A mass failure model for the initial degradation of fault scarps, with application to the 1959 scarps at Hebgen Lake, Montana

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A Mass Failure Model for the Initial Degradation of Fault Scarps, with Application to the 1959 Scarps at Hebgen Lake, Montana

by Lewis Kogan and Rebecca Bendick

Abstract  Calculation of earthquake scarp ages from scarp morphology usually assumes that scarp materials reach their angle of repose immediately after a rupture. However, observations of the 1959 Hebgen Lake, Montana, earthquake scarp and similar features worldwide confirm that scarps require a finite period of mass failure to reach the initial conditions for hillslope diffusion, so the age of features less than 1000 yr old cannot be accurately estimated with methods based only on the linear diffusion equation. We apply a numerical model of this interval of mass failure degradation to vertical initial-angle scarps from the 1959 rupture at Hebgen Lake, Montana. The mass failure rate coefficient, $R_M$, ranges from $1.0 \times 10^{-2}$ to $1.2 \times 10^{-1} \text{ m} \cdot \text{yr}^{-1}$ for young scarps at Hebgen Lake and nine other locations, and has little or no dependence on climate conditions such as annual temperature range or average rainfall. Including an interval of mass failure gives more accurate age estimates where a scarp age is of the same order as the characteristic mass failure relaxation time of 10–1000 yr.

Online Material: Raw scarp survey data and MATLAB code for the mass failure model.

Introduction

Techniques for estimating the age of fault scarps and other abrupt topographic steps are based on the assumption that the shape of these features changes in a systematic way as a function of exposure time. These techniques were mainly developed because scarp ages, hence rupture timing, are of special interest to the fields of paleoseismology, neotectonics, and seismic hazard analysis. At the same time, direct methods for determining this timing, especially paleo-seismic trenching (e.g., Sieh, 1978; Rubin and Sieh, 1997; Liu et al., 2004) and cosmogenic exposure dating (e.g., Schlagenhauf et al., 2010; Nissen et al., 2009) are expensive, time consuming, and localized even as earthquake scarps are ubiquitous and increasingly well characterized as a result of new advances in terrestrial and aerial laser ranging.

Standard methods for morphologic scarp dating are based on the one-dimensional (1D) linear diffusion approximation (Nash, 1980), which assumes that the time evolution of a scarp profile is described by $\frac{\partial y}{\partial t} = c \frac{\partial^2 y}{\partial x^2}$, where $y$ is the height of the profile at position $x$, $t$ is time, and $c$ is a rate constant. Physically, the applicability of this relation requires that transport of slope particles is a linear function of the slope gradient and a rate constant, as it is for hillslope creep (Andrews and Bucknam, 1987). The diffusive rate constant, $c$, is taken to be equal to $\kappa t$, the product of a constant particle diffusivity and a time interval, such that if $\kappa$ is known, the scarp age, $t$, can be calculated from a 1D profile. Several studies support the use of constant diffusivity, hence this linear relation, in most cases (Buchun et al., 1986; Hanks and Schwartz, 1987; Hsu and Pelletier, 2004; Kokkalas and Koukouvelas, 2005). However, recent efforts by Roering et al. (2001) and Carretier et al. (2002) indicate that the linear approximation is poor for slopes at or beyond their angle of repose, requiring either nonlinear diffusion or two phases of linear diffusion with different diffusivities. The general use of the diffusion approximation for geomorphology has been thoroughly reviewed by Nash (1986), Machette (1989), Avouac (1993), and Hanks (2000).

Both linear and nonlinear diffusion approximations for hillslope transport assume that the initial condition is the angle of repose of the substrate material (Colman and Watson, 1983; Hanks et al., 1984; Nash, 1984; Andrews and Hanks, 1985; Avouac, 1993; Arrowsmith et al., 1998; Roering et al., 2001). This assumption is reasonable for an undisturbed hillslope (Gilbert, 1877; Wood, 1942; Carson and Kirkby, 1972; Young, 1972). The assumption is also reasonable for features with ages on the order of thousands to tens of thousands of years, as the diffusive profile loses sensitivity to the initial condition in the limit of large $t$ (Nash, 1984; Andrews and Hanks, 1985; Hanks and Andrews, 1989; Arrowsmith et al., 1998; Hanks, 2000). However,
many studies that use the diffusion approximation (Wallace, 1977; Wallace, 1980; Buchun et al., 1986; Kurushin et al., 1997; Suter, 2008a; Suter, 2008b) acknowledge that it may actually take decades to several hundred years to achieve a repose-angle initial condition, and nonlinear and composite scarp evolution simulations (Roering et al., 2001) point to a failure of the repose assumption at high angles or after instantaneous disturbances. Furthermore, recent work suggests that recurrence intervals for intermediate-to-large seismogenic faults may be only several hundred years (Chlieh et al., 2007; Zielke et al., 2010) and just more than 1 k.y. on smaller faults (Wesnousky et al., 2005). Therefore, while the diffusion approximation is certainly useful for active hillslopes, the uncertainty in age constraints introduced by the assumption of instantaneous repose angle can be comparable to the age of earthquake scarps and therefore misleading in hazard estimation where scarp morphology provides timing. In particular, normal fault scarps often have steep initial slopes much greater than the angle of repose, which persist until mass wasting reduces the scarp to the diffusive initial condition of the repose angle. In this case, finite-angle diffusive models of scarp age, such as Hanks and Andrews (1989), which assume instantaneous achievement of repose, underestimate age by the interval of mass failure processes. Alternatively, infinite-angle diffusive models such as Carretier et al. (2002) can overestimate scarp age by several orders of magnitude if the interval represented by an apparent rapid-rate coefficient, actually the period of mass wasting, is either omitted or truncated in favor of a standard soil diffusion coefficient. The apparent dependence of \( \kappa \) on scarp height noted for diffusion models (Avouac, 1993; Arrowsmith et al., 1998) may also be related to the time constant of the gravitational collapse phase, which is directly related to initial scarp height since the time required to bury the scarp under a debris apron at repose depends on its height.

