Géographie physique et Quaternaire

Geomorphological and vegetation interaction and its relationship to slope stability on the Niagara Escarpment, Bruce Peninsula, Ontario

L'interdépendance de la géomorphologie et de la végétation : répercussions sur la stabilité des pentes de l'escarpement du Niagara, péninsule de Bruce, Ontario

Geomorphologisches und Vegetations-Wechselwirken und seine Beziehung zur Abhangsstabilität am Niagara Steilhang, Bruce Halbinsel, Ontario

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Volume 34, numéro 1, 1980

URI : https://id.erudit.org/iderudit/1000386ar
DOI : https://doi.org/10.7202/1000386ar

Aller au sommaire du numéro

Éditeur(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (imprimé)
1492-143X (numérique)

Découvrir la revue

Citer cet article

Moss, M. R. & Nickling, W. G. (1980). Geomorphological and vegetation interaction and its relationship to slope stability on the Niagara Escarpment, Bruce Peninsula, Ontario. *Géographie physique et Quaternaire*, *34*(1), 95–106. https://doi.org/10.7202/1000386ar

Résumé de l'article

La stabilité du front de l'escarpement du Niagara est un élément de première importance dans le cadre du développement éventuel de cette ressource naturelle. Afin de fournir les données de base à un projet de planification de l'aménagement, on a entrepris une étude pilote dans la région des baies de Hope et de Barrow de la péninsule de Bruce. Les résultats montrent que la plus grande partie de l'érosion initiale et l'augmentation de la déclivité des pentes est le résultat de mouvements glaciaires qui se sont produits au-dessus de la partie supérieure de l'escarpement. Les versants ont conservé la raideur de leur pente, alors que le niveau du lac Algonquin était bas, ce qui a eu pour effet de concentrer l'érosion dans la partie relativement plus fragile de la formation de Fossil Hill. À l'heure actuelle, seuls certains secteurs de l'escarpement sont instables. Bien qu'ils semblent dispersés au hasard, ils sont en fait associés à certaines conditions. L'instabilité est plus grande là où les couches plus résistantes reposent sur des couches plus fragiles de shiste altéré et affecté par des mouvements de masse et de dolomie fortement fracturées. La pauvreté de la végétation et la dominance du *Thuja occidentalis* nous permettent de repérer facilement ces zones de plus grande activité.

Géogr. phys. Quat., 1980, vol. XXIV, n° 1, p. 95-106.

GEOMORPHOLOGICAL AND VEGETATION INTERACTION AND ITS RELATIONSHIP TO SLOPE STABILITY ON THE NIAGARA ESCARPMENT, BRUCE PENINSULA, ONTARIO

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ABSTRACT The stability of the face of the Niagara Escarpment is a critical issue in the possible development of this important natural resource. In an attempt to provide background data for future resource management strategies a pilot study was initiated in the Hope and Barrow Bay section of the Bruce Peninsula. Results indicate that most of the initial erosion and steepening of the slopes resulted from the movement of glacial ice over the upper Escarpment. These steep slopes were maintained by low water stages of Lake Algonquin which resulted in the concentration of erosion in the relatively weak Fossil Hill Formation. At present instability is localized to certain parts of the Escarpment and appears to be both spatially random and sporadic, but is generally associated with certain conditions. Instability is usually found where outcrops of more resistant beds are being presently undercut by the weathering and mass wasting of weaker shale and heavily jointed dolomite beds. This activity is recognizable by lack of vegetation or by the dominance of *Thuja occidentalis*.

RÉSUMÉ *L'interdépendance de la géomorphologie et de la végétation: répercussions sur la stabilité des pentes de l'escarpement du Niagara, péninsule de Bruce, Ontario.* La stabilité du front de l'escarpement du Niagara est un élément de première importance dans le cadre du développement éventuel de cette ressource naturelle. Afin de fournir les données de base à un projet de planification de l'aménagement, on a entrepris une étude pilote dans la région des baies de Hope et de Barrow de la péninsule de Bruce. Les résultats montrent que la plus grande partie de l'érosion initiale et l'augmentation de la déclivité des pentes est le résultat de mouvements glaciaires qui se sont produits au-dessus de la partie supérieure de l'escarpement. Les versants ont conservé la raideur de leur pente, alors que le niveau du lac Algonquin était bas, ce qui a eu pour effet de concentrer l'érosion dans la partie relativement plus fragile de la formation de Fossil Hill. À l'heure actuelle, seuls certains secteurs de l'escarpement sont instables. Bien qu'ils semblent dispersés au hasard, ils sont en fait associés à certaines conditions. L'instabilité est plus grande là où les couches plus résistantes reposent sur des couches plus fragiles de shiste altéré et affecté par des mouvements de masse et de dolomie fortement fracturées. La pauvreté de la végétation et la dominance du *Thuja occidentalis* nous permettent de repérer facilement ces zones de plus grande activité.

ZUSAMMENFASSUNG *Geomorphologisches und Vegetations-Wechselwirken und seine Beziehung zur Abhangsstabilität am Niagara Steilhang, Bruce Halbinsel, Ontario.* Die Stabilität des Niagara Steilhanges ist von besonderer Bedeutung für eine mögliche Entwicklung dieser wichtigen Naturquelle. In dem Versuch Hintergrunddaten für zukünftige Verwaltungsstrategien zu beschaffen, wurde in der Hope und Barrow Bucht, Teil der Bruce Halbinsel eine Vorarbeitsforschung begonnen. Die Resultate zeigen, dass der grösste Teil der ursprünglichen Erosion und die Steilung des Abhanges durch die Bewegung vom Gletschereis über den oberen Abhang verursacht wurde. Diese Steilhänge wurden durch tiefe Wasserstände des Algonquin Sees erhalten, welche auch die Ursache der Erosionskonzentration in der verhältnissmässig schwachen «Fossil Hill» Formation ist. Zur Zeit ist die Unbeständigkeit auf bestimmte Teile des Steilhanges lokalisiert und scheint sowohl räumlich begrenzt und sporadisch zu sein, ist aber im allgemeinen mit bestimmten Verhältnissen verbunden. Unbeständigkeit ist gewöhnlich dort zu finden, wo Vorsprünge von widerstandsfähigem Gestein jetzt durch die Verwitterung unterschnitten werden und schwere Zerstörung von schwächeren Schalen und sehr zerklüftetem Dolomitgestein eintritt. Diese Tätigkeit ist durch das Fehlen jeglicher Vegetation oder durch das Vorherrschen von *Thuja occidentalis* gekennzeichnet

INTRODUCTION

The Niagara Escarpment in the Bruce Peninsula is one of the most striking landforms in southern Ontario. Here the Escarpment forms the west coast of Georgian Bay as a series of cliffed headlands and bays of outstanding natural beauty (Fig. 1). Partly as a result of this and also because of its relative ease of access from the major population centres of southern Ontario, upper New York State and Michigan, the Escarpment has come under increasing pressure from recreational, commercial and residential land uses. Such land uses are often in direct conflict with attempts to conserve and preserve the natural features of the area.

