Geomorphology and Climate

Edited by Edward Derbyshire

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Edward Derbyshire
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Preface

Despite its impressive bulk, the literature concerned with the manner and extent of variations in specific landforms or suites of landforms with climate leaves largely undefined the essential nature of the relationship. The traditional approaches to the subject, embodied in the terms climatic geomorphology and climato-genetic geomorphology, have been concerned either with the establishment of climatic-morphological regions by deductive/inductive reasoning using gross climatic parameters, or, on the premise that landform contrasts due to climatic differences become evident only on a broad scale, the presentation on a world map of regional groupings of distinctive morphological character arising either directly from climate or indirectly through the media of vegetation and soils. These approaches to the problem reached their acme in the period 1950–1965. It is to be doubted whether they can usefully be taken any further at present, as their generalizations rest on quite loosely defined ideas on the process relations linking climatic regime and geomorphic form. Further progress in climatic geomorphology will depend directly on the degree of success achieved in defining this fundamental relationship. This will involve an increasing use of instrumentation to monitor both geomorphological and appropriate climatic parameters, the design of specific and long-term experiments and the use of multivariate statistical methods. It is the purpose of this volume to attempt a statement of current practice and thinking on this central issue of climatic geomorphology by means of extended technical essays by fifteen authors coming from Europe, Australia and North America The essays exemplify both practical and theoretical approaches. In presenting their own distinctive analysis of the process–form relationship problem, the authors direct attention to some of the outstanding questions and suggest means by which they may be answered.

Contents

Chapter One — **Geomorphology and climate: background**
EDWARD DERBYSHIRE .. **1**
1.1 Introduction .. 1
1.2 The zonal concept .. 2
1.3 Spatial and temporal scales of variation in processes and landforms .. 3
1.4 Climatic data .. 16
1.5 Conclusion .. 17

Chapter Two — **Chemistry of rock weathering: fundamental reactions and controls**
CHARLES D. CURTIS .. **25**
2.1 Introduction .. 25
2.2 Chemical reactions .. 31
2.3 Thermodynamics and kinetics: quantification 37
2.4 Solids: a simple approach .. 45
2.5 Chemical formulation of weathering reactions 47
2.6 Conclusion .. 56

Chapter Three — **Rock weathering and climate: quantitative and experimental aspects**
STEPHEN T. TRUDGILL .. **59**
3.1 Introduction .. 59
3.2 Leaching sysems .. 61
3.3 Surface systems .. 82
3.4 Climate as a factor .. 89

Chapter Four — **Mass-wasting, slope development and climate**
MICHAEL A. CARSON .. **101**
4.1 Varieties of mass-movement .. 101
4.2 Mechanisms of mass-movement .. 110
4.3 Characteristic and threshold angles of slopes in non-cohesive material .. 119
4.4 Models of slope profile development by mass-movement .. 124
4.5 Mass-movement and climate .. 128

Chapter Five — **Catenas in different climates**
CLIFFORD D. OLLIER .. **137**
5.1 Case studies of soils and slopes 137
5.2 Soil and slope elements 149
5.3 Some models of slope evolution in relation to soils 152
5.4 Asymmetrical valleys and soil distribution .. 158
5.5 Some principles of methodology 162
5.6 Summary of soil–slope relationships 165
5.7 Conclusion 166

Chapter Six — **Valley-side slopes and climate**
BARBARA A. KENNEDY .. **171**
6.1 Introduction 171
6.2 Two contrasting studies 173
6.3 The vexed question of asymmetrical valleys .. 180
6.4 Conclusion 199

Chapter Seven — **The role of extreme (catastrophic) meteorological events in contemporary evolution of slopes**
LESZEK STARKEL .. **203**
7.1 Introduction 203
7.2 Types of extreme meteorological phenomena and the associated processes 213
7.3 Comparison of the role of extreme processes in various zones 232
7.4 The role of extremes in the maturation or rejuvenation of slopes 237
7.5 Relation of extreme phenomena to climatic changes 240
7.6 Final remarks 241

Chapter Eight — **Hydrological slope models: the influence of climate**
MICHAEL J. KIRKBY .. **247**
8.1 Introduction 247
8.2 The hydrological budgeting model 249
8.3 The sediment transport model 252
8.4 Simulation procedure 253
8.5 Simulation results 254
8.6 Approximate analytical model 261
8.7 Conclusions 266

