Massive collapse of volcano edifices triggered by hydrothermal pressurization

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ABSTRACT

Catastrophic collapse of steep volcano flanks threatens lives at stratovolcanoes around the world. Although destabilizing shallow intrusion of magma into the edifice accompanies some collapses (e.g., Mount St. Helens), others have occurred without eruption of juvenile magmatic materials (e.g., Bandai). These latter collapses can be difficult to anticipate. Historic collapses without magmatic eruption are associated with shallow hydrothermal groundwater systems at the time of collapse. Through the use of numerical models of heat and groundwater flow, I evaluate the efficacy of hydrothermally driven collapse. Heating from remote magma intrusion at depth can generate temporarily elevated pore-fluid pressures that propagate upward into an edifice. Effective-stress deformation modeling shows that these pressures are capable of destabilizing the core of an edifice, resulting in massive, deep-seated collapse. Far-field pressurization only occurs with specific rock hydraulic properties; however, data from numerous hydrothermal systems illustrate that this process can transpire in realistic settings.

Keywords: landslides, volcanoes, collapse, slope stability, hydrothermal systems, numerical models.

INTRODUCTION

Massive, destructive edifice collapses have dramatically sculpted over 200 stratovolcanoes, including Mount St. Helens and Mount Rainier in the United States. Historic collapses have killed ~20,000 people (Siebert, 1984; Siebert et al., 1987). Although some edifice collapses occur with eruption of juvenile magma, others do not. Collapses without magmatic eruption can lack obvious precursory activity, such as seismic shaking, dramatic ground deformation, or changing volcanic gas emissions, thereby lessening predictive capabilities and heightening risk. Furthermore, without the destabilizing effects of shallow edifice intrusion, deep-seated collapse presents a mechanical puzzle. Understanding the processes instigating these collapses is critical for assessing the hazards of, as well as for comprehending the long-term evolution of, volcanoes.

Herein I investigate the efficacy of pore-fluid pressurization caused by heating to destabilize large regions of a volcano without intrusion of magma directly into the edifice. Pressurization of pore fluids has been observed in volcanic systems (Bjornsson et al., 1976; Watanabe, 1983), inferred from hydrothermal breccias (Sillitoe, 1985), invoked to aid fault slip (Lachenbruch, 1980; Mace and Smith, 1987), and postulated to trigger volcano flank failure near intrusion (Reid, 1994; Elsworth and Voight, 1995; Day, 1996). Because large edifice collapses without magmatic eruption are difficult to monitor directly, I use numerical models to address three questions: (1) Can thermal pressurization of pore fluids from remote magma intrusion propagate into an edifice? (2) Are these far-field pressures sufficient to induce deep-seated edifice collapse? (3) Is hydrothermally driven collapse plausible, given realistic volcano properties?

HYDROTHERMALLY DRIVEN MASSIVE EDIFICE COLLAPSES

Enormous (>0.1 km^3) edifice collapses can excavate rock from deep within steep volcano flanks, often creating steep-walled amphitheaters with gently sloping floors (Siebert, 1984; Siebert et al., 1987). This morphology contrasts strongly with that produced by typical large rock avalanches, where extensive failures typically yield thinner source scars. These thinner landslides (Fig. 1A, inset) may be triggered by strong seismic shaking (i.e., Ontake, Japan; Okusa et al., 1987) or prolonged infiltration of rain (i.e., Casita, Nicaragua; Kerle and van Wyk de Vries, 2001). Deep-seated edifice collapses can occur with or without magmatic eruption. Many collapses, such as that at Mount St. Helens, United States, in 1980 (Voight et al., 1983), occur with concurrent or subsequent eruption of juvenile magmatic material, reflecting shallow magma intrusion into the edifice. Stress changes associated with shallow intrusion can provoke slope instability (Elsworth and Voight, 1995; Iverson, 1995). In contrast, other deep-seated collapses have occurred without magmatic eruption and lack juvenile eruptive products; these are unlikely to have been directly triggered by magma intrusion into an edifice. Figure 1B (inset) illustrates the massive modification of Bandai volcano, Japan, without magmatic eruption.

Potentially destabilizing conditions for historic edifice collapses without magmatic eruption are shown in Table 1. These include shallow groundwater systems, hydrothermally altered and potentially weakened rocks in the edifice (Reid et al., 2001), or large earthquakes (Voight and Elsworth, 1997). Although some collapses were accompanied by earthquakes or involved hydrothermally altered rocks, these conditions were not universally present. However, all showed evidence of a shallow hydrothermal groundwater system within the edifice near the time of collapse; such evidence also indicates a deeper magmatic heat source. Given this association, I examine whether a deeper magmatic heat source can provoke hydrothermally driven massive collapse.

