Geomorphology LAB
FAULT-SCARP DEGRADATION

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Supplies Needed
- calculator
- straight-edge ruler

PURPOSE

The evolution of the Earth's surface over time is governed by the balance between constructional (tectonic) processes and destruction (erosional) processes. One of the simplest illustrations of this balance is the case of fault scarps, which are steep slopes formed where a fault has ruptured the ground surface during an earthquake. Construction of a fault scarp occurs in seconds and is followed by degradation of the scarp over many years. In some cases, degradation can be modeled numerically, so that the shape of the slope in the past or in the future can be inferred. This tool is particularly valuable in paleoseismology because it sometimes can be used to determine the ages of ancient earthquakes from fault scarps that otherwise would be impossible to date. This exercise will show you the basics of slope degradation modeling and how to use such models to date fault scarps.

INTRODUCTION

How slopes evolve over time is a question that geomorphologists have been debating for more than a century. William Morris Davis (1899) argued that erosion over long periods of time tends to make slopes less steep and more rounded. In contrast, Walther Penck (1924), a German geomorphologist, argued that slopes represent a dynamic balance between erosion and uplift. According to Penck, slopes were straight, convex, or concave as a result of changes in uplift rates as the slopes formed. The followers of Davis and Penck waged ideological warfare for many decades until most scientists realized that ideology makes bad science. Davis's theory underestimated the variability of tectonic processes, and Penck's theory underestimated the variability of erosional processes. Most geomorphologists today focus on the individual processes that shape the landscape.

Weathering-limited slopes versus Transport-limited slopes

Two steps are necessary for erosion to act upon a surface: weathering and transport. Weathering is the step that loosens rock. Various physical, chemical, and biological processes act to pull rock apart into individual blocks, grains, or molecules. Those processes alone, however, are insufficient to erode anything. Where weathering alone occurs on a surface, a cover of loose sediment or soil accumulates, eventually covering the rock and protecting it from further weathering action. For erosion to occur, weathered material must be *transported* away.

Both weathering and transport are present on most slopes, but one of the two usually occurs somewhat faster than the other. Which process is faster profoundly shapes a slope. The slower process *limits* erosion. Geomorphologists classify slopes as either **weathering limited** (weathering occurs more slowly than transport) or **transport limited** (transport is the slower process). Weathering-limited slopes are characterized by bare rock exposed at the surface and gradients that can be very steep, even vertical. Transport-limited slopes are characterized by a cover of sediment at the surface. Unconsolidated sediment can never be steeper than the angle of repose of the material (25–30° in sand), so that transport-limited slopes tend to be less steep. The dominant erosional process on transport-limited slopes is **creep**, which refers to the slow movement of sediment as a result of gravity. Other processes such as raindrop impacts and frost action also contribute to downslope creep. Most importantly, sediment creep is a process that can be simplified and represented by a numerical model. In contrast, erosion on weathering-limited slopes is much more difficult to quantify.

Diffusion Modeling

The evolution of a transport-limited slope through time can be evaluated quantitatively by assuming that sediment transport is a **diffusion process**. Diffusion also describes how chemicals in solution move from areas of high concentration to areas of low concentration, and how heat moves from areas of high temperature to areas of low temperature. In sediment diffusion, gravity carries sediment from an area of high elevation (the top of the slope) toward an area of low elevation (the base of the slope). Without fresh uplift or downcutting, diffusion tends to make slopes smoother and less steep over time.

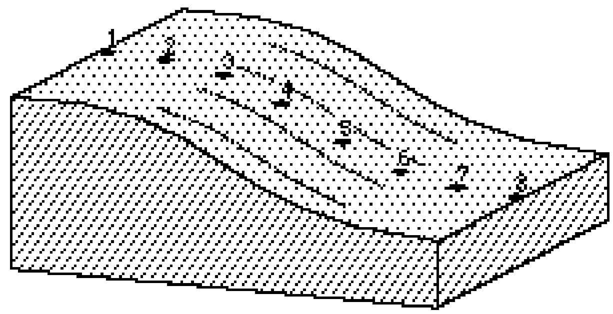


Figure 1. An elevation profile across a slope is measured at several points.

In the field, a geologist typically measures the elevations of a series of points in a line perpendicular to the scarp using surveying equipment. The heights of those points and the distances between them are used to construct a cross section.

In order to calculate rates of sediment diffusion, it is necessary to subdivide a slope into a series of short segments. Calculations are easiest if all segments have the same width. If a slope has been profiled in the field, then slope segments can be the intervals between measured points. Diffusion models look at each of these segments as a tall column of sediment (Figure 2). Like a series of small basins over which a waterfall flows, each segment receives input (water on the waterfall; sediment on the slope) from the segment above it and sends discharge into the segment below.

