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A climatic classification for geomorphological purposes
Classification des climats selon une approche géomorphologique
Eine Klimaklassifikation für geomorphologische Belange.

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Résumé de l'article

On remet ici en question la délimitation de zones morpho-climatiques jusqu'ici purement descriptive. On exclut de la classification les zones sub-glaciaires, les régions de montagnes qui sont azonales et les régions désertiques liés au relief. On peut alors distinguer six zones fondamentalement différentes et toutes caractérisées par une morphodynamique récente particulière. Elles sont définies par des types de processus et de formes typiques et séparées entre elles par des valeurs limites d'ordre météorologique. 1. La zone subpolaire de gélifluxion et de débris cryoclastiques. 2. La zone tempérée d'action modicofluviale et de formes reliques. 3. La zone subtropicale de ruissellement et de torrents. 4. La zone paratropicale d'action éolienne et de regs. 5. La zone tropicale d'aplanissement et d'inselbergs. 6. La zone équatoriale de glissements et de vallées.

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A CLIMATIC CLASSIFICATION FOR GEOMORPHOLOGICAL PURPOSES

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ABSTRACT In this paper we reconsider the definition of climatic geomorphological zones, which until now has been merely descriptive. By excluding the subglacial zone, azonal mountain regions and adibiatic deserts, it is possible to recognize six zones which are essentially different and characterized by specific types of morphogenesis. Each is categorized according to typical processes and landforms and delineated by means of meteorological threshold values: 1. The subpolar zone of solifluction and frost-shattered debris. 2. The moderate zone of modicofluvial action and relict forms. 3. The subtropical zone of slope wash and seasonal rivers. 4. The paratropical zone of eolian action and dry debris. 5. The tropical zone of sheet wash and inselbergs. 6. The innertropical zone of landsliding and valleys.

RÉSUMÉ *Classification des climats selon une approche géomorphologique.* On remet ici en question la délimitation de zones morpho-climatiques jusqu'ici purement descriptive. On exclut de la classification les zones sub-glaciaires, les régions de montagnes qui sont azonales et les régions désertiques liés au relief. On peut alors distinguer six zones fondamentalement différentes et toutes caractérisées par une morphodynamique récente particulière. Elles sont définies par des types de processus et de formes typiques et séparées entre elles par des valeurs limites d'ordre météorologique. 1. La zone subpolaire de gélifluxion et de débris cryoclastiques. 2. La zone tempérée d'action modicofluviale et de formes reliques. 3. La zone subtropicale de ruissellement et de torrents. 4. La zone paratropicale d'action éolienne et de regs. 5. La zone tropicale d'aplanissement et d'inselbergs. 6. La zone équatoriale de glissements et de vallées.

ZUSAMMENFASSUNG *Eine Klimaklassifikation für geomorphologische Belange.* Die bisher rein deskriptive Abgrenzung klimageomorphologischer Zonen wurde neu überdacht. Unter Ausgliederung der subglazialen Zone, der azonalen Gebirgsareale sowie der durch sie verursachten Reliefwüstengebiete sind sechs prinzipiell unterschiedliche Zonen rezenter Morphodynamik auszuscheiden, durch eine Auswahl typischer Formen und Prozesse zu kennzeichnen und durch meteorologische Schwellenwerte voneinander zu trennen: 1. Die subpolare Solifluktions — und Frostschuttzone. 2. Die gemässigte Modicofluvial — und Reliktformenzone. 3. Die subtropische Hangspülungs — und Torrentenzone. 4. Die randtropische Äol — und Trockenschuttzone. 5. Die tropische Flächenspül — und Inselbergzone. 6. Die innertropische Rutschungs — und Tälerzone.

INTRODUCTION

The idea of dividing the globe into morphoclimatic zones originates with BÜDEL (1950), who emphasized landforms and processes, and TRICART and CAILLEUX (1955), who used an approach based on vegetation and its geomorphological effects in the different zones (Fig. 1). The French classification was a brilliant achievement at the time, but remained undeveloped. Büdel, on the other hand, devoted 30 years to an elaboration of his classification, and as a result it is logically developed and accurate in detail (BÜDEL, 1977). His system incorporates the effect of atmospheric circulation patterns on landforms and processes; however, his map lacks a clear separation of the azonal regions (Fig. 2).

HAGEDORN and POSER (1974) emphasized the importance of present-day geomorphologic processes thus skirting the issue of classifying relict landforms inconsistent with present climatic conditions. Since their system is based on regional geography, it lacks sufficient generalization to the global scale (Fig. 3).

WILHELMY'S classification (1974) should also be included in this discussion, since it was significant to German climatic geomorphology (Fig. 4). His names for the zones, however, are an inconsequent mixture of climatological, biogeographical or geomorphological terminology, and his map offers only minor advantages over that of TRICART and CAILLEUX (1955).

THE NEW CLASSIFICATION

The definition of climatic geomorphology zones, which until now has been merely descriptive, has been re-examined in my thesis (BEYER, 1978) (Fig. 5). Büdel's system provided basic theoretical material, and the treatment of the subject by Hagedorn and Poser contributed to the development of a process-oriented approach. In the final analysis, morphoclimatic zones were determined by the natural divisions resulting from atmospheric circulation patterns. The system of seven belts of differing morphological processes corresponds roughly to Flohn's system based on the climatic influence of four major pressure belts with "steady" climates and three adjacent belts with "alternating" climates (FLOHN, 1950).

The postulation of a causal link between climatic classifications and climatic geomorphology, along with an associated definition of zones according to specific threshold values which are easily obtained and globally applicable, give us *a climatic classification system useful for geomorphological purposes*. Although it is an "effective" classification, it also contains significant "genetic" elements (BLÜTHGEN, 1964). A further innovation is the geomorphological orientation, using the factors of climate, principal morphodynamic processes, and typical recent land forms to denominate the zones in a homogeneous form.

Some areas are exceptions. For example, the polar ice caps inhibit direct atmospheric action in land surface formation. However, this factor is dealt with via creation of a subglacial zone. The zone limit in the direction of the equator is the extent of permanent ice cover and is defined by the 0°C-isotherm for the warmest month.

Mountain regions, which are azonal in their areal distribution, should also be excluded; the hypsometrical change in landforms is very important in this case. Since adibiatic deserts owe their formation exclusively to surrounding mountains and are not situated at a distinct latitude, they should be placed in a separate category.

Allowing for these exceptions, we are left with six zones of differing recent morphodynamic activity. The areal distribution is given for each, followed by an analysis of typical landforms and processes. Finally, the limits of the zones are defined according to meteorological threshold values.

1. THE SUBPOLAR ZONE OF SOLIFLUCTION AND FROST-SHATTERED DEBRIS

AREAL DISTRIBUTION

This zone includes northern Canada; Alaska; coastal regions of Greenland; the extreme northeastern parts of Europe; and the whole of Siberia.

CHARACTERISTIC LANDFORMS AND PROCESSES

One of the most striking features of this zone is the cover of debris ranging in size from small fragments to large blocks. Genesis is attributed to an efficient mechanical weathering caused by the expansion of water as it freezes in rock cracks.

In general, the smaller fragments are characteristically sorted to form various kinds of frost-patterned ground. The freeze-thaw cycle, with its associated changes in volume, causes the coarser material to migrate slowly to the surface.

Because frost-patterned ground is formed by periodic, morphologically efficient ground frost, this type of landform is more highly developed in regions of permafrost.

