doi: 10.1111/j.1365-3121.2004.00567.x

The effect of internal gas pressurization on volcanic edifice stability: evolution towards a critical state

Mark E. Thomas,[1] Nick Petford[1] and Edward N. Bromhead[2]

[1]*School of Earth Science and Geography, and* [2]*School of Engineering, Kingston University, Kingston KT1 2EE, UK*

ABSTRACT

Results from simple physical and numerical models investigating the effects of increased internal pore-fluid pressures of a Mohr–Coulomb volcanic edifice are presented. Physical experiments make use of a heap built from angular sand on top of a stiff substrate of variable angle, with the provision for injection of internal fluid (gas) pressures into the base. The resulting failure geometries arising from internal pressurization of the model appear similar to some natural examples of sector collapse. Two-dimensional limit equilibrium models analysing 42 500 possible failure surfaces were run with internal pressures (P_0) in the range 5–35 MPa, and show that the potential critical failure surface migrates to increasingly deeper levels with increasing internal pressure. Although internal pressurization alone is unlikely to reduce the factor of safety (F_S) below unity, the edifice is driven towards a state of criticality that will render in susceptible to any internal or external perturbations.

Terra Nova, 16, 312–317, 2004

Introduction

Studies during the last two decades have raised awareness of the life- and property-threatening hazards resulting from volcano instability (e.g. Tilling, 1995; McGuire *et al*., 1996; Siebert, 1996; Wolfe and Hoblitt, 1996; McGuire, 1998). Much new interest arose following the climactic May 1980 eruption of Mount St Helens, caused by a massive landslide on the volcano's northern flank.

Geotechnical engineers and geologists studying landslides are familiar with fluid pressurization by water, and its modifying effects on the shear strength of soils and rocks (e.g. Voight, 1978; Bromhead, 1986). Ordinarily, this pressurization is by groundwater of meteoric origin, and is rarely artesian, being hydrostatic and related to a groundwater level within the slope. Groundwater bodies created by infiltration from the surface lead to shallow landsliding and thus slopes that are stable against deeper-seated modes of failure (e.g. Bromhead, 1995). Recently, Voight and Elsworth (2000) have proposed a novel, highly non-linear instability mechanism for the hazardous collapse of lava domes in which dome failure is instigated by gas overpressure. As a first step towards understanding edifice failure at a basic level, we have modelled a destabilizing mechanism involving gas pressurization (e.g. Gerlach *et al*., 1996) that affects the entire interior of the edifice and the external expression of which is a deep-seated failure mode (landslip), which might be the cause of catastrophic eruption. Our model thus differs from other recent studies of volcano instability (e.g. Reid *et al*., 2001), in which the effects of internal fluid pressures are ignored and collapse is driven purely by gravity acting on regions of weak (hydrothermally altered) rock.

Initial results of an ongoing programme of physical and numerical modelling designed to examine in detail the role of internal (fluid) pressurization in promoting failure in conical structures (heaps) are described. Using simple scaling arguments, it is shown that a volcanic edifice may be regarded as a heap of (Mohr–Coulomb) granular material and that the failure surface resulting from internal (gas) pressurization is deep seated. Rock mass field data show that the edifice is likely to be weak, and using values of natural examples from Snowdonia, Tenerife (Thomas *et al*., 2004) and work published by Voight *et al*. (1983), we simulate the change in the factor of safety as a function of internal pressurization. We show that this important but largely unquantified processes may in some circumstances play a major role driving the volcanic edifice towards a critical state (e.g. Hill *et al*., 2002).

Correspondence: Mark E. Thomas, School of Earth Science and Geography, Kingston University, Kingston KT1 2EE, UK. Tel.: +44 (0)20 85742000 ext. 61011; e-mail: markthomas@kingston.ac.uk

