Volcano collapse promoted by hydrothermal alteration and edifice shape, Mount Rainier, Washington

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ABSTRACT

Catastrophic collapses of steep volcano flanks threaten many populated regions, and understanding factors that promote collapse could save lives and property. Large collapses of hydrothermally altered parts of Mount Rainier have generated far-traveled debris flows; future flows would threaten densely populated parts of the Puget Sound region. We evaluate edifice collapse hazards at Mount Rainier using a new three-dimensional slope stability method incorporating detailed geologic mapping and subsurface geophysical imaging to determine distributions of strong (fresh) and weak (altered) rock. Quantitative three-dimensional slope stability calculations reveal that sizeable flank collapse (>0.1 km^3) is promoted by voluminous, weak, hydrothermally altered rock situated high on steep slopes. These conditions exist only on Mount Rainier's upper west slope, consistent with the Holocene debris-flow history. Widespread alteration on lower flanks or concealed in regions of gentle slope high on the edifice does not greatly facilitate collapse. Our quantitative stability assessment method can also provide useful hazard predictions using reconnaissance geologic information and is a potentially rapid and inexpensive new tool for aiding volcano hazard assessments.

Keywords: landslide, volcano, debris flow, slope stability, hydrothermal alteration, Mount Rainier.

INTRODUCTION

Enormous (>0.1 km^3) flank collapses have dramatically reshaped more than 200 volcanoes worldwide (McGuire, 1996; Siebert et al., 1987) and pose one of the most sudden, destructive, and life-threatening of volcanic events. About 20 000 people have been killed by historic flank collapses (Siebert et al., 1987), and understanding how, why, and where volcano slopes collapse is paramount to evaluating long-term volcano evolution and immediate hazards. Many of Earth's ~700 stratovolcanoes endanger residents of developing nations (Simkin and Siebert, 1994), so techniques are especially needed for rapid and cost-effective assessment of hazards. Numerous processes, such as magma intrusion and earthquake shaking, can destabilize a volcanic edifice (Voight and Elsworth, 1997), and this abundance of contributing factors complicates collapse predictions. Some large collapses have involved weak, clay-rich, hydrothermally altered rocks (Siebert, 1984; Lopez and Williams, 1993), whereas others have not (Voight et al., 1983). The ability of low-strength, clay-rich rocks to retain pore water during collapse enhances their rapid transformation into far-traveling debris flows (Carrasco-Nuñez et al., 1993; Iverson et al., 1997), which greatly extends their destructive reach. More than 55 Holocene volcanic debris flows have originated from Mount Rainier, Washington (Crandell, 1971), and the largest flows traveled >70 km into the Puget Sound lowland (Fig. 1). Similar future events would devastate densely populated areas. With a newly developed tool for quantitatively assessing three-dimensional gravitational slope stability (Reid et al., 2000), we analyze the potential instability of Mount Rainier using geologically and geophysically mapped distributions of fresh and altered rocks.

FLANK COLLAPSES AT MOUNT RAINIER

At Mount Rainier, some volcanic debris flows or lahars began as fluid-saturated flank collapses (large landslides), whereas others were likely triggered by pyroclastic flows entraining snow and ice, glacial outburst floods, or torrential rains. Hydrothermally derived clay minerals are abundant in some of the most widespread lahar deposits, including the massive ~3.8 km^3 Osceola Mudflow of 5600 yr ago (Crandell and Waldron, 1956; Vallance and Scott, 1997), the ~0.2 km^3 Round Pass mudflow of ~2600 yr ago, and the ~0.26 km^3 Electron mudflow of ~500 yr ago (Scott et al., 1995). This association is evidence that weakening of edifice rocks by acid sulfate-argillic hydrothermal alteration promoted flank collapse (Crandell, 1971; Scott et al., 1995).

