HILLSLOPE MATERIALS & PROCESSES

M.J. SELBY

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Preface

The study of hillslopes is of concern to many scientists – geologists, pedologists, hydrologists, engineers, and geomorphologists. As a result the literature on the subject is dispersed through many books and journals and the approaches to the subject are varied. In writing this text I have attempted to draw on all the relevant disciplines and particularly to use the contributions of the exponents of rock and soil mechanics. Work by geomorphologists during the last twenty years has concentrated on the study of processes: I hope to modify this concern by emphasising the importance of rock and soil resistance to erosion and in so doing to re-assert the importance of geological influences on hillslope forms and development.

Considerable attention has been paid to the study of landslides because they are important as processes modifying the landscape; they are of economic significance – direct and indirect costs of landslides in the United States alone have been estimated to exceed $1 000 000 000 per year at 1976 prices; and landslides also provide an opportunity for quantitative study of the forces acting on hillslopes.

I am deeply indebted to a number of people for their help and tolerance during the preparation of this book: my wife drew some of the diagrams and took more than a fair share of our domestic responsibilities allowing me to concentrate on writing; of my colleagues Dr A. W. P. Hodder spent many hours critically reading and commenting on the whole text and I also received valued advice and comments from Professor H. S. Gibbs on Chapters 2 and 3; Drs R. J. Eyles and M. J. Crozier of Victoria University commented on Chapters 4, 5, 6, and 7; Dr P. J. Hosking of Auckland University also read much of the text and Dr R. J. Wasson of the Australian National University commented on the section on talus deposits and alluvial fans. Any errors or misrepresentations which remain are entirely my responsibility. I also wish to thank Mrs Margaret McLean for typing and retyping the text, Frank Bailey and Ken Stewart for draughting most of the diagrams, and Rex Julian for preparing the photographic prints. All photographs not otherwise acknowledged are my own.

The fieldwork on which many of my observations are based was carried out during leave from the University of Waikato and on expeditions of its Antarctic Research Unit. I am most grateful to the Council of the University for making this possible.

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Symbols used

A	area
A_j	total surface area within a rock joint
*c	cohesion
c'	cohesion with respect to effective stresses
c_r	residual cohesion
e	void ratio, kinetic energy
E	potential energy
F	factor of safety of a slope against landsliding
g	the acceleration due to gravity
G_s	specific gravity
H, h	height of slope, depth
h	piezometric height
H_c	critical height for slope stability
h_c	depth of crack
i	roughness angle of asperities in a rock joint
k	hydraulic conductivity
LL	liquid limit
l	length
m	mass, decimal part of depth (as in mz)
n	porosity
PL	plastic limit
PI	plasticity index
Q	total discharge per unit of time
R	hydraulic radius
r	the radius of the arc of a plane of sliding
S	slope
SL	shrinkage limit
s	shear strength at failure
u	pore-water pressure
V	water pressure in a tension crack, velocity
v	voids, velocity
W	weight
z	depth, thickness of overburden
z_w	depth of water
α (alpha)	angle of inclination of a failure plane
β (beta)	slope angle
γ (gamma)	unit weight of soil or rock at natural moisture content (the symbols γ_d and γ_{sat} may be used for dry and saturated soil respectively.)
γ_w	unit weight of water
ϵ (epsilon)	linear strain
ρ (rho)	bulk density
σ (sigma)	total normal stress
$\sigma_1, \sigma_2, \sigma_3$	major, intermediate and minor principal stresses respectively
σ'	effective normal stress
τ (tau)	shear stress
* ϕ (phi)	angle of internal friction
ϕ_r	residual angle of internal friction
ϕ'	angle of internal friction with respect to effective stresses
ϕ_j	joint friction angle
ϕ_{jr}	residual angle of friction along a rock joint
ϕ_p	maximum or peak value of internal friction

* In order to distinguish the parameters c and ϕ for the various shear strength test conditions the subscripts u, cu, and d are used to denote undrained, consolidated-undrained, and drained respectively, e.g. c_u.

Contents

1

Introduction

Hillslopes occupy most of the land surface with the exception of terraces and plains formed by river deposits. Even extensive surfaces, like the Great Plains of North America and the plateaux of Africa, are largely formed of hillslopes of low angle between crests of interfluves and valley floors. The most spectacular hillslopes are the great rock cliffs of the high mountain chains and the extensive valley slopes of deep gorges in uplifted plateaux.

