dr. James T. Kirkland
Dr. Marie E. Morisawa
Dr. Jorge Rabassa
Dr. James Sorauf
Dr. Francis Wu

2. The following SUNY-Binghamton students substantively contributed as field and laboratory assistants in collection and processing of data.

Donald Ash
Robert Gillespie
John Hobgood
Stephanie Kasza
Ina Levy
JoAnne Morreale
Fran Porebski
Lester Smith
Carol Terrana

3. Dr. Leonard Palmer, Consulting Geologist, Portland State University, Portland, Oregon.

4. In addition to the above, many support-line personnel in the Department of Geological Sciences assisted in clerical work, typing, drafting, and other technological services.

APPENDIX G

LIST OF PROFESSIONAL CONTACTS

Dr. James Street	St. Lawrence University
Dr. Ernest Muller	Syracuse University
Mr. Jeffrey Thew	Atlantic Testing Laboratory
Mr. Robert Brossoie	Atlantic Testing Laboratory
Dr. Frank Ravetta	SUC-Potsdam
Dr. Jan Teresmae	Brock University
Dr. Nelson Gadd	Canadian Geological Survey
Dr. Pierre La Salle	Quebec Department of Natural Resources
Dr. Elihu Yatsu	University of Guelph
Dr. John D. Sims	U.S. Geological Survey
Dr. P.L. LaRochelle	Laval University
Dr. Robert Lafleur	Rensselaer Polytechnic Institute

In addition various personnel from the following agencies supplied helpful information and data.

St. Lawrence County-U.S. Department of Agriculture, Soil Conservation Service

Jefferson County-U.S. Department of Agriculture, Soil Conservation Service

New York State Department of Transportation, Watertown Office

APPENDIX H
MICROEARTHQUAKE SURVEY AND MODERN SEISMICITY

As part of this project, we made a preliminary microearthquake survey in the Massena area. With the cooperation of Dr. Frank Revetta at Potsdam we installed three stations: (1) Long Sault Dam, (2) Massena Airport and (3) water intake #2.

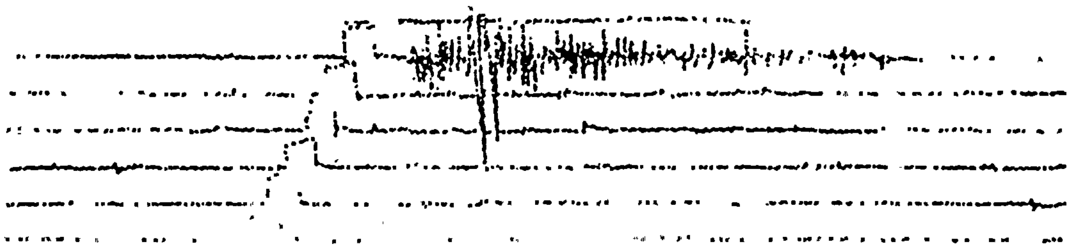
These stations include: (1) a 2 Hz geophone, (2) amplifier capable of 140 db gain, (3) variable filter, (4) a temperature controlled crystal clock, and (5) a smoke paper recorder. Of the three stations, Long Sault Station has the highest amplification.

In a period of two weeks, we obtained several good records in Long Sault Dam (Fig. H-1) showing signals that occurred at the middle of the night which could not be quarry blasts. The shape of these events resemble microearthquake signals obtained elsewhere. With an approximate gain of 10^7 at 12 Hz the events are probably in the magnitude 0 range.