Current models of edifice failure

A number of models have been proposed to explain structural failure and collapse of a volcanic edifice in both fast and slow modes, in response to one or more internal or external triggers. Commonly cited examples include magma chamber replenishment, dyke emplacement and volcanogenic earthquakes (typically M > 5 close to or directly beneath a volcano) and intense rainfall (e.g. Elsworth and Voight, 1995; McGuire, 1998). In addition to the well-documented triggers, hydrothermal activity is recognized to play an important role in weakening the rock mass and rendering it more susceptible to mechanically induced structural failure (e.g. van Wyk de Vries *et al*., 2000; Reid *et al*., 2001). Despite this, some important questions remain. For example, major volcanic eruptions are also frequently preceded by emission of large quantities of volcanic gases in conjunction with vigorous fumerole activity, or steam generated by heating of groundwater (e.g. Pyle *et al*., 1996; Gerlach *et al*., 1996; Mouginis-Mark *et al*., 2000). However, although the emission of volcanic gasses and their compositions are routinely monitored, the mechanical effects of the gas phase on the shear strength and structural integrity of the edifice have been mostly overlooked. Gas sources include deep magma reservoirs and the progressive dehydration of the volcano's hydrothermal system (Tilling, 1995). Another factor is the process of volcanic spreading (Borgia, 1994; Merle and Borgia, 1996), but sector collapse events are thought only to occur if spreading is not efficient (Borgia *et al.*, 2000), and therefore no further consideration is given to this mode of destabilization.

Edifice strength

The strength of an edifice is a property that requires careful consideration in volcano stability simulations. Indeed, the concept of edifice strength becomes critical when considering internal fluid pressurization, as the use of unrealistically high-strength parameters raises the nonsensical idea of a 'floating' volcano, in which the edifice is so strong that the internal pressure can counteract its weight without failing. The structure then becomes neutrally buoyant. Although uniaxial laboratory tests on fresh intact basalt will yield a compressive strength of 100–350 MPa (Schultz, 1995, 1996), a volcanic edifice is not simply intact rock but is cut through by a range of discontinuities, including faults, fractures and layering defined by discrete lava flows. Field approximations of the rock mass strength of crystalline volcanic material are surprisingly low, with cohesion values ranging from 300 kPa to 3.2 MPa (Voight *et al.*, 1983; Schultz, 1995, 1996; Watters *et al.*, 2000; Thomas *et al.*, 2004).

Internal pressurization

Pressurization from within the edifice is known to happen at all active volcanoes. It is well recognized that recorded gas emissions are generally more than the amount predicted from petrological studies of the crystal content of the erupted products (de Hoog *et al.*, 2001), suggesting the magma de-gases within the edifice. There is also the additional factor of dehydration (boiling) of active hydrothermal systems during a volcanic eruption producing elevated gas pressures. Robertson *et al.* (1998) and Sparks (1997) give estimates of values for internal system pressurization for parts of a volcanic system. Robertson *et al.* (1998) showed that a minimum pressurization of 27.5 MPa was required to explain the locations of the largest ballistics produced by the 1996 eruption of Soufriere Hills Volcano, Montserrat; Sparks (1997) suggested typical excess pressures of 5–20 MPa. Sparks (1997) also suggested maximum theoretical excess pressures of close to 50 MPa, although due to permeable flow within the edifice, these theoretical pressures are rarely reached. These values are not a homogeneous pressure present throughout the edifice, but are presented here to demonstrate values of local pressure that have been measured or interpreted within a volcanic edifice.

Physical modelling

Initial experiments have been carried out with a simple uniform cone constructed of air-dried angular (sharp) sand, with provision for internal pressurization by gas (compressed air) at a controlled rate pumped through the base (Fig. 1a). Angular sand was used because of its higher internal angle of friction and repose compared with other types of granular material. The cone was created by raining particles from above and rested upon a stiff substrate of variable angle. The models were run with substrate angles of 5–20°. Using scaling arguments (below) and following the Buckingham Π theorem (Middleton and Wilcock, 1994), the controlling parameters for a conical heap of sand are given in Table 1. From Table 1 we can see that there are five variables minus three dimensions equal to two independent dimensionless products, the stability number N and a non-named group Φ:

Table 1 Geometric and mechanical variables for a conical heap of sand

Variable	Definition	Dimensions
c	cohesion	kN m^{-2}
ϕ	friction angle	–
H	height	m
α	slope angle	–
γ	unit weight	kN m^{-3}

$$N = \frac{c}{\gamma H} \quad \text{and} \quad \Phi = \frac{\tan\phi}{\tan\alpha} \qquad (1,2)$$

A model perfectly represents the prototype if the two dimensionless groups are the same for both. The Φ parameter is matched if the ratio of the friction angles and the slope angles are the same. Estimates of the angle of friction for a volcanic pile suggested by other authors (Jaeger and Cook, 1979; Voight *et al.*, 1983; Watters and Delahaut, 1995) match closely the 38° friction angle of the sand used. Thus a model volcanic edifice needs the same slopes as its prototype.