Heavily glaciated Mount Rainier is built of stratified andesite and dacite lavas with some pyroclastic flow deposits, minor tephras, and only one exposed lava dome. Alteration is most intense adjacent to radial dikes and associated open fractures that bisect the edifice in an east-west belt; alteration increases in extent and degree approaching the volcano's summit (Fig. 2A). Dikes and alteration on the upper west flank of the volcano, in the Sunset Amphitheater area, formed in the interval 270–200 ka and are flanked to their north by fresh lavas erupted about 300–170 ka. Relatively unaltered lavas to the south of the altered belt were erupted 240 to ~10 ka (Sisson et al., 2001). Tertiary plutonic and metamorphosed volcaniclastic rocks underlie the Pleistocene and Holocene volcanic edifice (Fiske et al., 1963).

The gigantic Osceola Mudflow (Vallance and Scott, 1997) removed large masses of highly altered rock, as well as the dike and

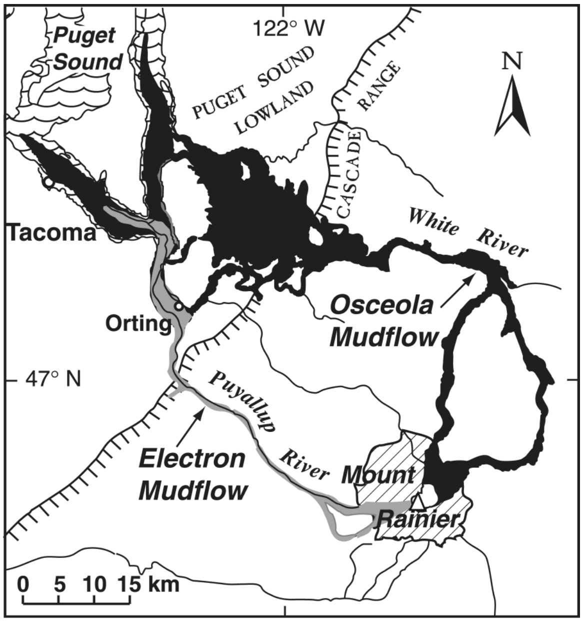

Figure 1. Extent of widespread Osceola Mudflow and Electron mudflow deposits from Mount Rainier. These deposits contain hydrothermally derived clay minerals and likely originated from flank collapses. Modified from Scott and Vallance (1995) and Vallance and Scott (1997).

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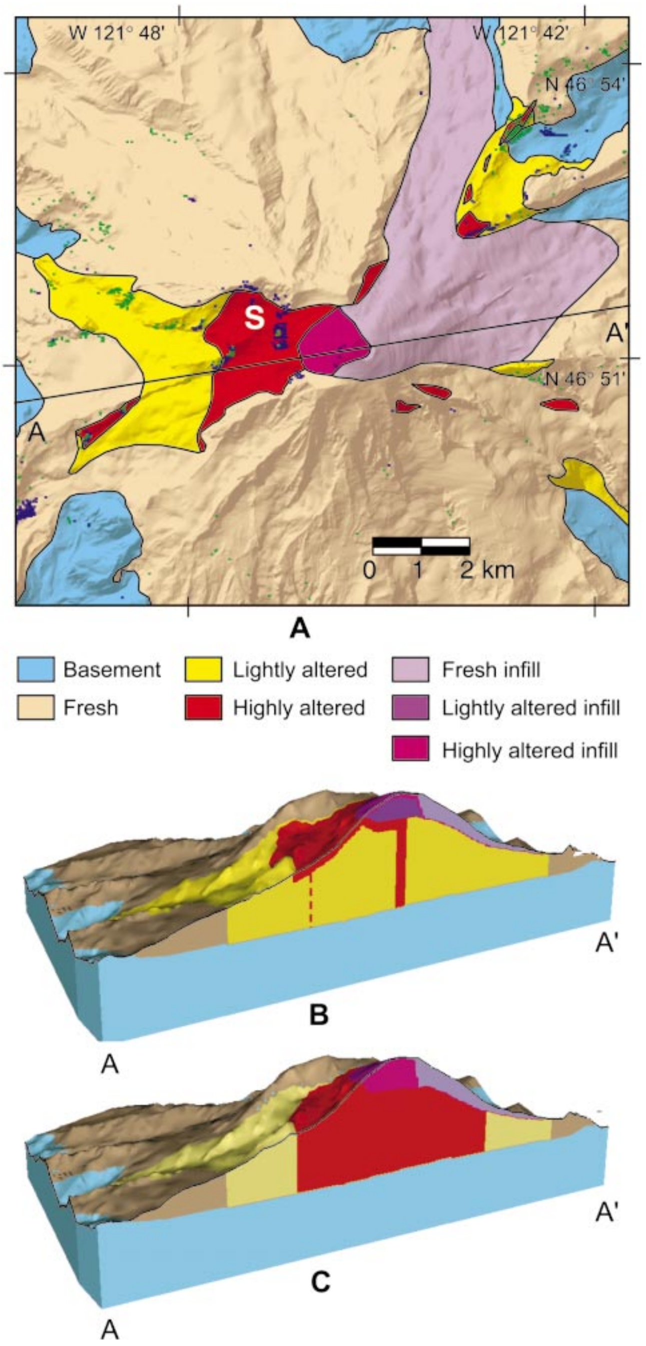