The advent of ground-based and aerial LiDAR (light detection and ranging) for geomorphology makes it likely that many new scarps of unknown age will be identified in seismically active landscapes, requiring improved methods for accurate morphological dating without the intensity and expense of either paleoseismic trenching or cosmogenic dating. In the following sections, we describe the temporal shape evolution of scarps of known age from the 1959 Hebgen Lake earthquake in southwest Montana and then develop a method for approximating the mass failure interval of scarp evolution based on the descriptions. Finally, we compare the mass failure rate coefficient from Montana to nine other young scarp localities globally.

**Observations**

1959

On August 8, 1959, an \( M 7.3 \) normal earthquake shook the region around Hebgen Lake, Montana, creating 29 km of normal fault scarps in two main segments (Fig. 1), cutting through a variety of unconsolidated surface deposits. Historic United States Geological Survey (USGS) photographs (Fig. 2) taken in the days following the 1959 earthquake show that the initial scarp angle at Cabin Creek, Site 31, Red Canyon Creek, and near the Duck Creek and Highway Maintenance Station sites (Fig. 1) was very nearly vertical. At Grayling Creek and Chokecherry Lane, the initial scarp angle is approximately 70°. The gently curving slope immediately above the scarp in the Grayling Creek profiles is also visible in photographs taken the day after the earthquake and may imply the existence of a composite scarp, with the 1959 rupture breaking at the bottom of a much older feature.

A USGS postseismic survey (Witkind, 1964) provides initial scarp heights and dips along with some slickenside rakes from mapping undertaken immediately after the rupture, with observations made at intervals of 2000 ft along the mapped surface trace. The exact methods used for these measurements are not described. We assume that they were made with tapes, stadia rods, and Brunton compasses. The fault scarps are also described qualitatively in limited descriptions including the material hosting each scarp subsegment. The surveyors note that the local scarp dip depends on the host material, with vertical soil scarps and scarp dips in unconsolidated colluvium of 60°–85°. The scarp heights are also described as dependent on the substrate material rather than the corrected absolute displacement or the geodetic Hebgen Basin subsidence model. Ancillary scarp features related to gravitational slumping and rotation, as well as tensional fracturing, especially of the hanging wall, are also cataloged, indicating that some gravitational transport was coincident or immediately subsequent to the rupture. In no case, however, does the survey team describe a scarp at the angle of repose at the initial survey.
Subsequent scarp surveys were conducted at Cabin Creek, Site 31, Red Canyon Creek, and Grayling Creek in 1978 by Wallace (1980) and near the Duck Creek and Maintenance Station sites in 1979 by Nash (1984) (Fig. 1). These measurements were intended to test the relationship between scarp age and morphology, especially to calibrate rate coefficients for diffusive models of scarp evolution. The exact scarp profiling methods are not described in Wallace (1980) but were probably tape and dip measurements. Repeat photographs were also taken of the scarps (Fig. 2). In 1978, scarps at Cabin Creek, Site 31, and Red Canyon Creek still exhibited a vertical free face, but this vertical segment was substantially shorter than the original scarp height. The average slope angle and the slope angle at the scarp midpoint had

Figure 2. Repeat photographs of scarp areas discussed in the text. More information about the 1959 photographs can be found in the Data and Resources section, the September 1978 photographs are taken from pdf files of Wallace (1980) and Nash (1984). The original photographs used in these studies have been lost. The color version of this figure is available only in the electronic edition.
decreased in all cases, and in most cases the mean sediment size on the scarp had increased, with the finer component differentially transported to a debris apron at the base of the scarp (Wallace, 1980). Near the Duck Creek and Highway Maintenance sites, the curvature of the basal and crestal slope discontinuities had decreased (Nash, 1984), but Nash implies that a small free face could still be observed at these sites in 1979.