For a 2000-m-high volcanic cone, taking c to be 1 MPa (1000 kN m^{-2}), and γ to be 25 kN m^{-3}, Eq. (1) gives a stability number (N) of 0.02. To achieve this stability number for a 0.2-m-high pile of sand ($\gamma =$ 20 kN m^{-3}), substituting these values again into Eq. (1) $c = 0.08$ kN m^{-2} (80 Pa), which is practically unmeas-

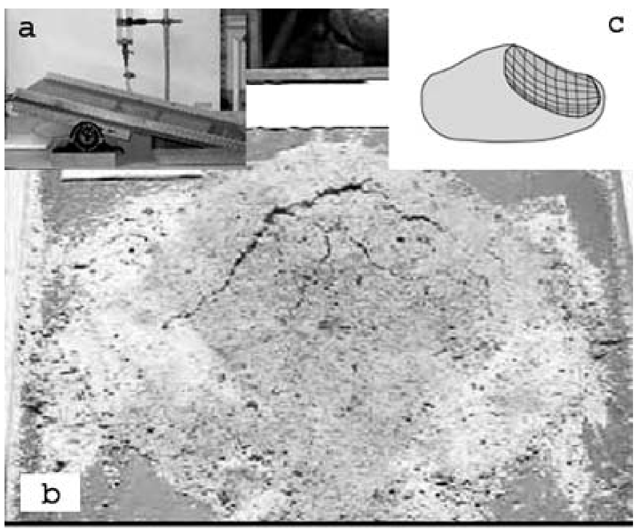

Fig. 1 Sandpile model with air pressurization: (a) experimental set-up, (b) surface expression of failure surface and (c) diagrammatic representation of the failure surface.

urable in the laboratory. Capillary tensions in air-dried sand would probably exceed this equivalent (Schellart, 2000). Hard though it may be to believe, a heap of sand on the laboratory workbench does truly represent a perfectly scaled model of a large volcanic edifice.

The fluid pressures scale on the basis of the maximum pressure (u), H and γ through the pore pressure ratio r:

$$r = u/\gamma H \quad (3)$$

This is also a linear scaling, so the reduced size of the physical model is realistic. What does not scale linearly is the rate dependency of the collapse mechanism, and the propagation of fluid pressures throughout the edifice. Theses effects must be scaled on the basis of a time factor, which depends on rock mass permeability, fluid–rock relative compressibility, unit weight of the pore fluid and some critical size parameter termed drainage path length raised to the power 2. Modelling rate effects is outside the scope of this paper, except in a qualitative sense.

Numerical modelling

Numerical analysis into the effects of gas pressurization was carried out using two-dimensional limit equilibrium models. Limit equilibrium models use the most widely expressed index of stability, the factor of safety (F_S), which for a potential failure surface is defined as the ratio of shear strength to shear stress:

$$F_s = \int_L s / \int_L \tau \quad (4)$$

where s is the shear strength, τ is the shear stress and the integration takes place along the length (L) of the failure surface. Numerical calculations were conducted using an in-house slope stability analysis package following the iterative method of Bishop (1955). This form of stability analysis is commonplace in geotechnical engineering and merits no further discussion. Factors of safety of 1 or less imply instability. Ordinarily, analysis is conducted on a plane section through a slope about a centre of rotation, and two-dimensional methods of analysis usually give satisfactory results for simple cases. This approach was used by Voight and Elsworth (2000) as a general geometry for their limit equilibrium analysis of shallow flank and deep-seated edifice failure. Although our analysis is restricted to two dimensions, three-dimensional methods have been developed and applied to, *inter alia*, non-uniform surface topography and loading, which arguably is closer to the case represented by an unstable volcanic edifice.