To resolve many of the existing land use conflicts and to plan for ordered development of the area, the Government of Ontario established the Niagara Escapment Task Force in 1972. One of the major objectives of the Task Force was "to protect the Escapment's distinct characteristics and to ensure a balanced future use of Escapment lands" (ONTARIO, MINISTRY OF TREASURY, ECONOMICS AND INTERGOVERNMENTAL AFFAIRS, 1973, p. 1).

One of the most critical concerns within the area is that of slope stability. Little is known about the stability of the scarp face in this area, yet statements on the current nature of slope stability are being used both by potential developers on the one hand and conservationists on the other. Their various arguments range, respectively, from statements of extreme stability with no evident change, to those of extreme instability, with rockfalls of major hazard proportions.

The objective of this paper is to investigate the problem of slope stability in the area, to define both its temporal and spatial expression, and to suggest a method by which land planners can readily identify areas where consideration should be given to this factor.

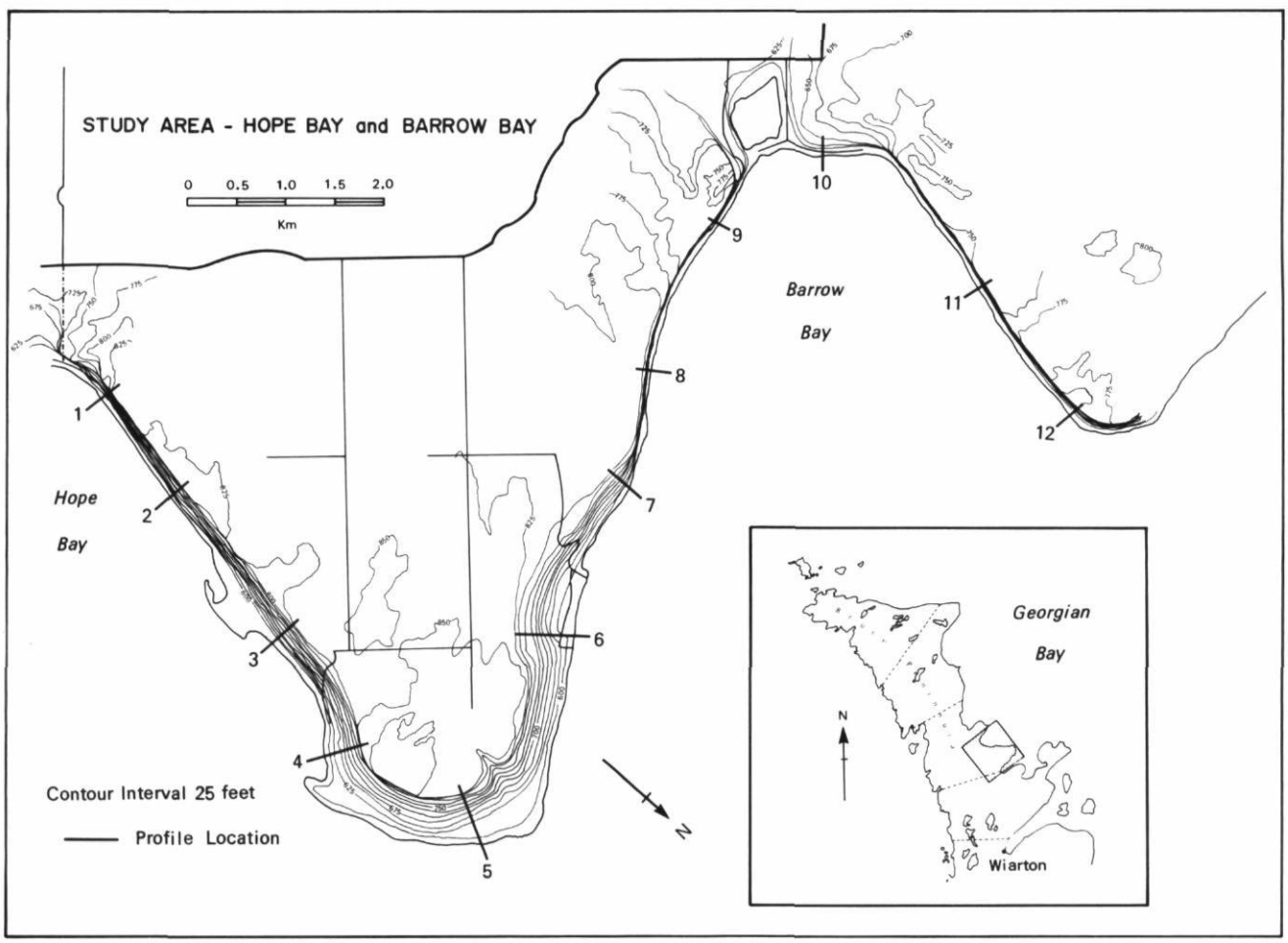

FIGURE 1. Hope and Barrow Bay study area (location inset). *Carte de localisation de la région à l'étude.*

SLOPE STABILITY

The stability of natural slopes can be defined by several different methods. For example, a quantitative assessment can be based on the relationship between the strength characteristics of the material which make up the slope and the stress placed on this material under various hydrological conditions. Measurements of this nature, however, are often costly, difficult to obtain and necessitate the detailed laboratory testing of the material. An alternative to this approach is simply to investigate the morphological characteristics of the slopes in relation to the sediment characteristics, frequency of recent activity and vegetation characteristics. For instance, a slope composed of relatively large material having a low angle of repose is indicative of stable conditions. Similarly slopes which have a deep, well developed soil profile and mature vegetation cover can also be viewed as relatively stable. Conversely slopes which are dominated by freshly fractured, recently moved debris, shallow disturbed soil profiles and immature vegetation can be viewed as relatively unstable.

