Process in Geomorphology

Edited by Clifford Embleton

and John Thornes

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Notation in mathematical formulae

Except where otherwise defined, the following general conventions are used throughout the book. The list is far from exhaustive; to list every quantity or term, including subscripts, would greatly increase the length of the list and would be self-defeating. As far as possible, we have used traditional forms of notation, such as τ for shear stress and μ for both friction and viscosity, even where this results in several parameters having the same symbol. Thus there are inevitably overlaps in usage, so that terms must be defined on each occasion that they are introduced in the text. This list merely attempts to bring some uniformity to the use of the commoner symbols.

C	Centigrade
J	joule ($kg\,m^2\,s^{-2}$)
K	Kelvin
M	mega –
N	newton ($kg\,m\,s^{-2} = J\,m^{-1}$)
W	watt ($kg\,m^2\,s^{-3} = J\,s^{-1}$)

cal	calorie
cm	centimetre
g	gram
ha	hectare
hr	hour
kg	kilogram
km	kilometre
l	litre
m	metre
mg	milligram
ml	millilitre
mm	millimetre
s	second
t	tonne
yr	year

kN	kilonewton
μm	micrometre
Hz	hertz (cycle per second)
Pa	pascal
Pl	poiseuille

A cross-sectional area; basin area
C wave celerity
D diameter; particle size; coefficient of thermal conductivity; Dean's parameter
Dd drainage density
E modulus of elasticity
F force; Froude number; safety factor
G gravitational constant
H heat of fusion
I rainfall intensity; immersed weight
K hydraulic conductivity; von Karman constant
KE kinetic energy
L slope length; unit length
M mass
P pressure; energy flux
PE potential energy
Q discharge; aeolian sand transport
R Reynolds number
S shear strength
T temperature; wave period
V velocity; volume
W weight; power
Z gravitational potential energy

a acceleration; area
c cohesion; volume concentration
d distance, depth, thickness
f infiltration rate; fall time of a sediment particle; Darcy-Weisbach factor
g acceleration due to gravity
h vertical interval, height, depth
i hydraulic gradient
k coefficient; permeability
l length
m mass
p pressure (water, ice, etc.); probability
q discharge per unit area
r radius; roughness
s slope
t time
u pore-water pressure
v velocity, volume
w width
x, *y*, *z* coordinate axes

Δ (delta) change
Θ (theta) sediment transport

α (alpha) slope, angle
β (beta) beach slope
γ (gamma) bulk density, unit weight

ε	(epsilon)	strain; diffusion
θ	(theta)	angle
λ	(lambda)	coefficient of expansion; wave-length
μ	(mu)	friction; viscosity
μ_*	(mu)	shear velocity
π	(pi)	coefficient (3.14159...)
ρ	(rho)	density (fluids)
σ	(sigma)	normal stress; surface tension
τ	(tau)	shear stress; shear strength; tractive force
υ	(upsilon)	kinematic viscosity
ϕ	(phi)	angle of friction; potential energy
ψ	(psi)	tension, suction
ω	(omega)	sediment fall velocity

Preface

The idea of this book grew out of a course of lectures given to second and third year undergraduates in King's College and the London School of Economics as one of the 'options' in geomorphology. In spite of the appearance of several texts in the last ten years or so dealing with particular systematic aspects such as fluvial geomorphology or glacial geomorphology, there has been a lack of a detailed and comprehensive text on 'process geomorphology'. The last twenty years have seen a rapid expansion of interest in geomorphological processes. Prior to the 1950s, studies of the operation and nature of particular processes were relatively few. Many of the most important investigations had been undertaken by engineers (for example, studying fluvial processes in connection with river control, the weathering of building materials or the stability of slopes), and there was little understanding of many fields of process geomorphology such as the mechanics of ice movement and glacial erosion, the formation of desert dunes or hillslope processes; still less was the interaction of these processes in particular environments or their rates of action appreciated. The growth rate of work in process geomorphology can be judged by the fact that, of the 1100 references cited in this book, 68 per cent relate to publications since 1960.