Chapter Nine — **Erosion rates and climate: geomorphological implications**
IAN DOUGLAS .. **269**
9.1 Introduction 269

9.2 Aspects of climate of geomorphic significance 270
9.3 Hydrometeorological approaches to erosion 278
9.4 Hydrometeorological variables and sediment yield 279
9.5 Scale and erosion rates 282
9.6 Problems in assessing erosion rates for geomorphological studies 283

Chapter Ten **Drainage networks and climate**
Kenneth J. Gregory **289**
10.1 Introduction 289
10.2 World variation 291
10.3 Variation within morphoclimatic zones 300
10.4 Drainage network changes 307
10.5 Conclusión 310

Chapter Eleven **The role of climate in the denudation system: a case study from West Malaysia**
Royston P. C. Morgan **319**
11.1 Introduction 319
11.2 Framework of study 319
11.3 Procedure 321
11.4 Results of the analysis 329
11.5 Interpretation 329
11.6 Morphogenetic regions 337
11.7 Evaluation.. 340

Chapter Twelve **Lithology, landforms and climate**
Ian Douglas **345**
12.1 Introduction 345
12.2 Theoretical aspects of the stability of rock materials in relation to climate 346
12.3 Concept of ultimate landforms in response to denudation 350
12.4 Implications of structure.. 353
12.5 Experimental designs to test the theories of climatic geomorphology 354
12.6 Examples of sandstone, schist and basaltic landforms in different climates 356
12.7 Climate, time, lithology and landform 361

Chapter Thirteen **Process, landforms and climate in limestone regions**
David I. Smith and Timothy C. Atkinson **367**
13.1 Introduction 367
13.2 Erosion processes and their measurement .. 368

13.3 Erosion rates, water hardness and climate .. 373
13.4 The distribution of erosion in the landscape 388
13.5 Limestone landforms, landscapes and climate 390
13.6 Morphometric analysis of limestone landscapes 395
13.7 Conclusions 407

Chapter Fourteen **Criteria for the recognition of climatically induced variations in granite landforms**
MICHAEL F. THOMAS **411**
14.1 Introduction 411
14.2 The nature of granite and granitoid rocks .. 412
14.3 Some structural features of granitoid rocks .. 413
14.4 The alteration of granites 415
14.5 Regolith characteristics and climate 417
14.6 The landforms of granitoid rocks 426
14.7 Conclusions 440

Chapter Fifteen **The climatic factor in cirque variation**
EDWARD DERBYSHIRE AND IAN S. EVANS **447**
15.1 Introduction 447
15.2 Climate and glacier distribution.. 448
15.3 Climate and cirque aspect 456
15.4 Climate and cirque altitude 460
15.5 Climates within cirques 463
15.6 Cirque development 465
15.7 Climate and cirque form 473
15.8 Conclusion 488

Index 495

CHAPTER ONE

Geomorphology and Climate: Background

EDWARD DERBYSHIRE

1.1 Introduction

The central concern of climatic geomorphology is the extent to which variations in the elements of climate, notably solar energy and moisture, are reflected in geomorphic processes to produce distinctive suites of landforms. The narrow view of the subject matter of climatic geomorphology, which arises from undue emphasis on the continental European tradition stressing global regionalization and broad qualitative associations of landforms and climate, is likely to minimize its methodological significance (Morgan, 1970). On the other hand, the broadest views of the subject, equating it with the greater part of dynamic and historical geomorphology (glacial, periglacial, arid and fluvial geomorphology of both current and Pleistocene landscapes) may leave the subject so loosely defined that its identity becomes lost, again leading to an underestimation of its potential significance (e.g. Clayton, 1971).

The mainstream of literature in climatic geomorphology (Stoddart, 1969; Rohdenburg, 1971; Rathjens, 1971; Derbyshire, 1973) has been dominated by two great methodological traditions: first, the application of the concept of zonality based essentially on climatological and ecological principles and, second, the inductive definition of climate–process provinces based on assumed general relationships between the efficacy of selected geomorphic processes and standard climatic means.