FAR-FIELD EFFECTS OF TRANSIENT THERMAL PRESSURIZATION

Heating of fluids in restricted pores can dramatically increase fluid pressures (Lachenbruch, 1980; Delaney, 1982; Mace and Smith, 1987). Can remote intrusion of magma cause elevated pore-fluid pressures in an overlying volcano edifice? To investigate this question, I use the U.S. Geological Survey numerical

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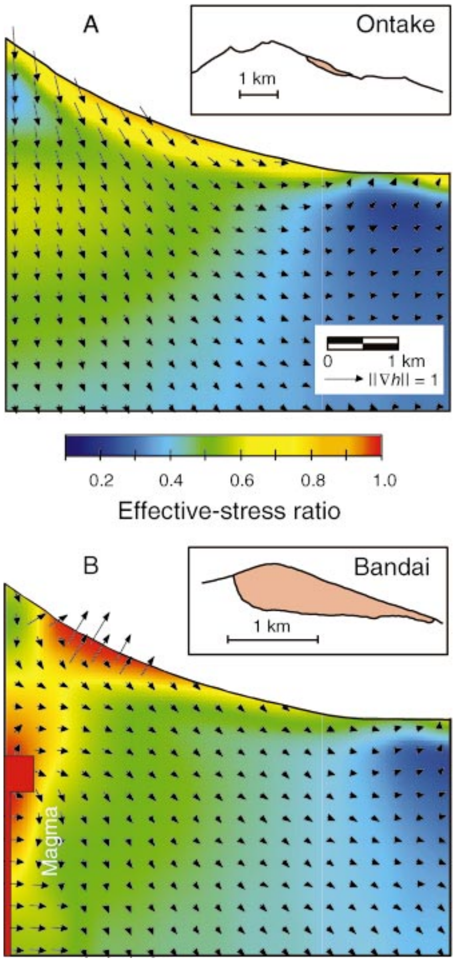

Figure 1. Effective stresses and groundwater-flow vectors in radially symmetric volcano edifice. Higher effective-stress ratios indicate more unstable areas. Vectors show groundwater hydraulic head gradient, *h*. Model configurations are shown in Figure DR1 (see footnote 1 in text). A: Effective-stress field with topography-driven, cold groundwater flow. Inset shows section through earthquake-induced failure on Ontake volcano in Japan (Okusa et al., 1987). B: Effective-stress field with thermal pressurization of pore fluids induced by magma intrusion at depth. Inset shows section through large collapse at Bandai volcano in Japan (Sekiya and Kikuchi, 1889).

TABLE 1. SELECTED STRATOVOLCANO EDIFICE COLLAPSES WITHOUT MAGMATIC ERUPTION

Volcano, date, and location	Fatalities	Evidence of shallow hydrothermal system*	Altered rocks in avalanche	Earthquake*	References
Bandai, 1888 (Japan)	461	phreatic eruptions	Yes	Yes	Sekiya and Kikuchi (1889)
Mayu-yama, 1792 (Japan)	14,524 (with tsunami)	hot water from scarp	—	Yes	Siebert et al. (1987)
Papandayan, 1772 (Indonesia)	2957	explosive eruption	Yes	No	Siebert et al. (1987)
Iriga, 1628? (Philippines)	unknown	phreatic eruptions	No†	?	Aguila et al. (1986)
Ritter, 1888 (Papua New Guinea)	~3000 (with tsunami)	vapor emissions 1 week prior to collapse	No†	No	Johnson (1987), Simkin and Siebert (1994)

*Prior to or during collapse.
†Little or no alteration observed in edifice and/or avalanche deposits.

model HYDROTHERM, version 2.2 (Hayba and Ingebritsen, 1994). HYDROTHERM can simulate the nonlinear, two-phase (vapor-liquid), coupled flow of heat and water over the pressure-temperature range relevant to magmatic-hydrothermal systems; it also accounts for in situ changes in fluid density that create thermal pressurization.

