SLOPE AND VALLEY FORMS IN THE CLAY LOWLANDS OF THE OTTAWA AREA

by

RAYMOND LESLIE CROOK

A THESIS

SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF ARTS

DEPARTMENT OF GEOGRAPHY

UNIVERSITY OF OTTAWA

OTTAWA, ONTARIO

DECEMBER, 1972

ACKNOWLEDGEMENTS

I would like to express my gratitude to the many people who have assisted me and provided encouragement at various stages during this study. In particular, I wish to thank my supervisor, Dr. H.M. French, for his direction, patience, encouragement, and constructive criticism of the research, compilation and writing stages of the thesis.

Considerable appreciation is also extended to Dr. L.B. Leopold for his constructive criticism of earlier drafts of the thesis and to Professor D.E. Erskine, who identified plant species in the field, who discussed the significance of the botanical findings with me at length, and who encouraged me in general by his interest in the study at all stages.

I am indebted to the Department of Geography of the University of Ottawa, and to Dr. H. Morrissette in particular, for ensuring that I had sufficient funds to complete this research. I am also grateful to the Department of Geography of the University of Victoria which willingly allowed me to use its facilities and expertise. In particular, I wish to thank Dr. M.A. Micklewright, Mr. I.H. Norie and Mr. J.F. Bryant for their invaluable assistance and constructive suggestions in the preparation of the figures and text for reproduction.

Thanks go to Mrs. Wendy Foremen who typed the final draft of the thesis and to Miss Margaret Cowan who, in addition to typing earlier drafts, was always a source of help and encouragement.

Finally, I wish to acknowledge the assistance of all of those field assistants, librarians, etc., without whom , the study would have been infinitely more difficult.

ABSTRACT

The thesis examines the forms and origins of small valley systems within the clay lowlands around Ottawa and is particularly concerned with the respective roles of past and present conditions in shaping their evolution. The valleys exhibit major variations in form and discharge. They may be dry and V-shaped or may possess a perennial but underfit stream which meanders upon an alluvial floodplain. Three valley systems which reflect these contrasts were selected for detailed observation. They are located at Gatineau, Trend Village and Gloucester Glen.

The roles of contemporary processes in the shaping of slope and valley form were evaluated with the aid of field observations of form, discharge, slope processes, microclimate, soils and vegetation. The fundamental control of land form appears to be the behaviour of the basal stream. No significant variations of slope form with aspect were noted whereas three main types of slope system were identified which depend upon the influence of the basal stream.

(i) Slopes on the outer bends of meanders in floodplain valleys are powerfully undercut. Their soils and plant associations are degraded. Maximum angles are steep, rates of curvature are high and forms are dominantly convex.

(ii) Slopes which experience no undercutting within such valleys support developing soils and plant associations. A basal concavity may be present. Rates of curvature tend to be low

and maximum angles are gentle. At Gatineau, where undercutting is absent in many of the seasonally dry valleys, slope form is complex, consisting of successive convexo-concave sequences. The mid-slope facets are probably terraces. The present slopes appear to be static and probably resemble those at the time when active fluvial processes ceased.

(iii) In many of the dry valleys, discharges are active during the spring melt. Slope forms reflect the balance between weak processes of fluvial undercutting and gravitational processes. Soils and vegetation associations appear to be at arrested stages of development as a result of this equilibrium. The maximum angles, rates of curvature and the relative developments of convex and concave slope segments depend upon this balance.

The role of historical conditions in the shaping of the valleys is indicated by the characteristics of present-day discharges. The valleys were initiated on the surface which emerged from beneath the Champlain Sea and, for which, maximum and minimum dates are approximately 10,000 B.P. and 7,500 B.P. respectively. The extensive terrace systems of the Ottawa River reflect both discharge decline and base level decline since the regression. Palynological evidence suggests that, during the regression, climatic conditions were cool and moist (9,000 to 8,000 B.P.) and, as such, would have been ideal for valley initiation. The subsequent warmer, drier phase could then have encouraged the onset of underfitness which has produced the present meandering streams. Where the additional influence of base level decline was

also considerable, valleys may have been rendered dry and currently experience discharges only during the spring melt. Such valleys are usually V-shaped. In conclusion, the present forms of the valleys and their slopes are a direct response to the impact of these historical circumstances upon basal stream activity.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF SYMBOLS

A	Gloucester Glen
B	Trend Village
C	Gatineau
Cc	concave slope segment
CV	coefficient of variation - $\frac{SD\%}{\bar{x}}$
Cx	convex slope segment
DF	degrees of freedom
F	frequency
Hi	the alternative hypothesis
Ho	the null hypothesis
i	the value of the lowest boundary of the lowest class of a frequency histograph
k	the range of each class in a frequency histogram
L_{max}	the index of asymmetry for maximum angles
L_{mean}	the index of asymmetry for mean angles
Mo	mode
N	number of individuals in a population
p	the probability associated with the occurrence under Ho of a value as extreme as or more extreme than the observed value
R	rectilinear slope segment
s	level of significance, probability of rejecting Ho when it is true
SD	standard deviation
T Total	indicates the entire distribution of an observed variable i.e. of the combined observations from the three study areas
'U'	the statistic in the Mann/Whitney 'U' test
$\bar{x}$	arithmetic mean
X^2	chi square
z	the deviation of the observed value from the mean under Ho when SD = 1; z is normally distributed
Zi	intermediate slope zone
Zl	lower slope zone
Zu	upper slope zone

C H A P T E R O N E

INTRODUCTION

1(a) The Aims of the Thesis

The object of this thesis is to investigate the form and origin of certain small valleys in the Ottawa area. These valleys are minor tributary developments of the Ottawa River drainage system and they are usually incised within late-Quaternary surficial materials. With the aid of slope profile data and other quantitative field observations, the study attempts to assess the relative roles of past and present physical conditions in the shaping of these valleys. Special emphasis is directed towards the relationship between slope form and process.

The only major work which directly concerns such valleys is that of J.A. Heginbottom (1967) whose investigations were conducted in the Montreal area. Other similar valleys, however, are common in many parts of the Ottawa River valley between Montreal and Pembroke. They represent a phase of fluvial downcutting which was initiated during the last 10,000 years and which has been intimately linked with the development of major river terraces.

In a regional sense, the relevance of the study lies in its attempt to contribute towards a further understanding of events in the recent geomorphological evolution of the Ottawa area. These events begin with the waning of the Wisconsin ice sheet which was the most recent glacial phase in eastern North America. Deglaciation was accompanied by a marine transgression into the Ottawa-St. Lawrence lowlands. By approximately 10,000 years ago, this major marine incursion, which has been termed the Champlain Sea, had begun itself to give way to freshwater and subaerial condit-

ions. This transformation and subsequent events are perhaps less well documented than those of the marine phase itself.

The present study, by describing and attempting to interpret some of the landform assemblages of the region, complements research on other aspects of the post-marine phase, such as the nature and dating of the regression of the sea (see E. Antevs, 1925, 39; J.A. Elson, 1963, 68, 69; J.A. Elson and J.B. Elson, 1959; N.R. Gadd, 1961, 63), the characteristics of post-marine deposits (see W.A. Johnston, 1916, 17; Antevs, 1939, Gadd, 1961, 63), the magnitude of recent isostatic uplift (see T.C. Kenney, 1964), the post-marine evolution of the main channels of the Ottawa, Gatineau and Rideau Rivers (see Johnston, 1917; J.W. Goldthwait, 1933; Gadd, 1963; J. Lemenestral, 1966; G.D. Hobson, 1970), the dating of the abandoned courses of these rivers (see R.J. Mott and M. Camfield, 1969), the nature of the major terrace assemblages (see Johnston, 1916, 17; Goldthwait, 1933; J.R. Mackay, 1949) and the trends in late-Quaternary climatic fluctuations (see J.E. Potzger, 1953; J. Terasmae, 1959, 60, 61; J. Terasmae and P. Lasalle, 1968).

The study is also of interest in that it considers an area in which slope instability is a significant engineering problem. Fluvial processes are frequently operative within Champlain Sea sediments in the vicinity of Ottawa. The deep-water facies of this sediment sequence is a fine blue-grey clay which is highly sensitive and prone to liquefaction (E. Penner, 1965). Where the processes of incision and undercutting produce high-angle slopes

within this material, rapid slumping may follow. In the past, such clay slopes have been considered from an engineering standpoint, for example by C.B. Crawford and W.J. Eden (1967) and by W.J. Eden and R.J. Mitchell (1970). In the present study, however, land form is considered to be a component of an integrated system which also comprises a series of fluvial, climatic, biological and lithological variables. Geomorphological research which seeks to explain environmental variables as responses to each other is now commonplace (see, for example, M.A. Melton, 1958; J.T. Hack and J.C. Goodlett, 1960; J. de Ploey and J. Savat, 1968; M.A. Carson, 1969a) and frequently involves a systems approach (see, for example, Hack, 1960; F. Ahnert, 1967; R.J. Chorley, 1967; A.J. Conacher, 1967; C.S. Denny, 1967).

The remainder of Chapter One considers the recent geomorphological history of the Ottawa area and describes three field sites which were selected for detailed investigation during this study. Chapter Two discusses the significance of slope form. The chapter begins with a critical review of some of the theories which have been advanced in order to interpret the relationship between slope form and slope processes. This is followed by a consideration of the relevance to slope form studies of the characteristics of lithologies, slope processes, fluvial processes and historical factors. In Chapter Three, field observations are presented concerning the nature of slope and valley forms within the three local study areas. The forms of 103 measured slope profiles are classified and parameters of angle, dimension and shape are considered

and compared. In Chapter Four, the characteristics of both past and present processes in the study areas are reviewed. The first part of the discussion consists of a summary of field observations on the nature of present-day processes, soils, vegetation assemblages and microclimates. The latter part of the chapter considers the role of historical conditions in initiating and shaping the valleys. In the concluding chapter, an explanation of the nature and variation in slope morphology is attempted. Three slope models are constructed and, within each, the characteristics of present slope systems are related to the historical conditions which have influenced slope development.

1(b) The Geomorphological History of the Ottawa Area

A review of the geomorphological history of the Ottawa area is essential to any consideration of the nature and origin of the valleys. The area consists of two physiographic regions. In the north are the PreCambrian uplands of the Canadian Shield which are bounded to the south by the Eardley escarpment. To the south are the lowlands of the Ottawa valley. These are veneered by Quaternary materials which overlie both PreCambrian rocks and Ordovician limestones and shales.

A.E. Wilson (1946) has examined the bedrock and economic geology of the area, and Johnston (1916, 17), Antevs (1925, 39) and Gadd (1961, 63) have reviewed and discussed its Quaternary evolution. It appears from such studies that the main topographic

features of the area, which are present today, were already in existence during the immediate pre-Pleistocene period. Although the Quaternary era did not drastically modify these features, it produced the landforms and materials which are the object of the present study.

The nature of the advance and retreat of the Wisconsin ice sheet in the Ottawa area has been documented by both Gadd (1961,63) and V.K. Prest (1970). There is little evidence of previous ice sheets. Deglaciation produced a rise in sea level which was more rapid than the isostatic response of the land to the removal of the ice overburden. Retreat of the ice was accompanied initially by the formation of large freshwater lakes but this transitory phase was rapidly replaced by marine conditions. The approximate extent of the marine inundation, which is known as the Champlain Sea, is indicated in Figure 1.1 (p.7). In the Ottawa valley itself, marine conditions extended to some miles beyond Pembroke. The Sea was responsible for the deposition of large tracts of marine sediments (Fig. 1.2,p.8). Some landforms were wave-washed and reshaped, and others, such as sand bars and spits, were created. It appears that, after attaining an early maximum depth, the Sea shoaled and there was a gradual transformation from marine to subaerial conditions.

The importance of this change should be stressed because it was at some time during the post-marine phase that the tributary valleys were initiated. The nature and dating of this transformation has been the object of conflicting interpretations. Gadd (1961,

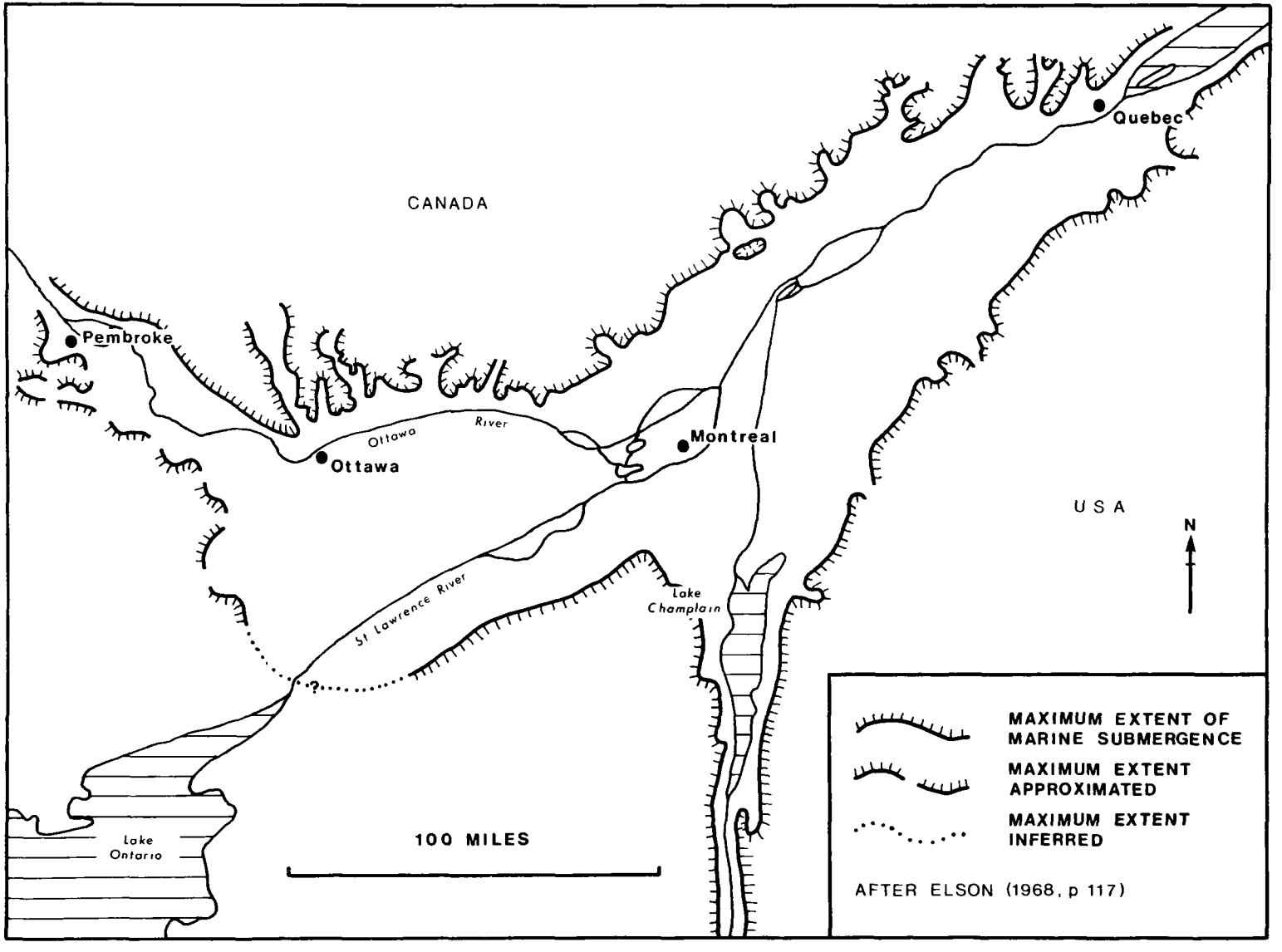


FIG. 1.1. THE MAXIMUM EXTENT OF THE CHAMPLAIN SEA

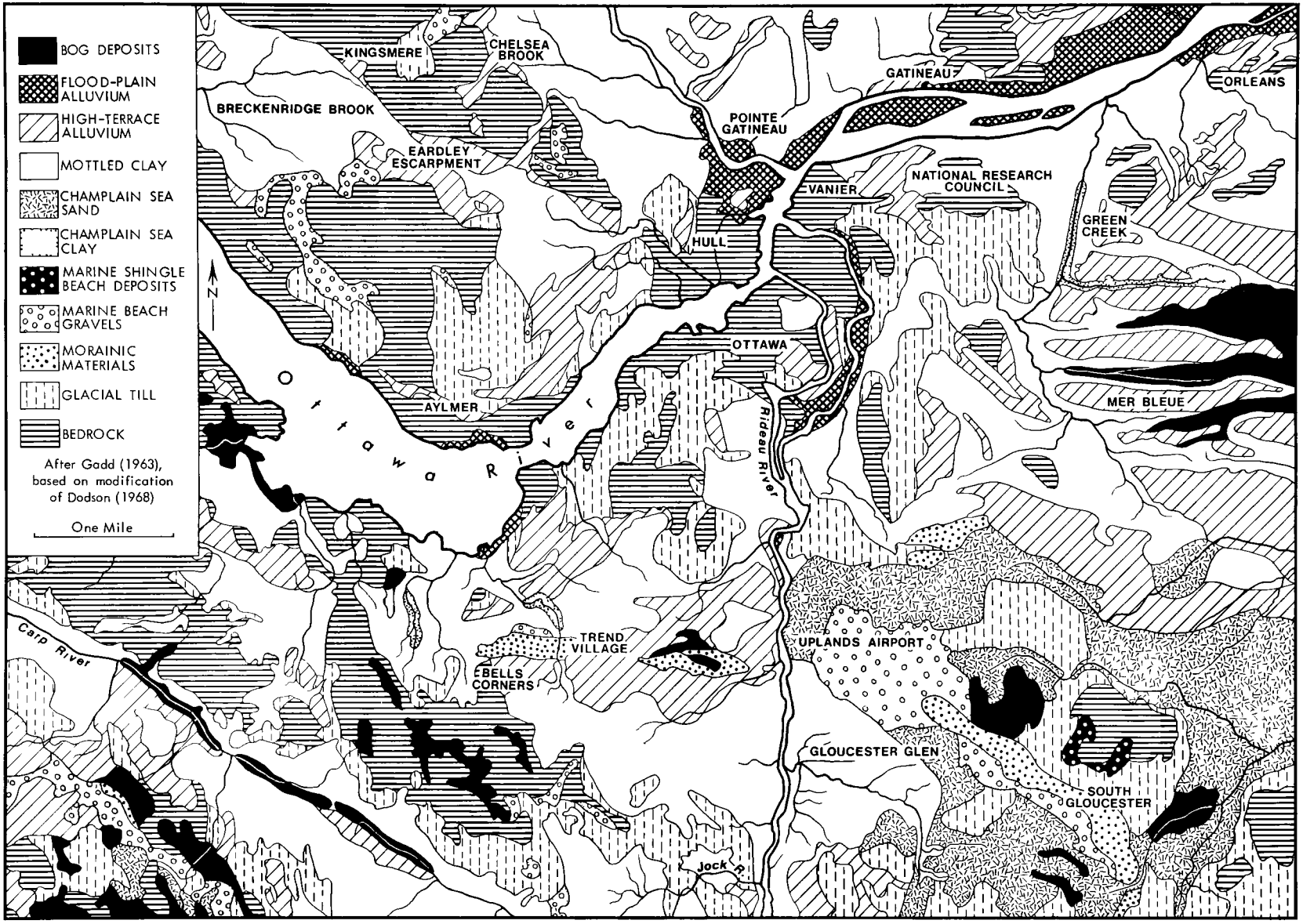


FIG 1.2 THE SURFICIAL GEOLOGY OF THE OTTAWA AREA

63) has argued that marine conditions ceased when the level of the waters in the valley had declined to an elevation of approximately 325 feet because it is only below this elevation that non-marine sediments overlie marine sediments. Antevs (1939), however, had contended that there was a later marine incursion which he termed the Ottawa Sea. His hypothesis depended particularly upon the recognition of two clays of marine origin.

Gadd (1961, 63) has described these two clays. The older Champlain Sea clay is light grey, massive, soft, fossiliferous and exhibits traces of oxidation above the water table. The younger brown mottled clay is brown to brownish grey and is stratified in places with alternating light and dark bands. It is stiff, non-calcareous, oxidized and tends to be mottled, even below the water table. Gadd postulated that the latter is a freshwater derivative of the former which has been redeposited by ancestral stages of the Ottawa River. The proposal implies that freshwater conditions have been continuous since the retreat of the Champlain Sea.

In support of this hypothesis, it is possible to demonstrate that there has been considerable isostatic recovery in the area. The most recent radiocarbon dating for Champlain Sea fauna is L604D which was determined for shells discovered at an elevation of 350 feet in the Ottawa area (W. Dyck and J.G. Fyles, 1962). The age of the shells is estimated to be 10,200 ±200 B.P. According to J.R. Curray (1965), mean world sea level at that time was approximately 200 feet below its present elevation (Fig. 1.3, p.10). By adding this figure to that for the altitude of the shells, one

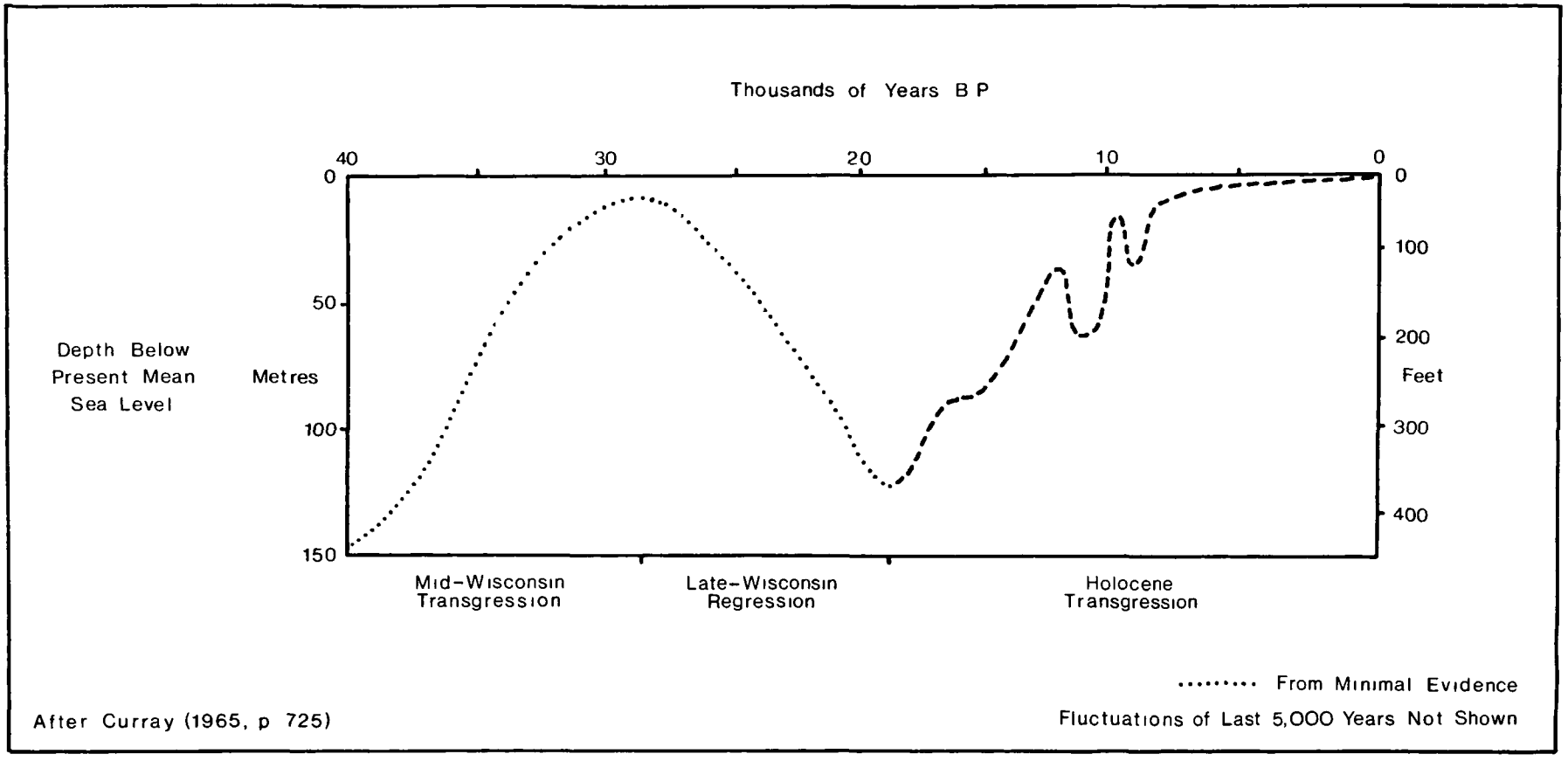


FIG. 1.3. LATE-QUATERNARY FLUCTUATIONS IN SEA LEVEL

may calculate that the minimum net isostatic uplift at the dated site has been 550 feet since 10,200 B.P. (see Kenney, 1964, for discussion of procedure). The net rise in sea level since that time has been 200 feet and Figure 1.3 suggests that this rising trend has been consistent rather than fluctuating. There have been no reports of ice re-advances in the Ottawa area during this period which might have resulted in isostatic downwarping. Under these circumstances, a phase of more recent marine conditions is unlikely.

Despite the differences which have been stated, the hypotheses of Gadd and Antevs are similar in that they involve the deposition of a clay since the retreat of the Champlain Sea. Since the clay which overlies the Champlain Sea clay is areally very extensive (Fig. 1.2, p.8), such a phase of deposition would have been of major proportions. Furthermore, since this clay characteristically veneers the fluvial terraces into which the small tributaries are incised, these latter could not have been initiated until after the clay was deposited.

In 1965, a different interpretation of the origin of the upper clay was offered by Crawford and Eden who demonstrated that many of the geotechnical characteristics of the two clays are similar. It should be noted that these authors employ criteria for distinguishing the clays which are different from those which Gadd has employed. In areas where Gadd has identified the brown mottled clay, however, Crawford and Eden describe a clay which is overlain by an oxidized crust. More recently, it has been stated that,

> The weathered crust of Leda clays....(This is

> an engineering term for the Champlain Sea clay) ....is of variable thickness and may extend to a depth of 10m. It is identified by decreasing field vane strength with increasing depth....The crust consists of two layers: an upper oxidized layer which extends approximately to the depth of seasonal variation of the groundwater table, and a lower layer of gray clay. The upper portion of the crust is strongly fissured and may allow water to move freely through the clay. (Eden and Mitchell, 1970, p.285).

It is possible, therefore, that the brown mottled clay is a leached crust of the marine clay. This hypothesis accords with other evidence which suggests that, within the Ottawa area, the post-marine phase has been characterized by the dominance of processes of erosion.

It appears that, initially, an undulating, bedrock-controlled marine plain began to emerge as relative sea level declined. Field evidence suggests that the altitude of this plain would have lain between 300 and 360 feet (Gadd, 1963; Crawford and Eden, 1965; Lemenestral, 1966). As an example of this evidence, Crawford and Eden have demonstrated that normally-consolidated clays occur between these elevations whereas clays at lower elevations have become progressively more overconsolidated as a result of loading by the sediment overburden (Fig. 1.4, p.13). Most of the small tributaries in the Ottawa area appear to have been initiated on this surface. The radiocarbon date L604D (Dyck and Fyles, 1962) provides a maximum age of 10,200 B.P. for this surface. The exposure of the marine plain to subaerial processes, however, was probably rather gradual. As Gadd (1961) has reported, considerable quantities of meltwater discharge

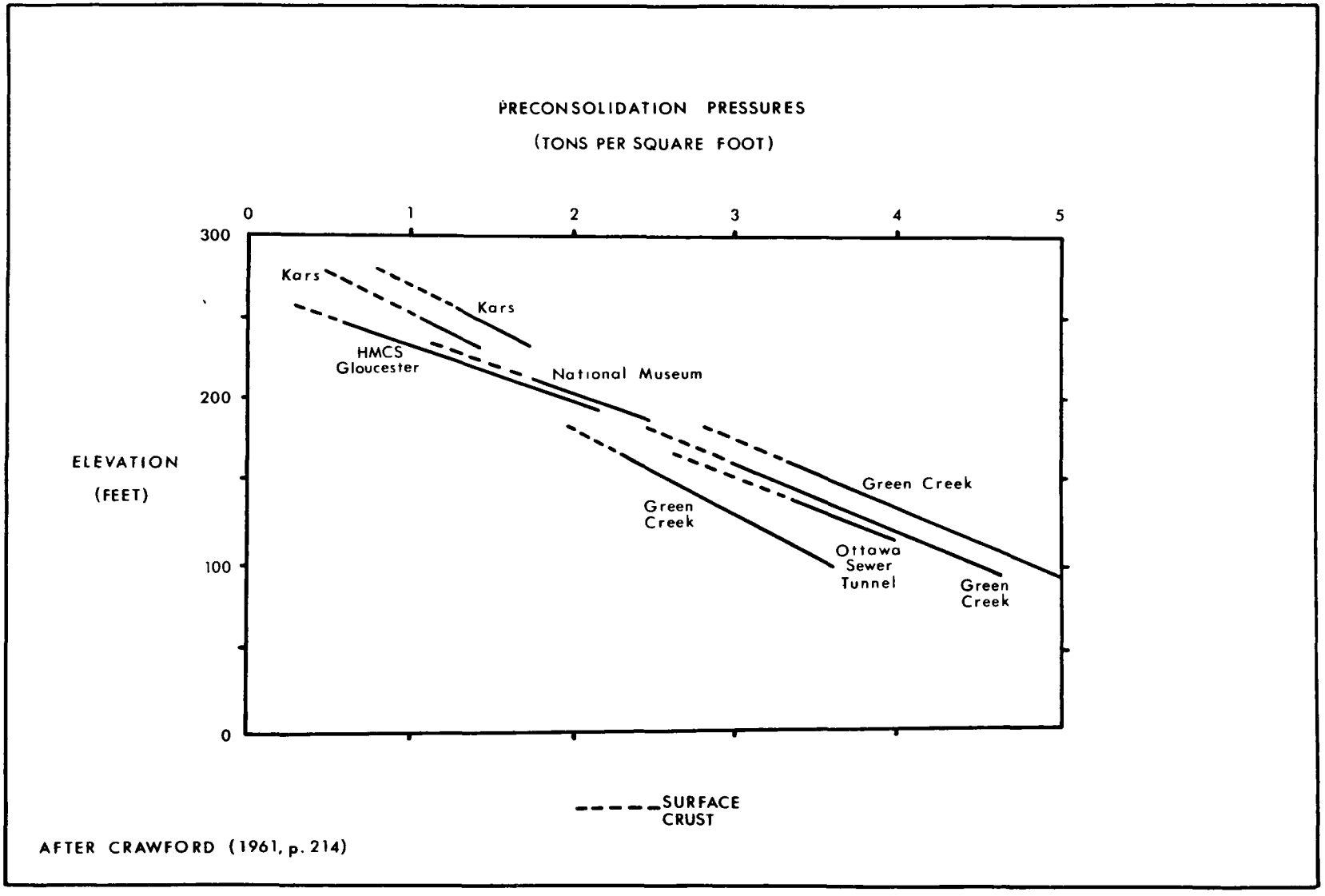


FIG. 1.4. PRECONSOLIDATION PRESSURES FROM BOREHOLES IN LEDA CLAYS AT OTTAWA

from Lake Algonquin, a predecessor of the Great Lakes, were supplied to the Ottawa River through the Fossmill channel near Mattawa. As this source of discharge declined, that of the Ottawa River was reduced. Of the several channel outlets in the Mattawa area, the most recent was closed by 5,250 B.P. (radiocarbon date GSC-1162), a date which was derived from wood fragments. During this phase of discharge decline, the Ottawa River was also influenced by the decline in elevation of regional base level. The river began to dissect both its alluvium and the marine clay beneath it. If the small tributary valleys were initiated at this time, it is possible that they developed as extended consequent streams on the emerging surface. A similar process of stream initiation was envisaged for the Montreal area by Heginbottom (1967).

As a result of the declines in both discharge and base level elevation, the Ottawa River developed a series of terraces. These features are discontinuous and are associated with veneers of channel, bar, delta and spit deposits (Gadd, 1963 - see Figure 1.2, p.8). The approximate locations of the bluffs and terraces are mapped in Figure 1.5 (p.15). The information for this figure was obtained from an analysis of topographic sheets and aerial photographs. Although the terraces are discontinuous and have been locally influenced by warping, an attempt to identify and classify the various levels has been reproduced in Figure 1.6 (p.16). The inferred marine surface varies in elevation between 360 and 290 feet, partially because of rock control, warping and local tidal scour or fluvial erosion. Younger terraces are frequently divided

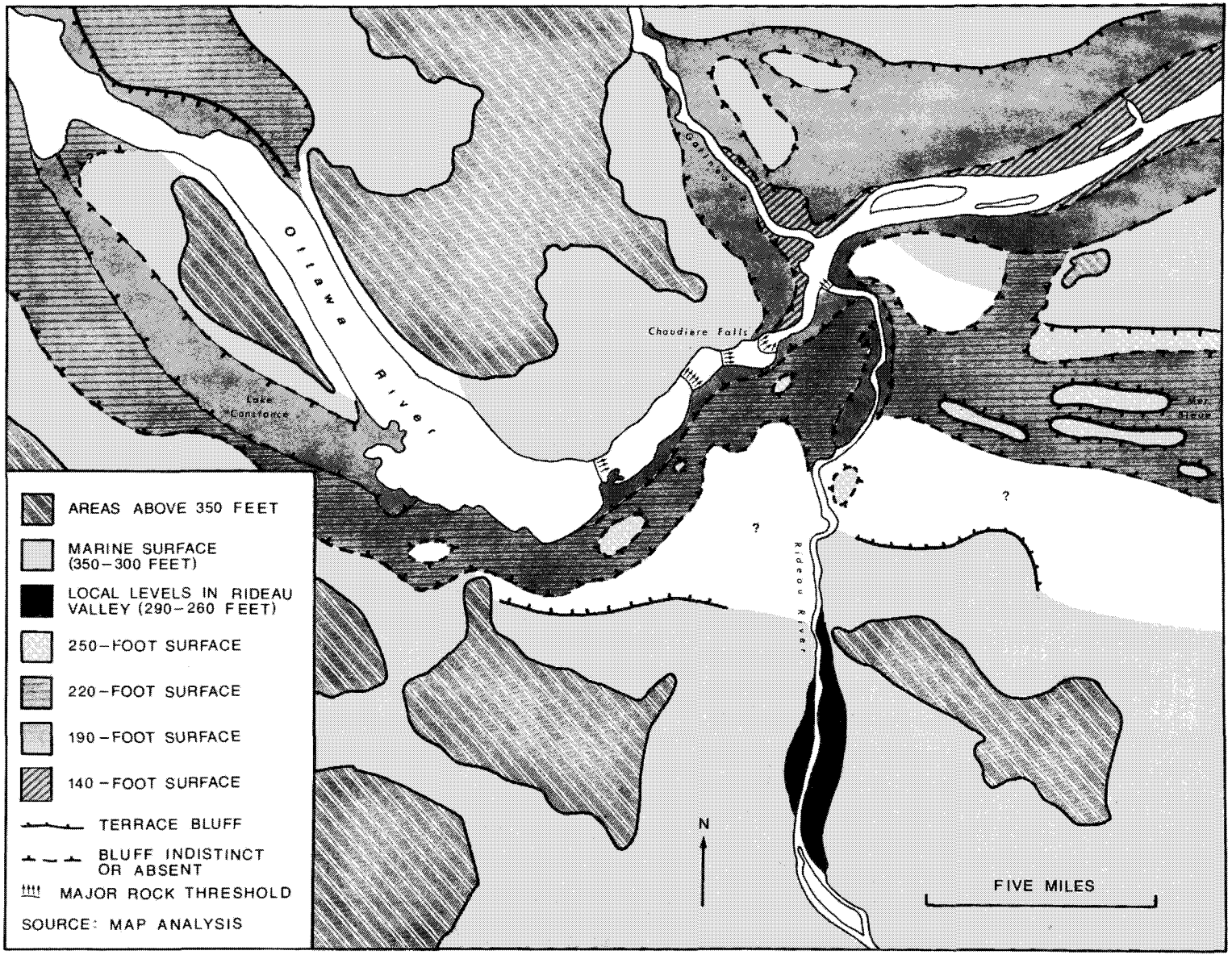


FIG.1.5. APPROXIMATE LOCATIONS OF BLUFFS AND TERRACES IN THE OTTAWA AREA

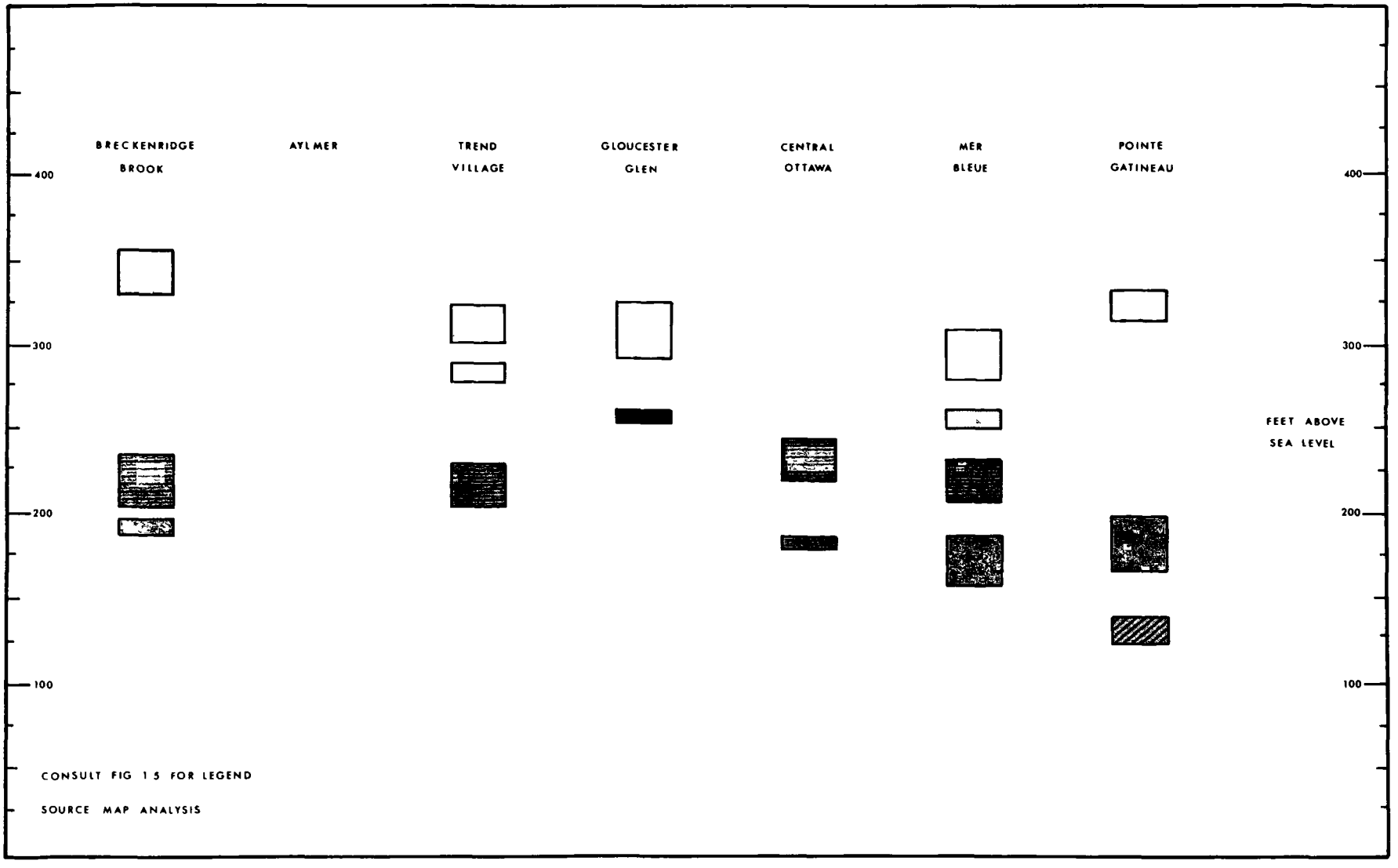


FIG. 1.6. PROPOSED CORRELATION OF TERRACE LEVELS IN THE OTTAWA AREA

by islands whose summits represent the dissected remnants of older terraces. The most recent terrace, which is at an elevation of approximately 140 feet, occurs only below the Chaudière Falls.