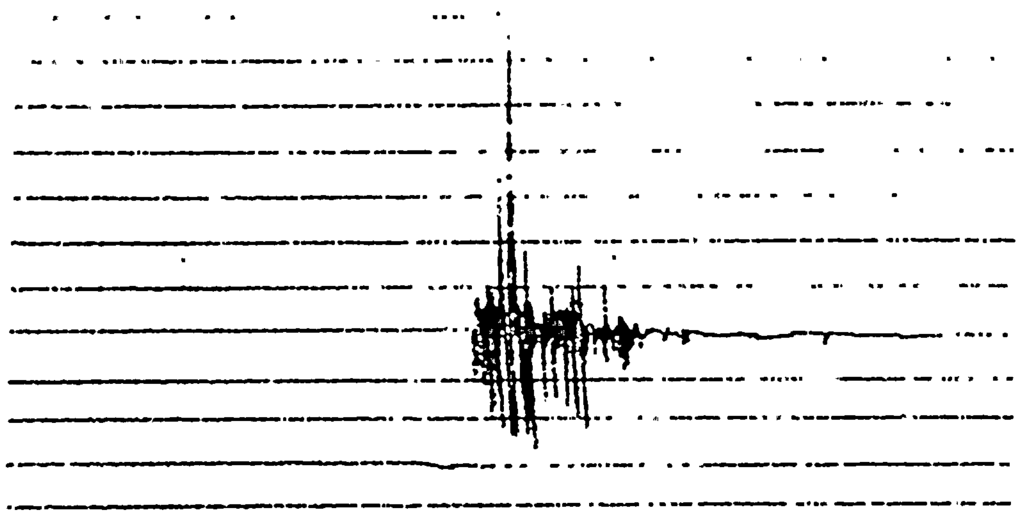
Therefore, we think the Massena area may indeed be still active seismically. However, to pursue this, we plan to set up a two components station at Long Sault to verify this result.

In Figure H-2, we have plotted the Lamont-Doherty seismic network result of 1974. The map shows substantial activity along the St. Lawrence, Attica and Hudson Valley areas.