2008

Twenty-three scarp profiles across the 1959 Hebgen Lake earthquake scarp were surveyed in October of 2008. Using a TOTAL station, three or four profiles were measured at each of seven sites: Cabin Creek, Site 31, Red Canyon Creek, Grayling Creek, Chokecherry Lane, Maintenance Station, and Duck Creek (Fig. 1). Profiles were surveyed by walking across the scarp orthogonal to strike; the three-dimensional (3D) data is reduced to two dimensions by projecting distances in the X and Y directions onto the strike-normal profile axis. These survey measurements are accurate to tenths of meters. Trenching investigations were conducted near four of the sites nine years prior to the surveys (Schwartz, 2000). At each site, the location of the filled trench is obvious, and these disturbed areas were avoided while surveying.

Profiles (Fig. 3) at Cabin Creek, Site 31, Red Canyon Creek, and Chokecherry Lane appear to capture single scarps from the 1959 event. At Duck Creek and Maintenance Station, multiple 1959 scarps are observed in all but one of the profiles. In several of the profiles, a steepening of slope at the uppermost 0.5 m of the scarp or a lessening of scarp angle at the lowermost 0.5 m is observed, but primarily the scarp slopes have abrupt slope changes at the crest and base. Frequently, the angle of the hillslope above the scarp is not equivalent to the angle of the hillslope below. At the seven sites, the discrepancy in hillslope angle above and below the scarp ranges from 0° to 18°.

We see less evidence for major variation in mid- and lower scarp slope than was recorded in 1978, but we do observe a small, lower-angle segment at the base of many profiles. The transition from the scarp face to the original fan surface at the crest and base of the profiles remains as distinct as in 1978. Most notably, the scarp angles in the profiles at Cabin Creek, Site 31, and Red Canyon Creek are equal to or slightly larger than the maximum angles of debris slopes measured at these sites in 1978. Measured scarp angles at Grayling Creek are lower than the maximum angle but within the range of angles measured at this location.

Figure 3. Observations of scarp profiles in 2008 (circles) from TOTAL station surveys in the Hebgen Lake earthquake region with the best-fitting linear diffusion profile shown as a dashed line, and the best-fitting mass failure model shown as a solid black line. For Cabin Creek, an alternative mass failure model with a small free face is shown in gray.
by Wallace. Extrapolating Wallace’s observations at the Grayling Creek site to the site at Chokecherry Lane (<1 km distant and similar in height, aspect, and terrain) suggests negligible changes in slope angle there. Using Nash’s estimate of repose angle for active debris slopes in obsidian sand and gravel near West Yellowstone, Montana, for both the Duck Creek and Maintenance Station sites (~10 km distant and similar to Nash’s West Yellowstone site in terrain and scarp material), the profiles at these locations have angles lower than repose; none of the profiles now exhibit a free face.

Modeling

Diffusion Methods

Parameters for diffusion modeling of the Hebgen Lake scarps, including hillslope angle $\beta$, scarp slope $\theta$, and initial vertical scarp height $h_0$, were determined by inspection, except for $\theta$, which was estimated with a root-mean-squares minimization routine to find the best fit to the linear diffusion-equation solution of Hanks and Andrews (1989) (Hilley and Arrowsmith, 2003). Measured values are given in Table 1. Where profiles capture multiple scarps at Duck Creek and Maintenance Station, we reduced the profile to the largest single scarp where possible before modeling.

Forward calculations of the age of the Hebgen Lake scarp profiles measured in 2008 using this estimated $\theta$ with the finite-angle method of Hanks and Andrews (1989) give the nonsensical result that $\kappa t$ is equal to zero because the scarps have not yet, or have only recently, achieved uniform repose angles. Alternatively, the method of Carretier et al. (2002) can be used to calculate $\kappa_0$, an initial rapid rate constant prior to diffusive equilibrium, if we assume that the Hebgen scarp slopes reach their repose angle in 2008, thus fixing $t = 50$ yr. In this case, computed $\kappa_0$ values range from $2.0 \times 10^{-3}$ to $2.6 \times 10^{-2}$ m$^2$.yr$^{-1}$, with most values near $2.2 \times 10^{-2}$ m$^2$.yr$^{-1}$. This is slightly more than an order of magnitude larger than estimates for $\kappa$ for the Basin and Range (Hanks, 2000), including estimates from terrace risers in southwestern Montana near Hebgen Lake (Nash, 1984).

