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Diffusion Equation Model for Geomorphic Dating

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For the application of the diffusion equation, slope height and maximum slope angle are calculated from the plotted slope profile. Using denudation rate as a solution for the diffusion equation, an apparent age index can be calculated, which is the total amount of denudation through total time. Plots of slope angle versus slope height and apparent age index versus slope height are useful for determining relative or absolute ages and denudation rates. Mathematical simulation plots of slope angle versus slope height can generate equal denudation-rate lines for a given age. Mathematical simulations of slope angle versus age for a given slope height, for equal denudation-rate at a particular profile site, and for comparing to other sites having controlled ages.

Key Words: geomorphic age dating, diffusion equation, denudation rate, geomorphometry, apparent age.

1. Introduction

Slope changes as a function of time are measured by geomorphometric parameters that such as slope length, slope gradient, slope height, and convex and concave curvatures, as well as nonmorphometric parameters such as surface material, soil, and stratigraphy. Empirically changing landforms can be viewed as relative, and perhaps absolute, dating possibilities, as in field observations of degrading slopes, extending crest rounding, drainage network development, drainage dissection, and alluvial aggradation.

The diffusion equation has been successfully applied to many physical phenomena such as heat flow, viscous flow, and chemical dispersion. It has also been used to model tectonic modifications such as dating scarp-forming earthquakes. Initial morphology of new fault scarps is modified through erosional degradation of crest slopes and depositional aggradation on foot-slopes. These changing forms can be successfully modelled by the diffusion equation. Currently, applications of this method are extending to geomorphic modifications of coastal slopes, glacial tills or moraines, and fluvial terraces.

The diffusion equation has been traditionally confined to the following basic assumptions: (1) unconsolidated and homogeneous material (sand, gravel, or sandy gravel), (2) closed system over the whole slope length(similar volumes of deposited and eroded materials), and (3) noncatastrophic or regular processes(creep, wash, or

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micro-rolling). However, applications are now beginning to include landforms and processes beyond the limits of these basic assumptions. For example, consolidated materials, fluvial processes such as gulling, and open slope systems have been modelled.

2. Previous Studies

Slope modifications analogous to the diffusion equation was identified by G.K. Gilbert, who compared erosional rounding of the badland crest to heat conduction in wedge-shaped bodies (Gilbert's field notes in Hanks *et al.*, 1984). He was also aware of fault scarp erosion as a function of time (Gilbert, 1928).

Culling (1960 ; 1963 ; 1965) first proposed a linear diffusion model, as a model of soil creep processes. His model is process-response, based on assumptions of (1) random downslope movement of individual grains, (2) soil creep as the dominant process, and (3) movement rate as a function of slope angle (1963 and 1965).

Hirano (1975) presented a mathematical diffusion model of slope development based on the boundary conditions of various equilibrium states : establishing, steady, and destroyed. Trofimov and Moskovkin (1984) presented diffusion models of slope development having a (1) linear coefficient, (2) quadratic coefficient, (3) vertical lowering of base level (downcutting), (4) stable base level with horizontal undercutting, (5) steady-state regime of undercut slopes, and (6) pediment and scree slopes. Both Hirano and Trofimov and Moskovkin extended diffusion model applications to more variable slope phases, but not to real data.

Wallace noted that the relative ages of fault scarps were indicated by their geomorphometry (1977). He formulated relationships between dominant erosional processes and scarp ages, with initial gravity-controlled slopes changing to debris — and wash — controlled slopes, and then to wash — and splash — controlled slopes.

Bucknam and Anderson (1979) empirically quantified the relation between slope angle and height for fault scarps of different ages using graphic plots, and showed that younger slopes have steeper maximum angles. Later, this simple plotting method was used for geomorphic dating of various initial conditions, climates, and materials : fault scarps (Colman and Watson, 1983 ; Mayer, 1984 ; Hanks *et al.*, 1984 ; Machette, 1986 and 1988 ; Zhang *et al.*, 1986 ; Pearthree and Calvo, 1987), river terraces (Colman, 1983), marine terraces (Crittenden and Muhs, 1986), and glacial terraces (Pierce and Colman, 1986).

Nash (1980a, 1980b, 1981 and 1984) applied simple linear models to lake coastal slopes, fault scarps, and fluvial terraces under different lithologic and climatic conditions. His diffusivity, c, is related to the lithology, climated and aspect (directional orientation) of a slope. Sterr (1985) tried to present quantitative analysis of scarp profiles using morphometric parameters : maximum slope angle, scarp height, crest position, and crest curvature.