From this information, it is possible to suggest the main adjustments in drainage pattern which may have taken place since the initiation of the post-glacial Ottawa River. Four main stages are recognized in Figure 1.7 (p.18). At stage one, during the marine regression, an estuary existed which was between five and seven miles wide and which possessed several islands. With the development of stage two (the 220-foot surface), most of the discharge became confined to the Mer Bleue path. At the 190-foot stage (stage three), the Ottawa River above the Chaudière Falls was almost in its present position with the exception of a path of discharge through the Lake Constance area. Furthermore, the Mer Bleue path was now abandoned because further downcutting was inhibited by a rock threshold in the vicinity of Alfred, some forty-five miles to the east of Ottawa. The drainage had been totally diverted to the more northerly channel which it presently occupies. This channel, however, had been operative at least as early as the 220-foot stage since morphological evidence suggests connecting channels. The major features of the present drainage pattern in the Ottawa area are indicated in stage four. The Lake Constance channel is dry and the 140-foot surface is in the process of development downstream from Ottawa. Downcutting further upstream is inhibited by the rock threshold at the Chaudière Falls.

Radiocarbon dates are available only for the 220-foot

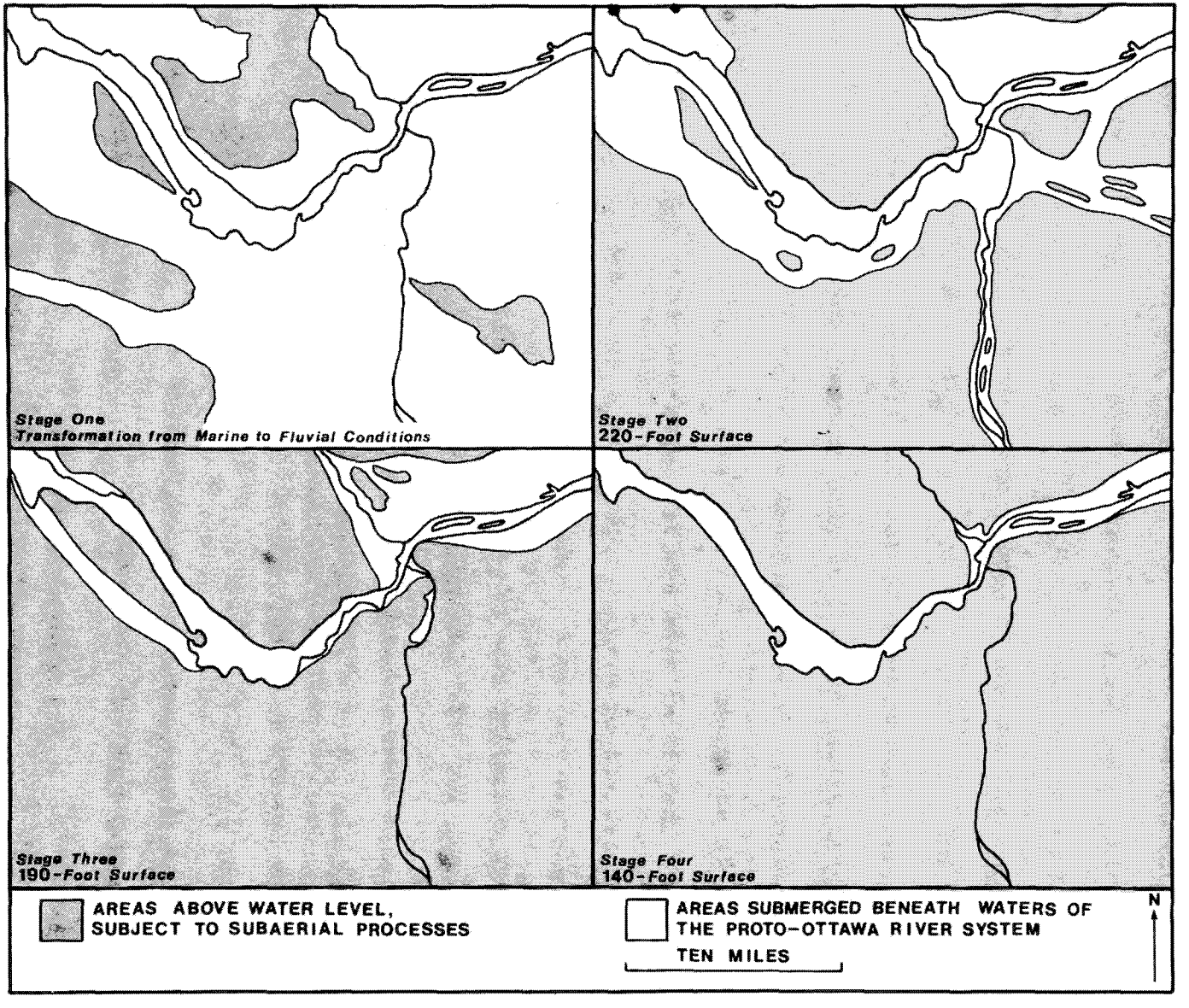


FIG.1.7. STAGES IN THE DRAINAGE EVOLUTION OF THE OTTAWA AREA SINCE THE RETREAT OF THE CHAMPLAIN SEA

surface and are presented in Table 1.1 (p.20). There are two dates for the minimum age of the abandoned channels in the Mer Bleue region, one at 6,750 B.P. and the other at 7,650 B.P. Other dates are available from Catherine Street and Richmond Road. It appears from this data that, during the 2,500 years which followed the termination of the Champlain Sea, the marine surface and several fluvial terraces had been abandoned and the 220-foot surface had been created. During that period, therefore, the Ottawa River achieved approximately 100 feet of downcutting. During the succeeding 7,500 years, perhaps only 60 feet of downcutting has been achieved, and this only below the Chaudière Falls. Furthermore, 7,500 years constitutes a minimum age for the emergence of the marine surface upon which the study valleys were initiated.

The evolution of the drainage pattern in the Ottawa valley would undoubtedly have been influenced by important regional climatic fluctuations. Both temperature and precipitation influence runoff, discharge, and sediment yield so that cool and moist climatic conditions favour the operation of fluvial erosion processes (G.H. Dury, 1964a). The findings of Potzger (1953), Terasmae (1959, 60, 61) and Terasmae and Lasalle (1968), which are applicable in general to the Ottawa-St. Lawrence lowlands, are presented in Table 1.2 (p.21). The investigations of these researchers, which were based upon palynological evidence, indicate a change from cool and moist to warm and dry conditions and a subsequent return to cool and moist conditions. It may be that either of the cool, moist periods (from 8,000 to 9,000 years ago or during the

TABLE 1.1. MINIMUM RADIOCARBON DATES FOR THE 220-FOOT SURFACE AROUND OTTAWA

DATE CODE	DATE (YEARS B.P.)	LOCATION	ALTITUDE (FEET)	STRATIGRAPHY	COLLECTOR	REPORTER
GSC 548	6750±150	MER BLEUE 45°23'20"N 75°31'0"W	220	GYTTJA	J. TERASMAE (1959)	LOWDON, FYLES AND BLAKE, 1967
GSC 681	7650±210	MER BLEUE 45°30'0"N 75°30'20"W	225	GYTTJA	J. TERASMAE (1959)	LOWDON,AND BLAKE 1968
GSC 628	7870±160	CATHERINE ST 45°24'N 75°42'W	220	GYTTJA	J. TERASMAE (1959)	LOWDON, FYLES AND BLAKE, 1967
GSC 547	8220±150	RICHMOND RD 45°21'N 75°48'W	235	WOODY PEAT	N.R. GADD & J. TERASMAE (1961)	LOWDON, FYLES AND BLAKE, 1967
GSC 546	8830±190	GLADSTONE AVE 45°42'12"N 75°42'37"W	200	GYTTJA	R.J. MOTT (1966)	LOWDON, FYLES AND BLAKE, 1967

TABLE 1.2. POLLEN ZONES IN THE ST. LAWRENCE LOWLANDS IN THE POST-GLACIAL PERIOD

PROBABLE AGE (YEARS B.P.)	POLLEN ZONES OF POTZGER AND COURTEMANCHE (1953-1956)	POLLEN ZONES FOR ST. LAWRENCE LOWLANDS BY TERASMAE AND LASALLE (1959-1968)	
POST-GLACIAL 2,000	Q5 COOL, MOIST	I	I.S. Spruce D.S. Hemlock
4,000	Q4 WARM, MOIST	II	I.S. Beech, Hemlock S.S. Spruce, Fir, Birch D.S. Pine
6,000	Q3 WARM, DRY	III	I.S. White Pine D.S. Spruce, Fir, Hemlock, Beech
8,000		IV	I.S. Jack Pine, Fir D.S. Spruce, Birch
LATE-GLACIAL 9,000	Q2 COOL, MOIST	V	Spruce Maximum
10,000	Q1 WARM	VI	I.S. Pine, Birch, Alder, NAP. D.S. Spruce
12,000		VII	I.S. Spruce, Willow NAP.
14,000		VIII	I.S. Boreal sp., Spruce D.S. NAP

After Terasmae (1959) and Terasmae and Lasalle (1968).

I.S. = Increasing Species; D.S. = Decreasing Species;

S.S. = Supporting Species; NAP = Non-arboreal pollen.

last 2,000 years) could have favoured the initiation of the tributary valleys. None of these valleys has been dated by radiocarbon analysis, however, so that such speculation is reserved until Chapter Four where the evidence of valley form is considered.

1(c) Study Sites and Field Observations

For the purpose of field investigations, three areas were selected for study. It was required (i) that the field sites be located in different parts of the Ottawa area, (ii) that they be easily accessible and (iii) that they be free from obstacles to surveying such as dense covers of vegetation. The latter criterion is debatable, however, in view of the possible anthropogenetic nature of the valleys (see Heginbottom, 1967). Several potentially-suitable valley sites were located on maps and air photographs and these were subsequently examined in the field.

The three sites which were chosen are known in this study as Gloucester Glen (A), Trend Village (B) and Gatineau (C) - see Figure 1.8 (p.23). Three, one and four valleys respectively were considered at these locations. The valleys possess both north-south and east-west alignments in order to ensure the presence of slopes of various aspects. The vegetation in the valleys varies from associations of closely-cropped grasses where grazing occurs, to the initial stages of a bush association where grazing has been discontinued. Dense bush associations were avoided although trees are present in some valleys.

The brown mottled clay is present in all of the study valleys but the underlying Champlain Sea clay outcrops only rarely.

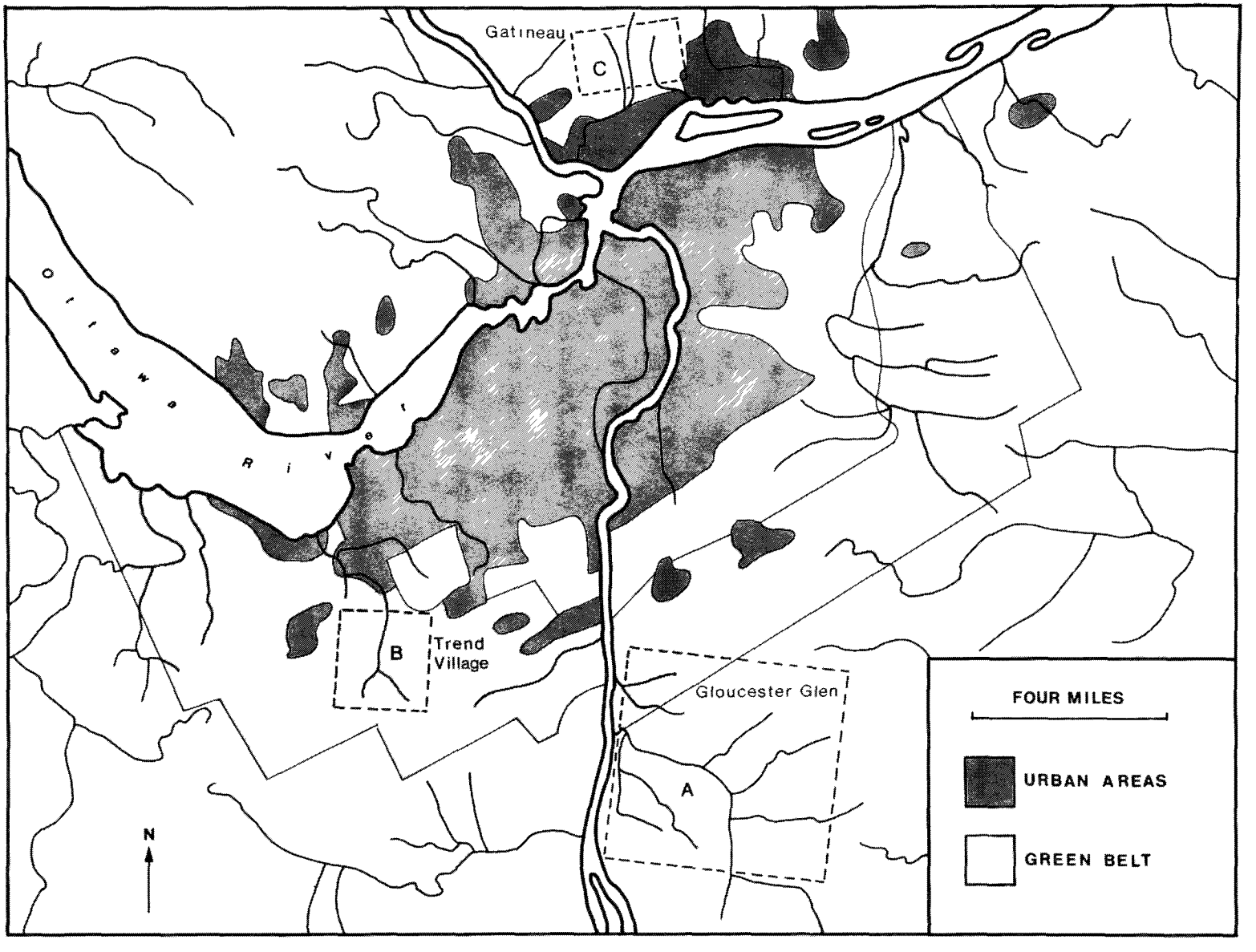


FIG. 1.8. THE LOCATION OF FIELD STUDY AREAS AROUND OTTAWA

The brown mottled clay appears to have been especially successful in attracting valley development. It is the dominant surficial material not only of the three areas of study but also of most of the other minor fluvial systems, as demonstrated in Figure 1.2 (p.8).

Morphology within the study valleys is varied. The valleys at Gatineau are short and deeply incised. Channel gradients here are steep whereas slope angles are lower than elsewhere. At Gloucester Glen and Trend Village, valleys are longer, slope angles are steeper and channel gradients are gentler than at Gatineau. The valleys at the three sites are also graded to various terrace levels which are related to different stages of drainage evolution.

The Gloucester Glen area (Fig. 1.9, p.25; Plate I, p.26) is located three miles to the south of Uplands Airport. At this site, a valley complex has become incised into the inferred marine surface to a depth of between twenty and thirty feet. In this area, which is adjacent to the Rideau River, the surface is underlain by brown mottled clay and ranges in elevation from 300 to 315 feet. It is flanked by areas which rise to approximately 375 feet on marine beach materials. The drainage system is graded to the floodplain terrace of the Rideau River which is situated at approximately 260 feet.

The drainage pattern at Gloucester Glen is dendritic and most tributaries appear to reach the main trunk valley (valley A1) from the north. The trunk stream is approximately seven miles in length. It is perennial and drops sixty-five feet along a course which meanders over a wide floodplain (Plate II, p.27). The valley-

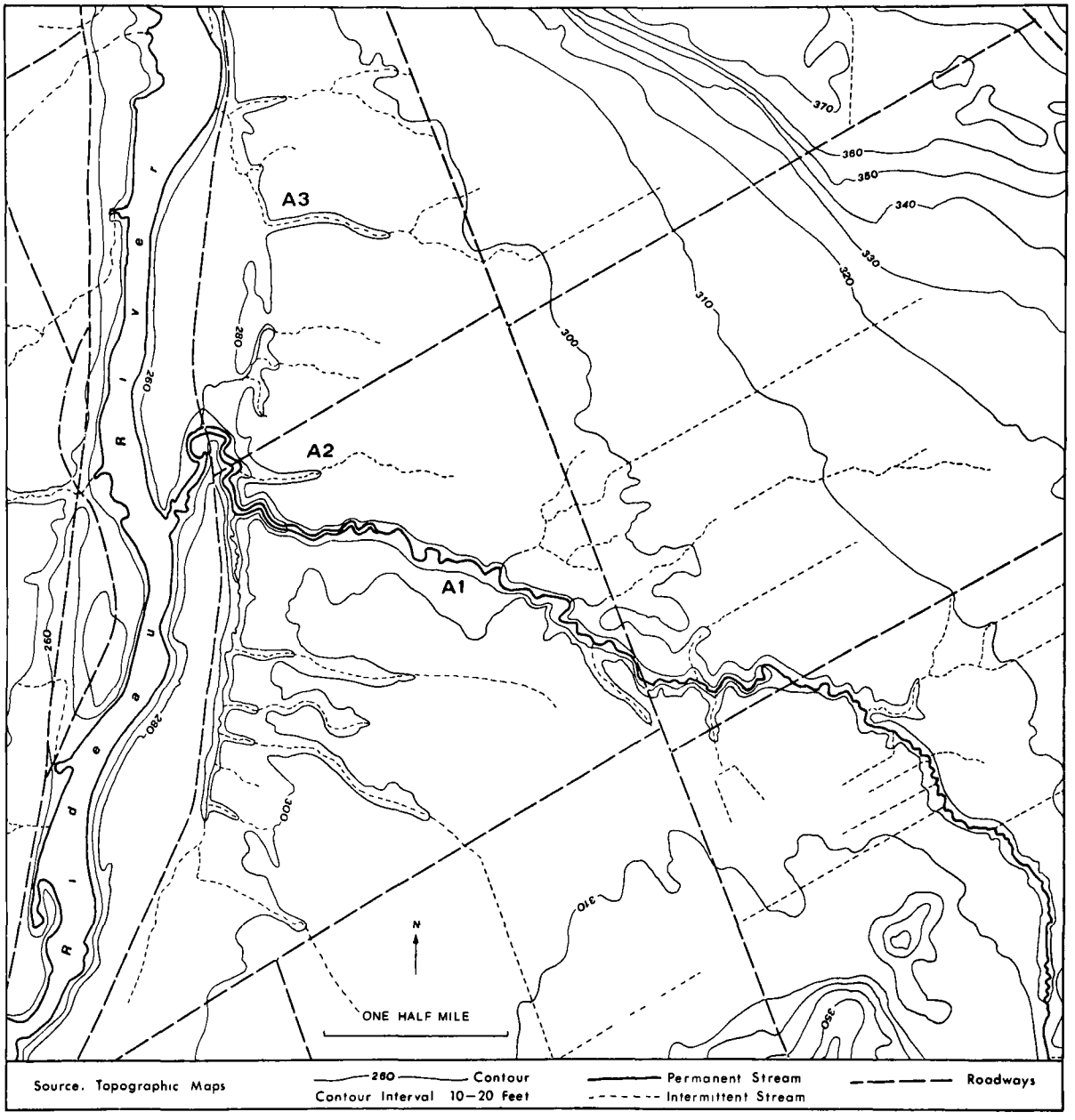


FIG 1 9 THE FIELD STUDY AREA AT GLOUCESTER GLEN

Plate I. Vertical aerial photograph of the study area at Glouces-ter Glen; scale approx. 1:15,900. (A19864-114, Air Photo Division, Canada Department of Energy, Mines and Resources).

Plate II. Valley A1, showing a detail of the channel and floodplain (grid ref. 469148).

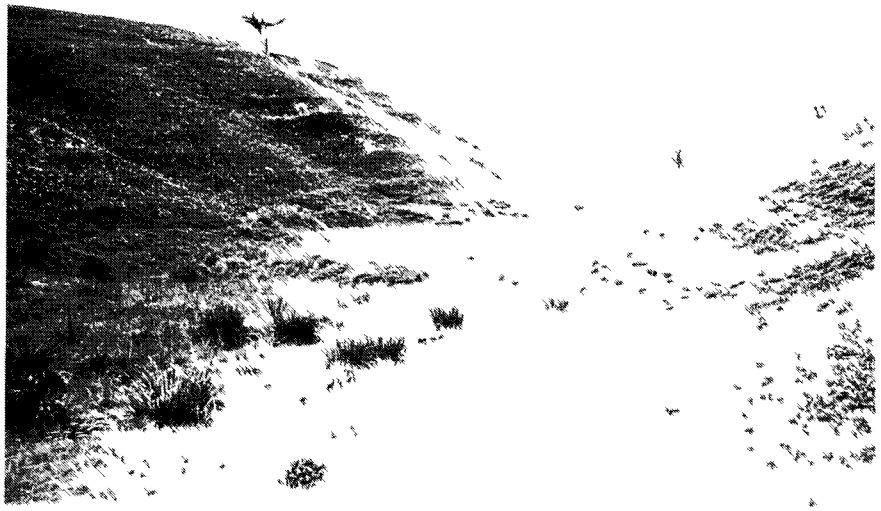


Plate III. Valley A2 looking upstream; slope terracettes and the dry channel containing moisture-loving sedges and [illegible] (grid ref. 457154).

side slopes are locally undercut by the stream and may attain angles of forty-two degrees. In valleys A2 and A3, discharge occurs only during the spring melting period. Valley A2 lacks a floodplain (Plate III, p.27) whereas, in valley A3, a small floodplain is situated astride a narrow incised channel (Plate IV, p. 29).

The stream network at Trend Village (Fig, 1.10, p.30; Plate V, p.31) flows northwards to the Ottawa River at Graham Bay and, in its lower reaches, passes through the urban developments of Leslie Park and Bayshore. The main stream (B1) crosses three terraces of the Ottawa River along a course of approximately seven miles during which it drops in elevation by 100 feet. The stream is incised into brown mottled clay on the lowest terrace, which varies in elevation between 210 and 230 feet (the 220-foot surface). The stream is entrenched into the Champlain Sea clay on the second terrace (270 to 290 feet) which is separated from the marine surface by a minor bluff (Fig. 1.5, p.15). This bluff is capped by marine gravels. At this point, brown mottled clay outcrops in the valley sides. The upper terrace (the marine surface, at 310 to 320 feet) is thinly veneered with alluvial sands which have been dissected to expose the brown mottled clay. On this surface, the valley possesses a floodplain. Stream undercutting has produced slopes which locally attain maximum angles of forty-five degrees. The volume of water which occupies the channel fluctuates seasonally but a continuous flow is maintained, even during summer (Plate VI, p.32). The drainage pattern varies

Plate IV. [illegible] area [illegible] channel [illegible] are [illegible].

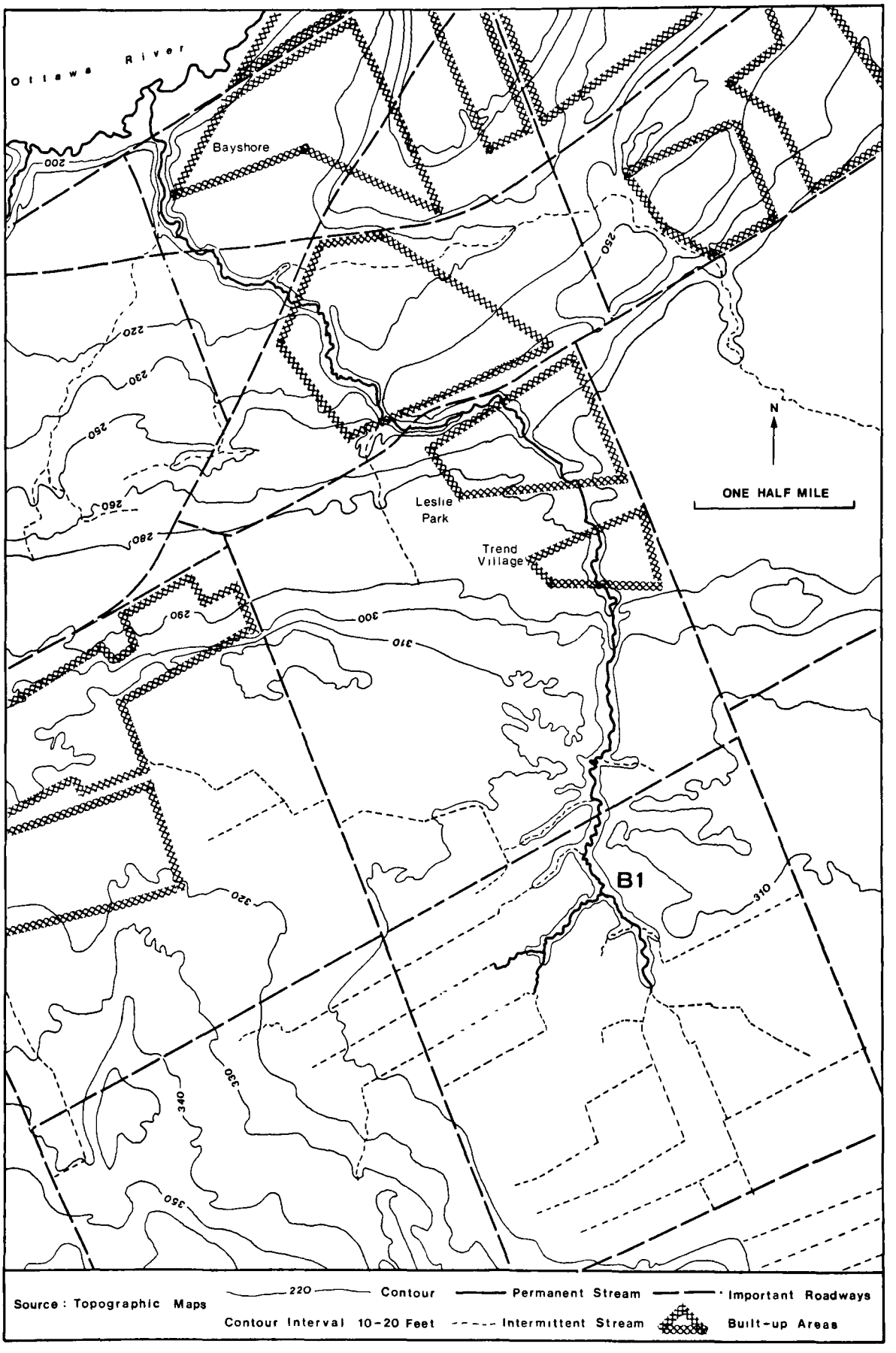


FIG 1 10 THE FIELD STUDY AREA AT TREND VILLAGE

Plate V. Vertical aerial photograph of the study area at Trend Village; scale approx. 1:2,500. (A20033-16 Air Photo Division, Canada Department of Energy, Mines and Resources).

Plate VI. Valley B in July; note the development of a bush association on the floodplain, stream discharge is small and the channel is over grown; the moraine surface is located above the valley (grid ref. 385184).

from terrace to terrace. It is dendritic on the upper surface where most tributaries are from the west. Further downstream, tributaries are absent.

The valleys at Gatineau (Fig. 1.11, p.34; Plate VII, p.35) are confined to a terrace bluff which separates terrace levels at 325 to 330 feet (the marine surface) and 150 to 200 feet (the 190-foot surface). The higher surface is capped by fine alluvial sands but the study valleys are incised into the underlying brown mottled clay. The bluff is approximately 100 feet high and the valleys which traverse it experience a considerable loss of elevation over distances which are usually less than one half mile. Valley depths are variable and may range from greater than seventy feet to less than ten feet. The smaller valleys are often unbranched and quasi-parallel,occurring as closely-spaced indentations in the terrace bluff. Larger valleys occasionally assume a dendritic pattern. The valleys lack floodplains and their headward limits are characterized by shallow depressions which do not possess fluvial channels (Plate VIII, p.36). The valleys are dry for most of the year (Plate IX, p.36) and fluvial processes do not appear to be effective.

The selected study valleys provide an opportunity for the consideration of many physical factors which may contribute to their present characteristics. Variations may be associated with differences in age, history, alignment and present physical environments. It is also possible to consider the modifying influences of man's activities. In some valleys, the tree vegetation has been

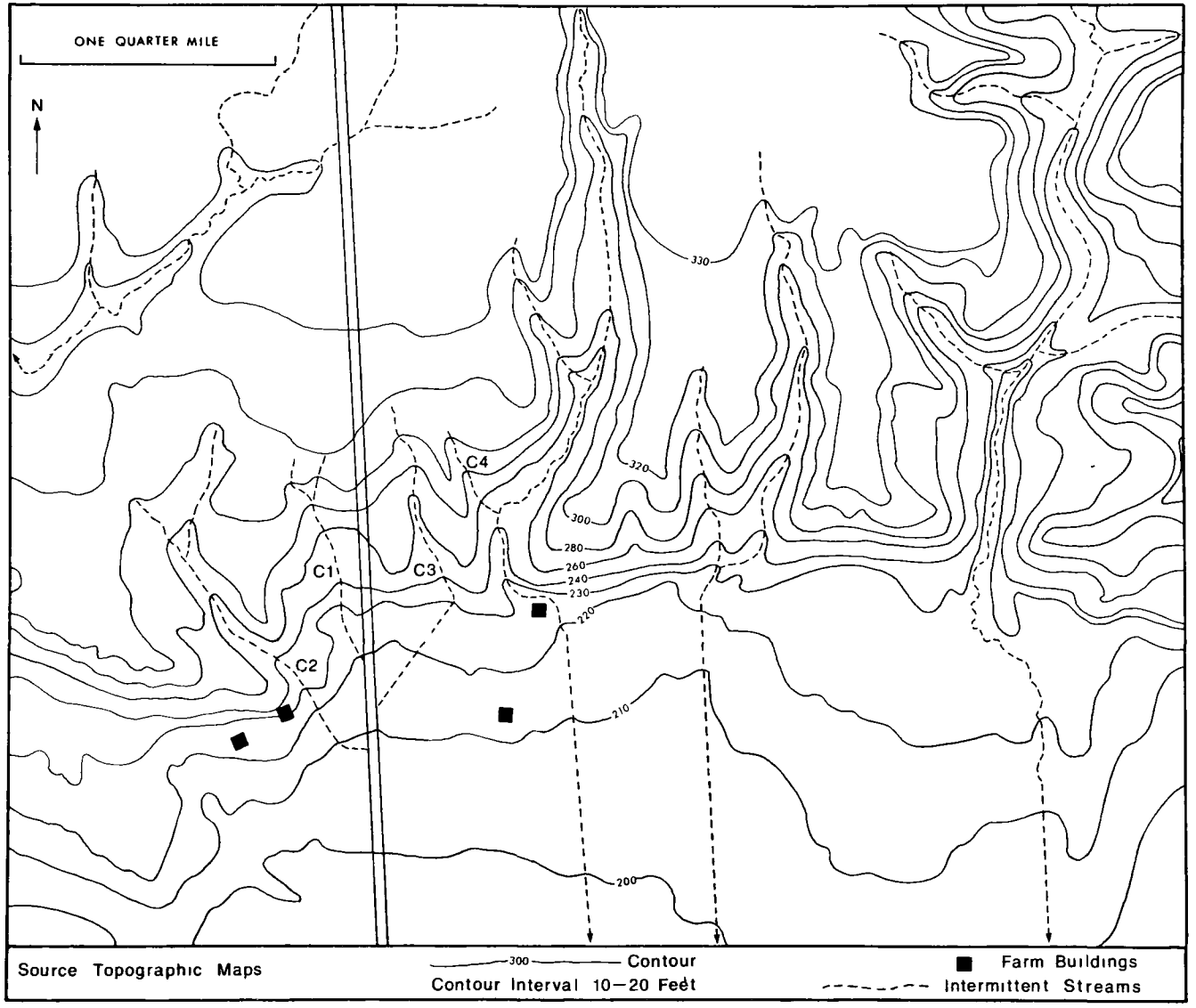


FIG 1 11 THE FIELD STUDY AREA NEAR GATINEAU

Plate VII. Vertical aerial photograph of the study area at Gatineau; scale approx. 1:5,800. (A20885-169, Air Photo Division, Canada Department of Energy, Mines and Resources).

Plate VIII. A detail of a typical small dry valley incised into the bluff at Gatineau; there is no distinct channel form (grid ref. 476383).

Plate IX. A detail of valley C3; the channel is indistinct; a prominent mid-slope facet is visible in the foreground (grid ref. 472382).

cleared. Grazing presently occurs in all valleys except valley B1. In the latter valley, it was necessary to confine field observations to the upper reaches because of the considerable downstream modifications which have resulted from urban expansion. Even in the upper section of the valley, however, urban developments are beginning to encroach and refuse dumping occurs in places.

During the present study, a variety of field observations were recorded at the study sites. In each valley, the longitudinal profile and several slope profiles were measured in order to provide an indication of the nature of slope and valley form. The slope profiles have been classified into straight and curved segments. Several morphological parameters are derived from this quantitative data. These parameters include the maximum and mean angles of slope, valley cross-profile dimensions and indices of cross-profile asymmetry.

In each valley, a regolith transect was conducted. Several soil pits were excavated along the selected cross-profiles and soil profiles were described with respect to horizoning, depth, texture, structure and colour. In three valleys, vegetation transects were conducted in order to note variations in the composition of floristic associations. In valley A2, some microclimatic data were collected from the opposing north-facing and south-facing slopes of one cross-profile. The data include soil temperatures, soil moisture contents and the depths of snow accumulation. Fluvial and gradational processes were noted but it was not feasible to undertake quantitative process measurements because of the brief duration of the study.

C H A P T E R T W O

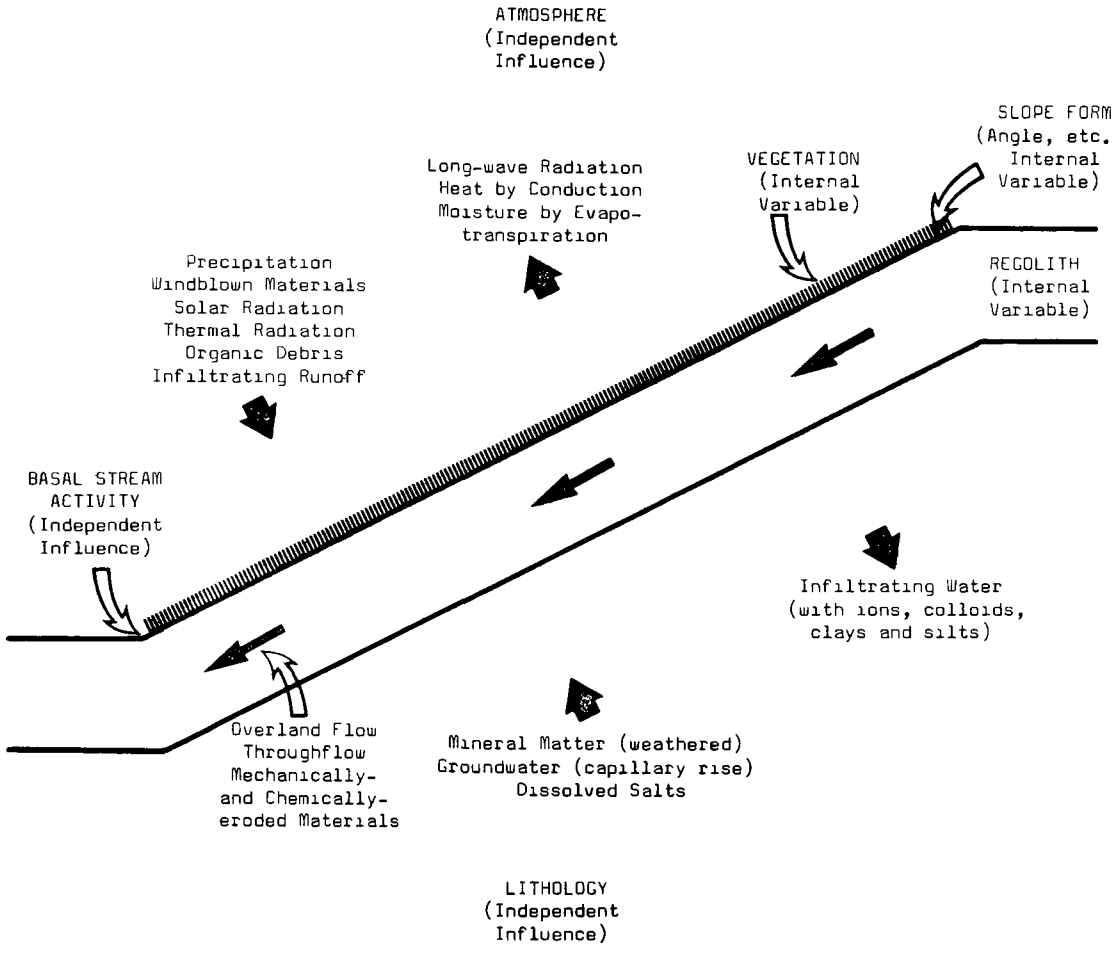
THE IMPORTANCE AND SIGNIFICANCE OF SLOPE FORM

2(a) Introduction to the Problem

It is possible to view whole landscapes as assemblages of slopes of varying form and gradient so that slope studies have assumed great significance in geomorphology. These studies have been characterized by a complex variety of approaches and objectives which have contributed to the many diverse interpretations of slope form.