This result could be considered an initial local estimate for the high-angle diffusivity, $\kappa_0$. However, even the diffusion models with this high apparent diffusivity (Fig. 3) reveal systematic misfit. At Cabin Creek, Site 31, Red Canyon Creek, and Grayling Creek (and to a lesser extent at the other locations), the diffusion curve overestimates the vertical position of the upper scarp, underestimates the vertical position of the lower part, or both. Dietrich et al. (2003) argue against such nonphysical modifications of transport laws to fit observations such as large $\kappa_0$ as a proxy for gravity-driven mass transport in favor of appropriate physical representation of known processes. We therefore develop a more physically realistic model for the early interval of fault-scarp evolution.

Table 1

<table>
<thead>
<tr>
<th>Profile</th>
<th>Initial Vertical Offset (m)</th>
<th>Upper Slope</th>
<th>Lower Slope</th>
<th>Scarp Slope</th>
<th>Initial Slope (Estimate)</th>
<th>Model $b$</th>
<th>Best-fit $\kappa t$</th>
<th>$\kappa$ (m$^2$.yr$^{-1}$)</th>
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The offset, slope angles, and scarp angles are taken from surveys in 2008 and from inspection of historical photographs. Values for $b$, $\kappa t$, and $\kappa$ are calculated using a least squares fit to the linear diffusion equation of Hanks and Andrews (1989).
where mass failure changes the scarp shape until the angle of repose is reached.

Gravitational Transport

In order to develop this model for the initial period of (nondiffusive) scarp degradation, we revisit qualitative observations. Wallace (1977) performed perhaps the most detailed study of the evolution of fault scarp morphology, investigating a large set of scarps in poorly indurated materials in Nevada. These scarps formed initially as a steep offset in the topography (a free face) with a sharp crest and base. Initial scarp angles were 50°–90°, steeper than the angle of repose, so that initial degradation was gravity- and debris-controlled: material loosened from the scarp free face was transported downward by falling and deposited at the scarp base at the angle of repose, forming a debris slope. The steep free face above the debris slope retreated from the rupture point as it raveled, a process Wallace referred to as “slope replacement” (Young, 1972). Eventually, the free face was completely buried by the debris wedge, and continued slope decline was wash-controlled. More recent work on scarp evolution treats this sequence similarly; both Avouac (1993) and Arrowsmith et al. (1998) note the importance of gravitational collapse and mass failure, respectively, but still assume that it is instantaneous. Roering et al. (2001) uses a nonlinear diffusion equation that allows for much more rapid transport rates at and above a critical slope angle analogous to the angle of repose, which effectively represents the role of gravitational transport without exactly describing the physical mechanisms involved (vanMilligen and Bons, 2002; Roering et al., 2002). The Carretier et al. (2002) method also allows for rapid early-shape changes by separating scarp evolution into two discrete intervals with different rate constants. The model described here attempts to address the early, rapid evolution of scarp shape with a model derived directly from the observations of mass failure, rather than finding an equivalent diffusion relation with an artificially elevated rate constant serving as a proxy for gravitational failure.

We therefore construct a simple model where an initial free face undergoes parallel retreat until it is entirely buried by the colluvial debris slope (Wood, 1942). To do so, we describe a two-dimensional (2D) scarp profile as four linear surfaces: the upper and lower hillslopes with fixed endpoints at infinity, the free face, and the upper surface of the debris wedge (Fig. 4). For this 2D scarp profile, conservation of mass requires the area lost from the retreating free face to equal the area of the growing debris wedge. If the angle of the upper and lower hillslopes, \( b_u \) and \( b_l \); angle of repose, \( \theta_R \); initial vertical scarp height, \( h_0 \); and rate of scarp retreat, \( R \), are known, the size and position of the debris wedge and remaining free face can be calculated at any time. Once the length of the debris fan base is known, it is simple to solve for the position of the upper debris fan slope and the remaining free face relative to the initial rupture plane. (See Appendix for complete derivation of the model. MATLAB® source code is available as an electronic supplement to this paper).

Figure 4. Example 2D cross sections for scarps during the mass failure interval. At \( t = 0 \), a finite offset is created in the landscape with a height, \( h_0 \). The slope angle above the offset, \( b_u \), and below the offset, \( b_l \), need not be the same. At \( t = 1 \), the free face of the scarp has retreated uphill from its initial position at a rate, \( R \), and decreased in height as it is buried by a debris apron at the angle of repose, \( \theta_R \). The mass failure time interval ends when the entire free face has been buried by the debris apron, so that the former scarp is now a slope resting at \( \theta_R \). At this time, linearly diffusive evolution of the section initiates.

