8-2010

Volcano collapse promoted by progressive strength reduction: new data from Mount St. Helens

Mark E. Reid
United States Geological Survey

Terry E. C. Keith
United States Geological Survey

Robert E. Kayen
United States Geological Survey

Neal R. Iverson
Iowa State University, niverson@iastate.edu

Richard M. Iverson
United States Geological Survey

See next page for additional authors

Volcano collapse promoted by progressive strength reduction: new data from Mount St. Helens

Abstract

Rock shear strength plays a fundamental role in volcano flank collapse, yet pertinent data from modern collapse surfaces are rare. Using samples collected from the inferred failure surface of the massive 1980 collapse of Mount St. Helens (MSH), we determined rock shear strength via laboratory tests designed to mimic conditions in the pre-collapse edifice. We observed that the 1980 failure shear surfaces formed primarily in pervasively shattered older dome rocks; failure was not localized in sloping volcanic strata or in weak, hydrothermally altered rocks. Our test results show that rock shear strength under large confining stresses is reduced ~20% as a result of large quasi-static shear strain, as preceded the 1980 collapse of MSH. Using quasi-3D slope-stability modeling, we demonstrate that this mechanical weakening could have provoked edifice collapse, even in the absence of transiently elevated pore-fluid pressures or earthquake ground shaking. Progressive strength reduction could promote collapses at other volcanic edifices.

Keywords

Edifice collapse, Shear strength, Mount St. Helens, Landslide

Disciplines

Volcanology

Comments

This article is published as Reid, Mark E., Terry EC Keith, Robert E. Kayen, Neal R. Iverson, Richard M. Iverson, and Dianne L. Brien. "Volcano collapse promoted by progressive strength reduction: new data from Mount St. Helens." *Bulletin of Volcanology* 72, no. 6 (2010): 761-766. DOI: 10.1007/s00445-010-0377-4.

Authors

Mark E. Reid, Terry E. C. Keith, Robert E. Kayen, Neal R. Iverson, Richard M. Iverson, and Dianne L. Brien

Bull Volcanol (2010) 72:761–766
DOI 10.1007/s00445-010-0377-4

SHORT SCIENTIFIC COMMUNICATION

Volcano collapse promoted by progressive strength reduction: new data from Mount St. Helens

Mark E. Reid · Terry E. C. Keith · Robert E. Kayen · Neal R. Iverson · Richard M. Iverson · Dianne L. Brien

Received: 8 February 2010 / Accepted: 20 April 2010 / Published online: 20 June 2010

Abstract Rock shear strength plays a fundamental role in volcano flank collapse, yet pertinent data from modern collapse surfaces are rare. Using samples collected from the inferred failure surface of the massive 1980 collapse of Mount St. Helens (MSH), we determined rock shear strength via laboratory tests designed to mimic conditions in the pre-collapse edifice. We observed that the 1980 failure shear surfaces formed primarily in pervasively shattered older dome rocks; failure was not localized in sloping volcanic strata or in weak, hydrothermally altered rocks. Our test results show that rock shear strength under large confining stresses is reduced ~20% as a result of large quasi-static shear strain, as preceded the 1980 collapse of MSH. Using quasi-3D slope-stability modeling, we demonstrate that this mechanical weakening could have provoked edifice collapse, even in the absence of transiently elevated pore-fluid pressures or earthquake ground shaking. Progressive strength reduction could promote collapses at other volcanic edifices.

Keywords Edifice collapse · Shear strength · Mount St. Helens · Landslide

Introduction

Worldwide, more than 200 steep stratovolcanoes have collapsed catastrophically; in historical times edifice collapses have killed thousands of people (Siebert et al. 1987; Siebert 1996). Understanding the processes controlling edifice collapse is crucial to assessing long-term volcano evolution as well as forecasting imminent hazards. Massive edifice failures can be promoted by a wide variety of destabilizing factors such as over-steepened slopes, underlying fault structures, magma intrusion, elevated pore-fluid pressures, or earthquake loading (McGuire 1996; Voight and Elsworth 1997; Reid 2004), but rock shear strength plays a fundamental role in geomechanical models aimed at understanding and forecasting such collapses. Despite its importance, shear strength tests of material from the failure surfaces of large volcano collapses remain rare.