A recurring problem in slope form analysis has been the apparent absence of a simple relationship between slope form and process. The nature of this relationship was perhaps a secondary factor in the cyclical framework of W.M. Davis who concentrated upon the significance of general base level and the evolution of landforms through long periods of time. Many recent studies, however, have investigated local situations in order to explain morphological variations as specific responses to complex local physical systems (see, for example, A.N. Strahler, 1950; Hack, 1960; Hack and Goodlett, 1960; Conacher, 1967; Carson, 1969a).

The approaches to these studies provide a suitable conceptual framework within which to investigate the forms, processes and external controls which are present. The slope may be viewed as a system within which form evolves as materials are exchanged with the surrounding environment. These exchanges are influenced by biological, lithological, climatic and fluvial variables. It is possible to incorporate the form, the processes of exchange and the controlling variables within a single conceptual open system model, as illustrated in Figure 2.1 (p.40).



Adapted from Strahler, 1968, p. 1001.

FIG. 2.1. EXCHANGES BETWEEN THE SLOPE SYSTEM AND ITS ENVIRONMENT

The following review of literature discusses the complex nature of slope form, the state of knowledge concerning the relationship between slope form and process, the diversity of local controls and the conflicting interpretations which have been proposed for the evolution of slopes through time. As such, the review constitutes a necessary background to further studies of slope form and provides a comment upon the validity of a systems approach to the issues which are considered in this study.

2(b) Interpretations of Slope Form

The profiles of slopes are often classified into their component convex, concave and rectilinear slope segments for descriptive purposes. Distinctive assemblages have been identified as a result, including the convexo-concave slope of humid temperate latitudes and the free face/debris slope form of semi-arid areas (H. Baulig, 1940, 57). Explanations of the origins of these segments, however, are diverse and contradictory.

Convexities are usually attributed to erosional processes. In 1909, G.K. Gilbert wrote that "....On the convexity, the amount of soil to be removed increases down-slope; a progressively steeper slope is therefore required for its removal." (cited in A. Young, 1963, p.28). Baulig (1940) supports this statement in general although he disputes some of Gilbert's premises, including the assumptions that both rates of weathering and regolith thickness are constant over the convexity. N.M Fenneman (1908) suggested, in a

similar hypothesis, that the increase in the volume of wash in a downslope direction in turn increases its erosional and transportational powers so that downslope steepening occurs.

In contrast, it has also been stated that the summit of the divide experiences the most effective denudational processes so that a convexity develops through summit flattening. This notion was suggested by G. Götzinger (1907) and expanded upon by W. Penck (1924), A.C. Lawson (1932) and O. Lehmann (1933) - these authors are cited in Young (1963a, p.28). It is also believed that convexities may result from the weathering of a bedrock surface beneath a talus apron (A. Wood, 1942; J.P. Bakker and J.W.N. Le Heux, 1946, 47).

The origin of concave segments has been attributed to both erosional and depositional processes. G.K. Gilbert (cited in J. Dylik, 1968, p.7) reasoned that concave surfaces are associated with concentrated runoff. It may be argued that rills possess the same relationships among their hydraulic parameters as do streams which develop concave profiles, and slope concavities have often been attributed to rill wash (Fenneman, 1908; Baulig, 1940; R.E. Horton, 1945; C.A Cotton, 1952). On many concavities, however, rills may be entirely absent or are present only periodically, perhaps after heavy rainfall (B.W. Sparks, 1960, p.64).

Deposition occurs on many basal concavities and slope regoliths are frequently thicker in these zones than elsewhere. Lawson (1932) actually asserted that these zones are entirely depositional but A. Jahn (1963) demonstrated that the concavities may be

more correctly interpreted as zones of net accumulation. He has concluded that rates of erosion which are associated with rill wash on the basal concavity may far exceed the rates of erosion which are maintained by soil creep on the summit convexity.

Rectilinear segments frequently occur between convex and concave segments and, in many instances, they may form the maximum angle segments. One may reason that such segments reflect a balance between those processes which fashion convexities and concavities respectively (Baulig, 1940). The significance of maximum slope angles has been assessed by Strahler (1950, pp.684-685) as follows:

> Within an area of essentially uniform lithology, soils, vegetation, climate and stage of development, maximum slope angles tend to be normally distributed with low dispersion about a mean value determined by the combined factors of drainage density, relief and slope-profile curvature.

This view envisages an equilibrium form which reflects conditions within an integrated physical environment.

Rectilinear segments have been said to retreat parallel to themselves, particularly where they are characterized by rapid mass movements. It is argued that ground loss, when measured perpendicular to the slope surface, occurs at the same rate over the entire surface (P. Birot, 1968, p.61). S.A. Schumm (1956a) and Carson (1969b) have described rectilinear segments which appear to be transportational slopes. On such surfaces, an equilibrium exists between the material which is brought from upslope and the material which is evacuated downslope so that there is no net ground loss.

In summary, it is clear that there is no simple relationship between slope form and process. The literature has, however, identified important considerations which include not only the nature of slope processes but also the characteristics of the bedrock, the effectiveness of fluvial processes and the influences of historical conditions. It is imperative that the relationships of these factors to slope form be examined further.

2(c) Environmental Controls

(i) Geotechnical Influences

Bedrock and its regolith are the elements of resistance to the processes which operate within the slope system. Materials may be cemented, granular and resistant or unconsolidated, non-cohesive and weak. Geotechnical properties such as strength, structure, dip, chemical composition and weathering history may vary from slope to slope or even within individual slopes. Several authors have noted the different degrees of development of convex, concave and straight segments on differing lithologies in Belgium (P. Macar and R. Fourneau, 1960; Fourneau, 1960-1961; Macar, 1963). Macar and Fourneau (1960) have noted also that unconsolidated materials adjust more rapidly to environmental conditions than cemented rocks. Slopes tend to be steeper in loose sands than in schists or sandstones, following the recent initiation of slope-steepening processes.

On slopes in coherant rocks, failures are not often deep-seated and are usually confined to the regolith zone. In Champlain Sea sediments and other unconsolidated materials, however, failures may occur at any depth. The sources of strength in such materials are cohesion, internal friction and pore water pressures. Cohesion is ionic bonding among soil particles and water molecules and tends to be greatest in clays (Crawford, 1963). Where cohesion is lacking, materials cannot support slope gradients which exceed the angle of repose, a property which is determined by internal friction between particles (A. van Burkalow, 1945). Cohesive forces, however, may permit slopes to assume steeper inclinations, especially during periods of drought when negative pore pressures reinforce the strength of the material. In oversaturated soils, pore pressures are positive and act against the atmosphere to alleviate normal stress and, in consequence, to reduce soil strength (R.H. Karol, 1960, pp.48-50; Carson, 1969b).

The permeability of materials influences the nature of the processes which affect them. For example, Schumm (1956a) has demonstrated that creep is an effective process on permeable materials whereas surface wash becomes relatively more important as the infiltration capacity of the soil declines. Materials with high waterholding capacities are susceptible to failure by flow rather than by sliding. They also experience greater impacts from both freeze-thaw processes and wetting and drying cycles.

(ii) Slope Processes and Slope Form

Many studies have been devoted to the relationship between slope forms and the processes which shape them but few principles have been established. For example, it is a common premise of deductive models of slope evolution that the rates of operation of slope processes are positively correlated with slope angle (see W.E.H. Culling, 1960, 63; A.E. Scheideggar, 1961, 64; Young, 1963b; de Ploey and Savat, 1968). Yet field observations by both Young (1960) and M.J. Kirkby (1967) have failed to demonstrate this relationship. In addition, R. Common (1966) points out that the stability of a slope depends on many factors other than slope angle and the associated gravitational stress. One is compelled to agree with Chorley (1964a, p.71) in his conclusion that

> ....neither the manner of evolution of the slope nor the processes responsible can be unambiguously deduced from the slope form alone....All erosional slope forms present ambiguities if one attempts to reason simply and directly from form to process, and it is now patently apparent that no distinctive slope form is uniquely linked to a given climatic or tectonic erosional environment.

The work of C.D. Holmes (1955) and M.J. Mulcahy (1961) has shown that the functions of slope surfaces of similar angles may be erosional, transportational or depositional, depending upon their position on the profile and on conditions in the local environment.

From field observations, however, it appears that within specific areas of fairly uniform conditions, slope processes operate within definite ranges of slope angles. Jahn (1960) contends that, in Spitzbergen, rockfalls occur on slopes above 40 degrees, talus aprons with dry gravitational sliding on surfaces between

30 and 40 degrees, creep on humid talus slopes inclined between 15 and 25 degrees, and solifuction on slopes of between 2 and 25 degrees.

Carson (1969a) has attempted to explain such findings by formulating a model of succeeding phases of slope development. Each phase is characterized by a threshold angle of slope below which its characteristic process(es) cease to operate. For example, evolution from a vertical rock face may involve four succeeding phases; a rock slope of large blocks, a talus slope, a moist talluvial slope and a soil slope. In a later article (M.A. Carson and D. Petley, 1970), the concept of the threshold angle is held to imply that, as the minimum gradient for a particular process is reached, that process will be replaced by a new process with a lower threshold unless a compensating process of slope steepening is operative. Sets of processes with different thresholds, therefore, are likely to characterize small regions.

The main factor in the differentiation of slope processes throughout the world appears to be climate (Common, 1966). As a result, variations in slope form in different parts of the world have been recognized. The contrast between the convexo-concave slope of humid latitudes and the free face and debris slopes of semi-arid areas is an example.

Within a single region, climatic processes vary from slope to slope with aspect. Aspect and slope angle control the amount of insolation on a surface at any given latitude (B.J. Garnier, 1968). In addition, winds operate in preferred directions to create wind-

ward and leeward slopes. Such microclimatic contrasts are often sufficient to promote asymmetry of valley cross-profile form. Interpretation of slope asymmetry requires care, however, since this phenomenom is also caused by structural variations, asymmetrical drainage development and differential stream undercutting (H.M. French, 1967). R.F. Hadley (1961) has expressed the opinion that, in many parts of North America, the north-facing slope is usually steeper than the south-facing slope which experiences more rapid slope processes. These processes lead to accumulations of debris at the base of the south-facing slope which deflect the stream channel against the north-facing slope. This slope, which is steepened by undercutting, is more capable of maintaining its gradient than the opposite slope because of its greater vegetation cover and moister, more cohesive soil. French (1967) has demonstrated, however, that steeper slopes have been identified in many areas of North America and Europe which possess various orientations. These steeper slopes, furthermore, are not consistently either the wetter or drier or the cooler or warmer of the two slopes. It is clear that the literature concerning asymmetrical slopes and valleys is ambiguous and conflicting.

Vegetation may influence the nature and rate of operation of slope processes. According to G.K. Gilbert (cited in Chorley, 1959, p.503), a plant cover promotes weathering and rock disintegration but retards the removal of the loosened debris. Most workers have emphasized its capacity to protect the soil from erosion, for example, K.G. Smith (1958) and Chorley (1964b).

Unlike climate, however, vegetation is considerably influenced by the slope system. Schumm (1956b) reported that, at Perth Amboy, New Jersey, gentler slopes appear to support more vegetation. It is probable that, as slope angle increases and gravitational processes become more effective, plants experience progressively more difficulty in becoming established within the mobile rooting medium. Floristic associations, therefore, may reflect the effectiveness of slope processes. As regolith mobility increases, the succession may be halted and the plant association may be maintained in an equilibrium condition (as an immature climax) or may even be degraded.

The maturity of soil profiles on a slope is a similar index of the effectiveness of surface processes. P.H.T. Beckett (1968) has written concerning the Aufbereitung concept of W. Penck which alleged that soil materials are progressively reduced with time and become increasingly susceptible to removal. Penck believed that the rate of removal is proportional to slope angle and it follows that the degree of maturity of a soil is inversely proportional to slope angle because soils require ever-declining angles of slope in order to ensure their continued evolution. P.A. Furley (1968) has presented field evidence which partially supports the Aufbereitung theory; but its precepts limit its applicability to convex and straight surfaces which experience only shallow surficial processes, such as sheet wash, creep and rain splash erosion. Variations in soil maturity with topography have been noted by many other workers, including C.D. Ollier and A.J. Thomasson (1957),

Young (1963a) and French (1967). Such variations may be obscured, however, where seepage moisture migrates over the slope by throughflow rather than by vertical infiltration (Kirkby and Chorley, 1967).

(iii) Fluvial Processes and Slope Form

Slope form is a component of valley form and it is therefore logical to expect that fluvial processes exercise a considerable influence upon it.

In V-shaped valleys, downcutting and slope undercutting are simultaneous processes where the slope base merges with the channel bank. The ultimate gradient of the slope may depend upon the relative efficacies of two processes: (i) the downslope transportation of debris; (ii) the erosion and transportation of materials by the basal stream.

In floodplain valleys, downcutting is negligable and slope undercutting occurs only locally. Valley depth and slope height are relatively constant. The floodplain level is not built up because most deposition occurs in the form of lateral accretion in shifting meanders (M.G. Wolman and J.P. Miller, 1960). Lateral erosion occurs on the outer bends of meanders (M.G. Wolman and L.B. Leopold, 1957). Where the latter are adjacent to the valley-side slopes, undercutting and slope steepening occurs. Often, the erosive capacity of the stream far exceeds the transportational capacity of processes of mass movement. In such situations, the slopes tend to be oversteepened to the maximum gradients which the bedrock materials are able to support. Away from these points of localized erosion, undercutting is absent and slope processes reduce slope angles with-

out interruption. It appears that even floodwaters do not undercut these slopes because of the absence of the turbulent flow which characterizes water motion within the main channel (Dury, 1954).

The form composition of the slope profile has been found to vary with basal fluvial activity. Culling (1965) and P. de Bethune (1967) have argued that, theoretically, convexities should tend to increase in length and to acquire progressively lower rates of curvature where slow mass movements are operative. Observations of the processes of soil creep by Schumm (1956a) and of rainsplash erosion by de Ploey and Savat (1968) support this contention.

Active fluvial processes at the base of the slope, however, oppose this tendancy. Strahler (1950) and Culling (1963) observed that the rates of curvature on divides increase directly with such drainage basin parameters as the density of valley spacing and available relief. Rates of curvature tend to increase, therefore, in areas of downcutting and channel extension. On slopes which are powerfully undercut, the upper convexity is reduced in length and assumes a high rate of curvature. Furthermore the development of a basal concavity may be entirely suppressed (Baulig, 1940). In such situations, the maximum angle segment is located near the base of the slope which is dominantly convex in form. The basal segment often occurs as an undercut scar without soil or vegetation (R.W. Packer, 1964; Birot, 1968, pp.60-61). The overall effect of undercutting appears to be to simplify the form of the slope profile. When basal fluvial activity ceases, variations in process and structure are more likely to produce a complex slope form.

As a further indication of the connection between slope form and fluvial processes, a relationship between slope angle and channel gradient has often been cited. W.M. Davis predicted that these two variables would be positively correlated and Strahler (1950) conceived of the relationship as a delicate adjustment which reflects the quantity of slope debris to be removed by the stream. Strahler devised a slope ratio (channel slope / hillslope gradient) for the investigation of this notion. Field observations suggested to him that the slope ratio declines as valley development proceeds so that, for example, as stream segments attain higher orders in a drainage basin, their channel gradients become less whereas those of the adjacent slopes increase.

Melton (1960) has noted a further relationship between slope angle and channel gradient. He has illustrated from data in Wyoming that, as channel gradient increases, its influence eventually dominates other controls of slope angle and, by producing efficient removal of material from the foot of the slope, leads to symmetrical valley cross-profiles.

(iv) Slope Evolution

Early theories of slope development have emphasized the evolution of geometric form through time. These evolutionary concepts were parts of elaborate cycles of landscape development. In W.M. Davis's cycle of peneplanation, slopes decline in angle about a fixed local base level once maturity has been achieved. In this concept, the slope resembles a closed system and the peneplain is a land surface at maximum entropy. L.C. King(1953) proposed a cycle

of pediplanation in which the end-product was also a flat surface. Throughout the cycle, however, the slopes retreat parallel to themselves; they are free to migrate and are not fixed in position by a local base level. Such slopes resemble more closely open systems in a steady state. W. Penck's model of landscape development (1924) involved two successive trends in the evolution of a slope through time. Initially, a convexity develops as fluvial downcutting accelerates but, later in the cycle, when downcutting ceases to operate, sweeping concavities consume the divides by the process of slope replacement. Explanation of this change is assisted by visulalizing the slope as a series of facets of varying gradient. During the development of the concavity, steep facets retreat rapidly to be replaced at their bases by gentler facets (Penck's model is described in M. Simons, 1962).

Cyclical approaches to the interpretation of slope form have been criticized in recent studies. Chorley (1965, p.25) considered that,

> The relationship between gradient and rate of mass transfer is more partial and complex than Davis assumed....such that some aspects of landscape geometry may be relatively unchanging throughout large segments of "cyclic time", whereas the detailed pattern of change of others may be neither progressive nor continual.

Hack (1960) argued that one may satisfactorily explain landscape features as responses to the conditions which prevail at the time of the study. Chorley(1965) also felt that this approach transfers the emphasis of research to the complex problems of the relationships between form and process. S.A. Schumm and R.W. Lichty

(1965) have concluded that historical studies such as those of Penck, King and Davis tend to underestimate the unity within the landscape whereas recent quantitative studies have suppressed temporal considerations and ignored sequential and migrating changes.

For some problems of landscape interpretation, a reasonable explanation may only be sought from a comparative evaluation of past and present conditions. For example, although the form of floodplain valleys with meandering streams is often attributable to the characteristics of the present discharge, Dury (1964a, 64b, 65) has demonstrated the importance of much larger discharges during the past in the fashioning of these valleys. Many such valleys in Europe and North America are misfit and climatic conditions for the onset of underfitness appear to have been widespread in the immediate post-glacial period. Misfit valleys may be contrasted with those which have not undergone the same Quaternary history and which, therefore, possess different form and discharge characteristics.

The general expansion and evolution of a drainage network constitutes a further illustration of sequential development. Many of the dimensions of drainage basins increase allometrically (see, for example, Schumm, 1956b; Hack and Goodlett, 1960; Leopold, Wolman and Miller, 1964, pp.131-150; Hack, 1965; L. Wilson, 1968). Slope form parameters, such as height, length and maximum and mean angles, may increase as part of the general process of growth (Schumm, 1956b; Fourneau, 1960-1961; C.S. Carter and R.J. Chorley, 1961). In conclusion, therefore, it is often useful to interpret some

aspects of slope form within an evolutionary context, rather than through a simple time-independant conceptual framework.

2(d) The Slope as a System

Recently a systems approach has been employed by several authors in order to interpret slope form (see, for example, Culling, 1960, 63; Ahnert, 1967; Jahn, 1968). In these studies, the emphasis is directed towards the ratio of materials supplied to materials removed from slope surfaces. Ahnert, for example, reasoned that the removal of materials exceeds supply on convex surfaces whereas the reverse occurs on concavities and inputs and outputs are balanced on straight segments. Carson (1969a) suggested, by contrast, that (i) outflow exceeds inflow at all points on a slope which is retreating parallel to itself, (ii) outflow equals inflow at the slope base but the outflow/inflow ratio increases upslope where the slope is declining in an angle and (iii) outflow equals inflow at all points on the slope except at the summit where slope rounding is occuring.

It should be possible, logically, to develop further the applicability of a systems viewpoint in the study of slopes. In the present study, emphasis is directed away from the denudational balance towards the balance between the opposing tendancies towards slope steepening and slope angle reduction.

Open systems maintain their activity through the continuous net imports of energy and materials from the surrounding environ-

ment. Slope systems which are open may be maintained by processes of slope steepening such as fluvial undercutting. These processes offset the tendancy of slope processes to produce lower slope angles and, in turn, more gradual slope processes. Where the opposed tendancies are balanced, slope gradient becomes the morphological manifestation of a steady state.

As systems become more stable, they approach maximum entropy and experience a decline in their rates of adjustment. Such systems are partially closed and incur net losses of energy and materials. The slope system cannot be completely closed because of the complex nature of its exchanges with its external environment (Fig. 2.1, p.40). Nevertheless, in situations where processes of slope steepening are insignificant, a decline in the rate of activity within the system may be predicted.

These principles constitute the framework for consideration of the present attributes of slopes within the Ottawa area. This approach permits the simultaneous consideration of form and its controls, those factors which were reviewed in section 2(c).

C H A P T E R T H R E E

SLOPE AND VALLEY FORM IN THE OTTAWA AREA

3(a) Field Observations of Slope Form

Slope form was investigated by means of the measurement and analysis of two-dimensional slope profiles. Slope profiles have frequently been employed in slope studies, for example, by M.J. Clark (1965) and A.F. Pitty (1969), because of the absence of suitable techniques for the simultaneous analysis of all three dimensions, including the lateral extent, of the slope.

Several profiles were measured in each of the eight selected valleys, 103 profiles in total. This sample size was considered to be practicable, given the time available and the methods of observation. Furthermore, J. Tricart and J. Muslin (1951) suggested that 100 slope profiles is an adequate sample size for the analysis of form in any one region. It is not possible, of course, to generalize on the question of a sufficient sample size for slope profiles since each derived parameter possesses a different coefficient of variation. In the present study, for example, the employed sample yielded fairly precise mean values for the distributions of maximum and mean angles. Using the procedure which was outlined by F.C. Mills (1965, pp.671-676), it was calculated that, for each of these distributions, there was a six percent chance of failure to locate the sample mean within ± 1.96 standard deviations of the true mean (i.e. within 95 percent confidence limits). For other parameters with greater coefficients of variation, the risk of such a failure was greater.

A sampling design was established which was intended to reduce to a minimum the bias involved in the location of the sites

for slope profile measurement. A number of problems, however, were encountered. For example, slope plans may exhibit pronounced variations, as observed by Pitty (1966). They may be spurs, hollows or side slopes (Fig. 3.1, p.60) and Pitty contends that only side slopes are amenable to slope profile analysis. His argument is as follows. Profiles should be measured along the lines of steepest slope (the orthogonal lines), which are perpendicular to the contours, because the maximum effect of the force of gravity, which generates mass movements, is assumed to be directed down the steepest available gradient. Such directions are straight and parallel in side slopes (Fig. 3.1A) but diverge on spurs (Fig. 3.1B) and converge in hollows (Fig. 3.1C). The processes of distribution of materials over the slope, therefore, may be expected to be more complex on spurs and in hollows than on side slopes. Pitty proposes that, in order to avoid the presence of unlikes within a supposedly homogeneous population, slopes with orthogonal deviations of greater than five degrees should be excluded from consideration.

Slopes in the Ottawa area, however, frequently possess spurs and hollows. Such forms are either absent or of limited development in valleys A2 (Plate X, p.61), A3 (Plate IV, p.29), C2 (Plate XI, p.61) and C4. Many other valleys possess sweeping valley meanders and the valley-side slopes are characterized by a succession of pronounced spurs and hollows which may be interspaced with side slopes. These are present in valleys A1 (Plate XII, p.62), B1, C1 and C3 (Plate IX, p.36), for example. During field measurement, therefore, an arbitrary maximum orthogonal deviation of forty degrees was permitted.

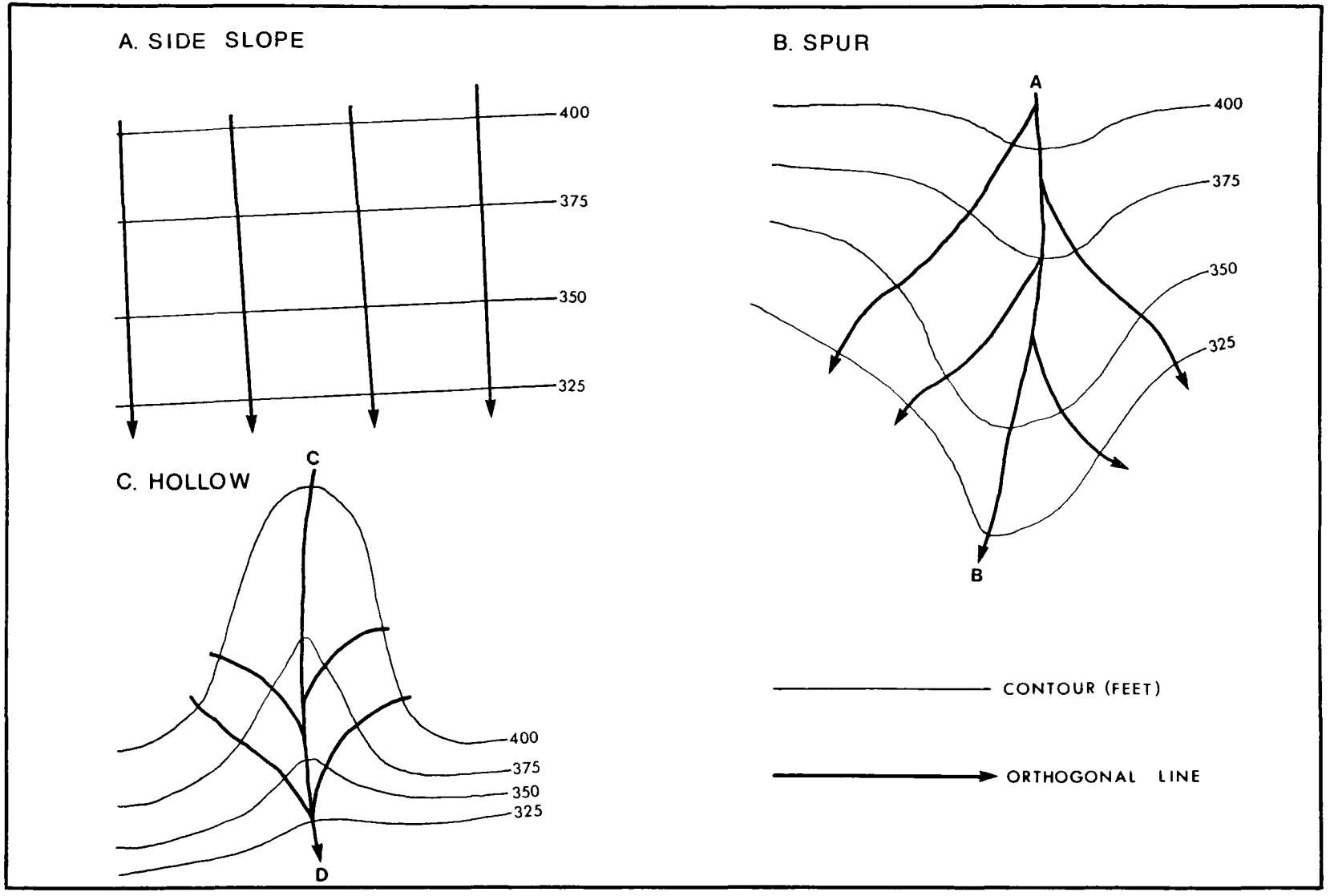


FIG. 3.1. VARIATIONS IN SLOPE PLANS

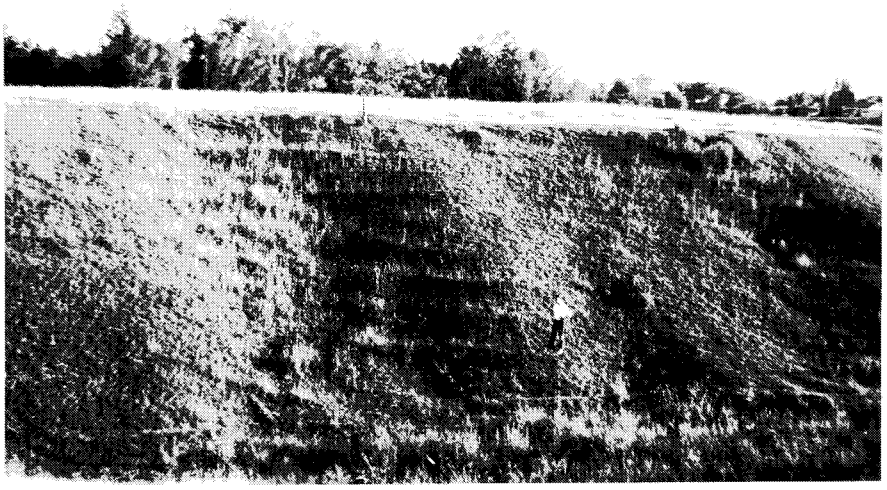


Plate X. A detail of the north-facing slope in valley A2; terracettes and incipient spur and hollow development are visible; the upper surface is the marine surface (grid ref. 459153).

Plate XI. Terracetting on the east-facing slope in valley C2; the terracettes are continuous down-valley but are especially prominent on spurs (grid ref. 469381).

Plate XII. Spur Slope in valley A1; the feature is in the process of stabilization following undercutting during a previous flood season (grid ref. 472148).

Profiling was begun in most valleys (A2, A3, C1, C2, C3 and C4) as near to the valley mouth as possible. As an arbitrary rule, each subsequent cross-profile was located upvalley of the preceeding cross-profile by a distance which was two-thirds of the length of the longest of the two slope profiles which had comprised the previous cross-profile. The ruling worked well in those valleys where spur and hollow development is limited. In such valleys, orthogonal deviations were usually considerably less than forty degrees. In valleys A1 and B1, however, it was almost impossible to locate orthogonal lines which deviated by less than forty degrees except on the crests of the spurs (line AB in Figure 3.1B) or in the troughs of the hollows (line CD in Figure 3.1C). The restricted number of suitable locations for sampling in these two valleys detracts to an unknown degree from the otherwise systematic sampling procedure. The sites for profiling are located in Figure 3.2 (p.64).

Where profiles were selected for study, their lower endpoints were located either at the bank of the basal stream, where present, or in the middle of the seasonally-dry channel. The location of the upper endpoint was more arbitrary. Many of the slopes in the Ottawa area grade upwards into gently-inclined river terraces with slope angles of two degrees or less. For this study, therefore, it was convenient to assume that the lower limit of operation of slope processes is 2.5 degrees, although this limit has been variously stated as 5 degrees for creep (W. Penck, cited in Leopold, Wolman and Miller, 1964, p.349), 2 - 5 degrees for solifluction (Jahn, 1960), 2 - 3 degrees for solifluction (Leopold, Wolman and

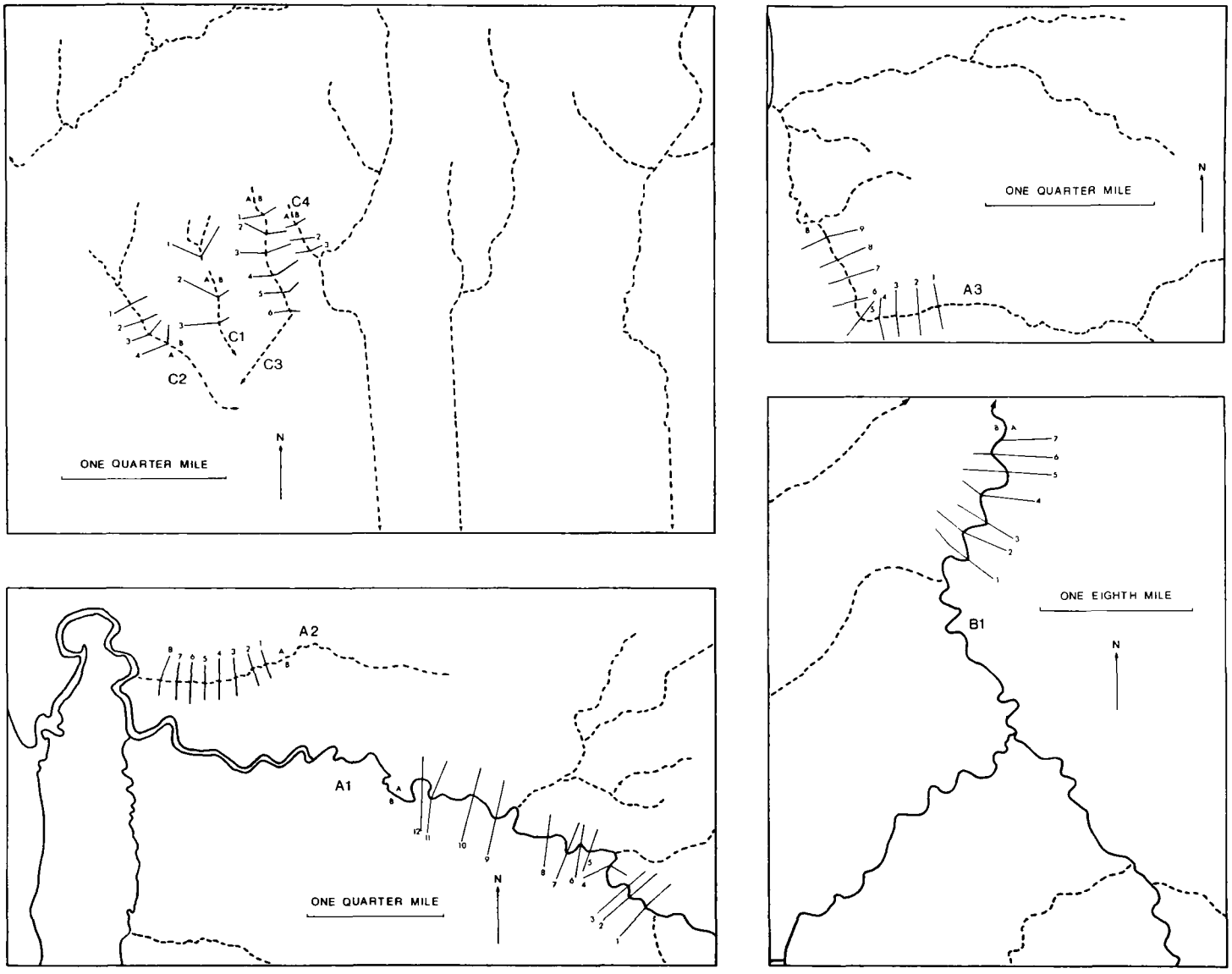


FIG. 3.2. THE LOCATIONS OF MEASURED SLOPE PROFILES IN THE STUDY AREAS

Miller, 1964, p.346), 2 - 3 degrees for mass movements in general (Jahn, 1954 - cited in Dylik, 1968, p.10), 1.5 degrees for wash and creep (Strahler, 1950), 1 degree for seepage moisture (B.T. Bunting, 1961) and 1 degree for block movements (C.R. Twidale, 1967). The upper slope zone was terminated either where a value of zero degrees was recorded or after angular measurements of less than 2.5 degrees had been recorded over 100 feet of terrain.

For the purpose of measuring angular variations along the sample profiles, the use of an abney level and a pair of range poles was considered to combine precision with rapidity in field observation. Figures are accurate to within $\pm$0.5 degrees. Theodilite surveys would have been unjustifiably time-consuming and the pantometer (Pitty, 1968) was considered to be inadaptable to the measurement of slope segments of greater than five feet in length.

Slope angles were measured at twenty-five feet intervals along the profile. This standard measuring span was considered to be desirable although irregular measured lengths have been employed by some researchers (Carson and Petley, 1970). In other work (R.A.G. Savigear, 1952), the boundaries between measured segments were subjectively located on "breaks of slope". The standardized length allows each angular measurement to carry equal statistical weight as an individual in a population. Furthermore, the inherant angular variation of each profile may be considered to have been systematically sampled. The twenty-five feet measuring intervals worked well with long slope profiles but tended to overgeneralize short profiles such as those which characterize valleys B1 and

C2. Breaks of slope may be displaced and angular differences (angular discontinuities) between measured lengths may become exaggerated on short slopes.

The slope profiles have been graphically reconstructed without vertical exaggeration and are presented in Figures 3.3 to 3.10 (pp.67 to 74).