The solifluction process is very common and enhanced by ground frost. During the summer, surface ice melts and infiltration of the water is prevented by the permafrost layer. Soils above the permafrost layer become saturated with water.

Valleys have broad, debris-covered bottoms. During the cold season, when water is scarce, the bedrock is shattered by frost and loosened, creating favourable conditions for erosion due to the sudden high volume of water during snow melt ("ice-rind effect", BÜdel, 1969).

Many of the phenomena occuring in adjacent regions with tundra vegetation are similar to those in regions without vegetation cover. Nevertheless, frost action remains the principal factor and some landforms, such as pingos, are due to the existence of permafrost.

In considering typical zonal landforms and processes, it is not advisable to introduce a separate subpolar zone with tundra vegetation which would be of equivalent importance to the other six zones. However, its classification as a sub-zone within the subpolar region, characterized by weaker morphodynamic processes, is reasonable and a practical solution.

A final note should be made on the landforms in areas of retreating permafrost (CAILLEUX, 1971), particularly those caused by solitabetion[1]. They should be used as criteria of zone definition only if they are caused by recently-occurring cyclic processes which are not due to a major change in climate.

METEOROLOGICAL THRESHOLD VALUES

The above description of landforms and processes has clearly shown that the freezing point is of particular significance; the freezing and thawing of water has many important consequences for landform genesis. Various effects are of particular note. For one thing, the oscillation of temperatures around the freezing point is of primary significance. Frequency of freezing and thawing, together with time, are the decisive factors in the widespread shattering so typical of periglacial regions; the formation of patterned ground is also substantially affected by this frequency factor.

The frequency of freeze-thaw cycles is dependent on microclimatic conditions, since frost must occur frequently enough and penetrate deeply enough to be morphologically effective. Therefore the appropriate meteorological threshold value will be an approximation based on some relationship such as that between the number of morphodynamically effective frost cycles and standard air temperature measurements. The maximum number of effective cycles occurs when the annual mean temperature is between 0°C and −2°C (HEYER, 1938).

As mentioned previously, the presence of permafrost is considered the second most important element. Since indices become unwieldy and inaccurate when all significant factors have been integrated, an exact definition of permafrost using a meteorological threshold value is not possible. For these reasons, the definition of limits based on an annual isotherm is preferable and corresponds closely to the outer limit of discontinuous permafrost in the direction of the equator. The annual isotherm of −1°C is generally accepted for this purpose.

The annual isotherm of −1°C gives a fairly accurate indication of a high frequency of frost cycles and discontinuous permafrost (KARTE, 1978).

2. THE MODERATE ZONE OF MODICOFLUVIAL ACTION AND RELICT FORMS

AREAL DISTRIBUTION

This zone includes southern Canada; certain areas of the U.S.A. east of the Rocky Mountains; Europe, with the exception of the Mediterranean region; the northeastern part of China; the southern tip of South America; the southeastern tip of Africa; southeastern Australia; and parts of Tasmania and New Zealand.

CHARACTERISTIC LANDFORMS AND PROCESSES

Since we are dealing here with present day landforms and processes, the method is not appropriate for this zone. Because recent morphological activity has been very weak, inherited landforms have not been fundamentally altered. Although fluvial erosion has produced some alteration of large valley bottoms, this process is also moderate in its effect.

Soil erosion is one of the most intensive processes in this zone; however, this erosion is largely anthropic in origin and agriculture is largely responsible for partial destruction of the protective vegetation cover.

METEOROLOGICAL THRESHOLD VALUES

Since meteorological factors of land formation are of moderate effect in this zone, they do not contribute to a reliable identification.

For this reason it is appropriate to include in this zone all those areas not characterized by the active morphodynamic systems of the adjacent zones. The poleward limit is therefore determined by means of the annual isotherm of −1°C, and the equatorward limit by the corresponding threshold value of the subtropical zone, which remains to be discussed.

3. THE SUBTROPICAL ZONE OF SLOPE WASH AND SEASONAL RIVERS

AREAL DISTRIBUTION

This zone includes northern parts of westcoast U.S.A.; an area east of the Rocky Mountains at the same

1. The term "solitabetion" (from Lat. *tabere* — to melt) is substituted for the less accurate "thermokarst". "Karst" should only be applied for areas of water-soluble rock.