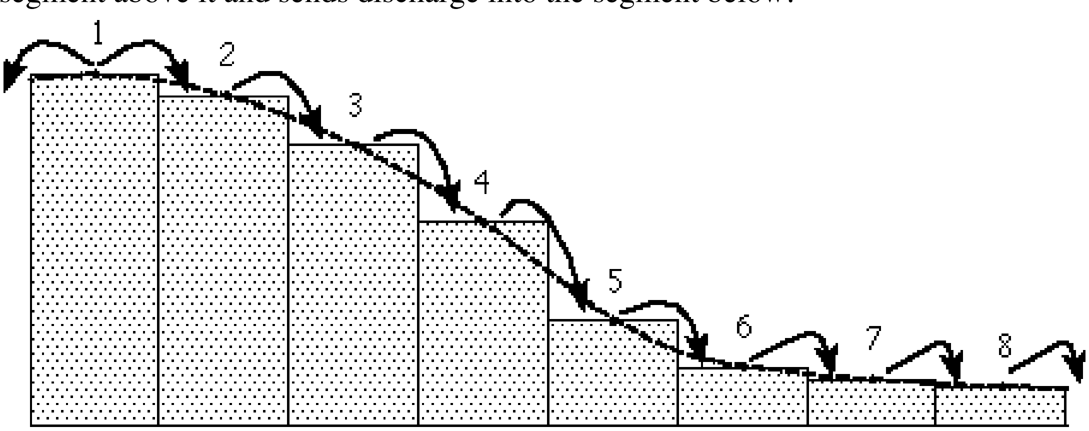


Figure 2. In order to model a slope, it is convenient to imagine the slope as several discrete segments with sediment moving from the highest segment into successively lower segments.

Sediment diffusion can be evaluated quantitatively by using the **Continuity Equation**:

$$\frac{\delta z}{\delta t} = \frac{\delta R}{\delta x} \qquad (1)$$

where **z** is the height (elevation) at any given point on a slope, **R** is the rate of sediment movement, **x** is horizontal distance, and **t** is time (Table 1 below summarizes all the parameters used in this chapter). The Continuity Equation is one of the simplest equations in science: translated into English, it simply states that the change in elevation through time at a point equals the difference between the amount of sediment *arriving at* that point and the amount of sediment *leaving*. For example, a 10 m wide slope segment that receives 20 m^2 of sediment from upslope (on a two-dimensional cross section, volume is measured in m^2) and sends 30 m^2 downslope thereby loses 10 m^2, and an average of 1 m of material erodes from that 10 m length of the slope.

Table 1. Parameters used in calculating slope diffusion.

Parameter	Explanation	Units
z	elevation	meters
t	time	years
R	sediment flux rate	m^2/ yr
x	horizontal position	meters
$\delta z/\delta t$	elevation change over time	m / yr
$\delta R/\delta x$	change in transport rate	m^2/ yr^2
κ	diffusivity	m^2/ yr
$\delta z/\delta x$	slope gradient	none

There is a second equation on which diffusion modeling is based. This equation relates the rate of sediment transport (R), a constant (κ, called *diffusivity)*, and the slope gradient ($\delta z/\delta x$):

$$R = \kappa \times \frac{\partial z}{\partial x}. \qquad (2)$$

Other, more complicated versions of this equation exist, but this simpler version can be used where sediment transport is caused mainly by creep. The diffusivity constant (κ) is very important here. Diffusivity characterizes how easily the sediment can be moved and how much the local climate can move it. Diffusivity varies substantially from one area to another. In order to estimate the sediment-transport rate (R), it is necessary to measure diffusivity in the field or infer it indirectly.

FAULT-SCARP DEGRADATION

A *scarp* is defined as a steep slope or a steep portion of a larger, less steep slope. Scarps can form as a result of many different geomorphic processes. *Fault scarps* form when a fault ruptures the surface during an earthquake. Quantitative modeling of sediment diffusion has proven extremely useful when it is applied to fault scarps. Specifically, when a geologist identifies a fault scarp in the field, he or she most commonly wants to find out *when* the earthquake that caused that fault scarp occurred. Given the shape of the fault-scarp profile, given assumptions about how the scarp looked when it first formed, and given the value of the diffusivity constant, the geologist can estimate when the scarp formed.