3(b) Classification of Slope Form

(i) Method

The form of the measured slope profiles was classified into convex, concave and rectilinear segments, employing a method which has been adapted from the suggestions of other authors. In many studies of slope form, as in the present study, the basic data consist of sequences of measured length inclinations along two-dimensional profiles. The identification of curved and straight segments, therefore, has usually depended upon the patterns of these sequences. For example, French (1967) recognized rectilinear segments on slopes where at least three consecutive measured inclinations were present which varied in angle within one degree of each other. Fourneau (1960-1961) identified both straight and curved segments where consistent trends could be observed through three consecutive measured lengths of the profile. Lambert (1960-1961), however, insisted that five consecutive measured lengths were required for the recognition of each type of slope segment. Other

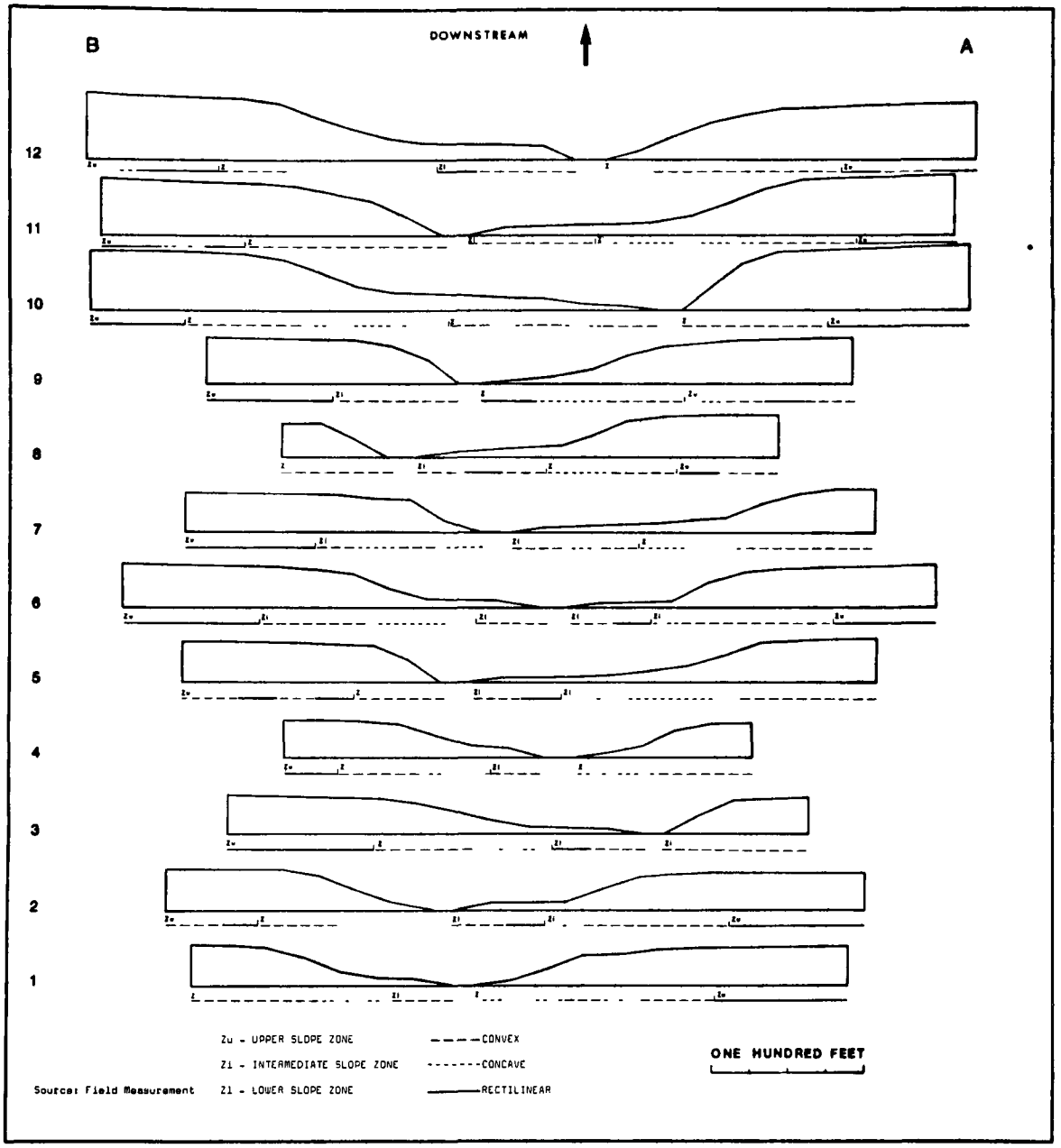


FIG. 3.3. SLOPE PROFILES IN VALLEY A1

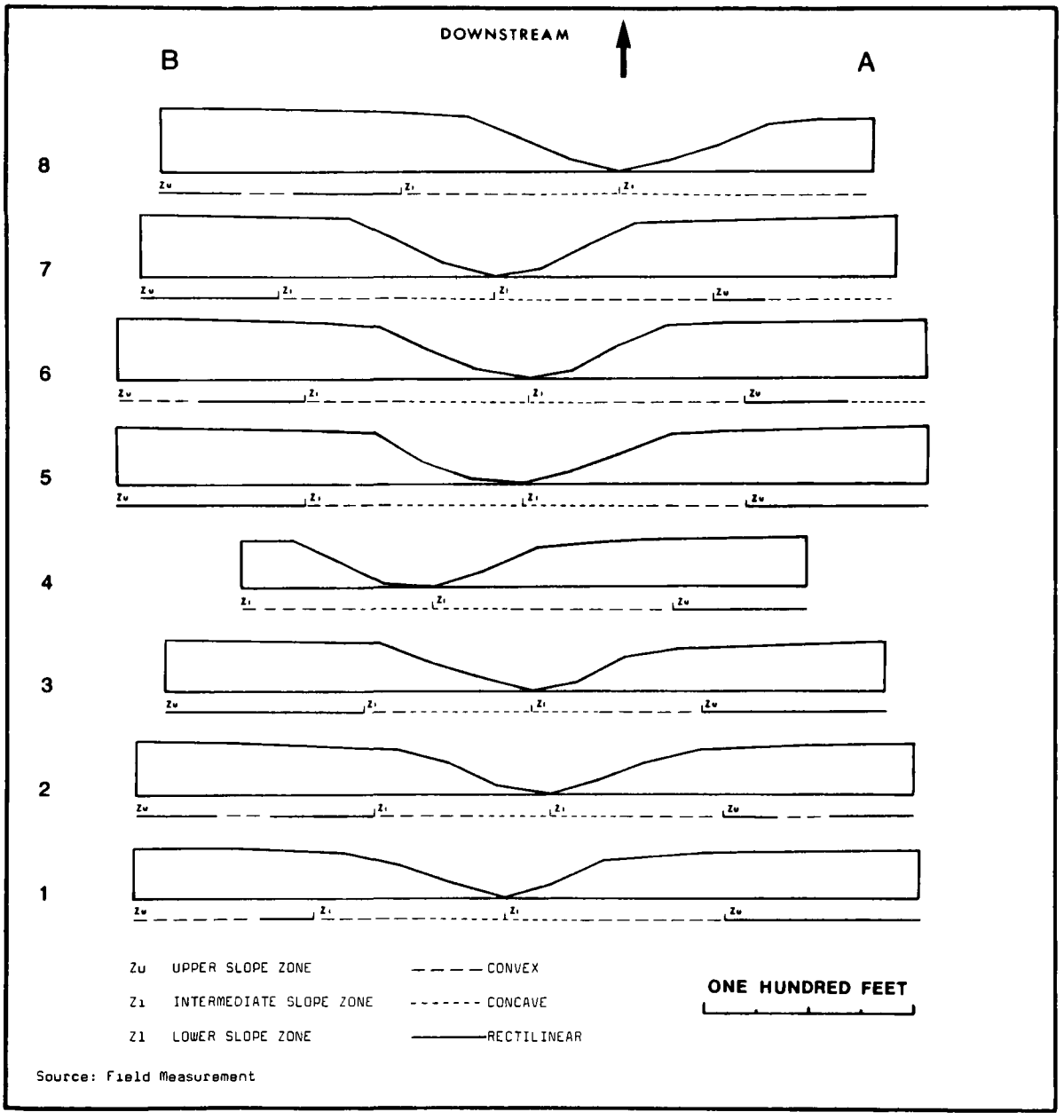


FIG. 3.4. SLOPE PROFILES IN VALLEY A2

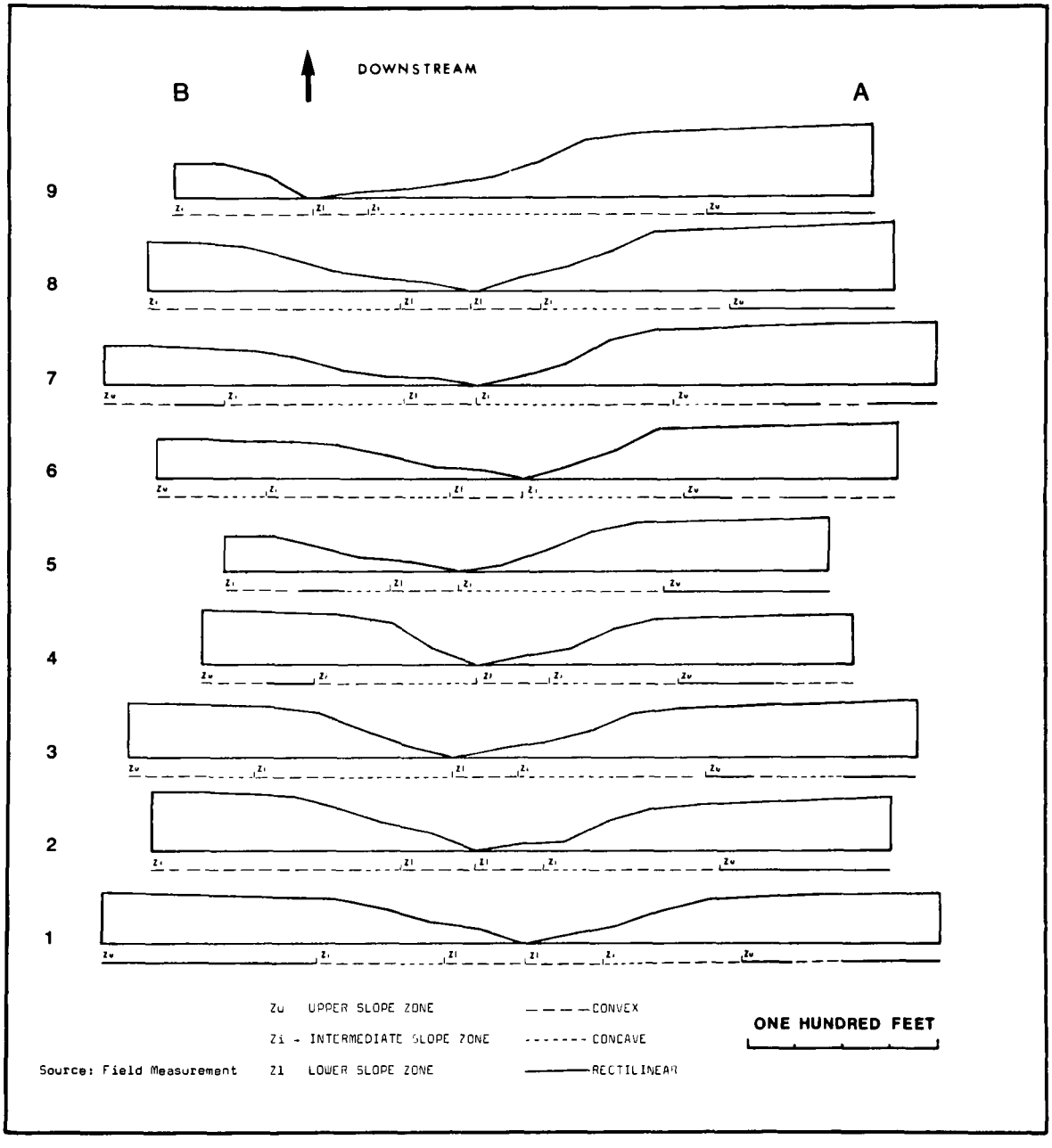


FIG 3.5. SLOPE PROFILES IN VALLEY A3

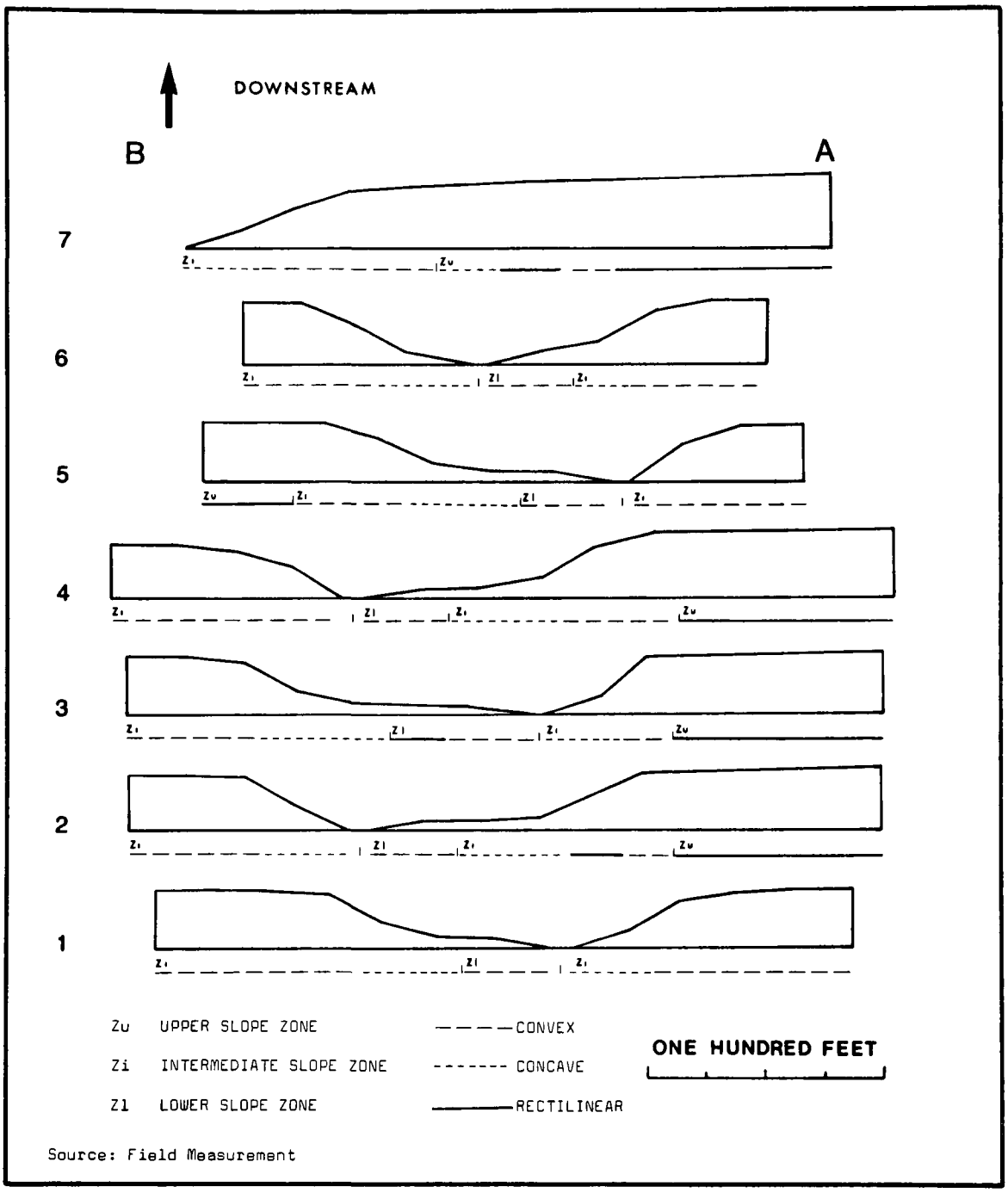


FIG. 3.6. SLOPE PROFILES IN VALLEY B1

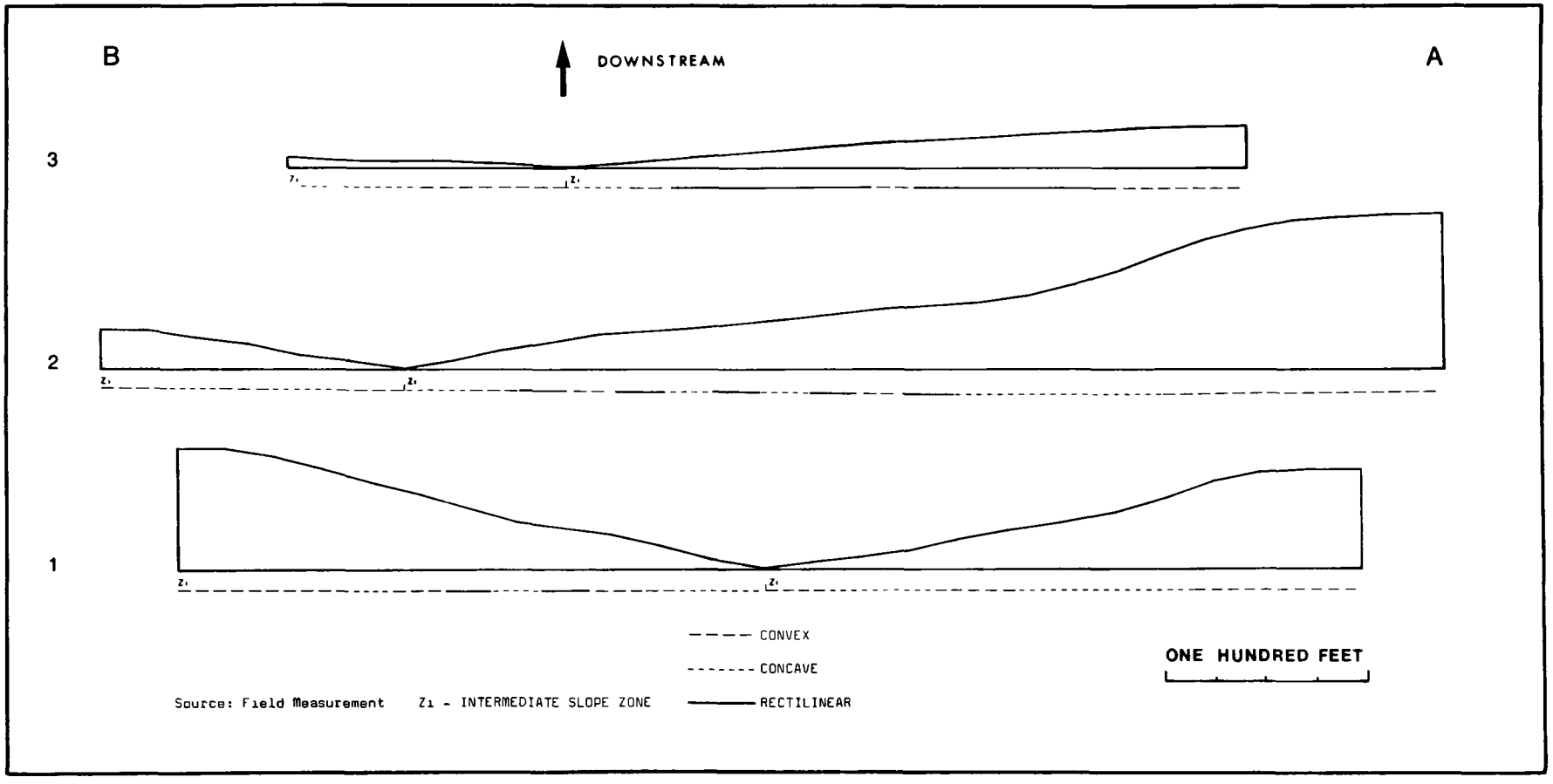


FIG. 3.7. SLOPE PROFILES IN VALLEY C1

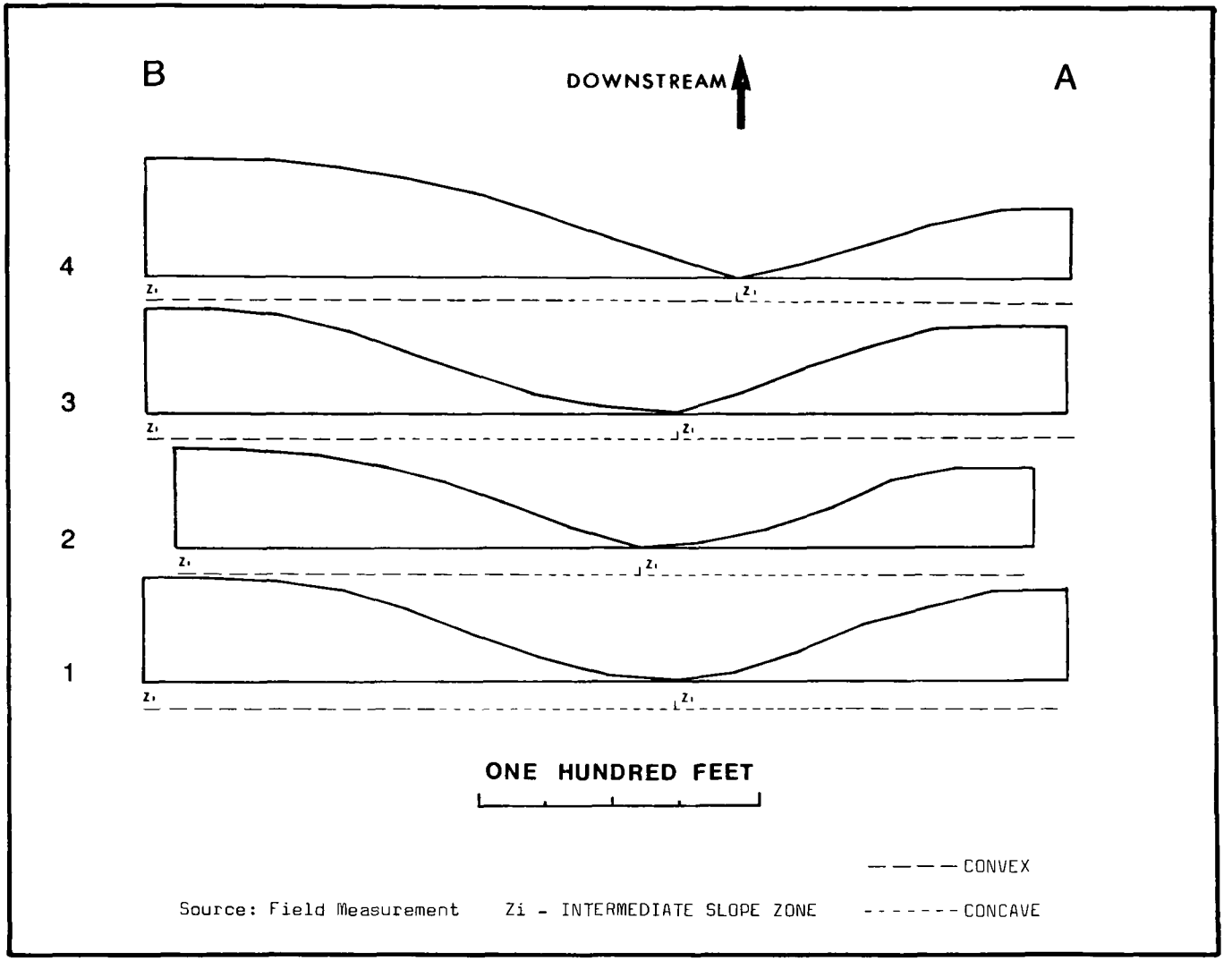


FIG. 3.8. SLOPE PROFILES IN VALLEY C2

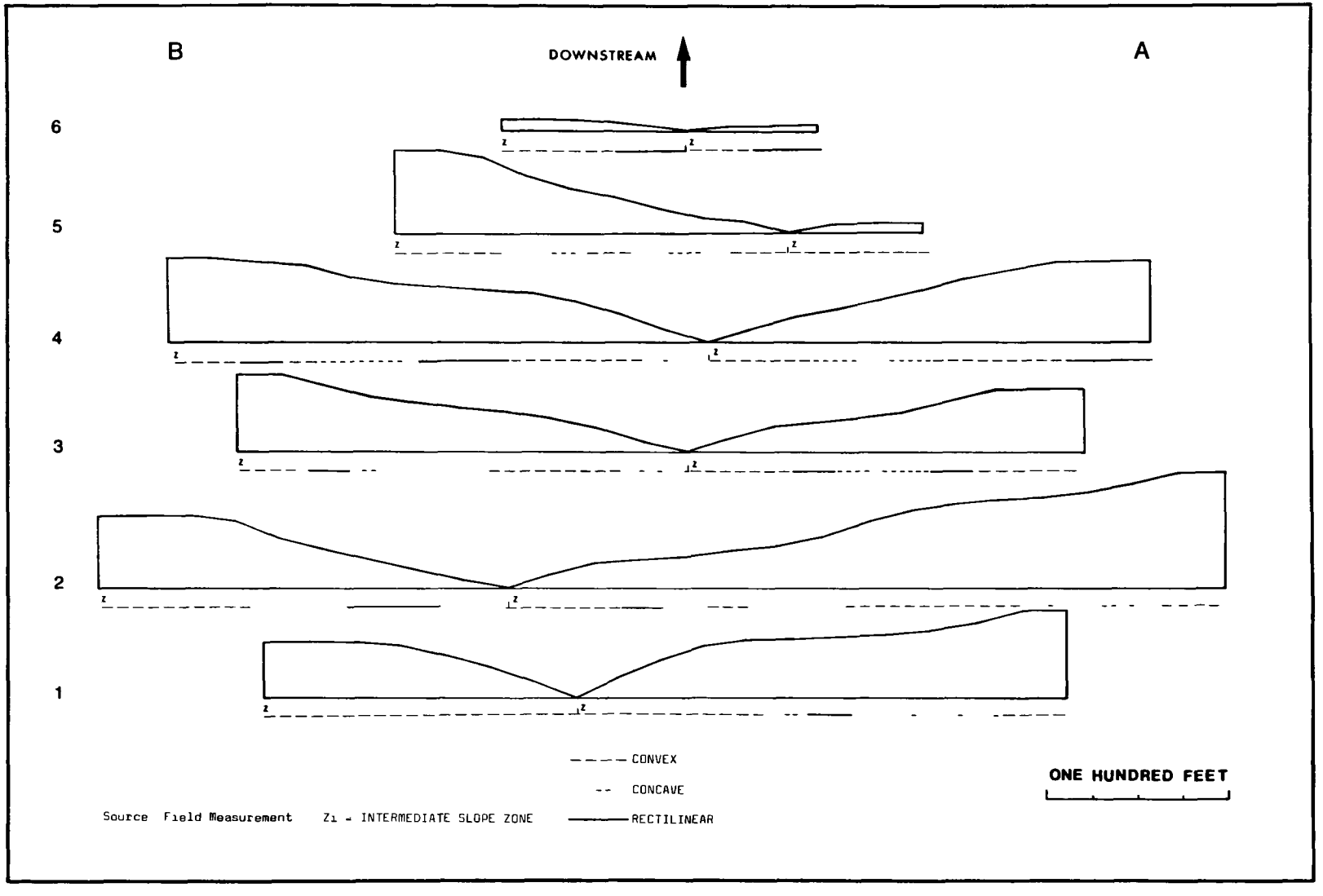


FIG 3.9. SLOPE PROFILES IN VALLEY C3

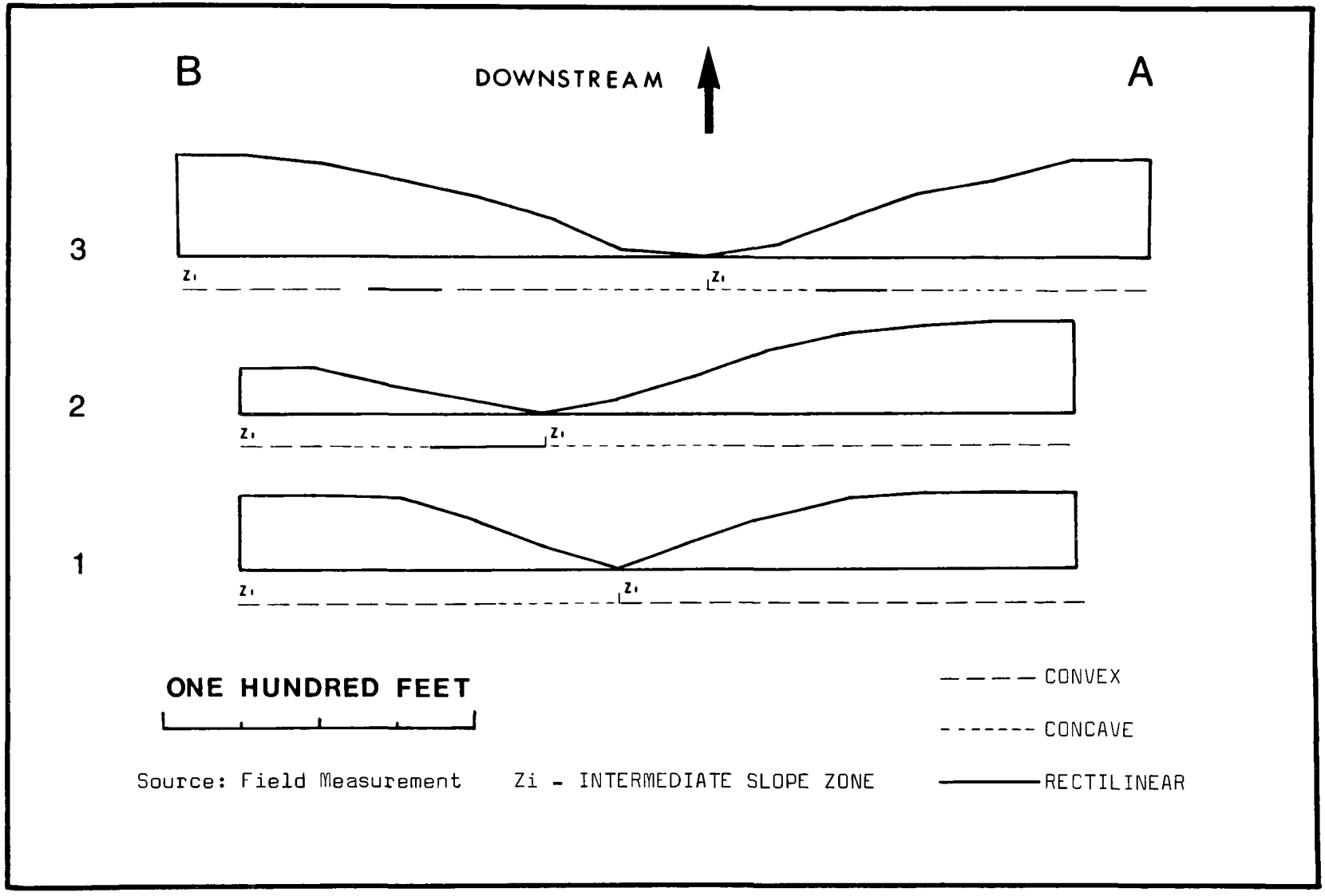


FIG 3.10. SLOPE PROFILES IN VALLEY C4

types of sequence were considered to be complex.

Savigear (1965, 67) collected similar field data but employed a different principle of subdivision. He assumed that different segments adjoin at breaks of slope and inflections which constitute readily recognizable discontinuities in the field. He distinguished true breaks of slope from apparent breaks of slope which are present only in the graphically-reconstructed profiles. These latter may occur where the measured length spans are so long that they misrepresent the true form. Although the text is far from clear, it appears that a visual appraisal is considered to be adequate for the identification of boundaries between slope segments.

Field measurements are employed by Savigear to confirm and supplement the field observations. In each profile, the difference in angle between each pair of measured lengths is calculated. This value, the angular difference, is termed an angular discontinuity if greater than zero degrees. In convexities, such values are positive and, in concavities, negative. A criticism of this approach to classification is that it appears to employ angular discontinuities as both integral parts of curved segments, and as breaks of slope between different types of segments, without any precise regulations which render these usages mutually exclusive. Furthermore, the method of defining a break of slope requires clarification.

Young (1963a) suggested a complex nomenclature for slope form classification based upon the location of individual segments in relation to the overall profile. For example, the segment at the slope summit may be termed "crestal". "Sequences" of slope segments

are also recognized and constitute any convexo-concave series. These ideas have influenced the present classification. Young, however, is not concerned with the practical questions of segment delimitation, either in his explanatory paper (1963a) or in a later article (1964).

The present classification is designed for use upon basic data which consist of constant measured lengths of known inclination. The recognition of breaks of slope is not required, and the criteria for segment delimitation are such that each segment type is mutually exclusive.

The basis of segment differentiation is the pattern of the angular discontinuities. Convex (+) and concave (-) segments are sequences of discontinuities of the same sign. These segments are recognized when at least one angular discontinuity of ±1 degree or more is present. A straight segment is identified when at least one angular difference of zero degrees or ±0.5 degrees is present. The latitude of ±0.5 degrees is intended to accomodate the possibility of slight measuring error. Any sequence of angular differences of zero degrees or ±0.5 degrees, therefore, constitutes a straight segment.

In all cases, the slope segment boundaries occur at the midpoints of the measured lengths between different angular discontinuity patterns. Since the measured spans are twenty-five feet in length, the shortest slope segment which may be delimited by the classification is also twenty-five feet in length. Figure 3.11 (p.77) illustrates an actual example of the classification.

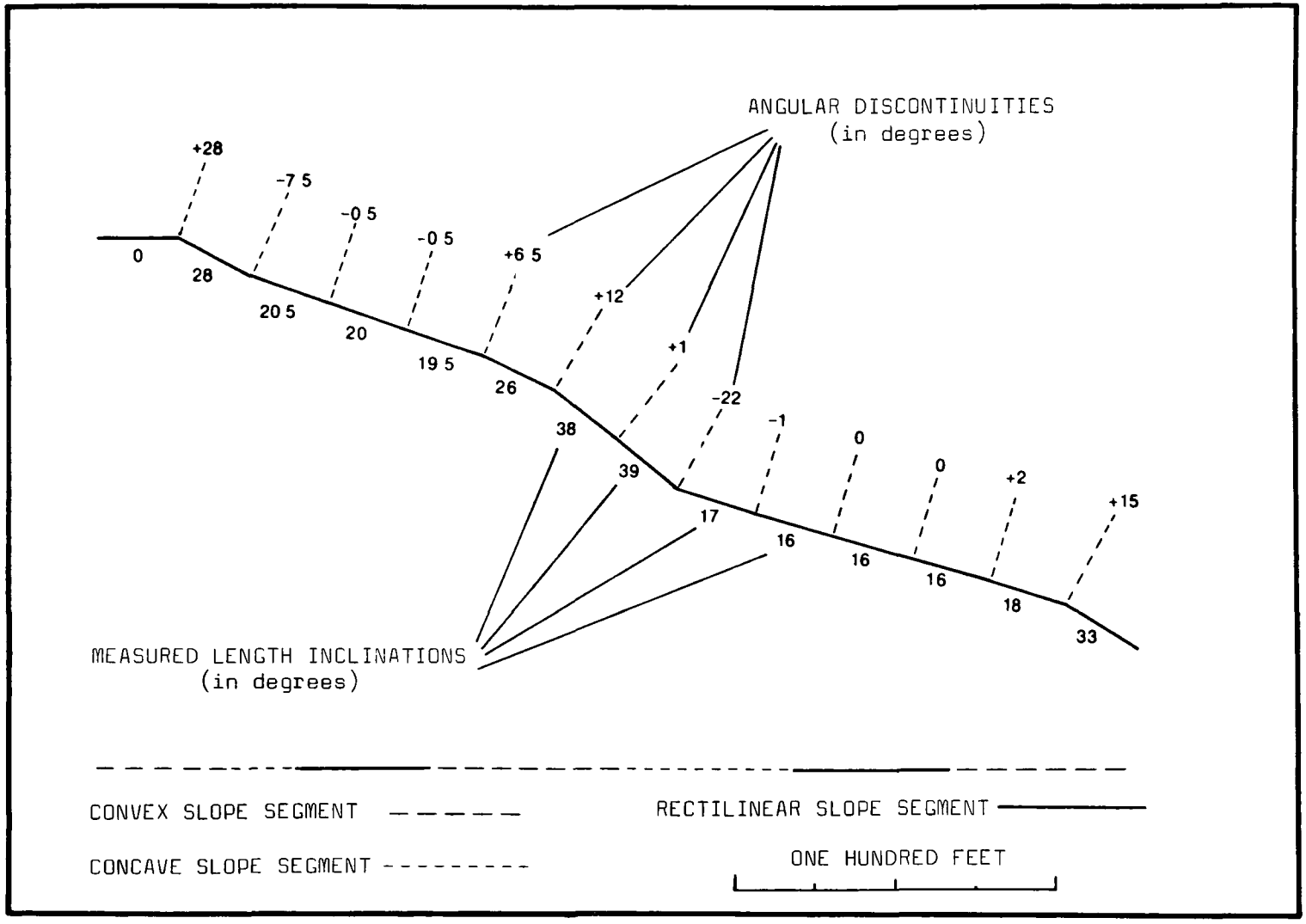


FIG. 3.11. AN EXAMPLE OF THE OPERATION OF THE SLOPE FORM CLASSIFICATION

A segment sequence is recognized where an upper convex and lower concave unit are present, whether in an uninterrupted form (CxCc) or partially interspersed with rectilinear segments (as, for example, in the sequence CxRCxRCc). Half sequences are also identified which contain only a convex unit. The segment sequence was first defined by Young (1963, 64). He argues that the evolutionary trends of different convexo-concave sequences on a slope are, in some degree, independant.

(ii) Slope Form in the Field Areas

As a preliminary step in the analysis of the slope form data, three types of slope zone were recognized in order to facilitate the comparison of slope profiles. The three zones, which are termed the upper, intermediate and lower slope zones, originate from differing combinations of processes. It proved undesirable, therefore, to compare entire slope profiles at every stage of the analysis.

The upper slope zone merges imperceptibly into terrace surfaces which are related to ancestral stages of the Ottawa River. There are no obvious sites within this transitional zone at which to locate the upper endpoint of the slope profile. Where present, the zone constitutes a surface which is inclined at less than 2.5 degrees (see section 3(a), p.63). A lower slope zone, also of low gradient frequently occurs. It usually constitutes a toe slope, a part of the floodplain terrace of the basal stream. The upper boundary of this zone is sited at the base of the concavity which rises up into the intermediate zone. The latter occurs on each profile. It contains the maximum angle of slope and may perhaps be regarded as the slope

sensu stricto (Dylik, 1968) because it experiences perceptible slope processes which the upper and lower zones do not. Furthermore, it is beyond the reach of direct fluvial processes although it may display evidence of indirect fluvial influences such as lateral erosion.

These different slope zones occur in various combinations in different study valleys. In valley A1 (Fig. 3.3, p.67), which is incised into an extensive terrace, the upper slope zones are found on all profiles. The presence of a lower floodplain zone depends upon the position of the meandering channel. Toe slopes intervene between the channel and the intermediate zones on the insides of meander bends. The outer banks of these bends may abut directly against the intermediate zone (Plate XIII, p.80). A similar pattern emerges in valley B1 (Fig. 3.6, p.70; Plate VI, p.32), although occasionally the upper zone is short or absent because gradients of zero degrees are encountered close to the slope summit. The three zones occur on many slopes in valley A3 (Fig. 3.5, p.69; Plate IV, p.29) although the lower zone is narrow and less obvious in the graphically-reconstructed profiles. Valley A2 (Fig. 3.4, p.68; Plate X, p.61) contains slopes without any lower floodplain zone but with well-developed upper and intermediate zones. In the valleys at Gatineau (Figs. 3.7 to 3.10, pp.71-74), the intermediate zones dominate the profiles. Floodplains are absent here and extensive gently-inclined surfaces do not occur adjacent to the slope crest (see, for example, Plate XIV, p.80).

The variable form of the intermediate zone contrasts with the relative uniformity of the upper and lower slope zones. The

Plate XIII. An undercut scar in valley A1, immediately following the flood season (grid ref. 475145).

