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A THEORETICAL FRAMEWORK FOR DISCUSSION OF CLIMATOLOGICAL GEOMORPHOLOGY

by
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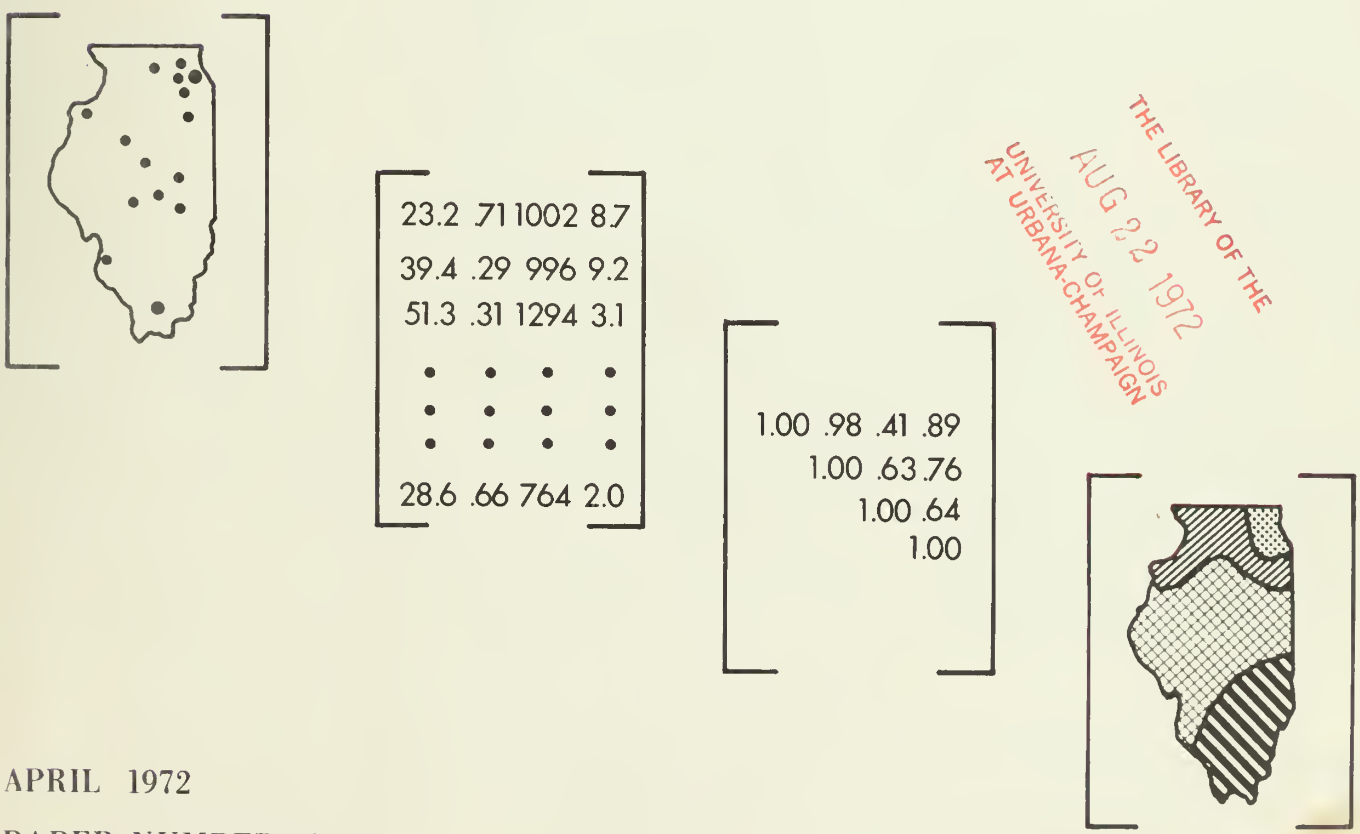

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ABSTRACT

The paper outlines a theoretical structure for the synthesis of experimental data on weathering processes into a predictive model for rates of denudation in nature. Following a general discussion on graphical representation of multivariate functions, the relative rates of chemical weathering for any temperature -- runoff combination are deduced. A field of iso-weathering lines permits analysis of the sensitivity of weathering rates to variations in climatic parameters.

The methodology developed is applied to the process of limestone dissolution. Predicted rates of weathering, based on laboratory determined values of calcite solubility, show the same trend in runoff -- temperature dependency as do measurements in nature. More accurate field data are needed to improve our understanding of regional variation in weathering rates.

INTRODUCTION

Two basic ideas underlie the study of climatic geomorphology. One is that different climates, by affecting processes, develop unique assemblages of landforms. Systematic climatic geomorphology is the analysis of these processes and forms plus their relationship to climate, and has the aim of defining morphogenetic regions on a world-wide basis. The other postulates that climatically controlled landform features have been continuously superimposed on each other due to the rapid climatic fluctuations throughout late Cenozoic time (Büdel, 1963). Although evidence supporting these ideas is generally lacking, general agreement about their validity appears to be widespread (Stoddart, 1968).

Despite explicit recognition of the direct cause and effect relationship between climate and geomorphic processes, climatic geomorphology still lacks the conceptual -- methodological framework necessary to build precise process -- response models which can be subjected to field or laboratory testing. Consequently, climatic geomorphologists, rather than attacking the problem from the process viewpoint, correlate the world-wide distribution of some vaguely defined "characteristic" landforms with chosen climatic parameters thought to be significant in the sculpturing of the

Earth's surface.

Although the effect of climate on landforms was clearly recognized by W. M. Davis and A. Penck (see Stoddart, 1968) around the turn of the century, systematic study of correlations between climate and landforms is a modern development. In 1948 the leading German climatic geomorphologist, Julius Büdel, established eight "Formkreisen", i.e., zones of broad landform homogeneity. The extent and boundaries of these zones were thought to be related to climate in general terms (Büdel, 1948). Partly because of the mixture of climatic and morphologic criteria applied in defining the zones of his 1948 classification, Büdel later revised his scheme by reducing the number of zones to five, in each case using morphologic criteria for their definition (Büdel, 1963).

Although this approach may ultimately yield a mappable classification useful in recognition of "fossil" landforms representing earlier climatic episodes, little, if anything, is gained in understanding the inherent cause and effect relationship. A potentially more fruitful approach was taken by Louis Peltier who based his nine "Morphogenetic Regions" on assumed uniform intensity and relative significance of the dominant geomorphic processes within well-defined climatic zones (Peltier, 1950). Peltier considered mean annual rainfall and temperature as being the most significant climatic parameters and examined the hypothetical effects of each on dominant weathering and erosion processes.