Owing to difficulties of accessing rocks deep within volcanoes, most previous studies estimated edifice rock strength from surface or borehole samples, and they commonly focused on rocks that were progressively weakened by acid sulfate-argillic hydrothermal alteration (Watters et al. 2000; Hürlimann et al. 2001; Thomas et al. 2004; Zimbelman et al. 2004; Moon et al. 2005; Thompson et al. 2008) and thereby promoted edifice instability (Lopez and Williams 1993; Reid et al. 2001). Other researchers have suggested that forcible magmatic intrusion might

Editorial responsibility: B. van Wyk de Vries

Electronic supplementary material The online version of this article (doi:10.1007/s00445-010-0377-4) contains supplementary material, which is available to authorized users.

M. E. Reid (✉) · T. E. C. Keith · R. E. Kayen · D. L. Brien
U.S. Geological Survey,
345 Middlefield Rd.,
Menlo Park, CA 94025, USA
e-mail: mreid@usgs.gov

N. R. Iverson
Department of Geological and Atmospheric Sciences,
Iowa State University,
Ames, IA 50011, USA

R. M. Iverson
U.S. Geological Survey,
1300 SE Cardinal Ct. #100,
Vancouver, WA 98683, USA

weaken edifice rocks (Voight et al. 1983; Donnadieu et al. 2001), but they did not examine its ramifications.

The post-1980 collapse crater of Mount St. Helens (MSH) stratovolcano, WA, USA (Fig. 1a), located in the Cascade magmatic arc, offers an exceptional opportunity to examine and test rocks directly from the failure surface of a modern, massive, and well documented edifice collapse. In the spring of 1980, a large graben formed at the summit of MSH as the north flank bulged outward subhorizontally tens of meters (Fig. 1a) over several months at 1.5–2.5 m/day in response to an intruding cryptodome (Lipman et al. 1981). Shearing along a summit fault or basal shear zone likely accommodated this deformation (Donnadieu et al. 2001) and cryptodome intrusion may have been guided by pre-existing faults (Lagmay et al. 2000). Then on 18 May this flank failed catastrophically over the course of ~1 min in a series of retrogressive landslide blocks, accompanied by a magnitude 5+ earthquake (Fig. 1c). The failure triggered an enormous lateral blast and Plinian eruption, created a north-facing horseshoe-shaped crater, and produced a 2.8 km^3 debris-avalanche deposit (Voight et al. 1983). Some researchers have proposed that this collapse was promoted by weakened, hydrothermally altered dome rocks rich in smectite (Swanson et al. 1995). Although lava domes grew within the breached crater between 1980–1986 and 2004–2008, some rocks exposed by the 1980 collapse remain accessible.

Here, we describe the nature and degree of hydrothermal alteration of edifice rocks containing the 1980 MSH landslide shear surfaces and present shear strength test results from the inferred failure surface. Our laboratory strength tests mimic conditions in the pre-collapse edifice, and replicate both large initial stresses deep within the edifice and strength changes following large strain, as occurred during cryptodome intrusion. We then examine the implications of our strength measurements for the gravitational stability of the pre-collapse edifice using a quasi-3D slope-stability analysis.

Nature of rocks containing the 1980 Mount St. Helens failure surfaces

Previous geologic interpretations (Glicken 1996) as well as our field observations of the post-1980 crater walls indicate that the core of the pre-1980 MSH edifice was composed primarily of older Quaternary dacite domes overlain by outward dipping layers of basalt and andesite lavas and pyroclastic flow deposits as well as a summit dome (Fig. 1c). Older domes were more extensive in the northern sector of the edifice, and most of the 1980 failure surfaces propagated through these domes (Fig. 1c). The domes (mostly of Pine Creek age, 3.0 to 2.5 ka) consist of gray, fine-grained, porphyritic dacite typically shattered into sub-decimeter blocks (Hausback 2000). Some of the domes are intruded by at least three sets of 1–4 m thick andesite and basalt dikes (M. Clynne, USGS, pers. com.). Pervasive shattering may be related to repeated dome emplacement or earlier flank failures; field relations between the domes, dikes, and overlying rocks indicate that much of this cataclasis occurred prior to 1980 (J. Pallister, USGS, pers. com.). Failure in 1980 was not localized within weak layers sub-parallel to the ground surface, as has been proposed for other volcano collapses (McGuire 1996). However, the distribution of shattered older domes may have helped localize 1980 failure surfaces.