Nonlinear diffusivities have been suggested (Andrews and Hanks, 1985 ; Pierce and Colman, 1986) and a nonlinear model was introduced by Andrews and Bucknam (1987). There are important considerations which must be made concerning the effects of scarp height and slope aspect (Pierce and Colman, 1986), and the effect of far-field slope (Hanks and Andrews, 1989) on diffusivity. Comprehensive explanations of the diffusion equation and geomorphic dating have been undertaken by Mayer (1987), Colman (1987), and Machette (1989).

3. Diffusion Equation Modelling

The diffusion equation applied to slope implies that the change in elevation of a point is proportional to the profile curvature at that point ; with time the crest and the foot-slopes become rounded and the maximum slope angle decreases on the

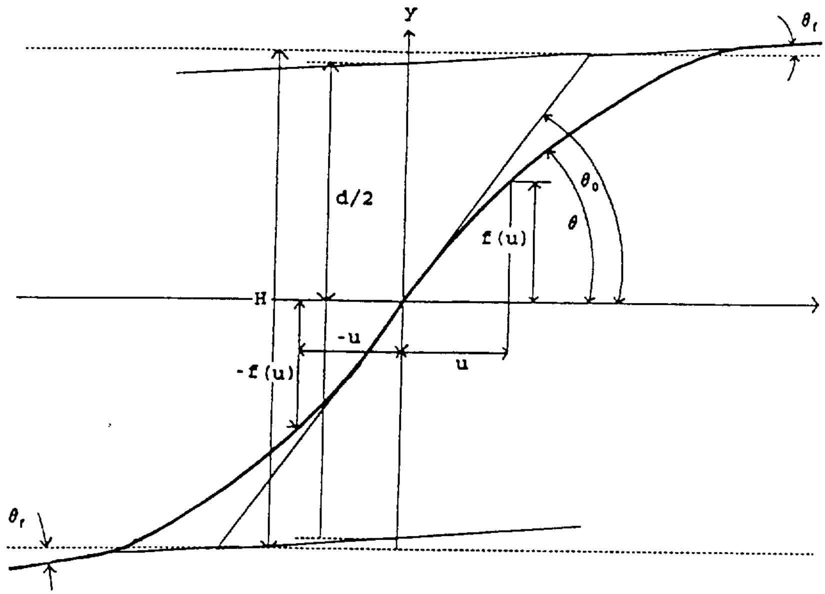

Figure 1. Slope geometry for diffusion equation, where d is surface offset, H is slope height, θ is present maximum slope angle, θ_0 is starting angle (generally angle of repose), θ_f is far-field slope, c is diffusivity of denudation rate, t is age of slope after start of diffusion process, and u and f(u) are arbitrary x and y coordinates.

straight mid-slope (Colman and Watson, 1983). Figure 1 shows the geometry of a fault scarp of shoreline slope. Variables symbolized in this figure are offset, height, time, far-field slope, relative elevation, tangent of the angle of repose, mass diffusivity, far-field slope angle, and maximum slope angle.

Application of the diffusion equation model assumes the following: (1) effects of the lenght along the slope are neglected, (2) there is no overall lowering of the constant base level of the slope, and (3) the initial formation of the slope is by a single event and subsequent degradation of the slope is under constant conditions (Colman and Watson, 1983). The denudation rate coefficient, c, does not vary with position or time (Pierce and Colman, 1986). In this study, far-field effects are neglected. If eolian or fluvial processes strongly affect the slope profile, the model is not valid.

If deudation rate c is independent of x, a lenear equation is the general case.

$$\frac{\partial y}{\partial t}=c\frac{\partial^2 y}{\partial x^2}$$

Solutions to the equation are derived for both a vertical slope and a slanting slope with a planar initial profile (Colman and Watson, 1983). The latter case is fitted to the angle at which diffusion processes start. The denudation rate is derived from the solution to the diffusion equation in case of angle of repose (Lee, 1993). This equation for the denudation rate was first used in the analysis of actual field data by Pierce and Colman (1986).

$$c=\left(\frac{H}{4t^{\frac{1}{2}}\tan\theta_0 erf^{-1}(\tan\theta/\tan\theta_0)}\right)^2$$

Using the above equation, denudation rate, c, or the producft of the denudation rate and slope age, ct, can be calculated from the present maximum slope angle at a given height with an assumed constant