Although this morphological approach does not allow for the prediction of slope failure and movement rates, it does provide a qualitative assessment of the slopes' development and relative stability at the present time and in the recent past.

LITHOLOGY

The nature of the bedrock exposed within the study area is summarized in Table I. The stratigraphic succession is one of interbedded Silurian and Ordovician shales and dolomites of varying hardness (LIBERTY and BOLTON, 1971). The intervening beds of shale forms weaker rock exposures. However, great variability exists in the lithological characteristics of the individual members. Also with the exception of outcrops of the Amabel, Fossil Hill and lower members of the Cabot Head Formation the remaining members are buried by talus and in some cases beach deposits making interpretation difficult. There is little evidence of surficial deposits of glacial origin in the area.

METHODS

Given the somewhat complex interrelationships between the environmental variables involved, a two-stage approach to the problem was taken. Initially a reconnaissance survey of the study area was undertaken in order to obtain an overall picture of the general interrelationships between the scarp-face features and the related vegetation within the study area as a whole. Secondly, more detailed studies of one-kilometre selected sections of the Escapment were made.

TABLE I

Bedrock geology of the Niagara Escarpment in the Hope-Barrow Bay area (LIBERTY and BOLTON, 1971)

Formation	Member	Lithology
Amabel	Colpoy Bay	bluish grey, fine crystalline dolomite
	Lion's Head	tan, sublithographic dolomite
Fossil Hill		thin and thick bedded, brown, porous, fossiliferous dolomite
Cabot Head	St. Edmund	massive brown dolomite
	Wingfield	ribbon bedded, greenish grey dolomite
	Dyer Bay	bluish grey dolomite
	Cabot Head	soft, red and green shale

LAND UNITS

To obtain the general understanding a series of 12 profiles were surveyed perpendicularly from the shoreline to points approximately 5 m back from the crest of the Escapment. Profiles were derived from distance measurements taken by tape between each break of slope. The angle of each of these slope sections was measured in every case using an Abney level. No attempt was made to interpret the lithological characteristics of surface material at this stage but a simple measure of vegetation cover was made by noting the numbers of individuals of each species that covered the transect lines. Note was also taken of the depth and amount of soil cover. The location of the twelve profiles is indicated in Figure 1.

By using the basic profile data in conjunction with two recent sets of air photographs for the study area (1971 and 1976), it was possible to obtain a more comprehensive picture of the land surface as a whole. For convenience this information can be organized into a series of land units. Each of the land units recognized has, therefore, the common attributes of a limited range of slope angle, topography, soil development, and dominant vegetation. At the scale used the more individual features such as talus cones, debris slides, etc., were not included. The distribution of these land units is shown in Figure 2 and the details summarized in Table II.

ONE-KILOMETRE SECTIONS

At the second level of more detailed data collection five individual sections of the area were selected (A to E on Fig. 2 and Fig. 3). These were chosen to represent a range of conditions reflecting slope, aspect and lithology. Each section extended for 1 km in length along the Escarpment and data were collected from the scarp crest down to the shoreline. In each section the

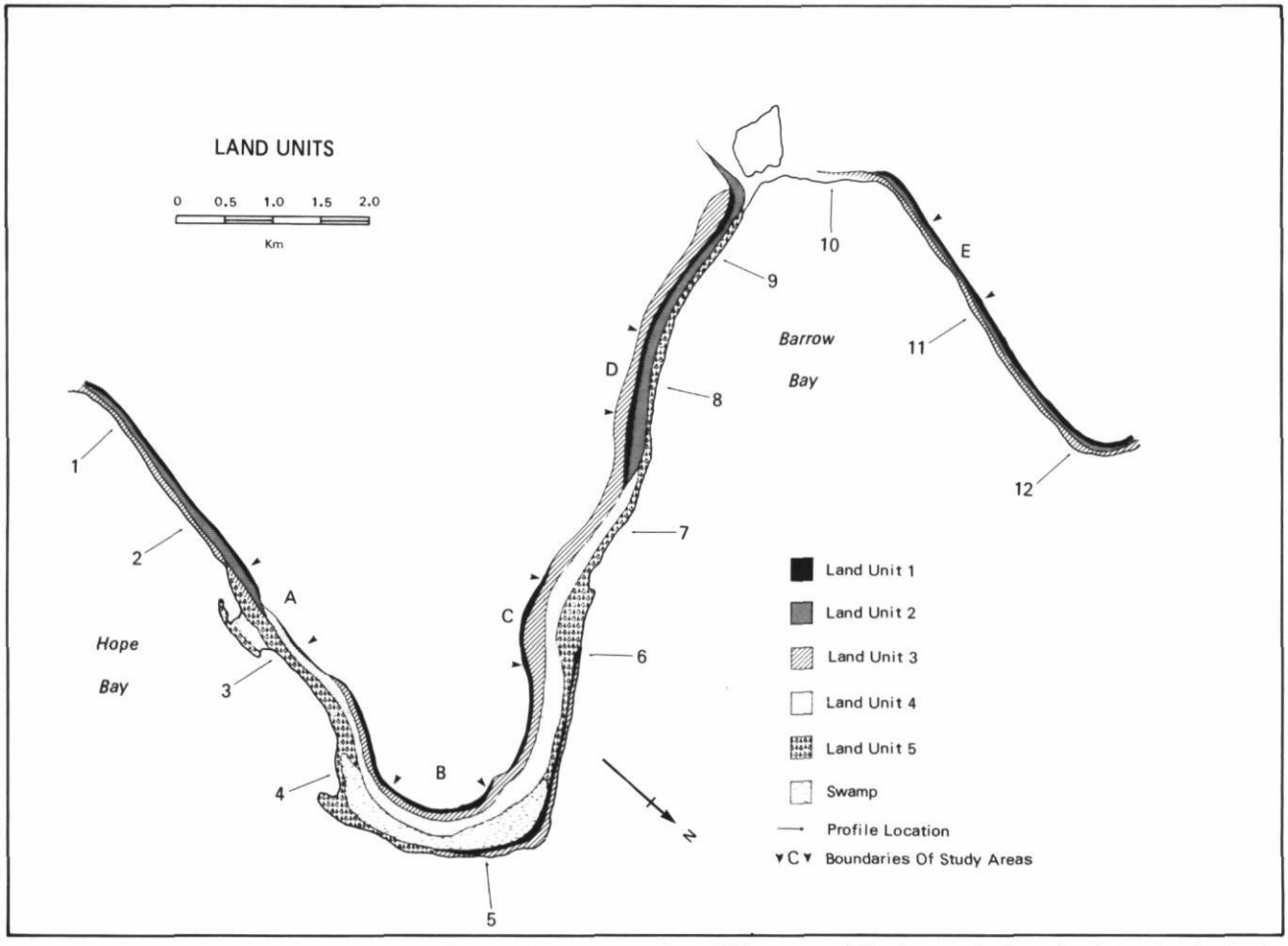

FIGURE 2. Land units in the Hope and Barrow Bay area. For characteristics of the individual units see Table II.