Prior to the 1980 collapse, fumerolic activity produced localized hydrothermal alteration of the upper edifice (Deither et al. 1981) and older MSH rocks beneath the modern edifice contain propylitic alteration (Clynne et al. 2008). Because hydrothermal alteration has been implicated in promoting stratovolcano slope failure, including the MSH collapse (Swanson et al. 1995), we searched for assemblages and distributions of alteration minerals in domes exposed in the 1980 crater walls and crater breach in the northern sector of the edifice (Fig. 1b). During sampling we targeted potentially altered rocks, particularly near fracture and dike contact zones, as well as typical dome rocks. We examined 42 samples using a combination of binocular microscopy, petrographic microscope oil immersion, petrographic thin sections, and X-ray powder diffraction.

We observed few visual indications of alteration in the older dacite dome rocks. The finely holocrystalline groundmass of the domes is generally a mix of plagioclase, α-cristobalite, quartz, magnetite, ilmenite, amphibole, and pyroxene. Studies of similar groundmass assemblages indicate shallow, pre-extrusion decompression and crystallization as occurs during magma ascent (Blundy and Cashman 2001). The groundmass of older and deeper (Smith Creek age, 4.0 to 3.3 ka) domes contains no α-cristobalite; quartz is more abundant than plagioclase, but there are no associated minerals to indicate that the quartz is of hydrothermal origin. Almost no dacite samples, even those that appear altered, contain clay or other alteration minerals: two samples contain well-crystallized, disseminated smectite. Minor localized alteration, consisting of irregularly disseminated minor amounts of hydrous Fe oxide minerals, occurs immediately adjacent to some dikes, and likely formed during dike intrusion. In fractures, very scarce, <1 mm thick coatings consist of up to 75% well-crystallized smectite or smectite plus hydrous Fe oxide. Overall, we observed no extensive areas with clays that might significantly weaken dome rocks.