1.2 The zonal concept

On a global scale, variations in characteristics of the atmosphere–lithosphere interface may be described as zonal, in that they conform to the broad zonation of solar-derived energy and water availability from equator to poles. A notably early attempt to quantify relationships of this kind was Humboldt's study of vertical zonation of temperature in mountain areas in 1817. While work at this time was preoccupied with temperature zonation, some workers (including Dove in 1846 and Linsser in the late 1860s) recognized the moisture factor as paramount in the definition of some climates.

The stimulus to these developments in climatological study was the need to understand the nature of plant growth and plant distribution. With the exception of xerophiles, the physiological classification of vegetation by de Candolle, dating from 1874, is based on temperature tolerance limits which can be directly related to the major thermal zones of the earth set out by Supan in 1879. Wladimir Köppen's map of 1884, which included considerations of seasonality, was a direct stimulus to the mapping of zonal vegetation. Both Drude and Schimper in the last decade of the nineteenth century recognized the great zonal vegetation associations of the world on a physiognomic basis, zoned according to both moisture and temperature gradients. Thus, the best known classification of world climates (Köppen, 1923) is essentially phytogeographical and based on de Candolle's thermal zones.

The phytogeographically-based climatic classifications can be compared with the concept of zonal soils, made up of great soil groups (Dokuchaev; see Glinka (1915) and Marbut (1928, 1935)), the terminology of which is partly phytophysiognomic and partly pedological. The relationship of soil bodies to mean climate, acting through natural vegetation, is a strong one at the continental and global scales. The zonal soil groups, with their intrazonal variations, are conceptually similar to Clements's (1936) climatic climax of the zonal vegetation formations and their edaphic or physiographic sub-climaxes (Tansley, 1929 and 1935) respectively. However, just as the development of phytosociological methods (Whittaker, 1953; Poore, 1955–56; Becking, 1957; Odum, 1964) has underlined the inadequacy of Clements's view of the association for dynamic study of plant communities at the field and regional scales (Pears, 1968), so the concept of zonal soils is not a practical tool in field soil classification. The dependence of a zonal classification, however refined, on the relative importance of processes assumed to have produced the soils inhibits its practical application. The view of many field pedologists on this question is expressed by Leeper (1964, pp. 21–22) in the following words:

> The textbook, orthodox classification of Northern Hemisphere writers is along different lines. They do not consciously list the properties of profiles ... in order to find a self-consistent answer. On the contrary, they already know the answer, whether by intuition or by copying an earlier worker who must have been similarly inspired. A product of such a grouping is the 'chernozem', which is a soil of the following properties ... But the chernozem is also *defined* as belonging to perennial grassland under a continental climate with very cold winters, warm and moist summers, and about 18 inches of precipitation annually. If it is found in a different climate we are not allowed to call it a chernozem, however many features of the profile there may be in common. Clearly, the naming of a soil has here been confused with naming a geographical region; and the geographer's attempt to draw boundaries around what he regards as a natural region is notoriously a matter for individual decision.

There is abundant evidence that many soils of the world contain relic elements in their profiles (Morrison and Wright, 1967; Yaalon, 1971; cf. Ollier, Chapter 5) arising from the time lag in the response of pedogenic processes to environmental changes, notably those affecting climatic–edaphic–vegetation relationships. Accordingly, soil classification is being based increasingly on the properties of the soils in the field (Leeper, 1956; Northcote, 1960), the basic unit varying from the modal soil (Kubiëna, 1953) to the soil series or polypedon

(US Department of Agriculture 1960), although some fundamental deficiencies of the USDA system have been set out by Webster (1968).