Les différentes unités de terrain dans la région à l'étude. Les caractéristiques de chacune des unités sont données dans le tableau II.

TABLE II

Characteristics of land units in the Hope-Barrow Bay area

Land Unit	Slope	Dominant Vegetation	Soil Development
1	>45°	*Thuja occidentalis* or no vegetation cover	(none)
2	20-45°	*Thuja occidentalis* with occasional *Betula papyrifera*	insignificant
3	<20°	*Betula papyrifera* with occasional *Thuja occidentalis, Acer saccharum, Fraxinus americana*	<5 cm intermittent
4	>20°	*Acer saccharum, Fraxinus americana, Ulmus americana*	5-10 cm intermittent
5	<20°	*Betula lutea, Acer* spp. dominant with occasional *Betula papyrifera*, and *Thuja occidentalis*	5-10 cm intermittent

land units recognized in Table II were identified. Any non-conforming areas of the ground surface within each of the land units were then analyzed. This involved those areas identified in some way as distinct landform features as opposed to the more general slope characteristics based upon the structural characteristics identified in the land units. Included were all debris accumulations features (talus cones, talus creep, rock fall and rock debris features). The angles and lengths of slope facets in each of these features were measured. In certain instances the surface features are sufficiently extensive and form the general surface slope form of the land unit. In other instances the surficial features form much steeper slope angles than the general slope form of the land unit. Lithology, source and mean size of the surficial debris was measured in $2m^2$ sample quadrats on the slope facets. Within these quadrats the long, intermediate and short axes of 25 randomly selected surface boulders were measured and their lithology

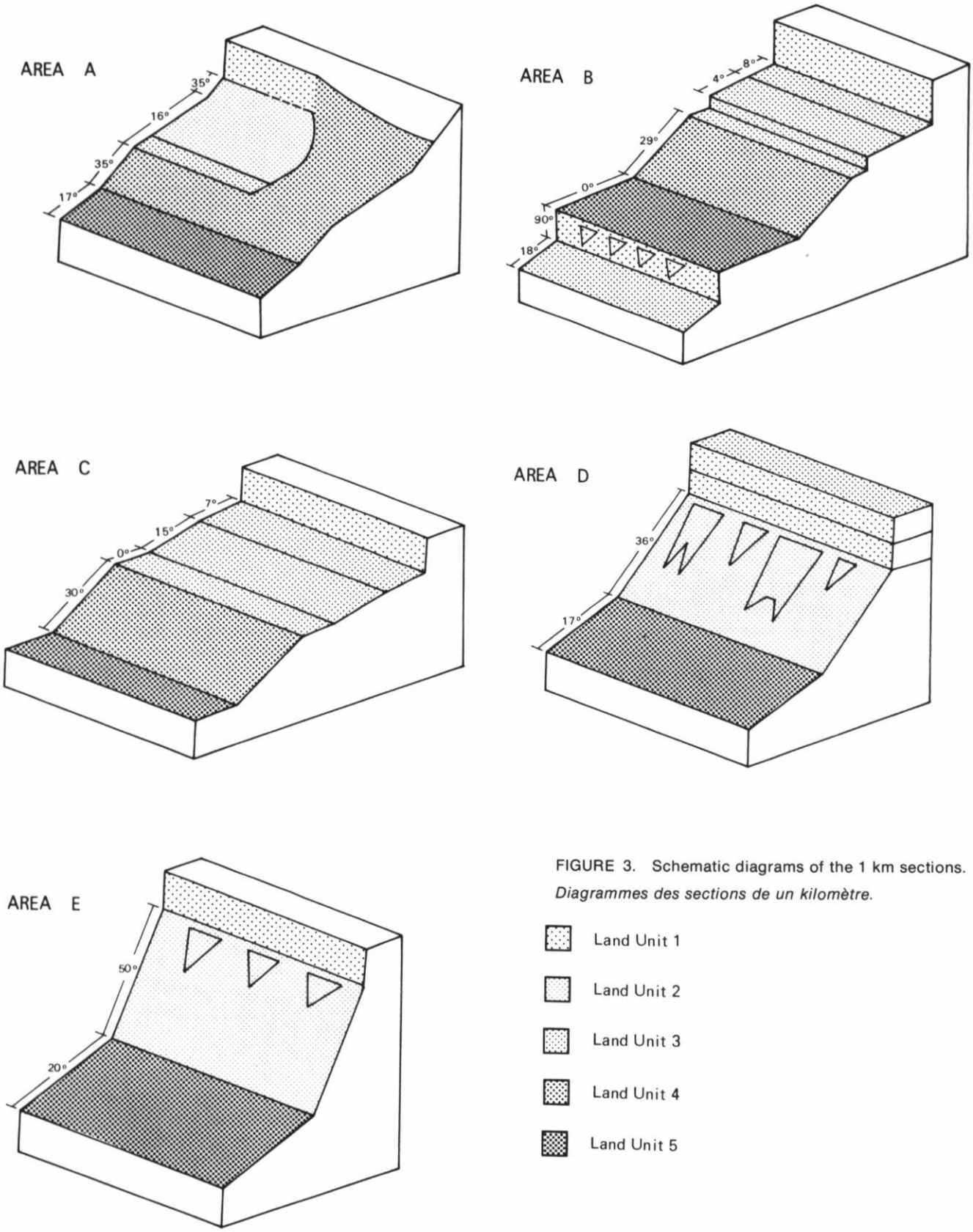

FIGURE 3. Schematic diagrams of the 1 km sections.
Diagrammes des sections de un kilomètre.

identified. The relative degree of *in situ* weathering of surficial rock debris and soil depth were also recorded. The surface form of each of these 1 km sections is shown in Figure 3.

