LA-UR - 93- 3699

Title: **Role of Magma-Water Interaction in Very Large Explosive Eruptions**

Author(s): Greg A. Valentine

Submitted to: International Seminar on Physics of Vapor Explosions
Tomakomai, Japan
25-29 October 1993

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

MASTER

ROLE OF MAGMA-WATER INTERACTION IN VERY LARGE EXPLOSIVE ERUPTIONS

Greg A. Valentine
Geoanalysis Group, Mail Stop F665
Los Alamos National Laboratory
Los Alamos, NM 87545 USA
Tel: 1 505 665 02'9
Fax: 1 505 665 3 ,87

ABSTRACT

An important class of explosive eruptions, involving large-scale magma-water interaction during the discharge of hundreds to thousands of cubic kilometers of magma, is discussed. Geologic evidence for such eruptions is summarized. Case studies from New Zealand, Australia, England, and the western United States are described, focusing on inferred eruption dynamics. Several critical problems that need theoretical and experimental research are identified. These include rates at which water can flow into a volcanic vent or plumbing system, entrainment of water by explosive eruptions through lakes and seas, effects of magma properties and gas bubbles on magma-water interaction, and hazards associated with the eruptions.

INTRODUCTION

The purpose of this paper is to discuss geologic evidence for and examples of explosive magma-water interaction in large-volume eruptions of silicic magma, and to pose some problems on this topic which would benefit from theoretical and experimental analysis. The eruptions which I will focus on are those which discharge several tens to thousands of cubic kilometers of magma from subsurface reservoirs. The evacuation of such large quantities of magma from these reservoirs, or chambers, invariably results in subsidence of the overlying terrain to form depressions called calderas. These calderas form closed basins which collect large amounts of ground- and surface water and those which form in coastal environments commonly form large bays. As a result, subsequent eruptions are prone to magma-water interaction.

The plan of the paper is as follows. First, I will briefly describe some of the criteria which geologists use in the field to identify hydrovolcanic deposits from caldera-forming eruptions. Next I will summarize specific cases which illustrate the general behavior of these eruptions. Most of the cases which have been studied to date have been eruptions of tens to approximately one hundred cubic kilometers of magma; these include the Wairakei (New Zealand), Cana Creek Tuff (Australia), and Whorneyside Tuff (England) eruptions (this is not intended to be an exhaustive list). Brief mention will also be made of evidence for magma-water interaction in eruptions approaching or exceeding 1000 km^3 in volume in the southwestern United States. All of these eruptions are prehistoric. Finally, important issues that need to addressed for these eruptions will be described, including the necessary flux of water into a high discharge rate eruption, the effects of magma properties, and the climatic effects of large hydrovolcanic eruptions compared with those driven mainly by magmatic gases. Throughout the paper I have tried to minimize the use of volcanological jargon, although it is unavoidable in places. The reference list is not exhaustive but is intended to provide some key works from which the interested participant in this symposium can obtain most of the information currently available on this topic.

1. CRITERIA FOR RECOGNIZING MAGMA-WATER INTERACTION IN LARGE ERUPTIONS

1.1. Particle Characteristics

Perhaps the most important clue for hydrovolcanic activity in silicic eruptions is the morphology of the erupted ash under microscopic (optical and scanning electron) examination. The reader is referred to the excellent book by Heiken and Wohletz [1] for a detailed presentation of observation and interpretation of ash morphology. There are two main ways that magma can fragment to form ash (particles < 2 mm in diameter) and larger particles. One way is by exsolution of dissolved volatiles to form bubbles (vesicles) which then expand as magma rises and is decompressed (Sparks [2], Toramaru [3]). When the bubbles attain some critical volume fraction, which lies between about 0.6-0.85 depending on the composition and crystal content of a magma (in theoretical models the critical value is commonly assumed to be 0.75), the magma fragments and accelerates upward. The fragmented magma mainly consists of small pieces of quenched bubble walls and lesser quantities of lumps of quenched, highly vesicular, magma froth (pumice). This process is referred to as magmatic fragmentation because it is driven by gases that originally resided within the magma. An example of ash produced by magmatic fragmentation is shown in Figure 1a.