Conceptually, the present condition of climatic geomorphology appears in many ways comparable to the state of climatic classification in the early years of this century, the Anglo-American school of phytogeography in the 1930s and soil science before 1950. The great syntheses of climatic geomorphology represented by the work of Julius Büdel (notably his 1948 and 1963 papers) and Tricart and Cailleux (1965, 1972) are monoclimactic in concept and global in scale. Criteria, as with the early climatic and vegetation classifications, are mixed. Büdel maps landform assemblages partly on climatic criteria. In its emphasis on the importance of the role of vegetation and in the extended treatment accorded to vertical zonation, or *étagement* (cf. Büdel (1968) and Derruau (1968); for developments of this idea at different scales, see, for example, Bik (1967), Grishankov (1973), Kotarba and Starkel (1972), Hastenrath and Wilkinson (1973) and Morariu and Mac (1974)), the classification of Tricart and Cailleux is rather more sophisticated. Inevitably, however, it is dependent on several non-morphological criteria. Like the obsolete soil classifications of Marbut (1928, 1935) and Robinson (1949), the bases of the mapped entities are processes, and factors assumed to control them, rather than the nature of the entities themselves. Moreover, just as the classifications designed to represent vegetation associations and soil groups at the continental scale break down at the regional and field scales, so too do those of climatically-grouped landform suites. Thus, in the present state of knowledge of geomorphological dynamics, especially in the humid and wet–dry tropics (Tricart, 1972; Thomas, 1974), the scale factor is a major constraint on the application of the principle of zonality. In cryonival regimes, despite the wealth of distinctive microforms and associated sedimentary structures which appear to show a notable degree of sensitivity to, and a relatively simple dependence upon, the temperature climate (Poser, 1948; Tricart, 1963 and 1969; Tricart and Cailleux 1965 and 1972), the wide range of process environments and the variability of the process balance is evident from several major reviews published in recent years (Troll, 1958; Embleton and King, 1975; Péwé, 1969; Washburn, 1973; Ives and Barry, 1974). Even in glaciated regions, the determination of climate as a factor in variation in the most common and typical landforms such as cirques is a problem of some considerable complexity (Chapter 15).

1.3 Spatial and temporal scales of variation in processes and landforms

While climatic geomorphology may have reached a stage in its development when the 'moribund nature of classification' (Hare, 1973) should be admitted, it is justifiable to view as useful existing landform classifications based on the intrinsic properties of landforms (Passarge, 1926) together with the dominant processes responsible for their formation (Rathjens, 1971). As the most satisfactory maps of climate, vegetation and soils have such a basis, landform maps used to test the strength of the climatic factor in morphogenesis should use landform criteria. To employ climatic–geomorphic or pedological–biogeographical criteria is, at least in part, to beg the question.

In a review of geomorphological mapping, Tricart (1965) described maps on a scale of 1:500,000 or greater as essentially morphostructural, climatically specific landforms being lost because of generalization (cf. Büdel (1948) and Murphy (1968, 1971). At scales between 1:500,000 and 1:5,000, structure can be regarded as given. These maps display one or more of the following data types: morphometric, morphographic (e.g. degree-of-slope maps), morphogenetic (incorporating laboratory results etc.) and chronological. While regional morphogenetic maps of phenomena produced under a single, distinctive morphoclimatic regime (e.g. fluvial (Pels, 1964); glacial (Derbyshire and coworkers, 1965); periglacial (Kaiser, 1960); arid (Grove, 1958; Grove and Warren, 1968)) or maps attempting a more comprehensive coverage of forms (Tricart, 1965; Tricart and Vogt, 1967; Brown and Crofts, 1973) may be of considerable interest in terms of climatogenetic geomorphology, morphometry is potentially of greater interest to geomorphologists seeking to define the influence of climate upon current landform change. Despite the suggestive results of Peltier's (1962) objectively derived data on mean relief, mean slope and mean number of drainageways per unit distance to differentiate glacial and tropical landscapes from others in terms of number/slope relationships, applications of the method remain rare and the deficiency is recognized by Smith and Atkinson (Chapter 13) as a major one in the study of limestone landscapes. At the regional scale, application of this method to slope gradients holds promise as a means of determining the role of climate in landform, as Melton (1960) and Kennedy (Kennedy and Melton, 1972) have shown, although the process links remain inferential (Kennedy, Chapter 6).

Over the past quarter of a century, the treatment of spatial geomorphic data has evolved from the representation of elements such as slope facets (Waters, 1958; Savigear, 1965) as 'a specialised form of topographical mapping' (Tricart, 1965), to a coherent form of background data for analysis of specific problems, both pure (e.g. Brunsden and Jones (1972) and Derbyshire and coworkers (1975)) and applied (e.g. Dearman and Fookes (1974) and Brunsden and coworkers (1975)). The range of spatial analytical techniques now appears to be widening rapidly (Chorley, 1972) and may well redress an imbalance particularly evident in British research work between process geomorphology and areal geomorphology (Mather, 1972). While this group of techniques has obvious relevance to climatic–geomorphic problems (Evans, 1972; see also Chapter 15), the extent to which the results are intellectually satisfying will depend on the confidence with which the climate–process–form links underlying them can be elucidated. For this purpose, climatic geomorphology can be regarded as a specialized branch of process geomorphology as well as a generalized extension of it (Büdel, 1963).