This book is concerned solely with exogenic processes, broadly those modifying the Earth's surface from the outside and powered principally by solar or gravitational energy. Although geothermal energy is relevant to a few exogenic processes, such as glacier sliding and processes in permafrost areas, processes depending on the interior energy sources of the Earth, including the whole range of tectonic activity, will not be considered. The book begins with some general considerations of the nature of energy, forces and resistances, the properties of materials, and the nature of fluid flow. It then deals with groups of processes systematically —weathering, mass movements, fluvial, glacial, nival, aeolian and marine—before a final chapter reviews their position in the environment and their interrelationships.

Many people apart from the authors of the book have helped in its production, and we are grateful to all of them. Most of the line drawings have been prepared by Roma Beaumont, Alison Hine and Gordon Reynell in the King's College drawing office, and among those who have helped in the typing we would like to thank Victoria Blank, Bridget O'Donnell, Anne Rogers and Hilary Salter.

Clifford Embleton
John Thornes

18 December 1978

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Introduction

J. B. Thornes

In geomorphology the word process is a noun used to define the dynamic actions or events in geomorphological systems which involve the applications of forces over gradients. Such actions are caused by agents such as the wind and falling rain, waves and tides, river- and soil-water solutions. Where the forces exceed the resistances in these natural systems, change occurs by deformation of a body, by change in position or by change in chemical structure. Change in the form of the Earth's surface indicates the operation of such processes, but lack of observable change need not imply that no processes are operating. This may be because the rate of operation of the process is small, because the ratio of force to resistance is small, resulting perhaps in the dissipation of energy in friction, or because the forces and resistances are fairly balanced.

In geomorphology a major task is to understand the relationships between form and process. They may be expressed in a cause-and-effect chain or, for example, by the rates of change of operation of one with respect to rates of change of the other. Simple representations of these relationships are called models. Process-response models, where the word 'response' means form or structure, are often used to describe and explain the relationships. The models may be reached inductively, that is, by the observation and combination of particular instances, or by deduction, in which one proceeds from known or assumed relationships in the physical world to argue about the consequences of these relationships. Sometimes one proceeds by experimentation which may involve either or both of these approaches, as outlined in the second section of this chapter.

Processes in relation to space and time

Geomorphologists consider processes at various levels of spatial resolution. At the finest level one may be concerned, for example, with the filling of pore spaces in the soil by moving water. An example of a process at a very coarse scale is thermal convection below the Earth's crust. In this way processes are understood to be spatially nested; infiltration occurs within the soil, the migration of the weathering front within a hillside and so on. Geomorphologists have chosen, at least in recent years, to consider levels of resolution mainly of the order of a few hundred square kilometres or less, especially when investigating processes. Because of variations in the substratum upon which the processes operate and because the type and intensity of the processes vary from place to place, the resulting landforms are highly variable. What we view as the dominant process depends on the spatial scale at which we observe the surface. Looking at a few square metres of rock-cut platform, we might perceive the most important process to be the feeding habits of marine organisms. On the broader scale of about 1 km^2, the pattern and dynamics of wave attack may be mainly responsible for form. At the largest scale, covering several thousand square kilometres, regional isostatic adjustment might be most important.

Processes also occur at varying rates. A force may be applied rapidly or slowly; its magnitude may be large or small. If we observe a particular form or assemblage of forms over a short period, there may be little change either because the forces are small or because they have not operated for a sufficient length of time. If the nature or rate of operation of the processes change, there may be a corresponding change in the landforms. Sometimes the response is instantaneous, as when a large flood passes through a channel. At other times the response may be quite slow or there may be 'dead time' when nothing happens to landforms to reveal the change in process. The time taken for the system to respond to externally imposed changes is called its reaction time. Reaction time in geomorphological systems may be intimately tied up with spatial resolution as well as the time-scale involved. If an effect has to 'diffuse' through the landscape, as a knickpoint moves in a river, then the distance over which the diffusion takes place and the rate of diffusion are important controls on the reaction time.