Because of their extent the study of slopes has always been close to the heart of geomorphology although most geomorphological work on slopes, carried out before the middle of the twentieth century, was related to the classical models of slope evolution proposed by W. M. Davis, Walther Penck, and L. C. King. Only since the 1950s has much attention been paid to processes of hillslope denudation, and the study of slope material strength and resistance has been brought into the subject only in the 1970s.

Slope systems

Weathering and removal of rock and soil on hillslopes is not a uniform process in either time or space: it is episodic and depends upon the availability of energy and a transporting medium. As a result hillslopes can be regarded as a system of stores (Figs. 1.1, 1.2) which are periodically unlocked by processes. Very resistant stores, such as are provided by massive hard rock outcrops, may only yield material at very infrequent intervals. Soil slopes in a humid tropical climate may yield solutes almost continuously, but solids by landslide processes much less frequently. Each process, therefore, has its own magnitude and frequency of operation which is controlled by the resistance of the hillslope rock and soil, and by the intensity of the denudational processes.

By tracing and measuring the movement of material from hillslopes by different processes, and by measuring the modification of hillslope form produced by them, it is possible to evaluate short-term changes of slope profiles. In theory this should eventually provide an understanding of how hillslopes evolve. In most environments hillslopes change too slowly for the progression from long steep slopes to slopes of lesser angle to be observed. That such changes occur is indicated from geological sections, in which erosional surfaces have been cut across complex structures to produce unconformities which may be preserved in the depositional record. Attempts to compensate for the lack of observations of slope change usually involve one of two possible procedures. In a few rather rare situations space may be substituted for time, as where Savigear (1952) was able to measure slope profiles along a cliff which had been protected from wave attack at its base for varying periods, so that a sequential development of hillslope forms was assumed to have been produced. Less secure methods involve the measurement of different slope profiles in one area and the assembly of these profiles into a sequence. Such methods are extremely uncertain because the underlying assumption of sequential change cannot be verified.

The second method – that of the development of process-response models – forms the basis of most modern hillslope geomorphology (Fig. 1.3). Analysis involves the measurement of the resistance of rock and soil to change, the force and mode of action of a process causing change, and variation in the rate of change through time and in space. A model seeks to link variations in the rate of change over the hillslope to development of slope profiles (frequently by using differential equations). Field or laboratory methods often involve the establishment of a statistical relationship between a slope change and measurements of soil or rock properties and a process