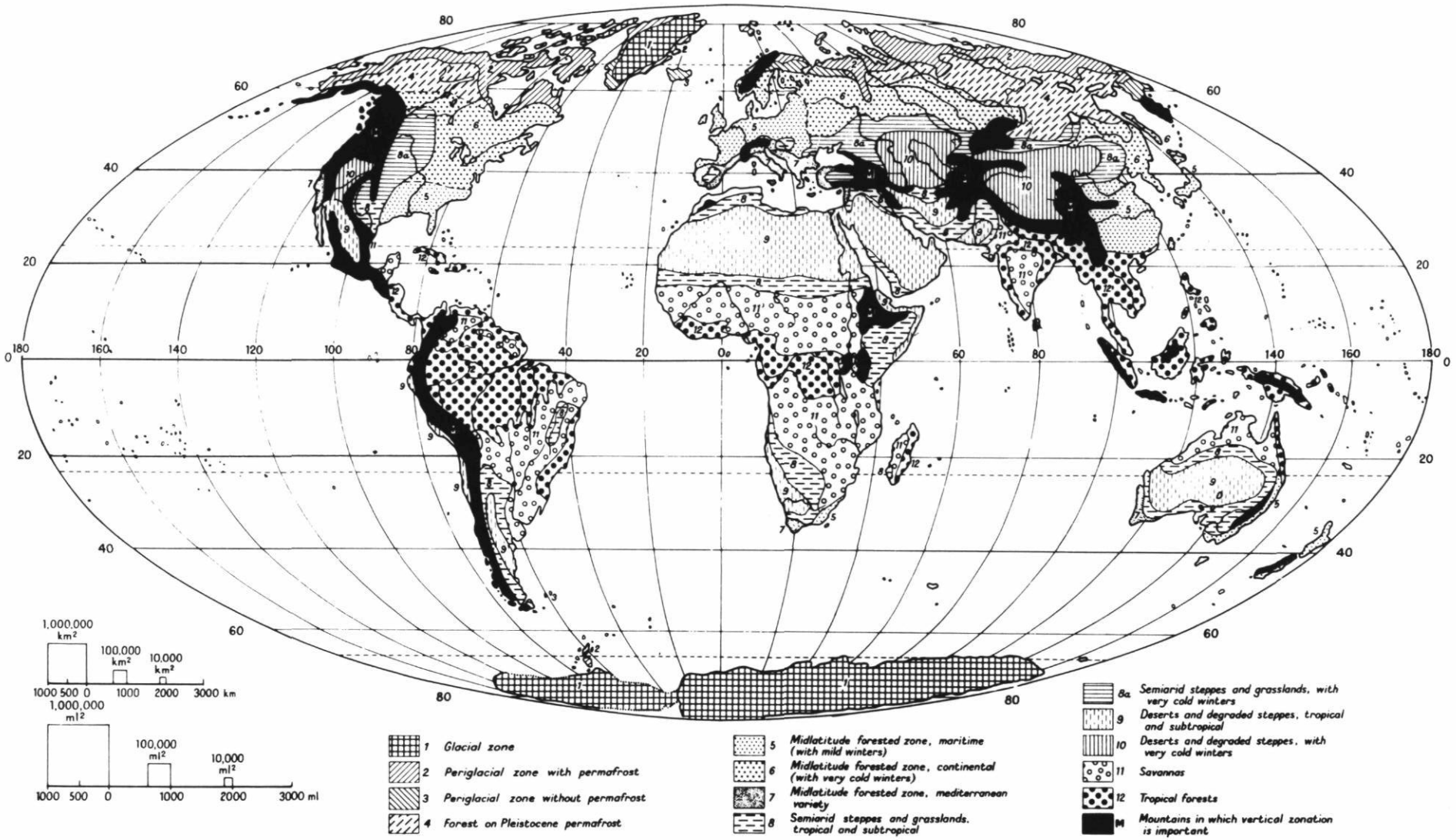

1,000,000 km²
100,000 km²
10,000 km²
1000 500 0 1000 2000 3000 km
1,000,000 mi²
100,000 mi²
10,000 mi²
1000 500 0 1000 2000 3000 mi
1 Glacial zone
2 Periglacial zone with permafrost
3 Periglacial zone without permafrost
4 Forest on Pleistocene permafrost
5 Midlatitude forested zone, maritime (with mild winters)
6 Midlatitude forested zone, continental (with very cold winters)
7 Midlatitude forested zone, mediterranean variety
8 Semiarid steppes and grasslands, tropical and subtropical
8a Semiarid steppes and grasslands, with very cold winters
9 Deserts and degraded steppes, tropical and subtropical
10 Deserts and degraded steppes, with very cold winters
11 Savannas
12 Tropical forests
M Mountains in which vertical zonation is important

FIGURE 1. Morphoclimatic zones of the earth (from TRICART and CAILLEUX, 1965, Fig. 49).

Les zones morphoclimatiques du Globe (tiré de TRICART et CAILLEUX, 1965, fig. 49). 1. Régions glaciaires. 2. Régions périglaciaires à pergélisol. 3. Régions périglaciaires sans pergélisol. 4. Forêts sur pergélisol quaternaire. 5. Zones forestières de moyennes latitudes, maritimes ou sans hivers rudes. 6. Zones forestières de moyennes latitudes avec hivers rudes. 7. Zones forestières de moyennes latitudes — variété méditerranéenne. 8. Steppes et prairies subarctiques. 8a. Steppes et prairies subdésertiques avec hivers rudes. 9. Déserts et steppes dégradées sans hivers rudes. 10. Déserts et steppes dégradées avec hivers rudes. 11. Savanes. 12. Forêts intertropicales. M. Régions accidentées où l'étagement joue un rôle prédominant.

latitude; Mediterranean Europe; some coastal regions of North Africa; western Asia; China north of the Changjiang; the area surrounding the La Plata region; the southwestern tip of Africa; southern parts of Australia; parts of Tasmania.

CHARACTERISTIC LANDFORMS AND PROCESSES

The characteristic gullying of slopes in this zone is due to the intensive slope wash created by the seasonal distribution of precipitation.

Since there has been anthropic intervention in ecological processes over a long period of time, it is difficult to evaluate whether the morphodynamic processes forming large valley bottoms with layers of debris are principally natural or pseudo-natural in origin. The fact that regions with large monthly differences in precipitation are generally subject to a high amount of fluvial erosion supports the hypothesis that the formation of the typical valley bottoms is caused by a characteristic seasonal variation in rainfall.

Frequent landslides, however, must be attributed for the most part to anthropic intervention. These particular forms of mass wasting do not therefore enter into a discussion of factors of climatic geomorphology, particularly since they are more often associated with specific petrographic or stratigraphic conditions.

METEOROLOGICAL THRESHOLD VALUES

Defining the limits of the subtropical zone in terms of the usual meteorological mean values is not very appropriate, since the critical factor is the seasonal variation in precipitation.

The question is which of the two elements of pronounced drought or heavy rainfall is more significant. Although pronounced drought inhibits the growth of vegetation and delays soil formation processes, it has no direct geomorphological effect. On the other hand, gullying by slope wash and periodic runoff points up the importance of periodic precipitation; it facilitates the transport of rubble on slopes and the deposition of debris.

The wettest month, and not the driest, should therefore form the basis for the index; the following is then appropriate:

The seasonal basis of active development processes and landforms in the subtropical zone of slope wash and seasonal rivers can be expressed by means of a simple index.

In this zone belong all regions where, for a summer rainy season, precipitation during the wettest month is double the monthly average, or, for a winter rainy season, precipitation during the wettest month is more than one-and-a-half-times greater than the monthly average.

The index is therefore:

$$\text{Summer Rainy Season} \quad \frac{\text{Precipitation — wettest month}}{\text{2 X Average monthly precipitation}} = 1$$

$$\text{Winter Rainy Season} \quad \frac{\text{Precipitation — wettest month}}{\text{1.5 Average monthly precipitation}} = 1$$

For the subtropical zone of slope wash and seasonal rivers, the resulting figure is greater than 1.

The need to establish causality has been met through a seasonally-based expression. The factors of 2 and 1.5 could not have been reached by theoretical means alone, but rather by comparing the areal distributions of characteristics in the zone to be defined with corresponding characteristics in other geomorphological zonations.

In addition to periodicity of precipitation, there must also be present the minimum amount of rainfall necessary to sustain the characteristic processes. Thus the precipitation threshold of desert zones has priority in defining the limit between the subtropical zone and desert zones. Moreover, a thermal threshold value is also necessary when the subtropical zone borders on the tropical zone, since the latter is also characterized by periodic rainfall. This threshold value should be well-defined in dealing with the tropical zone, because the capacity of its morphodynamic system to shape land surfaces is significantly greater.

A satisfactory definition towards the moderate zone requires one other threshold value, since temperatures around −1°C set off the morphological mechanisms of the subpolar zone. Since it is very effective in land formation, this mechanism can modify landforms even if only of short duration in the annual cycle.

A value based on a period of low temperatures is appropriate, since low temperatures can produce a change over an entire winter period, which is three months according to meteorological definition. Therefore, if three months of low temperatures serve as the criterion for frost-action efficiency, *a three-month period of temperatures below −1°C is used to define the poleward limit of the subtropical zone, in conjunction with a seasonality index.*