Just as forms are influenced by process, so processes are influenced by form. The terrain over which an ice sheet moves will help to determine the hydraulic conditions at the bed and this in turn will affect the nature and rate of movement. Steepening of a river-channel gradient by deposition may increase the velocity and decrease the depth, which then affect the amount of scour. Such a series of events, when one change begets another which itself affects the original change, is called feedback. When the result is to reinforce the initial change the feedback is said to be positive. This occurs, for example, in the growth of a snow patch. The patch may, through nival processes, cause enlargement of the hollow which then catches more snow. When the sequence leads to damping of the initial deviation, the feedback is said to be negative. Thus, for example, in a gravel stream during the passage of a flood wave, the channel tends to become wider and shallower until the depth falls so much that transport is inhibited by increased friction and narrowing follows. Negative feedback tends to lead to a steady condition of form properties. Systems experiencing positive feedback or responding rapidly to some externally imposed change in the nature or rate of operation of the processes are said to show transient or dynamically unsteady behaviour. The investigation of process-form relationships by observation of form may be most profitable at these times.

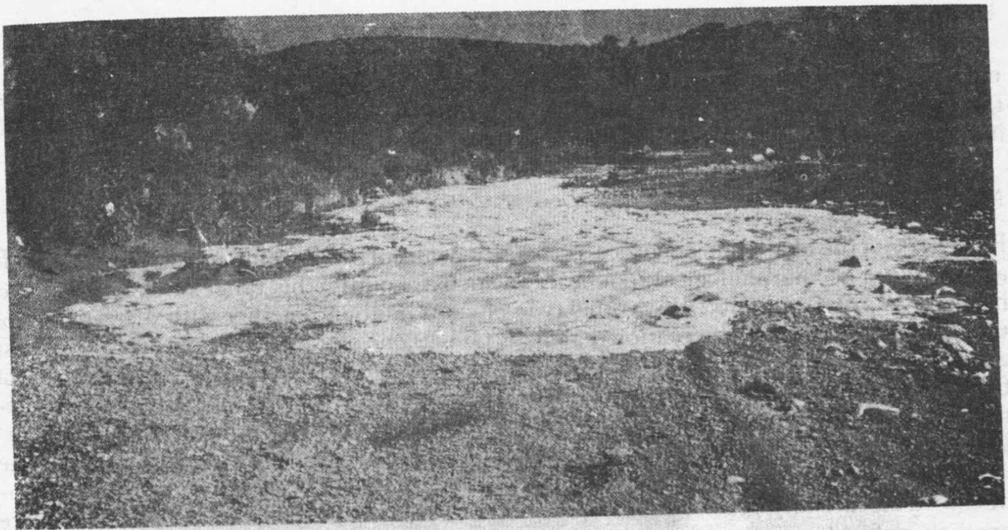
Approaches to the investigation of process