Plate XIV. A view of the narrow divides on either side of valley C3; a prominent facet is present below the slope summit on the farther slope; in the background is the 190-foot surface (grid ref. 472383).

intermediate zone has been isolated, therefore, from the rest of the profile for much of the ensuing discussion since it was discovered, during preliminary analysis, that differences within it tended to be confused or masked when the profiles were considered in their entirety.

Using the classification of slope form which is outlined in section 3(b)i, the segment structure of each profile has been plotted beneath it in Figures 3.3 to 3.10 (pp.67 to 74). The upper slope zones exhibit very minor fluctuations of gradient which may be associated with complex sequences of segments. The lower slope zone is usually of simpler form, consisting of a long gentle convexity which terminates at the margin of the fluvial channel.

The forms of the intermediate zones are classified in Table 3.1 (p.82). Seven major groups of segment sequences are identified which may be subdivided into twenty individual patterns. The simplest patterns, which comprise one complete or partial segment sequence only, are most commonly observed and constituted ninety percent of the observed profiles. Sixty-seven percent of the profiles possess a simple convexo-concave sequence. This type dominates at Gloucester Glen in all three valleys but especially in valley A2 (Fig. 3.4, p.68) and valley A3 (Fig. 3.5, p.69; Plate IV, p.29). It is also common at Trend Village (Fig. 3.6, p.70; Plate VI, p.32). At Gatineau, convexo-concave slopes are infrequent except in valley C2 (Fig. 3.8, p.72). Thirteen percent of the slopes are totally convex and comprise partial segment sequences. Such slopes occur occasionally in all of the study areas, but are most frequent in valley A1 (Plate XIII, p.80).

TABLE 3.1. THE PATTERNS OF SLOPE SEGMENT SEQUENCES ON THE INTERMEDIATE ZONES OF SLOPE PROFILES

GROUP	NUMBER OF SEQUENCES	TYPE	DESCRIPTION (DOWN SLOPE→)*	A1	A2	A3	B1	C1	C2	C3	C4	ALL VALLEYS
1	½	1A	Cx	6	-	2	2	-	-	2	1	13
		1B	RCx	-	-	-	-	-	-	1	-	1
		1C	CxR	-	-	-	-	-	-	1	-	1
2	1	2A	CxCc	17	16	16	10	1	7	-	2	69
		2B	CxRCxCc	-	-	-	-	-	-	-	1	1
		2C	CxRCxRCxCc	-	-	-	-	1	-	-	-	1
		2D	CxRCc	-	-	-	1	-	-	-	-	1
		2E	CxCcRCc	-	-	-	-	-	-	1	-	1
		2F	CxCcR	1	-	-	-	-	-	-	1	2
3	1½	3A	CxCcCx	-	-	-	-	-	1	-	-	1
		3B	RCxCcCx	-	-	-	-	-	-	1	-	1
		3C	CxRCcRCx	-	-	-	-	-	-	1	-	1
		3D	CxCcRCcCx	-	-	-	-	-	-	1	-	1
4	2	4A	CxRCcCxCc	-	-	-	-	-	-	1	-	1
		4B	CxRCxCcRCxCc	-	-	-	-	-	-	1	-	1
		4C	CxCcCxRCc	-	-	-	-	-	-	-	1	1
5	2½	5A	CxCcCxCcCx	-	-	-	-	2	-	1	-	3
6	3	6A	CxCcCxRCcRCxCc	-	-	-	-	1	-	-	-	1
7	3½	7A	CxCcRCxRCcRCcRCxRCcCx	-	-	-	-	1	-	-	-	1
		7B	CxCcCxCcCxCcRCx	-	-	-	-	-	-	1	-	1
				24	16	18	13	6	8	12	6	103

*Cx = convex; Cc = concave; R = rectilinear

No other segment sequence was found to recur with regularity. Of the twenty different sequences, the CxCc and Cx types constitute eighty-one percent. The remaining patterns (with the exception of the CxRCc and CxCcR varieties) are confined to the Gatineau area. They often contain more than one segment sequence and are so complex that they rarely occur more than once. Group 7 contains 3½ segment sequences, and Group 6, 3. The repetition of sequences is indicative of some degree of faceting in mid-slope and, although several sequences may be present, one faceted level is usually particularly prominent (Plate IX, p.36; Plate XIV, p.80). In valley C1 (Fig. 3.7, p.71), for example, pronounced flattening occurs at the base of the highest sequence on profiles 1A and 2A, although other sequences are present. In profile 1B, the most well-developed levelling is at the base of the middle of three sequences. Occasionally, two major facets may be present, for example, in profile 2A of valley C3 (Fig. 3.9, p.73). The complexity of slope form in the Gatineau area is a remarkable contrast to the simple patterns which occur at both Gloucester Glen and Trend Village. The origin of the facets at Gatineau is doubtful but could be related to either slope processes or fluvial terracing.

Significant variations may be detected in the relative dimensions of different types of slope segment on individual slope profiles. For the purposes of demonstrating these variations, both the height and length of an individual segment may be expressed as a percentage of the total height and length respectively of the slope. Percentage form composition data are presented here for the

intermediate slope zones. A general impression of the relative proportions of different slope segments in each area may be obtained from Figure 3.12 (p.85). Convex segments, on average, constitute more than half of the total lengths and heights of profiles, their contributions to these dimensions varying between 52 and 62 percent. The concave proportion is lower and varies from 30 percent of slope length at Gatineau to 45 percent of slope height at Gloucester Glen. The rectilinear component of the slope is negligable except at Gatineau where its average contribution to slope length is 10 percent.

The percentage form structures for individual slope profiles are plotted on trivariate graphs in Figure 3.13 (p.86). In Figure 3.13A, the concentration of slopes at the base of the graph is indicative of the almost complete lack of rectilinear segments on all slopes at Gloucester Glen and Trend Village. There is some evidence of rectilinear development on 15 of the 32 slopes at Gatineau. On most slopes more than 50 percent of slope length is convex. A similar pattern is revealed in Figure 3.13B, although concave development exceeds convex development on greater than 50 percent of the profiles. It is probable that there are a few short rectilinear segments which have not been detected by using the twenty-five feet measured length, but there is no doubt that most sloping surfaces are curved rather than rectilinear in the field areas.

The rates of curvature of the convex and concave slope segments of the intermediate zone were calculated with the aid of the following formula from Young (1963a, 64):-

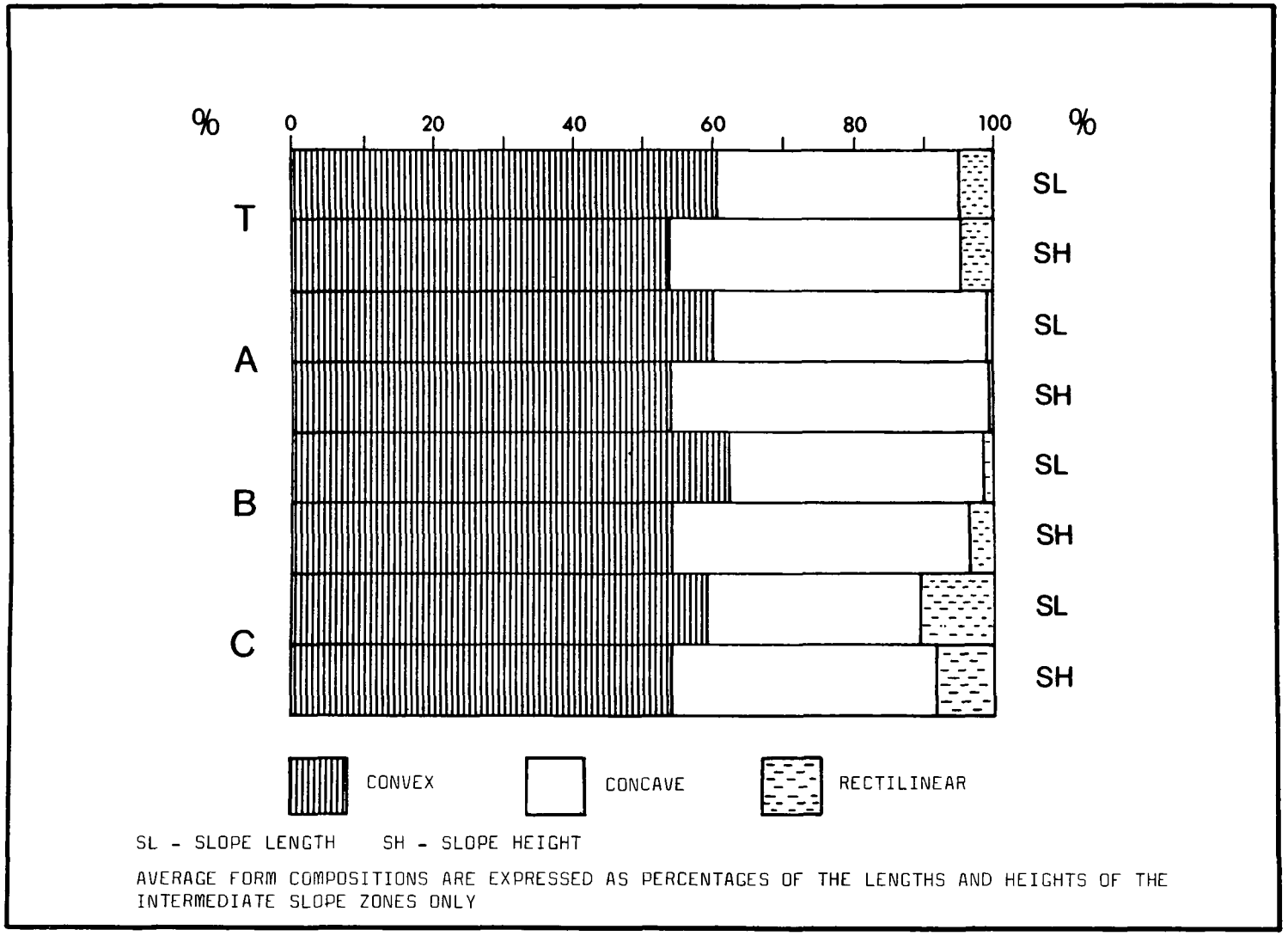


FIG. 3.12. BAR GRAPH OF THE AVERAGE PERCENTAGE FORM COMPOSITION OF THE MEASURED SLOPE PROFILES

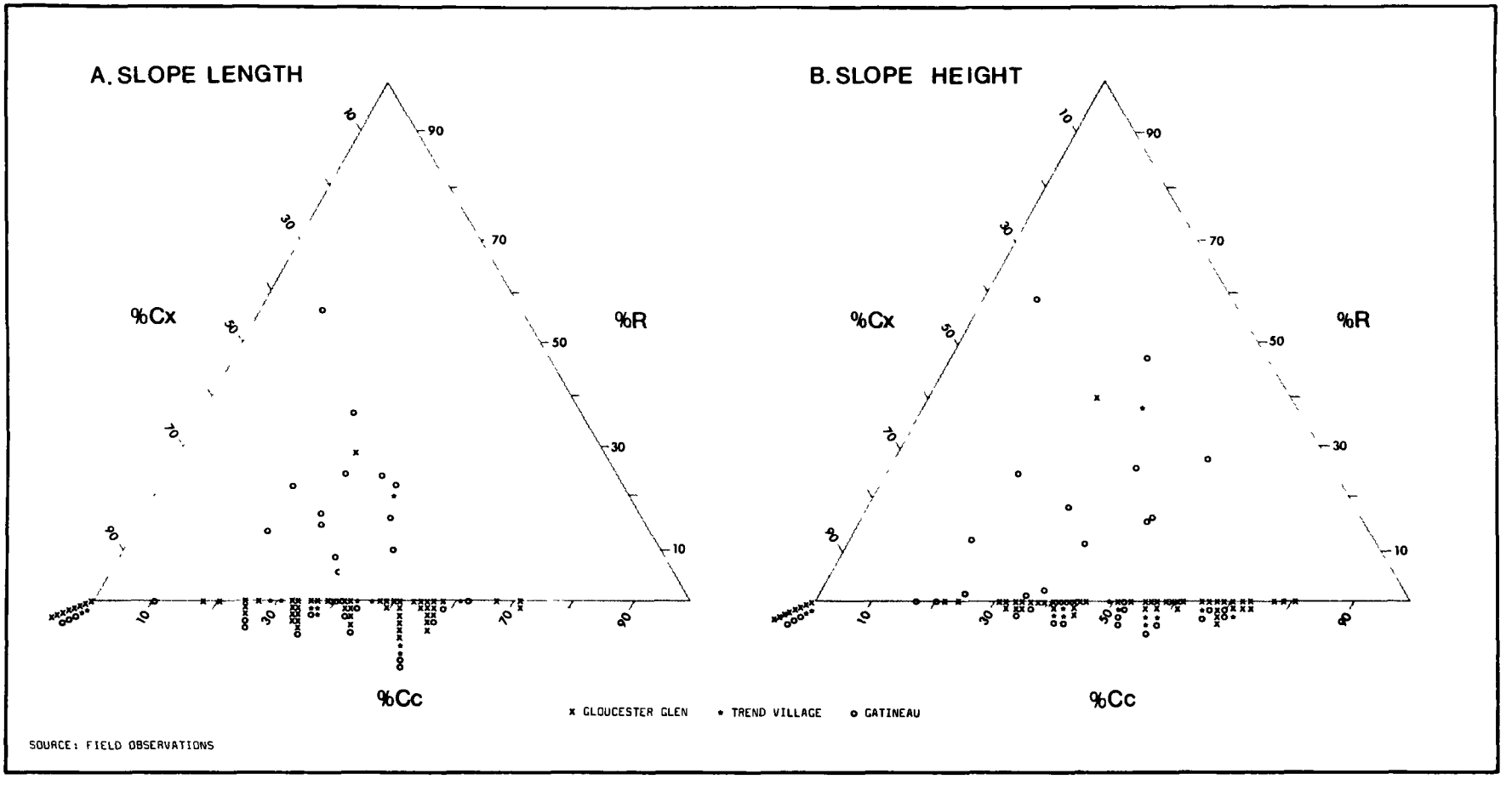


FIG. 3.13. TRIVARIATE GRAPHS OF THE PERCENTAGE FORM COMPOSITION OF INDIVIDUAL MEASURED SLOPE PROFILES WITH RESPECT TO SLOPE HEIGHT AND SLOPE LENGTH

$$\frac{A \pm B}{L} \times 100$$

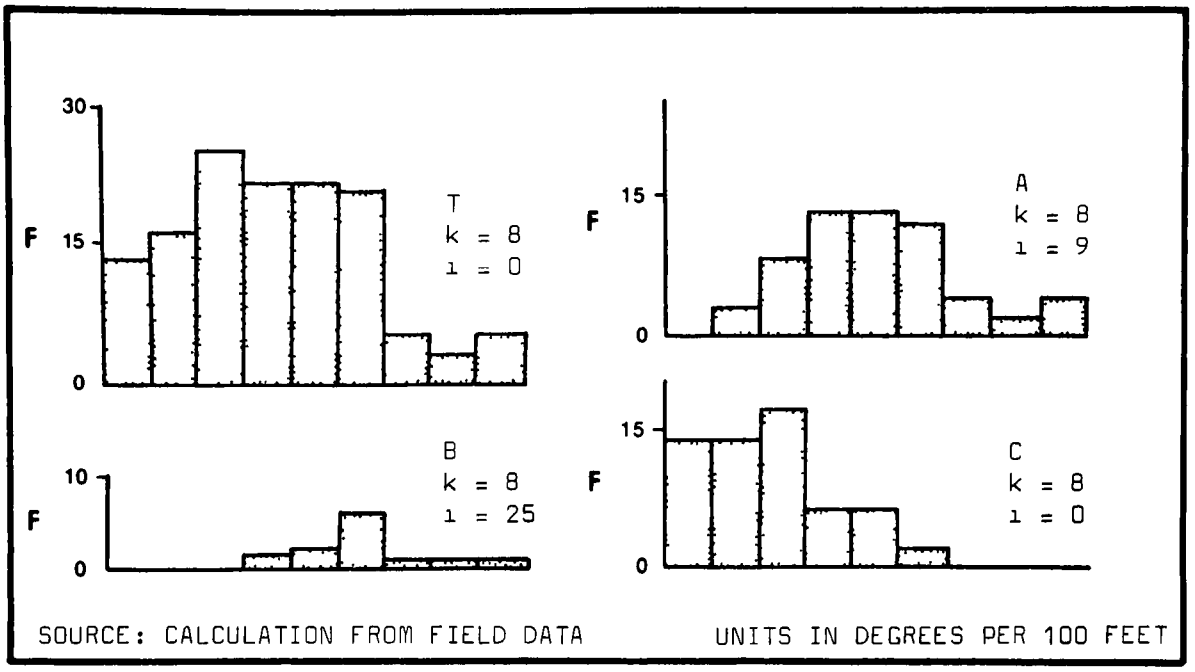
Where A = the angle of the highest measured length
B = the angle of the lowest measured length
L = the ground length in feet

The units of measurement of the rates of curvature are degrees per 100 feet. Multiplication by 100 is performed in order to transform the observed rates of curvature (for segments of varying length) to rates for a unit ground length of 100 feet. Rates as expressed are then directly comparable.

The frequency distributions of rates of curvature for all profiles are reproduced in Figure 3.14 (p.88). It may be seen that very few convex segments possess rates of curvature which exceed 48 degrees per 100 feet (Fig. 3.14A). Rates of convexity assume their greatest magnitudes at Trend Village where the mean rate of curvature is 52.31 degrees per 100 feet, and their least values at Gatineau where the mean is 18.51 degrees (Table 3.2A, p.89). The distribution is not highly peaked and the great inherant variation is indicated by values of the coefficient of variation. A similar pattern emerges with respect to concavities (Fig. 3.14B, Table 3.2B). Measures of central tendancy exhibit considerable contrasts and rates at Trend Village far exceed those elsewhere. The rates of curvature in the upper and lower slope zones are rather low and rarely exceed 4 degrees per 100 feet.

In summary, it has been demonstrated that, at Gloucester Glen and Trend Village, the intermediate zones of most slopes are convexo-concave whereas, at Gatineau, they are often much more

A. CONVEXITIES



B. CONCAVITIES

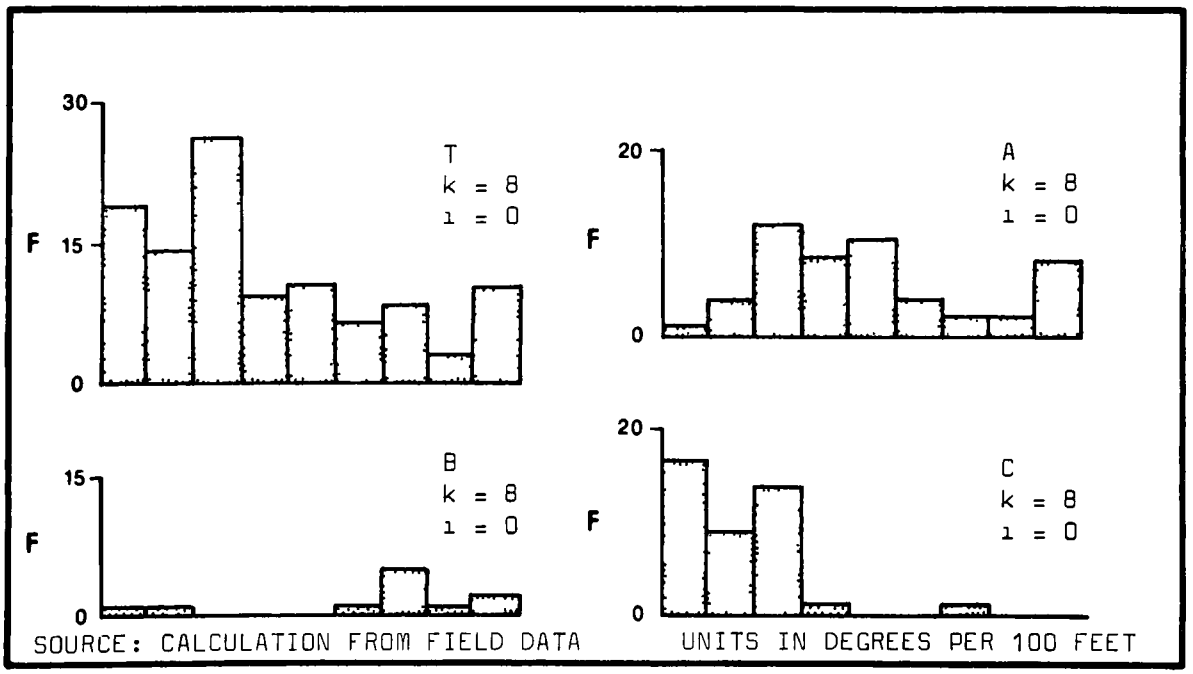


FIG. 3.14. FREQUENCY HISTOGRAMS OF RATES OF CURVATURE ON THE MEASURED SLOPE PROFILES

TABLE 3.2. CHARACTERISTICS OF RATES OF CURVATURE OF CURVED SEGMENTS ON THE INTERMEDIATE SLOPE ZONES

A. CONVEXITIES*

	N	$\bar{x}$	Mo	SD	CV%
TOTAL POPULATION	129	30.79	20.00	21.45	69
GLOUCESTER GLEN (A)	59	37.92	32.00	18.50	48
TREND VILLAGE (B)	13	52.31	44.00	33.82	64
GATINEAU (C)	57	18.51	20.00	10.83	58

*Values in degrees per 100 feet for $\bar{x}$, Mo, SD.

B. CONCAVITIES*

	N	$\bar{x}$	Mo	SD	CV%
TOTAL POPULATION	105	29.78	20.00	22.34	75
GLOUCESTER GLEN (A)	52	37.67	20.00	20.77	55
TREND VILLAGE (B)	11	51.82	52.00	26.97	52
GATINEAU (C)	42	14.23	4.00	8.76	61

*Values in degrees per 100 feet for $\bar{x}$, Mo, SD.

complex. On individual profiles, the character of the convex and concave segments may be rather contrasted and either segment type may dominate. Rectilinear segments are almost completely lacking on slopes except in the Gatineau area. The rates of curvature of convex and concave segments tend to be greatest at Trend Village and least at Gatineau.

3(c) Maximum and Mean Angles of Slope

The maximum angle of slope is the steepest measured length inclination on a given profile. It has been considered to be a sensitive index of fluctuations in local conditions and it apparently assumes a normal (i.e. Gaussian) distribution of low variability where environmental conditions are fairly uniform (Strahler, 1950). Descriptive statistics for this parameter in the Ottawa area assume the following values:-

AREA	N	$\bar{x}$	Mo	SD	CV%
TOTAL	103	22.65	21.93	6.71	30
A	58	23.91	22.60	5.24	22
B	13	29.77	28.60	5.01	17
C	32	17.78	19.97	6.07	34

(values in degrees for $\bar{x}$, Mo, SD).

The highest mean value occurs at Trend Village and the lowest at Gatineau. Variability within the data is low when compared to that within populations of other parameters of slope form, values of the coefficient of variation not exceeding thirty-four percent. This fact illustrates the tendancy for maximum angles to cluster around mean values. Frequency histograms of these distributions (Fig. 3.15,

p.92) suggest that they may be approximately normal except at Gatineau. The graphs also demonstrate differences from place to place in the range of mean angle values. A test of difference, the Mann/Whitney 'U' test, was performed between each pair of areas in order to investigate these variations. A null hypothesis stated that, for each pair of areas,there are no differences in their maximum angles except for chance variations. The data were ranked and a one-tailed region of rejection was employed since the direction of difference under the alternative hypothesis was predicted from the mean values. The results were as follows:-

AREAS IN TEST	z	p*	HYPOTHESIS ACCEPTED
A/B	-3.38	0.001	Hi
A/C	4.50	0.001	Hi
B/C	-5.07	0.001	Hi

*s=0.05

The alternative hypothesis was accepted in each test, confirming the existence of significant differences in maximum angles among the three study areas. These differences presumably reflect differences in the relative efficacies of agents which increase or decrease slope gradients.

The location of the maximum angle on a slope was calculated as the position of the maximum angle upslope from the bottom endpoint, expressed as a percentage of total slope length. All slope zones were included in the calculation of total slope length because it was felt that the activity of the basal stream would considerably influence this parameter (see section 2(c)iii, p. 51). It was desirable, therefore, that the parameter reflect the distance of the maximum angle from the basal channel. Values of zero percent

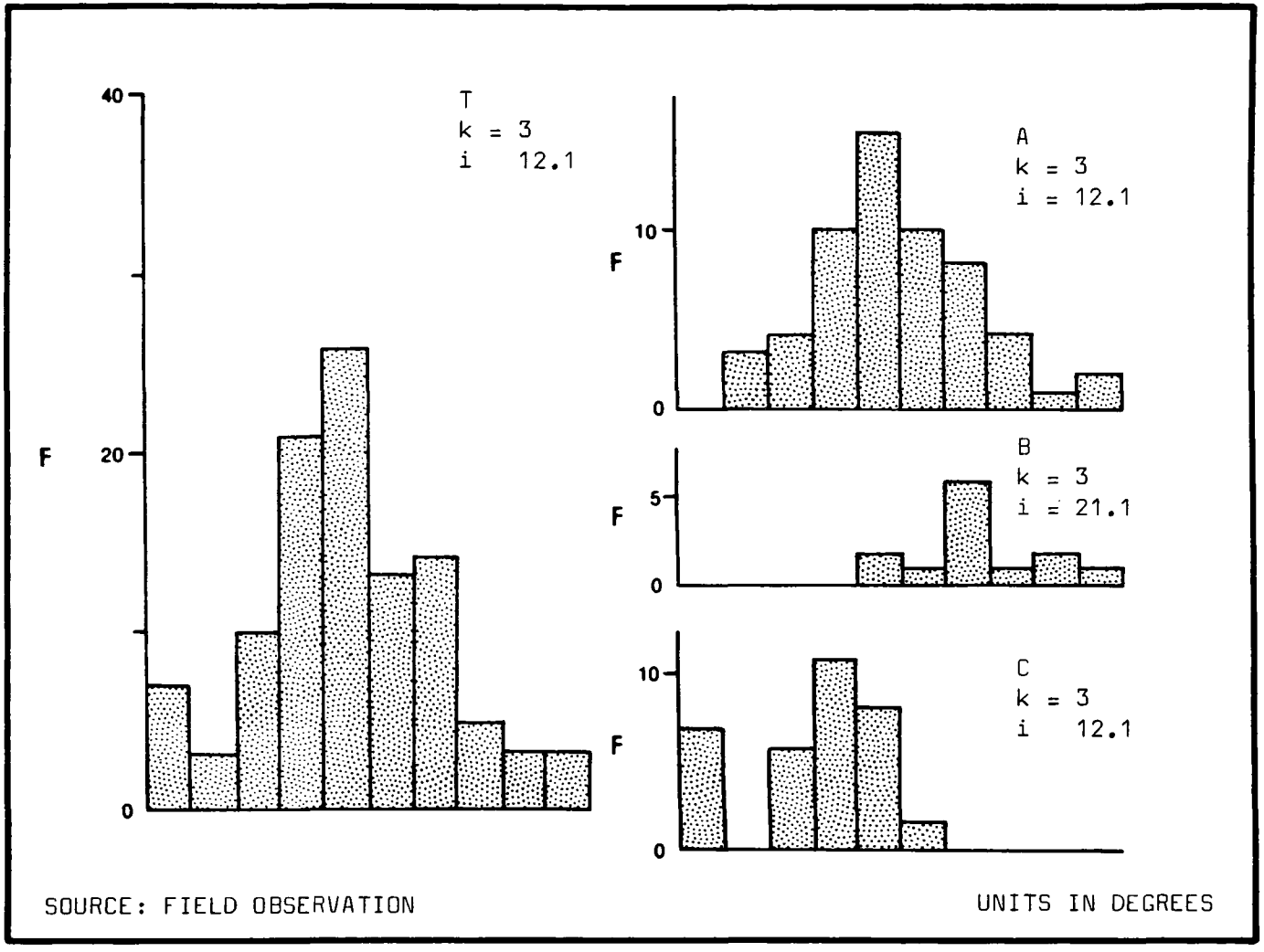


FIG. 3.15. FREQUENCY HISTOGRAMS OF MAXIMUM SLOPE ANGLES ON THE MEASURED SLOPE PROFILES

indicate that the maximum angle is adjacent to the fluvial channel. The mean value of this parameter for the region was 27.43 percent and varied from 26.30 percent at Gatineau to 32.21 percent at Trend Village. The distribution of this parameter is positively skewed (Fig. 3.16, p.94) and it appears that, in all areas, maximum angles tend to occur near the slope base. A Mann/Whitney 'U' test was unable to detect any significant differences among the study areas in the location of maximum angles on slope profiles. This finding is surprising in view of the significant differences in maximum angles among the study areas and suggests a lack of sensitivity of this index to contemporary local fluvial discharge regimes.

The mean angle of slope is the average inclination of the slope profile and is derived from slope height and slope length data. It has been calculated here as the average inclination of all three slope zones so that it reflects the morphometry of the valley rather than local conditions within the intermediate zone solely. This parameter of slope form is believed to be more stable and less sensitive to change than the maximum angle of slope. This is demonstrated by the following descriptive statistics:-

AREA	N	$\bar{x}$	Mo	SD	CV%
TOTAL	103	9.01	7.86	2.81	31
A	58	8.48	7.42	2.36	28
B	13	10.78	-*	3.61	34
C	32	9.45	10.55	2.94	31

(values in degrees for $\bar{x}$, Mo, SD; * bimodal).

Mean values are similar, dispersion is low and values of the coefficient of variation are little greater than those for maximum angles. The distribution of mean angles for the total area

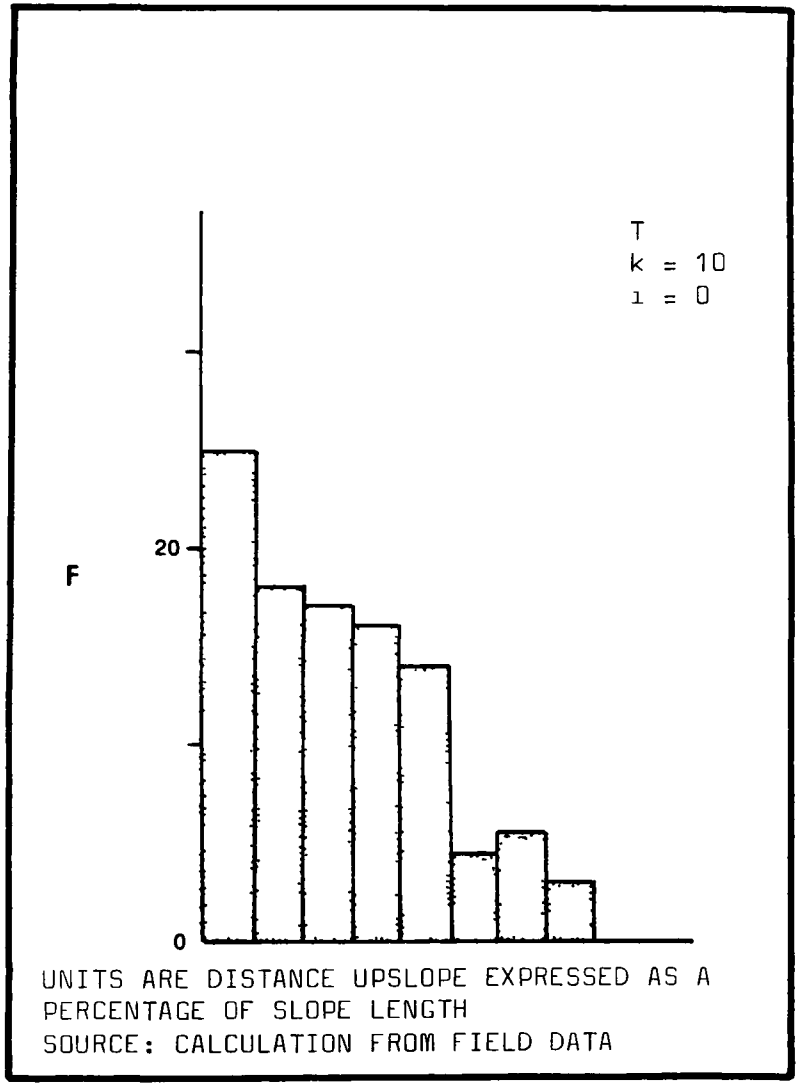


FIG. 3.16. FREQUENCY HISTOGRAM OF THE LOCATION OF MAXIMUM SLOPE ANGLES ON THE MEASURED SLOPE PROFILES

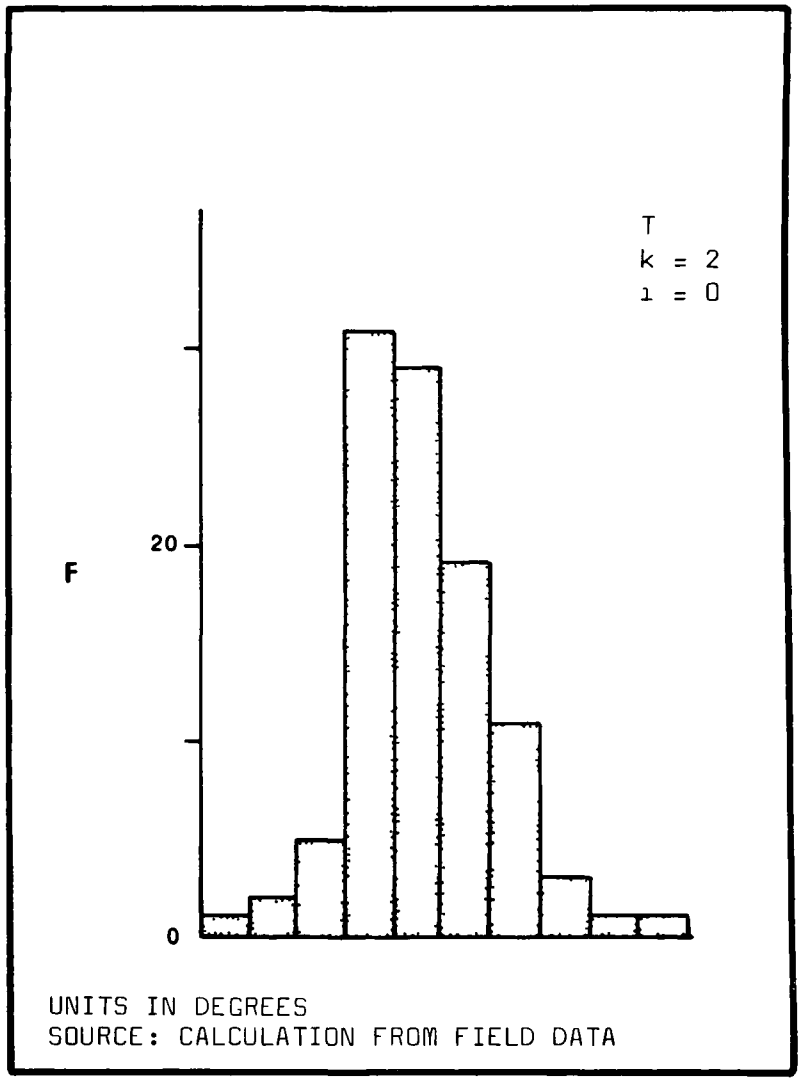


FIG. 3.17. FREQUENCY HISTOGRAM OF MEAN SLOPE ANGLES OF THE MEASURED SLOPE PROFILES

(Fig. 3.17, p.94) approaches a normal one but is slightly negatively skewed. Few mean angles of slope exceed sixteen degrees.

The relationships of both maximum and mean slope angles to the dimensions of the slope were graphed. Data from the Gatineau area were plotted separately from those of the other study areas because of the differences in slope form which have already been noted between these areas.

The plots of maximum angle against both slope height and slope length (Fig. 3.18, p.96) reveal no systematic patterns in any areas since maximum angles are influenced more by local conditions than by regional morphometric dimensions. At both Gloucester Glen and Trend Village, however, where slope height is relatively invariant, the mean angle exhibits a strong negative relationship with slope length (Fig. 3.19, p.96). Any factors which influence slope length, such as the migration of the basal stream channel or the width of local water divides, chiefly determine, therefore, variations in mean angle. No close relationships are evident between mean angle and either height or length at Gatineau. In this area, slope height is very variable and factors which control this parameter, such as fluvial downcutting or divide wasting, must also be considered in order to explain variations in mean angle.