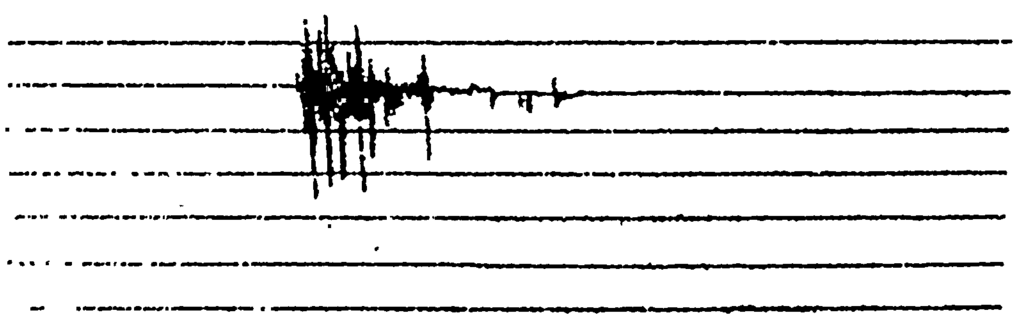
Prepared by Francis Wu



a. June 20 1914 UT

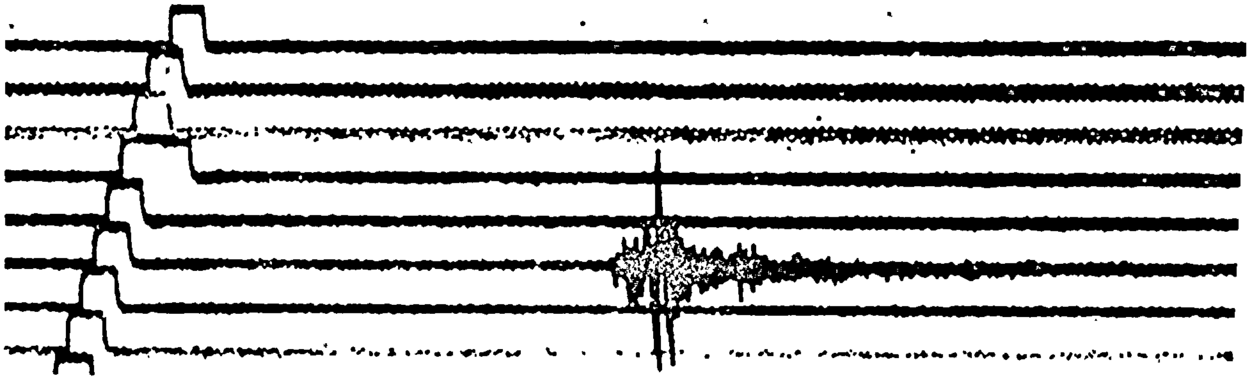


b. June 23 1818 UT

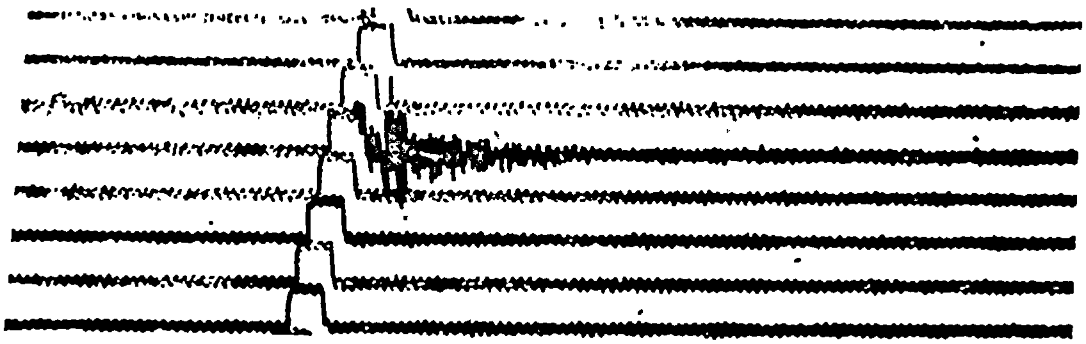


c. June 23 2058 UT

Fig. H-1. Seismograph records showing possible microearthquakes near Massena, New York.



d. June 25 0220 UT



e. June 25 0504 UT

Fig. H-1 (continued)

EARTHQUAKES Recorded at Lamont-Doherty Geological Observatory
Jan. - Dec 1974
• Red dots indicate confirmed or suspected earthquakes
• Green indicates unconfirmed events