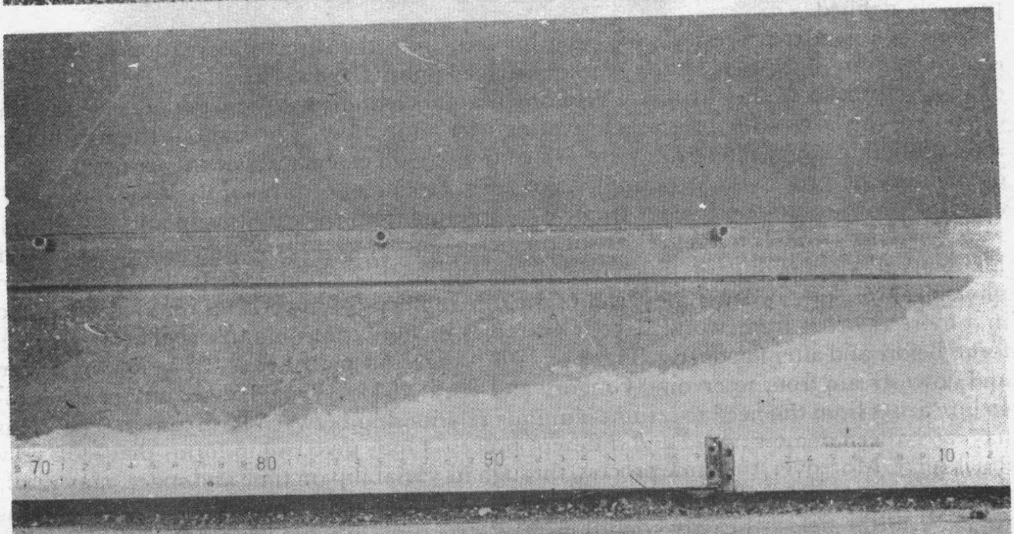
Geomorphologists have been concerned with investigations of process in three frameworks. First, they have sought to account for an evolution of forms in terms of an evolution of processes. The main intellectual thrust of this activity has been in determining the sequence of forms and deposits. The assumption is that the processes are understood. A second group has focused on the spatial and temporal variations of the processes and particularly on problems of the magnitude and frequency of events. The third group has considered mainly the relationships between form and process. Throughout, however, it has been generally recog-

Plate I (*upper*) A sharp wave front moving through an ephemeral channel after an intense storm. The white front results from the escape of air under hydrostatic pressure. (J.B.T.)

(*middle*) A laboratory model of the same phenomenon showing the wetting front developing in the subsurface materials in relation to the opportunity time for infiltration. (E. Cory)

(*lower*) Microfilm output of a computer simulation of the discharge in a large ephemeral channel under identical conditions. The extreme left-hand peak represents the upstream end of the channel. The lower peaks show the same simulated wave front farther down the channel. Diminution of flow results from infiltration into the bed. (G. Butcher, J. B. Thornes)





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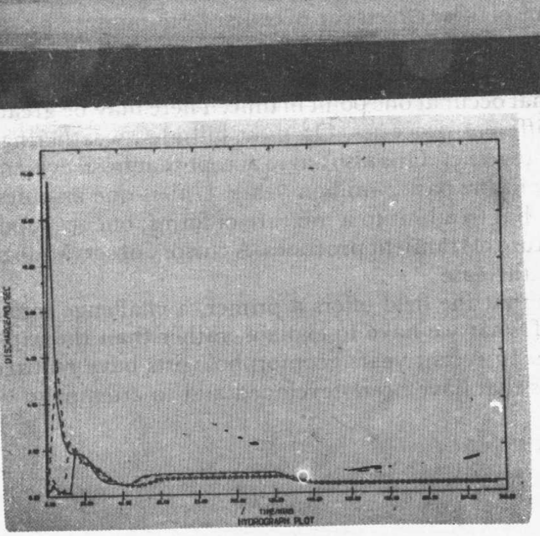

HYDROGRAPH PLOT

nized that the problems of investigation of processes in the field, in the laboratory and in the office are essentially different (Plate I). Certainly, all these modes of working are necessary if advances are to be made within the frameworks outlined above.

Fieldwork

Fieldwork is crucial to studies of process because it confronts the investigator with associations and events of geomorphological significance which are outside his range of experience and hence prompt his curiosity. It was this type of confrontation together with a steadiness of thought and accuracy of observation that made Gilbert one of the greatest pioneers in process geomorphology. The same confrontation led Leopold to his remarkable investigations of fluvial processes and forms (Leopold, 1978). Although fieldwork can be an informal, sometimes almost incidental, activity, it is important because it provides the data for the examination of empirical relationships, for the parameterization of theoretical models and for the verification of existing theoretical concepts. These are, or should be, much more formal activities based on carefully developed field programmes, in which objectives and procedures are precisely defined.