The vegetation cover on each feature recognized was also sampled and data collected by standard phytosociological techniques. Measurements taken were those of species density, dominance and frequency. From these basic measurements an 'importance value' (I.V.) for each species in each stand could be determined (MUELLER-DOMBOIS and ELLENBERG, 1974, p. 119). The same measurements were made at the tree (>10 cm d.b.h.[1]), the sapling (2.5 to 10 cm d.b.h.) and the seedling levels (<2.5 cm d.b.h.). In this way an indication of reproduction and future community structure may be derived. Additional biotic features noted were for evidence of the impact of any recent debris movement in terms of damage, bending, etc., and any evidence of vegetation recovery after such events.

CHARACTERISTICS OF THE FIVE ONE KILOMETRE SECTIONS

AREA A

In the Hope Bay area the dolomitic Amabel Formation usually forms the caprock of the Niagara Escarpment. In Area A the upper members (Calpoy and Lion's Head) form an impressive cliff face in the southwestern end of this study site but to the northeast they have been partially removed by glacier ice and mass wasting.

The remnant of the lower part of the Lion's Head dolomite is now covered by a stable scree slope comprised of debris 20 to 25 cm in diameter. On this slope a soil profile 15 to 20 cm deep has developed in the interstices between the surface debris and sustains a 'mature' white birch (*Betula papyrifera*) forest cover.

In contrast, to the southwest, where the cliff face is exposed, the Lion's Head dolomite is being actively undercut by the weathering and mass wasting of the weaker Fossil Hill Formation. Debris supplied from the Fossil Hill and Lion's Head dolomite has formed a steep (35°) active scree slope at the base of the cliff face.

The debris found on the surface of the scree slope is freshly fractured, has a mean diameter of 42 cm and is dominated by material from the Fossil Hill Formation. The relative instability of this slope segment is indicated by the freshness of the debris and the complete lack of soil and vegetation cover.

This active scree slope merges with, and partially covers, a more stable, gentle (16°) slope segment which is covered with large blocks of Amabel caprock (150-450 cm in diameter). The large blocks are almost entirely moss covered with organic rich soil filling the interstices between blocks. The entire slope segment is dominated by *Betula papyrifera* (I.V. 83.7) with subdominants, white cedar, *Thuja occidentalis* (8.5) and basswood, *Tilia americana* (6.9). Beneath this overstory is a sapling community dominated by mountain maple, *Acer spicatum* (78.9) with ash, *Fraxinus americana* (13.0) and sugar maple, *Acer saccharum* (4.1) as subdominants. The seedling layer is entirely dominated by *Acer spicatum* with only the occasional record of *Betula papyrifera* reflecting regeneration of any of the dominant species. Although the geomorphic and related biotic evidence does not indicate any recent movement of surface debris the nature of the biotic data suggests that this community is in a state of flux from one dominated by birch to one dominated by maples.

This stable segment terminates at a 2 to 3 m high cliff face comprised of a thinly bedded dolomite member which is only found on the southwestern side of the study area. It decreases in height to the northeast becoming buried by stable debris which had probably originated in the past from the weathering of the Fossil Hill Formation.

Beneath the small steep face on the debris slope the slope angle is steep (35°) but this appears relatively stable because of the lack of fresh debris, evidence of a more mature forest community with reasonable soil cover (depth 20 cm) and many old, decaying trees. This community is again dominated by *Betula papyrifera* (72.3) but with other major species common within mature deciduous forests *i.e. Acer saccharum* (9.1), ironwood *Ostrya virginiana* (8.9) and beech *Fagus grandifolia* (5.2). Although the understory is dominated by *Cornus alternifolia* other members indicate the succession by *Ostrya virginiana* (25.0), *Betula papyrifera* (13.0) and *Acer spicatum* (11.9). This same composition is reflected in the seedling layer. This slope segment extends to the northeast and merges with the stable slope segment which is dominated by debris brought down at sometime in the past fro the now buried Fossil Hill Formation.

At the base of the Escarpment the slope becomes much gentler (17°) and the average size of the surface debris considerably larger (mean 1.8 m). Although a wide range of boulder sizes and lithology are evident in this slope segment the most striking features are the large blocks (up to 4.3 m) of Colpoy Bay dolomite which dominate the slope. The larger blocks, as well as the smaller material, are heavily moss covered and show distinct signs of intensive *in situ* chemical and physical weathering. Between the larger blocks a relatively deep soil profile (20 cm) has developed. Also a mature *Betula papyrifera* — *Acer spicatum* forest cover has developed.

1. d.b.h. — diameter at breast height.

In this area therefore, the downslope vegetation sequence reflects increasing maturity from the upper slope units to the lower (though not necessarily less steep) units. Birch retains its dominance throughout and although the upper sections contain many cedars subsequent replacement of these by deciduous species (ironwood, sugar maple, beech) is common in the less active, lower slopes.

AREA B

Study Area B is located at the headland between Hope and Barrow Bays (Fig. 2). As a result of this exposed position the Escarpment face has been subjected to vigorous erosion by glacial ice (STRAW, 1968) and to a lesser extent by wave attack. The greater erosion has resulted in the Amabel Formation being cut back several hundred meters from the present shoreline.

At this site the lower member of the Amabel Formation (Lion's Head dolomite) forms a continuous cliff face 20-30 m high across the entire study area. At the base of the cliff face the weaker Fossil Hill Formation is exposed in several locations and is actively undercutting the Lion's Head dolomite. The larger and deeper undercuts may have been caused by wave attack rather than by *in situ* weathering. The presence of a relatively large, possibly wave-cut or wave-modified cave in the Fossil Hill near the centre of the study area and the limited amount of fresh debris at the base of the cliff lend support to this argument.

Below the cliff face the Fossil Hill Formation is buried by a gently sloping surface (4° to 8°) which extends lakeward approximately 150 m ending at a small scarp (approximately 10 m high) formed by what is thought to be the St. Edmund member of the Cabot Head Formation. The surface of the gentle slope is comprised predominantly of material (40 to 50 cm in diameter) derived from the Fossil Hill Formation. However, many large blocks (75 to 100 cm) of Amabel caprock are also found across this gentle slope. The surficial boulders are heavily moss covered and are partially buried in a relatively deep soil which averages 10 cm in depth.