3(d) Characteristic Angles

It has often been asserted that slope angles characteristically recur within particular landscapes. "Characteristic angles

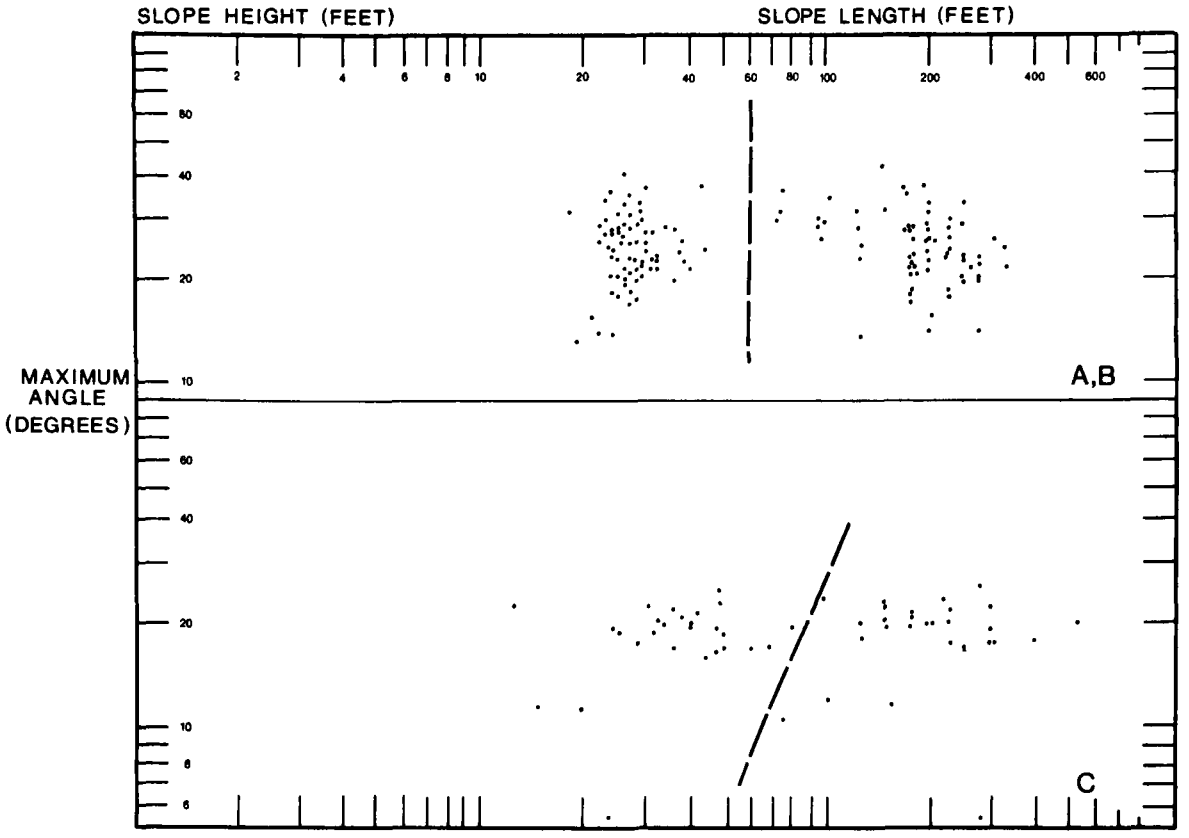


FIG. 3.18. BIVARIATE GRAPHS OF THE RELATIONSHIPS BETWEEN MAXIMUM SLOPE ANGLES AND SLOPE DIMENSIONS

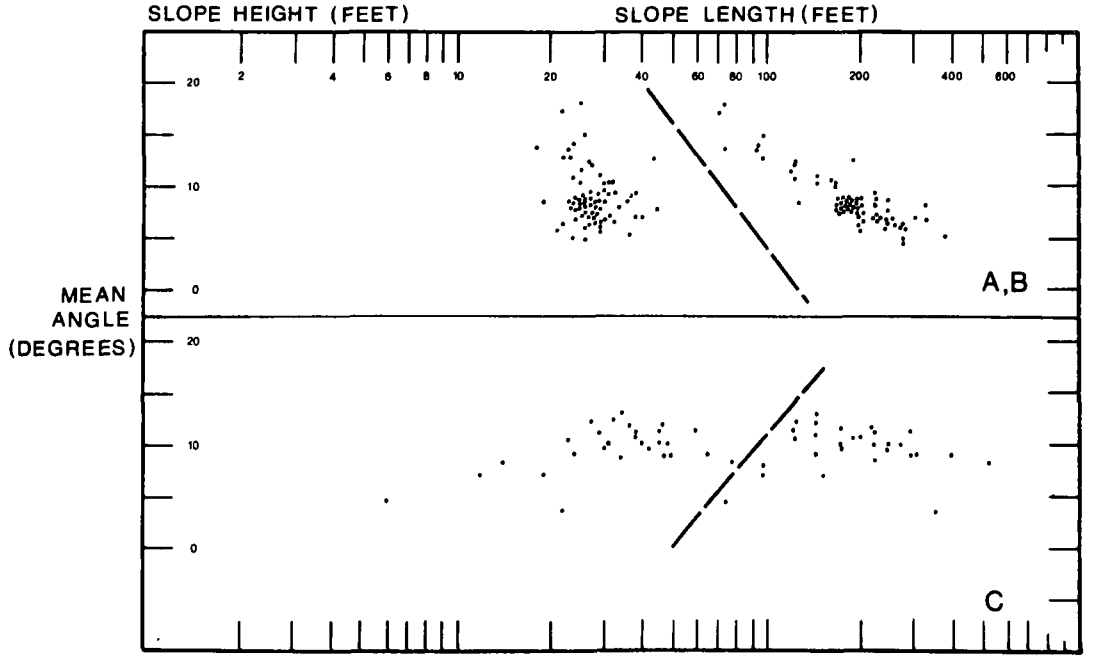


FIG. 3.19. BIVARIATE GRAPHS OF THE RELATIONSHIPS BETWEEN MEAN SLOPE ANGLES AND SLOPE DIMENSIONS

of slope are those which most frequently occur, either on all slopes, under particular conditions of rock type or climate, or in a local region." (Young, 1961, p.126). Carson and Petley (1970) suggest that recurring angles may reflect thresholds for the operation of particular processes and that these are controlled by the strength characteristics of the soil. Macar (1963) and G. Seret (1963) have emphasized the need to seek explanations for them within their area of origin and Clark (1965) has criticized certain authors who have attempted to ascribe world-wide significance to characteristic angles which have been derived from local situations.

In an attempt to recognize characteristic angles in the Ottawa area, attention was focused upon the measured length inclinations. The search for characteristic angles met with limited success only. An important problem was that no standard procedures are available for selecting them from a population. One cannot, for example, select only values for which the highest frequencies are recorded because, where distributions are strongly positively skewed, as in the present case, no values could be selected in the higher range. Equally, one cannot select all modal values since these modes may possess frequencies only slightly in excess of neighbouring classes and may be due solely to chance. Some modal values, furthermore, may contain lower frequencies than other values which do not form modes in the distribution.

Tests were performed in order to determine whether or not characteristic angles could be validly identified in the Ottawa area. The populations of measured length inclinations were organized into

histograms with a class interval of one degree. Each modal class was selected for testing (see Table 3.3A, p.99). Each mode was considered in turn and became part of a small histogram with five classes, the others being the two on either side of it in the major distributions. For each set of five classes, a null hypothesis stated that no differences occur in the frequencies in each class except for those which may be attributed to chance. A Chi Square test was then performed during which the observed frequencies were compared with the average frequencies among the five classes. Where the value of Chi Square was found to be significant at the five percent level, the modal class in the histogram was considered to constitute a characteristic angle.

The results have been summarized in Table 3.3B. Low angles only occur in significantly high quantities. Values between zero and 2.5 degrees constitute 42 percent of all measured length inclinations, including 53 percent of those at Gloucester Glen, 50 percent of those at Trend Village and 23 percent of those at Gatineau. The percentages are especially high at Gloucester Glen and Trend Village where the upper and lower slope zones are well-developed. Both 2 degrees and 5 degrees are characteristic of the entire region, 2 degrees at Gloucester Glen, 1 degree at Trend Village and zero degrees at Gatineau. The 5-degree class is prominent at Gatineau but was not found to be significantly larger than neighbouring classes. Since low-angle surfaces (below 2.5 degrees) may not even experience slope processes, the only legitimate characteristic angle is probably 5 degrees.

TABLE 3.3. CHARACTERISTIC ANGLES AMONG THE MEASURED LENGTH INCLINATIONS.

A. MODES IN DISTRIBUTIONS[x] OF MEASURED LENGTH INCLINATIONS[+]

T			2	5	7		9		12	14	17	19		23	26	28		36
A			2		7				12	14	17	19		23		28		
B		1				8		11			17			23		28	30	
C	0			5			9		12		17		22					

([x]K = 1 degree; [+]values in degrees)

B. CHI SQUARE VALUES WHICH TEST THE SIGNIFICANCE OF THE MODES

T			83.68*	10.50*	6.23		1.00		3.74	3.57	0.82	6.89		3.75	4.43	7.00		?
A			104.42*		3.00				4.55	5.80	1.13	1.75		1.71		?		
B		23.88*				?		?			?			?		?	?	
C	24.20*			8.73			3.90		3.82		0.50		?					

(DF = 4; * $p \leq 0.05$; ? - frequencies < 5, too low for Chi Square test).

3(e) Valley Morphometry

(i) Channel Gradient

The relationship between channel gradient and slope form was reviewed in section 2(c)iii,p.52. The literature suggested that a relationship exists between slope angles and channel gradients which reflects the amount of debris to be transported. In the present study, the longitudinal profiles of all of the study valleys except valley C4 were measured with the aid of an automatic level. The diagrammatic reconstructions of these profiles (Fig. 3.20, in pocket) demonstrate that the steepest gradients are found at Gatineau where the average gradients are 4°20' for valley C1, 2°30' for valley C2 and 4°10' for valley C3. Much lower gradients occur in the other field areas. Valley A2 possesses an average gradient of 0°50' and channel gradients in other valleys do not exceed 0°30'.

From Figure 3.20, it is obvious that a major scale variation exists among the study valleys. The length of the surveyed stretch of valley A1 is approximately 13,500 feet whilst none of the valleys at Gatineau exceed 2,500 feet in length. The length of valley B1 is greater than the figure suggests since only its upper reaches were levelled.

The data from these observations also suggest that an inverse relationship exists between slope gradients and valley gradients among the study valleys. This may be simplistically demonstrated by calculating an average slope ratio for each study valley which is a modification of that which was proposed by Strahler (1950).

The average slope ratio (average channel gradient/average value of measured maximum slope angles) appears to decrease as valleys become larger. It assumes its lowest values in the valleys of greatest length (A1 = 0.0066; B1 = 0.0110). In valleys A2 and A3, which are of intermediate length, the ratio values are 0.0339 and 0.0223 respectively. The highest ratio values occur in the short valleys at Gatineau (C1 = 0.3006; C2 = 0.1208; C3 = 0.2192). The ratio serves to demonstrate, therefore, the presence of fundamental contrasts in valley form.

(ii) Downvalley Variations in Slope Form

The position of a slope within a valley may exert a control upon slope form. Carter and Chorley (1961), for example, have revealed correlations between maximum and mean angles of slope and stream order. Similar relationships were sought in the present study by tabulating the relationships between a series of slope form parameters and valley location (Table 3.4, pp.102 and 103). The values for slope form parameters which are entered into this table are averages for the two slopes which comprise the cross profile at any one location within a valley.

Slope height demonstrates a definite downstream increase in valleys A1 and A2, but height is relatively constant in valleys B1 and C2 and appears to decline downstream in valleys C1 and C3 where the valley channels and intervening divides merge into a single flat surface at approximately 200 feet.

There do not appear to be any distinct trends in the variations of slope length within the valleys except perhaps for a

TABLE 3.4. DOWNVALLEY VARIATIONS IN SOME SLOPE FORM PARAMETERS.*

VALLEY	CROSS-PROFILE	DISTANCE FROM VALLEY MOUTH (FEET)	SLOPE HEIGHT (FEET)	SLOPE LENGTH (FEET)	MAXIMUM ANGLES (DEGREES)	MEAN ANGLES (DEGREES)
A1	1	10,850	25.5	208.5	21.3	7.1
	2	10,650	26.0	222.5	20.8	6.9
	3	10,500	24.0	183.0	21.0	9.6
	4	10,150	24.3	147.5	21.5	9.5
	5	9,820	28.0	221.5	27.8	7.5
	6	9,625	28.5	261.0	24.3	6.2
	7	9,400	27.0	222.0	26.5	7.0
	8	9,100	25.5	156.5	31.3	12.0
	9	8,400	30.3	213.5	29.0	8.4
	10	8,100	39.5	282.5	28.5	9.0
	11	7,650	38.0	273.5	24.8	8.1
	12	7,400	41.0	285.5	23.5	8.2
A2	1	1,133	24.0	189.0	21.5	7.2
	2	1,000	24.8	186.5	23.3	7.5
	3	825	24.5	173.0	24.0	8.0
	4	700	23.0	136.0	24.8	10.3
	5	566	27.0	194.5	26.0	7.8
	6	433	29.3	193.5	26.5	8.5
	7	300	30.5	182.0	27.5	9.5
	8	150	29.5	171.5	23.3	10.3
A3	1	2,560	27.5	222.5	18.0	6.9
	2	2,410	30.0	197.5	23.8	8.7
	3	2,244	29.5	209.5	22.3	8.1
	4	2,111	28.0	173.5	28.5	9.3
	5	1,978	24.0	161.0	17.5	8.4
	6	1,845	26.0	197.5	19.8	7.5

*Values are averages for the two slope profiles which comprise each cross-profile.

TABLE 3.4. (CONT.).*

VALLEY	CROSS-PROFILE	DISTANCE FROM VALLEY MOUTH (FEET)	SLOPE HEIGHT (FEET)	SLOPE LENGTH (FEET)	MAXIMUM ANGLES (DEGREES)	MEAN ANGLES (DEGREES)
A3 (cont.)	7	1,670	27.5	222.0	22.0	6.8
	8	1,520	32.0	199.5	20.5	9.0
	9	1,320	28.0	187.0	28.8	10.5
B1	1	21,630	25.0	145.0	29.3	10.0
	2	21,550	25.0	156.5	26.5	10.4
	3	21,425	25.5	157.0	35.0	9.3
	4	21,320	26.0	163.5	31.8	10.0
	5	21,140	24.8	124.5	31.0	13.1
	6	21,050	26.5	108.5	28.5	13.8
	7	21,000	-+	-+	-+	-+
C1	1	580	54.0	295.0	17.5	10.3
	2	230	48.0	337.5	15.8	7.7
	3	0	13.5	213.0	4.5	3.5
C2	1	398	36.0	173.0	21.3	11.8
	2	280	32.5	160.0	22.3	11.3
	3	150	35.0	172.5	20.3	11.5
	4	0	36.0	173.0	19.0	11.8
C3	1	898	39.5	222.5	23.3	10.0
	2	632	52.0	312.5	19.8	9.5
	3	482	38.0	235.0	17.0	9.1
	4	282	46.0	273.0	18.0	9.5
	5	132	26.0	146.0	17.0	8.3
	6	0	4.0	88.0	3.5	2.4
C4	1	214	23.5	135.5	19.8	9.8
	2	100	22.0	135.0	15.8	8.9
	3	0	20.0	130.0	17.0	9.2

*Values are averages for the two slope profiles which comprise each cross-profile

+Cross-profile 7 in valley B1 incomplete

fluctuating downstream decline in valley C3. A slight but distinct rise in maximum angle inclinations may be recognized in valleys A1 and A2 in a downstream direction and in valleys C1 and C3 in an upstream direction. Mean angles decline downstream in valleys C1 and C3, probably in association with the similar decline in slope height. They also exhibit a slight downstream increase in valleys B1 and A2, in the latter valley as a reflection of the corresponding increase in slope height. One may conclude that, although some trends may be identified, other explanations, probably more locally based, are required to interpret variations in many slope form parameters.

(iii) Valley Cross-Profile Characteristics

The forms of valley cross-profiles depend upon the controls which fashion the two slope profiles which comprise them. In the present study, an attempt was made to quantify some aspects of cross-profile characteristics. Several parameters were derived. Those which are concerned with dimensions are treated separately from those which consider slope asymmetry.

Dimensions

Three indices of cross-profile dimensions were investigated. They are based upon similar parameters which were developed by Heginbottom (1967) and are illustrated in Figure 3.21 (p.105).The cross-sectional area of the cross-profile is the area, in square feet, which is contained by the valley sides, the basal channel and a line which joins the upper endpoints of the two slope profiles. The centre depth of the cross-profile is the vertical distance, in feet,

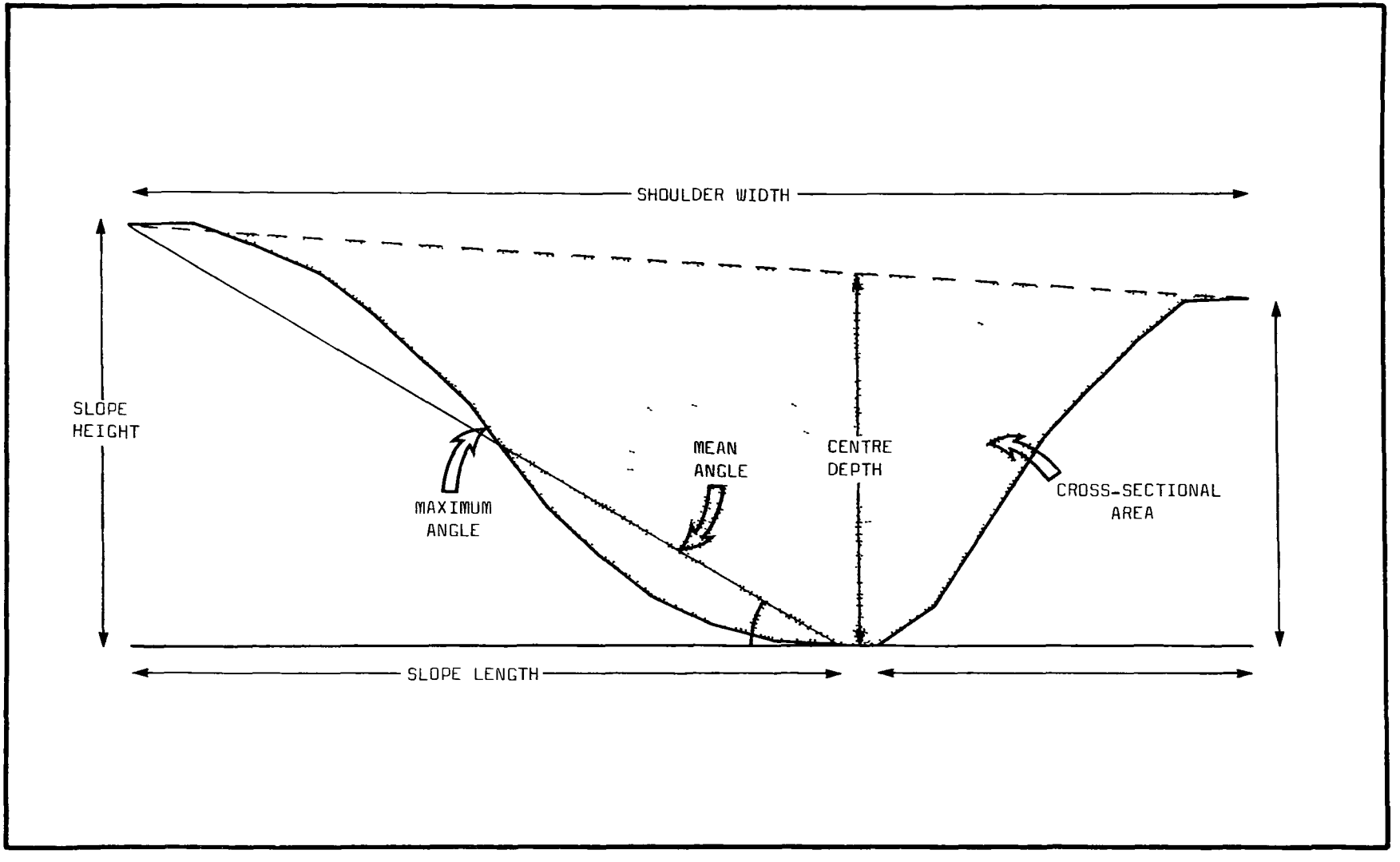


FIG. 3.21. PARAMETERS OF SLOPE AND VALLEY FORM

between the centre of the basal channel and a line which connects the upper endpoints of the two slope profiles. The shoulder width of the cross-profile is the distance, in feet, between the upper endpoints of the two slope profiles.

Table 3.5 (p.107) records the maximum and minimum dimensions of each of these parameters for each valley. The valleys at Gatineau, which are shortest in length, tend to possess the greatest cross-profile dimensions, particularly valleys C1 and C3. The cross-profiles of these two valleys are larger with respect to all three dimensions than those of the long valleys, A1 and B1. The range of values between the maximum and minimum dimensions at Gatineau is also greater than elsewhere and reflects the gradual transition from ridge-and-valley topography on the terrace bluff to the flat terrain of the 190-foot surface. Valley B1 exhibits the least range of variation in cross-profile dimensions.

It has been argued that various areal and linear dimensions of drainage basins tend to increase allometrically during drainage development (see section 2(c)iv, p.54). In order to test the applicability of this hypothesis to the study valleys, seven variables of slope and valley form were compared to each other within a simple shot-gun correlation matrix, using all cross-profiles. The rank correlation coefficient, Spearman's rho, was employed to assess the degree of correlation between each pair of variables. Parametric statistics were avoided because some populations were not normally distributed. No attempt was made to eliminate interdependancy among the variables. In addition to the three cross-profile di-

TABLE 3.5. VALLEY CROSS-PROFILE DIMENSIONS

VALLEY	SHOULDER WIDTH (FEET)		CENTRE DEPTH (FEET)		CROSS-SECTIONAL AREA (SQUARE FEET)	
	MAX.	MIN.	MAX.	MIN.	MAX.	MIN.
A1	381	227	41	24	1710	600
A2	216	141	30.5	23	550	305
A3	290	193	30	22	715	420
B1	221	170	26.5	24.5	565	445
C1	595	325	53	9	2960	355
C2	268	268	36	32	950	750
C3	546	221	58	13	2510	390
C4	248	193	25	19	590	340

mensions, slope height, slope length, mean angle and maximum angle were included in the analysis (see Table 3.6, p.109).

The five dimensional parameters are positively intercorrelated. The correlations are highly significant in many instances and appear to accord with the principle of allometric growth except in valley B1. However, the results are not conclusive since the principle implies a constant ratio rather than a simple correlation between variables.

The angular parameters tend to be correlated with each other but exhibit only limited relationships with the dimensional parameters. Local factors which modify slope angles, such as basal fluvial activity, have probably overridden any relationships which might otherwise exist between the two sets of parameters. It should be noted, for example, that both maximum and mean angles are negatively correlated with slope length, a dimension which is itself susceptible to local fluvial activity. As further evidence of these local factors, many of the corss-profiles are asymmetrical.

Cross-Profile Asymmetry

Slope asymmetry may be considered with respect to both maximum and mean angles of slope. Several attempts have been made to develop indices which quantify the degree of slope asymmetry. In the present study, indices of asymmetry were calculated according to Grimberieux (1954-1955). The maximum angle index of asymmetry,

$$L_{max} = 1 - \frac{\text{gentle slope maximum angle}}{\text{steep slope maximum angle}}$$

TABLE 3.6. SHOT-GUN CORRELATION MATRIX FOR PARAMETERS OF SLOPE AND VALLEY FORM[+]

	CENTRE DEPTH	SHOULDER WIDTH	CROSS-SECTIONAL AREA	SLOPE HEIGHT	SLOPE LENGTH	MAXIMUM ANGLE	MEAN ANGLE
T	0.18	-0.05	0.05	0.16	-0.54**	0.32**	
A	0.08	-0.22	-0.14	0.02	-0.76**	0.51**	MEAN
B	0.01	-0.16	-0.17	-0.65*	-0.98**	0.68**	ANGLE
C	0.19	-0.20	0.01	0.26	-0.14	0.53**	
T	-0.12	-0.39**	-0.16	-0.04	-0.32**		
A	0.10	-0.13	0.03	0.23	-0.29*		MAXIMUM
B	-0.02	0.26	0.23	-0.52	-0.68**		ANGLE
C	0.04	-0.22	-0.09	0.16	-0.16		
T	0.41**	0.50**	0.45**	0.63**			
A	0.31*	0.46**	0.41**	0.52**		SLOPE	
B	0.11	0.18	0.07	0.72**		LENGTH	
C	0.52**	0.73**	0.62**	0.81**			
T	0.75**	0.51**	0.59**				
A	0.75**	0.38**	0.45**		SLOPE		
B	0.45	-0.13	-0.33		HEIGHT		
C	0.65**	0.60**	0.68**				
T	0.78**	0.86**					
A	0.52**	0.87**		CROSS-			
B	-0.47	0.05		SECTIONAL			
C	0.83**	0.91*		AREA			
T	0.64**						
A	0.43**		SHOULDER				
B	0.00		WIDTH				
C	0.69*						
		CENTRE DEPTH					

[+]Spearman's nonparametric correlation coefficient rho was employed to test the relationship between each pair of variables.

* Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

whilst the mean angle index of asymmetry,

$$L_{mean} = 1 - \frac{\text{gentle slope mean angle}}{\text{steep slope mean angle}}$$

The range of the indices is from 0.0 (symmetry) to 1.0 (extreme asymmetry). This is preferable to the index which was developed by Tricart (1947) and which required comparison between values of different orders of magnitude (either 0.1 to 1.0 or 1.0 to infinity) depending upon the orientation of the steepest slope. The values of Grimberieux's indices are directly comparable but do not indicate the direction of steepest slope. Figure 3.22 (p.111) illustrates the distributions of L_{max} and L_{mean} within the Ottawa area. The lowest values of the indices are modal which suggests that many cross-profiles depart little from symmetry. More than seventy percent of the cross-profiles, however, exhibit some degree of asymmetry.

The relationships of valley asymmetry to the orientation of the steepest slope are plotted in Figure 3.23 (p.111). L_{max} asymmetry tends to be greatest for cross-profiles in which the steep slope faces between 271 and 315 degrees. L_{mean} is greatest where steep slopes face towards either the 91-180-degree zone or the 271-315-degree zone, which is significant because these are opposed directions. No consistent pattern of variation with aspect, therefore, is likely to emerge. The implication of this finding is that local factors are more likely to explain slope asymmetry whereas the influences of regional factors such as aspect are insignificant.

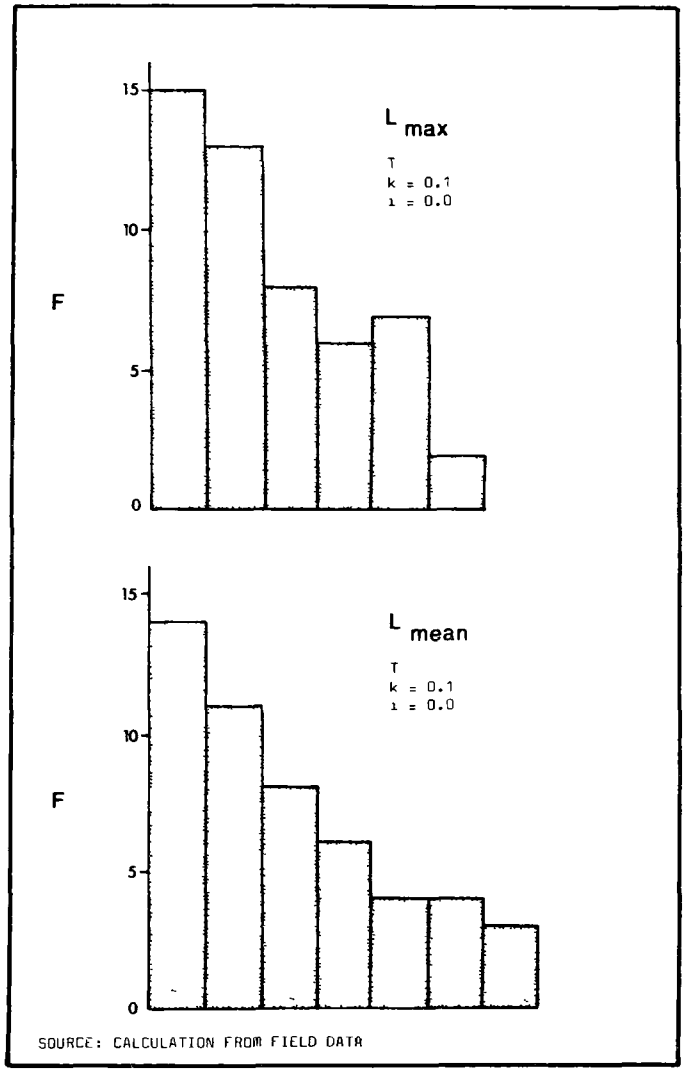


FIG. 3.22. FREQUENCY HISTOGRAMS OF INDICES OF VALLEY CROSS-PROFILE ASYMMETRY

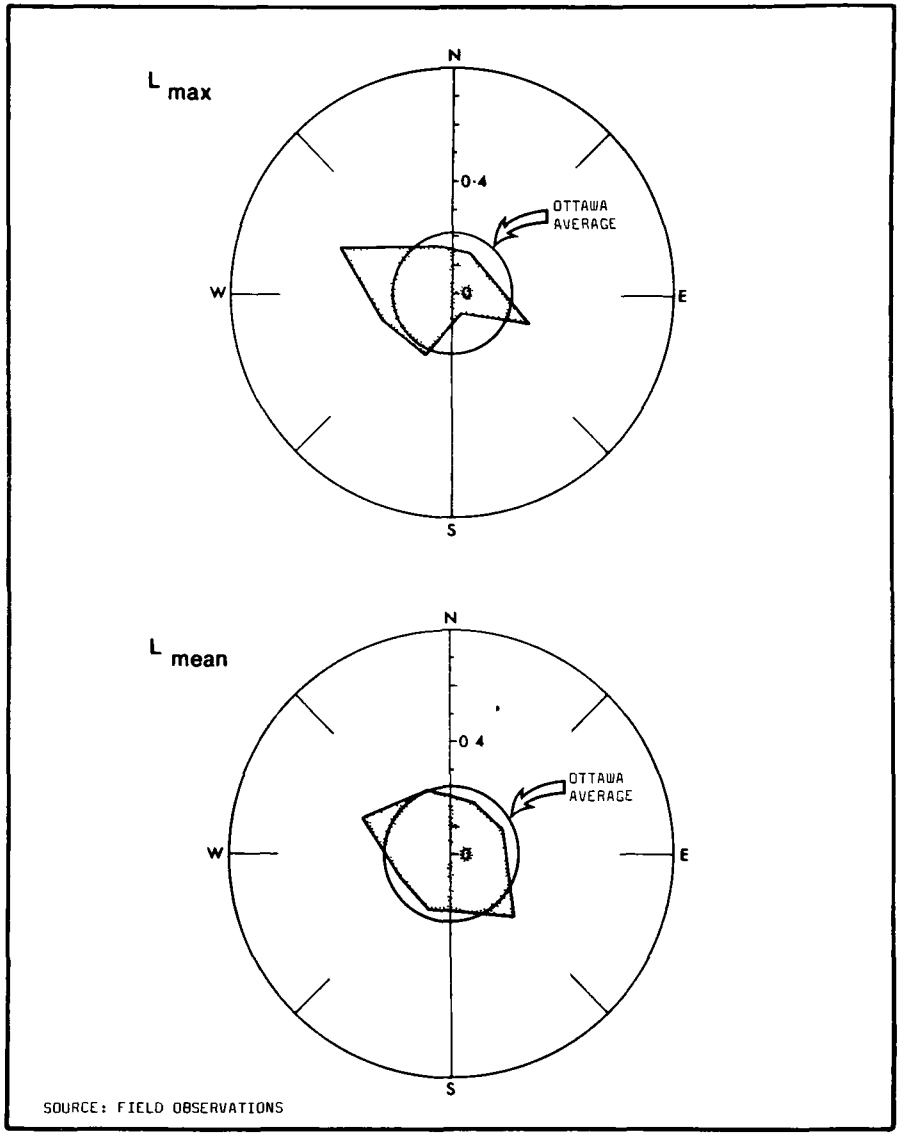


FIG. 3.23. ROSE DIAGRAMS OF THE RELATIONSHIP BETWEEN ASPECT AND THE STEEPER ASYMMETRICAL SLOPE

3(f) Summary and Conclusions

The preceding description has served to highlight some of the similarities and contrasts which are to be found among those valleys which were originally selected as typical of the Ottawa area. Variations may be identified with respect to slope forms and valley dimensions.

Slopes at Gloucester Glen and Trend Village possess extensive upper terrace zones and, in both A1 and B1, a lower floodplain zone may also be present. These low-gradient zones are virtually absent at Gatineau. Simple convexo-concave forms dominate at Gloucester Glen and Trend Village whilst much greater complexity is observed on the higher Gatineau slopes where the convexo-concave sequence may be repeated more than once. The convex segments are most extensive in all areas and rectilinear development is limited. The only area where the latter occurs even rarely on slopes of greater than five degrees is the Gatineau area. The rates of change of ground slope are greatest at Trend Village and least at Gatineau where the gradients change more slowly over much longer distances.

Maximum angles tend to be greatest at Trend Village and least at Gatineau which represents an inverse correlation with channel gradient. These maximum slope segments are located close to the base of slopes in all areas. Mean angles showed little variation among the three study areas, which is perhaps surprising because of the considerable range of values of both slope height and slope length. Attempts to locate characteristic slope angles in the Ottawa area did not succeed. The most common inclinations,which are

below 2.5 degrees, are probably too low to experience slope processes. There is a gradual tapering off in the frequencies of angles above these low values. There are no significant breaks in the distributions and those modes which are present do not possess frequencies which are significantly greater than those in other classes.

Several of the slope form parameters were found to exhibit some relationships with each other and also with parameters of cross-profile morphometry. The position of slopes within individual valleys was found to influence certain of their characteristics, notably slope height, maximum angle and mean angle. Cross-profile dimensions tend to be positively intercorrelated in allometric fashion. These dimensions are greatest and most variable at Gatineau, whereas fluctuations in these parameters in valley B1 are negligable. Such findings may suggest the influence of general drainage development on form. Other relationships, however, suggest more local influences. Mean angles are positively related to maximum angles but are inversely proportional to slope length. In addition, many cross-profiles are asymmetrical but no consistent pattern of orientation of the steepest slope is encountered.

C H A P T E R F O U R

THE ORIGIN AND DEVELOPMENT OF THE VALLEYS

It is possible to view the initiation and subsequent development of the tributary valleys within the context of the post-glacial evolution of the Ottawa area. These landforms may also be viewed, however, as a response to interactions within the present physical environment. The discussion in this chapter combines both of these approaches in attempting to account for the present form of the valleys.

In section 4(a), the relationships between present-day processes and valley form are considered. Slope processes are described and the influences of external controls such as fluvial processes and climate are also discussed. The characteristics of slope regoliths and vegetation associations are summarized. It is argued that soil profiles and plant communities are indices of the effectiveness of slope processes because they tend to become more immature as the rates of operation of slope processes increase (see section 2(c)ii, pp.48 to 50).

Evidence of the historical factors which have contributed to the development of the valleys is reviewed in section 4(b). This evidence concerns both the pattern of post-glacial climatic flucuations and the decline in the elevation of regional base level.

4(a) Present-Day Processes

(i) Climatic Influences

Geomorphological processes in the Ottawa area today reflect the considerable seasonal extremes of the regional climate. During the winter months of predominantly sub-freezing temperatures

(December to March), fluvial and gravitational processes are dormant in the study valleys. The critical phase for these processes is the six weeks of snow melting which commences in early April. At this time, runoffs and discharges are at their greatest. During the summer months, fluvial discharges are shrunken or cease entirely and runoff processes are most active during short-term phases of intense rainfall. Precipitation increases again during the fall and freeze-thaw cycles occur in November and early December.

The period of greatest interest, therefore, is the phase of spring melting. Field observations suggest that, at this time, the regional climate is significantly modified on slopes of varying aspect. A series of spot-readings of temperature were recorded on cross-profile 6 in valley A2 (a typical north-south profile) during the winter of 1969-1970. Three soil moisture cells were located two inches apart and three inches below the soil surface on the maximum angles of both the north-facing and south-facing slopes. Measurements were recorded, using a soil moisture meter. Average temperatures from the three cells are reported in Table 4.1 (p.117). As expected, the south-facing slope is consistently warmer than the opposing slope. The south-facing slope began to thaw before April 7th whereas the north-facing slope remained frozen for at least one further week. Visual observations revealed that parts of the north-facing slope were covered with snow and ice until the end of the first week in May, which was two weeks after thawing had ceased on the south-facing slope.

Readings of soil moisture content were also collected (Table 4.1). The resistance of the soil (in ohm units) is inversely

TABLE 4.1. OBSERVATIONS OF SOIL TEMPERATURES AND MOISTURE CONTENTS ON CROSS-PROFILE 6, VALLEY A2.

DATE	NORTH-FACING SLOPE		SOUTH-FACING SLOPE		PRECIPITATION** (INCHES)		
	TEMPERATURE (°F)[x]	SOIL MOISTURE READINGS (OHMS)[x]	TEMPERATURE (°F)[x]	SOIL MOISTURE READINGS (OHMS)[x]	IN LAST 24 HOURS	IN LAST 48 HOURS	IN LAST 7 DAYS
05-11-69	41	NR	43	NR			
08-11-69	45	NR	46	NR			
11-11-69	41	NR	42	NR			
16-11-69	41	NR	43	NR			
26-11-69	32	10.36^{5}	33	10.27^{4}	0.30	0.40	1.06
15-12-69	25	-*	27	-*	0.42	0.46	0.64^{+}
27-01-70	20	-*	21	-*	0.09^{+}	0.22^{+}	0.40^{+}
01-02-70	21	-*	25	-*	NIL	0.01^{+}	0.81^{+}
01-04-70	27	-*	31	-*	NIL	NIL	0.46^{+}
07-04-70	30	-*	44	10.40^{3}	NIL	NIL	1.27^{+}
15-04-70	33	10.20^{3}	50	10.80^{3}	NIL	NIL	NIL
01-05-70	50	10.50^{3}	63	10.25^{5}	NIL	NIL	0.51
03-05-70	48	10.58^{3}	55	10.35^{5}	0.04	0.12	0.12
05-05-70	51	10.50^{3}	56	10.30^{5}	NIL	NIL	0.12
10-05-70	46	10.40^{3}	53	10.18^{5}	0.24	0.28	0.96
29-05-70	55	10.10^{5}	69	10.30^{5}	NIL	NIL	0.44
01-06-70	64	10.24^{5}	68	10.30^{5}	0.13	0.13	0.57

[x]Readings from soil moisture meter MC-300A, manufactured by Soiltest Inc., Illinois.
*In frozen ground, the meter does not give readings for soil moisture.
**Data from Monthly Meteorological Summary, Uplands Airport climatic station.
[+]Includes water equivalent for snowfall where 10 in. snow = 1 in. rain.
NR - No readings

proportional to the soil moisture content. The table indicates that, on April 7th, the south-facing slope recorded a low resistance (10.40^3 ohms). The soil on the south-facing slope appeared to be saturated. At this time, the north-facing slope remained frozen and saturated conditions were not initiated for a further week. By May 1^{st}, the surface of the south-facing slope was dried and sun-cracked but high moisture contents were observed on the north-facing slope until mid-May. The persistence of snow on north-facing slopes was noted in all valleys with east-west alignments (Plate XV, p. 119). Precipitation rates during the melting period do not appear to have influenced significantly the soil moisture readings (Table 4.1). During thawing, the resistance readings were low whether or not recent precipitation had occurred.

The disappearance of snow from the south-facing slopes was more rapid despite the fact that they tend to attract greater accumulations of snow. The depth of these accumulations depends upon the degree to which slopes are exposed to the prevailing winds. The latter for the six months of snowfall (November, 1969 to April, 1970) are plotted in Figure 4.1 (p.120). The radiating scale on the rose diagram indicates the number of days on which a particular wind direction was prevalent during this period. Winds from the north-by-west quadrant are dominant so that the lee slopes which attract snow deposition face the south-by-east quadrant. On five occasions during the winter of 1969-1970, snow depth variations were observed along profile 6 in valley A2 (Fig. 4.2, p.121). Snow deposits in November were greatest on the north-facing slope because it receives

Plate XV. The confluence of valleys A1 and A2 during the flood season; in the latter, snow accumulations are greater on the north-facing slope (grid ref. 456154).