The principal simplifying assumptions of the model are that (1) the initial free face is vertical and undergoes parallel retreat at a constant rate until completely buried and (2) all mass removed from the free face is conserved in a debris wedge at the scarp base. The assumption of an infinite-angle free face becomes less appropriate as the initial scarp angle approaches the angle of repose. Parallel retreat of the free face theoretically occurs in homogenous materials (Nash, 1980), but for surface ruptures which expose inhomogenous layers, scarp retreat will occur faster in less consolidated layers (Ota et al., 1997). Conservation of mass may be violated by development of low-angle wash slopes at the toe of the debris slope or high-angle slopes connecting the free face to the debris slope, as were observed by Wallace.
(1977). It is also important to note that the assumption of constant retreat rate implies that the flux decreases over time. Alternatively, an assumption of constant flux from the free face would produce a retreat rate that increased over time. For most cases, we expect that the error resulting from these simplifications will be small. The resulting representation, like the diffusion model, describes the scarp geometry as a function of exposure time.

Similar to other morphologic dating techniques, the model requires only a small set of easily obtained geometric parameters ($b_0$, $b_1$, $h_0$, and $\theta_R$), and an appropriate estimate for the rate coefficient (the rate of free-face retreat), $R_M$. In order to derive $R_M$ estimates from the Hebgen Lake data, the timing of nondiffusive degradation at each scarp site must be determined. None of the profiles surveyed at Hebgen Lake in 2008 retained a distinct near-vertical free face (although some profiles were observed to steepen slightly toward the top), which implies that mass failure degradation had terminated by the time of the survey. The scarps at Cabin Creek, Site 31, Red Canyon Creek, Grayling Creek, and the Maintenance Station were photographed or measured prior to 2008 (Witkind et al., 1962; Witkind, 1964; Wallace, 1980). At Cabin Creek, Site 31, and Red Canyon Creek, a free face still existed in 1978 but had vanished by 2008. At Grayling Creek, the free face photographed in 1959 had disappeared by 1978, although a significant steepening at the top of the scarp still existed at that time. Nash (1984) implies that a very small free face was still visible in places near the Maintenance Station site in 1979, but documentation is otherwise scarce. These estimates allow bounds on the time required for complete removal of the free face at each site, $t_r$. At Cabin Creek, Site 31, and Red Canyon Creek, $20 \text{ yr} < t_r \leq 50 \text{ yr}$; at Grayling Creek and Highway Maintenance Station, $t_r \leq 20 \text{ yr}$. Using applicable parameter estimates from Table 1 for $b_0$, $b_1$, $h_0$, and $\theta_R$, and qualitative constraints for $t_r$, we determine minimum and maximum values (where possible) for $R_M$ (Fig. 5) by forward modeling of each scarp profile.

Results

$R_M$ estimates at Hebgen Lake range from $1.0 \times 10^{-2}$ to $1.2 \times 10^{-1} \text{ m yr}^{-1}$. Many of the larger estimates are in fact minimum values from sites where $0 \leq t_r \leq 20 \text{ yr}$ (Grayling Creek and Maintenance Station). Observations by Wallace (1980) of a steep upper scarp segment at Grayling Creek in 1978, and the implication (Nash, 1984) that a very small free face was still visible in places near the Maintenance Station site in 1979, suggest that a very small free face could be observed in places near the Highway Maintenance Station site in 1979, that the estimate for $t_{r\text{max}} \approx t_r$, and minimum $R_M$ estimates at these sites are very near the actual free-face retreat rates. At Cabin Creek, Site 31, and Red Canyon Creek, observed free faces were still 1–2 m high in 1978. Perhaps an additional 15–30 yr was required to remove these free faces, so actual retreat rates at these sites are likely nearer to our estimated minimums. Therefore, the observed span is an accurate representation of the true range of $R_M$ values at Hebgen Lake.

The observations (1) that at least three and likely five of the sites have not undergone observable scarp-angle decline in 30 yr; (2) that slope transitions at the crest and base of our surveyed scarps remain sharp and well defined; and (3) that small steep segments at the top of the scarp slope exist in about 30% of our profiles imply that these scarps are (or were until very recently) still active debris wedges beneath retreating free faces and remain at their angle of repose.

To place rough bounds on a global range of applicable values for the mass failure retreat rate ($R_M$), we also make estimates for necessary model parameters ($b_0$, $b_1$, $h_0$, $\theta_R$, and...
minimum/maximum $t_r$) from direct measurements, plotted scarp profiles, and scarp photographs of young scarps representing a variety of geographic regions and climate regimes. This set includes scarps from the 1957 Gobi-Altay earthquake in Mongolia (Kurushin et al., 1997); the 1915 Pleasant Valley (Wallace, 1977) and 1954 Fairview Peak (Caskey et al., 1996) earthquakes in Nevada; the 1739 Yinchuan earthquake in China (Buchun et al., 1986); the 1983 Borah Peak earthquake in Idaho (Hanks and Schwartz, 1987; Machette, 1987); the 1995 Nojima earthquake in Japan (Ota et al., 1997); the 1887 Sonora earthquake in Mexico (Suter, 2008a, b); the 1999 Izmit earthquake in Turkey (Klinger et al., 2003); and the 1981 Kaparelli earthquake in Greece (Kokkalas and Koukouvelas, 2005). The mass failure model is used to estimate minimum and maximum $R_M$ values at each location. Global $R_M$ values (Fig. 6) and the corresponding estimates for $b$, $b_0$, $h_0$, $\theta_R$, and minimum/maximum $t_r$ are shown (Table 2), along with the source of observations. Due to the disparate and frequently qualitative nature of the observations, no attempt is made to quantify the formal uncertainty in $R_M$. However, this uncertainty is likely less than one order of magnitude.

