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Spatial and temporal variations in erosion measurements

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ABSTRACT In 1969 nine erosion study sites were installed in the Red Deer River badlands of Alberta, Canada. A decade of data collection and 4500 point measurements show mean erosion rates of the order of 4.00 mm year^{-1}. This is considerably in excess of the estimated geological norm for this region (0.021-0.04 mm year^{-1}. Computer simulated time lapse analyses of the data reveal short term sporadic pulses of erosional activity marked by distinct thresholds. These are separated by longer periods of relative inactivity. The 10 year study shows that prolonged periods of very detailed field measurement are required for the collection of reliable data since, even in geologically rapidly changing environments, such as badlands, relatively little change occurs for most of the time. Moreover, processes that appear erratic or sporadic in the short-term may be part of a steady trend over a longer time span. The results suggest the creation of a remarkably consistent pattern of change over a wide range of slopes and lithologies.

Variations spatiales et temporelles dans les mesures d'érosion
RESUME En 1969, neuf sites ont été amenagés en Alberta, Canada, pour l'étude de l'érosion dans les terres ravinées et arides ("badlands") de la vallée de la Red Deer. Les 4500 mesures ponctuelles effectuées pendant une période de 10 ans révèlent un taux moyen de 4.00 mm par an. Ce chiffre est beaucoup plus élevé que la norme géologique établie pour cette région (0.021-0.04 mm par an). Une étude des données à partir d'un programme de temps simulé sur ordinateur révèle des impulsions d'activité d'érosion sporadiques et caractérisées par une attaque clairement définie. Les périodes d'activité sont séparées par des périodes prolongées de quasi-inactivité. Les études conduites durant 10 ans montrent qu'il est nécessaire d'effectuer de nombreuses mesures sur le terrain pendant de longues périodes afin d'amasser des données sures puisque, même dans des environnements caractérisés par une évolution géologique rapide (comme c'est le cas dans les badlands), les changements significatifs se produisent au cours de périodes relativement courtes alors que la plupart du temps on observe une situation relativement stable. De plus, il se peut que

des processus qui apparaissent isolés et sporadiques dans une perspective à court terme, fassent partie d'une tendance régulière lors qu'on les considère au sein d'une période prolongée. Les résultats obtenus suggèrent la création d'un mode de changement remarquablement consistant pour une grande variété de pentes et de lithologies.

INTRODUCTION

Many long term investigations of fluvial processes and sediment transport have been made and a large amount of information and data relating to these topics have been collected. Yet, comparatively little is known about real erosion rates and the spatial and temporal production of sediment from land surfaces. Although several inferential investigations have been undertaken on sediment yields and erosion rates, these usually have been based either on stream sediment loads or on other non-direct measurement techniques (e.g. Judson & Ritter, 1964; Menard, 1961). The method of calculating erosion rates is usually done by mathematically redistributing the stream sediment load uniformly over the area of the watershed to give a regional erosion rate. Such a procedure is simple but it contains serious misconceptions and errors and it can produce grossly misleading results (Ahnert, 1970; Campbell, 1977a, 1977b; Trimble, 1977).

While direct surface measurements are preferable, and provide a more reliable source on which to base estimates of erosion rates and sediment yields, these are often difficult to obtain from a logistical, observational and instrumental point of view. Many land surfaces change imperceptibly, and only highly accurate measurements taken over protracted periods may produce meaningful results. Hence, most of the few direct measurement investigations undertaken to date have concentrated on landscapes that are undergoing relatively rapid changes in the short-term geological sense. These include studies of badlands (Campbell, 1970a, 1974; Bryan & Campbell, 1980; Schumm, 1956a, 1956b; Smith 1958) and of alpine environments (Gardner, 1969, 1979; Luckman, 1978; Rapp, 1961).