Peltier's inductive approach, adapted by Leopold et al., is a first step towards a process -- response model for landform development (Leopold et al., 1964). However, serious criticism can be raised. For one thing, the analysis of the effects of rainfall and temperature on geomorphic processes does not rest on precise quantitative work but rather on general impressions. Secondly, the climatic parameters chosen are not necessarily those of the greatest geomorphic significance.

Peltier himself partly answered the first criticism by undertaking a unique quantitative study of such parameters as mean relief, mean valley slope and drainage density for selected climatic zones (Peltier, 1962). Although objective, a morphometric analysis yields little insight into the operating processes; therefore, Peltier's approach is merely a quantitative version of Büdel.

AN OBJECTIVE, SYNTHETIC APPROACH TO CLIMATIC GEOMORPHOLOGY

Considerable effort has been devoted to climatic geomorphology during the last 25 years (for reviews see: Wilson, 1968; Stoddart, 1968; Ollier, 1969). In light of the previous discussion, however, one must agree with Wilson that morphogenetic analysis is still a subjective technique by which correlation is made between climate and landforms (Wilson, 1968). One reason for slow progress in understanding may be that a complete analysis of climatic geomorphology, as hitherto conducted, consists of the examination of a vast array of interrelated problems, such as the recognition of regions; the interrelationship of climate, process, and landform; the existence of climatic-morphologic cycles; climatic change and superimposed features in multigenetic landscapes.

In order to achieve an objective assessment of the importance and nature of the climatic impact on landform development, this problem-complex must be broken down sufficiently to allow a precise analysis of cause and effect in a single chain of events. In a morpho-climatic synthesis, the climatic parameters are the independent variables whose effect on long-run equilibrium landforms are to be evaluated. The obvious first step, therefore, is to determine, as precisely as present understanding of weathering and erosion permits, the rates of denudational processes as functions of climatic variables. Secondly, taking into account bedrock lithology and structure, different rates of denudation and consequent erosional landforms can be evaluated for any combination of relevant climatic variables. In the third stage, after having determined equilibrium landforms, the effects of tectonism and late Cenozoic climatic fluctuations must be analyzed before a correlation between theoretically deduced and real world landforms can be made.

Obviously, considerable work is needed at each step before an integrated body of knowledge on climatic geomorphology is built. The present paper outlines a methodological framework for step one. A theoretical structure is developed permitting a synthesis of climatic data and experimental knowledge on specific weathering processes into a predictive model for rates of denudation in nature as functions of x number of climatic variables. The general discussion concerns chemical weathering; due to scarcity of data, however, the specific process of limestone dissolution was chosen for a numerical testing of predicted versus observed rates of denudation.

DEFINITIONS AND ASSUMPTIONS

Weathering: The process of rock alteration due to instability of minerals exposed to the atmosphere.

Rate of weathering: M, the amount of mass per unit area per unit time which changes its structure from one defined state to another.

Erosion: The net removal of material from an area.

Rate of erosion: A, amount of mass removed per unit area per unit time.

This analysis is restricted to processes in short run dynamic equilibrium, *i.e.*, processes of such type and scale that (1) the rate of energy outflow from the system is equal to the rate of energy input; and (2) while climate remains unchanged the proportion of the total energy shared by the various weathering and erosion processes remains constant.

THE THEORETICAL STRUCTURE

General

The following variables are used: while P traditionally represents precipitation, in this paper P will stand for runoff unless otherwise specified; T is temperature and W represents wind. These are directly and/or indirectly active agents of denudation. In each analysis a combination of these, or related variables such as intensity of precipitation, heat fluctuations, etc., must be applied. The effects of man, animals, vegetative cover and soil organisms are to some extent related to climate, hence an indirect climatic impact on landforming processes. An explicit functional relationship between the rate of denudation and these factors is presently impossible to construct and they are combined into one variable, R. Gravity, although the prime agent of erosion, is completely independent of climatic factors and has no place in a study of climatic geomorphology. Obviously, weathering and erosion are interdependent, therefore, the rate of one process must be included in the expression for the other. The following functional equations can be derived:

$$M = f\,(P, T, W, R, A) \tag{I}$$

$$A = g\,(P, T, W, R, M) \tag{II}$$

Time is included as an implicit variable in both functions. In morphoclimatic regionalization annual means (for the variables P through A) are most conveniently used; effects of climatic change through time can be analyzed if the explicit time-dependency of the variables can be derived. Annual fluctuations in rates of denudation at a given locality are analyzed by applying monthly mean values for the variables.

The rate of weathering or erosion may be graphically represented by a five dimensional surface. P, T, W and R are climatically interrelated; when their effects on geomorphic processes are considered, however, they are independent as a first approximation. To depict this surface, two arbitrary variables, X_1 and X_2, are considered (Fig. 1). The relationship between M and any one of the variables is obtained by projecting from the surface into the corresponding plane. For a constant value of X_2 (notation $\overline{X}_2$), M as a function of X_1 is:

$$M = f\,(X_1, \overline{X}_2), \text{ with } X_3 \ldots X_5 \text{ assumed constant.}$$

In Fig. 1 this curve on the M surface is labeled P - P', its projection in the MX_1 plane is p - p'. $M_0 = f\,(0, \overline{X}_2)$ where $M_0 \geq 0$ (In Fig. 1 $M_0 = 0$).

Isolines are defined as the locus of points in variable space which correspond to a constant value of the dependent variable in observation space. Mathematically, isolines in five dimensional space are given by any combination of $X_1 \ldots X_5$ which makes $f\,(X_1 \ldots X_5)$ a constant.

In the three dimensional case depicted in Fig. 1 isolines will appear as the projection in X_1X_2 plane (d - d') of the curve cut by the intersection of the M surface and a plane parallel to the X_1X_2 plane at a given height (D - D'). This plane represents constant value of M.