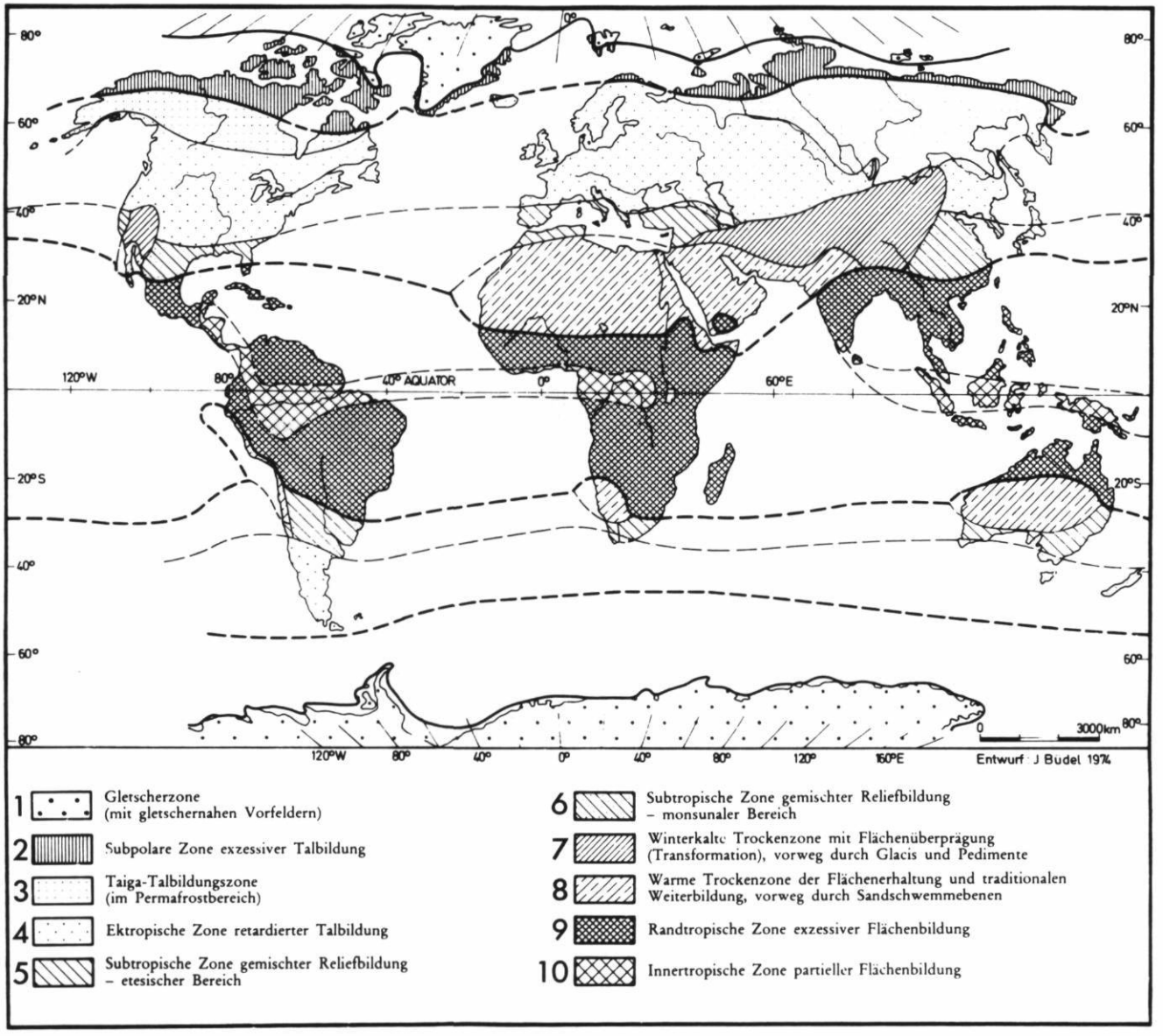


FIGURE 2. The present-day morpho-climatic zones (from (BÜDEL, 1977, Fig. 13). 1. Glacier zones. 2. The sub-polar zone of excessive valley-cutting. 3. The taiga zone of valley-cutting (within the permafrost realm). 4. The extra-tropical zone of retarded valley-cutting. 5. The subtropical zone of mixed relief development — mediterranean realm. 7. The winter-cold arid zone of surface overprinting (transformation), mainly by glacis and pediments. 8. The warm arid zone of plains preservation and traditionally continued planation, mainly by fluvio-eolian sandplains. 9. The peritropical zone of excessive planation. 10. The inner tropical zone of partial planation.

Les zones morphoclimatiques actuelles (tiré de BÜDEL, 1977, Fig. 13). 1. La zone glaciaire. 2. La zone subpolaire de dissection intense. 3. La zone de taïga de dissection (en milieu de pergélisol). 4. La zone extratropicale de dissection faible. 5. La zone subtropicale de mophogénèse mixte (milieu de type méditerranéen). 6. La zone subtropicale de mophogénèse mixte (régions de mousson). 7. La zone aride aux hivers froids d'altération aréolaire en évolution vers les glacis et les pédiments. 8. La zone aride chaude de préservation des aplanissements anciens, de poursuite des processus d'aplanissement par épandage fluvio-éoliens. 9. La zone péritropicale d'aplanissement intense. 10. La zone intertropicale d'aplanissement partiel.

4. THE PARATROPICAL ZONE OF EOLIAN ACTION AND DRY DEBRIS

AREAL DISTRIBUTION

This zone includes the desert regions of Southern California; the Sahara, Somalia, Arabian, and Great Indian Deserts; the Atacama Desert; the Namib and large parts of the Kalahari; and the desert regions of central Australia.

CHARACTERISTIC LANDFORMS AND PROCESSES

Vegetation cover, which would reduce the effects of air temperature on soil and rock surfaces, is sparse or non-existent in semi-desert and desert regions; differences between day and night temperatures are often considerable. These regions therefore constitute a second zone where physical weathering is highly efficient. Over time there have been generated great amounts of sharp-edged debris similar to that produced in the subpolar zone by frost-shattering.

The products of this characteristic weathering are also present at the base of steep slopes, where debris-covered areas mark the transition between mountains and closed depressions filled with fine-grained sediments. The origin of these pediments is under dispute. Büdel's explanation is the simplest and most plausible: tropical desert relief is a remnant of an "excessive planation of the rock surface in a long, humid, pre-Pleistocene age" (BÜDEL, 1958; 1977, p. 159). Pediments are therefore mostly relicts and irrelevant to our present discussion. On the other hand, dry debris, which is recently formed, should be taken into consideration, since it has been produced by the arid morphodynamic system and it overlays the fossil landforms.

The morphodynamic efficiency of periodically active water is considerable. Rare but violent rainstorms cut groove systems and generate strong erosional activity in the wadis. Traces of closed-depression drainage can be found as progressively finer sediments in the dry lakes of alkali flats. The difference from the formation of valley landscapes in other regions is that this lesser amount of rainfall is not of sufficient magnitude to cut a continuous fluvial system or to fill the hollows with material.

In desert regions, special attention should be paid to eolian processes and the formations they produce. Landforms produced by wind action can be divided into two basic groups: those created by deflation or corrasion and those caused by accumulation. Deflation and corrasion work in tandem; serir, hammada and reg are major landforms caused by removal of finer particles and exposure of rock surfaces; blowouts should also be mentioned.

The major results of eolian accumulation are the different forms of dunes. They all require the same general conditions for formation: sufficient activity of the wind and the presence of sufficient amounts of sand, which has been produced by mechanical weathering and partly shifted by fluvial action.

METEOROLOGICAL THRESHOLD VALUES

Given this inventory of processes and landforms, two factors are to be considered: first, wind action; second, a pronounced dryness. The dryness gives rise to specific weathering processes and characteristic fluvial action.

The wind factor is not a zonal phenomenon; in fact, tropical desert zones are relatively calm. However, the efficiency of eolian action is dependent on precipitation; low precipitation inhibits vegetation cover and therefore protection from wind erosion. What is to be determined is the degree of aridity necessary to produce characteristic processes and landforms of the paratropical zone.

By itself, rainfall data are inadequate. The fact that evaporation increases with increasing temperatures cannot be neglected, since this is a controlling factor in the growth of vegetation. Because vegetation, in turn, has a significant effect on eolian activity, this relationship is very important. Therefore temperature should also be incorporated and we should refer to indices of aridity.

An aridity index serves to show when the amount of evaporation equals that of precipitation. It is appropriate for use in causal determination towards the subtropical zone, which is characterized by periodic runoff. However, in the paratropical zone, any runoff will quickly cease because the region is "arid", *i.e.*, the possible rate of evaporation is higher than that of precipitation. The question then lies in choosing the best index for our purposes.