The physical values used in our calculations are those defined previously by Voight *et al.* (1983) for the Mt St Helens edifice: cohesion (c, 1000 kPa (1 MPa)), angle of friction (ϕ, 40°) and unit weight (W, 24 kN m^{-3}), with a pore pressure ratio (u) of 0.3. These values were used as they are in the middle of the range of values presented by Schultz (1995, 1996), Thomas *et al.* (2004), Voight *et al.* (1983) and Watters *et al.* (2000).

Results

Physical modelling

The effects of internally pressurizing a sandpile model described above are shown in Fig. 1(b,c). Viewed from above, an arcuate crack is clearly visible traversing the summit and flanks of the pile. Several smaller radial cracks are also evident. This style of deformation was typical of the response of the pile to internal pressurization. A sketch (Fig. 1c) of the internal geometry of the slip surface after the failed portion had been removed confirms its deep-seated nature. Unsurprisingly the effect of increasing the angle of the base resulted in larger volume failures with a shorter time to failure from the onset of pressurizing the model. A key observation is that the surface expression and geometry of the failure surfaces (Fig. 2) are similar to those observed at Mount St Helens (Donnadieu *et al.*, 2001), Mount Etna (Tibaldi and Groppelli, 2002) and La Palma (Day *et al.*, 1999). Detailed morphological comparisons have not been conducted, and the similarities are purely in physical appearance.

Numerical modelling

Numerical results obtained from limit equilibrium modelling independent from the physical models are shown in Figs 3 and 4. Calculations were set up to take into account the effects of: (1) no source of internal fluid pressurization (dry), (2) internal fluid pressurization produced by ground water infiltration only (wet) and (3) an edifice with a source of internal gas pressurization plus groundwater infiltration (wet plus internal).

A total of 42 500 possible failure surfaces were analysed during each simulation. For both cases, two model geometries were used (Fig. 4) to represent the volcano edifice, a uniform cone and one (more realistic) with topography similar to the pre-1980 eruption Mount Helens. In this paper there is no attempt to model Mount St Helens and it is only the topography that is used in the numerical models. Results of both experiments are summarized in Table 2. The internally pressurized area was defined as 75% of the volume of the defined edifice topography and the pressure was set at 100% at the pressure boundary (Fig. 4) and 0 at the 75% limit, with a linear distribution of pressure between the two boundary conditions.

Figure 3 shows a plot of factor of safety (F_S) against depth (km) calculated for a simple uniform cone for a range of internal pressures from 5 to 35 MPa. For both model types, a potential shallow instability is always present (Fig. 3). However, the end effect of increasing pressure is to (1) drive the potential critical failure surface deeper into the interior of the edifice and (2) decrease the factor of safety for that potential failure surface.

Considering a simple cone, an internal pressure of 25 MPa, a value close to the estimates of Robertson *et al.* (1998), displaces the potential critical failure surface from a shallow potential instability to depth of 3.2 km from the centre of rotation (Fig. 3). Further increasing the pressure to 35 MPa lowers the F_S to below unity and makes the slope unstable without any additional factors being considered.

The effect of driving the potential critical failure surface deeper within the cone is that the volume above the critical failure surface is increased substantially relative to external pressurization by groundwater infiltration (Fig. 4). Should the volcanic edifice fail, then the potential volume of