Along an isoline the total differential of the f-function is zero. Still considering X_1 and X_2 as the only variables the following relation for the isoline is derived:

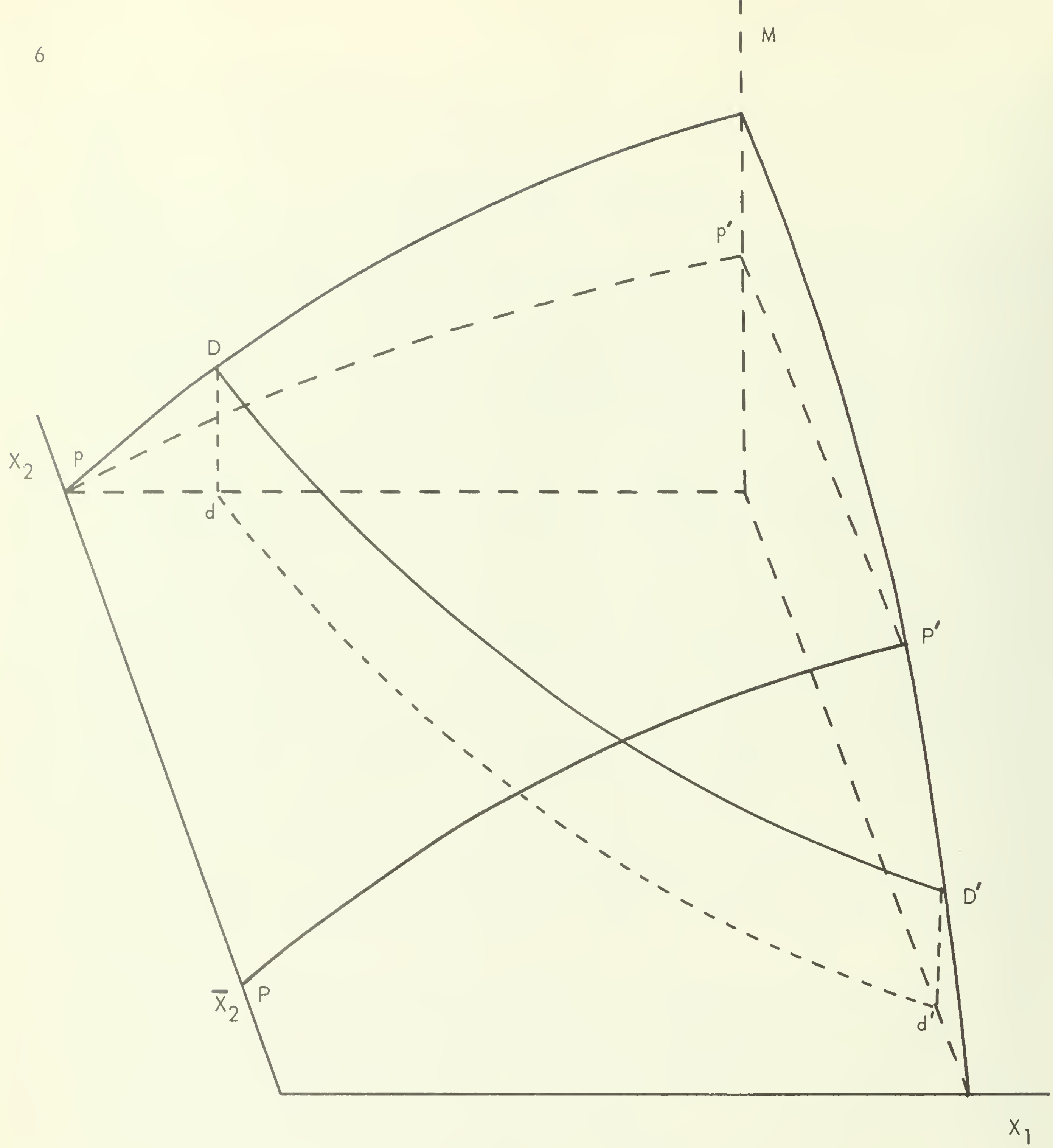

Fig.1. Weathering rate , M, as function of two variables, X_1 and X_2. For a constant value of X_2 ($\overline{X}_2$), M as a function of X_1 is given by the line P – P′, which is projected into the MX_1 plane as p – p′. D – D′ is the trace of the intersection between the M surface and a plane representing a given constant rate of weathering. The projection of D – D′ into the X_1X_2 plane gives the iso-weathering line d – d′.

$$dM = \frac{\partial f}{\partial X_1} dX_1 + \frac{\partial f}{\partial X_2} dX_2 = 0$$

Hence, (III)

$$\frac{dX_1}{dX_2} = - \frac{\frac{\partial f}{\partial X_2}}{\frac{\partial f}{\partial X_1}}$$

dX_1 / dX_2 gives the slope of an isoline in the X_1 X_2 diagram. These curves are convex to the origin when an increase in variable X_i implies an increase in f, i.e. when:

$$\frac{\partial f}{\partial X_i} > 0 \qquad (i = 1, 2)$$

Equation III demonstrates the magnitude of change in variable X_1 needed to compensate for a given change in X_2 in order to keep weathering (or erosion) at a constant level of intensity. Rather than operating with traditional morphogenetic regions, the concepts of "iso-weathering lines" and "iso-erosion lines", lines in X_1X_2 space along which weathering and erosion have constant intensity are introduced. The exact shape of the lines is determined by equation III. These isolines are spatial and can be mapped. They indicate for example the increase in temperature that compensates for a given decrease in precipitation to retain a constant weathering rate.

Chemical Weathering

All further discussion is restricted to chemical weathering, where total annual runoff, P, and mean annual water temperature, T (averaged over the time when T > 0° C), are considered the only significant variables.

Rates of chemical weathering, as conceived by Peltier (1950), Leopold et al. (1964) and Wilson (1968) are shown in Fig. 2, a,b,c. They indicate an increase in the rate of chemical weathering from dry-cool to humid-warm climates. However, the boundary lines between the various zones are rather arbitrarily drawn and no quantitative assessment of rates of weathering can be made.