Figure 2. A: Generalized surface distribution of hydrothermally altered and post–Osceola collapse volcanic rocks. Green pixels—surficial exposures of weak argillic alteration; dark purple pixels—surficial exposures of strong argillic alteration, both detected using AVIRIS (Crowley and Zimbelman, 1997); pixels at low elevations are altered material transported in debris flows. S is Sunset Amphitheater area. A-A′ is line of section in B and C. B: Three-dimensional perspective with cutaway along section A-A′ showing best-estimate interpretation of internal-edifice geology from detailed geologic mapping and geophysics. Dashed line shows western limit of intense alteration that extends to basement in Sunset Amphitheater north of line of section. Most volcanic rocks infilling Osceola crater beneath summit are inferred to be lightly altered. C: Three-dimensional perspective showing simplified internal geology if widespread intense subsurface alteration is assumed.

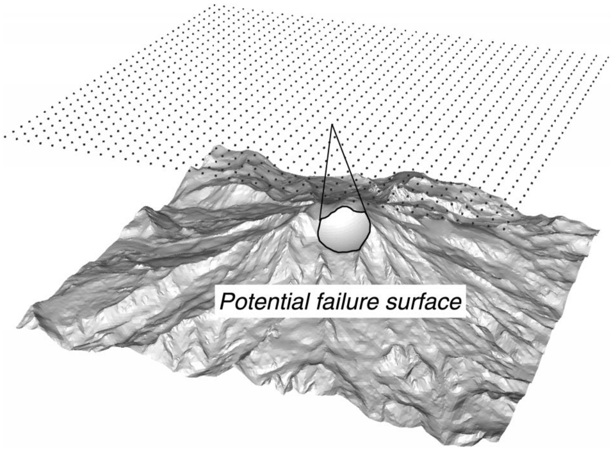

Figure 3. Shaded relief image of Mount Rainier's west flank showing one layer of three-dimensional search grid above edifice (dots). Rock volume from a potential failure has been removed from topography to illustrate failure surface. Three-dimensional slope stability is computed for each of millions of potential failure surfaces encompassing wide range of depths and volumes.

fracture system, from the summit and most of the upper east slope of the volcano, leaving an east-northeast–facing amphitheater. Subsequent eruptions after 5.6 ka built a new summit cone within this scar, and fumarolic activity has intensely altered part of the new summit (Fig. 2A). The Round Pass and Electron mudflows originated from failure of hydrothermally altered rocks in the Sunset Amphitheater area on the upper west flank. Although some stratovolcanoes have collapsed normal to dike orientations (Siebert, 1984), no known large collapses at Mount Rainier have followed this pattern.

