Topographic fingerprints of bedrock landslides

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ABSTRACT

Bedrock landslides in mountainous regions may be triggered by either storms or earthquakes; the dominant mechanism in a region affects both landscape evolution and landslide hazard. We describe a simple observational test to distinguish between storm and earthquake triggers based on a probabilistic measure of hillslope morphology. In areas that are dominated by storm-triggered landslides, steep topographic slopes are concentrated on the lowermost parts of the hillslopes. Storm triggers act primarily on the hillslope toes, and landslides preferentially remove material from those locations, giving rise to inner gorges. Areas where most landslides are earthquake triggered have more uniform spatial distributions of steep topographic slopes, because coseismic shaking causes failures at both ridge crests and hillslope toes. Earthquake-triggered landslides lead to planar hillslopes and rare or absent inner gorges.

Keywords: landslides, hillslopes, landscape evolution, inner gorges.

INTRODUCTION

Erosion of montane landscapes occurs by valley incision and hillslope mass wasting (Burbank et al., 1996). A common first-order control on rates and patterns of mass wasting is the occurrence of storms or earthquakes. The magnitudes and recurrence intervals of these events influence the spatial and temporal delivery of sediment to channels and the landslide hazard. The question of whether storm or earthquake triggers dominate the erosional evolution of a montane region is thus fundamentally important. Previous studies of mass wasting (e.g., Keefer, 1994) and sediment transport (Hovius et al., 2000) that have addressed this question were based upon historical records that rarely spanned more than 100 yr and may not have included high-magnitude, low-frequency landslides. Because such landslides are volumetrically important (Kelsey, 1988; Hovius et al., 1997), it is difficult to extrapolate historical studies over time scales relevant to landscape evolution.

Storms and earthquakes can preferentially affect different parts of a montane landscape (cf. Iverson and Reid, 1992; Bouchon and Baker, 1996). The best evidence of the long-term importance of each trigger may therefore be locked in the landscape. We propose a simple method to distinguish between landscapes dominated by storm and earthquake landslide triggers. We first test the method in mountain ranges with known historical landslide-triggering records, and then extend the approach to landscapes in which the dominant triggering mechanism is unknown.

TRIGGERING MECHANISMS AND LANDSLIDE LOCATION

Landslides are triggered by the imposition of body forces on hillslope materials. Such forces are commonly caused by earthquakes or storms. Relative base-level fall occurs in most active montane landscapes and provides a sufficient condition for long-term hillslope erosion. Storms and earthquakes may periodically excite such landscapes, causing locally increased erosion rates and clustering of landslides in space and time.

Iverson and Reid (1992) found that seepage forces in near-saturated hillslopes cause significant changes in effective stresses. Spatial gradients in seepage force increase the body forces on hillslope materials and so drive failure (Iverson and Reid, 1992). Failure potential is considerably higher at the toe of a saturated hillslope than elsewhere because of localized upward- and outward-directed components of the seepage force. Hillslope saturation due to storms should, and does, cause landslides that cluster near hillslope toes (Megahan et al., 1978), although storm triggered, middle and upper slope failures involving both bedrock and colluvium have also been documented (e.g., Reneau et al., 1990). Because landslide magnitude commonly follows a power-law distribution (Hovius et al., 1997), the most frequent landslides will be small and will remove material only from hillslope toes. Densmore et al. (1997) proposed that the resulting steep toes are destroyed only by the occurrence of infrequent, high-magnitude slope-clearing landslides. Thus a landscape in which landslides are triggered by storms should contain at least some steep hillslope toes (Fig. 1), termed inner gorges by Kelsey (1988).

Vertically incident seismic waves are diffracted by surface topography such that ground accelerations may become strongly amplified toward ridge crests (e.g., Davis and West, 1973; Geli et al., 1988; Bouchon and Baker, 1996). The occurrence of landslides at or near ridge crests during moderate to large earthquakes has been attributed to this effect (e.g., Harp et al., 1981; Harp and Keefer, 1990). This clustering of landslides would cause preferential erosion of ridge crests. However, ground accelerations are pervasive, and all parts of hillslopes—including those already at risk from groundwater seepage—are likely to show an increased propensity to...