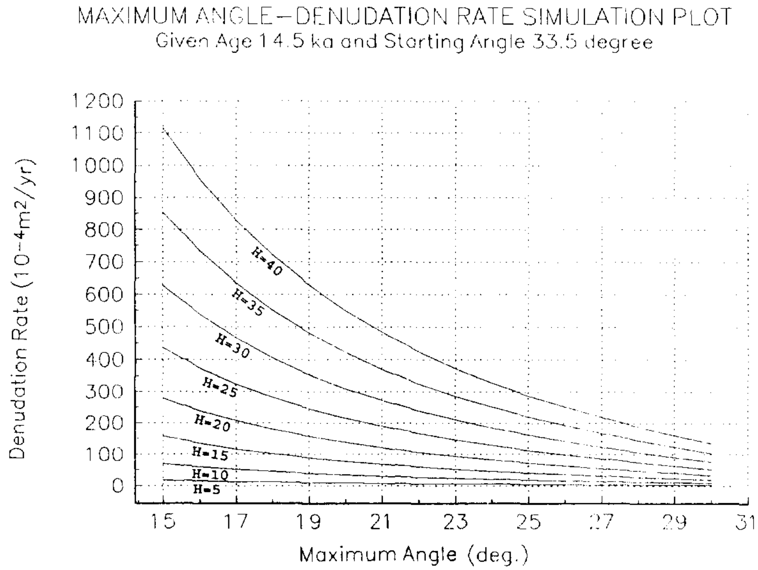

Figure 2. Sensitivity of denudation rate to maximum angle and slope height.

starting angle.

Figure 2 shows the sensitivity of denudation rate to the present maximum slope angle and slope height. At a given age and starting angle, the greater the maximum angle of slope is, the more resistant the slope material is. This means that slope is relatively insensitive to height. A large slope angle means a small change of slope from the starting angle during a given time. Slopes of low maximum angle generally have less resistant materials and are very sensitive to slope height.

Initial slopes of free faces retteat rapidly

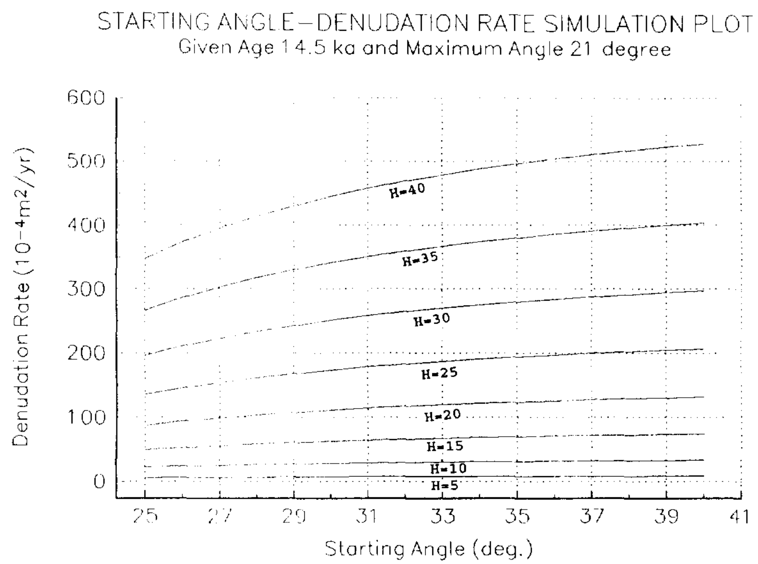

Figure 3. Sensitivity of denudation rate to starting angle and slope height.

to reach the angle of repose, which is typically 33^0–35^0, for unconsolidated alluvium (Machette, 1988). Along the Wasatch fault zone, most of the 500-to 1,000-yr old scarps have lost their free face and have retreated to an angle of repose of less of 38^0 (Machette, 1988). The angles of repose in well-sorted sand is about 30^0. In gravelly sand, the angle increases to 35^0–36^0 (Rahn, 1969). Generally, the angle of repose is the starting angle for the diffusion equation modelling, and is independent of aspect and slope height (Pierce and Colman, 1986).

The denudation rate is more sensitive to the starting angle with greater slope heights for a given age and present maximum slope angle (Figure 3). Denudation rate is proportional to the square of slope height in the diffusion equation model. In the case of high slopes, one should be careful to determime the starting angle with material characteristics in mind.

Determining accurate value of denudation rate (also known as mass diffusivity, degradation rate coefficient, and coefficient of diffusion), is important for age determinations. The degradation rate is related to material properties, paleo-and modern climates, and vegetation (Machette, 1989).

From the solution of the diffusion equation, the values of the product of c and t can be calculate. For example, if the age of the slope is known, a certain denudation rate is ct/t_d (Nash, 1980a), where t_d is the known age. The diffusion equation can also provide ct values.