Fault scarps that cut unconsolidated sediment or soil are very promising for diffusion modeling because they form instantaneously and then systematically degrade afterward. Older fault scarps are smoother and less steep than recent fault scarps. In principle, a geologist could measure a profile across any fault scarp and then calculate exactly how much time is represented by the degradation of the profile. In practice, several criteria must be met for a solution to be possible:

A) The scarp must be transport-limited. Fault scarps on bedrock cannot be modeled using diffusion.

B) After the earthquake occurred, the scarp must have quickly collapsed to the angle of repose (25–30° in sand).

C) It must be possible to measure, infer, or assume a value for diffusivity (κ).

D) The scarp must have formed in a single rupture event.

Of these criteria, the C often is the most difficult to meet. It is never possible to determine the age of a fault scarp without knowing the value of diffusivity. One method for inferring diffusivity is outlined in the exercise that follows.

Given the four criteria above, several solutions give the time (t) since a fault scarp formed. The following is the solution given by Colman and Watson (1983):

$$\kappa t = \frac{d^2}{4\pi} \frac{1}{(\tan\theta - \tan\alpha)^2}, \qquad (3)$$

where d is the vertical separation between the upper slope and the lower slope, θ is maximum scarp angle, and α is far-field slope angle (see Table 2). These parameters can be measured easily on a cross section across a fault scarp, as illustrated in Figure 3.

Table 2. Additional parameters for calculating fault-scarp degradation (also see Table 1 and Figure 3).

Parameter	Explanation	Units
d	vertical displacement on a scarp	meters
π	pi = 3.14159	none
θ	maximum scarp slope angle	degrees
α	average far-field slope angle	degrees

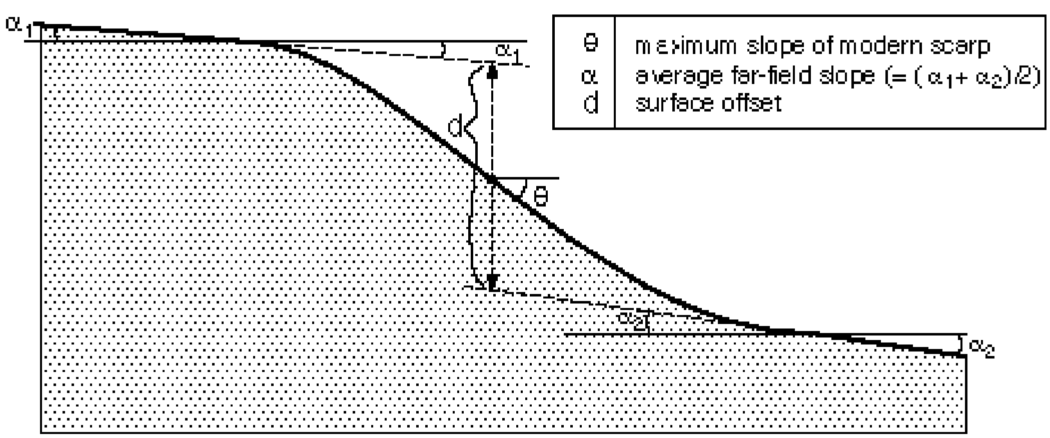
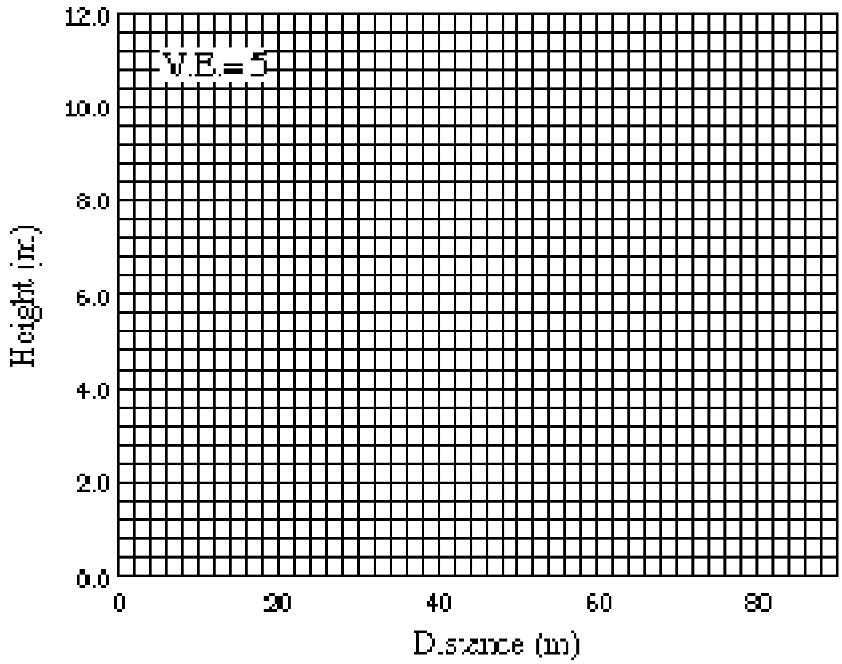


Figure 3. Measurements that need to be made on a fault scarp in order to solve Equation 3.