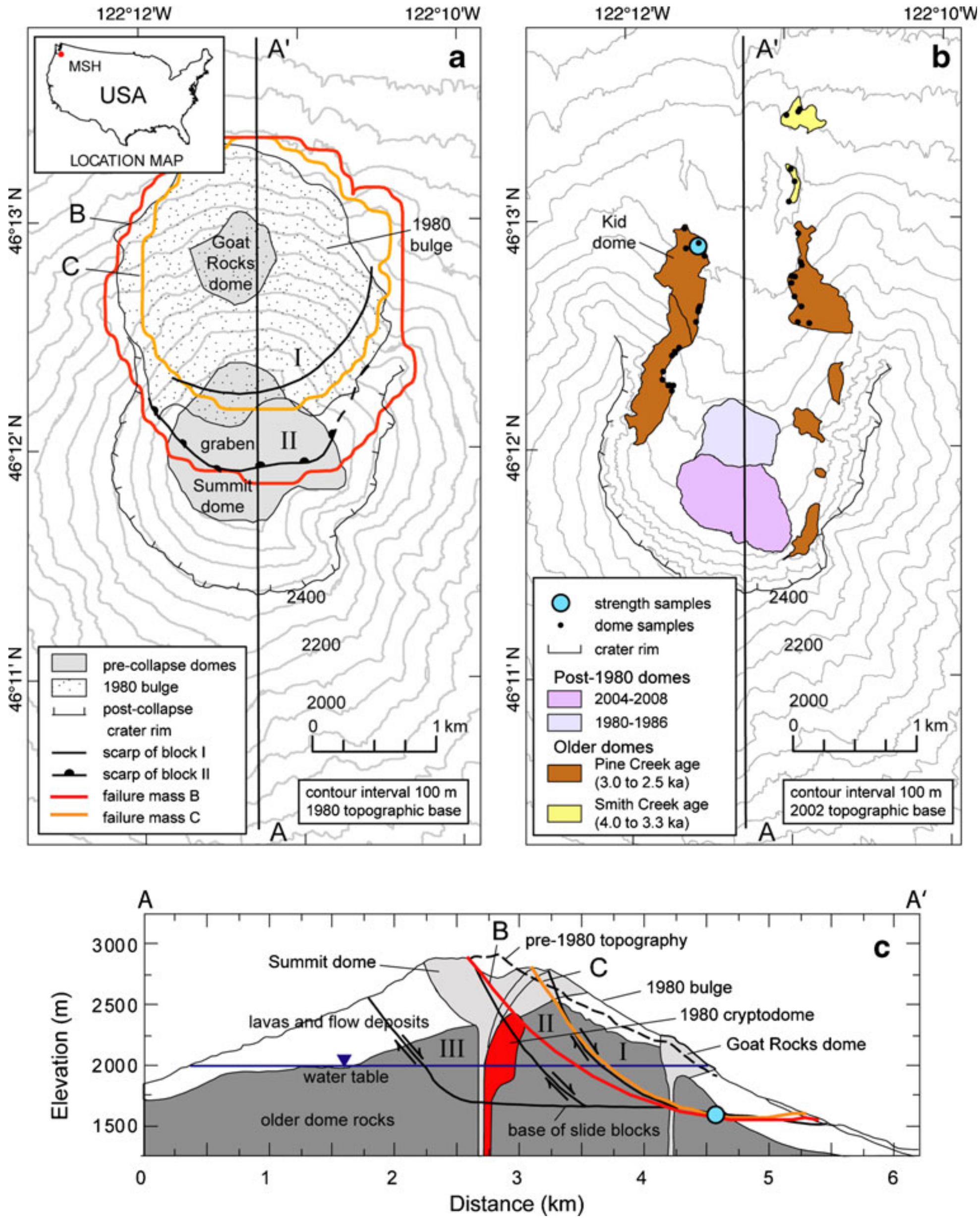

Fig. 1 **a** Map showing deformed Mount St. Helens (MSH) edifice with extent of 1980 north flank bulge (Moore and Albee 1981), summit scarp of slide block II, head scarp of slide block I after Voight et al. (1983), and outlines of the two potential failure masses (B and C) used in our slope-stability analysis, projected onto topography. Topographic base as of May 12, 1980, prior to collapse. A-A′ locates cross section shown in (**c**). Inset map shows location of MSH. **b** Map showing post-1980 domes and older domes exposed by the 1980 collapse. Dome locations from Hausback (2000), D. Sherrod (USGS, pers. com.), and our mapping. Many of the older domes are partially covered by younger deposits. Blue circle locates strength samples and points locate samples analyzed for hydrothermal alteration. **c** Cross section through pre-collapse MSH showing north flank bulge, extent of summit dome (*light gray*) and older domes (*gray*), inferred extent of 1980 cryptodome (*red*) after Donnadieu et al. (2001), and failure surfaces of the three landslide blocks (I, II and III) after Glicken (1996). Two potential spherical failure surfaces (B and C in colors) and inferred water table used in slope-stability analysis are also shown. Spherical surface B intersects the graben headwall and slide toe

Shear strength of dome rocks

When rocks or soils are progressively sheared to large strains, an initial peak in strength is commonly followed by a reduced residual strength (Lambe and Whitman 1969; Hoek and Bray 1981). Earlier strength tests on MSH specimens focused on disturbed and remolded debris-avalanche deposits that showed little evidence of such peak strength behavior (Voight et al. 1983). In contrast, we focus on the strength of rocks near the inferred basal sliding surface of the 1980 failure blocks I and II at the crater mouth (Fig. 1b, c). These rocks, having limited exposure, consist of shattered, unaltered dacite that readily disaggregates into sand-sized particles when stressed. We sampled this material at two sites about 30 m apart near the intact remains of the Pine Creek age Kid dome (Hausback 2000), but the locality may be part of a large mega-block of dacite left from the 1980 massive rockslide (Fig. 1b). We collected 10 relatively undisturbed samples by lightly tapping 7.5 cm OD thin-walled steel tubes into the highly shattered rock, excavating them, and sealing them for transport. We also collected disturbed bulk material for ring-shear tests. Samples were subsequently stored in a temperature and humidity controlled room prior to testing. Tests using a field excavation method yielded a dry bulk density of 2100 +/− 100 kg/m^3 (n=6).

We determined the quasi-static drained shear strength of the undisturbed specimens using a triaxial testing device, equipped with high-pressure components to mimic overburden stresses at MSH prior to the 1980 collapse. We performed a series of these tests on our tube samples under different isotropic confining stresses, ranging up to ~5 MPa. Many of the tests revealed both a peak and residual strength during their failure history, while undergoing a maximum axial strain of ~20% (Fig. 2a). We also determined residual shear strength using a specially constructed large volume ring-shear apparatus (Iverson et al. 1997) that can impose arbitrarily large quasi-static shear strains to mimic large deformations of edifice rocks prior to flank collapse. Total displacement during the ring-shear tests was ∼1 m, several orders of magnitude larger than in the triaxial tests. After shearing, the dry bulk density of the material was 1970 +/− 30 kg/m^3 (n=3). Details of the testing procedures can be found in the "Electronic Supplementary Materials" available online.