The second mechanism for explosive fragmentation of magma is by a fuel-coolant interaction between magma and externally derived water. This is referred to as hydrovolcanic or phreatomagmatic fragmentation, and has been described in detail by Wohletz [4]. If the magma has not vesiculated or is only partially vesiculated it will fragment into blocky, dense (nonvesicular or poorly vesicular) ash particles. An example is shown in Figure 1b. In this example the magma was slightly vesicular, but was not fragmented by magmatic processes, as indicated by the curviplanar surface which cross cuts a vesicle. Most eruptions are driven by some combination of the two fragmentation processes. For example most documented phreatoplinian eruptions (described below) were caused by magma which was already somewhat vesiculated interacting with external water. The products of this mixed process are dominated by fine-grained ash comprised of both bubble wall fragments and poorly vesicular, blocky shards (Self and Sparks [5]).

Another type of clast that indicates hydrovolcanic activity is accretionary lapilli, which are spherical or subspherical aggregates of ash particles that rain out of eruption plumes as "mudballs." Accretionary lapilli are typically a few millimeters to a centimeter in diameter. Schumacher and Schmincke [6] review the occurrences of accretionary lapilli and describe in detail the types which are found at the Laacher See volcano in Germany. The detailed processes which produce accretionary lapilli are a current topic of investigation, but it is known that they result from aggregation of ash onto wet particles or nuclei and hence require the presence of liquid water in an eruption cloud. The presence of sparse accretionary lapilli in a pyroclastic deposit does not necessarily demand a hydrovolcanic eruption, but an abundance of such lapilli commonly does indicate hydrovolcanism.

1.2. Fallout deposits

Large magnitude, silicic hydrovolcanic eruptions can have high standing buoyant plumes from which ash falls out to produce deposits which blanket the terrain and have certain characteristics which distinguish them from fallout deposits of magmatic eruptions (Self and Sparks [5]). These deposits and the eruptions which produce them are called "phreatoplinian." They are fine grained throughout their extents, with median diameters rarely exceeding 0.5 mm (more commonly the median diameters are 0.1-0.25 mm), reflecting extremely efficient fragmentation of the erupting magma due to explosive interaction with water (compare with median diameters of tens of centimeters for proximal fallout deposits from magmatic eruptions of similar magnitude). Phreatoplinian deposits exhibit improved sorting with increasing distance from vent because the rare coarse particles fall out in proximal areas along with fine ash, as opposed to deposits from magmatic eruptions where sorting generally changes very little downwind. The overall sorting of phreatoplinian deposits can be somewhat poorer than their magmatic counterparts, which are sorted according to settling velocities of particles, because of rain flushing effects.

Phreatoplinian deposits are dispersed away from their vents in a similar manner to magmatic eruptions of similar magnitude, covering areas of 50 km^2 to more than 100,000 km^2 (Self and Sparks [5]). Dispersal depends on height of eruption plumes (a.k.a. columns), and this range of values implies plume heights of a few kilometers to several tens of kilometers. Plume height in turn is strongly dependent on entrainment and heating of ambient air. It seems likely that phreatoplinian eruption columns exit their vents at cooler temperatures than magmatic eruptions because of the quenching effect of water and the energy required to vaporize it, and this would seem to limit the ability of the column to heat entrained air. This effect may be counterbalanced by the fact that phreatoplinian eruptions produce much finer grained ash than magmatic eruptions so that the heat that does remain in the particles after magma-water interaction is more efficiently transferred to the gas phase (higher surface area to volume ratio for the particles). Another effect which may counterbalance the low eruption temperature is condensation of water in the steam-laden plume as it rises and cools. This would release latent heat and therefore regain a portion of the energy lost in the magma-water interaction.