There are other similar ways to estimate c values for slopes of known ages (Mayer, 1984). Using the diffusion equation, a range of c values can generate a series of synthetic slope profiles, one of which provides a best match to a profile of known age. This results in a sample of c value can generate a series of synthetic maximum slope angles for a range of slope heights, with one member of the series providing a best fit between the synthetic and actual data (Nash, 1980a). c is based on field data and is affected by many factors that contribute to slope morphology ; therefore, the variability of c can be reflected in scatter about the regression line of maximum slope angle and slope height (Mayer, 1984).

The value of c may vary according to material and climatic conditions and gener-

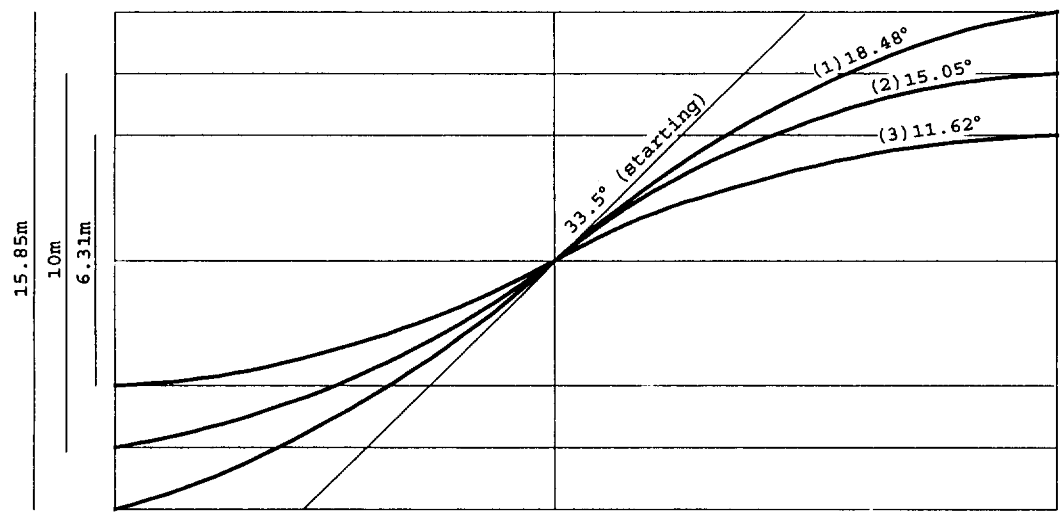

Figure 4. Relation between maximum slope angle and slope height at a given age (120 ka). Height : (1) 15.85m, (2) 10m, and (3) 6.31m. Profile Site : highest shoreline of Lake Diamond, 6061 ft. Nevada.

ally will be determined as an average over the range of microclimate conditions in an area of slope sites (Hanks *et al.*, 1984). However, according to Machette (1986) in his study of central New Mexico, rates of slope degradation during the latest Pleistocene (15 to 10ka) must have been about one-third to one-forth of those during the Holocene can be explained by the shifting to more frequent high-intensity summer storms. Pierce and Colman (1986) presented valuable studies of degradation rate as affected by height and aspect-related micro climate: the rate increased 10-fold with scarp height, and the rate on south-facing scarps was two times that on north-facing

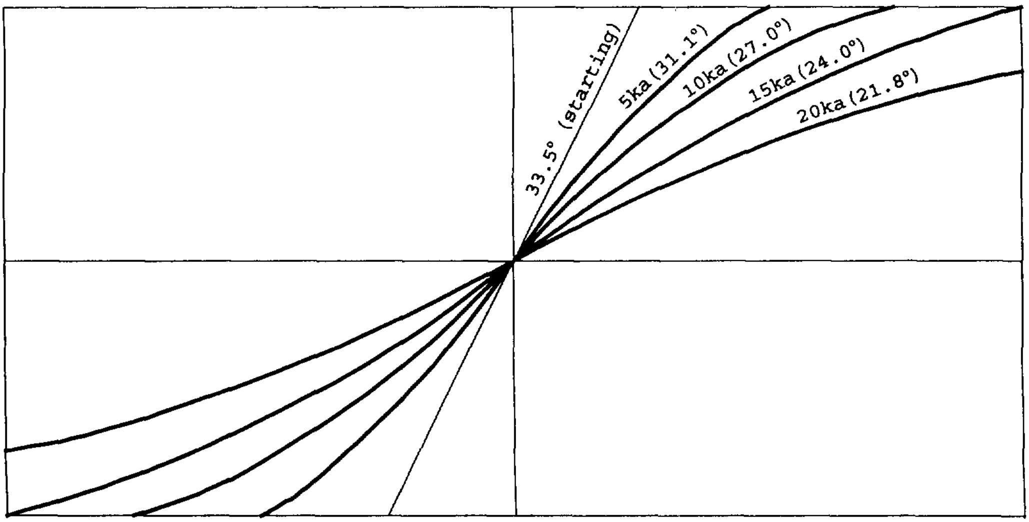

Figure 5. Relation between maximum slope angle and slope age at a given height (25.12m). Ages change from 5ka, 10ka, and 15ka (present value), to 20 ka, with constant denudation rate $c=125(10^{-4}$ m^2/yr). Site: south-facing slope of the Stockton Bar, Utah.