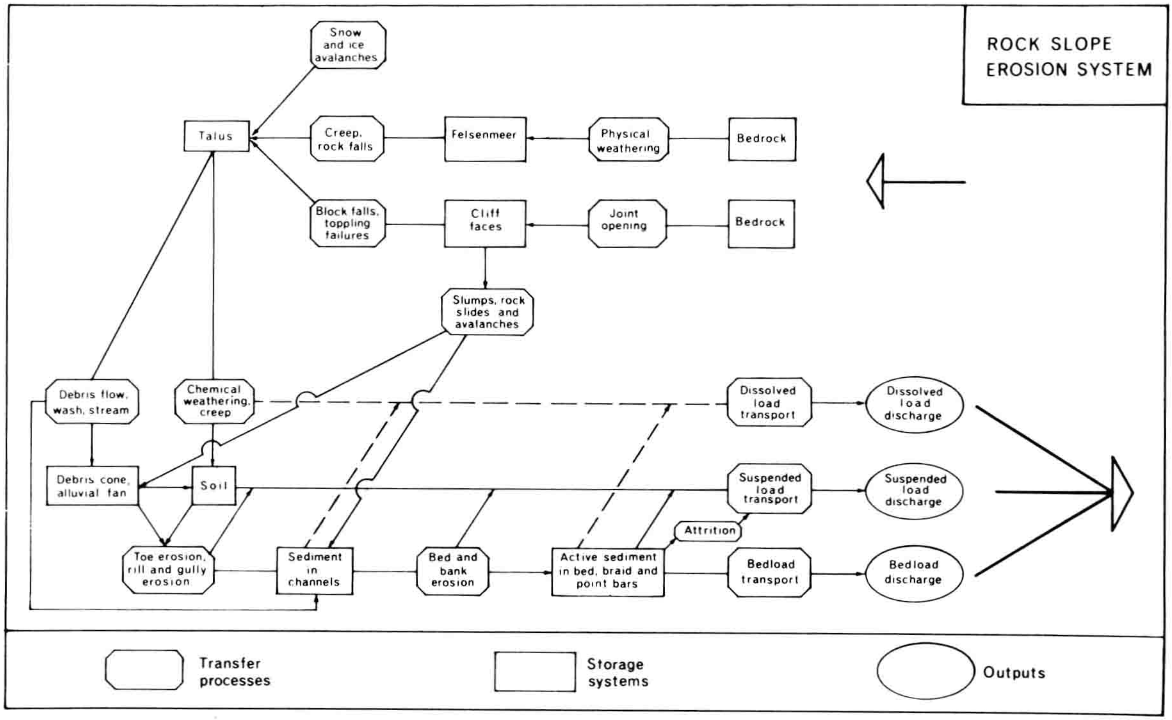


Fig. 1.1 The system of stores and transfer processes on a rock slope.

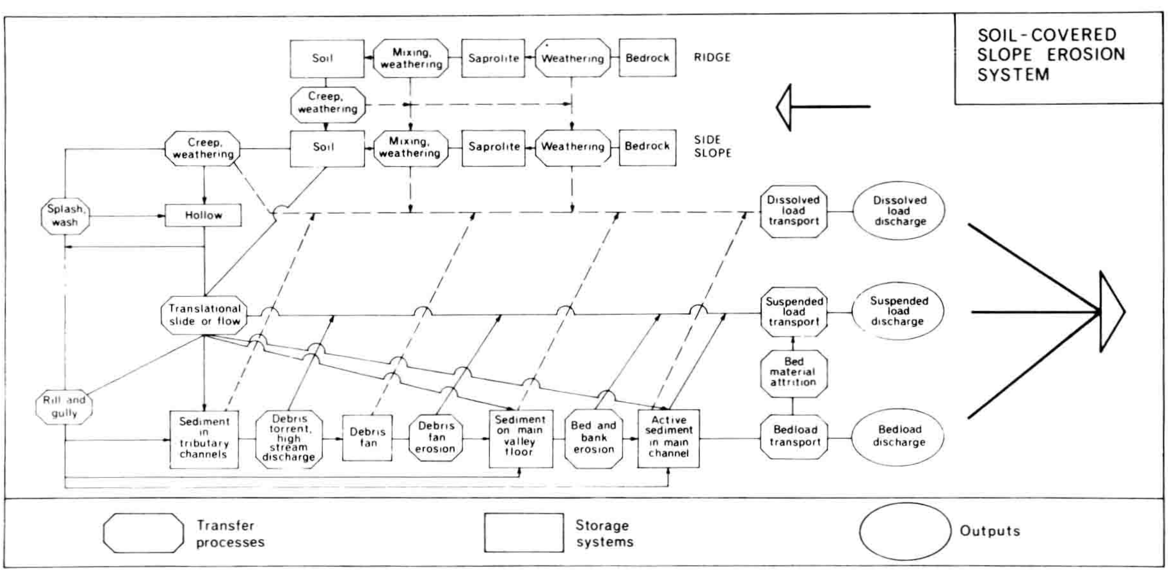


Fig. 1.2 The system of stores and transfer processes on a soil-covered slope.

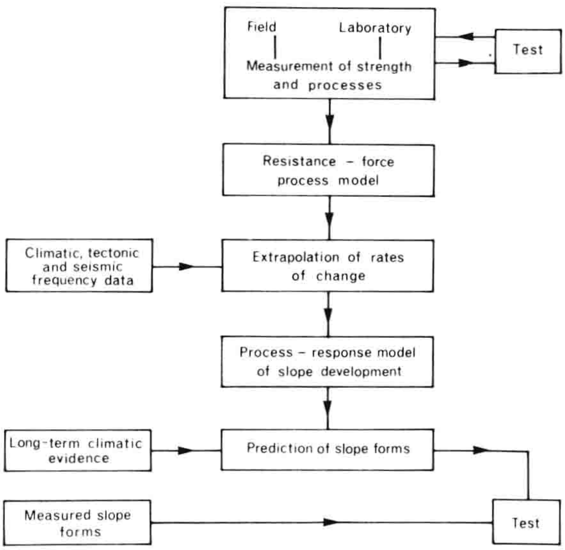


Fig. 1.3 The pattern of hillslope studies (modified from Carson and Kirkby, 1972).