1) Using the elevation and distance measurements for the ten points in profile A-A', plot a cross section of the fault scarp.

Point #	Dist. (m)	Height (m)
1	0	0.00
2	10	0.30
3	20	0.90
4	30	2.00
5	40	4.20
6	50	7.50
7	60	8.70
8	70	9.80
9	80	10.40
10	90	10.60



2) Calculate the gradient angle between points #1 and #2 and the gradient angle between Points #9 and #10 (remember that a gradient angle equals arctan[rise ÷ run]). You should see that these two angles are α_1 and α_2. Calculate α for this scarp.

3) Find the steepest interval between adjacent points on this profile. Calculate the gradient angle of that interval. This angle is θ. Why can't you just measure the angle using a protractor?

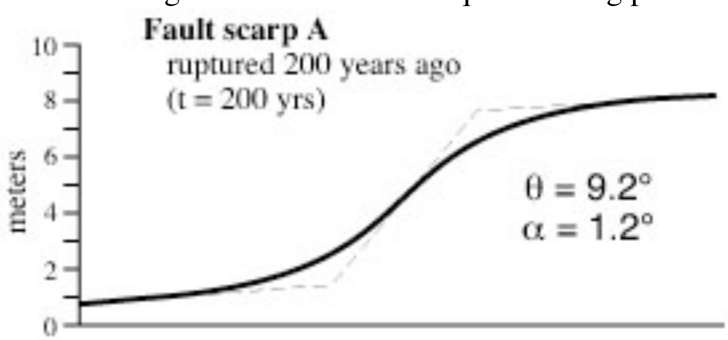
4) Using the graph on the above, measure d for this scarp. Remember to convert your measurement (cm on this page) into real-world height (in meters) using the vertical scale on the graph.

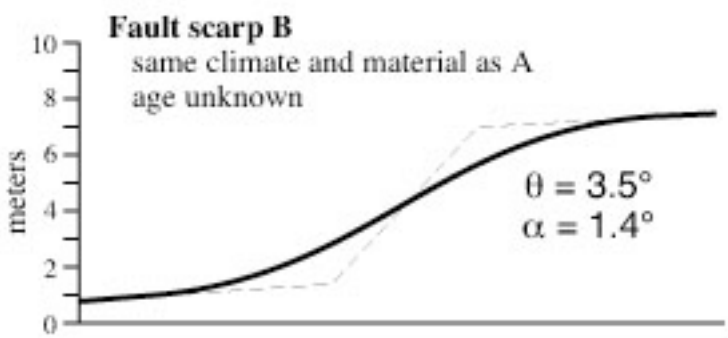
5) Assume that this fault formed 120 years ago (t = 120 yrs). Use Equation 3 to calculate the value of diffusivity on this scarp.

Equation 3 and other solutions like it assume that the faulting event (at t = 0) cut a scarp across a smoothly sloping surface made of homogeneous and unconsolidated sediments, and that that scarp degraded to the angle of repose immediately. This solution provides a simple and easily applicable relationship between the geometry of a scarp today, diffusivity, and the age of the scarp.

The Two-Scarp Problem

A geologist has identified two fault scarps along an active fault zone. Historical records show that one of the scarps (Scarp A) formed during a damaging earthquake 200 years ago. The other scarp (Scarp B) formed during some unknown earthquake during prehistoric time.





6) Using Scarp A, calculate the value of diffusivity (κ).

7) Assuming that the two scarps are cut in the same material, estimate the age of the earthquake that formed Scarp B.

8) A third scarp is identified on the same fault system, with the following measures: $d = 5.5$ m, $\alpha = 1.6°$, $\theta = 2.8°$. Using the same assumptions as above, estimate the age of the earthquake that formed Scarp C.

9) Given the information above, estimate the average recurrence interval (number of years between earthquakes) of ground-rupturing earthquakes on this fault zone.

10) Predict in what year the next ground-rupturing earthquake will occur on this fault zone. What are some problems with this prediction?

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