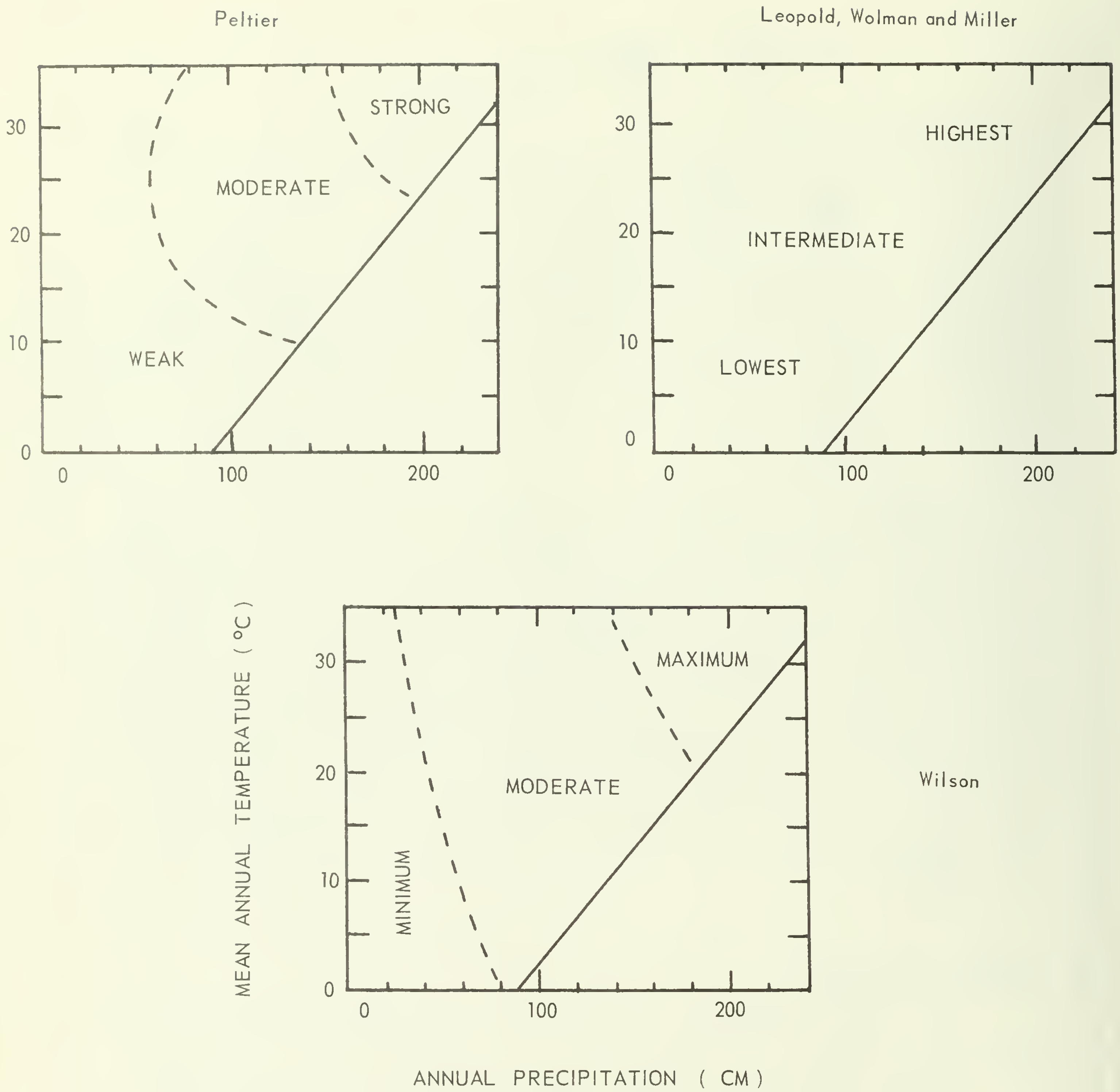

Fig.2. Relative rates of chemical weathering as function of mean annual temperature and precipitation. Modified after Peltier (1950), Leopold at. al. (1964) and Wilson (1968).

Based upon principles in the last paragraph a field of iso-weathering lines for chemical weathering can be generated (Fig. 3, a and b). For processes of chemical weathering, except limestone solution, the rate of weathering increases with temperature. For many processes the increase is approximately exponential (Ollier, 1969). However, to simplify analysis a monotonically increasing function, $M \propto h(T)$, ($\propto$ means proportional to) is assumed. Clearly, rate of weathering increases with runoff. However, the increase is less than linear because higher runoff reduces the probability that the chemical solutions will reach equilibrium. Hence, M is proportional to some increasing function of P, $M \propto k(P)$.

The rate of chemical weathering can be written:

$$M \propto h(T) \cdot k(P) \tag{IV}$$

Based on these assumptions, the weathering rate surface takes the shape shown in Fig. 3a. M is zero when P is zero because no water is available to transport the solution products. M must also be zero when $T \leq 0°C$ because water is frozen. Depending on the process, however, the increase in M as soon as temperature rises above freezing may be slow or rapid. The iso-weathering lines are always convex to the origin and asymptotic to the P or T axis. When h (T) and k (P) are explicitly defined, equation III determines the exact slope of the lines at any point.

Fig. 3b illustrates iso-weathering lines corresponding to five equidistant weathering intensities ($M_1 \ldots M_5$) in Fig. 3a. Based on this iso-line chart the following general conclusions about chemical weathering can be derived: (1) for low temperature environments (tundra and cold continental climates) no appreciable chemical weathering occurs regardless of runoff; (2) for high temperatures and low runoff (hot deserts) a small increment in precipitation causes a relatively large increase in weathering rate (because iso-lines are densely spaced parallel to the P axis); (3) for humid hot climates (tropical rainforest) increased runoff causes a relatively small increase in weathering rates, whereas a minor temperature rise causes a large increase in weathering rate. Thus in hot deserts local variations in rates of chemical weathering are determined primarily by variations in runoff, whereas in hot humid climates temperature variations have the most significant effects