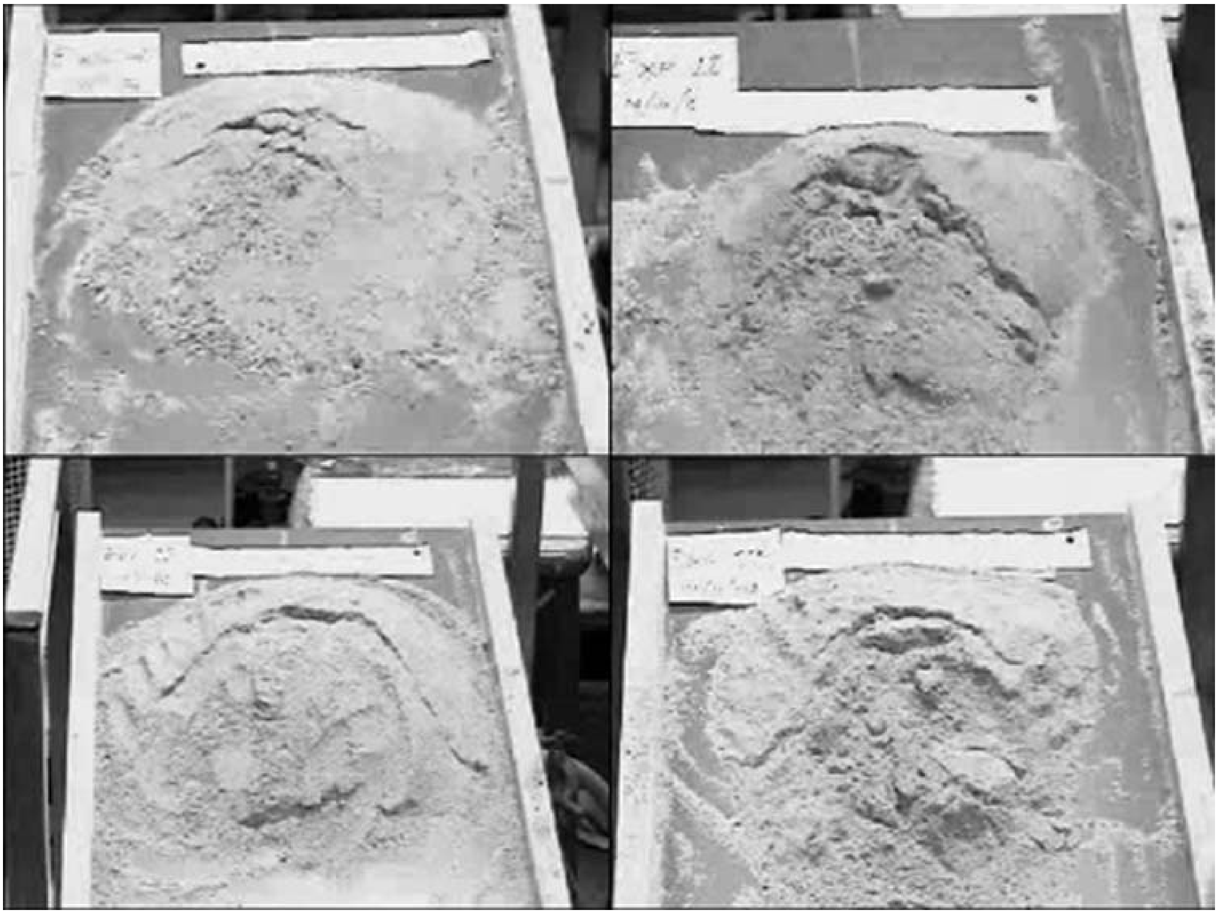

Fig. 2 Digital video stills showing the surface expressions of failure surfaces in the sand-pile models. All these images are from models conducted on 5° slopes.

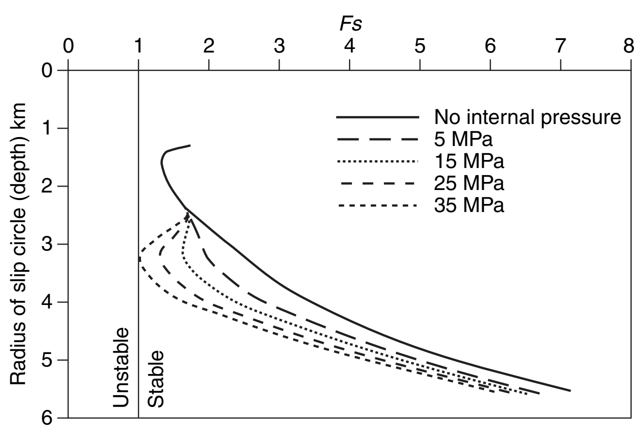

Fig. 3 Plot of factor of safety (F_S) against depth for a uniform cone, calculated at increasing internal pressure. Note that the shallow instability is still present in all cases, but instead of steadily increasing with depth as in the curve at no internal pressurization, F_S starts to decrease at depth when considering increasing internal pressure, until at an internal pressure of 25 MPa, the critical failure surface is no longer shallow, but is located at 3.2 km depth. (Note that all depths are taken from the slip circles to centre of rotation and are not measurements below ground level.)

material liberated during failure will be far greater.