Many aridity indices have been examined for their utility to geomorphological studies; some have been designed for biogeographical purposes only and others lack a causal link with morphodynamic processes because they incorporate atmospheric moisture, saturation of vapor pressure, etc. Moreover, these complex indices with extraordinary meteorological parameters are not useful for global calculations. Therefore an index combining only temperature and precipitation data is applied.

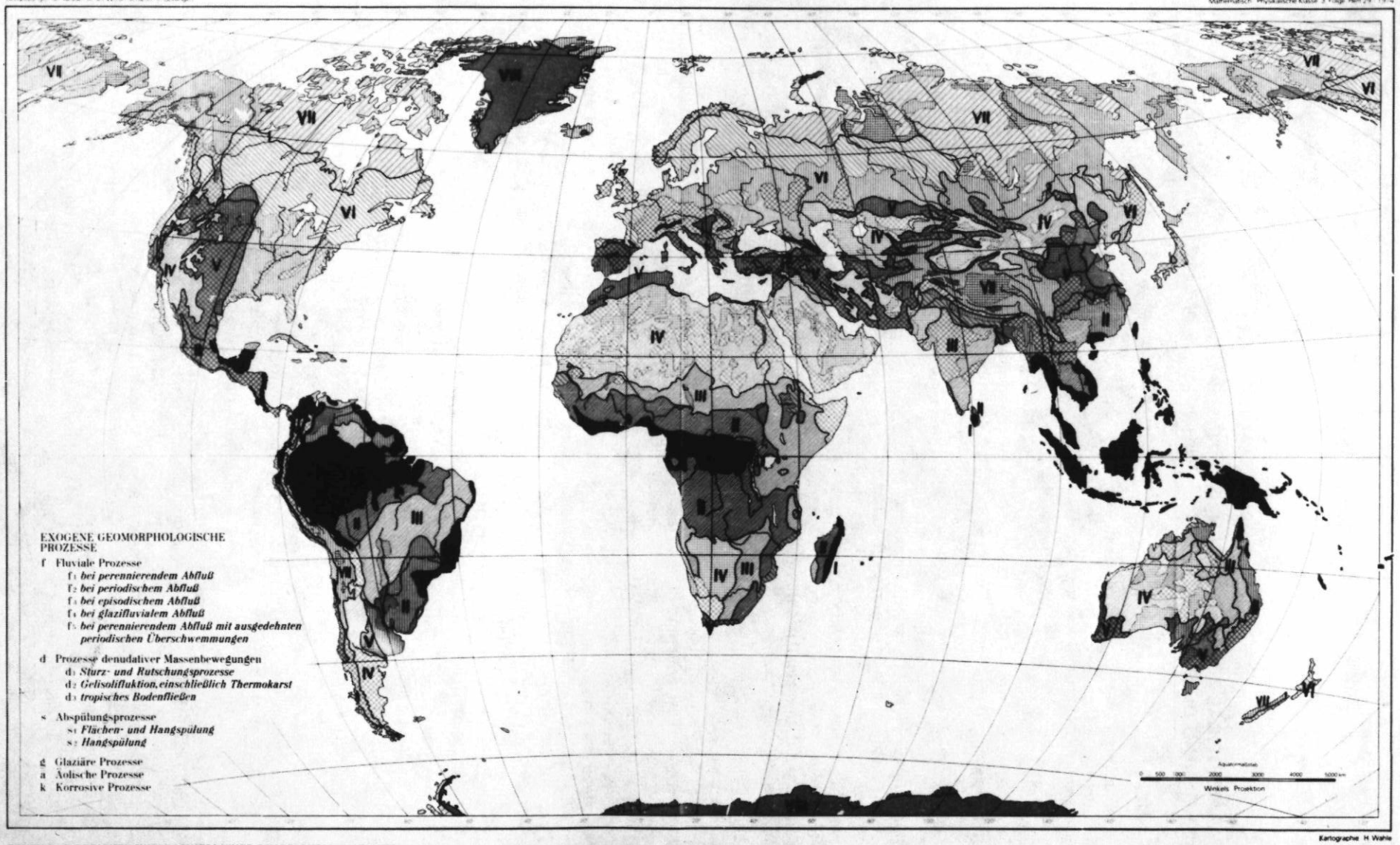
For these reasons the discussion is limited to whether an index of annual values, as introduced by KÖPPEN (1931) or one based on the number of humid months, as introduced by LAUER (1951) following de MARTONNE's ideas (1926), is more appropriate for geomorphological purposes. Lauer himself has called his method a "climatological foundation in numbers for the vegeta-

RÄUMLICHE ORDNUNG DER REZENTEN GEOMORPHOLOGISCHEN PROZESSKOMBINATIONEN

von Jürgen Hagedorn und Hans Poser

Abhandlungen der Akademie der Wissenschaften in Göttingen

Mathematisch-Physikalische Klasse 3. Folge Heft 29 1974



Kartographie: H. Wahle

ZONEN UND REGIONEN UNTERSCHIEDLICHER PROZESSKOMBINATIONEN (Große Buchstaben kennzeichnen dominante Prozesse innerhalb der Zonen)

ZONE I: *Intensivste fluviale Prozesse, sehr starke Massenbewegungen* ($F_1 D_1 d_3$)
Region:
1 $f_1 d_1 d_3$ 3 f_5
2 f_1 4 k

ZONE II: *Fluviale Prozesse und Flächenspülung* ($F_1 S_1$)
Region:
1 $f_1 s_1$ 3 $f_1 s_2 d_1$ 5 f_5
2 $f_1 s_2$ 4 f_1 6 k

ZONE III: *Intensivste Flächenspülung* ($f_2 S_1 d_1$)
Region:
1 $f_2 s_1$ 3 f_5
2 $f_2 s_1 d_1$ 4 k

ZONE IV: *Intensivste äolische Prozesse, episodisch starke Flächenspülung, episodische fluviale Prozesse* ($f_3 s_1 A$)
Region:
1 $f_3 a$ 3 $f_3 s_1 d_1 a$ 5 f_5
2 $f_3 s_1 a$ 4 $f_3 s_2 d_1 a$

ZONE V: *Intensive Hangspülung und periodisch starke fluviale Prozesse* ($f_2 S_2 d_1$)
Region:
1 $f_2 s_2$ 3 $f_2 a$ 5 $f_2 s_2 d_1 a$
2 $f_2 s_2 d_1$ 4 $f_2 s_2 a$

ZONE VI: *Mäßige fluviale Prozesse, sonstige Prozesse besonders schwach* ($f_1 s_2$)
Region:
1 f_1 2 $f_1 s_2$ 3 $f_1 s_2 d_1$ 4 $f_1 s_2 a$

ZONE VII: *Frostdynamische Prozesse, intensive Abspülung und fluviale Prozesse, einschließlich Thermoerosion* ($F_2 S_2 D_2$)
Region:
1 $f_2 d_2$ 2 $f_2 s_2 d_1 d_2$ 3 $f_1 d_1 d_2$ 4 $f_2 d_2 a$ 5 $f_4 d_1 d_2 g$

ZONE VIII: *Glaziäre Prozesse* (G)

FIGURE 3. Spatial distribution of the combinations of recent geomorphological processes (from HAGEDORN and POSER, 1974,). I. Most intense fluvial processes, very strong mass movements (F_1, D_1, d_3. II. Fluvial processes and sheet wash (F_1, S_1). III. Most intense sheet wash (f_2, S_1, d_1). IV. Most intense eolian processes, episodical strong sheet wash and episodic fluvial processes (f_3, s_1, A). V. Intense slope wash and periodic strong fluvial processes (f_2, S_2, d_1). VI. Moderate fluvial processes, other processes especially weak (f_1, s_2). VII. Cryodynamic processes, including thermoerosion, intense slope wash and fluvial processes (F_2, S_2, D_2). VIII. Glacial processes (G). f. Fluvial processes: f_1, by perennial runoff; f_2, by periodic runoff; f_3, by episodic runoff; f_4, by fluvio-glacial runoff; f_5, by perennial runoff with periodic inundations. s. Wash processes: s_1, sheet wash; s_2, slope wash. d. Mass movement: d_1, falls and slides; d_2 gelifluction; d_3, tropical solifluction. k. Solution (karst). g. Glacial processes. a. Eolian processes.