Most commonly, processes have been inferred from the direct observation of form, or change of form in the field. Early workers such as Agassiz and Gilbert laid the foundations of modern process studies by direct field observation combined with seemingly effortless induction of the large-scale processes operating over wide areas. Throughout the first half of the twentieth century inferences were drawn from field evidence about the nature and rate of operation of processes. As examples, consider the inferences drawn by Wayland (1947) as to the processes responsible for tropical weathering from the extensive plains of low latitudes or King's (1962) inferences about the occurrence and magnitude of sheet wash from his observations of pediplains. Such inferences continue to form an essential part of geomorphological thinking because they lead to the development of hypotheses that can be tested in a more rigorous framework. Recent examples include the comparison of river-channel forms before and after floods (e.g. Thornes, 1976; Anderson and Calver, 1977), and upstream and downstream from reservoirs (Gregory and Park, 1974). A major difficulty in this procedure arises from the need to assume a unique relationship between form and process. This has rarely been demonstrated and different processes may give rise to forms that look very much alike. Moreover, the same process, through its variability in time and space, may result in widely differing forms. Finally we have to admit that the form–process relationship as we see it in the field is heavily conditioned by structure, lithology and, in most places, by human activity. Some of these effects can of course be minimized by careful and well designed experiments.

A further major difficulty which we face when inferring process from form is the multiplicity of processes that occur at one point in time. There may be great difficulty in disentangling the effects of different processes. On most hillsides, weathering, creep and erosion by running water occur together. One also has to accept that fossil evidence indicates substantial variations of climate in the past 2 million years. Unless one assumes a very rapid response to such changes, one has to admit to a mixture of forms, one set superimposed on the other, resulting from a mixture of transient processes. A cursory observation of almost any landscape confirms that this is the case.

It seems to follow that the field offers a primer, a challenge to our explanatory powers, a realistic tableau of what we have to explain, rather than the explanation itself. It does, however, offer more. In recent years geomorphologists have realized the need to validate the models of process that have been developed and to attempt to verify them. Validation involves two operations: first, the appreciation of the likely domain over which process inputs operate in terms of magnitude and frequency; secondly the determination of constants (parameters) in physical relationships. Examples of the latter include Manning's *n* or the exponents in velocity equations for overland flow. Verification involves checking the expected outcomes of process models against the field data. Do the models propounded on the basis of flume experiments hold over a satisfactory range in the natural environment? Do the predicted zones of scour and deposition along a model beach actually occur in the life-sized version? These questions require much more rigorous designs of field observation than the 'priming' activities mentioned earlier and in recent years the main effort in field studies has been in this direction. Among the most successful examples of fieldwork have been observations on the mechanics of glacier movements (e.g. Meier, 1960); the evaluation of hydrological processes in small catchments, such as the Waggon Wheel Gap experiments (Bates and Henry, 1928) and studies of process rates in the coastal zone (McClean, 1967).

The major difficulties here are the inherent sampling problems and the cost of providing and maintaining expensive instrumentation. It is a paradox that the very variability of the field environment, which one seeks to incorporate into theories, makes the assessment of 'real' conditions a virtual impossibility. The other major problem lies in the severe technical constraints linked with the constant need not to interfere with the process under observation. Soil creep, bedload transport and soil-water movement illustrate these problems well. The coming of the neutron probe and the consequent breakthrough in the measurement of soil moisture exemplifies the severity of these technical limitations.

Laboratory investigations

The field provides data on the spatial and temporal ranges of inputs and parameters for models. It enables interrelationships among complex processes to be observed and it is the standard against which our understanding of process- and form-relationships must finally be judged.