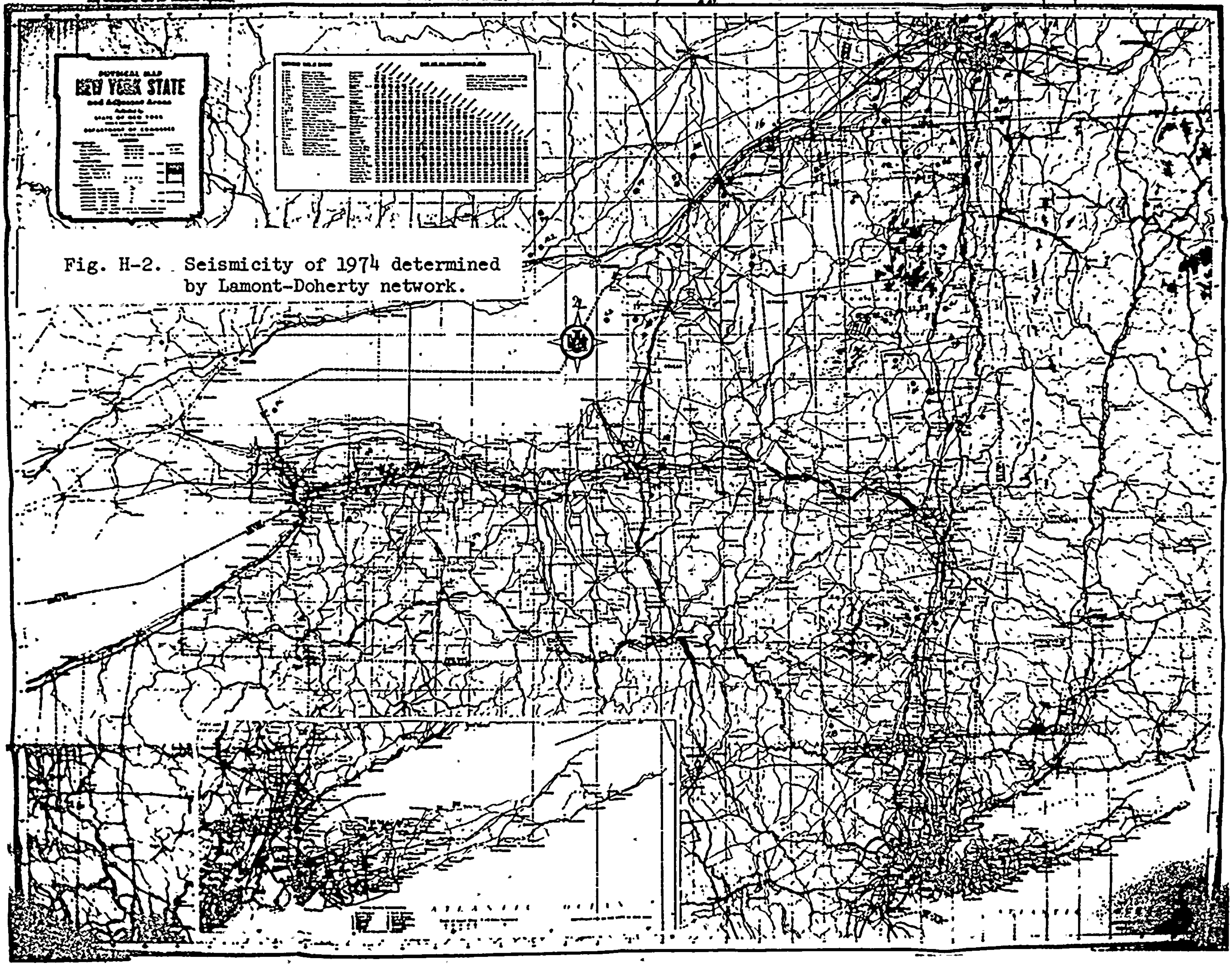


Fig. H-2. Seismicity of 1974 determined by Lamont-Doherty network.

APPENDIX I

FIELD LOCALITY INFORMATION

The following descriptions provide site information of those areas numbered on Plate 1 and which are discussed as "localities" throughout the text. All quadrangles listed are U. S. Geological Survey topographic maps of scale 1:24,000 in New York State.

Locality 1. Gravel pit in kame delta on south side of Route 12E about 5 mi. west of Clayton. Adjacent to Cedar Point State Park. St. Lawrence Quadrangle.

Locality 2. Gravel pit in kame delta on south side of southwest trending ridge at Frontenac Springs. About 3.5 mi. southwest of Clayton on blacktop road. St. Lawrence Quadrangle.

Locality 3. Gravel pit in the LaFargeville kame moraine. North side of road 0.4 mi. west of De La Farge Corners. La Fargeville Quadrangle.

Locality 4. Gravel pit in the LaFargeville kame moraine. South side of road 0.4 mi. west of De La Farge Corners. La Fargeville Quadrangle.

Locality 5. Sand pit in the LaFargeville kame moraine. South side of road 0.1 m. west of De La Farge Corners. La Fargeville Quadrangle.

Locality 6. Gravel pit in the LaFargeville kame moraine. East side of north-south blacktop road 1.3 mi. south of De La Farge Corners. La Fargeville Quadrangle.

Locality 7. Pop-up in Potsdam sandstone, on Bailey Settlement Road, 3.7 mi. southwest of Alexandria Bay. Alexandria Bay Quadrangle.

Locality 8. Newberry sand pit, 1 mi. southeast of Alexandria Bay. South side of Seven Gables Road. Deltaic deposits. Alexandria Bay Quadrangle.

Locality 9. Marion Construction Gravel Pit. South side of Route 11, about 8.5 mi. southwest of Gouverneur. Kame and kame delta deposits. Natural Dam Quadrangle.

Locality 10. Road cut exposed during new construction of Route 11. East side of road near Marion Construction Company. About 8.5 mi. southwest of Gouverneur. Natural Dam Quadrangle.

Locality 11. Gouverneur County/Town Gravel Pit, 2 mi. south of Natural Dam. Kame and kame delta deposits. Natural Dam Quadrangle.

Locality 12. Abandoned sand pit 1 mi. west of Pyrites on the Eddy Pyrites Road. Canton Quadrangle.

Locality 13. Canton Sanitary Landfill Site 1 mi. west of Pyrites on blacktop road. Canton Quadrangle.