My simulations use a two-dimensional, radially symmetric domain to represent a three-dimensional (3-D) cone; the ground-surface profile is based on Mayon stratovolcano in the Philippines. Edifice rocks are assumed to be homogeneous, isotropic, incompressible, and fully saturated. Model parameters, typical of volcanic rocks, as well as initial and boundary conditions are similar to those used by Hayba and Ingebritsen (1997) and are shown in Figure DR1[1]. To start the pressurization process, a small body (~0.2 km^3) of magma at 900 °C, fed by a 50-m-radius conduit, instantly intrudes to a depth of 2.5 km beneath the volcano peak (Fig. 2A); this intrusion remains fixed through the simulation period.

Pore-fluid pressurization following instantaneous intrusion is a transient process (Fig. 2). In this example, the edifice initially contains a cold, topography-driven groundwater system with flow downward high on the edifice and upward at the edifice base (Fig. 1A). At an early time (0.1 yr) after intrusion, the highest fluid pressurization (relative to the initial pressures) is localized near the intrusion top (Fig. 2A). One year after intrusion, the region of highest pressurization has propagated upward into the core of the edifice (Fig. 2B). Ten years after intrusion, fluid pressurization has nearly dissipated through the ground surface (Fig. 2C); however, the leading edge of thermal disturbance has not yet reached the edifice core. Given parameters typical of Earth materials, fluid-pressure effects travel much faster than thermal effects (Delaney, 1982). Eventually, pressures drop below the initial conditions as fluids warm and become less dense; this long-duration pattern is documented in other simulations (Cathles, 1977; Norton and Knight, 1977; Hayba and Ingebritsen, 1997). My results illustrate that elevated pressures can propagate far from an intrusion as a transient phenomenon.

STRESSES WITHIN A VOLCANO EDIFICE

Is far-field thermal pressurization sufficient to destabilize large regions and produce deep-

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[1] GSA Data Repository item 2004062, Figure DR1, numerical model configurations, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

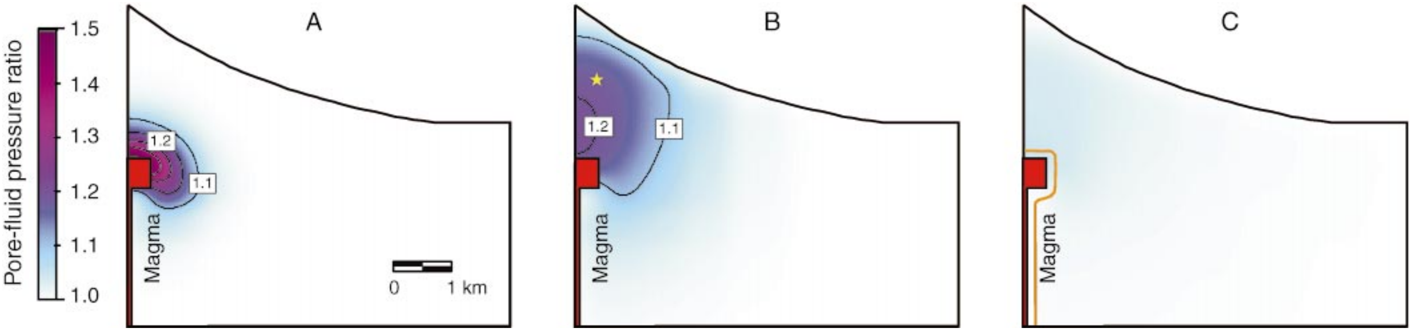

Figure 2. Sequence of transient thermal pore-fluid pressurization following instantaneous magma intrusion at depth. Pore-fluid pressure ratio is relative to initial, cold, topography-driven groundwater pressures. Rock porosity is 0.05 and intrinsic permeability is 5 × 10^{-16} m^2. Model configurations are shown in Figure DR1 (see footnote 1 in text). A: 0.1 yr following intrusion. B: 1 yr following intrusion. Elevated pressures have propagated into edifice. Star indicates location of edifice pressures analyzed in Figure 3. C: 10 yr following intrusion. Elevated pressures have dissipated; orange line near intrusion shows limit of advancing thermal heating.

seated collapse? The shear failure of fluid-saturated rock is governed by its effective-stress distribution, where effective stress is the total stress modified by fluid pressure (Terzaghi et al., 1996). Here I examine 3-D effective-stress fields within a saturated edifice in two scenarios: (1) topography-driven groundwater flow, as might result from infiltrating rain or snowmelt, and (2) elevated fluid pressures in the core of the edifice, caused by far-field hydrothermal pressurization. The latter scenario can be modeled without considering heat-induced stress modification of the edifice; the rapid movement of the fluid-pressure front effectively decouples the pressure and temperature fields over the time scale of interest (Fig. 2).