Répartition des processus morpho-génétiques récents (tiré de HAGEDORN et POSER, 1974). I. Processus fluviatiles très intenses et mouvements de masse importants (F_1, D_1, d_3). II. Processus fluviatiles et ruissellement en nappe (F_1, S_1). III. Ruissellement en nappe important (f_2, S_1, d_1). IV. Processus éoliens très intenses et ruissellement en nappe épisodique (f_3, s_1, A). V. Ruissellement intense et processus fluviatiles périodiques intenses (f_2, S_2, d_1). VI. Processus fluviatiles modérés associés à d'autres processus particulièrement faibles (f_1, s_2). VII. Processus cryodynamiques incluant thermoérosion, ruissellement intense et processus fluviatiles. (F_2, S_2, D_2). VIII. Processus glaciaires (G). f. Processus fluviatiles: f_1, écoulement pérenne; f_2, écoulement saisonnier; f_3, écoulement épisodique; f_4, écoulement fluvio-glaciaire; f_5, écoulement pérenne avec innondations périodiques, s. Ruisselement: s_1, ruissellement en nappe; s_2, ruissellement de versant. d. Mouvement de masse: d_1, éboulement et glissement; d_2, gélifluxion; d_3, solifluxion tropicale. k. Dissolution. g. Processus glaciaires. a. Processus éoliens.

tional landscapes of the tropics" (1951, p. 285); his index is therefore principally of biogeographical significance. Köppen's index relies more closely on the amount of annual precipitation available for morphodynamic processes; climatic stations with the same number of humid months can receive varying amounts of annual precipitation. However, as regards morphology, absolute quantity and intensity are the critical factors. When rainfall is violent and episodic, the effect of evaporation on the reduction of runoff becomes less crucial and therefore of less importance to the morphodynamic system.

By combining annual precipitation with temperature, Köppen's index takes an intermediate position between a simple precipitation measurement and the use of isohygromenes. The former is related to periodic fluvial processes, the latter to eolian processes controlling vegetation.

Therefore Köppen's aridity measure is used to define the poleward limit of the paratropical zone.

Despite its simplicity, but also because of it, this definition is satisfactory, since even more sophisticated calculation by computer with integration of sixteen variables has produced similar results (STEINER, 1965). On the other hand, when dealing with regions close to the pole, SCHREIBER's parabolic aridity equation (1973) would have to be applied.

5. THE TROPICAL ZONE OF SHEET WASH AND INSELBERGS

AREAL DISTRIBUTION

This zone covers the extreme southern parts of the U.S.A.; major portions of the Caribbean region; parts of Peru, Ecuador, Venezuela; Bolivia; Paraguay; northern Argentina; large portions of Brazil excluding the Amazon region; the area of Africa between the dry regions of the Sahara and the Namib/Kalahari, except the equatorial rainforest regions; India; parts of Sri Lanka; southeast Asia and China south of the Changjiang; northern and eastern parts of Australia; parts of the islands in southeast Asia.

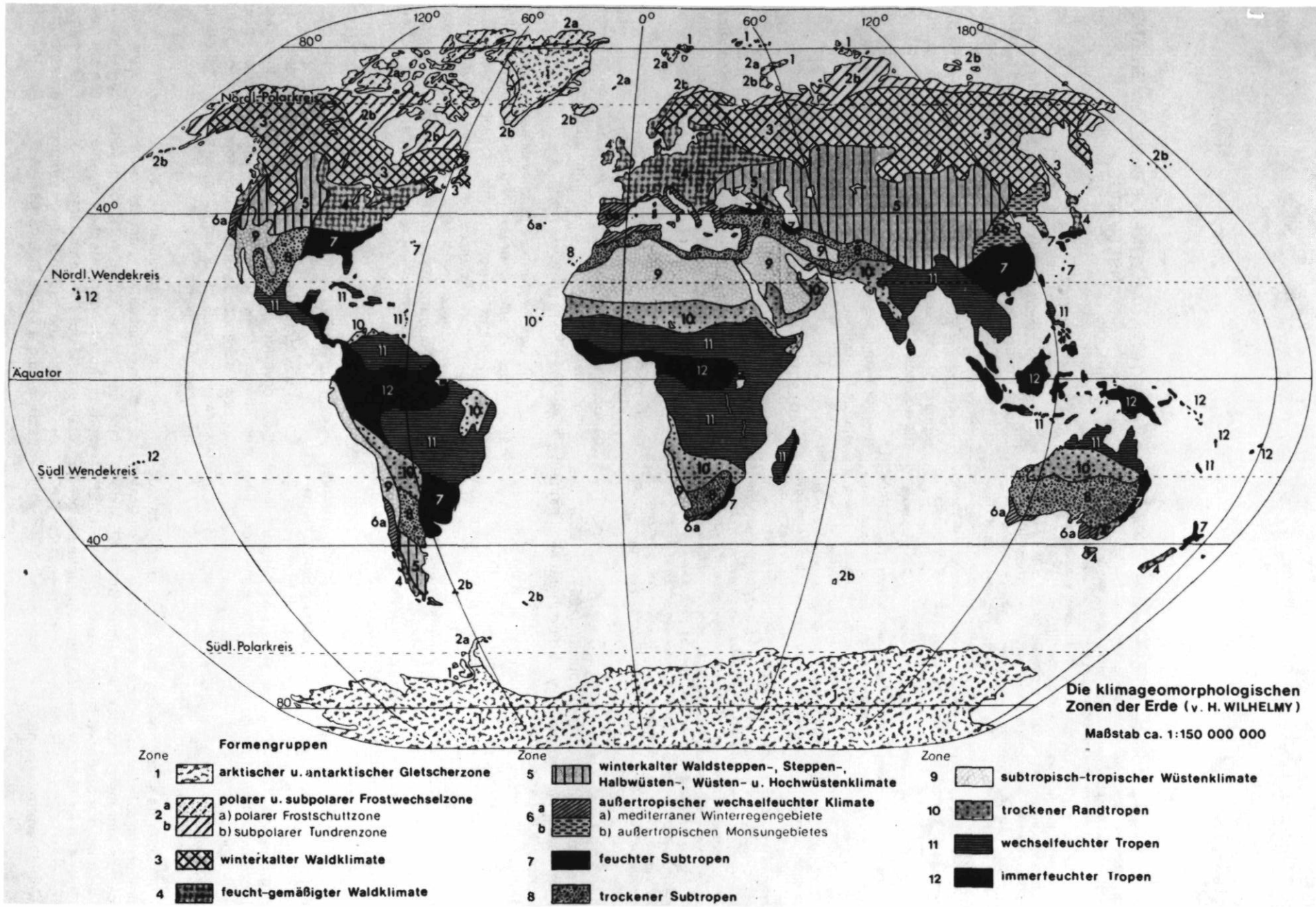
CHARACTERISTIC LANDFORMS AND PROCESSES

The first fully-developed theory of morphogenesis for this zone was produced by BÜDEL (1957). Strong chemical weathering of bedrock and limited vegetation density due to periodic humidity are regarded as the principal contributing factors. While a high intensity of chemical weathering produces a soil surface which can easily be removed, bedrock is continually decomposed by the combined action of high temperatures and periodic humidity; thus the rock surface remains to some extent covered by weathering products ("double planation surface", BÜDEL, 1957.