Vegetated debris-fall features within this section are encountered in units 3 and 4. Within the upper facet of unit 3 (slope angle 8°) the codominants are *Acer saccharum* (29.4) and *Fraxinus americana* (32.3) with elm, *Ulmus americana* (10.3) and *Betula papyrifera* (16.1) as important subdominants. In the shrub layer *Acer saccharum* remains dominant (47.2) with *Acer spicatum* (21.9) and dogwood, *Cornus alternifolia* (13.7) important subdominants with *Ulmus americana* and *Fraxinus americana* present. Seedlings reflect the same assemblage. This upper section, therefore, lying immediately below the free face (unit 1) shows all the attributes of a mature, relatively stable, deciduous forest community.

However, within this same unit but on a lower slope facet (4°) with more evidence of current mechanical breakdown of surface materials, the vegetation is dominated by a mixed community with *Betula papyrifera* (33.4), *Populus balsamifera* (21.2), *Thuja occidentalis* (21) and *Acer saccharum* (19). Although there is significant admixture of *Cornus alternifolia* in the shrub and seedling layer the dominants appear to be reproducing themselves. One reason for this continuity may be the fact that whereas the bedrock may be breaking up *in situ* there is no evidence of debris input from the higher units.

A wide (61 m) relatively steep (29°) slope segment extends lakeward from the base of the low scarp formed by the St. Edmund dolomite. Most of the surficial debris is buried beneath a soil mat averaging 12 cm in thickness. The surficial rocks which are exposed (mean size 50 cm diameter) are well rounded and moss covered. The rounded nature of the debris and the uniform slope angle of this segment suggests that this area may have been wave worked, for some period of time, by a high water stage of Georgian Bay. In general, the nature of the surface material indicates that there has been little or no recent accumulation or movement. The assumption is supported by the presence of the relatively deep soil profile (12 cm) and the forest cover dominated by *Thuja occidentalis*, *Populus balsamifera* and *Acer saccharum*.

This segment merges with a wide flat bedrock bench which appears to have developed on the Dyer Bay member of the Cabot Head Formation. The flatness of the topography has resulted in very moist soil conditions which is reflected in a vegetation cover dominated by *Thuja occidentalis*, service berry (*Amelanchier* spp.) and other shrub species. This flat bedrock bench ends abruptly at a near-vertical face resulting from the active undercutting of the Dyer Bay dolomite by wave attack in the weak underlying Cabot Head shale. Recession of the Dyer Bay member has resulted in the formation of a 20 m wide low angle slope (18°) which extends from the shoreline to the cliff base. This slope is comprised of debris 20 to 40 cm in diameter derived predominantly from the Cabot Head shale and to a lesser extend from the Dyer Bay dolomite. Talus material indicates much current activity yet with a reasonable vegetation cover dominated by *Thuja occidentalis* (40.6) and *Populus balsamifera* (45.7) with *Betula papyrifera* (13.1) subdominant. In spite of the apparent freshness and current talus deposition activity, this community appears to be successfully reproducing itself at both the shrub and seedling levels. The surface of the slope has a soil cover averaging 8 cm in depth which thins towards the cliff face.

A small active scree slope 2 to 3 m in height extends along the base of the Dyer Bay cliff face. At two locations where more active undercutting has occurred larger talus cones 10 to 12 m in height have developed. Although the cones are dominated by shale debris an apron of large dolomite blocks 1 to 3 m in diameter is located at the base of each cone. Little soil has developed on these scree or talus cones. Vegetation which does colonize these areas is frequently buried by the falling of fresh rock debris. These latter features are being currently modified by coastal process usually associated with storm-wave activity (DAVIDSON-ARNOTT, MOSS and NICKLING, 1978).

AREA C

Study Area C is located on the southern shore of Barrow Bay approximately 2 km west of Cape Dundas (Fig. 2). The morphology, stability and related vegetation pattern of this site are very similar to those of Study Area B with two major exceptions. The Colpoy Bay dolomite has been eroded well back beyond the study site. The lower member (Lion's Head dolomite) again forms a near vertical cliff at the top of the study site as a result of undercutting in the Fossil Hill dolomite. A relatively stable, heavily vegetated surface composed of three identifiable facets slopes gently (0° to 15°) away from the cliff face terminating approximately 90 m downslope at a series of poorly defined bedrock benches. These benches are thought to be formed in the Cabot Head Formation and hold a similar altitudinal position to the well developed scarp face formed in the Cabot Head Formation in study area B.

Again within this section unit 1 is completely devoid of surficial rock accumulation but unit 3 may be divided into three subsections, each with characteristic talus deposits and associated vegetation. Within the upper facet of unit 3 the low angle slope (7°) has talus-related communities dominated by *Acer saccharum* (38.0) but with high admixtures of *Ostrya virginiana* (18.0), *Tilia americana* (13.0), trembling aspen, *Populus tremuloides* (11.9) and *Betula papyrifera* (11.3). The shrub layer is almost entirely dominated by *Acer saccharum* and the seedling layer shows evidence of reproduction by several of the local dominants (*Acer saccharum, A. spicatum, Ostrya virginiana* and *Betula papyrifera*). Hence both the nature of the vegetation cover and the related geomorphic materials indicate that in this location, immediately below the free face of unit 1, the surface conditions reflect a good deal of long-term stability.

The mid-slope facet of unit 3 (slope 15°) reflects a similar set of conditions with the addition of beech, *Fagus grandifolia* (9.9), in the overstory. Again, the lower unit (0° slope) with a ground surface of talus-like material, exhibits a similar vegetation cover and similar indication of lack of recent surface movement or recent accumulation.

Below the bedrock benches a heavily vegetated stable surface comprised of large rock debris slopes steeply (30°) down to a flat swampy terrace which extends 200 to 300 m out to the present shoreline. The nearshore edge of this terrace is covered by a wide shingle beach. The 30° slope unit has talus related communities dominated by *Betula papyrifera* (30.0) and *Ostrya virginiana* (30.0) with *Acer saccharum* (18.0) and *Tilia americana* (4.0) as subdominants. These same species appear to be reproducing themselves and *Acer spicatum* becomes an element in the understory although it rarely becomes a significant dominant. Again all the evidence points to the relative old age of the talus material and the relative stability of this section of the Escarpment.