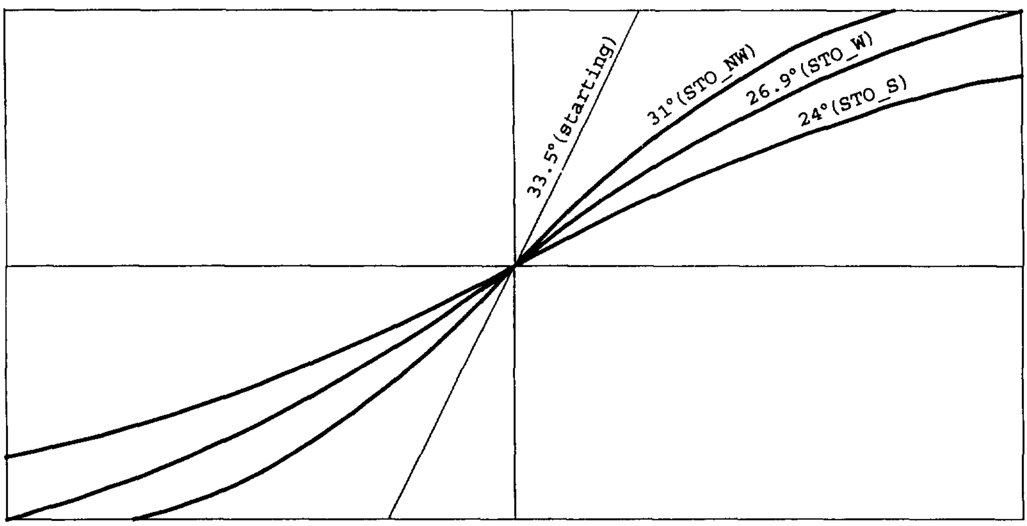

Figure 6. Effect of the slope facing direction at a given height (25.12m) and age (145.5ka). Sites: Stockton Bar and Spit, Utah.

scarps for 2-m height.

Figures 4, 5, and 6 show various effects on the slope morphology, especially present maximum angle, using calculated values of the denudation rate c from simulations of real profiling data (Lee, 1993). Each profile is conceptual in shape, based on a diffusion equation solution of the c rate. A particular equation fit to one of the profiles can be solved easily by numerical analysis with computer programmings or mathematical solution tables for calculating numerical values of x and y at a certain point.

4. Denudation Rate and Apparent Age Index

Denudation rate c can be calculated from the analytical solution of the diffusion equation. The following characteristics of the denudation rate are widely observed in actual data. (1) The rate c decreases with time.

Denudation rate may act linearly at earlier times of angle of repose and then gradually change to nonlinear types, such as the linear-and-cubic model of Andrews and Bucknam (1987) and finally again become linear when gradients become very low. (2) The rate c changes according to climatic conditions, material properties, and aspect. For example, the grain size of unconsloidated materials strongly control degradation rates (Dodge and Grose, 1980). (3) The calculated c rate is an apparent value as related to the present maximum slope angle: it is actually the average throughout the total time interval following the start of diffusive slope profile processes. (4) For a given profile, the c rate is more affected by creep on the upper portion of the slope profile. Below the inflection point, in the mid-slope, transported materials temporarily mantle the surface and wash processes replace the creep action. Wash processes cause the lower portion of the profile to become less concave and increase denudation rate.

One of principal assumptions is that a slope profile is a closed system for the application of the diffusion equation. In nature, completely closed systems such as inner foot-slopes of lagoons and craters are very rare cases. Most of these cases are not exactly closed systems, because denuded (weathered and eroded) and transported materials leave the system slowly. If, however, the amount of removed material is very small compared to the time duration, the system may act as a pseudo-closed system, which can be modelled by the diffusion equation.

The value ct can be derived easily from the solution of the equation for the c rate. When the value of $\tan\theta_0$ is given as the starting diffusive slope angle or angle of repose, and $\tan\theta$ and H values are acquired from field data, the value of ct can easily be induced. Since ct is the total degradation amount after starting diffusive slope profile processes, c is ths average rate throughout the total ago of the slope.