To compute effective-stress fields, I use deformation analysis, based on poroelastic theory (Biot, 1941), to determine linearly elastic stresses and infinitesimal strains in a saturated porous material with groundwater flow. This approach was fully described elsewhere (Iverson and Reid, 1992; Reid, 1997). Although mechanical strain induced by intrusion can affect pore-fluid pressures, such effects are often much less than thermal pressurization effects (Elsworth and Voight, 1995). Model conditions are shown in Figure DR1 (see footnote 1). The ratio of the maximum shear stress to the mean effective normal stress, $|\tau_{\max}|/(-\sigma'_{m})$, derived from the Coulomb-Terzaghi failure rule (Terzaghi et al., 1996), provides a dimensionless index of the shear-failure potential at any point within an edifice. This stress ratio is independent of material strength, provided that strength has a uniform angle of internal friction and no cohesion (Iverson and Reid, 1992); more unstable areas have higher ratios.

With topography-driven groundwater flow (Fig. 1A), the highest stress ratios (0.6–0.8) occur in a thin band near the edifice surface, indicating that relatively thin failures are likely. This result agrees with observations of relatively thin flank failures induced by rainfall. In contrast, when fluids are pressurized in the core of the edifice by remote magma, the groundwater field creates strong outwardly directed flow near the intrusion and at the ground surface (Fig. 1B). This pattern leads to higher stress ratios (near 1.0) in the core as well as near the ground surface, indicating that deeper failure is likely. Thus, pore-fluid pressurization in the core could provoke large, deep-seated edifice collapses.

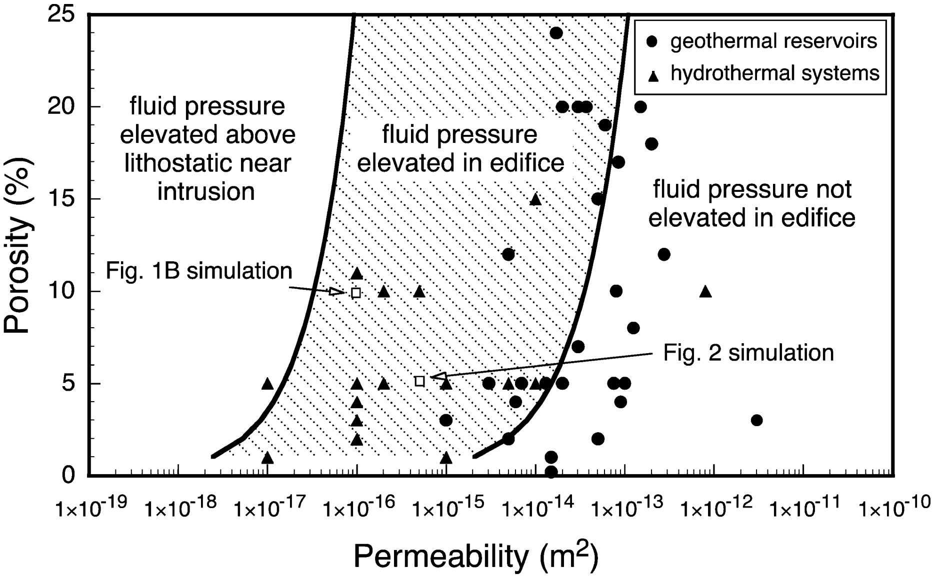

Figure 3. Sensitivity of thermal pressurization to rock intrinsic permeability and porosity. Striped region shows permeability and porosity combinations that lead to elevated fluid pressures in overlying edifice following magma intrusion at depth. Low values of permeability lead to fluid pressures in excess of lithostatic near top of intrusion. High values of permeability lead to pressure dissipation and minimal (<5%) disturbance of original edifice pressures. Data points show values determined from geothermal reservoirs (Bjornsson and Bodvarsson, 1990) or inferred from hydrothermal systems (Manning and Ingebritsen, 1999) (solid symbols). Values for simulation results in Figures 1B and 2 are also shown (open symbols).