Discussion

Our numerical results and scaling analysis suggest that internal fluid pressurization may be significant in promoting deep-level instabilities within a volcanic edifice. It is fully accepted that the physical models may be an oversimplification of the problem and we acknowledge that internal pressurization is unlikely to be the sole cause of catastrophic edifice collapse. It may nevertheless contribute significantly to the growing number of recognized mechanisms that complicate collapse predictions (e.g. Reid *et al.*, 2001). In particular, it provides a mechanism for driving the edifice close to its critical state (Hill *et al.*, 2002).

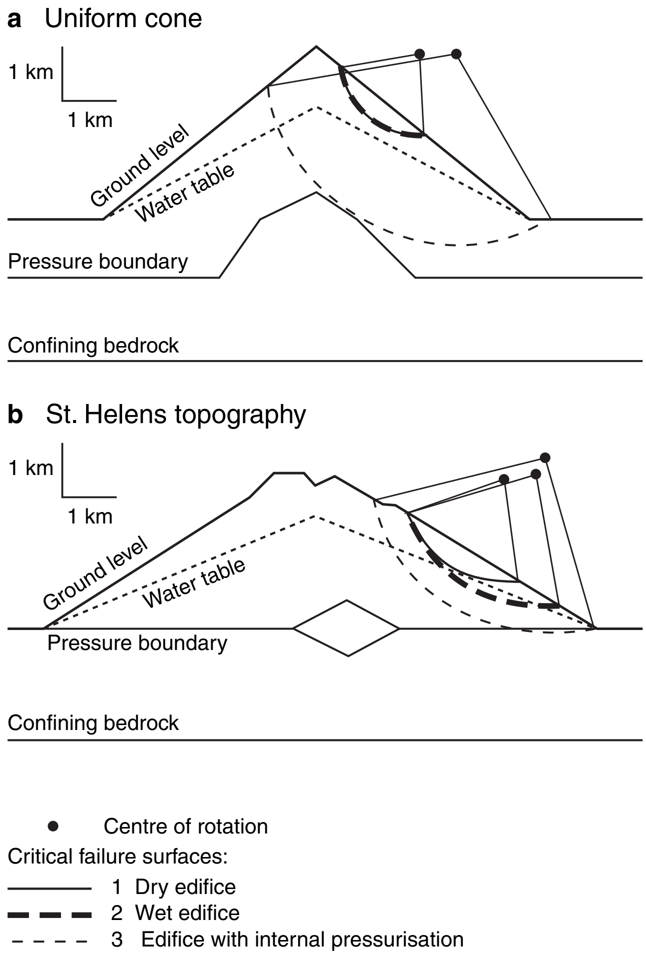

Fig. 4 Potential critical failure surfaces for a uniform cone (a), and an edifice with pre-1980 Mount St Helens like topography (b), potential failure surfaces for a 'dry' edifice, a 'wet' edifice and a 'wet' edifice plus internal gas pressurization are shown. Results are summarized in Table 2.

Table 2 Factor of safety (F_S) for the potential critical failure surfaces in Fig. 4 from the limit equilibrium modelling (numbers refer to pressurization regimes outlined in the text)

Uniform cone			St Helens topography		
1	Dry	1.73	1	Dry	1.99
2	Wet	1.32	2	Wet	1.53
3	Wet plus Internal	1.30	3	Wet plus Internal	1.33

Internal gas pressurization is a phenomenon that must happen to some extent in all active volcanoes, as the recorded gas emissions are generally more than the amount predicted from petrological studies of the crystal content of the erupted products (de Hoog *et al.*, 2001; Wallace, 2001). This suggests the magma has a gas-rich phase at depth. This, coupled with magma de-gassing at shallower levels, could lead to excess upward-propagating pore pressures. In addition, dehydration (boiling) of active hydrothermal systems during magma emplacement leads to considerable elevated pore pressures (Reid, 2004). Once a volcanic system has reached a critical state, collapse my be initiated by any previously studied triggers (Dieterich, 1988; Iverson, 1995; McGuire *et al.*, 1996; Voight and Elsworth, 1997). Indeed, if the edifice has been sufficiently weakened by hydrothermal alteration, internal pressurization may itself bring about the onset of collapse.

Acknowledgements

We would like to thank Stan Vince for help with technical support, and Barry Voight, Derek Elsworth, Bill McGuire and Chris Kilburn for helpful discussions during the formative stages of this work.