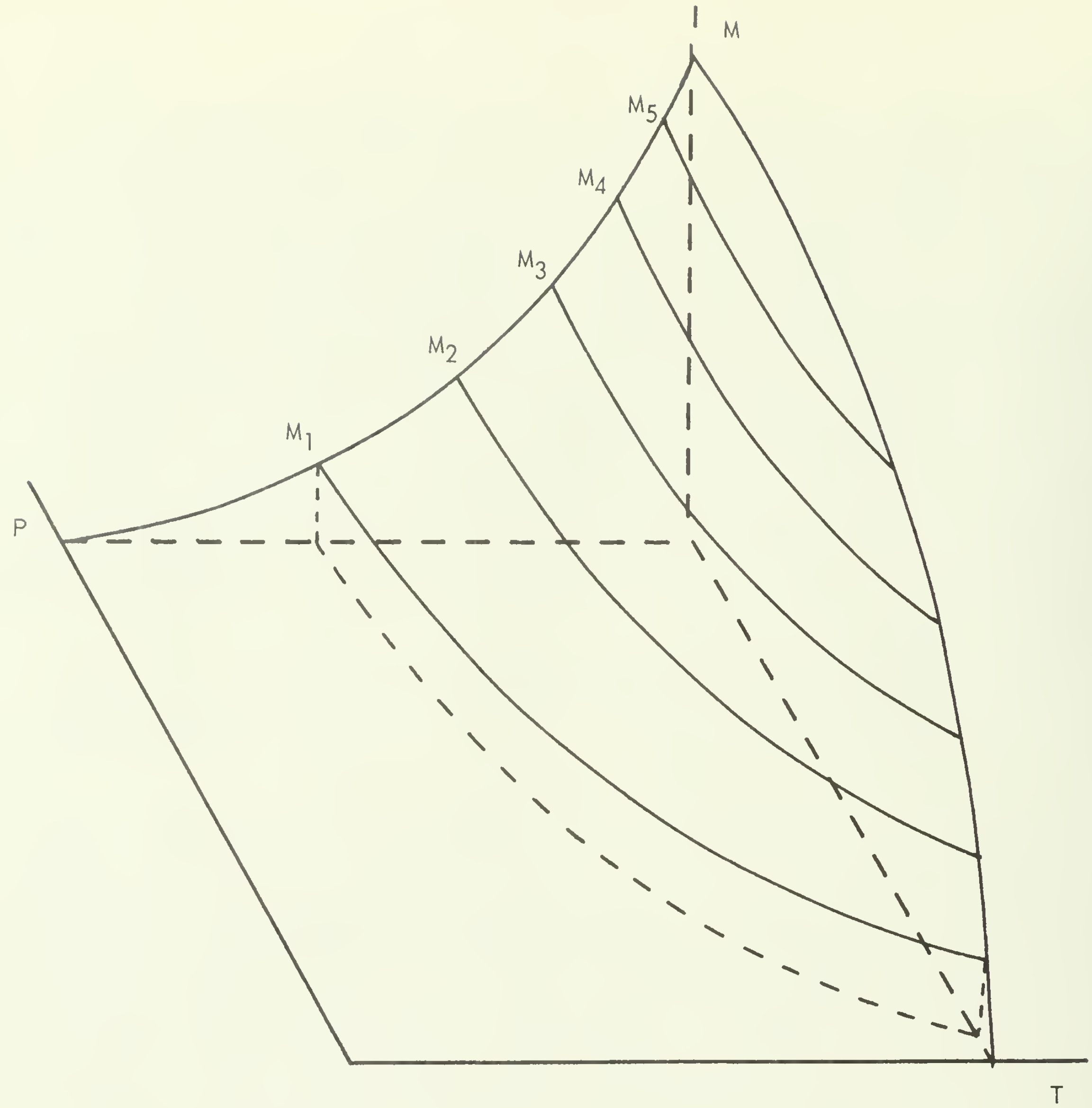

Fig. 3a. Rate of chemical weathering as function of runoff (P) and temperature (T).

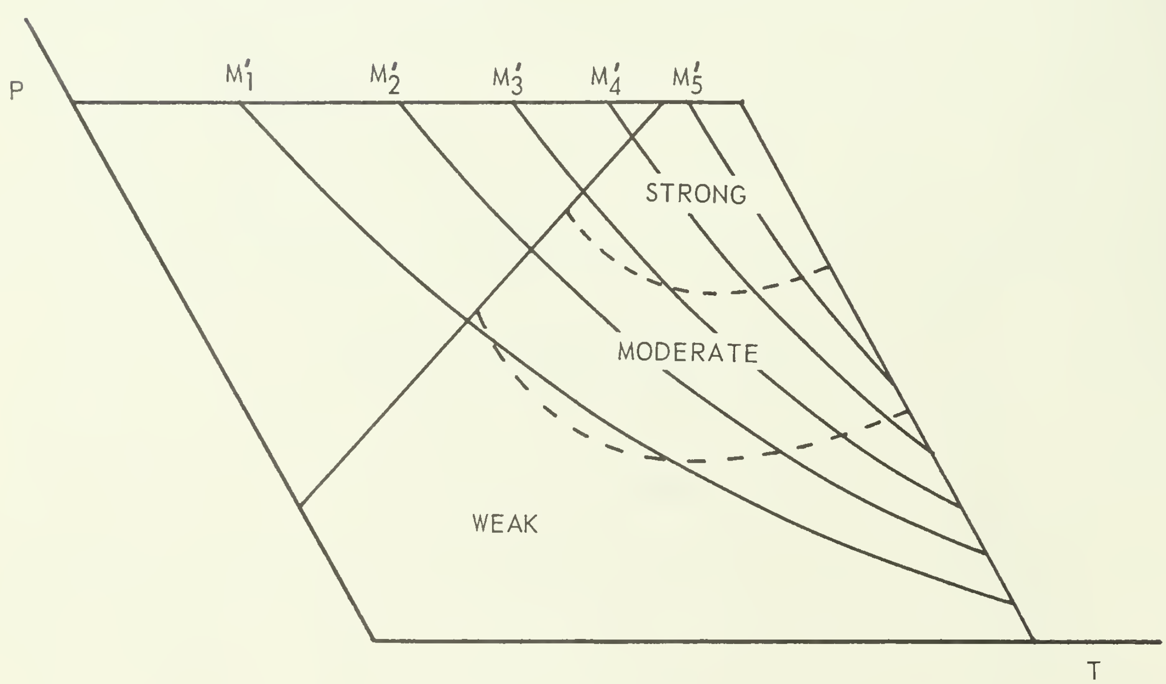

Fig. 3b. Iso–weathering lines $M_1' \ldots M_5'$ in the PT plane correspond to weathering intensities $M_1 \ldots M_5$ in fig. 3a. Superposed on the isoline chart are Peltier's (1950) three zones of chemical weathering.

on the weathering rate.

Peltier's three zones of chemical weathering can be superposed on the isoline chart (Fig. 3b). P in Peltier's diagram refers to precipitation, while here it indicates runoff. This partly explains why the boundaries between Peltier's zones at low temperatures follow the same trend as the isolines, while at higher temperatures where runoff constitutes a smaller percentage of the precipitation they cut across the iso-weathering lines.

When the exact h (T) and k (P) functions are known, numerical values for the weathering rate for any P - T combination can be derived. Of course the graphs do not reveal any more information than can be deduced directly from the functions but they do make visualization easier. Furthermore, when analysis of a complex group of processes is undertaken and only the general shape of the partial functions is known, a graphical representation permits an assessment of the relative importance of changes in the independent variables.

Iso-weathering lines in a precipitation - temperature diagram (thermohyet diagram) are well suited to the study of local annual variations in weathering rates. Thermohyet diagrams form more or less regular closed loops with characteristic shape and orientation for each climatic regime (Strahler, 1969). The orientation of the diagrams relative to the field of iso-weathering lines determines the annual variation in weathering intensities.

Fig. 4 shows a hypothetical iso-weathering chart, modelled after the one previously derived for chemical weathering. Mean monthly precipitation, P', (runoff data are not available) and temperature, T, are the axis variables; weathering rates $I_1 \ldots I_3$ are numbered in order of increasing intensity. Superposed on the weathering chart are thermohyet diagrams representative of four different climatic regimes.