HYDRAULIC CONDITIONS PROMOTING PRESSURIZATION

Rock thermal and hydraulic properties influence the magnitude of fluid pressurization. The hydraulic diffusivity of fluid-saturated rock—defined as $k/(n\mu\beta)$ by Delaney (1982), where k is rock intrinsic permeability, n is rock porosity, μ is dynamic viscosity of the fluid, and β is isothermal compressibility for fluid mass in a fixed volume of porous material—greatly influences the magnitude and duration of thermal pressurization. Permeability and thus diffusivity can vary over many orders of magnitude in volcanic rocks, making it one of the most uncertain parameters controlling far-field pore-fluid pressurization. Given the volcano configuration described here, I examine the role of permeability and porosity in promoting far-field fluid pressurization.

Significantly elevated fluid pressures within the edifice are unlikely both for very high and very low values of hydraulic diffusivity. Heating of fluids in higher-diffusivity rocks will allow fluids to expand, flow, and dissipate elevated pressures; thus elevated fluid pressures will not propagate into the edifice. This condition, shown in Figure 3, is indicated by a $<5\%$ increase in fluid pressure within the edifice. With very low diffusivity rocks, flow is retarded and high fluid pressures occur near the intrusion. High pressures may lead to hydrofracturing or brecciation of the rock, effectively increasing rock permeability. Pressures required to induce hydrofracturing depend on the stress state of the rocks; however, hydrofracturing is very likely if the fluid pressure exceeds lithostatic stress. Figure 3 also shows conditions where fluid pressures in excess of lithostatic are generated near the top of the intrusion.

Between these two extremes, intermediate hydraulic diffusivities allow fluid pressurization to propagate upward into the edifice without hydrofracturing; the striped region in Figure 3 shows the range of hydraulic properties creating a $>5\%$ increase in edifice fluid pressures. This range spans the transition from hydrothermal systems dominated by conduction to those controlled by advection of heat; such a transition often occurs around a permeability of $\sim10^{-16}$ m^2 (Norton and Knight, 1977; Hayba and Ingebritsen, 1997). For simulations with this intermediate range of hydraulic properties, the time lag between magma intrusion at depth and elevated pressures reaching midway into the edifice varies between $\sim$2 weeks for higher-diffusivity rocks and 3.3 yr for lower-diffusivity rocks. Maximum elevated pressures high within the edifice occur tens to hundreds of years after intrusion.

How plausible is pore-fluid pressurization from magma intrusion at depth, given stratovolcano rocks? Numerous values of rock permeability and porosity, determined in explored geothermal reservoirs (Bjornsson and Bodvarsson, 1990) and estimated in hydrothermal systems by heat or solute-transport observations or inferred from metamorphic systems (Manning and Ingebritsen, 1999), are also shown in Figure 3. Many of these values would permit far-field fluid pressurization, given the modeled scenarios. However, volcanoes can be extremely heterogeneous; rock layering, conduits, and cap rocks influence fluid-pressure evolution. High-permeability rocks, such as those found in Kilauea volcano (Ingebritsen and Scholl, 1993) or modeled in Poas volcano (Sanford et al., 1995), or large unsaturated regions within an edifice (Hurwitz et al., 2003) decrease the likelihood of far-field fluid pressurization. Hydrothermal alteration of edifice rocks (Lopez and Williams, 1993) can reduce rock permeability and enhance the transmission of thermal pressurization. Shallower, larger, or hotter intrusions would likely increase fluid pressurization (Delaney, 1982). My simulations assume a simplified volcanic system. Nevertheless, they illustrate that destabilizing far-field pressurization of fluids is plausible under realistic conditions and could occur in complex volcanic settings given favorable permeability structures.

CONCLUSIONS

Massive edifice collapse of stratovolcanoes can transpire without magma intruding into the edifice; such failures may occur without the precursory activities that often accompany shallow intrusion. Historical documentation indicates that volcano edifices undergoing this type of collapse contained shallow hydrothermal systems. Numerical modeling demonstrates that heating from a remote magma intrusion can temporarily elevate pore-fluid pressures and that these pressures can propagate upward into an overlying volcano edifice. Given a specific range of hydraulic properties, these elevated pressures can modify effective stresses, destabilize the core, and provoke hydrothermally driven collapse of an edifice. Hydraulic properties capable of generating destabilizing fluid pressures are present in many hydrothermal systems, making such a mechanism plausible for explaining these collapses; such pressurization effects may be destabilizing in other volcanic settings as well. Because fluid pressurization can propagate rapidly, detection would require intensive monitoring of pore-fluid pressures and/or deformation in the edifice. Nevertheless, hydrothermal pressurization potentially threatens the mechanical stability of volcano edifices.

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