Unlike Study Area B the Dyer Bay dolomite, which is thought to underlie the flat terrace, does not form a scarp face close to the present-day shoreline. This suggests that the contact between the Dyer Bay formation and the weaker Cabot Head shales is located at some depth below the present low water level.

AREA D

Study Area D is located on the southern shore of Barrow Bay approximately 2 km from the bayhead (Fig. 2). Although the morphology of this site is much less complex than those sites previously discussed the slopes appear to be considerably more active.

At this site the upper member of the Amabel Formation is exposed in close proximity to the shoreline as was the case at site A. The upper and lower members form a near vertical cliff face 30 to 40 m in height which extends across the study areas. In contrast to the other sites, however, a large section of the Fossil Hill Formation is also exposed as a vertical section below the Amabel formation.

The Fossil Hill is actively spalling away in large vertical sheets several centimetres in thickness and up to 50 cm in diameter. The weathering and mass wasting of the Fossil Hill Formation has triggered similar spalling in the relatively weak Lion's Head dolomite resulting in the undercutting of the more massive Colpoy Bay member. This debris from the Fossil Hill and Lion's Head dolomites has formed an extensive scree slope which traverses the entire study area. Although the surface debris is dominated by material from these two members massive blocks (2 to 3 m diameter, 0.5 to 1.5 m thick) of upper Colpoy Bay caprock are also found on the scree slope. These large blocks were usually located near the base of the scree slope many metres from the active free face.

Despite the fact that the average angle of the scree slope is relatively uniform (35°), there appears to be a considerable spatial variability in the stability of the slope facet which is indicated by the soil and vegetation pattern. In general the slope has a fairly well developed soil up to 18 cm in depth with a significant forest cover on the majority of the debris features showing a simple community dominated by *Thuja occidentalis* (68.0) with *Betula papyrifera* (32.0) with future trends indicated by the re-establishment of *Thuja* but with *Fraxinus americana* as the subdominant. This tree cover often shows signs of recent disturbance such as up-rooting, curved trunks, and broken limbs caused by falling debris. At four sites, however, the upper portion of the scree slope was almost totally devoid of vegetation and soil cover. These sites are made up of freshly fractured rock debris which tends to increase in size from the cliff face downslope. In conjunction with this size change there is also an increase in the amount of vegetation cover and soil development in a downslope direction.

This relatively active scree slope merges with a more gently sloping surface (17°) near the base of the Escarpment. Here the debris covered slope extends approximately 32 m from the base of the previously mentioned scree slope to the Barrow Bay shoreline. Large interlocking Amabel caprock blocks up to 4.5 m in diameter form the surface. These are presently weathering *in situ*. A well developed soil 17-20 cm in depth partially buries the lower moss covered boulders.

Associated with this lower unit is a vegetation community which appears to be self-perpetuating with *Thuja occidentalis* (32.0), *Betula papyrifera* (33.0) and *Acer spicatum* (22.0). The presence of *Thuja* here, as on certain other sites, may suggest some relatively recent clearance of this site by human activity and its subsequent revegetation.

AREA E

Study Site E, located on the north shore of Barrow Bay is very similar to Area D in both morphology and stability characteristics. A few minor differences, however, are apparent. The scree slope developed below the Amabel free face at this site is considerably steeper (50°) than that found in Area D and in general appears to be somewhat more unstable. This is indicated by the thinner soil development and the greater occurrence of recent vegetation dammage caused by the impact of falling rock debris. Also a somewhat different vegetative response is evident. Below unit 1 is the steeply sloping section of unit 2 (slope 50°). Here the features show the results of current spalling of material from unit 1 and accumulation as talus features. The related vegetation is a pure stand of *Thuja occidentalis*. Lower downslope, but remaining in unit 2 and where accumulation of larger debris takes place, the vegetation remains *Thuja*-dominated but with the addition of *Betula papyrifera* as an occasional species.

The active nature of rock fall on this slope is further demonstrated by the presence of several relatively large, oversteepened, coalescing talus cones which fringe the bottom of the free face. The greatest proportion of surficial debris on these cones is freshly fractured and is primarily derived from the Fossil Hill Formation which is clearly exposed across the entire study site. These are unvegetated.

This steep, unstable slope facet intersects with a gently sloping (20°) bedrock bench which is trought to represent the upper surface of the Dyer Bay dolomite. Large blocks of Amabel caprock (primarily Colpoy dolomite), 3 to 6 m in diameter and up to 3 m in thickness, are encountered on the surface. This debris appears to have been deposited more recently than similar debris on the basal slope segment of study Area D where greater soil development and *in situ* weathering is found. On this basal slope unit the vegetation is a more mixed association with *Thuja occidentalis* (44.7), hemlock *Tsuga canadensis* (27.3), *Betula papyrifera* (21.6) and *Populus tremuloides* (6.5). With the exception of *Populus* each of these species appears to be successfully reproducing itself and again *Acer spicatum* is represented in the seedling layers.

SLOPE STABILITY/VEGETATION RELATIONSHIPS

Table III summarizes the major findings from the foregoing discussion. Areas within the one-kilometre sections are identified with respect to the existence of the various land units and those where evidence of instability exists are indicated separately. It should be noted, however, that the term instability is used in a rather general sense and does not necessarily indicate a situation where the stresses acting on large expanses of the Escarpment face and associated deposits exceed their internal strengths. In almost all cases the instability is represented only by sporadic rock fall from the Fossil Hill and Amabel Formations.

The size and amount of debris derived from these sources varies considerably both spatially and temporarily at the present but is relatively small in comparison to the expanse of the free face and the size of the very stable deposits beneath it. The assumption that the Niagara Escarpment in this area is unstable is therefore somewhat misleading. At times, in various locations the Escarpment area may be somewhat "hazardous" because of isolated debris falls but is not unstable in a true engineering sense.