Since ct is not constant, the c value is not constant. Therefore, c can be considered as an apparent rate at a given time, t, and ct as an apparent age. ct values are total degrada tion amounts deived from measured vlaues of slope angle (θ) and slope height (H) of present day and present apparent c rate.

The regression slope is steeper with higher denudation rates of older ages. The reason for this is that the value of ct is indirectly proportional to the squared value of the height, and is inversely proportional to the squared value of the inverse error function relatintg to maximum slope angle. ct can be calculated from the equation: $\{H/4t^{1/2}\tan\theta_0 \mathrm{erf}^{-1}(\tan\theta/\tan\theta_0)\}^2$ (for detailed mathematics, Lee, 1993, Appendix B). Comparison of slope degradation in terms of ct accounts for (1) the rdeuced absolute rates of transport as the surface gradients decrease, and (2) volume differences based on the correct relation between height and volume (Pierce and Colman, 1986).

When comparing two different ct values for different slopes with-the same $\tan\theta$, the following equation can be derived, as proposed by Nash(1980a).

$$(c_1t_1)/(c_2t_2)=(H_1/H_2)^2$$

rearranging,

$$(t_1t/_2)=(c_2/c_1)(H_1/H_2)^2$$

or

$$(c_1/c_2)=(t_2/t_1)(H_1/H_2)^2$$

If the ages and heights of two slopes are known, and their ages are different, a denudation rate can be calculated which is indicative of the climatic conditions during the time interval after the older slope and before the younger one.

Denudation rates for discrete intervals in the late Pleistocene can be calculated using a step-function equation (Machette, 1988) under conditions of similar height, material, and aspect.

$$ct=c_1t_1+c_2t_3+\cdots+c_nt_n,$$
$$\text{where } t=t_1+t_2+\cdots+t_n$$

The differences of c values for different time intervals suggests that lower rates are due to increased vegetation cover and surface stability in the late Pleistocene (Machette, 1988). If factors such as material, aspect, and time interval or age are well controlled, this equation may provide a basis for the study of climates during particular late Pleistocene intervals.

5. Simulation of Diffusion Models

If we evaluate the equation for denudation rate, the relationship between slope angles and slope height can be identified for a given age and denudation rate. Figure 7 presents sxamples of this relationship (Lee, 1993). Each line is an equal denudation-rate line, which depicts the relationship between the maximum slope angle and the slope height as predicted by the diffusion

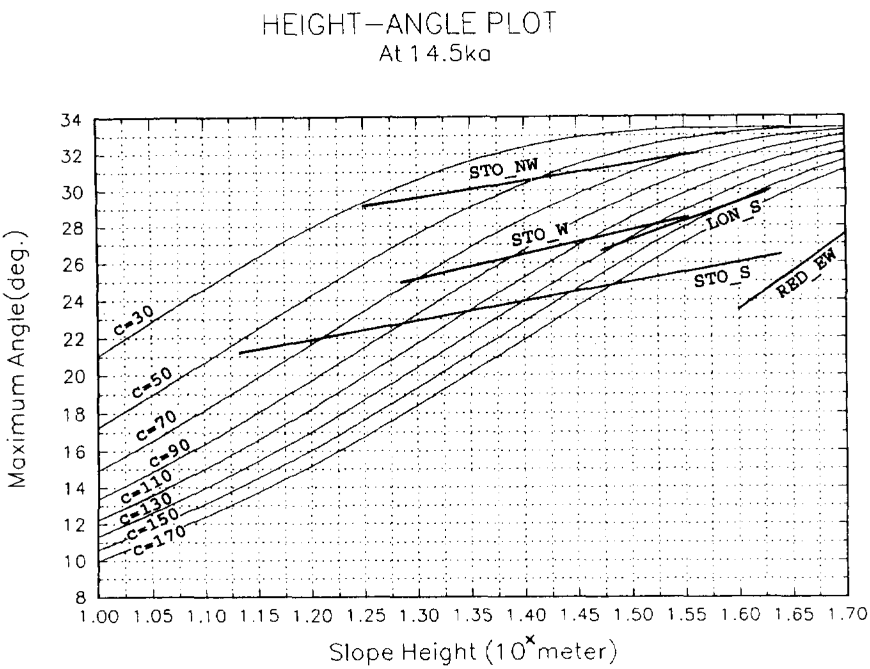

Figure 7. Simulation plots of the slope angle versus slope height with various denudation rates at age 14.5 ka.

equation model for a given degradation rate (from c=30 to 170 $10^{-4}m^2/yr$) at a given age (14.5 ka) and starting angle (33.5^0). This simulation plot follows the method of Pierce and Colman (1986, Figure 8, p.877). For example, near the left edge of line c=70, a slope of height 12.59m (log H=1.1) has a maximum angle of 18^0 and a 20-m slope has an angle of approximately 23.5^0.