Iquitos, Peru, represents equable tropical rainforest climate and consequently a moderate range of variation in weathering rate. The unique combination of cool - wet winters and warm - dry summers characteristic of a Mediterranean regime (Santiago, Chile) results in a thermohyet diagram whose long axis is subparallel to the iso-weathering lines, i.e. the rate of chemical weathering is practically constant throughout the year. Maximum annual fluctuation in rate of chemical weathering is found

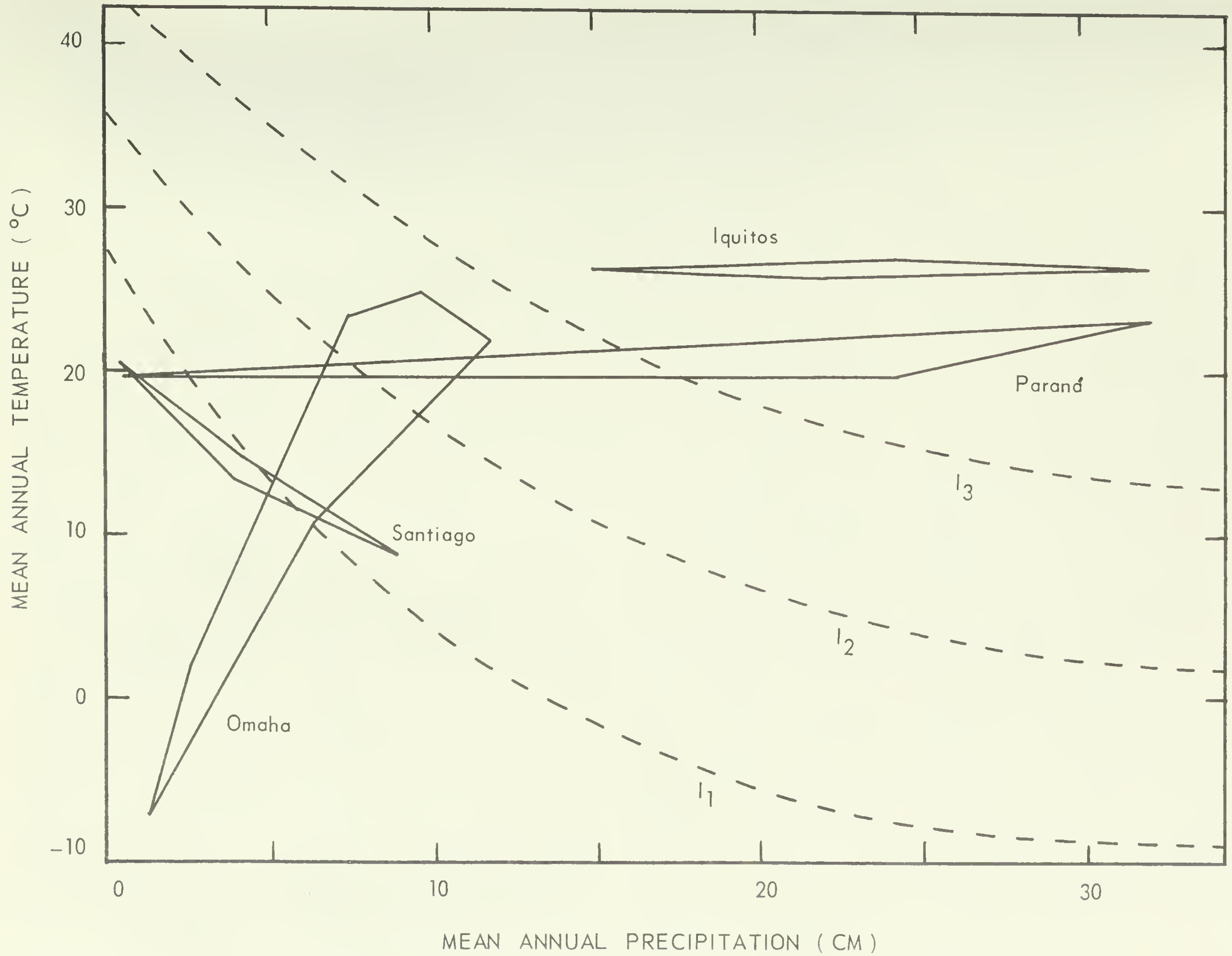

Fig.4. Thermohyet diagrams representing four climatic regimes are superposed on a hypothetical chart of isolines for chemical weathering. Increasing rates of weathering, $I_1 < I_2 < I_3$. Tropical rainforest climate, Iquitos, Peru. Savanna climate, Paraná, Brazil. Mediterranean climate, Santiago, Chile. Continental climate, Omaha, Nebraska.

in climatic regimes with warm - wet summers and cool - dry winters. Examples are Paraná, Brazil, representing tropical savanna climate, and Omaha, Nebraska, representing continental climate.

CHEMICAL WEATHERING OF LIMESTONE: A CASE STUDY

Extensive studies have been made of limestone regions and the importance of solution weathering. Thus the role of climate in denudation is well documented (Sweeting, 1965, 1966). Denudation of limestone has been chosen to illustrate the applicability of the previously developed theory for the following reasons: (1) weathering rates are very high. In areas such as the Alaskan panhandle and western Norway, where limestone weathering is most efficient, estimated denudation rates range from 5 to 8 meters per thousand years (Corbel, 1959); (2) the relatively homogeneous chemical composition of the rock simplifies analysis; (3) laboratory experiments and widespread field measurements provide adequate data supply. However, limestone weathering does have the opposite temperature dependency to the one assumed in the general discussion of chemical weathering.

The following chemical reactions are involved in the solution of limestone:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3 \qquad (V)$$

$$H_2CO_3 \rightleftharpoons H^+ + (HCO_3)^- \qquad (VI)$$

$$CaCO_3 + H^+ + (HCO_3)^- \rightleftharpoons Ca^{++} + 2\,(HCO_3)^- \qquad (VII)$$

$CaCO_3$ is soluble in pure water but concentration of calcium and bicarbonate ions is very low. First when a weak carbonic acid is formed by the reaction of atmospheric CO_2 with water (eq. V), limestone solution proceeds at high rate. The equilibrium amount of CO_2 in water increases with increased partial pressure of CO_2 in the air and decreases with increasing temperature of the water (Miller, 1952). The solubility of $CaCO_3$, therefore, shows parallel behavior.

Although Miller's analysis of the relationship between temperature and solubility of calcium carbonate is fundamental to the study of limestone weathering, the laboratory results are not directly applicable to the natural process. The following complications affect limestone weathering. The amount of CO_2 in water is influenced: (1) by the speed and size of falling raindrops; (2) by the amount of decaying organic matter in the soils; (3) by the action of soil bacteria and photosynthesis of green plants. The permeability of the rock and the presence of minerals other than calcite in the limestone affect solubility. Some of these factors have been analyzed and concentration of Ca^{++} ions is known for various kinds of equilibria (Garrels and Christ, 1965). A limitation to the applicability of these results, however, is that many limestone dissolving processes in nature never attain equilibrium.