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Figure 1. Hypothetical hillslope cross sections showing (A) storm and (B) earthquake triggering of bedrock landslides. Dashed lines are prelandslide topography; solid lines are postlandslide. Landslide deposits are not shown; local storage of landslide debris is minimal in erosive channel reaches of interest in this study. Also shown are expected probability distributions of steep topographic slopes as function of distance from channel.
fail during large earthquakes. Repeated landsliding during large earthquakes should erase any inner gorges resulting from interseismic baselevel fall or storm activity (Fig. 1).

We hypothesize that the spatial distribution of landslides imposed by the dominant triggering mechanism in a region sets the mean or typical hillslope morphology. Specifically, we propose that the presence or absence of inner gorges in a montane landscape, as measured by the spatial distribution of steep slopes, should provide a fingerprint of the primary landslide-triggering mechanism. The observed clustering of storm-triggered landslides near channels suggests that their repeated occurrence over geologic time should produce inner gorges. Conversely, repeated earthquake triggering of landslides should sculpt planar hillslopes in which inner gorges are rare or absent.

STUDY AREAS

We selected study areas in which historical landslides have been primarily triggered by either storms or earthquakes. Reliance on historical data sets may be misleading if the relative importance of different landslide triggers has changed over geologic time; thus in each case we chose two examples from different climatic and tectonic settings. We also examined an area in which both triggering mechanisms have been documented, and areas in which no historical landslides have been described. We avoided areas of intense glacial erosion, in which landslides would tend to localize on steep valley walls independent of the landslide-triggering mechanism.

Areas Dominated by Storms

The Coast Ranges in northwestern California have a wet climate and relatively low historical seismicity. The mean annual rainfall is 1.25–3.0 m. Harden et al. (1995) showed a correlation between major storms and stream-side debris slides in the Redwood Creek basin between 1936 and 1976. Kelsey et al. (1995) found that storm-triggered stream-bank failures and debris slides were responsible for 99% by volume of historical mass wasting. Repeated stream-side landslides on hillslopes underlain by competent sandstone and siltstone have produced a prominent inner gorge along parts of Redwood Creek (Kelsey, 1988). Historical rates of storm-triggered mass wasting in this catchment are several times higher than those associated with seismicity (Keef er, 1994).

Historical landslides in the Lochsa River basin, north-central Idaho, have also been predominantly triggered by storms. Mean annual precipitation in the basin varies from 0.5 to 1.8 m, and historical seismic activity has been extremely low (Stover et al., 1986). Debris slides mapped by Megahan et al. (1978) were caused primarily by rainfall or snow melt and consequent high groundwater levels. Half of these landslides occurred either on the lowermost third of the hillslopes or in the channel (Fig. 2, inset).

Areas Dominated by Earthquakes

The Santa Susana Mountains in southern California receive a mean annual rainfall of 0.45 m. They were severely shaken during the 1994 Mw 6.7 Northridge earthquake, during which widespread landslide occurred in the folded late Miocene to Pleistocene sedimentary rocks that underlie the range (Harp and Jibson, 1995). These landslides were predominantly dry debris slides as much as several meters thick, many of which extended up to ridge crests (Harp and Jibson, 1995).

The Finisterre Mountains of northern Papua New Guinea receive a mean annual rainfall of 3–5 m. The range-bounding Ramu-Markham fault last ruptured in 1993 in a series of Mw 6.3 to 6.9 earthquakes (Stevens et al., 1998); such events have an estimated recurrence interval of 50–60 yr (Ripper and Letz, 1993). Landslides triggered by these earthquakes clustered near ridge crests and hillslope toes (Fig. 2, inset). We attribute the former cluster to ridge-crest shaking, and the latter cluster to dynamic pore-pressure changes in saturated lower hillslopes. The total volume of seismically released debris was equivalent to ~350 yr of interseismic mass wasting.