THREE-DIMENSIONAL GRAVITATIONAL INSTABILITY

A wide variety of mechanisms can lead to volcano collapse. However, at the most fundamental level static gravitational instability is controlled by interplay between the three-dimensional stress field and the spatial distribution of rock shear strengths. Gravitational stresses derive from rock unit weight, γ, and topography. We start with these basic conditions and ignore stress-field modifications or time-dependent deformation caused by pore-fluid pressure, earthquake shaking, magma intrusion (Voight et al., 1983), or gravitational spreading (Borgia, 1994; van Wyk de Vries and Francis, 1997; van Wyk de Vries et al., 2000). The distribution of rock shear strengths also controls the location of flank failure. Rockslides can start along weak structural discontinuities, such as joints or fractures. However, the sliding surface of a large failure (>0.1 km^3) ignores local small features, and may be arcuate if discontinuities are closely spaced (Hoek and Bray, 1981). Hydrothermal alteration can lower rock shear strength (Watters and Delahaut, 1995) over wide areas (Frank, 1985, 1995; Lopez and Williams, 1993), so alteration could be important for promoting and localizing large collapses.

We thoroughly search for unstable regions throughout the Mount Rainier edifice by computing the stability of $\sim 29 \times 10^6$ spherical potential failure surfaces that intersect the volcano, as represented by a 100 m digital elevation model. We examine potential failures encompassing a wide variety of depths and volumes between 0.1 and 3.5 km^3; each failure has a rotational center in a three-dimensional search grid above the edifice (Fig. 3). Stability of each potential failure is determined using a geotechnical three-dimensional method of columns limit–equilibrium slope stability analysis (Reid et al., 2000). We assume, as is often done for closely jointed rock (Jaeger and Cook, 1979), that average shear resistance, τ, acting on a potential failure surface is given by the Coulomb failure rule, $\tau = c + \sigma_n \tan \phi$, where c is

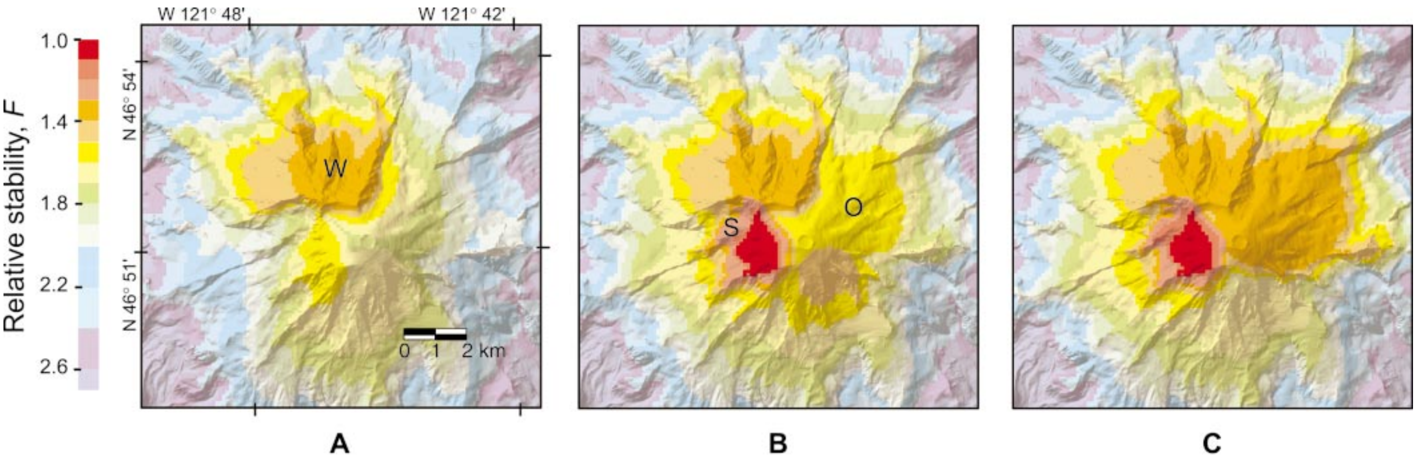

Figure 4. Predicted relative slope stability using different three-dimensional strength distributions for Mount Rainier edifice, portrayed on shaded relief. Each map combines results from ~29 × 10^6 potential failure surfaces and shows lowest (least stable) factor-of-safety value for any failure underlying each 100 m digital elevation model point. A: Homogeneous rock strength case (no effect of alteration). W is Willis Wall area. B: Variable rock strength case using best-estimate distribution of alteration derived from combined detailed geologic and aeromagnetic observations. S is Sunset Amphitheater area; O is area of volcanic rock erupted after 5.6 ka collapse and largely filling Osceola crater. C: Variable rock strength case, in which simplified assessment assuming extensive subsurface alteration is used.