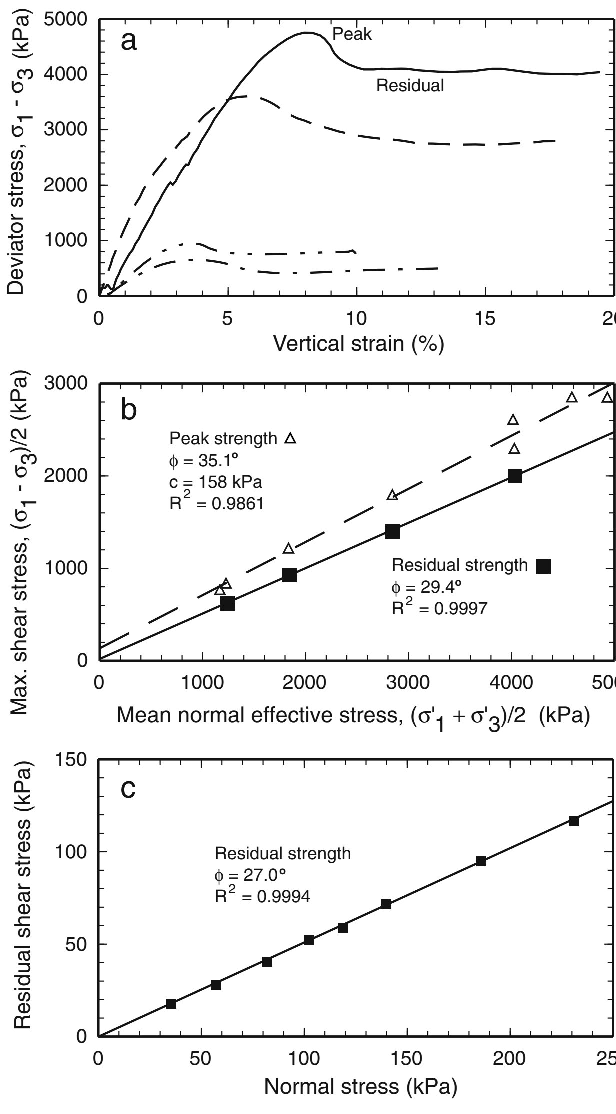

Fig. 2 Results of shear strength tests on older dome rocks within the MSH edifice. σ_1 and σ_3 are principal stresses and prime designates effective stress, as described in Lambe and Whitman (1969). **a** Stress/strain behavior during four triaxial tests (at different confining stresses) showing peak and residual strength conditions. **b** High-pressure triaxial test results showing peak (35°) and residual (29°) friction angles computed using stresses at failure. **c** Large volume, large strain ring-shear test results showing residual friction angle (27°)

Results of the triaxial tests at high confining stresses (Fig. 2b) showed that peak strength of the relatively undisturbed material was represented by an angle of internal friction, ϕ, ~35° with some cohesion. This ϕ value is typical of unaltered igneous rocks and granular materials (Hoek and Bray 1981). At the conclusion of the triaxial tests, the MSH specimens had a residual $\phi \sim 29°$ with no cohesion (Fig. 2b). The large-strain ring-shear tests yielded a similar residual $\phi \sim 27°$ (Fig. 2c), even though testing conditions differed significantly. The 17–23% reduction in friction angle during quasi-static shearing likely resulted from changes in bulk density and comminution of grains, common for granular materials (Lambe and Whitman 1969). Other tests on remolded volcanic granular flow materials showed decreases in frictional strength of 3–11% (Samuelson et al. 2008). For comparison, extensive acid sulfate-argillic alteration of volcanic rocks, without undergoing large strain, can reduce frictional strength by 30–65% (Watters and Delahaut 1995; Zimbelman et al. 2004).

Implications for edifice instability

Inferences about collapse triggering mechanisms are directly influenced by values of rock shear strength. For example, some researchers have analyzed the 1980 MSH collapse using 2D or quasi-3D limit-equilibrium slope-stability analyses that assume ϕ=40° (Voight et al. 1983; Reid et al. 2000; Donnadieu et al. 2001). Their results imply that both high pore-fluid pressures and loading from accompanying earthquake ground shaking were needed to provoke failure. Others have argued, on the basis of seismological analyses, that the collapse itself produced the accompanying earthquake (Kanamori et al. 1984; Brodsky et al. 2003). To maintain stability in the absence of elevated pore pressures or earthquake loading, other models show that ϕ>30° (Donnadieu et al. 2001) or ≥27° (Paul et al. 1987) is necessary. With ϕ=30°, transient gas overpressurization may have been sufficient to trigger collapse (Vinciguerra et al. 2005).