Recent work on slopes and slope processes exemplifies the general trend towards systematic measurement of component variables in geomorphic research. In reviewing the literature on rates of slope retreat, Young (1974) presents figures on rates of soil creep, solifluction, surface wash, solution and landsliding under different climates. Surface wash appears to be the dominant process in savanna and semi-arid climates, but it is exceeded in importance by creep in humid temperate lands while under rainforest both are rapid. Solution is important in all humid climates, but the precise quantitative significance of solifluction, both in present and former periglacial climates, has not been determined. While slopes which suffer catastrophic denudation appear to be affected most by events with a recurrence interval of 10–50 years, there is little information on the relative importance of catastrophic and continuous processes in slope retreat. This, together with a general dearth of studies designed to establish the relationship between form and process in the light of soil mechanics principles, constitutes a major obstacle to the establishment of the role of climate in slope evolution (Carson, Chapter 4). Change of slope form and gradient with time constitutes a particularly challenging problem to the climatic geomorphologist because climate acts largely through ground hydrology which itself varies widely with bedrock type and the nature of the regolith (Kennedy, Chapter 6), especially in its degree of weathering as it affects porosity (Carson and Kirkby, 1971; Kirkby, 1973). Hydrological slope models underline the inadequacies of the present state of knowledge of the relationship of climate (evapotranspiration) to soil water storage acting through the vegetation cover (Kirkby, Chapter 8).

Detailed work on weathered mantles provides ample demonstration of the inadequacy of the evidence of form alone as a basis for testing the central relationship of climatic geomorphology (Ollier, Chapter 5; Thomas, Chapter 14). Following a study of periodic morphogenetic features of postglacial age in a savanna landscape in Papua, Mabbutt and Scott (1966), for example, concluded that a uniformitarian, monogenetic explanation of landforms and their associated soils was inadequate, even in low latitudes, and that morphogenetic systems erected on broad landscape traits are suspect because changes in stability, process and pedogenesis demand detailed field study of slopes and correlative deposits (cf. Louis's (1973) review).

It was suggested long ago (de Martonne, 1913) that the forms of fluvial erosion are sensitive indicators of variations in certain climatic elements, although four decades elapsed before the first attempts were made to test this contention quantitatively. Chorley (1957) found a direct relationship between drainage density and amount and intensity of precipitation and, using a comparative regional approach (Chorley and Morgan, 1962) explained differences in terms of variations in runoff intensities produced by varying rainfall amounts and differences in relief. At the same time, Melton (1957) explained most of the variation in drainage density in the southwestern United States in terms of one direct climatic variable (rainfall intensity) and two indirect climatic variables (percentage of bare surface area and infiltration), although it was recognized that the influence of particular rock types on the latter variable might be considerable. There is some evidence to suggest that permeable and impermeable rocks behave as two distinct sub-populations within a single climatic region and are responsible for the detailed variation of the spatial pattern produced by the climate, notably the precipitation/evaporation balance (Gregory, Chapter 10).

Traditional climatic and climatogenetic geomorphology, in its emphasis on landform classification in global zones defined climatically, biotically or in terms of types and rates of geomorphic processes (Strahkov, 1967), has produced a result of considerable geographical and palaeoclimatic interest: landforms and their correlative deposits constitute the essential underpinning of much Pleistocene climatic reconstruction, both static and dynamic (e.g. Poser (1948), Büdel (1959), Butzer (1957, 1958, 1963, 1971), Barry (1960), Pels (1966), Butler and coworkers (1973), Lamb and Woodroffe (1970), Derbyshire (1971, 1972); and Andrews and coworkers (1972)). However, morphological regionalization has contributed little of the kind of information required to test the strength of the relationship between macroclimatic and mesoclimatic parameters and landform assemblages. Much recent work in this field has been directed toward resource appraisal so that regions have been defined on phytological and pedological as well as geomorphological criteria (e.g. Kondracki and Richling (1972); for critique, see Speight (1974)). Nevertheless, there are signs of a movement towards areal mapping based on long-term field measurement and using a framework of systems theory as a means of establishing geosystems (Gvozdetskiy and coworkers, 1971) as a basis for the synthetic establishment of areal climatogenetic units.