It may be argued that measurements of these environments represent special cases, and that the techniques do not lend themselves readily to adoption in more "normal" landscapes where change is less rapid. Nevertheless, some direct measurement techniques have produced encouraging results in areas of slow change (Young, 1960). More significantly, they provide unit standards of measurement against which other techniques and observations in slower evolving landscapes can be compared; in other words they act as analogues (Thornes & Brunsden, 1977).

The present study is an analysis of 10 years of detailed direct surface measurements from nine slope segments in the badlands of the Red Deer River, Alberta. It describes and explains the measurement techniques and the spatial and temporal variations in erosion and surface change recorded over the period 1969-1979.

THE STUDY AREA

The nine slope segments on which the measurement sites are located, lie in a small (0.5 km^2) tributary basin of the Red Deer River in the badlands of Dinosaur Provincial Park, Alberta (Fig. 1); a region world famous for its wealth of dinosaurian fauna. The basin has a total relief of about 100 m with steep (30° average) valley-side slopes.

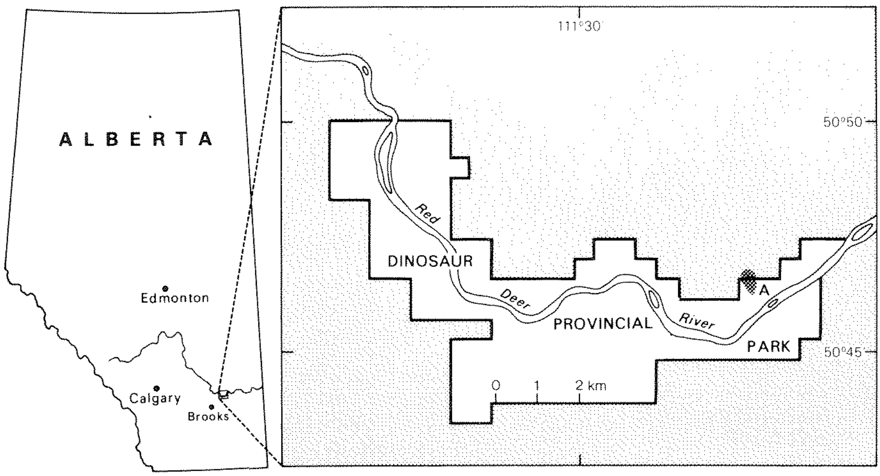

Fig. 1 Location of study basin (A) in Dinosaur Provincial Park, Alberta.

The regional bedrock geology consists of Upper Cretaceous deltaic sediments of the Oldman Formation (McCrossan & Glaister, 1966) which are an alternating sequence of almost horizontally bedded weakly-cemented river channel sandstones, levée deposits and flood plain clays. Many of the units are rich in volcanic ash-derived sodium montmorillonite. Vertical and lateral variations in lithology are frequent and abrupt, which produce equally sharp topographic changes in slope and create a complex response to surface and subsurface (piping) erosional processes (Bryan *et al.*, 1978; Bryan & Campbell, 1980). Mantling the bedrock and forming the flat prairie surface is a variable (3-5 m thick) cover of Wisconsin glacial till. The basin geology and plot locations are shown in Fig. 2, and their detailed characteristics are described in Table 1.

The regional climate shown in Table 2 for Brooks, 40 km south of the study area, is a continental-type with short warm summers during which the majority of the annual precipitation falls. Winters are cold but comparatively dry. The pattern of the climate determines the frequency and time intervals of field measurements. Changes in surface elevation are measured twice each year, typically in April and in October. The first measurement follows the winter period when access is difficult and the slopes are frequently snow covered but it precedes the onset of the summer rains, whereas the second measurement comes at the end of the summer rainy period. This pattern of measurements ensures that the effects of frost heave and slope wash, the two dominant