Each line of a particular denudation rate is derived by calculating values of the maximum angle at a given slope height. Regression lines of regional slope profile sites show constant-value lines of c modeled by the diffusion equation. Slopes of greater height have higher denudation rates.

This indicates the dependence of the denudation rate on slope height, because wash processes sometimes involve rilling or gulling (Pierce and Colman, 1986). The dependence of c on H is inversely related to the gradient of the regression slope (x-axis coefficient) of a regression line for a particular profile site. As the x-axis coefficient at a certain site is greater, the regression line transects less number of the c value lines and tends to run parallel with a particualr c value line. This means lower sensitivity of maximum angle to slope height and relatively lower c values at greater height of a certain profile site.

Sites having lower x-coefficients are more sensitive to the dependence of c on H. This means that their profiles have been affected by wash-related slope processes after the start of diffusive profiles processes. The slope site RED-EW has a high x-coefficient. Sites with abnormally high x-coefficients are not good examples for comparison with others using the relation between slope angle and slope height for age dating.

From the diffusion equation model, we can estimate the age or denudation rate at a given height, when a certain site has a well controlled age for comparison. The numerical simulation model for calculating age or denudation rate can be derved by solving the diffusion equation for c.

Figure 8 show an example of simulation models derved from the diffusion equation.

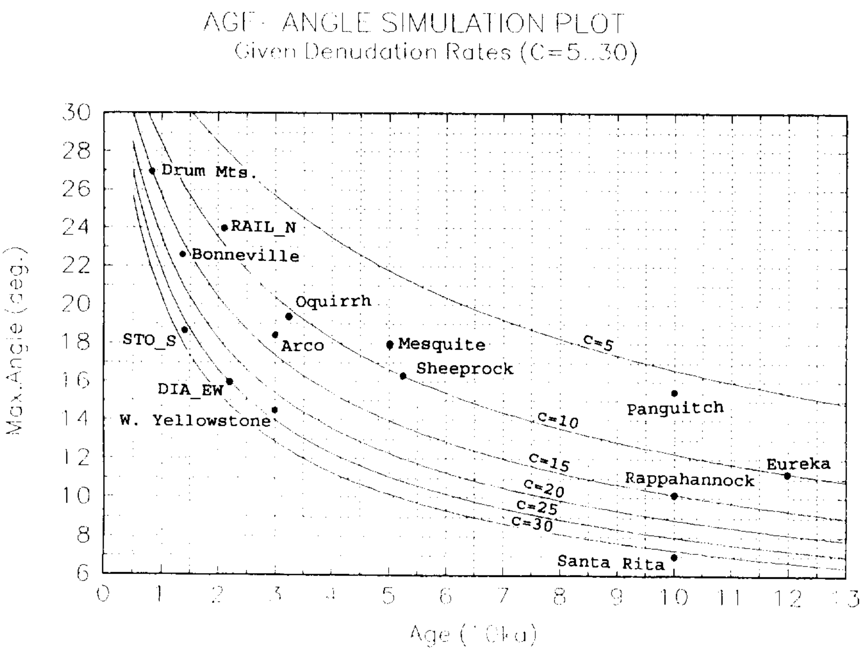

Figure 8. Angle-age simulation plot at height 7.94m with given denudation rates (from c=5 to c=30).

The equal-denudation-rate lines are plotted for a given height 7.94m (log H−0.9). Along all c-rate lines, maximum slope angles decrease rapidly at first and later decrease very slowly. This is because the denudation rate is proportional to the slope gradient, as predicted by the diffusion model. The denudation rate at each site depends on factors such as material, location, climate, direction and vegetation. This c rate is an apparent value, indicating an average rate through the total age. The apparent age of a certain site, estimated at a given height (7.94m), can be directly plotted if one parameter of the age and c rate is controlled. If the ages or c rates of some sites are compared using this model, and the differences between the compared ages is great, e.g. between 14.5 ka (Bonneville shoreline) and 120 ka (Eureka, north-facing of Lake Diamond), it is difficult to explain the meaning of comparative c rates because averaged c rates are used. However, the c rates at the 120 ka site can be estimated discrete intervals of age if younger reference sites of controlled ages exist and their material conditions are similar to the site of 120 ka.