![Figure 2. Probability distributions of digital elevation model cells having slopes that exceed 40°, as a function of distance from channel, for study areas in which historical landslides are storm or earthquake triggered. Distances are normalized by hillslope length to allow comparison between hillslopes of different sizes; 0 corresponds to hillside toe and 1 to ridge crest. Distance bin size is 2% of normalized hillslope length. Note asymmetrical distributions from storm-dominated areas (solid lines) compared with those from earthquake-dominated areas (dashed lines). Left inset shows hillside positions of storm-triggered debris slides and slumps in Clearwater National Forest, Idaho, including Lochsa River basin (modified from Megahan et al., 1978). Right inset shows hillside positions of earthquake-triggered debris slides in Finisterre Range, Papua New Guinea.](https://geology.gsapubs.org/)

Area With Both Triggers Active

In the Santa Cruz Mountains of central California, historical landslides have been triggered both by storms (e.g., Ellen and Wieczorek, 1988) and earthquakes (e.g., Keef er, 1998). Keefer (1994) found that historical denudation rates by earthquake-triggered landslides were significantly greater than those by storm-triggered landslides or fluvial sediment transport. However, Cole et al. (1998) argued that many of the landslides that moved during the 1989 Mw 7.0 Loma Prieta earthquake were reactivated portions of storm-triggered landslide complexes, implying that storm triggers may have been more important in the region over longer time scales.

Areas of No Documented Landsliding

The Old Woman Mountains in southeastern California underwent moderate extension between 19 and 16 Ma (Foster et al., 1991), and geologic observations suggest that they have been tectonically quiescent for ~10⁸ yr (Hileman et al., 1990). Mean annual rainfall in the region is 0.1 m. Hillslopes are developed on granitic and high-grade metamorphic rocks and weathering appears to be limited; there is little or no evidence of recent landsliding. The range as a whole is largely buried in its own waste, with a deeply embayed mountain front and an extensive bajada.

The Cortez and Toquima Ranges in central Nevada are representative examples of arid, tectonically active montane landscapes. Mean annual rainfall in both ranges varies from 0.15 to 0.3 m, depending on elevation. Unlike the Old Woman Mountains, the Cortez and Toquima Ranges show strong geomorphic evidence of active Quaternary range-front faulting (Wallace, 1978; Boden, 1986). Detailed chronologies of late Cenozoic seismic activity in these ranges are not known, nor have historical occurrences of landsliding been carefully documented in either range. However, few obvious landslide scars are visible.
TOPOGRAPHIC SIGNATURES

To test the hypothesis that the distribution of steep slopes in a montane landscape reflects the dominant control on long-term hillslope erosion, we asked two questions: (1) do inner gorges occur only in areas in which landslides are primarily storm triggered, and (2) if so, can slope distributions be used to determine the dominant landslide-triggering mechanism? Using digital elevation models (30 m resolution for the U.S. study areas, 50 m resolution for the Finisterre Range), we examined hillslope morphology over regions of 250–1000 km² in each study area. We calculated the distance between each grid cell having a slope that exceeded 40° and the nearest channel, normalized by the length of the hillslope to allow comparison between different study areas. The probability distribution of these normalized distances shows where steep slopes are most likely to occur (Fig. 2). A distribution skewed toward the valley floor implies the systematic presence of inner gorges. Conversely, a uniform distribution of steep slopes precludes the widespread existence of inner gorges.

Do Inner Gorges Occur Only in Areas of Storm-Triggered Landslides?

The spatial distributions of steep topographic slopes are markedly different between storm-dominated and earthquake-dominated study areas (Fig. 2). The Redwood Creek basin shows a very asymmetric distribution: 73% of the steep slopes are found on the lower 50% of the hillslopes. This concentration of steep slopes near the hillside toes is consistent with field descriptions of widespread inner gorges (Kelsey, 1988). Similarly, in the Lochsa River basin, 78% of the steep slopes are found on the lower 50% of the hillslopes. In contrast, the earthquake-dominated areas have much more uniform distributions; 58% and 57% of the steep slopes occur on the lower 50% of the hillslopes in parts of the Finisterre Range and the Santa Susana Mountains, respectively (Fig. 2). This uniformity agrees well with field observations of hillslopes in both regions, which are commonly planar.

Do Slope Distributions Reflect the Landslide-Triggering Mechanism?