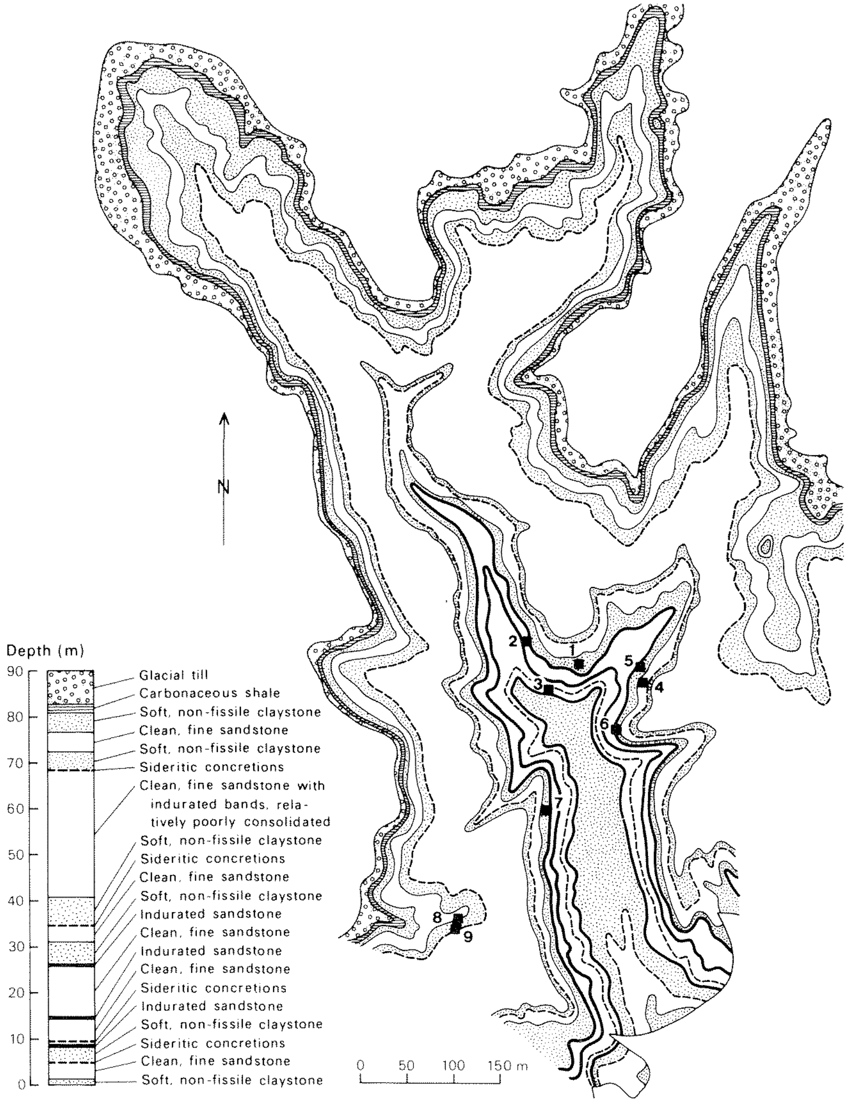

Fig. 2 Study basin geology and location of the nine erosion plot sites. Source: Faulkner (1970).

Table 1 Plot characteristics

Plot	Bedrock and surficial materials
1	Consolidated flood plain clays and shales with a disaggregated and fractured upper layer 5-10 cm deep
2	Alluviated pediment bench covered with laminar deposits of fine sand and silt
3	Alluviated pediment bench covered with laminar deposits of fine sand and silt
4	Dense compacted channel sandstone and levée deposits
5	Well-indurated shale base armoured with a thin, scattered cover of small clay-ironstone fragments
6	Highly desiccated sandy-shale with a sparse cover of clay-ironstone fragments
7	Friable poorly compacted shale with a scattering of clay-ironstone fragments
8	Flood plain clays and shales with a fractured upper layer 5-10 cm deep
9	Flood plain clays and shales with a fractured upper layer 5-10 cm deep