The methodology developed earlier in the paper is applicable to a study of the regional variation in the rate of limestone weathering. Mean annual water temperature and runoff are considered to be the only significant variables. Predicted rate of solution is based on laboratory determined parameters.

The Model

Using Miller's (1952) experimental results on the change in solubility of $CaCO_3$ with temperature of water, while assuming a constant CO_2 pressure equal to the average partial pressure of CO_2 in the atmosphere ($P_{CO_2} = 3.5 \cdot 10^{-1}$ mb), the weathering rate can be expressed as:

$$M = P\,(a - b\,T) \qquad \text{(VIII)}$$

where P is runoff, T is temperature, and a and b are coefficients. The relationship between solubility and temperature is not exactly linear, but within the limited temperature range affecting processes in nature, the linear function is a good approximation. The direct proportionality between M and P assumes that runoff is always saturated with calcium and bicarbonate ions before it is drained off the limestone area. The validity of this assumption is questionable for high runoff and bedrock of low permeability. However, the agreement with observed data is reasonably good. Functions with a rate of increase significantly less than linear (square root and logarithmic) were tried and found to give values for M which are far too low. With the following dimensions:

$$M = \text{tons/km}^2\text{/year}; \quad P = \text{mm/year}; \quad T = {}^\circ C$$

the coefficients have the following values:

$$a = 0.58 \ \text{tons/km}^2\text{/mm}$$
$$b = 0.011 \ \text{tons/km}^2\text{/mm/}^\circ C$$

Equation (VIII) yields the following expression for the iso-weathering lines in the P - T plane:

$$P = \frac{M_i}{a - b\,T} \qquad \text{(IX)}$$

where M_i designates any constant weathering rate. M is a linear function of T for constant P with slope -Pb, i.e. the slope increases with higher runoff. M is zero when T equals a/b. ($a/b = 53^\circ C$, expressed as T^* in Fig. 5). For constant temperature, M is a linear function of P with slope a - bT. The rate of weathering surface (Fig. 5) is convex with its "ridge" along the diagonal from the upper left to the lower right. Iso-weathering lines, therefore, will be curved from upper right to lower left in the P - T diagram shown in Fig. 6. The isolines never cross, nor do they intersect the $P = 0$ and $T = 53^\circ C$ lines.

Fig. 6 illustrates the predicted weathering rates (tons/km^2/year) for any P - T combination. The diagram indicates that within the realm of naturally occurring climates, the rate of limestone weathering varies between zero and 800 tons/km^2/year.

An interesting feature of this diagram is the trend of the gradient of the isoline field. Rate of weathering increases from dry - warm to cool - moist climates in contrast to the general pattern of chemical weathering derived previously. However, similar to other processes of chemical weathering, limestone dissolution is most sensitive to temperature variations in hot - wet climates and precipitation variations in cool - dry climates.

Observations

Corbel (1959) has gathered data on the rate of denudation of calcareous terrain in various climatic zones from tundra to humid tropical. Rates were calculated from measured concentration of calcium and

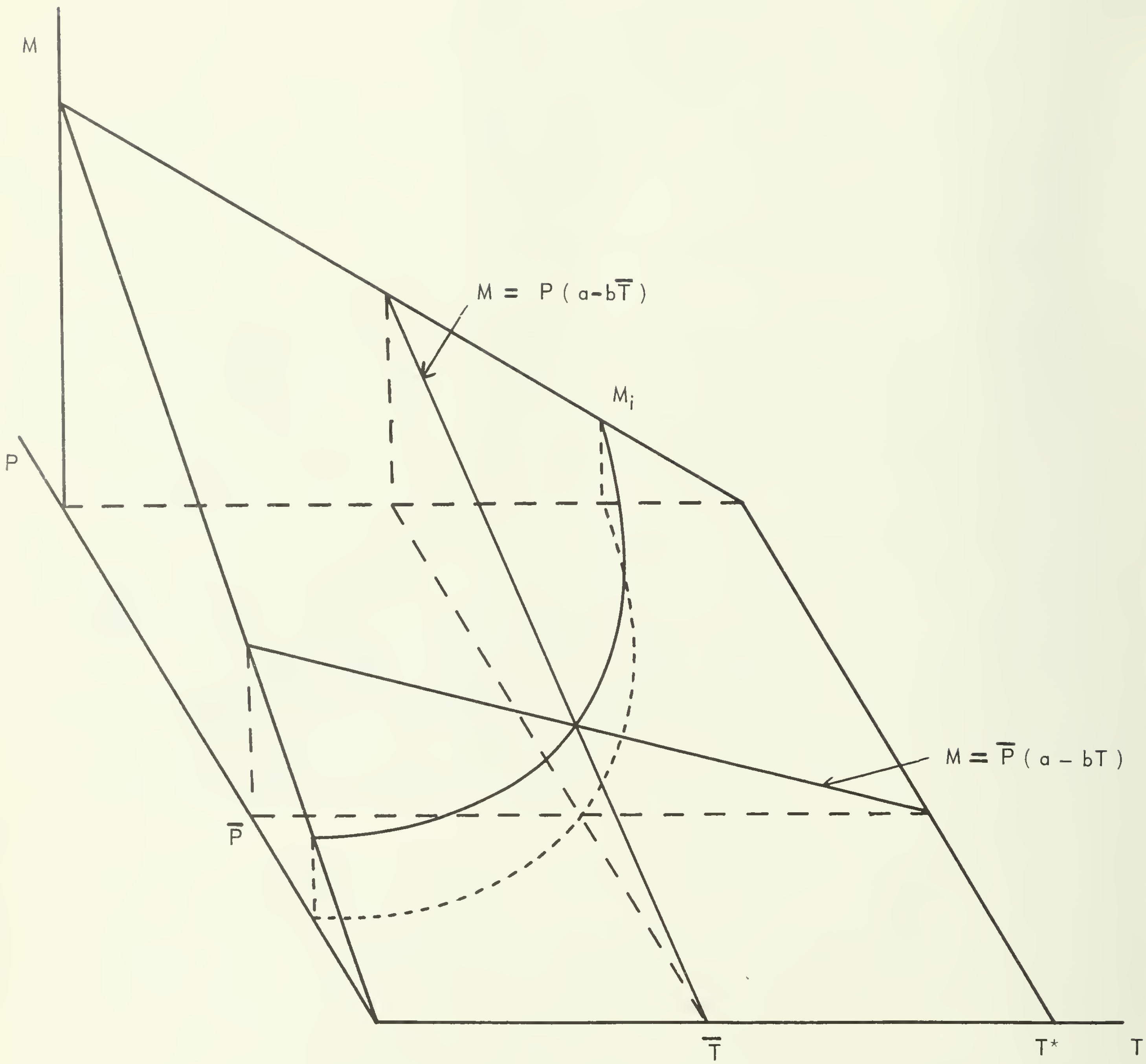

Fig.5. Graphic representation of the surface generated by the equation

$M = P(a - bT)$. See text.