cohesion, σ_n is total normal stress acting on the failure surface, and ϕ is the angle of internal friction of the rock. Summing the vertical forces and rotational moments acting on each rock column above the potential failure surface, we compute a factor of safety, F, for that surface (Reid et al., 2000). Instability is reflected in values of $F < 1$; low values of F indicate a propensity for collapse. We produce maps portraying the relative stability of different parts of the edifice (Fig. 4) by plotting the lowest F value of any potential failure surface underlying each digital elevation model point.

STABILITY OF MOUNT RAINIER'S FLANKS

We can assess the important effects of topography by assuming a uniform distribution of homogeneous rock properties. For Mount St. Helens, this homogeneous approach identified the well-documented (Voight et al., 1983) May 18, 1980, collapse location and approximate volume (Reid et al., 2000). Our stability results for a homogeneous Mount Rainier edifice, for which we use properties typical of strong fractured rock ($\phi = 40°$; $c = 500$ kPa; $\gamma = 24$ kN/m^3), predict the large, continuously steep Willis Wall area on the north flank as the least stable (Fig. 4A). However, no known large collapses originated from this area, although several small debris-flow deposits are in the Carbon River valley below the Willis Wall (Crandell, 1971; Scott et al., 1995). At Mount Rainier, the use of topography and homogeneous rock properties does not identify regions subject to past large collapses, and it is likely to be a poor predictor of future events.

Unlike Mount St. Helens, Mount Rainier has large areas of hydrothermally altered rocks in parts of the upper edifice (Frank, 1985, 1995; Zimbelman, 1996; Crowley and Zimbelman, 1997). For further analyses, we subdivided rock units into pre–Mount Rainier Tertiary basement rocks and three simple categories of edifice volcanic rocks distinguished by degree of acid sulfate–argillic alteration: fresh, lightly altered, and highly altered, on the basis of field observations and remote sensing (Crowley and Zimbelman, 1997). In lightly altered regions, alteration minerals are localized in highly porous rocks (pyroclastic flow matrix, flow-top rubble), as well as along fracture surfaces and vesicle infillings. In heavily altered areas, alteration has substantially or completely penetrated dense lava, dike, and clast interiors, largely obliterating original igneous minerals and textures. For each group, we assigned overall material properties for large (>0.1 km^3) failures, neglecting small discontinuities. On the basis of strengths estimated using field and laboratory shear tests on small specimens (Watters and Delahaut, 1995; Watters et al., 2000), we postulate that fresh volcanic rocks are relatively strong (as in the homogeneous case), more indurated basement rocks are slightly stronger than fresh rocks ($\phi = 42°$, $c = 600$ kPa, $\gamma = 24$ kN/m^3), lightly altered rocks are somewhat weaker ($\phi = 35°$, $c = 400$ kPa, $\gamma = 23$ kN/m^3), and highly altered rocks are even weaker ($\phi = 28°$, $c = 300$ kPa, $\gamma = 21$ kN/m^3). The shear strength of volcanic rocks can vary between and within edifice rock types, and this variability adds uncertainty to any analysis. Nevertheless, because our values delineate a reasonable relative ranking of strength (i.e., altered rocks are weaker than fresh), they provide a useful tool for assessing relative stability.