Approximately 65% ($\sigma$) of the global $R_M$ estimates fall within the range observed at the Hebgen scarps, although the full range of values appears to span nearly three orders of magnitude, from $10^{-3}$ to $10^0$ m·yr$^{-1}$. The average retreat rates observed in Yinchuan, China, are lower than those observed at Hebgen Lake, while retreat rates in Nojima, Japan, and near Borah Peak, Idaho, are larger. The estimated range of retreat rates at the Fairview Peak scarps in Nevada appears most similar to that observed at Hebgen Lake, Montana. Large $R_M$ variation at several sites (Gobi-Altay, Mongolia, and Pleasant Valley, Nevada) results from single observations of scarps that were nearly undegraded after many decades. It is difficult to gauge whether these very low rates are representative of poorly consolidated materials: if accurate, this would imply that poorly consolidated scarps could retain free faces for $>1$ k.y.; however, these scarps may reflect anomalous instances where areas of scarp material have become highly consolidated, in which case maximum $t_r$ values of several hundred years may be a more reasonable approximation.

### Discussion

Including significant uncertainty in our estimates of global $R_M$ values, the variation in retreat rate at any given

<table>
<thead>
<tr>
<th>Location</th>
<th>$h_0$</th>
<th>$b$</th>
<th>$\theta_R$</th>
<th>Qualitative Constraints</th>
<th>$R_M$</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gobi-Altay, Mongolia</td>
<td>5</td>
<td>5</td>
<td>25</td>
<td>Free face removed just before $t = 36$ yr</td>
<td>0.160</td>
<td>Max</td>
</tr>
<tr>
<td>Gobi-Altay, Mongolia</td>
<td>1</td>
<td>5</td>
<td>25</td>
<td>Free face remains at $t = 36$ yr</td>
<td>0.001</td>
<td>Min</td>
</tr>
<tr>
<td>Pleasant Valley, Nevada</td>
<td>2.5</td>
<td>5</td>
<td>35</td>
<td>Free face removed at $t = 50$ yr</td>
<td>0.030</td>
<td>Max</td>
</tr>
<tr>
<td>Pleasant Valley, Nevada</td>
<td>2.5</td>
<td>0</td>
<td>35</td>
<td>Free face = 85% of $H_g$ with 0.3 m retreat at $t = 59$ yr</td>
<td>0.001</td>
<td>Min</td>
</tr>
<tr>
<td>Fairview Peak, Nevada</td>
<td>2.5</td>
<td>7</td>
<td>35</td>
<td>Free face removed by $t = 20$ yr</td>
<td>0.090</td>
<td>Max</td>
</tr>
<tr>
<td>Fairview Peak, Nevada</td>
<td>2.5</td>
<td>0</td>
<td>35</td>
<td>Free face = 66% of $H_g$ at $t = 20$ yr</td>
<td>0.010</td>
<td>Min</td>
</tr>
<tr>
<td>Yinchuan, China</td>
<td>5.3</td>
<td>4.7</td>
<td>27</td>
<td>Free face = 1.2 m at $t = 245$ yr</td>
<td>0.013</td>
<td>Max</td>
</tr>
<tr>
<td>Yinchuan, China</td>
<td>4.4</td>
<td>1</td>
<td>30</td>
<td>Free face = 2.0 m at $t = 245$ yr</td>
<td>0.004</td>
<td>Min</td>
</tr>
<tr>
<td>Borah Peak, Idaho</td>
<td>Free face removed from $\sim2$ m scarp in 1 day</td>
<td>Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borah Peak, Idaho</td>
<td>2.5</td>
<td>200</td>
<td>33</td>
<td>$\sim40$-50% Free face remains at $t = 1$ yr</td>
<td>0.500</td>
<td>Min</td>
</tr>
<tr>
<td>Nojima, Japan</td>
<td>1.3</td>
<td>0</td>
<td>23</td>
<td>Free face removed at $t = 2$ yr</td>
<td>0.6</td>
<td>Max</td>
</tr>
<tr>
<td>Nojima, Japan</td>
<td>0.7</td>
<td>0</td>
<td>34</td>
<td>Free face removed at $t = 2$ yr</td>
<td>0.200</td>
<td>Min</td>
</tr>
<tr>
<td>Sonora, Mexico</td>
<td>0.65</td>
<td>7</td>
<td>20</td>
<td>Free face removed before $t = 120$ yr</td>
<td>0.010</td>
<td>Max</td>
</tr>
<tr>
<td>Sonora, Mexico</td>
<td>1.5</td>
<td>15</td>
<td>35</td>
<td>No debris present at $t = 120$ yr</td>
<td>Min</td>
<td></td>
</tr>
<tr>
<td>Izmit, Turkey</td>
<td>1.6</td>
<td>5</td>
<td>20</td>
<td>$\sim80$% Free face remains at $t = 1$ yr</td>
<td>0.100</td>
<td>Max</td>
</tr>
<tr>
<td>Kaparelli, Greece</td>
<td>0.7</td>
<td>7</td>
<td>36</td>
<td>Free face = 0.07 m at $t = 23$ yr</td>
<td>0.015</td>
<td>Min</td>
</tr>
</tbody>
</table>