Table 2 Climatic data for Brooks, Alberta

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mean daily temperature (°C)	−13.1	−10.4	−4.7	5.2	11.6	15.3	19.4	17.5	11.9	6.0	−3.1	−8.8	3.9
Mean rainfall (mm)	0.2	0.5	1.3	10.6	38.8	37.4	37.8	52.1	31.0	8.6	1.5	0.7	240.1
Mean snowfall (mm)	167.0	167.0	195.5	100.9	20.3	–	–	–	17.7	91.4	121.9	142.0	1023.7
Mean precipitation (mm)	17.0	17.3	20.8	21.6	40.8	37.4	37.8	52.1	32.7	17.8	13.7	15.5	344.0

erosional processes operating in the badlands, are both observed and monitored (Campbell, 1974).

INSTRUMENTATION AND MEASUREMENT TECHNIQUES

All measurements are taken using a lightweight movable frame that rests on permanently installed mounting posts (Campbell, 1970b). Twenty-five sliding rods in a one metre square grid configuration provide an accurate method of monitoring surface changes without interfering with surface form or processes. Over the 10 year period of record, 1969-1979, a total of 4500 measurements have been taken, each one accurate to ±0.5 mm. These form the data base for the analysis of surface changes. The data may be used to produce computer drawn contour diagrams or three-dimensional perspective displays of the plot surface at specific times of measurement and also for intervening periods by use of interpolation (Fig. 3). In Fig. 3 two computer produced perspective diagrams are shown for plot 4 at months 89 and 118. This was a period of low amplitude rapid changes across the plot surface (Fig. 4). The diagrams in Fig. 3 show the passage of a mass of sediment down the central rill system. Large scale sediment movement on all the plots is largely a discontinuous process and this particular sequence shows one such event. A complete sequence of these events for all plots provides a dramatic visual interpretation of progressive surface and form changes, but since this style of presentation does not lend itself to a written format the data are presented here in a standard graphic form (Fig. 4).

FORM, ELEVATION AND VOLUMETRIC CHANGES

Changes in the elevation and form of the nine plot surfaces can be seen in Fig. 4, which graphs the volume of material removed, and in Table 3 which shows the total amount of surface change and the angular changes of the slope that accompanied the erosional processes.

Table 3 shows that over the 10 year period of measurement only very slight changes in slope angle have occurred. Although all plots, except 4 and 8, show a lowering of slope angle, these reductions are very small and probably lie within the margin of

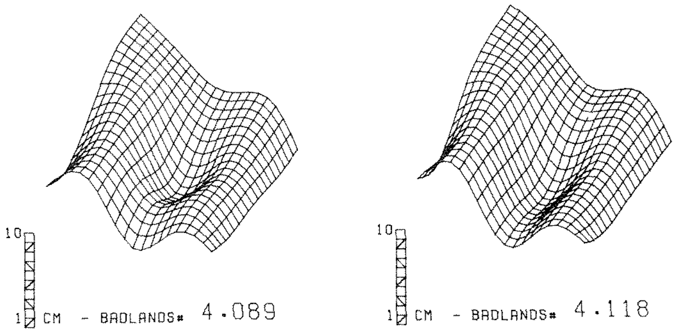

Fig. 3 Computer produced three dimensional perspective diagrams of plot 4 at months 89 and 118. Plots are one metre square; vertical exaggeration is 5X.

Table 3 Form, elevation and volumetric changes 1969–1979

Plot	Initial angle (°)	Final angle (°)	Mean surface change (cm)	Total volume change/horizontal m^2 equivalent ($cm^3 \times 10^3$)
1	21.69	21.22	−2.63	−3.66
2	4.94	4.93	+3.27	+2.26
3	5.98	5.70	+1.22	+1.45
4	33.02	33.22	−5.16	−5.89
5	26.82	26.49	−4.19	−5.67
6	40.75	40.27	−0.74	−2.21
7	47.06	46.00	−2.68	−6.44
8	7.37	7.86	−2.86	−2.81
9	13.04	12.14	−8.36	−8.96
			*Mean = −3.80	*Mean = −5.09

*Plots 2 and 3 excluded.

measurement error.