Erosion occurs during the rainy season, after dried soils have become saturated and further precipitation runs off in rills which pick up the smaller particles and carry them short distances, often only as far as the next barrier. Since the flowing water follows no fixed path and can, during subsequent showers, pick up soil particles at other points across the slope, the total effect of erosion is spatiai and not linear. The effect is further reinforced by fairly frequent sheet flooding during downpours. These processes account for the widespread peneplains in this zone.

The way drainage occurs is notable. Because of the thick covering of chemically weathered soil, there are no abrasive tools available and the possibility of linear erosion is reduced. Runoff therefore takes place in washed hollows of uniform flatness, culminating in barely eroding rivers.

Inselbergs are characteristic elevated formations on peneplains. Selective chemical weathering of the surface can create jutting rock formations, sometimes of considerable height; intensive weathering can sharpen their edges, but the cores remain protected. Over time, erosion of the surrounding surface increases the relative height of the inselbergs.



Die klimageomorphologischen Zonen der Erde (v. H. WILHELMY)

Maßstab ca. 1:150 000 000

FIGURE 4. The morphoclimatic zones of the Earth (from WILHELMY, 1974, Fig. 1). Groups of landforms: 1. The arctic and antarctic zone of glaciers. 2. The polar-subpolar zone of alternating frost: a) the polar zone of frost-shattered debris; b) the subpolar tundra zone. 3. Forest climates with cold winters. 4. Humid midlatitude forest climates. 5. Cold winter climates of forested steppes, steppes, semi-deserts, deserts and desert highlands. 6. Extratropical climates of alternating humidity: a) mediterranean winter rain regions; b) the extratropical monsoon region. 7. Humid subtropics. 8. Arid subtropics. 9. Subtropical — tropical desert climates. 10. Arid paratropics. 11. Tropics of alternating humidity. 12. Tropics of continual humidity.

Les zones morphoclimatiques de la Terre (tiré de WILHELMY, 1974, fig. 1). Les groupes de formes: 1. Les zones glaciaires arctiques et subarctiques. 2. La zone polaire et subpolaire de gel saisonnier: a) zone polaire de gélifraction; b) zone subpolaire de toundra. 3. climats de forêts aux hivers froids. 4. Climats de forêts humides des moyennes latitudes. 5. Climats aux hivers froids, des steppes arborées, des steppes, des semi-déserts, des déserts et des déserts de hautes terres. 6. Climat extratropical aux pluies saisonnières: a) régions méditerranéennes aux hivers pluvieux; b) régions de mousson extratropicales. 7. Régions subtropicales humides. 8. Régions subtropicales sèches. 9. Climats de déserts subtropicaux et tropicaux. 10. Régions paratropicales sèches. 11. Régions tropicales aux pluies saisonnières. 12. Régions tropicales humides.

METEOROLOGICAL THRESHOLD VALUES

The question in this case is to determine the extent in the direction of the pole of deep chemical weathering as the dominant morphodynamic process. In general, this extent is associated with the distribution of latosols (BÜDEL, 1977, p. 39). Their formation relies on chemical weathering, which is itself dependent on the combined factors of temperature and precipitation; since maximum weathering occurs at high temperatures with high precipitation, we need to find their minimum threshold values.

In German literature, these are normally defined by means of KÖPPEN's climatic classification (1931). It is assumed that the distribution of these soils can be correlated with the distribution of Köppen's A-climates in most cases, and thus his aridity index and the 18°C-isotherm for the coldest month are employed as criteria.

Taking precipitation as the primary criterion and subordinating temperature of the coldest month for the moment, the minimum threshold value is given as 360 mm (P = 2(18) [in cm]) for the hypothetical case in which the temperature of the coldest month is also the annual mean temperature in a region of winter rain. Where there is no marked seasonality, the threshold value is at least 500 mm (P = 2(18 +7)), and with summer rain at least 640 mm (P = 2(18 + 14))[2].

It is better to present such an absolute threshold value, since chemical weathering results from the action of infiltrating water, and evaporating water is thus of no significance. The seasonal distribution of precipitation has also little value in this case.

KREBS (1942, p. 17-20) has found that the isohyet of 500 mm is significant in relating the distribution of tropical inselbergs to annual precipitation. This coincides with PEDRO's delineation (1968, p. 464), which is based on the empirical regional studies of other authors. The absence of more detailed quantitative data necessitates the acceptance of this isohyet as the threshold value for precipitation.

The threshold value for temperature comes under consideration in defining the limits of the tropical zone where it borders on the subtropical zone. PEDRO (1968) gives the annual isotherm of 15°C as a suitable limit. In order to strike a medium between Köppen's index (the 18°C-isotherm for the coldest month) and Pedro's (annual isotherm of 15°C), the annual isotherm of 18°C is applied.

This combination of threshold values of 500 mm annual precipitation and 18°C annual mean temperature is doubtless the assumption most open to question in a study of this kind. Pedro (personal communication, 1978) points out the discrepancy between the areal distribution of the soils under examination and of the processes responsible for their development. Ten years after publication of his treatise, he himself regards the given threshold value of precipitation as being too low.

However, when a value much higher than 500 mm is applied, the zone's limits become expanded to such an extent that its area becomes incongruent with the area of operation of its morphodynamic system. Therefore, for lack of a more appropriate formula, *the combined threshold values of an annual precipitation of 500 mm and an annual mean temperature of 18°C are used to define the limits of the tropical zone.*