References

Bishop, A.W., 1955. The use of the slip circle in the stability analysis of slopes. *Geotechnique*, **5**, 1–17.

Borgia, A., 1994. Dynamic basis for volcanic spreading, *J. Geophys. Res.*, **99** (B9), 17791–17804.

Borgia, A., Delaney, P.T. and Denlinger, R.P., 2000. Spreading volcanoes. *Ann. Rev. Earth Planet. Sci.*, **28**, 539–570.

Bromhead, E.N., 1986. Pore water pressure manipulation in computerised slope stability analysis. In: *Proceedings, Midland Geotechnical Society Conference on Computer Applications in Geotechnical Engineering*, pp. 175–184. Midland Geotechnical Society, Birmingham.

Bromhead, E.N., 1995. *Water and Landslides*, pp. 42–56. Royal Academy of Engineering, London.

Day, S., Carracedo, J.C., Guillou, H. and Gravestock, P., 1999. Recent evolution of the Cumbre Vieja volcano, La Palma, Canary Islands: volcanic roft zone reconfiguration as a precursor to volcano flank instability. *J. Volcanol. Geotherm. Res.*, **94**, 135–167.

Dieterich, J.H., 1988. Growth and persistence of Hawaiian volcanic rift zones. *J. Geophys. Res.*, **93** (B5), 4258–4270.

Donnadieu, F., Merle, O. and Besson, J., 2001. Volcanic edifice stability during cryptodome intrusion. *Bull. Volcanol.*, **63**, 61–72.

Elsworth, D. and Voight, B., 1995. Dike intrusion as a trigger for large earthquakes and the failure of volcano flanks. *J. Geophys. Res.*, **100** (B4), 6005–6024.

Gerlach, T.M., Westrich, H.R. and Symonds, R.B., 1996. Preeruption vapour in magma of the climactic Mt. Pinatubo eruption: source of giant stratospheric sulphur dioxide cloud. In: *Fire and Mud: Eruptions and Lahars of Mt. Pinatubo, Philippines* (C. G. Newhall and R. S. Punongbyan, eds), pp. 415–433. University of Washington Press.

Hill, D.P., Pollitz, F. and Newhall, C., 2002. Earthquake–volcano interactions. *Physics Today*, **November**, 41–47.

de Hoog, J.C.M., Koetsier, G.W., Bronto, S., Sriwana, T. and van Bergen, M.J., 2001. Sulfur and chlorine degassing from primitive arc magmas: temporal changes during the 1982–83 eruptions of Galunggung (West Java, Indonesia). *J. Volcanol. Geotherm. Res.*, **108**, 55–83.

Iverson, R.M., 1995. Can magma-injection and groundwater forces cause massive landslides on Hawaiian volcanoes? *J. Volcanol. Geotherm. Res.*, **66**, 295–308.

Jaeger, J.C. and Cook, N.G.W., 1979. *Fundamentals of Rock Mechanics*, 3rd edn. Chapman & Hall, New York.

McGuire, W.J., Jones, A.P. and Neuberg, J. (eds) 1996. Volcano Instability on the Earth and Other Planets. *Geological Society Special Publication*, **110**.

McGuire, W.J., 1998. Volcanic hazards and their mitigation. In: *Geohazards in Engineering Geology* (J. G. Maund and M. Eddleston). *Spec. Publ. Geol. Soc. Lond.*, **15**, 79–95.

Merle, O. and Borgia, A., 1996. Scaled experiments of volcanic spreading. *J. Geophys. Res.*, **101** (B6), 13805–13817.

Middleton, G.V. and Wilcock, P.P., 1994. *Mechanics in the Earth and Environmental Sciences*. Cambridge University Press, Cambridge, pp. 74–83.

Mouginis-Mark, P.J., Crisp, J.A. and Fink, J.H., 2000. Remote Sensing of Active Volcanism. *Geophysical Monograph Series*, **116**.

Pyle, D.M., Beattie, P.D. and Bluth, G.J.S., 1996. Sulphur emission to the stratosphere from explosive volcanic eruptions. *Bull. Volcanol.*, **57**, 663–671.

Reid, M.E., 2004. Massive collapse of volcano edifices triggered by hydrothermal pressurization. *Geology*, **32**, 373–376.