Here, we use a quasi-3D limit-equilibrium slope-stability analysis, implemented in a program named SCOOPS (Reid et al. 2000), to investigate the effects of our measured reduction in shear strength on the stability of the pre-collapse edifice. We assume, as is commonly done for closely jointed rock (Hoek and Bray 1981), that average shear resistance, τ, acting on a potential failure surface is given by the

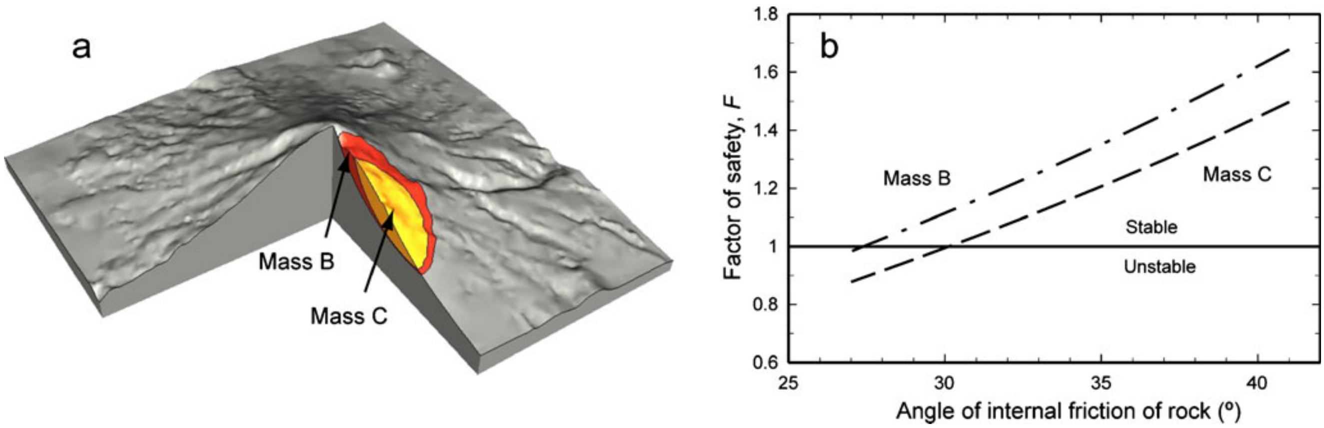

Fig. 3 Results of quasi-3D slope-stability analysis. **a** Perspective view of pre-collapse MSH edifice showing two potential failure masses (B and C) analyzed. **b** Computed limit-equilibrium factor of safety, *F*, as a function of the angle of internal friction, ϕ, for potential failure masses B and C. $F<1$ indicates instability

Coulomb-Terzaghi failure rule, $\tau = c + (\sigma_n - u)\tan\phi$, where c is cohesion, σ_n is total normal stress acting on the failure surface, and u is pore-fluid pressure on the same surface. Our analysis computes a factor of safety, *F*, for a potential failure by dividing the mass into columns and summing the vertical forces and rotational moments acting on each column above a spherical potential sliding surface. Instability is expressed by $F<1$. For MSH, we use a digital elevation model of the deformed edifice just prior to collapse because steepening from intrusion reduced stability by ~3% (Reid et al. 2000), an average rock unit weight of 24 kN/m^3, no cohesion, and a water table in the lower region of the edifice (Fig. 1b). Voight et al. (1983) assumed a higher water table, but subsequent groundwater modeling suggests that a relatively flat, lower water table may have been more likely (Hurwitz et al. 2003). Although MSH appeared to fail retrogressively in 1980, both slide blocks I and II were moving when eyewitness photographs of the collapse were taken (Voight et al. 1983), and it is conceivable that block II moved first, albeit at a slower rate (Donnadieu et al. 2001). Thus we assess the stability of each of these blocks independently using two potential failure masses, B and C (Fig. 3a). To focus on mechanical strength, we do not include poorly constrained, transient effects such as magma injection, pore-fluid pressurization, or earthquake loading, although these could promote instability.