6. THE INNERTROPICAL ZONE OF LANDSLIDING AND VALLEYS

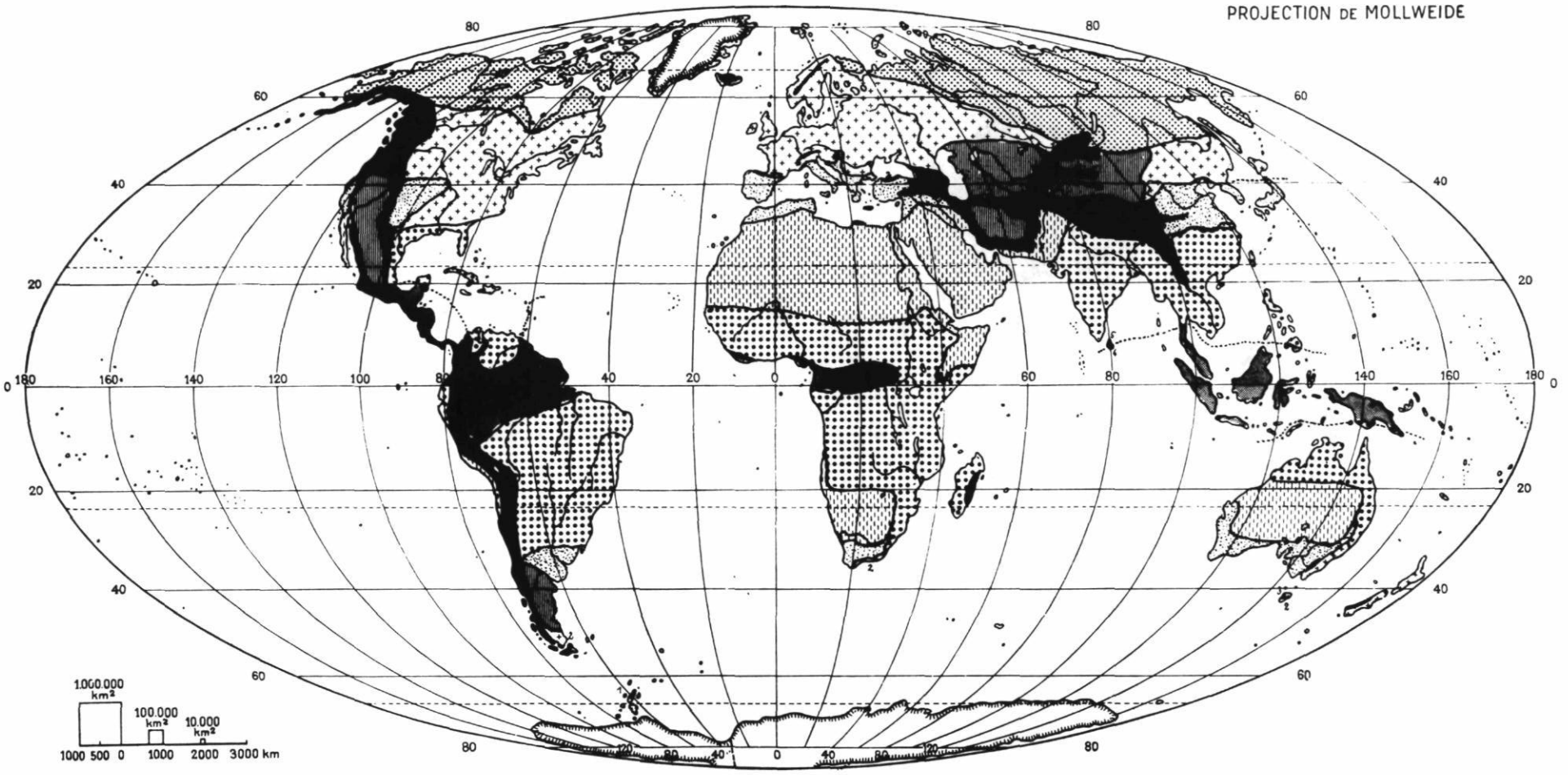
AREAL DISTRIBUTION

This zone includes tropical rainforest regions of Central America; the northwest of South America, the Amazon region, the Congo Basin, parts of the northeast coast of the Gulf of Guinea, eastern parts of Madagascar, parts of Sri Lanka, the Malay Peninsula, major portions of the islands in southeast Asia.

CHARACTERISTIC LANDFORMS AND PROCESSES

Since temperatures and precipitation rates are even higher in these areas than in the tropical zone, chemical weathering here reaches maximum efficiency; nevertheless, landforms are very different.

2. Winter Rain $P = 2T$
No Seasonality $P = 2(T + 7)$
Summer Rain $P = 2(T + 14)$



subglazialer Formenkreis

ausgegliederte Gebirgsareale

Reliefwüsten

1 subpolare Solifluktions- und Frostschuttzone

2 gemäßigte Modicofluvial- und Reliktformenzone

3 subtropische Hangspülungs- und Torrentenzone

4 randtropische Äol- und Trockenschuttzone

5 tropische Flächenspül- und Inselbergzone

6 innertropische Rutschungs- und Tälerzone

FIGURE 5. Climatic classification for geomorphological purposes by L. BEYER. 1. The subpolar zone of solifluction and frost-shattered debris; 2. The moderate zone of modicofluvial action and relict forms. 3. The subtropical zone of slope wash and seasonal rivers. 4. The paratropical zone of eolian action and dry debris. 5. The tropical zone of sheet wash and inselbergs. 6. The innertropical zone of landsliding and valleys.

Classification morphoclimatiques de L. BEYER. 1. La zone subpolaire de gélifluxion et de débris cryoclastiques. 2. La zone tempérée d'action modicofluviale et de formes reliques. 3. La zone subtropicale de ruissellement et de torrents. 4. La zone paratropicale d'action éolienne et de regs. 5. La zone tropicale d'aplanissement et d'inselbergs. 6. La zone équatoriale de glissements et de vallées.

A striking feature is the sharp-edged flanks of mountains, which illustrate the high mobility of the soil in the form of niches. The numerous landslides are caused by a combination of several factors: highly-efficient chemical weathering produces a thick covering layer of soil with great plasticity; high precipitation leads to saturation of the soil, thus diminishing friction; and frequent thunderstorms often trigger landslides.

Gravitational mass wasting is not limited to this one violent form. Continuous subsurface wasting also takes place where there are ground cavities produced by burrowing animals or root decomposition, and the results show as concave landforms. Their drainage also generally occurs through subsurface cavities.

Fluvial processes are of greater importance here than in the tropical zone. Lateral erosion is inhibited by dense vegetation, but abundant rainfall and highly-weathered soils provide the necessary conditions for the rapid erosion of river bottoms.

METEOROLOGICAL THRESHOLD VALUES

This survey of landforms and processes points out not only gradual but basic differences between the innertropical zone and the adjacent zone. Conditions for land formation seem to be similar to those of the tropical zone; for example, there is a thick covering layer of soil produced by chemical weathering in both zones. In order to define the limits, in light of such common traits, the critical factor of difference must be determined.

A study of the distribution of this zone in relation to tropical rainforest distribution reveals a high correlation which is not only areal but causal in nature. The vegetation of the rainforest protects the soil from direct climatic effects and is therefore a significant factor in the development of a morphodynamic system. Dense vegetation inhibits sheet erosion and promotes channel erosion; however, the absence of continuous spatial erosion contrasts with the effects of landslides and typical subsurface mass wasting.

The required meteorological threshold value should therefore be determined in light of the conditions responsible for the growth of the tropical rainforest. Particular attention is given to the level of precipitation, since this last also has a direct effect on landsliding and fluvial erosion. Because temperature is of negligible geomorphological consequence in the inner tropics, a definition based on this factor alone would be of little use.

In the literature, combination of minimum annual precipitation and a minimum number of humid months is unanimously accepted, although the values themselves differ. Since all recent studies suggest 1500 mm as the figure for minimum precipitation, it was not difficult to select an appropriate isohyet. The number of humid months has been determined by comparing the areal distribution of tropical rainforest with corresponding climatic diagrams. A minimum period of three months for duration of the non-humid season has proven appropriate, since any shorter interval gives misleading results, particularly in regions where annual precipitation is considerably higher than 1500 mm.

An additional threshold value of minimum temperature necessary for rainforest growth is not useful to geomorphological studies.

Therefore the annual isohyet of 1500 mm, together with an isohygromene of 9, are sufficient to define the limits of the innertropical zone.

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