A simple linear regression equation fitted to the rates of angular change for all plots is of the form:

$$y = 29.99 - 0.001x$$

where x is in months and y is slope angle in degrees. If this rate of lowering were maintained it would mean an average decline in slope angles of approximately 1° per 100 years. Such a rate of angular decline would be significant if it continued, but the natural variation of slope angles within the study region makes it unlikely that such a situation would prevail generally.

More importantly, there is no suggestion that steeper angled plots decline more rapidly, nor do plots located on materials of substantially different erodibility show any consistent variation to indicate that the weaker bedrock units decline in angle more rapidly. It is evident that macro-topographic considerations and the manner in which different lithologic units are related within the total slope form are the key factors in determining the slope angle of particular slope segments.

Rates of mean surface lowering (Table 3) also reveal no clear cut pattern of relationship between slope angle, material and erosion rate. Two of the plots, 2 and 3, which are located on

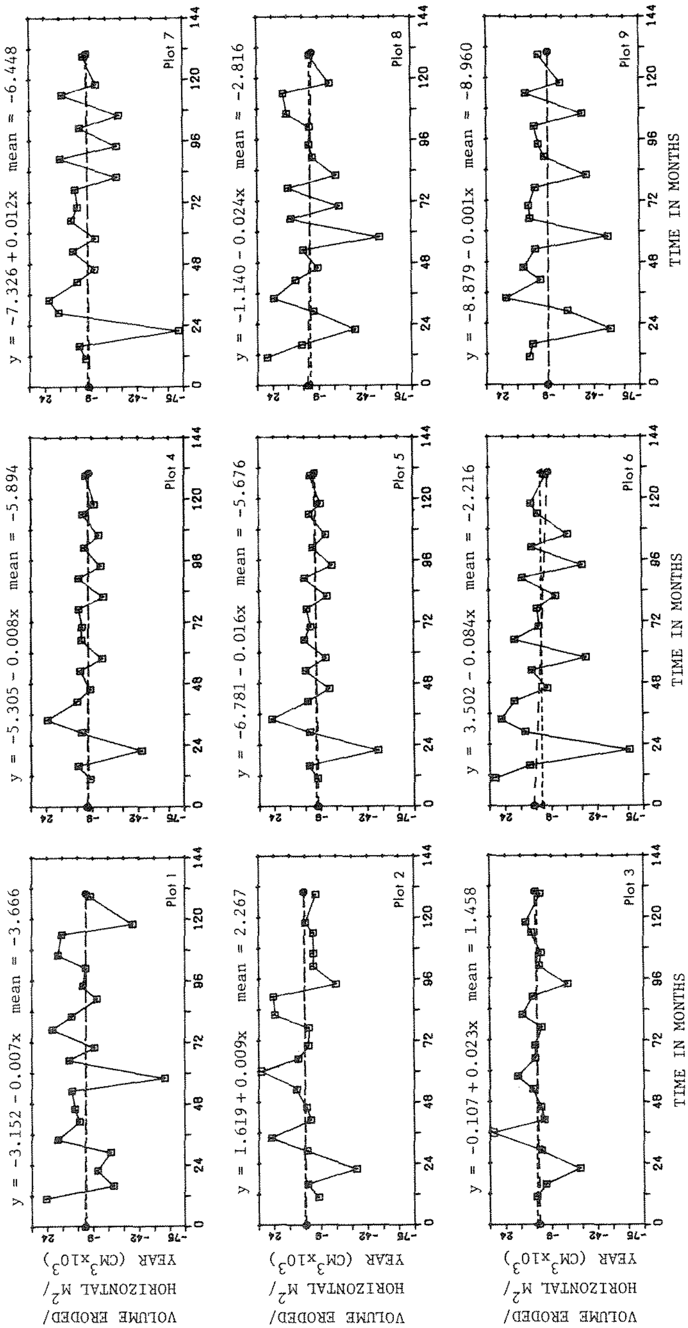

Fig. 4 Rates of volumes of material eroded (cm^3 × 10^3) for each plot with their linear regressions and means, 1969–1979.

small alluviated benches (Table 1) show an aggradational trend over the decade of measurement, though as will be seen below, this trend was not consistent over the entire decade.