Scarp heights, $b$ values, and repose angles were collected from the literature.
location appears to be comparable to, though not as large as, the variation between locations globally. This implies that the influence of internal factors such as lithology, induration, and vegetation type on free-face retreat may be more significant than that of external factors such as climate, latitude, or slope aspect. Expanding the global data set is required to undertake tests of significance for specific components. However, because mass failure scarp evolution is controlled by gravity, and not transport power, appropriate \( R_M \) values for morphologic dating of scarps is likely to be derived simply from a survey of scarp material and consolidation at any given site, in contrast to the diffusive rate constant \( \kappa \), which may depend on climate and climate history.

Comparison of \( R_M \) values with soil type (USDA Natural Resources Conservation Service, 1995) and the qualitative observations of the original postseismic survey (Witkind, 1964) at Hebgen Lake support the conclusion that \( R_M \) primarily depends on scarp material. Clay-rich alluvial fan material and colluvium at Cabin Creek, Site 31, and Red Canyon Creek are associated with vertical initial scarp angles and with the smallest \( R_M \) values; the gravely/sandy substratum at Grayling Creek and Duck Creek is associated with lower initial scarp angles (still above the repose angle) and with larger retreat rates. There are too few observations, however, to constrain an empirical rule.

We find that the fit of the mass failure model to the observed scarp profiles is significantly improved over the fit of the diffusion model at these sites (Fig. 3). The mass failure model still fails to capture what appear to be small, lower angle wash slopes at the base of several scarps and steepening near the top of some of the profiles. Where this is present, fit is improved by modeling a small free face, which requires allowing \( R_M \) values slightly smaller than the estimated minimum. The improved fit implies that free face retreat continues at a few of the scarps even though the vertical initial angle has not been preserved. Although a free face has not been present at Grayling Creek for \( \geq 30 \) yr, the poor fit of the diffusion model to the Grayling Creek scarp profiles suggests that the scarp morphology may be relatively unchanged since termination of mass failure degradation.

Conclusions

Consideration of mass failure processes in the initial period of scarp degradation provides an improvement over standard diffusion models used in geomorphic dating. For scarps in weakly consolidated materials, free faces may persist from decades to several hundred years, and mass failure must be addressed both for young scarps and scarps with event repeat intervals of \( \leq 1 \) k.y.. Estimates of \( R_M \), the scarp retreat rate, provide bounds on the critical rate parameter for this modeling technique and imply that \( R_M \) values may be primarily a function of scarp lithology and compaction.

The mass failure model presented here should serve as a useful addition to the current techniques in fault scarp age estimation. It provides a computationally inexpensive method to obtain age estimates from scarp geometry for actively raveling scarps. Combined with existing diffusion techniques (Arrowsmith et al., 1998; Carretier et al., 2002), the model could be used to improve the age resolution of both young and intermediate-age scarps. In addition to analysis of geomorphic data obtained by traditional ground-based methods (Kokkalas and Koukouvelas, 2005), morphologic dating techniques may be increasingly applied to airborne LiDAR and photometric surveys (Zielke et al., 2010; Hsu and Pelletier, 2004), where high data volume makes improved resolution possible and appropriate physical models increasingly important.

Data And Resources

The raw scarp profile data collected in this research effort is available as an electronic supplement to this paper. Other global scarp observations are from published references as noted. Historical photographs from the 1959 rupture are from the USGS Hebgen Lake photo collection. The 1959 photographs of scarp areas discussed in the text come from the USGS historical archive at http://libraryphoto.cr.usgs.gov, last accessed February 2010.