Given these conditions, we examine plausible effects of progressive reduction of shear strength on slope stability (Fig. 3b). Due to rock heterogeneity and the time-dependent development of shear surfaces during intrusion, ϕ undoubtedly varied along shear surfaces, but here we assume uniform spatial values. A decrease in ϕ from 35° to 29° (as observed in our shear tests using high confining stresses) reduces slope stability by ~20% and produces $F < 1$ in failure mass C (block I), indicating instability (Fig. 3b). Computed *F* values for both potential failure masses follow a similar pattern of reduction. The slip surface for failure mass B (block II) likely intersected the intruded, mechanically weak, cryptodome (Donnadieu et al. 2001) and thus may have been more unstable than we have computed. A higher water table, as assumed by Voight et al. (1983), would have provoked even more instability. Although these and other transient effects could contribute to instability, progressive strength reduction alone is sufficient to promote collapse.

Conclusions

Our observations at MSH identify destabilizing mechanisms capable of promoting edifice collapse elsewhere. Strength tests and slope-stability calculations illustrate that the 1980 edifice failure of MSH could have been precipitated by progressive deformation and strength reduction of previously shattered dome rocks due to cryptodome intrusion and gravitational loading. The subsurface distribution of these shattered rocks within the northern flank may have localized the formation of the 1980 collapse surfaces. Although the existence of weak strata sub-parallel to the edifice surface or weak, hydrothermally altered rocks might contribute to edifice instability at other stratovolcanoes, the 1980 collapse of MSH demonstrates that such conditions are not necessary for failure. Reduction in rock strength promoted by progressive shearing may provoke collapse, even in the absence of other destabilizing factors such as transiently elevated pore-fluid pressures or earthquake shaking. Progressive edifice shearing could be detected through comprehensive deformation monitoring, and its effects forecast by slope-stability analysis.

Acknowledgements We thank Tim Best for his field assistance at MSH. Reviews by Tim Davies, Jonathan Godt, John Pallister, Benjamin van Wyk de Vries, and Robert Watters helped improve this manuscript.

References

Blundy J, Cashman K (2001) Ascent-driven crystallisation of dacite magmas at Mount St. Helens, 1980–1986. Contrib Mineral Petrol 140:631–650

Brodsky EE, Gordeev E, Kanamori H (2003) Landslide basal friction as measured by seismic waves. Geophys Res Lett 30:2236. doi:10.1029/2003GL018485

Clynne MA, Calvert AT, Wolfe EW, Evarts RC, Fleck RJ, Lanphere MA (2008) The Pleistocene eruptive history of Mount St. Helens, Washington, from 300,000 to 12,800 years before present. In: Sherrod DR, Scott WE, Stauffer PH (eds) A volcano rekindled: The renewed eruption of Mount St Helens, 2004–2006. US Geol Surv Prof Pap 1750:593–627

Deither DP, Pevear DR, Frank D (1981) Alteration of new volcanic deposits. In: Lipman PW, Mullineaux DR (eds) The 1980 eruptions of Mount St Helens, Washington. US Geol Surv Prof Pap 1250:649–665

Donnadieu F, Merle O, Besson J-C (2001) Volcanic edifice stability during cryptodome intrusion. Bull Volcanol 63:61–72

Glicken H (1996) Rockslide-debris avalanche of May 18, 1980, Mount St. Helens Volcano, Washington. US Geol Surv Open-File Rep 96–0677:1–90

Hausback BP (2000) Geologic map of the Sasquatch steps area, north flank of Mount St. Helens, Washington. US Geol Surv Geol Invest Ser, Map I-2463, Scale 1:4000

Hoek E, Bray JW (1981) Rock slope engineering. Institute of Mining and Metallurgy, London

Hürlimann M, Ledesma A, Martí J (2001) Characterisation of a volcanic residual soil and its implications for large landslide phenomena: application to Tenerife, Canary Islands. Eng Geol 59:115–132

Hurwitz S, Kipp KL, Ingebritsen SE, Reid ME (2003) Groundwater flow, heat transport, and water table position within volcanic edifices: implications for volcanic processes in the Cascade Range. J Geophys Res 108:2557. doi:10.1029/2003JB002565

Iverson NR, Baker RW, Hooyer TS (1997) A ring-shear device for the study of till deformation: Tests on tills with contrasting clay contents. Quat Sci Rev 16:1057–1066

Kanamori H, Given JW, Lay T (1984) Analysis of seismic body waves excited by the Mount St. Helens eruption of May 18, 1980. J Geophys Res 89:1856–1866