such as rainfall. The primary difficulty in such methods is that of adequately sampling slopes, rock and soil types, and process types and rates. A second difficulty arises from the uncertain degree of inherited influences upon current hillslope forms, so that when a certain suite of slope forms is predicted from a sequence of processes the prediction may not be tested against natural slopes with a known history. There is at present little hope of developing predictive slope-form models which incorporate the multitudinous climatic, and hence process intensity, changes of the Quaternary. The emphasis of this book is therefore upon those components of hillslope studies which can be studied effectively – the strength of slope materials, the effect and intensity of processes acting on those materials and the resulting short-term changes on slopes.

Energy available for slope processes

The energy available for slope processes is derived from three sources: solar radiation, gravity, and endogenetic forces. Solar radiation directly promotes weathering processes but much of it is effective by driving the circulation of water in a hydrological cycle between the atmosphere, pedosphere, lithosphere, and ocean (see Fig. 5.1). Raindrops striking the ground, water flowing, and boulders falling or rolling downslope, have energy provided by the gravitational force that attracts them towards the centre of the earth. Endogenetic forces are generated by radioactive decay of natural isotopes producing heat. Geothermal heat drives volcanic activity and creates the stresses which are released in earthquakes. Over most of the land surface the energy available from solar and gravitational sources for geomorphic work is several thousand times greater than that available endogenetically. Only where volcanic activity, or sudden release of seismic energy, concentrates power can internal energy produce distinctive landforms or landforming processes.

Plan of the book

The book begins with a discussion of weathering because this process is responsible for the creation of soil and broken rock on which most hillslopes are formed, and because it is primarily responsible for the selective formation of many minor landforms on bare rock slopes, even though these landforms cannot develop until a transporting process removes the weathering products. Weathering also has the effect of producing residual crusts within the regolith, which can control the form of hillslopes under certain climatic regimes.

The resistance of rock masses and soils to imposed stresses is a neglected topic in geomorphology and has consequently been accorded more emphasis than is usual. In Chapter 4 the nature of strength, its measurement and assessment in the field and laboratory, is described so that the selective activities of erosional and transporting processes, discussed in the next three chapters, can be more readily understood. In Chapters 5 to 7 mass wasting is emphasised, partly because it is the dominant process of cliff retreat and partly because it is possible to show the relationship between resistance of materials and the forces acting to promote landsliding. The components of Chapters 2 to 7 and the linkages among them are, perhaps, most readily appreciated from a study of Figs. 1.1 and 1.2.

Tors and bornhardts are treated as a separate topic, rather than with other rock slopes, because much may be learnt from a study of them. Tors show us that structurally controlled weathering may pre-condition the shape of the land surface long before the surface of the soil is lowered by erosion to expose the results of differential weathering. Bornhardts provide examples of the control on landforms exerted by the spacing of joints and, more particularly, by the effect of sheeting on the form of the rock surface. The study of both tors and bornhardts provides a salutary warning that it is impossible to deduce the nature of the processes responsible for a landform from a study of only the shape of that landform.

The long-term evolution of hillslopes has always been a major topic in geomorphology and has traditionally been based upon changing slope morphology. The evidence for past processes is usually fragmentary and only decipherable from a close study of the deposits on, or at the base of, hillslopes. While stratigraphy may eventually assist us in deciphering the record of the past it is premature to attempt a detailed account of the methods and conclusions which may be reached. The nature of fluctuating climatic regimes throughout late Cenozoic time is only just being appreciated from studies of deep-sea cores and loess deposits. It is already evident that terrestrial deposits contain only a partial record of the past and that the relationship between slope forms and climatically controlled processes is far from adequately understood. The discussion of slope profiles, consequently, is confined to the types of models which may be used to study hillslope forms. The rates at which slopes change is discussed in Chapters 10 and 11.