It is instructive to compare the distributions presented here to those of other regions for which the mechanisms of landslide triggering are varied or unknown. For example, both storms and earthquakes have triggered widespread landsliding in the Santa Cruz Mountains, yet the distribution of steep slopes in the Santa Cruz Mountains shows strong evidence for the presence of inner gorges and is very similar to the storm-dominated Redwood Creek and Lochsa River basins (Fig. 3). This agrees with field observations of widespread inner gorges, and is consistent with the inference of prehistoric storm-triggered landsliding by Cole et al. (1998).

Steep slopes in the Old Woman Mountains are concentrated near the ridge crests, a distribution that is unlike the other study areas (Fig. 3). This pattern is consistent with observations and numerical models of tectonically inactive ranges, in which the range front becomes deeply embayed, catchments become alluviated (Ellis et al., 1999), and bedrock hillslopes evolve toward a concave-up form (Selby, 1982). In contrast, the distributions of steep slopes in the Cortez and Toquima Ranges are relatively uniform, suggesting the possible dominance of earthquake-triggered landslides and consistent with late Quaternary tectonic activity in both areas (Fig. 3). While it is possible that hillslopes in the Cortez and Toquima Ranges may have been shaped by large storm-triggered landslides, the lack of any observational evidence for historical landsliding—despite infrequent but intense recorded storms—suggests otherwise.

DISCUSSION AND CONCLUSIONS

The correspondence between inner gorges and landslide triggering by storms leads us to reexamine previous interpretations of inner gorges. Pencz (1953) described inner gorges as forming in response to base-level fall if the incision rate at the toe of the hillslope exceeded the erosion rate at the top. Kelsey (1988) proposed that formation of inner gorges requires special conditions, including the presence of competent bedrock, continued base-level fall, predominance of debris slides, lack of sediment storage in the channel reach, and an initially low relief topography. In his view, inner gorges were sculpted by large debris slides that removed material from the entire inner gorge wall, so that the gorge form evolved through parallel slope retreat.

Densmore et al. (1997) interpreted inner gorges as transient but recurrent landforms formed by the removal of material from the hillslope toe in response to base-level fall. They suggested that the common occurrence of inner gorges in montane landscapes was a function of both the time-averaged activity of landslides clustered at the hillside toe and the long return time between slope-clearing landslides. At any one instant in time, only a few hillslopes within a region will have recently had a large landslide, and only those hillslopes will appear relatively planar.

The frequency of slope-clearing landslides during large storms or earthquakes thus plays a large role in determining the survival of inner gorges. If slope-clearing landslides are triggered more frequently by storms than by earthquakes, then inner gorges will be rare even in storm-dominated areas, and the expected association of storm-triggered landslides and inner gorges will be obscured. Conversely, if slope-clearing landslides are triggered more frequently by earthquakes, then inner gorges should be even more strongly limited to storm-dominated areas. Unfortunately, data on rates of slope-clearing landslides are limited. Of the 306 largest landslides (14%) triggered by the 1993 Papua New Guinea earthquakes, 42 can be considered as slope-clearing events, involving at least 80% of the hillslope. A comparable proportion (10 of 90, 11%) of debris slides triggered by large storms between 1947 and 1974 in the Redwood Creek basin (Nolan et al., 1976) were slope-clearing events. Slope-clearing debris slides have been documented after both large earthquakes (Harp and Jibson, 1995) and large storms (Jones, 1973; Campbell, 1975), although accurate percentages from these examples are not known. If the frequency of slope-clearing landslides depends on the magnitude of the triggering event, then a major difficulty in comparing these data is assessing the relative magnitudes of different events.

With these caveats in mind, we propose that storm triggering of bedrock landslides and consequent clustering of landslides near hillslope toes give rise to widespread inner gorges. Landslides triggered by seismic shaking produce more planar, uniform hillslopes. Inner gorges may thus be a fingerprint not only of base-level fall and debris-slide dominance, as Kelsey (1988) argued, but also of the importance of climatic processes, acting primarily on the hillslope toes, in triggering bedrock landslides. Studies of landslide size and position in response to storms and earthquakes of varying magnitudes are required to fully test this assertion.
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