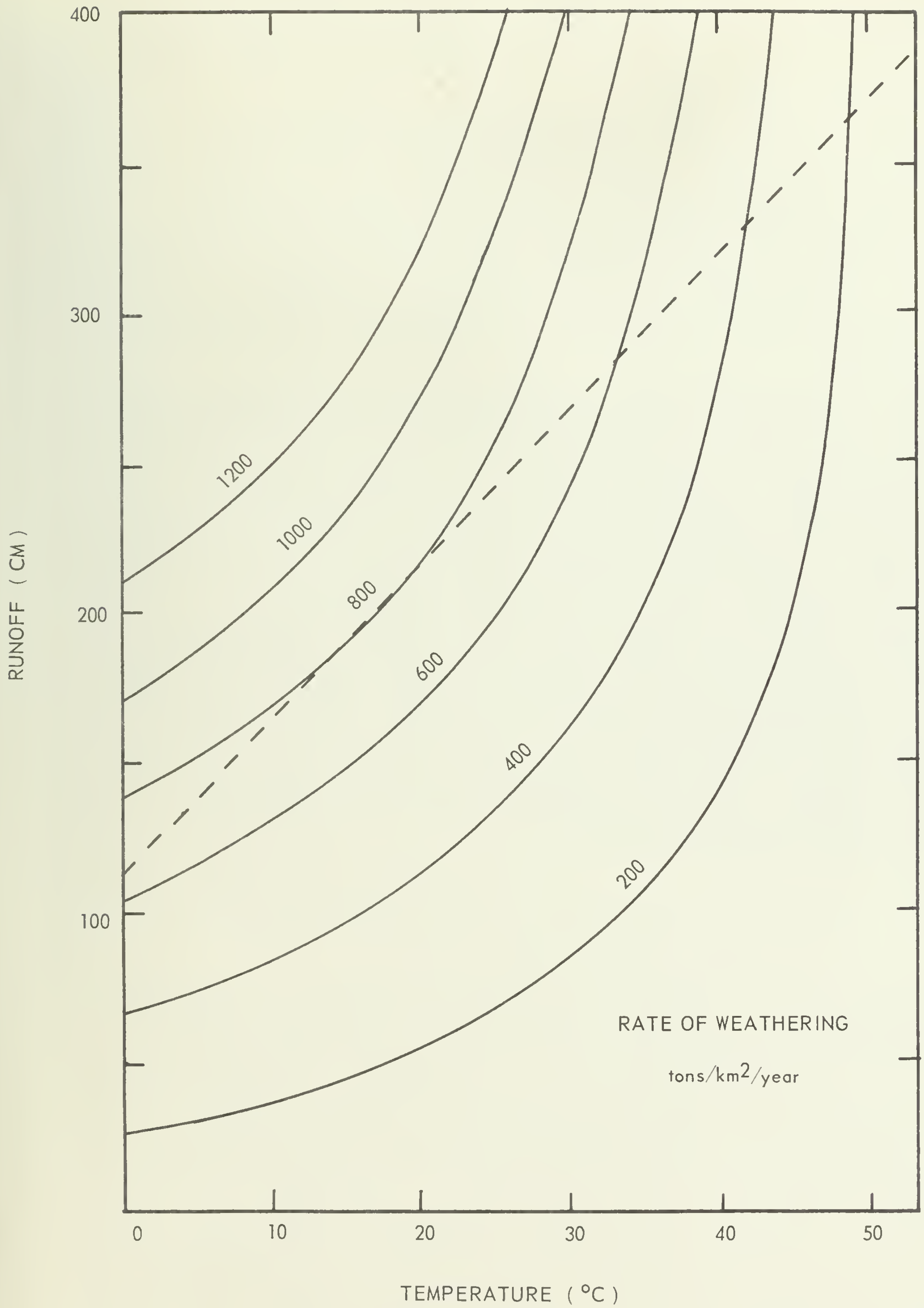

Fig.6. Rate of weathering of limestone as function of mean annual temperature and runoff. Numerical values based on laboratory determined solubility of $CaCO_3$.

— — — — indicates upper boundary of naturally existing climates.

bicarbonate in the runoff water. However, only in a few cases was the amount of actual runoff measured, and in no case was the average temperature of the runoff water given.

In tundra climates rates varying from 35 tons/km^2/year to 110 tons/km^2/year are found. Maximum intensity seems to be in cool humid west coast climates with rates varying from 3000 tons/km^2/year in British Columbia and southern Alaska, 1000 tons/km^2/year in western Norway to 308 tons/km^2/year in the Ben Nevis area of Scotland. In frost free areas such as coastal Ireland, the rate decreases to approximately 100 tons/km^2/year.

Little limestone weathering occurs in warm dry climates as illustrated by the Los Alamos area of New Mexico where the rate is estimated to be 1.0 ton/km^2/year. Southern Florida with a humid subtropical climate, has a denudation rate of about 13 tons/km^2/year while at Key West the rate is close to zero. The tropical rainforest climate at San Andres island off Colombia gives a rate of about 25 tons/km^2/year.

The data listed here suggest that trends derived from our model are actually found in nature. The predicted rates, however, have a narrower range than those actually measured. With more precise climatic data on rainfall, runoff and water temperature together with parameters expressing vegetation, basin topography and lithology, considerable improvement in the model is expected.

CONCLUSION

The methodological framework developed in this paper serves two major purposes: (1) when the functional relationship between rate of weathering and each separate variable can be deduced from physical and/or chemical considerations, then a mathematical or graphical analysis of the total function permits the derivation of relative intensities of weathering for any two specified climatic environments. Furthermore, the relative sensitivity of the weathering rate to changes in any variable can be deduced from the trend and spacing of the isolines; (2) where experimental data on an idealized weathering process are available, the methodology provides a basis for analyzing the goodness of fit between predicted and observed rates. Also, it clearly points out the type of data needed in order to increase basic understanding of the climatic effects on rates of denudation.

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No. 1 -- Dag Nummedal, A Theoretical Framework for Discussion of Climatological Geomorphology -- April, 1972.

No. 2 -- Charles Christian, Social Areas and Spatial Change in the Black Community of Chicago: 1950-1960 -- April, 1972.

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