2

Weathering processes

Weathering is the process of alteration and breakdown of rock and soil materials at and near the earth's surface by physical, chemical, and biotic processes. Igneous and metamorphic rocks, as well as deeply buried and lithified sedimentary rocks, are formed under a regime of high temperature and/or pressure. At the ground surface the environment is dominated by temperatures, pressures, and moisture availability more characteristic of the atmosphere and hydrosphere: thus rocks are altered by weathering to new materials which are in equilibrium with surface conditions. Weathering has three very important results: it is the process which renders resistant rock and partly weathered rock into a state of lower strength and greater permeability in which the processes of erosion can be effective; it is the first step in the process of soil formation; and during weathering the release or accumulation of iron oxides, lime, alumina, and silica takes place – where concentrated after initial solution these form indurated shells on rocks, or layers in the soil which may become hard and resistant to erosion.

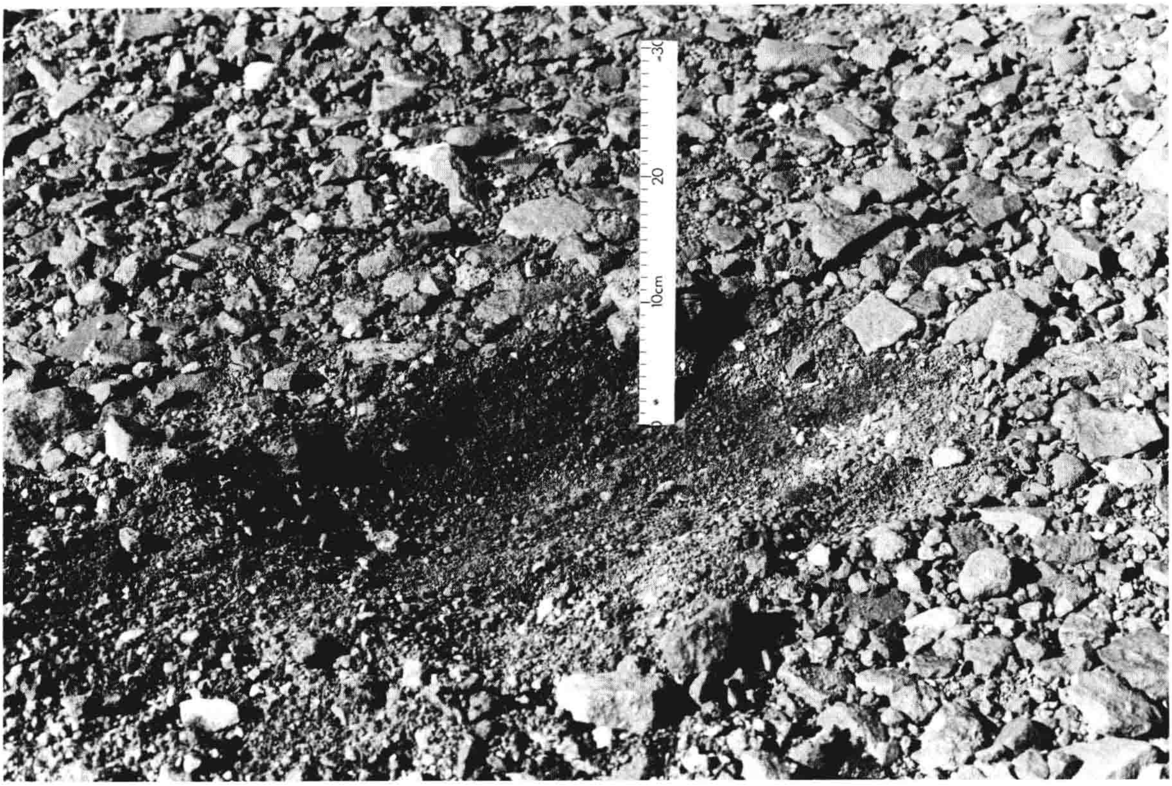
The alteration of rock by weathering occurs in place, that is *in situ*, and it does not directly involve removal processes. It may be characterised by the physical breakdown of rock material into progressively smaller fragments without marked changes in the nature of the mineral constituents. This disintegration process leads to the formation of a residual material comprising mineral and rock fragments virtually unchanged from the original rock (Plate 2.1). By contrast chemical alteration may induce thorough decomposition of most or all of the original minerals in a rock, resulting in the formation of material composed entirely of new mineral species, particularly of clay minerals (Plate 2.2). Biological weathering induced by biophysical and biochemical agencies is largely confined to the upper few metres of the earth's crust in which plant roots are active.