Locality 14. Barrett Quarry 1 mi. south of Norfolk on west side of Route 56. Rock quarry with Champlain Sea deposits and Ft. Covington till on top. Norfolk Quadrangle.

Appendix I - Field Locality Information (continued)

Locality 15. Extensive sand deposits in an "erg" type setting with dreikanters in abundance. Near Parishville with deposits extended on both sides of road and covering several hundred acres. Parishville Quadrangle.

Locality 16. Winnowed till area 11,000 ± 150 yrs. B.P. Sand and gravel pits in extensive area of small ridges 6 mi. northeast of Norfolk. Norfolk and Brasher Falls Quadrangles.

Locality 17. Abandoned sand pit 5 mi. southwest of Malone south of Route 11B. Kame and kame delta deposits. Malone Quadrangle.

Locality 18. Roadcut in new construction for Route 37 at the position of Fay 4.5 mi. north of Malone. Extensive sand and silt deposits of the Champlain Sea episode. Constable Quadrangle.

Locality 19. Five mi. east of Massena. Raquette River Quadrangle.

Locality 20. Malone till on north side of blacktop road about 6 mi. southeast of Canton. Pierrepont Quadrangle.

Locality 21. Champlain Sea clays (Leda Clay) exposures in Massena 12,000 ± 200 yrs. B.P. Near trailer court on south side of Raquette River, Massena Quadrangle.

Locality 22. Fine sands of Champlain Sea located 5 mi. east of Fort Covington. Carbon 14 date of 10,340 ± 130 yrs. B.P. Fort Covington Quadrangle.

Locality 23. Glacial erosion terrain. Route 12 east of Alexandria Bay near King Point State Park.