TABLE III

Summary of surface morphology/vegetation relationships on features associated with debris accumulation where debris accumulation features exist. Cross-hatched sections indicate sections with evidence of relatively recent debris movements. Dash (—) represents no vegetation or no soil development

Features associated with land unit no's / 1 km areas	1	2	3	4	5
A		— 35° 42, 23, 9 cm FH Bp with Th. and T.a. 16° 263, 114, 110 cm. FH		B.p., A.s, O.v., F.g. 35° 24, 18, 8, cm 20 cm FH , SE, W ?	B.p, A.s., O.v., F.g. 17° 179, 133, 91 cm 19 cm A., FH
B			A.s., F.a., U.a., B.p. 8° 48, 27, 13 cm — FH, A B.p., P.b., Th 4° 95, 59, 19 cm 10 cm FH, A	Th ., P.b., B.p. 29° 49, 32, 23 cm 12 cm SE, W, FH	
C			A.s., O.v., T.a. 7° 460, 247, 110 cm 15 cm A, FH A.s., O.v., T.a., F.g. 15° 240, 135, 89 cm 17 cm A, FH	B.p., O.v., A.s., T.a. 30° 83, 52, 30 cm < 3 cm A, FN, SE, W ?	
D		Th., B.p. 36° 198, 132, 33 cm 18 cm FH, A			Th., B.p., A.sp 17° 227, 117, 122 cm 17 cm A, FH.
E		Th., Th., B.p. 50° 14, 10, 3 cm — FH, A	Th., T.c., B.p. 20° 415, 261, 122 cm — A		

Key to items in Table III (each line refers to items 1 through 5 below).
1) Dominant vegetation: (listed in Table in order of importance) (B.p., *Betula papyrifera;* Th., *Thuja occidentalis;* T.a., *Tilia americana;* A.s., *Acer saccharum;* O.v., *Ostrya virginiana;* F.g., *Fagus grandifolia;* F.a., *Fraxinus americana;* U.a., *Ulmus americana;* P.b., *Populus balsamifera;* A.sp., *Acer spicatum;* T.c., *Tsuga canadensis).* 2) Slope angle (degrees). 3) Mean size of material (a, b, c axes in cm). 4) Soil depth (cm). 5) Primary source of surface material (A, Amabel Formation; FH, Fossil Hill Formation; SE, St. Edmunds member Cabot Head Formation; W, Wingfield member Cabot Head Formation).

The more active sites found along the Escarpment were located in study areas A, B, D, and E. Of these sites area E appears to be most active at present. The present instability of these sites has been identified by the presence of freshly fractured debris on active scree slopes, thin soil cover and immature vegetation dominated by white cedar (*Thuja occidentalis*). In all these sections this mass wasting is directly related to the exposure of the Fossil Hill Formation. This relatively weak, porous dolomite is actively being weathered out and is undercutting the more resistant Amabel Formation which forms the caprock to the Escarpment. Large blocks of the Amabel Formation have become detached along joint planes and have fallen downslope as a result of the undercutting. Because of their mass these blocks move well downslope, often reaching the gently sloping bedrock bench cut on the Dyer Bay member of the Cabot Head Formation.

Despite the active talus cones found at the base of the Fossil Hill Formation the large blocks of caprock found on the lower slopes appear to be relatively old. This suggests that present mass wasting on the Escarpment in this area is dominated by the weathering and spalling of small blocks of Fossil Hill dolomite rather than the more catastrophic failure of the large Amabel caprock blocks. It is thought that the massive undercutting responsible for the deposition of the greatest proportion of the caprock blocks is probably related to: (1) oversteepening of the scarp face by glacial ice, (2) more severe climatic conditions near the end of the last glacial advance, and (3) wave attack in the Fossil Hill Formation during the late Lake Algonquin stage of Georgian Bay (LEWIS, 1969).

The effectiveness of wave attack undercutting weaker sedimentary units is demonstrated in study area B. At this site the weak Cabot Head shales are presently exposed to direct wave attack during storms and high lake levels. The undercutting in these shales has resulted in the failure of massive blocks of Dyer Bay dolomite onto the backshore of the active shingle beach.

In study areas B and C the upper member of the Amabel formation has receded inland well beyond the study sites. Also, the Fossil Hill Formation and part of the lower Amabel member have been covered by scree from the two formations. The removal of this amount of the Amabel Formation has probably not resulted from mass wasting processes but more likely by glacial erosion. Support for this argument is the lack of debris found on the Escarpment which would have been present if mass wasting were the dominant process responsible for the recession of the face.

The action of glacial ice, which may have decreased the general slope angle of the Escarpment in this location coupled with the burying of the Fossil Hill Formation with scree has prevented more recent undercutting of the Amabel Formation. As a result of this glacial erosion, subsequent mass wasting and deposition of scree at the cliff base, the Escarpment in effect has stabilized itself. The decrease in the amount of debris fall has also allowed the development of a relatively thick soil cover and more mature vegetation communities on these slopes.

Table III also shows that at both a small scale (the land units) and at a larger scale in association with specific landform features (the 1 km sections) the forest cover has a very clear relationship with surficial conditions. In general, areas of currently active talus accumulation may be identified by the presence of *Thuja occidentalis* although *in situ* break-up of previously accumulated talus may also be indicated by the presence of this same species (Area B). Consequently, the presence of this species may be used to satisfy one of the major objectives of this study in that it may be used as a fairly reliable indicator of ground surface instability. Also, there is the additional advantage that this species is readily identifiable on air photographs. Therefore, initially, a rapid assessment of areas of potential surface instability may be made, although in each case ground observations are essential to overcome such problems as identified in Area B.

The presence of other tree species, particularly *Betula*, when growing in association with *Thuja*, may also be indicative of a community pattern developing on an area of somewhat greater stability and representing a somewhat later stage in development from the pioneer *Thuja* community. Human activities and land use history must also be taken into consideration when attempting to explain the significance of different species in community succession. Detailed patterns of community succession may also yield further information about community age. Here a distinction has to be made between those communities reproducing themselves and those which appear to be in some developmental stage towards community "stability". The underlying causes of these patterns may be, in part, environmentally controlled although caution should be exercised here given current thinking on community dynamics and the relative significance of the concepts of community succession and stability.

CONCLUSIONS

It is therefore quite evident that there are relationships between plant community characteristics and surficial materials and processes in this area. The information provided by such a study of their interrelationships can lead not only to an understanding of the processes currently operating on the Escarpment but also to a better understanding of the evolution of the area. The application of this information to particular resource management problems is fundamental but is, regrettably, frequently neither sought nor is it normally available. To the particular issue of the slope stability of the Escarpment such knowledge is essential. Given further data accumulation a model of surficial environmental processes, both geomorphological and biophysical, may be derived which has more general application to other areas of the Niagara Escarpment. Some tentative suggestions have been made by MOSS and ROSENFELD (1978). As part of an ongoing project, such a model may be developed but at this stage the basic relationships established here do lend themselves to further application in this particular resource management problem.

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