In the laboratory the emphasis is on the control of events in order to observe phenomena which, though present in the real world, cannot be examined because of their interaction with other land-forming processes. Moreover, the laboratory offers the opportunity to scale down space and speed up time, two of the major stumbling blocks in field experimentation. The third major role that laboratory work plays is as a first test of the adequacy of a theoretical model or a particular set of relationships within it. Finally, it offers an opportunity for simple empirical experiments to be carried out in anticipation that new and hitherto unexpected associations may be observed.

One of the areas of investigation in which laboratory studies have been most widely and successfully applied is that of hydraulic processes, and the role of the laboratory flume has been pre-eminent. Other investigations that have made use of controlled laboratory conditions include the early work of Griggs (1936b) on arid-zone weathering, experiments by Lewis and Miller on model glaciers (1955) and by van Burkalow (1945) on mass movement. Perhaps one of the most exciting and largest-scale experiments in recent years has been Schumm's attempt to produce an entire drainage basin system under cover (Schumm, 1973). Overall, however, geomorphologists appear to have been somewhat reluctant to carry process investigations into the laboratory.

Two types of study have been carried out. In the first, the mass, length and time properties of the model are maintained identical to those in the field but the inputs may be controlled for the purposes of the particular experiment. Under these conditions observations may be possible in the laboratory which are not feasible in the field. Well known examples include the investigation of erosional phenomena by sprinkler devices (e.g. Mosley, 1973) or the experiments to study the effects of freeze–thaw on rock particles (e.g. Potts, 1970). In the other type of laboratory investigation the models are scaled-down versions of the real-world processes.

The latter type are based on the concept of similarity. The basic proposition is that the fundamental units of the laboratory model bear a constant ratio to those of the real-world prototype. For length (l), mass (m) and time (t), these relationships may be expressed by:

$$l' = \lambda_l l''$$
$$m' = \lambda_m m''$$
$$t' = \lambda_t t''$$

where l' and l'' indicate length in the model and the prototype respectively; similarly for m', m'' and t', t''. Systems related to each other by proportionality of length are said to be geometrically similar. Those which are proportionately related in both length and time are kinematically similar, while systems related to each other by all three characteristics are dynamically similar. An important characteristic of dynamic similarity is that it implies identity of all the dimensionless laws governing the model and the prototype phenomena. In a truly dynamically similar model, therefore, one can study any property of the phenomenon under investigation.

In reality, major difficulties exist because in most hydraulic models the prototype fluid (water) is used and the value of gravity in the model is the same as that of the prototype because both are on Earth. Given that this is the case, the model builder has to ensure the dynamic similarity of at least those properties that are going to be observed. For example, if the width–depth ratio of a river channel is large, the mechanical properties in the central regions of the flow are not dependent on the ratio and therefore there is no need to achieve identity in this ratio.

The effort required to meet these conditions often leads to considerable technical complexity in laboratory models. Ramberg's (1964) attempt to simulate folding in the moraines of piedmont glaciers is an example of this. Here it is argued that the driving agency of an active glacier is almost entirely the difference in potential energy in different points in the ice body because inertial terms in the fluid dynamic equations are insignificant. The glacier model is whirled round in a centrifuge because the potential difference between two points is directly proportional to the centripetal acceleration. The arrangement is shown in Figure 1.1. Compared with models at rest in the field of gravity, strong and highly viscous visco-elastic materials can be used in the centrifuge. These do not flow under gravity and so the initial stage of the model can be constructed without sagging such as would occur in imitation substances soft enough to permit maturing of models at rest in the normal field of gravity. After the structures have developed, the results can be studied in detail without further appreciable deformation.

Office work

Investigations of processes by 'armchair' geomorphologists take three forms: the analysis of field data in order to investigate empirical relationships, the development of theories based on fundamental physical principles and the development of laboratory-type experiments on digital or analogue computers. All three levels have made highly significant contributions to the understanding of geomorphological processes.

In looking at *empirical* relationships emphasis had been laid on the relationships between 'factors' or agents and the response variables. Characteristically the work proceeded through multiple regression and correlation analysis. Although the methods have recently become