The mean rate of surface lowering from 1969 to 1979 (plots 2 and 3 excluded) amounts to 3.80 cm, or 3.8 mm $year^{-1}$. Such a rate of erosion is comparatively rapid in a geological sense but badlands are usually regarded as representing rapidly eroding landscapes. In fact, this rate is substantially less than some recorded in similar types of environments (Campbell, 1970a). On the basis of sediment load in the Red Deer River it has been calculated that the regional erosion rate for the Red Deer basin is of the order of 0.021-0.040 mm $year^{-1}$ (Slaymaker & McPherson, 1973). The difference between the two rates is about 2 orders of magnitude, but one is the result of averaging a rate for the entire basin and the other is derived from study of a very specific location. In fact, it can be shown that about 90% of the sediment load carried by the Red Deer River is derived from the badlands which occupy only about 2% of the basin area (Campbell, 1977a, 1977b).

Volumetric losses are equated in terms of total amount with the mean rates of surface lowering, except that for comparability the volumetric rates are calculated on the basis of horizontal surface equivalents. The pattern of these changes and the way they vary in space between sites and through time for each plot are shown in Fig. 4. The graphs for all plots show large and rapid variations about the mean rate of surface change, which is slightly positive for plots 2 and 3 and negative for all others.

For each plot a linear regression equation expresses the trend in the rate of volumetric change over the study period, and it is evident that, with the exception of plot 6, the overall rates of erosion are highly consistent, despite considerable differences between plots on particular occasions. However, these variations not only even out to produce remarkably uniform individual plot rates through time, but the patterns of behaviour for some plots are almost identical.

Plots 2 and 3, the aggrading surfaces, show with slight variation in amplitude, a consistent mode of surface change in which three phases of net aggradation alternate with phases of volumetric loss. Plots 4 and 5 are so closely similar in pattern as to be almost indistinguishable, yet their surface characteristics (Table 1) and their slope angles (Table 3) are different.

Two important findings emerge from records for all of the sites. First, it is clear that some erosional events have had sufficient magnitude to affect all surfaces equally. The time period around month 24 was uniformly one of major surface lowering. This was followed by an equally major period of surface aggradation. Evidently a major erosional threshold was exceeded on a plot-wide scale, and was undoubtedly the effect of a major storm and runoff period. However, not all plots respond equally to all threshold events, and different plots have different thresholds. For example, plots 1, 6, 8 and 9 all underwent major erosional phases at about month 60, whereas this event is not well marked at the other sites.

The second, and more important, finding is that regardless of the differences between the plots, with respect to angle, materials, topographic position and other variables, their internal rates of change are extremely constant when viewed over a 10 year time period. The entire group of slope segments not only behave in a highly comparable manner as seen above, but in the long-term the spatial and temporal differences even out to produce an overall pattern of response that is remarkably constant. It may well be that this is an expression of "time independence" (Young, 1972) or a "steady state" (Schumm, 1956b) behaviour.

When the behaviour of the plots is viewed in the short-term (2 or 3 years) these patterns of uniformity are not evident. For example, a series of measurements taken only over the first 3 years of the study, as Fig. 4 shows, would have produced entirely misleading results. Additionally, at some sites very little change takes place over many months and the plots show only low amplitudes of variation.

The study reveals not only the need to monitor changes in surface behaviour very accurately, and in a manner that provides volumetric data rather than simple single point measurements, but the necessity to establish, even in rapidly eroding areas, investigations of sufficient duration to detect the real trends of surface behaviour.