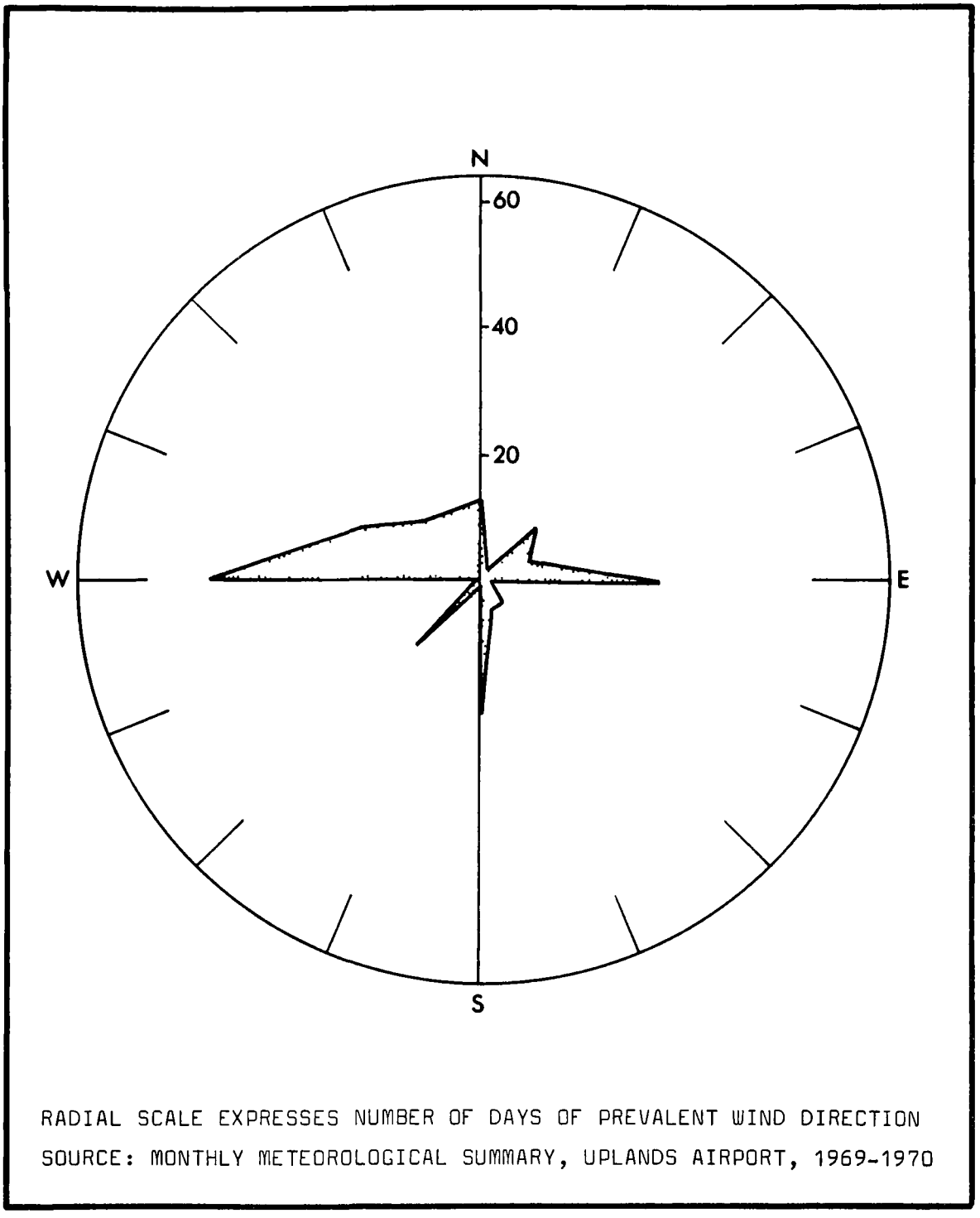


FIG. 4.1. ROSE DIAGRAM OF PREDOMINANT WIND DIRECTIONS AT UPLANDS AIRPORT BETWEEN NOVEMBER, 1969 AND MAY, 1970

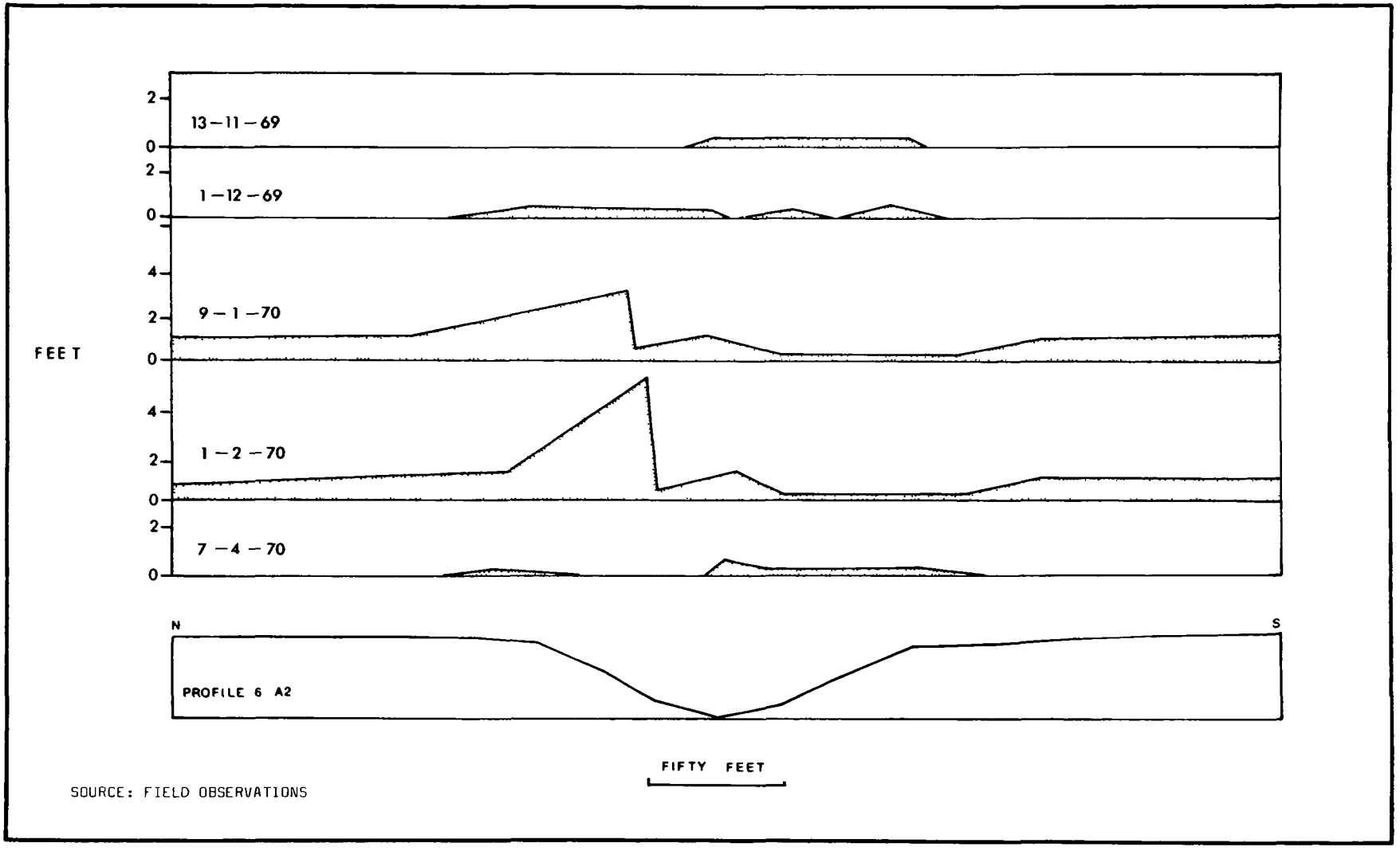


FIG. 4.2. VARIATIONS IN SNOW DEPTH ON CROSS-PROFILE 6, VALLEY A2, DURING THE WINTER OF 1969-1970

least insolation. During subsequent months, however, temperatures were below freezing and melting by insolation was less obvious. Snow accumulations built up on the leeward south-facing slope and the windward slope was swept bare. It is likely that the latter slope was probably frozen to a greater depth than the former because of the lack of a protective snow cover. Much of the snow on the leeward slope was supplied from the wind-swept terrace above it. This snow would cascade over a snow cliff which gradually advanced downslope (Plate XVI, p.123). Differential snow accumulation may explain why snow persisted longest on east-facing slopes at Gatineau where differences in insolation on opposite slopes of the valley may be expected to be minimal (Plate XVII, p. 123).

The hollows were the most favourable zones for snow accumulation on slopes of all aspects. During thawing, these hollows remained snow-covered when the spurs had been cleared of snow (Plate XVIII, p.124). Rivulets which drain from the accumulations within the hollows were found to cause a certain amount of gulley erosion (Plate XIX, p.124).

During the melting period, the surface regolith was very moist and mobile, partly because infiltration was restricted for some time by the frozen substratum. The addition of any stress to the surface material was sufficient to promote liquefaction since the brown mottled clay is highly sensitive. Small-scale mudflows occurred in the material above the frozen solum. Slope processes at this time were probably most effective on south-facing slopes where considerable quantities of snow and ice were dissipated over a

Plate XVI. The south-facing slope of valley A2 during the flood season; remnants of the snow cliff which is typical of this slope are present in a slope hollow (grid ref. 460153).

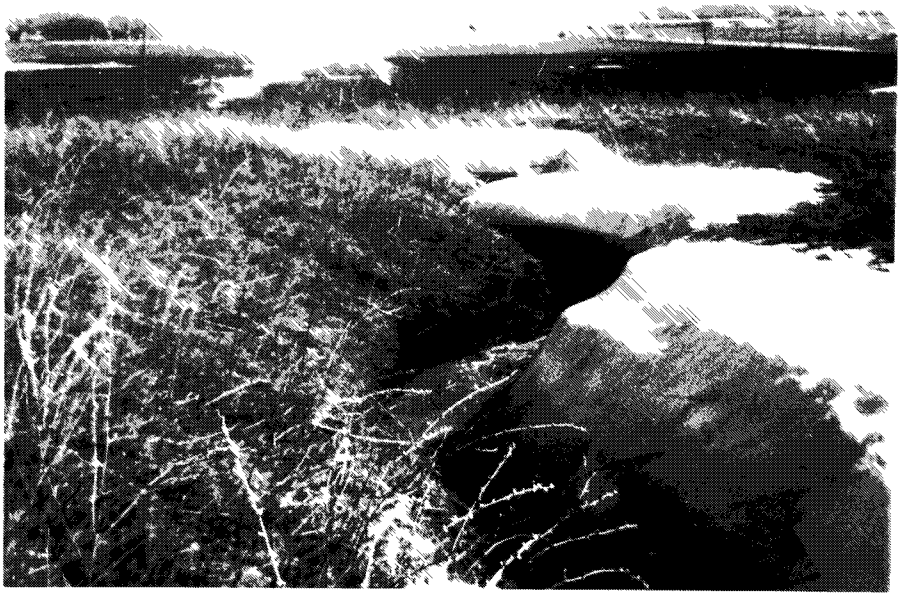


Plate XVII. A newly-developing erosional channel form in valley C3; snow remains on the east-facing slope (grid ref. 473381).

Plate XVIII. Valley A2, looking upstream during the flood season; flood-waters wash the bases of both slopes; snow is confined preferentially to hollows on the north-facing slope (grid ref. 460153).

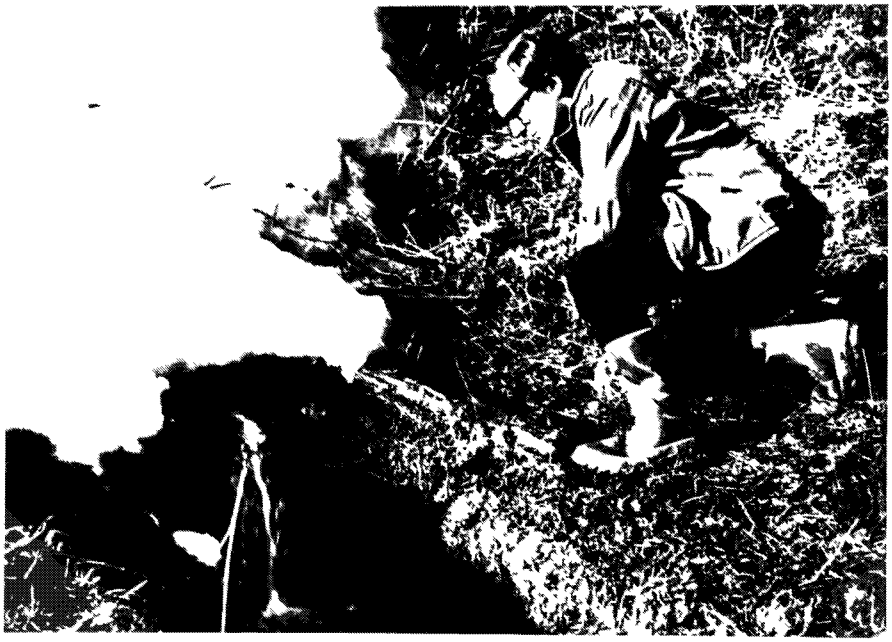


Plate XIX. Gulley formation at the base of a snow patch on the south-facing slope of valley A2 (grid ref. 457154).

short period of time. Rates of runoff on this slope may have been much greater than on the north-facing slope where, although the accumulations of snow were limited, they nevertheless required the greater period of time for melting. Despite the observed microclimatic variations with aspect, however, it has not been possible to detect corresponding variations in slope form. In no valleys except valley C1, where east-facing slopes possess greater elevations (Fig. 3.7, p.71), are maximum or mean angles consistently steeper on one slope than on the other. In section 3(e)iii, it was reported that valley cross-profile asymmetry bears a complex relationship to aspect, reflecting the influence of local factors. One may conclude therefore, that, if form is adjusted to present-day conditions, factors other than simple microclimatic variations and the resulting slope processes are responsible for variations in form.

(ii) Fluvial Processes

The streams within the study valleys are considerably influenced by seasonal climatic variations. They are frozen from December to April and are then very active until mid-May. After the snow melt, discharges decline in valleys A1 and B1 and cease entirely in the other valleys until the following spring. The most effective phase of fluvial processes, therefore, is the spring melting period.

Fluvial processes are more readily related to variations in slope and valley form than are microclimatic influences, particularly in the floodplain valleys, A1 and B1. Undercutting

of the valley-side slopes on the outer bends of meanders produces a very distinctive slope form which is characterized by an erosion scar near the base of the slope. An example in valley A1 (Plate XIII, p 80) was photographed in June, 1970, immediately after the cessation of a phase of undercutting during the spring flood. The surface of the scar consists of loose debris which is dry but highly mobile. The feature is fresh and both vegetation colonization and soil development are negligable. The angle of slope is thirty-seven degrees. In the turf above the scar, a transverse tension crack is present which indicates that the feature will eventually slump. Plate XX (p.127) illustrates an undercut scar from valley B1 which has become a natural haven for drifting snow and, as such, is susceptible to nivation processes.

Slopes which are removed from these loci of erosion do not appear to experience undercutting, even in the presence of large volumes of discharge during the flood season (Plate XXI, p.127). Floodwater levels during 1970, which may have been as much as eight feet above the level of the floodplain in valley A1, were indicated by floated debris which became lodged in trees and by silt deposits on the valley-side slopes (see also Plate XXII, p.128). The flood discharges appeared to deposit rather than to erode in areas away from the main channel and vegetation was veneered by a cohesionless alluvial silt (Plate XXIII, p.128).

It is probable that the non-undercut slopes in valleys A1 and B1 have been undercut at some time during the past but have been

Plate XX. Snow accumulation on an undercut scar in valley B1 (grid ref. 383183).

Plate XXI. The floodplain of valley A1 during the flood season (grid ref. 456152).

Plate XXII. In valley A 1, a tree trunk fractured eight feet above floodplain level by floating debris during the flood season (grid ref. 466'49).

Plate XXIII. Valley B1, immediately following the floods; vegetation on the floodplain is veneered by cohesionless silt (grid ref. 383184).

abandoned by the basal stream as a result of meander migration. Upon abandonment, the scars would experience slumping and then stabilization, vegetation colonization and soil development. Slow diffuse processes such as creep and rainwash then become dominant. Slope profile 6A in valley A1 (Plate XII, p.62) was in the process of stabilization at the time of photographing, not having been undercut for two years.

In order to investigate further the nature of the undercut and non-undercut slopes, using the surveyed profile data, a 2x2 contingency table was prepared. It compares the two types of slope in valleys A1 and B1 with respect to the type of slope segment which characterizes the foot of the slope.

BASAL CONCAVITY	UNDERCUT SLOPES	NON-UNDERCUT SLOPES	TOTAL
PRESENT	6	20	26
ABSENT	9	0	9
	15	20	35

A null hypothesis stated that there was no association between the process operating at the base of the slope and the type of segment at the base of the slope. A Chi Square test was performed and the value of X^2 (16.15 with DF = 1) was significant at the 0.001 level of probability, confirming the impression that concavities are largely absent from the base of the undercut slopes.

A Mann/Whitney 'U' test was performed in order to test the null hypothesis that there were no differences between the maximum angles which occur on the undercut scars and on the non-undercut slopes in valleys A1 and B1 except for chance variations. The

null hypothesis was rejected at the 0.001 level of probability with $z' = -4.09$. One may conclude, therefore, that undercutting is a process which is accompanied by slope steepening. Mean angles are also steeper on undercut slopes ($z = -4.04$ and $p < 0.001$). Rates of curvature appear to increase where undercutting occurs and it becomes obvious from an appraisal of the slope profiles in Figures 3.3 and 3.6 (pp.67 and 70) that undercutting leads to marked valley cross-profile asymmetry.

Less obvious relationships between slope form and fluvial processes occur in valleys A2, A3, C1, C2, C3 and C4, which contain ephemeral streams. At the time of snow melting, these valleys become water chutes. Floodplains are absent and the waters wash the bases of the slopes at all points (Plate XXIV, p.131). The erosive capacity of these chutes appears to be limited at present. Only in valley C3 was there evidence of downcutting during the spring of 1970 when a small channel began to be incised into the original, less distinct valley floor (Plate XVII, p.123). Both valley A3 (Plate IV, p.29) and valley C2 possess distinct erosional channel forms but these contain only isolated pools of water for most of the year. The channels of valleys A2, C1, C3 and C4 are occupied by plant communities with an affinity for waterlogged conditions. Species of plants which are particularly common include dark-green bullrush, softrush, several species of sedges and reed-meadow grass. The materials beneath these plant communities are both gleyed and dark blue in colour. There is little evidence of either erosion or deposition in these channels. The plant communities are easily able to withstand the dragging effects of flowing

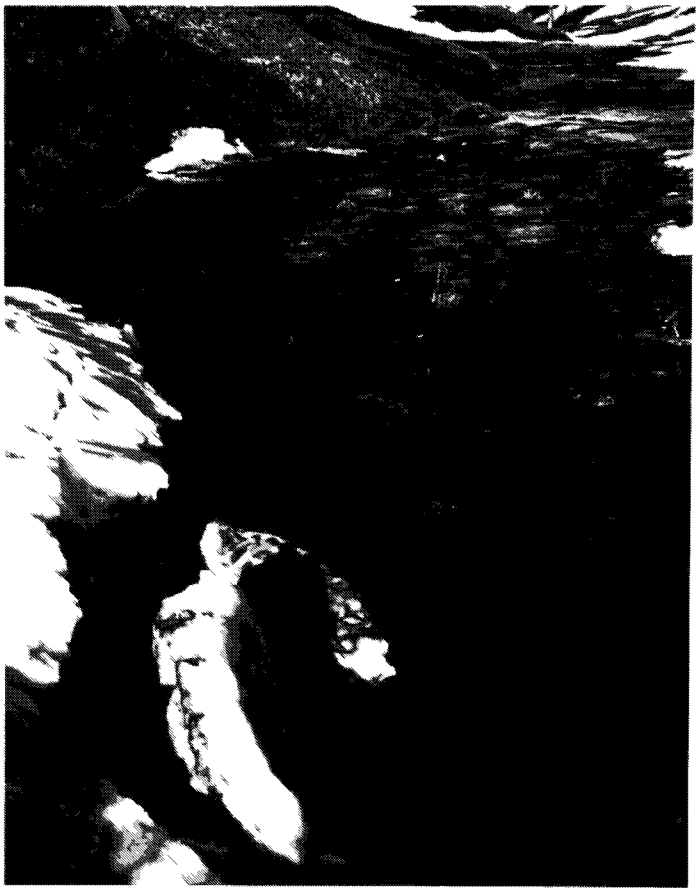


Plate XXIV. A detail of the channel in valley A2 during the flood season; vegetation covers the channel bed; undercutting may be occurring at the slope base on a small scale (grid ref. 460153).

water, even during the melting season (Plate XXIV, p.131). Undercutting is a minor process within these valleys and, although small-scale evacuations of material from the slope base occur, no major erosional scars are produced.

It is common on many of the slopes in valleys A2 and C2 for stabilization to have occured in the form of a series of slope terracettes which are indicative of a phase of small-scale rotational failures (Plates X and XI, p.61). It is possible that fluvial undercutting has influenced the development of these features since they are best developed on the upslope sides of spurs where basal fluvial activity may be expected to be greatest. As many as thirteen individual terracettes may be present in a single sequence in valley C3. Their dimensions are relatively constant, ranging from approximately two feet wide to three feet high.

Not all of the slopes in the ephemeral valleys, however, possess terracettes. Such micro-forms are absent from valleys A3, C1, C3 and C4, but, whether or not terracettes are present, the slope regolith in ephemeral valleys appears to be stable except during the spring, especially at Gatineau. The forms of the slopes in these valleys are illustrated in Figures 3.4 (p.68), 3.5 (p.69) and 3.7 to 3.10 (pp.71 to 74). Slope forms are basically convexo-concave at Gloucester Glen but are usually more complex at Gatineau. Maximum angles of slope, rates of curvature and valley cross-profile asymmetry, all of which tend to increase as fluvial processes become more effective, are least at Gatineau. The presence of several convexo-concave sequences on slopes at Gatineau is indicative of the

semi-independant evolution of different sections of the slopes, a situation which may not normally be associated with the activity of a powerful basal stream. The simpler forms and steeper angles of slope in valleys A2 and A3 may reflect either current or recent fluvial activity. Field observations, however, have failed to demonstrate effective fluvial erosion within them during the spring of 1970.

(iii) Vegetation and Soils

The development of either a mature soil profile or a mature climax vegetation association is hindered by movements within the slope regolith. The effectiveness of present-day slope processes on clay slopes around Ottawa, therefore, should be reflected in the maturity of their soils and plant associations.

Soils were examined at many sites in the study valleys and certain general characteristics became apparent. In all of the valleys, the parent material consists of a fine-grained lithology which possesses a blocky structure (Plate XXV, p.134). The colour varies little and is termed grayish brown (2.5Y 5/2) or dark grayish brown (2.5Y 4/2) according to the notations of the Munsell Soil Color Chart. The texture of the material varies from clay at Gatineau to silty clay at Gloucester Glen and Trend Village. The material is located in those areas which were mapped by Gadd (1963) as brown mottled clay. During soil development, the blocky structure breaks down into a progressively finer granular structure. Freeze-thaw cycles and wetting and drying cycles are likely to promote the disintegration of the blocky structure. It was also

Plate XXV. An excavated section of brown mottled clay near valley C1; the fissures are pressure-release cracks associated with the blocky structure of the material (grid ref. 472383).

observed that the granular aggregates tend to become finer as root content increases. On the summits of the slopes in all areas, a loamy material veneers the silty clay to depths up to fifteen inches. In the Gatineau area, this material has been termed the Pontiac Series by Lajoie (1967) who attributes it elsewhere (1962) to fluvial terrace deposition.

Soil development is undoubtedly least advanced on steep slopes. On erosion scars, the blocky material is either at the surface or is smothered by a veneer of cohesionless silt which is rarely greater than two inches in thickness. Vegetation is absent from the scars. On the maximum angle segments of slopes which are not experiencing powerful undercutting processes, the regolith is less mobile and a horizon of coarse granules (0.4 - 1.2 inches in diameter) rests on the surface of the parent material, perhaps to a depth of three inches. The vegetation cover which overlies the soil on the maximum angle is incomplete and bare patches of soil are exposed. On surfaces of lower inclination, such as the upper convexity or lower concavity, four soil horizons may frequently be recognized: (i) the basal horizon of blocky silty clay, (ii) a coarse granular horizon with few roots, (iii) a granular horizon (diameter of granules 0.1 - 0.4 inches) with dense root networks and (iv) a humus layer. Soil horizoning is aided by the fact that, on most slopes with inclinations of less than twenty degrees, the vegetation cover is complete and acts as an obstacle to soil mobility.

Soil profiles are best developed on the slope summits where

the parent horizon may be located at depths in excess of twenty inches. The loamy material which overlies the silty clay is more permeable than the latter so that leaching processes may be able to operate to greater depths than on other parts of the slope.

The most mature vegetation associations are also to be found at the summits of the slope profiles. At Gloucester Glen and Gatineau, domesticated long-term pastures occur on the slope summits. These pastures are maintained as immature climaxes by grazing. At Trend Village, however, grazing is absent. The alfalfa fields, which have been abandoned at the slope summits, have already been invaded by pasture grasses and are evolving towards a bush association.

On the slopes of the valleys, the plant associations are immature and reflect the disturbed site conditions. Grasses are able to become established on all but the steepest slopes but they become progressively less dominant as slope angle increases. Other species become prominent which could be classed as weeds in the sense that they do not provide the intended forage for cattle. Many are heliophile and are normally shaded out by the tall inflorescences of grasses in the pastures. Heliophile species include groundlevel sprawlers, such as white clover and silvery cinquefoil, and rosette-formers such as dandelion and plantain. As a solitary reflection of aspect, mosses are restricted to the steeper gradients of the moist, cool, north-facing slopes.

On the undercut erosional scars, a sequence of colonization may be identified. Initially, vegetation is absent. The first

pioneers are annuals such as yellow clover and horsetail which compete very poorly with perennials. The first perennial pioneers include wild strawberry, calico aster and long-leaved aster which tend to be absent from later associations. The heliophiles are among the early colonists and these are followed by the grasses. On the maximum angles of many slopes, the succession appears to have been halted and heliophiles and grasses co-exist. The disclimax is maintained by movements within the regolith and by grazing. Grazing by cattle is not essential to the maintenance of the equilibrium, however, since the associations on steeper slopes at Trend Village, where grazing is absent, are similar to those elsewhere.

One may conclude that the immature condition of both soils and plant associations on slopes, particularly on maximum angle segments, is indicative of the effective operation of present-day processes. There is no reason to believe, therefore, that the slope forms are not being shaped and modified by present-day processes. These forms are not relict features unlike the adjacent terrace surfaces which support more mature soil profiles and vegetation associations.

4(b) Past Processes

The initiation of the study valleys may have occurred at any time following the exposure of the marine surface to freshwater and subaerial conditions. The maximum possible age for this surface is ca. 10,200 years. During the succeeding 2,500 years, there was a phase of intensive downcutting which may have been accompanied

by the initiation of the tributary valleys. Without radiocarbon dates from materials within these valleys, however, it is difficult to link their development to the terrace chronology.

The following section reviews some indirect lines of evidence which may offer a method for the approximate dating of the valleys and gives some insight into the causes of their initiation, especially for those presently-dry valleys at Gatineau.

(i) The Significance of Dry and Misfit Valleys

Three main groups of valley-types appear to be present within the Ottawa valley: (i) dry or ephemeral valleys, (ii) valleys with perennial discharges which are misfit and (iii) valleys with perennial discharges which are normal. Misfit or underfit valleys are those which meander within more amply meandering valleys (Dury, 1964a). The valleys at the field sites appear to fall within the first two categories. In valley A1 and the upper reaches of valley B1, perennial streams meander across wide floodplains. The other valleys are dry except during spring. The lower reaches of valley B1, which were not examined in detail in the field, appear to represent the third group of valley-types.

Dry valleys are not uncommon in western Europe and parts of North America. They have been interpreted according to several hypotheses. A.J. Bull (1940) claimed that dry valleys may be formed on highly permeable strata which have been rendered impermeable by permafrost. During the permafrost phase, surface runoff is possible. The valleys which develop, however, are abandoned following the degradation of the permafrost. This hypothesis may be applicable to

chalk landscapes in western Europe (Ollier and Thomasson, 1957; E.H. Brown, 1969; French, 1972). In the Ottawa valley, however, the brown mottled clay is not highly permeable so that the theory is unlikely to explain dry valleys.

C.C. Fagg (1954) has interpreted dry valleys as the result of a decline in the water table. In the Ottawa area, base level decline has occurred in conjunction with fluvial downcutting and terrace formation. The effects of this phenomenom would have been experienced on a regional scale and could account for the ubiqiutous presence of dry valleys within the Ottawa valley.

It is also possible, however, that historical variations in runoff have contributed to the formation of dry valleys. Dury (1964a) has argued, on the basis of field evidence in both North America and western Europe, that many valleys have experienced greater discharges during the past for climatic reasons. Some of these valleys are now dry whereas, in others, the streams are misfit. It is postulated that meander wavelengths are proportional to discharge and that the wavelengths of major valley meanders, therefore, are indicative of discharges which may have been at least twenty times greater during the past than they are at present. In a later paper (1964b), Dury hypothesized that floodplain alluvial deposits originated from a sudden decline in the transporting capacity of streams. The cause of this decline and of the onset of underfitness was a reduction in precipitation.

It was part of Dury's argument (1965) that post-glacial fluctuations in temperature and precipitation have been sufficient

to cause major reductions in the volumes of stream discharges. Field evidence certainly suggests that temperature and precipitation exercise certain controls over runoff. Schumm (1965), for example, demonstrated that mean annual runoffs tend to be directly proportional to precipitation and inversely proportional to temperature. Sediment yields are inversely proportional to both precipitation and temperature since an increase in the latter promotes a greater vegetation cover which protects the soil from erosion. Whether or not these controls are able to produce discharge variations of the magnitude which are required by Dury's theories, however, is a matter of conjecture.

Dury (1965) concluded that cool, moist conditions during the immediate post-glacial period would have been most suitable for the initiation of valleys in North America. This is significant for the Ottawa-St. Lawrence lowlands where Potzger (1953), Terasmae (1959, 60, 61) and Terasmae and Lasalle (1968) have suggested that cool, moist conditions were present twice during the post-glacial phase (see Table 1.2, p.21). The first phase of such conditions, zone Q2(V), occurred between 8,000 and 9,000 years ago and the second phase, zone Q5(I), has occupied the last 2,000 years.

Zone Q2(V) coincides with the period during which the marine surface was exposed to subaerial conditions. The transformation to warmer, drier conditions in zone Q3(III) appears to correspond to the drastic decline in the volume of the Ottawa River discharge which accompanied the formation of the 220-foot surface. This climatic change, therefore, could have been a major factor in

producing dry and misfit valleys in the Ottawa area at that time. No similar climatic period has succeeded zone Q5(I) so that a very recent phase during which streams may have become misfit is less likely to have occurred.

(ii) The Initiation and Development of the Study-Valleys - A Conclusion

In summary, it appears that the cool moist climatic phase, zone Q2(V), which extended from 9,000 to 8,000 years ago, would have favoured the initiation of stream networks in the Ottawa area and that the subsequent climatic zone, Q3(III-IV) from 8,000 to 6,000 years ago, would have been suitable for the onset of underfitness within such networks.

Certainly, valley A1 and the upper reaches of valley B1 appear to satisfy Dury's criteria for the recognition of underfit streams. The dry valleys may also have been initiated in zone Q2(V) so that they too reflect, in some degree, the subsequent decline in regional precipitation. The complete cessation of flow at certain times of the year, however, suggests that such valleys have been affected by the additional influence of the declining regional base level and the resultant decline in the elevation of the water table.

The effects of a dropping base level appear to be especially great at Gatineau. The forms of the valleys suggest a phase of intense downcutting by short powerful streams which were able to keep pace with the rapidly-downcutting Ottawa River, at least until the formation of the 190-foot surface. This phase of down-

cutting may have been punctuated by short stillstands since there is some evidence that the valley sides are terraced. Further downcutting in response to the continued decline in base level was prevented by the bedrock outcrop which underlies the 190-foot surface adjacent to these valleys and which acted as an erosion threshold. At this time, which coincided with the dry conditions of zone Q3 (III-IV), the water table would have passed beneath the floors of these valleys.

The impact of the historical circumstances which are postulated above upon the present forms and processes within the study valleys may be predicted. The critical factor in the variations of slope forms and slope processes has been identified as the behaviour of the basal stream. The nature of this behaviour depends upon discharge regime, a stream characteristic which is, in turn, determined by historical factors. The concluding chapter demonstrates the far-reaching effects of these factors in producing different types of slope system.

C H A P T E R F I V E

CONCLUSION

5(a) Slope Systems in the Ottawa Area

It has been demonstrated that slope processes in the Ottawa area are active today in modifying slope form. In this sense, slope forms reflect present-day conditions and are not relict features. In particular, the overwhelming conclusion is that the characteristics of slope form are controlled by the activity of the basal stream. On the other hand, variations in the nature of fluvial processes have been found to depend upon historical factors and, in this sense, slope and valley forms reflect past conditions. With these qualifications in mind, three major types of slope system may be recognized in the small valleys around Ottawa.

(i) Powerfully-Undercut Slopes

The first type of slope system is represented by the undercut scar. The operations of the system are summarized in Figure 5.1 (p.145). Such systems occur in valleys where the streams have become underfit as the result of a decline in precipitation. Erosion in such valleys is predominantly lateral and is confined to the outer bends of meanders.

Undercutting produces a characteristic slope form which is convex, the maximum angle occurring at or near the slope base. During the formation of the scar, slope length decreases, any basal concavity is eliminated and maximum angle, mean angle and rates of curvature increase. Where one slope in a cross-profile is undercut, slope asymmetry is accentuated and shoulder width and cross-sectional area tend to increase.

Within this type of slope system, great imbalance exists.

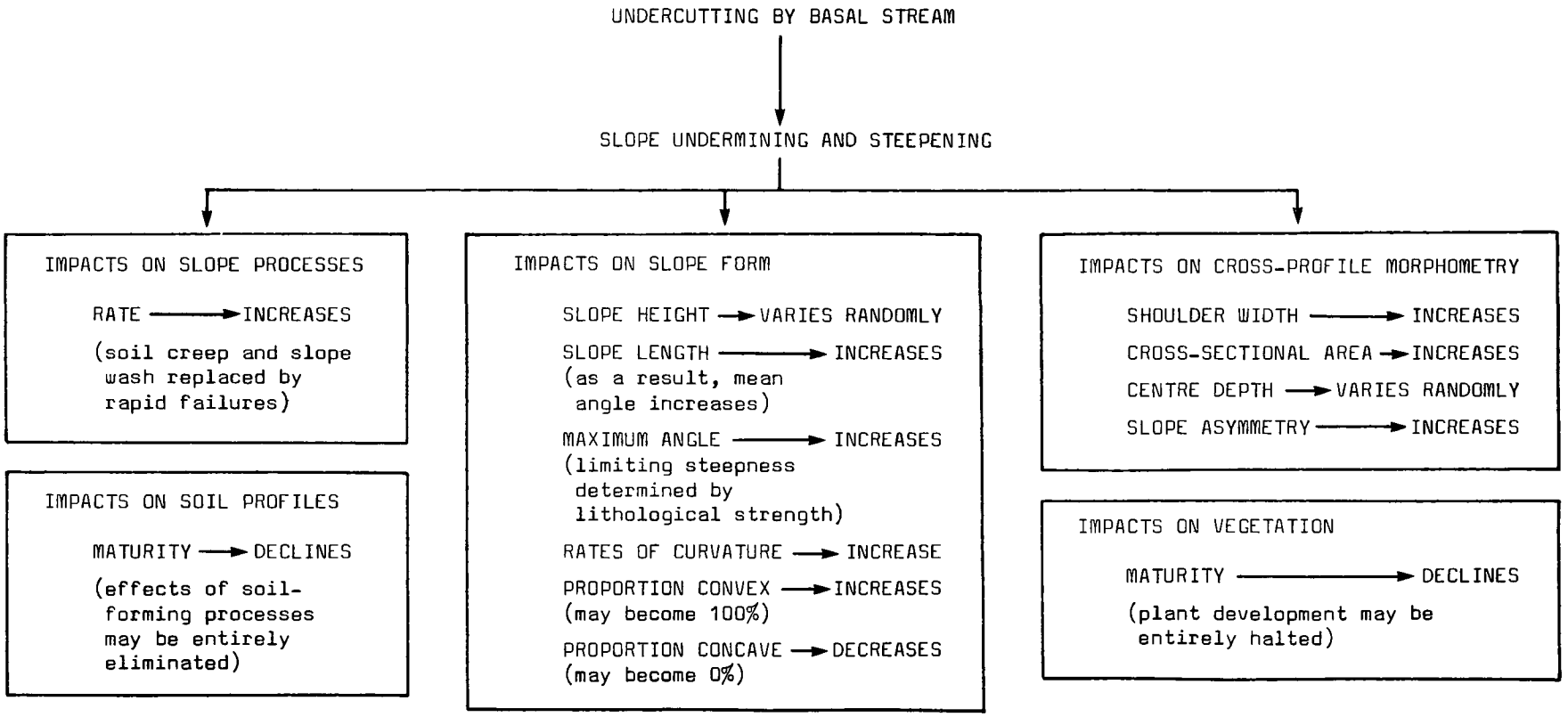


FIG. 5.1. POWERFULLY-UNDERCUT SLOPE SYSTEMS

Undercutting, the chief agent of slope steepening, is a much more efficient process than are the processes of debris downslope transportation, with the result that the development of soil profiles and vegetation communities is inhibited. The slope is often steepened to the limiting strength of the lithology so that instantaneous failure may be imminent. The limiting angle in the brown mottled clay may be as great as forty-five degrees. Of the sixteen undercut scars which were observed in the field, sixty-six percent possessed angles greater than thirty degrees. Although slope processes on such slopes may be very rapid as they strive to reduce slope angle to a more stable condition, these efforts are not usually successful until after the floods have subsided.