Lagmay AMF, van Wyk deVries B, Kerle N, Pyle DM (2000) Volcano instability induced by strike-slip faulting. Bull Volcanol 62:331–346

Lambe TW, Whitman RV (1969) Soil mechanics. Wiley, New York

Lipman PW, Moore JC, Swanson DA (1981) Bulging of the north flank before the May 18 eruption: Geodetic data. In: Lipman PW, Mullineaux DR (eds) The 1980 eruptions of Mount St Helens, Washington. US Geol Surv Prof Pap 1250:143–156

Lopez DL, Williams SN (1993) Catastrophic volcanic collapse; relation to hydrothermal processes. Science 260:1794–1796

McGuire WJ (1996) Volcano instability: a review of contemporary themes. In: McGuire WJ, Jones AP, Nueberg J (eds) Volcano instability on the Earth and other planets. Geol Soc London Spec Pub 110:1–23

Moon V, Bradshaw J, Smith R, de Lange W (2005) Geotechnical characterisation of stratocone crater wall sequences, White Island Volcano, New Zealand. Eng Geol 81:146–178

Moore JG, Albee WC (1981) Topographic and strucural changes, March–July 1980—Photogrammetric data. In: Lipman PW, Mullineaux DR (eds) The 1980 eruptions of Mount St Helens, Washington. US Geol Surv Prof Pap 1250:123–134

Paul A, Gratier JP, Boudon J (1987) A numerical model for simulating deformation of Mount St. Helens volcano. J Geophys Res 92:10,299–210,312

Reid ME (2004) Massive collapse of volcano edifices triggered by hydrothermal pressurization. Geology 32:373–376

Reid ME, Christian SB, Brien DL (2000) Gravitational stability of three-dimensional stratovolcano edifices. J Geophys Res 105:6043–6056

Reid ME, Sisson TW, Brien DL (2001) Volcano collapse promoted by hydrothermal alteration and edifice shape, Mount Rainier, Washington. Geology 29:779–782

Samuelson J, Marone C, Voight B, Elsworth D (2008) Laboratory investigation of the frictional behavior of granular volcanic material. J Volcanol Geotherm Res 173:265–279

Siebert L (1996) Hazards of large volcanic debris avalanches and associated eruptive phenomena. In: Scarpa R, Tilling RI (eds) Monitoring and mitigation of volcano hazards. Springer-Verlag, Berlin, pp 541–572

Siebert L, Glicken H, Ui T (1987) Volcanic hazards from Bezymianny- and Bandai-type eruptions. Bull Volcanol 49:435–459

Swanson DA, Hausback BP, Zimbelman DR (1995) Why was the 1980 bulge on the north flank of Mount St. Helens? Inter Union of Geodesy and Geophysics, XXI General Assembly 21:464

Thomas ME, Petford N, Bromhead EN (2004) Volcanic rock-mass properties from Snowdonia and Tenerife: implications for volcano edifice strength. J Geol Soc Lond 161:939–946

Thompson N, Watters RJ, Schiffman P (2008) Stability analysis of Hawaiian Island flanks using insight gained from strength testing of HSDP core. J Volcanol Geotherm Res 171:163–177

Vinciguerra S, Elsworth D, Malone S (2005) The 1980 pressure response and flank failure of Mount St. Helens (USA) inferred from seismic scaling exponents. J Volcanol Geotherm Res 144:155–168

Voight B, Elsworth D (1997) Failure of volcano slopes. Geotechnique 47:1–31

Voight B, Janda RJ, Glicken H, Douglass PM (1983) Nature and mechanics of the Mount St. Helens rockslide-avalanche of 18 May 1980. Geotechnique 33:243–273

Watters RJ, Delahaut WD (1995) Effect of argillic alteration on rock mass stability. In: Haneburg WC, Anderson SA (eds) Clay and shale slope instability. Geol Soc Am Rev Eng Geol 10:139–150

Watters RJ, Zimbelman DR, Bowman SD, Crowley JK (2000) Rock mass strength assessment and significance to edifice stability, Mount Rainier and Mount Hood, Cascade Range Volcanoes. Pure Appl Geophys 157:957–976

Zimbelman DR, Watters RJ, Firth IR, Breit GN, Carrasco-Núñez G (2004) Stratovolcano stability assessment methods and results from Citlaltépetl, Mexico. Bull Volcanol 66:66–79