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REFERENCES

Ahnert, F. (1970) Functional relationships between denudation, relief and uplift in large mid-latitude drainage basins. *Am. J. Sci.* 268, 243-263.

Bryan, R. B., Yair, A. & Hodges, W. K. (1978) Factors controlling the initiation of runoff and piping in Dinosaur Provincial Park badlands, Alberta, Canada. *Z. Geomorph.* Suppl. bd 29, 151-168.

Bryan, R. B. & Campbell, I. A. (1980) Sediment entrainment and transport during local rainstorms in the Steveville badlands, Alberta. *Catena* 7, 51-65.

Campbell, I. A. (1970a) Erosion rates in the Steveville badlands, Alberta. *Can. Geogr.* 14, 202-214.

Campbell, I. A. (1970b) Micro-relief measurements on unvegetated shale slopes. *Prof. Geogr.* 22, 215-220.

Campbell, I. A. (1974) Measurements of erosion on badlands surfaces. *Z. Geomorph.* Suppl. bd 21, 127-137.

Campbell, I. A. (1977a) Stream discharge, suspended sediment and erosion rates in the Red Deer River basin, Alberta, Canada. In:

Erosion and Solid Matter Transport in Inland Waters (Proc. Paris Symp., July 1977), 244-259. IAHS Publ. no. 122.

Campbell, I. A. (1977b) Sediment origin and sediment load in a semi-arid drainage basin. In: *Geomorphology in Arid Regions* (ed. by D. O. Doerhing), (Proc. Binghamton Symp., Sept. 1977), 168-185. Publ. in Geomorph., State University of New York, Binghamton.

Faulkner, P. H. (1970) Aspects of channel and basin morphology in the Steveville badlands, Alberta. Unpublished MSc Thesis, Department of Geography, University of Alberta.

Gardner, J. S. (1969) Observation of surficial talus movement. *Z. Geomorph.* 13, 317-323.

Gardner, J. S. (1979) The natural destruction of the Canadian Rocky Mountains: or the tempo of geomorphic change as revealed by slope processes. *Contact - J. Urban & Envir. Affairs* 2, 1-32. Faculty of Environmental Studies, University of Waterloo, Ontario, Canada.

Judson, S. & Ritter, D. F. (1964) Rates of regional denudation in the United States. *J. Geophys. Res.* 69, 3395-3401.

Luckman, B. H. (1978) Measurements of debris movement on alpine talus slopes. *Z. Geomorph.* Suppl. bd 29, 117-129.

McCrossan, R. G. & Glaister, R. P. (1966) *Geological History of Western Canada.* Alberta Soc. Petrol. Geol., Calgary, Alberta.

Menard, H. W. (1961) Some rates of regional erosion. *J. Geol.* 69, 154-160.

Rapp, A. (1961) Recent development of mountain slopes in Kärkevagge and surroundings, Northern Scandinavia. *Geogr. Ann.* 42, 71-200.

Slaymaker, H. O. & McPherson, H. J. (1973) Effects of land use on sediment production. In: *Fluvial Processes and Sedimentation* (Proc. Hydrol. Symp., May 1977), 158-183. NRC, Ottawa.

Schumm, S. A. (1956a) The role of creep and rainwash on the retreat of badland slopes. *Am. J. Sci.* 254, 693-706.

Schumm, S. A. (1956b) The evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bull. Geol. Soc. Am.* 67, 597-646.

Smith, K. G. (1958) Erosional processes and landforms in Badlands National Monument, South Dakota. *Bull. Geol. Soc. Am.* 69, 975-1007.

Thornes, J. B. & Brunsden, D. (1977) *Geomorphology and Time,* p. 26. Methuen, London.

Trimble, S. (1977) The fallacy of stream equilibrium in contemporary denudation studies. *Am. J. Sci.* 277, 876-887.

Young, A. (1960) Soil movement by denudational processes on slopes. *Nature* 188, 120-122.

Young, A. (1972) *Slopes.* Oliver and Boyd, Edinburgh.