Acknowledgments

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References


Mass Failure Model for the Initial Degradation of Fault Scarps, with Application to the 1959 Scarps


Roering, J., J. Kirchner, L. Sklar, and W. Dietrich (2002). Hillslope evolution by nonlinear creep and landsliding: An experimental study: Comment and Reply, Geology 30, 482.


Appendix

We model the mass failure degradation of an initially vertical scarp by simple slope replacement (Young, 1972). Mass removed by parallel retreating of the free face is conserved in the debris slope at the foot of the scarp. The upper and lower hillslopes, vertical offset (free face) and debris slope are represented by four straight segments. The origin (0,0) is considered the base of the free face at t = 0. If the
Consider the line forming the lower hillslope to connect point \((X_{1a}, Y_{1a})\) at the base of the vertical free face to a point \((m, \tan(-m \times b_1))\), and the upper hillslope to connect point \((X_{2a}, Y_{2a})\) at the top of the free face to a point \((-m, \tan(m \times b_u) + h_0)\), where \(m\) is large enough that the boundary conditions are at infinity. The line representing the vertical free face connects points \((X_{1a}, Y_{1a})\) and \((X_{2a}, Y_{2a})\). The line segment representing the top of the debris slope connects a point \((X_{1b}, Y_{1b})\) on the free face to a point \((X_{2b}, Y_{2b})\) on the lower hillslope. Because the free face remains always vertical, \(X_{1a} = X_{2a} = X_{1b}\).

The total area lost from the retreating free face is

\[
A = R_{Mt}h_0 + \frac{1}{2}h_cR_{Mt},
\]

(A1)

where \(h_c\) is the difference in offset between the upper and lower hillslopes at time \(t\) and time \(0\), when \(h_c = h_0, h_c = 0\) only if \(b_u = b_l\) and is equal to

\[
h_c = \frac{p \sin(E_s)}{\sin(90 - b_u)},
\]

(A2)

where \(E_s\), the difference in angle between the upper and lower slopes, is simply \(b_u - b_l\), and \(p\) is

\[
p = \frac{R_{Mt}}{\cos(b_l)}.
\]

(A3)

The area \((A)\) removed by free-face retreat equals the area of the debris wedge,

\[
A = \frac{1}{2}h_dq\cos(\theta_R).
\]

(A4)

Solving for the height of the debris wedge,

\[
h_d = \frac{2A}{q\cos(\theta_R)}.
\]

(A5)

Combining with equation (A1), we get

\[
h_d = \frac{2R_{Mt}(h_0 + \frac{1}{2}h_c)}{q\cos(\theta_R)}.
\]

(A6)

For the debris wedge, using the law of sines,

\[
\frac{h_d}{\sin(E_r)} = \frac{q}{\sin(90 - \theta_R)},
\]

(A7)

where \(E_r\) is the excess angle of repose, \(\theta_R - b_l\). Extracting \(h_d\) and setting this equal to equation (A6), we get

\[
h_d = \frac{q \sin(E_r)}{\sin(90 - \theta_R)} = \frac{2R_{Mt}(h_0 + \frac{1}{2}h_c)}{q\cos(\theta_R)}.
\]

(A8)

From here we can extract the length of the base of the debris wedge, \(q\):

\[
q = \sqrt{\frac{2R_{Mt}(h_0 + \frac{1}{2}h_c)}{\sin(E_r)\cos(\theta_R)}}.
\]

(A9)

Replacing \(h_c\) and \(E_r\) with the original parameters \(b_u, b_l, \theta_R, h_0, R_{Mt}\), we get a solution for the length of the base of the debris wedge along the contact with the lower hillslope,

\[
q = \sqrt{\frac{2R_{Mt}(h_0 + \frac{1}{2}h_c)}{\sin(E_r)\cos(\theta_R)}}.
\]

(A10)

Once the length of the debris fan base, \(q\), is known, it is simple to solve for the position of points \((X_{1a}, Y_{1a})\), \((X_{2a}, Y_{2a})\) and \((X_{1b}, Y_{1b})\), \((X_{2b}, Y_{2b})\), which define the free face and top of the debris fan, respectively, with position relative to the origin at the base of the initial rupture plane:

\[
X_{1a} = X_{2a} = X_{1b} = -R_{Mt},
\]

(A11)

\[
X_{2b} = q \cos(b_l) - R_{Mt},
\]

(A12)

\[
Y_{1a} = R_{Mt}\tan(b_l),
\]

(A13)

\[
Y_{2a} = R_{Mt}\tan(b_l) + H,
\]

(A14)

\[
Y_{1b} = \frac{q \sin(E_r)}{\sin(90 - \theta_R)} + Y_{1a},
\]

(A15)

\[
Y_{2b} = -q \sin(b_l) + Y_{1a},
\]

(A16)

where \(H\) is the total hillslope offset at time \(t\), \(h_0 + h_c\).