The ages of some sites, which are already approximately controlled, are used for denudation rates of the sites themselves and for denudation rates of the sites themselves and for ages or c rates of other sites that are compared in this model. As a constant slope height in this model, 7.94m (log H=0.9) is chosen because it is the most common height for comparison. Since at a given height of 7.94m, the slope angle is kinwn from the regression equation of the maximum slope angle versus slope height, it is easy to calculate the age, depending on the material characteristics, or calculate the denudation rate at the controlled age. It is assumed that (1) the starting slope angle is 33.5^0, which is generally accepted as the angle of repose, and (2) each denudation rate respects al factors affecting the rate, such as slope materials, ancient and present climates, location (latitude and altitude), aspect, and far-field slope.

6. Conclusion

The diffusion equation model is applicable for describing the geomorphic evolution of most kinds of slope profiles under conditions imposed by three basic assumptions: (1) homegeneous materials, (2) closed geomorphic systems, and (3) noncatastrophic, or regular (diffusive), slope processes.

Slopes that have well-controlled ages can be good references to the solution of absolute age or material characteristics. Well-known ages can be derived from episodes of drastic climatic changes or catastrophic floods.

Many slopes, with different aspect, material conditions, vegetation cover, slope heights and other factors have similar ages. It is possible to identify the effects of a certain factor such as vegetation, aspect, or far-field slope, if all other factors and parameters are assumed or given under normalized conditions.

The angle of repose, which is generally accepted as the starting angle, can be estimated if denudation rate and age are known. Denudation rate is particularly sensitive to starting angle on high slopes. If two slope profiles have similar slope factors and different slope gradients, the lower slope has the possibility of a younger-aged land slide or faulting origin.

In the field, slope profiling is easy, nondestructive, and inexpensive. Solutions for the diffusion equation model can be easily obtained through numerical analysis or from mathematical solution tables. The ages of some slopes can be accurately determined by isotopic dating methods and stratigraphic investigations. Therefore, the accuracy of the diffusion equation model as an additional geochronology tool can be tested by comparing its results with other geochronology methods.

Conclusively, the diffusion equation model is applicable for describing slope modifications after a particular geomorphic event.

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지형연대 측정을 위한 디퓨젼 공식 모델

이 민 부

디퓨젼 공식은 사면의 변화를 측정하여 지형의 변화를 측정하고 과거의 지형환경을 복원하는 하나의 방법이다. 주로 구조지형에 적용되어 왔으나 최근에는 해안, 빙하, 단구 등의 지형에도 적용되고 있다.

특정한 지각변화나 지형변화 후에 규칙적인 사면의 변화를 가정하여 지형변화의 정도, 지형변화된 시간을 예측한다. 기본적인 가정으로는 균일한 물질, 비교적 폐쇄적인 시스템, 규칙적인 사면변화가 요구된다. 근래에는

이러한 조건을 벗어나는 경우에도 조심스럽게 적용되고 있다.

급격한 변화를 가진 사면은 짧은 시간내에 안식각을 얻게되며 이때부터 디퓨젼 공식이 적용된다. 그리하여 현재 최대 사면각을 측정하여 안식각으로부터의 변화량이나 혹은 소모된 시간 (사면연대)를 알아낸다.

ct, 즉 사면삭박률과 사면연령의 합으로 주로 공식으로부터 계산되므로 ct 둘 중 하나를 알아내면 유용한 지형연대측정법이 된다. 따라서 기준이 될 수 있는 사면의 연대가 조사되면 그 사면의 지표물질의 특징을 알 수 있고, 지표물질상의 비교가 가능한 곳에서는 상대적인 연대가 측정 가능하다. 삭박률은 초기의 안식각, 사면의 높이, 현재의 사면각, 일사의 방향에 따라 민감한 반응을 보이므로 유의해야 한다.

시뮬레이션에 있어서, 현재 사면각과 사면의 높이 사이를 나타내는 그래프가 디퓨젼공식으로부터 얻어지는 데 여기에서 여러 지역의 사면각의 연령차이를 예측할 수 있고 현재의 사면각과 알려진 연령간의 그래프에서는 각 지역 사면의 물질적인 특징을 알 수 있다.

디퓨젼 모델은 대체적인 기본 가정을 지키면 지형변화를 기술하거나, 물질의 특징이나 기후변화를 어느 정도 알 수 있고, 따라서 과거의 환경을 복원하는 지형적 연대측정의 한 방법이 된다.

主要語: 지형연대측정, 디퓨젼 공식, 삭박률, 지형태학