Where slope steepening is gradual, the soil profiles and vegetation communities are progressively undermined. More often, however, rapid and deep-seated failures occur which expose fresh surfaces. All traces of previous soils and plant associations are effectively removed.

(ii) Weakly-Undercut Slopes

This type of slope system is believed to occur in valleys A2, A3 and C2. In these valleys, undercutting is a relatively minor process and slope processes are able to reduce the angle of slope below that of the limiting strength of the underlying material. The historical factors which have contributed towards the development of these slopes include declines in base level, water table elevation and precipitation. The net effect of these factors is to restrict present-day streamflow to the period of the spring melt. The runoff

during the spring appears to possess a greater erosive capacity in these valleys than in the other dry study valleys. Distinct fluvial channels are maintained in valleys A3 and C2 and, in valley A2, there were signs that small amounts of material are being removed from the base of the slopes.

Within weakly-undercut slope systems, an equilibrium exists between the processes of slope steepening and slope angle reduction and this balance is reflected in slope form (Fig. 5.2, p.148). The typical form is convexo-concave. The undercutting process is associated with an increase in slope height, mean angle, maximum angle, rates of curvature and the convex component of the profile. Slope processes tend to be associated with decreases in maximum and mean angles and rates of curvature, and increases in slope length and the concave proportion of the slope. In valleys in which such slopes occur, the cross-profile dimensions increase steadily and slope asymmetry is reduced because of the operation of similar processes beneath both valley sides.

The equilibrium within the system extends to the soils and vegetation communities (Fig. 5.2). On the maximum angles of slope profiles, where regolith mobility is great, both vegetation associations and soil profiles are maintained at an immature stage of development. Plant associations are characterized by the presence of heliophiles whereas grasses are restricted. Soil profiles usually consist of a thin, coarsely-granular horizon which is perhaps three to four inches deep and overlies the parent material.

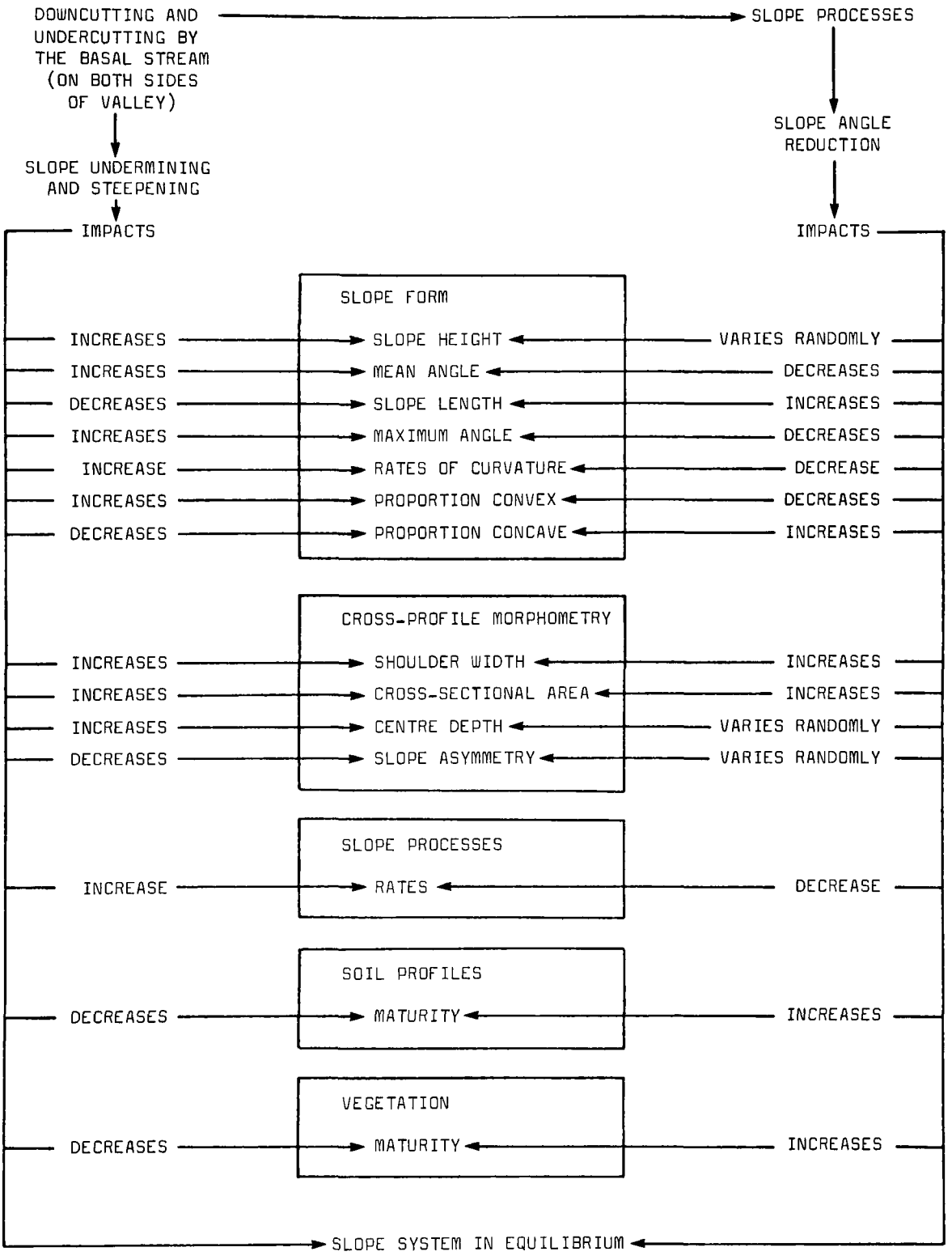


FIG. 5.2. WEAKLY-UNDERCUT SLOPE SYSTEMS

(iii) Non-Undercut Slopes

The third group of slope systems experiences no fluvial undercutting so that processes which act to reduce slope angle may operate unopposed (Fig. 5.3, p.150). Such systems occur in misfit valleys away from the loci of undercutting. It is probable that these slopes have been undercut during the past but have then been abandoned by the basal stream as the result of meander migration. Since a renewal of undercutting may be predicted for the future, such slope systems, like the powerfully-undercut systems, are relatively short lived. It is possible that undercutting is absent in many of the dry study valleys, notably valleys C1, C3 and C4. Field observations indicated that signs of erosion in these valleys during the spring melt are negligable.

Non-undercut slopes are like closed systems in that they develop towards a condition of maximum entropy. As slope processes reduce the angle of slope, their rates of operation are reduced in consequence. As a result, soil profiles and vegetation associations become more mature. Vegetation coverage of the soil may be complete and grasses tend to dominate associations, even on maximum slope angles. The evolution of these associations beyond the pasture stage is prevented at present by grazing.

As energy declines in these slope systems, maximum and mean angles, rates of curvature and the convex component of the profile tend to decrease whereas slope length and the concave proportion increase. Materials which accumulate at the base of the slope are not

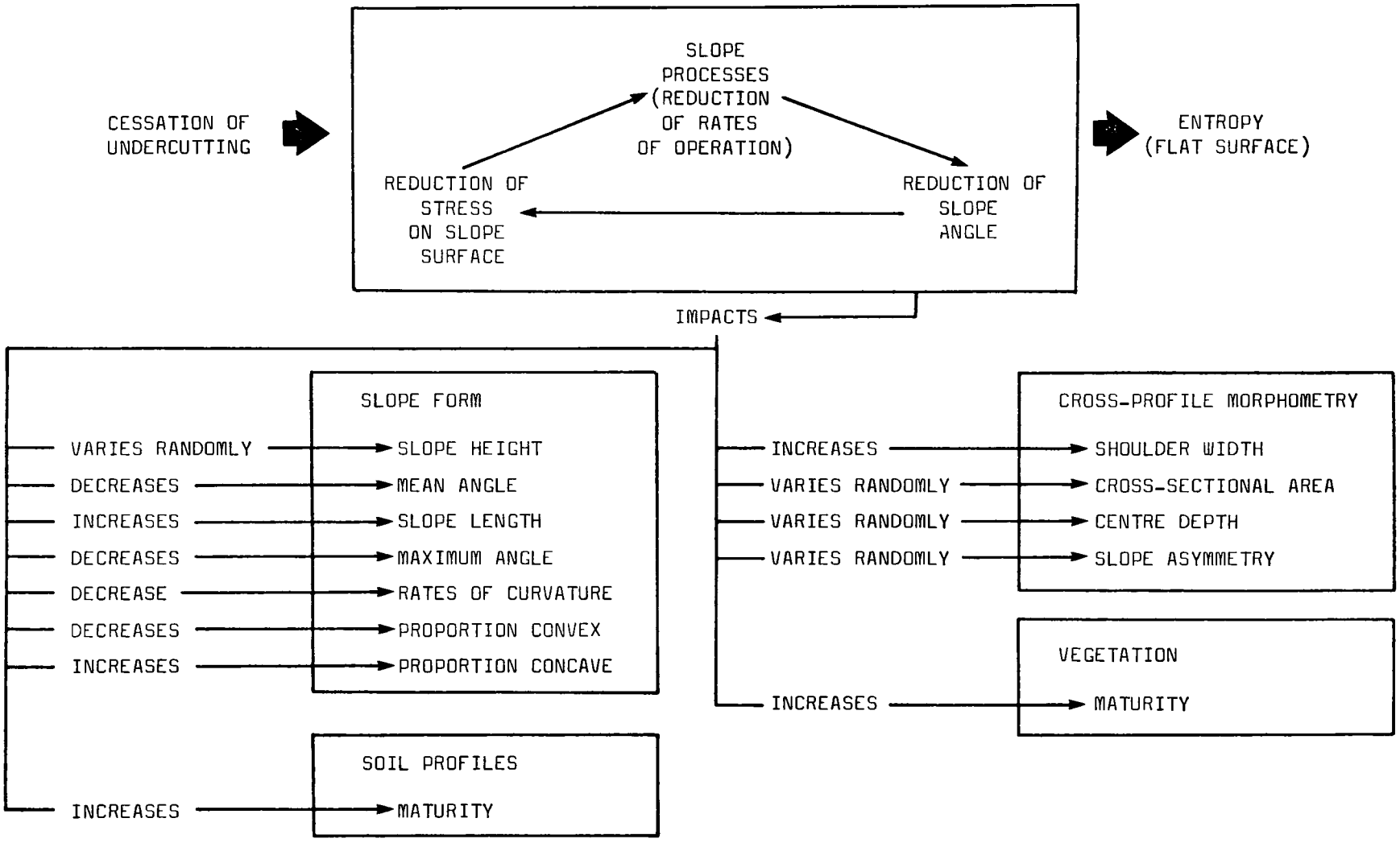


FIG. 5.3. NON-UNDERCUT SLOPE SYSTEMS

removed by the basal stream and are able to form depositional concavities. These deposits do not appear as scree forms but, rather, are indistinguishable from the parent material which is itself unconsolidated and fine-grained. Basal concavities are especially obvious on non-undercut slopes in misfit valleys.

It is difficult to predict changes in the cross-profiles of valleys in which these slope systems are present. If the opposing slope is undercut, slope asymmetry will become accentuated and shoulder width and cross-sectional area will increase. If both sides of the valley are free from undercutting, width may increase and depth decreases as materials are transported from the slope summit to the base of the slope.

Beneath the stable slopes at Gatineau, however, there is very little evidence of such accumulations. The slopes in valleys C1, C3 and C4 are of low inclination and yet have retained a basal convexity which suggests that adjustments to the cessation of fluvial processes have been so gradual that the slopes may be viewed as quasi-static. The latter are characteristically multi-sequential in form in contrast to the simple forms which are found in valleys with more active slope processes. One possible explanation of the irregular form is that there has been slumping in mid-slope. The mid-slope facets which are present, however, are extensive rather than localized features and may represent fluvial terraces which are now relict landforms.

5(b) Suggestions for Further Work

The age and origin of the study valleys must remain doubtful despite the indirect evidence which is cited in the report. It would be particularly useful, therefore, if materials could be located within these valleys which are suitable for dating by radiocarbon methods. Unfortunately, many of the tributaries contain no such deposits although dateable materials may occur in some misfit valleys where they have been buried by alluvial fill.

Other aspects of the post-glacial history of the Ottawa area also require further investigation. The preliminary work concerning local drainage development, which was based upon the analysis of topographic sheets, is in need of supporting field evidence. Since the questions of the origins of the Champlain Sea clay and the brown mottled clay are relevant to the reconstruction of recent events in the Ottawa area, the comparative evaluation of the geological and geotechnical investigations into these clays is imperative.

The models of slope development which are proposed require further field verification. Changes in the characteristics of slope systems are predicted largely from static evidence which could be gainfully supplemented by field measurements of surface processes. Of special interest are observations concerning the development and subsequent stabilization of erosion scars. More extensive data concerning soils and vegetation are necessary if the relationships of these latter to slope form are to be effectively analyzed. Such data would contribute eventually towards the construction of quantitative models of slope systems development.

SELECTED BIBLIOGRAPHY

(a) Regional studies relevant to the Ottawa-St. Lawrence Lowlands

Antevs, E. (1925). "Retreat of the Last Ice-Sheet in Eastern Canada." Geological Survey of Canada, Memoir 146.

_____. (1939)."Late Quaternary Upwarpings of Northeastern North America." Journal of Geology, Vol. XLVII, pp.707-720.

Crawford, C.B. (1961). "Engineering Studies of Leda Clay." In Soils in Canada - Geological, Pedological, and Engineering Studies. Edited by R.F. Legget. The Royal Society of Canada, Special Publications,No. 3. Toronto: The University of Toronto Press. Pp.200-217.

_____. (1963). "Cohesion in an Undisturbed Sensitive Clay." Geotechnique, Vol. XIII, pp.132-146.

_____. (1968). "Quick Clays of Eastern Canada." Engineering Geology, Vol. II, pp.239-265.

_____, and Eden, W.J. (1965). "A Comparison of Laboratory Results with In-situ Properties of Leda Clay." Proceedings, Sixth International Conference on Soil Mechanics and Foundation Engineering, Vol. I, pp.31-35.

_____, _____. (1967). "Stability of Natural Slopes in Sensitive Clay." Journal of the Soil Mechanics and Foundations Division (American Society of Civil Engineers), Vol, XCIII, Proceedings Paper 5324, pp.419-436.

Dansereau, P., and Gille, A. (1949). "Ecologie des Principaux Types de Pâturages des Environs de Granby." Bulletin du Service de Biogéographie (University of Montreal), No. 4.

Department of Transport. (1969-1970, Monthly). Monthly Meteorological Summary at Ottawa International Airport, Ont. Ottawa:Meteorological Branch, Canada Department of Transport.

Dodson, P. (1968). "A Study of Some Late Pleistocene Fluvio-glacial Sediments from Dawson's Pit, Lucerne, P.Q." Unpublished B.Sc. dissertation, Department of Geology, University of Ottawa.

Dyck, W., and Fyles, J.G. (1962). "Geological Survey of Canada Radiocarbon Dates I." Radiocarbon, Vol. IV, pp.13-26.

Eden, W.J., and Mitchell, R.J. (1970). "The Mechanics of Landslides in Leda Clay." Canadian Geotechnical Journal, Vol. VII, pp.285-296.

Elson, J.A. (1963). "Late Pleistocene Water Bodies in the St. Lawrence Lowlands." Geological Society of America, Abstracts, No. 76, p.54.

_____. (1968). "Champlain Sea." In The Encyclopedia of Geomorphology. Edited by R.W. Fairbridge. New York, Amsterdam, London: Rheinhold Book Co. Pp.116-117.

_____. (1969). "Radiocarbon Dates, Mya Arenaria Phase of the Champlain Sea." Canadian Journal of Earth Sciences, Vol. VI, pp.367-372.

_____, and Elson, J.B. (1959). "Phases of the Champlain Sea Indicated by Littoral Molluscs." Bulletin, The Geological Society of America, Vol. LXX, p.1596.

Gadd, N.R. (1961). "Surficial Geology of the Ottawa Area - Report of Progress." Geological Survey of Canada, Paper 61-19.

_____. (1963). "Surficial Geology of the Ottawa Map-area, Ontario and Quebec." Geological Survey of Canada, Paper 62-16.

Goldthwait, J.W. (ca. 1933). "The St. Lawrence Lowland." Unpublished manuscript for Geological Survey of Canada.

Hamel, A., and Dansereau, P. (1949). "L'Aspect Ecologique du Problème des Mauvaises Herbes." Bulletin du Service de Biogéographie (University of Montreal), No. 5.

Heginbottom, J.A. (1967). "Aspects of Gully Morphology along the Shield Edge North of Montreal." Unpublished M. Sc. dissertation, Department of Geography, McGill University.

Hobson, G.D. (1970). "Bedrock Features in the Mer Bleue Area by Seismic Methods." The Canadian Field Naturalist, Vol. LXXXIV, pp.35-38.

Johnston, W.A. (1916). "Late Pleistocene Oscillations of Sea Level in the Ottawa Valley." Geological Survey of Canada, Museum Bulletin No. 24.

_____. (1917). "Pleistocene and Recent Deposits in the Vicinity of Ottawa, with a Description of the Soils." Geological Survey of Canada, Memoir 101.

Kenney, T.C. (1964). "Sea-level Movements and the Geologic Histories of the Post-glacial Marine Soils at Boston, Nicolet, Ottawa and Oslo." Geotechnique, Vol. XIV, pp.203-230.

Lajoie, P.G. (1962). Soil Survey of Gatineau and Pontiac Counties Quebec. Research Branch, Canada Department of Agriculture, Quebec Department of Agriculture and MacDonald College, McGill University. Ottawa: Queen's Printer.

_____. (1967). Etude Pédologique des Comtés de Hull, Labelle et Papineau, Québec. Research Branch, Canada Department of Agriculture, Quebec Department of Agriculture and MacDonald College, McGill University. Ottawa: Queen's Printer.

Lemenestral, J. (1966). "Blackburn, Ontario - Quebec. Geomorphology." Geological Survey of Canada, Map 1264A.

Lowdon, J.A., and Blake, W. (1968). "Geological Survey of Canada Radiocarbon Dates VII." Radiocarbon, Vol. X, pp.207-245.

_____; Fyles, J.G.; and Blake,W.(1967). "Geological Survey of Canada Radiocarbon Dates VI." Radiocarbon, Vol. IX, pp.156-197.

Mackay, J.R. (1949). "Physiography of the Lower Ottawa Valley." Revue Canadienne de Géographie, Vol, III, pp.53-96.

Mott, R.J., and Camfield, M. (1969). "Palynological Studies in the Ottawa Area." Geological Survey of Canada, Paper 69-38.

Penner, E. (1965). "A Study of Sensitivity in Leda Clay." Canadian Journal of Earth Sciences, Vol. II, pp.425-441.

Potzger, J.E. (1953). "Nineteen Bogs from Southern Quebec." Canadian Journal of Botany, Vol. XXXI, pp.383-401.

_____, and Courtemanche, A. (1956). "A Series of Bogs Across Quebec from the St. Lawrence Valley to James Bay." Canadian Journal of Botany, Vol. XXXIV, pp.473-500.

Prest, V.K. (1970). "Quaternary Geology of Canada." In Geology and Economic Minerals of Canada. Edited by R.J.W. Douglas. Ottawa: Queen's Printer. Pp.

Terasmae, J. (1959). "Notes on the Champlain Sea Episode in the St. Lawrence Lowlands, Quebec." Science, Vol. CXXX, pp.334-336.

_____. (1960). "Part 1 - A Palynological Study of Post-glacial Deposits in the St. Lawrence Lowlands." In Contributions to Canadian Palynology No. 2, Geological Survey of Canada, Bulletin 56, pp.1-21.

_____. (1961). "Notes on Late-Quaternary Climatic Changes in Canada." Annals of the New York Academy of Sciences, Vol.XCV, pp.658-675.

_____, and Lasalle, P. (1968). "Notes on Late-glacial Palynology and Geochronology at St. Hilaire, Quebec." Canadian Journal of Earth Sciences, Vol. V, pp.249-257.

Wilson, A.E. (1946). "Geology of the Ottawa and St. Lawrence Lowland, Ontario and Quebec." Geological Survey of Canada, Memoir 241.

(b) Studies of slope forms, regoliths and processes.

Bakker, J.P., and Le Heux, J.W.N. (1946). "Projective - geometric Treatment of O. Lehmann's Theory of the Transformation of Steep Mountain Slopes." Proceedings, Koninklijke Nederlandsche Akademie van Wetenschappen, Series B, Vol. XLIX, pp.533-547.

_____, _____. (1947). "Theory on Central Rectilinear Recession of Slopes. I." Proceedings, Koninklijke Nederlandsche Akademie van Wetenschappen, Vol. L, pp.959-966.

Baulig, H. (1940). "Le Profil d'Equilibre des Versants." Annales de Géographie, Vol. XLIX, pp.81-97.

Beckett, P.H.T. (1968). "Soil Formation and Slope Development. I. A New Look at Walther Penck's Aufbereitung Concept." Zeitschrift für Geomorphologie, Vol. XII, pp.1-24.

Béthune, P. de. (1967). "Sur le Développement de la Convexité Sommitale des Versants." In L'Evolution des Versants. Edited by P. Macar. Vol XL of Les Congrès et Colloques de l'Université de Liège, pp.89-100.

Bunting, B.T. (1961). "The Role of Seepage Moisture in Soil Formation, Slope Development, and Stream Initiation." American Journal of Science, Vol. CCLIX, pp.503-518.

Burkalow, A. van (1945). "Angle of Repose and Angle of Sliding Friction: An Experimental Study." Bulletin, The Geological Society of America, Vol, LVI, pp.669-708.

Carson, M.A. (1969a). "Models of Hillslope Development under Mass Failure." Geographical Analysis, Vol, I, pp.76-100.

_____, and Petley, D. (1970). "The Existence of Threshold Hillslopes in the Denudation of the Landscape." Transactions, The Institute of British Geographers, No. 49, pp.71-95.

Carter, C.S., and Chorley, R.J. (1961). "Early Slope Development in an Expanding Stream System." Geological Magazine, Vol. XCVIII, pp.117-130.

Chorley, R.J. (1964a). "The Nodal Position and Anomalous Character of Slope Studies in Geomorphological Research." In "Slope Profiles: A Symposium." By C.E. Everard, R.J. Chorley and B.T. Bunting. Geographical Journal, Vol. CXXX, pp.70-73.

Churska, Z.; Galon, R.; and Roszko, L. (1967). "Degradation of Moraine Plateaux and Slope Processes Along the Lower Vistula Valley and Neighbouring Valleys." In L'Evolution des Versants. Edited by P. Macar. Vol. XL of Les Congrès et Colloques de l'Université de Liège, pp.75-88.

Clark, M.J. (1965). "The Form of Chalk Slopes." Southampton Research Series in Geography (Department of Geography, University of Southampton), No. 2, pp.3-34.

Common, R. (1966). "Slope Failure and Morphogenetic Regions." In Essays in Geomorphology. Edited by G.H. Dury. New York: American Elsevier Publishing Co., Inc. Pp.53-79.

Conacher, A.J. (1967). "A Systems Approach to the Description and Interpretation of the Landsurface of the Northern Half of the North Island, New Zealand." Earth Science Journal (The Waikato Geological Society), Vol. I, pp.118-123.

Cotton, C.A. (1952). "The Erosional Grading of Convex and Concave Slopes." Geographical Journal, Vol. CXVIII, pp.197-204.

Culling, W.E.H. (1963). "Soil Creep and the Development of Hillside Slopes." Journal of Geology, Vol. LXXI, pp.127-161.

_____. (1965). "The Theory of Erosion on Soil-covered Slopes." Journal of Geology, Vol. LXXIII, pp.230-254.

Dylik, J. (1968). "The Significance of the Slope in Geomorphology." Bulletin de la Société des Sciences et des Lettres de Lodz, Vol. XIX, pp.1-19.

Fenneman, N.F. (1908). "Some Features of Erosion by Unconcentrated Wash." Journal of Geology, Vol. XVI, pp.746-754.

Fourneau, R. (1960-1961). "Contribution à l'Etude des Versants dans le Sud de l'Entre Sambre et Meuse. Influence de la Nature du Substratum." Annales de la Société Géologique de Belgique, Vol. LXXXIV, pp.123-151.

French, H.M. (1967). "The Asymmetrical Nature of Chalk Dry Valleys in Southern England." Unpublished Ph. D. dissertation, Department of Geography, University of Southampton.

_____. (1971). "Slope Asymmetry of the Beaufort Plain, Northwest Banks Island, N.W.T., Canada." Canadian Journal of Earth Sciences, Vol. VIII, pp.717-731.

_____. (1972). "Asymmetrical Slope Development in the Chiltern Hills." Biuletyn Peryglacjalny, No. 21, pp.51-73.

Furley, P.A. (1968). "Soil Formation and Slope Development. 2. The Relationship between Soil Formation and Gradient Angle in the Oxford Area." Zeitschrift für Geomorphologie, Vol. XII, pp.25-42.

Garnier, B.J. (1968). "Estimating the Topographic Variation of Direct Solar Radiation: A Contribution to Geographical Microclimatology." Canadian Geographer, Vol. XII, pp.241-248.

Grimberieux, J. (1954-1955). "Origine et Asymétrie des Vallées Sèches de la Hesbaye." Annales de la Société Géologique de Belgique, Vol. LXXVIII, pp.267-286.

Hadley, R.F. (1961). "Some Effects of Microclimate on Slope Morphology and Drainage Basin Development." United States Geological Survey, Professional Paper 424-B, pp.B32-B34.

Jahn, A. (1960). "Some Remarks on Evolution of Slopes on Spitzbergen." Zeitschrift für Geomorphologie, Supp. I, pp.49-58.

_____. (1963). "Importance of Soil Erosion for the Evolution of Slopes in Poland." Nachrichten der Akademie der Wissenschaften in Göttingen - II - Mathematisch - Physikaliche Klasse, Vol. XII, pp.229-237.

_____. (1968). "Denudational Balance on Slopes." Geographia Polonica, No. 13, pp.9-29.

Kennedy, B.A. (1967). "A Comparative Study of Multiply - Controlled Valley Asymmetry in S.E. Wyoming and S.W. Manitoba." Unpublished M.A. dissertation, Department of Geography, University of British Columbia.

Kirkby, M.J. (1967). "Measurement and Theory of Soil Creep." Journal of Geology, Vol. LXXV, pp.359-378.

_____, and Chorley, R.J. (1967). "Throughflow, Overland Flow and Erosion." Bulletin of the International Society of Scientific Hydrology, Vol. XII, pp.5-21.

Lambert, J.M. (1960-1961). "Contribution à l'Etude des Pentes du Condroz." Annales de la Société Géologique de Belgique, Vol. LXXXIV, pp.241-250.

Lawson, A.C. (1932). "Rain-wash Erosion in Humid Regions." Bulletin, The Geological Society of America, Vol. XLIII, pp.703-724.

Lohnes, R.A., and Handy, R.L. (1968). "Slope Angles in Friable Loess." Journal of Geology, Vol. LXXVI, pp.247-258.

Macar, P. (1963). "Etudes Récentes sur les Pentes et l'Evolution des Versants en Belgique." Nachrichten der Akademie der Wissenschaften in Göttingen - II - Mathematisch - Physikaliche Klasse, Vol. XII, pp.71-84.

Macar, P., and Fourneau, R. (1960). "Relations entre Versants et Nature du Substratum en Belgique." Zeitschrift für Geomorphologie, Supp. I, pp.124-128.

Melton, M.A. (1960). "Intravalley Variation in Slope Angles Related to Microclimate and Erosional Environment." Bulletin, The Geological Society of America, Vol. LXXI, pp.133-144.

Ollier, C.D., and Thomasson, A.J. (1957). "Asymmetrical Valleys of the Chiltern Hills." Geographical Journal, Vol. CXXIII, pp.71-80.

Packer, R.W. (1964). "Stability Slopes in an Area of Glacial Deposition." Canadian Geographer, Vol. VIII, pp.147-151.

Pitty, A.F. (1966). "Some Problems in the Location and Delimitation of Slope-profiles." Zeitschrift für Geomorphologie, Vol. X, pp.454-461.

_____. (1967). "Some Problems in Selecting a Ground-surface length for Slope-angle Measurement." Revue de Géomorphologie Dynamique, Vol. XVII, pp.66-71.

_____. (1968). "A Simple Device for the Field Measurement of Hillslopes." Journal of Geology, Vol. LXXVI, pp.717-720.

_____. (1969). "A Scheme for Hillslope Analysis 1. Initial Considerations and Calculations." University of Hull Occasional Papers in Geography, No. 9.

Ploey, J. de, and Savat, J. (1968). "Contribution à l'Etude de l'Erosion par le Splash." Zeitschrift für Geomorphologie, Vol. XII, pp.174-193.

Savigear, R.A.G. (1952). "Some Observations on Slope Development in South Wales." Transactions, The Institute of British Geographers, No. 18, pp.31-51.

_____. (1967). "The Analysis and Classification of Slope Profile Forms." In, L'Evolution des Versants. Edited by P. Macar. Vol. XL of Les Congrès et Colloques de l'Université de Liège, pp.271-290.

Scheideggar, A.E. (1961). "Evaluation of Slope Development Theories." Journal of the Alberta Society of Petroleum Geologists, Vol. IX, pp.15-19.

_____. (1964). "Lithologic Variations in Slope Development Theory." United States Geological Survey, Circular No. 485.

Schumm, S.A. (1956a). "The Role of Creep and Rainwash on the Retreat of Badland Slopes." American Journal of Science, Vol. CCLIV, pp.693-706.

_____. (1956b). "Evolution of Drainage Systems and Slopes in Badlands at Perth Amboy, New Jersey." Bulletin, The Geological Society of America, Vol. LXVII, pp.597-646.

Seret, G. (1963). "Essai de Classification des Pentes en Famenne." Zeitschrift für Geomorphologie, Vol. VII, pp.71-85.

Strahler, A.N. (1950). "Equilibrium Theory of Erosional Slopes Approached by Frequency Distribution Analysis." American Journal of Science, Vol. CCXLVIII, pp.673-696 and 800-814.

_____. (1968). "Slope Analysis." In The Encyclopedia of Geomorphology. Edited by R.W. Fairbridge. New York, Amsterdam, London: Rheinhold Book Co. Pp.998-1002.

Tricart, J., and Muslin, J. (1951). "L'Etude Statistique des Versants." Revue de Géomorphologie Dynamique, Vol. II, pp.173-182.

Twidale, C.R. (1967). "Hillslopes and Pediments in the Flinders Ranges, South Australia." In Landform Studies from Australia and New Guinea. Edited by J.N. Jennings and J.A. Mabbutt. London, New York: Cambridge University Press. Pp.95-117.

Wilson, L. (1968). "Slopes." In The Encyclopedia of Geomorphology. Edited by R.W. Fairbridge. New York, Amsterdam, London: Rheinhold Book Co. Pp.1002-1020.

Wood, A. (1942). "The Development of Hillside Slopes." Proceedings of the Geologists' Association, Vol. LIII, pp.128-140.

Young, A. (1960). "Soil Movement by Denudational Processes on Slopes." Nature, Vol. CLXXXVIII, pp.120-122.

_____. (1961). "Characteristic and Limiting Slope Angles." Zeitschrift für Geomorphologie, Vol. V, pp.126-131.

_____. (1963a). "Some Field Observations of Slope Form and Regolith, and Their Relation to Slope Development." Transactions, The Institute of British Geographers, No. 32, pp.1-29.

_____. (1963b). "Deductive Models of Slope Evolution." Nachrichten der Akademie der Wissenschaften in Göttingen - II - Mathematisch - Physikalische Klasse, Vol. XII, pp.45-66.

_____. (1964). "Slope Profile Analysis." Zeitschrift für Geomorphologie, Supp. V, pp.17-27.

(c) Miscellaneous geomorphological studies.

Ahnert, F. (1967). "The Role of the Equilibrium Concept in the Interpretation of Landforms of Fluvial Erosion and Deposition." In L'Evolution des Versants. Edited by P. Macar. Vol XL of Les Congrès et Colloques de l'Université de Liège, pp.23-41.

Baulig, H. (1957). "Peneplains and Pediplains." Translated by C.A. Cotton. Bulletin, The Geological Society of America, Vol. LXVIII, pp.913-930.

Birot, P. (1968). The Cycle of Erosion in Different Climates. Translated by C.I. Jackson and K.M. Clayton. London: B.T. Batsford Ltd.

Brown, E.H. (1969). "Jointing, Aspect and Orientation of Scarp Face Dry Valleys near Ivinghoe, Buckinghamshire." Transactions, The Institute of British Geographers, No. 48, pp.61-75.

Bull, A.J. (1940). "Cold Conditions and Landforms in the South Downs." Proceedings of the Geologists' Association, Vol. LI, pp.63-71.

Carson, M.A. (1969b). "Soil Moisture." In Water, Earth and Man. Edited by R.J. Chorley. London: Methuen and Co. Ltd. Pp.185-195.

Chorley, R.J. (1959). "The Geomorphic Significance of Some Oxford Soils." American Journal of Science, Vol. CCLVII, pp.503-515.

_____. (1964b). "Geomorphological Evaluation of Factors Controlling Shearing Resistance of Surface Soils in Sandstone." Journal of Geophysical Research, Vol. LXIX, pp.1507-1516.

_____. (1965). "A Re-evaluation of the Geomorphic System of W.M. Davis." In Frontiers in Geographical Teaching. Edited by R.J. Chorley and P. Haggett. London: Methuen and Co. Ltd. Pp.21-38.

_____. (1967). "Models in Geomorphology." In Models in Geography. Edited by R.J. Chorley and P. Haggett. London: Methuen and Co. Ltd. Pp.59-96.

Culling, W.E.H. (1960). "Analytical Theory of Erosion." Journal of Geology, Vol. LXVIII, pp.336-344.

Curray, J.R. (1965). "Late Quaternary History, Continental Shelves of the United States." In The Quaternary of the United States. Edited by H.E. Wright, Jr. and D.G. Frey. Princeton, New Jersey: Princeton University Press. Pp.723-735.

Denny, C.S. (1967). "Fans and Pediments." American Journal of Science, Vol. CCLXV, pp.81-105.

Dury, G.H. (1954). "Contribution to a General Theory of Meandering Valleys." American Journal of Science, Vol. CCLII, pp.193-224.

_____. (1964a). "Principles of Underfit Streams." United States Geological Survey, Professional Paper 452-A.

_____. (1964b). "Subsurface Exploration and Chronology of Underfit Streams." United States Geological Survey, Professional Paper 452-B.

_____. (1965). "Theoretical Implications of Underfit Streams." United States Geological Survey, Professional Paper 452-C.

Fagg, C.C. (1954). "The Coombes and Embayments of the Chalk Escarpment." Proceedings of the Croydon Natural History and Science Society, Vol. XII, pp.117-13[illegible].

Hack, J.T. (1960). "Interpretation of Erosional Topography in Humid Temperate Regions." American Journal of Science, Vol. CCLVIII-A, pp.80-97.

_____. (1965). "Post-glacial Drainage Evolution and Stream Geometry in the Ontonagon Area, Michigan." United States Geological Survey, Professional Paper 504-B.

_____, and Goodlett, J.C. (1960). "Geomorphology and Forest Ecology of a Mountain Region in the Central Appalachians." United States Geological Survey, Professional Paper 347.

Holmes, C.D. (1955). "Geomorphic Development in Humid and Arid Regions: A Synthesis." American Journal of Science, Vol. CCLIII, pp.377-390.

Horton, R.E. (1945). "Erosional Development of Streams and Their Drainage Basins: Hydrophysical Approach to Quantitative Morphology." Bulletin, The Geological Society of America, Vol. LVI, pp.275-370.

Karol, R.H. (1960). Soils and Soil Engineering. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

King, L.C. (1953). "Canons of Landscape Evolution." Bulletin, The Geological Society of America, Vol. LXIV, pp.721-752.

Leopold, L.B.; Wolman, M.G.; and Miller, J.P. (1964). Fluvial Processes in Geomorphology. San Francisco, London: W.H. Freeman and Co.

Melton, M.A. (1958). "Correlation Structure of Morphometric Properties of Drainage Systems and Their Controlling Agents." Journal of Geology, Vol. LXVI, pp.442-460.

Mulcahy, M.J. (1961). "Soil Distribution in Relation to Landscape Development." Zeitschrift für Geomorphologie, Vol. V, pp.211-225.

Savigear, R.A.G. (1965). "A Technique of Morphological Mapping." Annals of the Association of American Geographers, Vol. LV, pp.514-538.

Schumm, S.A. (1965). "Quaternary Paleohydrology." In The Quaternary of the United States. Edited by H.E. Wright, Jr. and D.G. Frey. Princeton, New Jersey: Princeton University Press. Pp.783-794.

_____, and Lichty, R.W. (1965). "Time, Space and Causality in Geomorphology." American Journal of Science, Vol. CCLXIII, pp.110-119.

Simons, M. (1962). "A Morphological Analysis of Landforms: A New Review of the Work of Walther Penck." Transactions, The Institute of British Geographers, No. 31, pp.1-14.

Skempton, A.W. (1953). "Soil Mechanics in Relation to Geology." Proceedings of the Yorkshire Geological Society, Vol. XXIX, pp.33-62.

Sparks, B.W. (1960). Geomorphology. London: Longmans, Green and Co. Ltd.

Tricart, J. (1947). "Sur Quelques Indices Géomorphometriques." Comptes Rendus, Academie des Sciences de Paris, Vol. CCXXV, pp.747-749.

Wolman, M.G., and Leopold, L.B. (1957). "River Flood Plains: Some Observations on Their Formation." United States Geological Survey, Professional Paper 282-C.

_____ , and Miller, J.P. (1960). "Magnitude and Frequency in Geomorphic Processes." Journal of Geology, Vol. LXVIII, pp.54-74.

(d) Other references cited.

Mills, F.C. (1955). Statistical Methods. New York, Chicago, San Francisco, Toronto: Holt, Rinehart and Winston.

Munsell Color Company, Inc. (1954). Munsell Soil Color Charts. Baltimore, Maryland: Munsell Color Company, Inc.

Siegel, S. (1956). Nonparametric Statistics for the Behavioral Sciences. New York, Toronto, London: McGraw-Hill Book Co., Inc.

FIG 3.2C THE LONGITUDINAL PROFILES OF THE STUDY VALLEYS