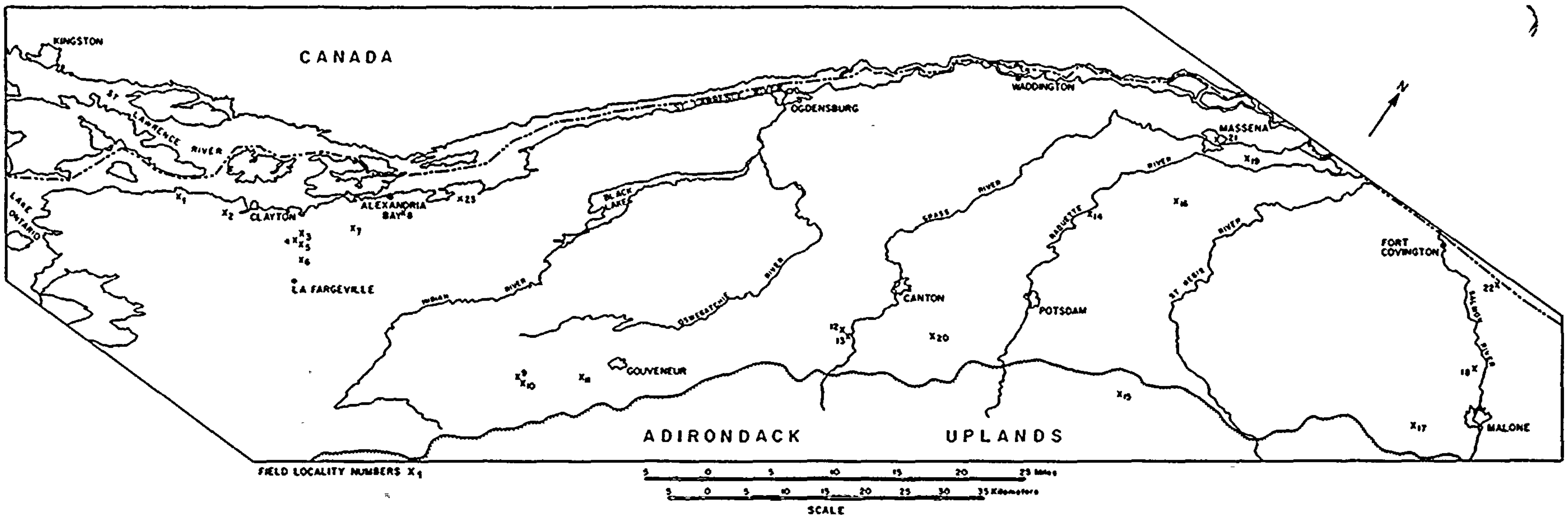
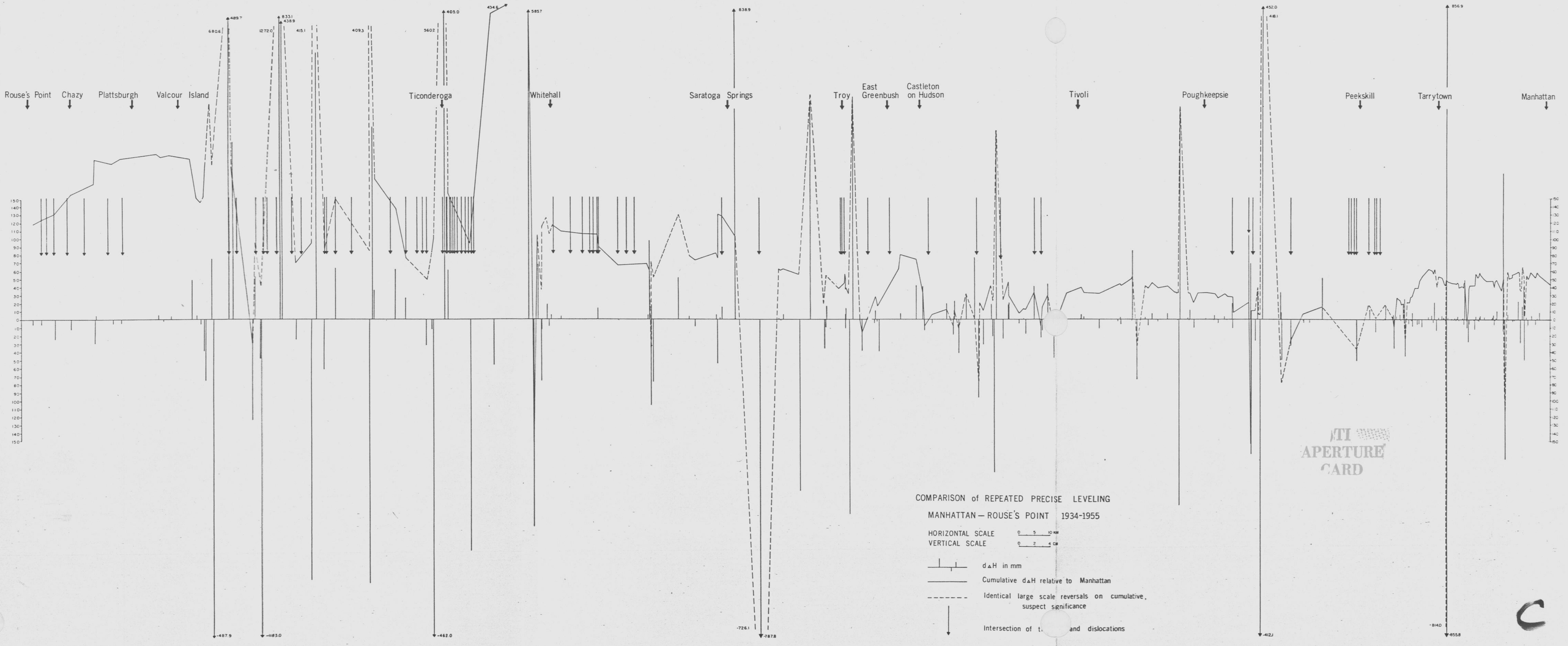


Plate 1. Location map of field sites and features of the St. Lawrence Lowland, New York.

APPENDIX J
SCALE OF OBJECTS IN PHOTOGRAPHS

The following measurements should be helpful for determining scale in the various photographs.

machete	24 in.
shovel handle	21 in.
trowel	10 in.
pen	6 in.
hunting knife	12 in.
pocket knife	6 in.
blackboard	10 in.
Homo sapiens, female	5.3 ft.
male, average	5.8 ft.



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