It must be appreciated that physical, chemical, and biological processes usually operate together. Also erosion takes place from the surface of the ground and within the soil by solution almost continuously so that, although we speak of weathering as a process of decomposition *in situ*, transport of the residuum of weathering may be simultaneous and assists in the continuation of weathering.

Soil

The end-product of weathering is said to be soil, but this statement can be confusing for the word 'soil' is used in at least two senses. For the soil scientist (pedologist) soil is a material which results from both weathering and soil-forming processes and it is the material in which plants grow: weathering alone will not produce the horizons (layers) which are the fundamental features of soils in this plant-related sense.

To the engineer, by contrast, soil is a broken-down rock material of relatively low strength and he commonly uses the term 'soil' to include low strength materials, such as clay-rich sedimentary rocks and unlithified sands, which have not been altered by soil-forming processes and which may not have been weathered since exposure at the ground surface. The engineer usually wishes to dispose of that organic soil which is the focus of the soil scientist's concern and he usually removes it from any excavation or work site before placing a structure on the ground. Geologists usually use the term 'regolith' to refer to the whole profile of weathered rock and unconsolidated rock material of whatever origin: it thus corresponds to all that material comprising the weathering zone together with unconsolidated superficial deposits. This definition is close to the usage of 'soil' in engineering and soil mechanics.



2.1 A residual soil, derived from glacial moraine, in which there has been little or no chemical weathering and hence no clay mineral formation, Antarctica.

Factors affecting soil weathering

Few generalisations can be made about the rate of weathering of minerals because of the numerous factors which can influence the process. However, climate and the physical and chemical composition of the parent rock are of outstanding significance.

Climatic influences

Climatic conditions determine the temperature and moisture regime in which weathering takes place. Under conditions of low rainfall, mechanical weathering is dominant and, therefore, comminution of particles occurs, with little alteration of their composition. With an increase in precipitation, more minerals are dissolved and chemical reactions increase so that chemical decomposition of minerals and synthesis of clays becomes more important. In humid temperate climates silicate clays are formed and altered. Speed of chemical reactions is greatly increased by a rise of temperature: a rise of 10 °C usually doubles or trebles the reaction rate. Increases of temperature also alter the relative mobility of minerals. Quartz, for example, is highly resistant to weathering in temperate climates, but fine-grained quartz particles are more easily weathered in tropical conditions, and in such climates iron and aluminium hydrous oxides are more resistant. The iron and aluminium oxides, therefore, tend to accumulate in tropical soils which get their red colour from the iron.

Another effect of climate is to control the vegetation and its production of litter. In humid tropical climates the production of organic matter is high – 3 300 to 13 500 kg/ha per year from tropical forests – compared with temperate forests that produce 900 to 3 100 kg/ha per year. This means that the supply of organic compounds to take part in chemical weathering is high in the tropical forests and low in the temperate ones. The appearance of the soils of these forests suggests the reverse because dark humus can accumulate in the

2.2 A soil with high kaolinite content formed on a sandstone. The presence of clay minerals is indicated by the shrinkage from drying of the upper part of the profile. The lower part of the profile is still moist.

cool forests but in the tropical ones organic matter is broken down very rapidly and much of the humus has a pale colour which makes it difficult to see. The turnover of tropical forest humus is about 1 per cent per day compared with 0.1 to 0.3 per cent in temperate forests.

The significance of climate has prompted the idea of weathering regions which approximately correspond to the distribution of major zonal soil groups (Figure. 2.1). This type of generalization is a useful model but it has to be qualified. Variations in soil type and weathering rates and depths depend not only upon differences in the kind of processes prevailing in climatic zones, but also upon the intensity of those processes. Broad schemes also have to be modified because they apply only to tectonically stable areas with adequate drainage. Uplands and depressions give rise to distinctive erosional and depositional processes which may mask zonal weathering processes. A further qualification is that zonal processes have been modified by climatic changes in large areas of the earth so that, although modern processes are occurring under modern climates, there may be relict weathering products in many areas derived from earlier climatic regimes.

In spite of these reservations we can detect areas of very thin weathering profiles in polar and desert zones where the absence of water and plants produces low weathering rates; intermediate rates occur in the temperate latitudes, and high rates in the humid tropics where weathering profiles are commonly