We derived a well-constrained estimate of three-dimensional alteration extent by combining detailed surface geologic mapping (Sisson et al., 2001) with subsurface geophysical imaging (Finn et al., 2001) (Fig. 2, A and B). High-resolution airborne magnetic measurements (Finn et al., 2001) can reveal the subsurface distribution of alteration, because alteration substantially reduces the strong magnetization of fresh volcanic rocks. Geophysical surveys indicate that summit alteration is thin, extending to depths of only 20–50 m. We estimated the shape and size of the Osceola crater and its subsequent infill by mapping the crater's exposed perimeter (including its geomorphic expression downslope to the northeast), combined with limiting the volume to that of the unbulked Osceola Mudflow (~2.5 km^3) (Vallance and Scott, 1997), and assuming the characteristic amphitheater shape of large volcano collapse craters (Siebert, 1984). Geophysical measurements (Finn et al., 2001) detect no large bodies of highly altered rocks beneath the fresh Osceola crater-filling lavas on the upper east flank; instead, we infer that lightly altered pre-collapse rocks floor the crater and underlie the fresh crater-filling lavas (Fig. 2B). Aeromagnetic anomalies identify additional highly altered areas, including a region largely concealed in the subsurface on the volcano's upper south flank. Only some of the highly altered rocks in Sunset Amphitheater extend to basement; many areas are <200 m thick (Fig. 2B).

Using this best-estimate distribution of alteration, our analysis predicts that the least stable part of the volcano is its upper west flank, in the basin of Sunset Amphitheater (Fig. 4B), where intensely altered rocks are widely exposed (Fiske et al., 1963; Frank, 1995; Crowley and Zimbelman, 1997). Here, potential failure volumes range between 0.1 and 0.4 km^3, although initial failures might become larger by retrogressing into the edifice. Failures might also depressurize a shallow hydrothermal or magmatic system, leading to explosive eruption, as transpired at Mount Rainier during the Osceola collapse (Vallance and Scott, 1997). The large (>0.2 km^3) Round Pass and Electron mudflows and numerous smaller debris flows originated from the west flank Sunset Amphitheater area in the past 6 k.y. (Crandell, 1971; Scott et al., 1995). The area of concealed altered rocks on the upper south flank is slightly less stable than the east flank, although values are similar to those of the very steep but relatively stable Willis Wall. Large regions of altered rock exposed low on the edifice (Fig. 2A) are unlikely to spawn large collapses.

RECONNAISSANCE STABILITY ASSESSMENTS

There is a pressing need for slope stability evaluations at other stratovolcanoes where time and costs preclude developing the comprehensive geologic information available for Mount Rainier. We investigate the utility of reconnaissance stability assessments by comparing our detailed best-estimate results to those based on a much-simplified three-dimensional distribution of alteration at Mount Rainier. This simplified distribution projects exposed altered rocks vertically downward to basement and assumes that highly altered rocks widely and shallowly underlie post-Osceola lavas on the volcano's upper east flank (Fig. 2C) (Frank, 1995; Zimbelman, 1996). For the simplified case, our analysis again identifies the Sunset Amphitheater area on the upper west flank as the least stable part of the edifice (Fig. 4C). A broad area on the volcano's upper east slope is predicted to be 20%–30% less stable than in the scenario that ignores alteration entirely, although values are similar to those of the Willis Wall. The overall similarity of stability patterns when simplified (Fig. 4C) and detailed (Fig. 4B) three-dimensional strength distributions are used confirms the utility of reconnaissance assessments.

CONCLUSIONS

Our three-dimensional analyses demonstrate that at Mount Rainier steep slopes combined with large volumes of weak rock control potentially large (>0.1 km^3) gravitational failures, and our results match the Holocene distribution of collapse-generated debris flows. Relatively strong rocks on the north and south flanks confine large instabilities to the upper west flank. Voluminous alteration on lower flanks or concealed in regions of gentle slope high on the edifice does not greatly enhance collapse hazard. For volcanoes like Mount Rainier, with large regions of both relatively strong and relatively weak rocks, collapse hazards can vary substantially from sector to sector, depending on the distribution and intensity of alteration and the local relief.

For many volcanoes, limited time and resources can preclude developing the detailed geologic and geophysical information used for stability assessments at Mount Rainier. Nevertheless, useful preliminary assessments of volcano flank stability can be produced rapidly using our three-dimensional technique, if a digital elevation model and simple knowledge of the intensity and distribution of altered rocks are available, as could be acquired from reconnaissance field investigations and remote sensing. More detailed information on volcano geologic history and internal structure, from intensive geologic and geophysical studies, greatly increases the accuracy and credibility of hazard assessments.

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