Reid, M.E., Sisson, T.W.B. and Brien, D.L., 2001. Volcano collapse produced by hydrothermal alteration and edifice shape, Mt. Rainier, Washington. *Geology*, **29**, 779–782.

Robertson, R., Cole, P., Sparks, R.J.S., Harford, C., Lejeune, A.M., McGuire, W.J., Miller, A.D., Murphy, M.D., Norton, G., Stevens, N.F. and Young, S.R., 1998. The explosive eruption of Soufrirer Hills Volcano, Montserrat, West Indies, 17 September, 1996. *Geophys. Res. Lett.*, **25**, 3429–3432.

Schellart, W.P., 2000. Shear test results for cohesion and friction coefficients for different granular materials: scaling implications for their usage in analogue modelling. *Tectonophysics*, **324**, 1–16.

Schultz, R.A., 1995. Limits on strength and deformation properties of jointed basaltic rock masses. *Rock Mechanics Rock Engineering*, **28**, 1–15.

Schultz, R.A., 1996. Relative scale and the strength and deformability of rock masses. *J. Struct. Geol.*, **18**, 1139–1149.

Siebert, L., 1996. Hazards of very large volcanic debris avalanches and associated eruptive phenomena. In: *Monitoring and Mitigation of Volcano Hazards* (R. Scarpa and R. I. Tilling, eds), pp. 541–572. Springer-Verlag, Berlin.

Sparks, R.S.J., 1997. Causes and consequences of pressurisation in lava dome eruptions. *Earth Planet. Sci. Lett.*, **150**, 177–189.

Thomas, M.E., Petford, N. and Bromhead, E.N., 2004. Volcanic rock-mass properties from Snowdonia and Tenerife: implications for volcano edifice strength. *J. Geol. Soc. Lond.*, in press.

Tibaldi, A. and Groppelli, G., 2002. Volcano-tectonic activity along structures of the unstable NE flank of Mt. Etna (Italy) and their possible origin. *J. Volcanol. Geotherm. Res.*, **115**, 277–302.

Tilling, R.I., 1995. The role of monitoring in forecasting volcanic events. In: *Monitoring Active Volcanoes* (W. J. McGuire, C. R. J. Kilburn and J. B. Murray, eds), pp. 369–402. University College London Press, London.

Voight, B. (ed.) 1978. *Rockslides and Avalanches. 1. Natural Phenomena*. Elsevier, Amsterdam.

Voight, B. and Elsworth, D., 1997. Failure of volcano slopes. *Geotechnique*, **47**, 1–31.

Voight, B. and Elsworth, D., 2000. Stability of gas-pressurised lava-domes. *Geophys. Res. Lett.*, **27**, 1–4.

Voight, B., Janda, R.J., Glicken, H. and Douglass, P.M., 1983. Nature and mechanics of the Mt. St. Helens rockslide-avalanche of 18th May 1980. *Geotechique*, **33**, 243–227.

Wallace, P.J., 2001. Volcanic SO_2 emissions and the abundance and distribution of exsolved gas in magma bodies. *J. Volcanol. Geotherm. Res.*, **108**, 85–106.

Watters, R.J. and Delahaut, D., 1995. Effect of argillic alteration on rock mass stability. In: *Clay and Shale Slope Instability, Review of Engineering Geology*, Vol. X (W.C. Haneburg and S.A. Anderson, eds), pp. 139–150. Geological Society of America, Boulder, CO.

Watters, R.J., Zimbelman, D.R., Bowman, S.D. and Crowley, J.K., 2000. Rock mass strength assessment and significance to edifice stability, Mt. Rainier and Mt. Hood, Cascade Range volcanoes. *Pure Appl. Geophys.*, **157**, 957–976.

Wolfe, E.W. and Hoblitt, R.P., 1996. Overview of the eruptions. In: *Fire and Mud: Eruptions and Lahars of Mt. Pinatubo, Philippines* (C. G. Newhall, and R. S. Punongbyan, eds), pp. 3–20. University of Washington Press.

van Wyk de Vries, B., Kerle, N. and Petley, D., 2000. Sector collapse forming at Casita volcano, Nicaragua. *Geology*, **28**, 167–170.

Received 5 March 2004; revised version accepted 16 July 2004