Hare (1973) has recently shown that climatology has emerged from a stage of development similar to that of traditional climatic geomorphology to enter one based on the understanding of climate and climatic variation in terms of energy and moisture balances. The reluctance of geomorphologists to move in the same direction is explained in terms of the length of the geomorphic time-scale and the magnitude–frequency relationship (Wolman and Miller, 1960) which encourages the employment of stochastic methods rather than those based on energy considerations. The energy–moisture balance approach appears to be particularly appropriate to climate–weathering–soil–plant relationships. While the factors and processes of rock weathering are now known in some detail (e.g. Keller, 1957), fundamental principles, such as those affecting the thermodynamic and kinetic stability of rock and regolith components (Curtis, Chapter 2), have not been applied in the investigation of specific surface and soils studies (cf. Ollier; Chapter 5). It is important to recognize that the study of biological factors in rock weathering is also in a rather retarded state (Ivashov, 1973).

An outline of the potential of general systems theory in geomorphological research has been given by Chorley and Kennedy (1971) and its potential in model building indicated in some detail by Chorley (1967, 1971, 1972). The development of this approach has been very uneven and it is particularly poorly developed in climatic geomorphology. Attempts to use hardware models with a specific climatic–geomorphic framework (e.g. Gavrilović (1972)) are quite rare. This is true of process–response models (Kirkby, 1971 and 1973), despite early initiatives in the use of mathematical models in the study of slope degradation (Scheidegger, 1961) and the evolution of drainage networks (Leopold and Langbein, 1962) and the general increase in the use of numerical methods in geomorphology (Chorley, 1966; Doornkamp and King, 1971), although the potential of the approach in examining climate–landform relationships is evident enough from the contributions of Trudgill (Chapter 3) and Kirkby (Chapter 8).

A particular problem is provided by the range in relaxation times within and between geomorphic systems (Allen, 1974) in comparison with those, say, in soil systems. Response to the climatically-stimulated extreme event, such as prolonged intense rainfall on hillslopes, the once in a century flood, a glacier surge or a succession of extended but milder winters in middle latitude mountains, may be immediate and the period between such events dominated by slow processes of modification (Starkel, Chapter 7). Variations in magnitude and frequency of specific meteorological or climatic events may result in a composite of forms expressing a spatial and temporal hierarchy (Douglas, Chapter 12). This was noted by Rapp (1960) in his classic study of current mass movements in northern Sweden. As a quantitative, long-term study of a dynamic landsurface in relation to meteorological variations, this work remains unique, although the approach has been applied in a more limited and localized way from time to time. For example, in the case of basally-eroded shale cliffs in east Devon, England, a long-term programme of mapping and analysis of related surface variables (slopes, soils, vegetation) has established that a condition of approximate balance exists between wave removal and replacement by shallow sliding, creep and small-scale rotational shear slide. Age and species composition of the vegetation on the cliff-face provide critical evidence of periodicity and rates of movement (Derbyshire and coworkers, 1975). Shallow sliding and small-scale rotational shears occur on a time scale of 1–3 years and correlate with high tides and severe easterly winds. Extreme storm events (high tides with easterly winds and heavy rainfall lasting several days) may produce excessive removal and oversteepening of the lower cliff such that large-scale shear slides are triggered. In this case, the cliff profile becomes composite: the rough balance between removal and supply of debris is re-established on the lower cliff while on the middle cliff occasional sliding and creep produce accumulation and partial stabilization by vegetation ensues. The time-scale in this case appears to be of the order of 30 years (Figure 1.1). In addition, sections of the cliff show evidence of having moved by shear sliding on an even larger scale. While there is no reliable evidence with which to date this order of movement, there is no known reference to them in the written record so that the time-scale involved may be of the order of some hundreds of years. Rates of movement for both bare and vegetated parts of the cliff, compounded of movements of the first and second order, suggest an average rate for retreat of the cliff top of 0·63 m/yr with a maximum of 1·03 m/yr, most of the surficial cliff debris and its vegetation mat being *in transit* under prevailing extreme conditions of climate and tide. Thus, the cliff illustrates