Bedding features of phreatoplinian deposits are commonly characterized by fine-scale lamination, although some deposits are only crudely stratified (e.g., Self and Sparks [5], Walker [7]). It appears that fallout from phreatoplinian eruptions is commonly accompanied by rainfall (probably condensing within the eruption plumes) and local microbedding caused by splashing rain drops is common in the deposits. In addition, deposits can exhibit internal gullying and erosion due to locally heavy rains during the eruptions. Slumping features are common in the deposits because they are often wet.

1.3. Deposits from pyroclastic currents

Large-volume silicic eruptions usually produce laterally-flowing, ground-hugging currents that are driven across the landscape by their high density relative to the atmosphere and by blast phenomena. The currents consist of a mixture of vapor and particles with a wide range of sizes and densities, and typically travel at speeds of tens to hundreds of meters per second. Resulting deposits can range from massive, poorly sorted beds (commonly referred to as ignimbrites) to stratified and cross stratified sequences (pyroclastic surge deposits), depending on the rate at which particles sediment out of the currents. Large ignimbrites from magmatic eruptions are deposited at high temperatures (greater than about 500 C) so that particles are still viscous and sticky, and, under their own overburden load, form welded zones where particles are partly or completely fused to each other. Ignimbrites from hydrovolcanic eruptions are deposited at much lower temperatures due to quenching during magma-water interaction, and because of this tend to be nonwelded to slightly welded. They also commonly contain accretionary lapilli which are rare in ignimbrites from magmatic eruptions. Examples of hydrovolcanic ignimbrites are described by Self [8] and McPhie [9].

Pyroclastic surge deposits share many similarities with windblown or waterlain sedimentary deposits, such as dunes, antidunes, chute-and-pool structures, and ripples; they are thought to form from currents with relatively low particle concentrations and highly unsteady flow. If the current is hot enough or has a low steam content (if it is diluted by entrained air, for example), the deposits are relatively well sorted and cross stratification is at low angles. These deposits are common from hydrovolcanic eruptions but can also occur in magmatic eruptions. Cooler, steam-rich currents can contain appreciable quantities of condensed water which causes particles to become cohesive. As a result, the deposits are relatively poorly sorted and high angle cross stratification is common; in some cases deposits are plastered onto near vertical surfaces (see Cas and Wright [10]). This type of surge deposit is a strong indicator of hydrovolcanic activity.

2. CASE STUDIES

In this section I very briefly summarize what is know about some of the best documented examples of hydrovolcanic caldera-forming eruptions. The goal is to provide descriptions of the main features of these eruptions which must be used as a framework for any theoretical or experimental studies. More detailed accounts of the eruptions can be found in the cited papers.

2.1. Wairakei Formation, New Zealand

The Wairakei Formation is the result of a large (>150 km^3 of magma) hydrovolcanic eruption approximately 20,000 years ago on the North Island of New Zealand. It has been described in detail by Self [8], and the information that follows is based on his account. The eruption was centered in the Taupo caldera, which currently has dimensions of about 25 x 35 km and is occupied by Lake Taupo, which is locally as deep as 125 m. The Taupo caldera has been a source of repeated large-volume eruptions since about 330,000 years ago (Wilson et al. [11]) and has had its current geometry since about 26,500 years ago (Wilson [12]). The Wairakei eruption was strongly influenced by the fact that much of it occurred through Lake Taupo.

The eruption consisted of six main phases. The first phase occurred as the eruption began in shallow water. A plume of fine grained ash rose into the atmosphere and deposited a phreatoplinian unit. This unit exhibits a slight increase in grain size toward its top which has been interpreted by Self [8] to record a gradual decrease in the ratio of water to magma, probably due to a combination of dropping lake levels and accumulation of debris around the vent which reduced the accessibility of water to the vent. This led to the second phase which was dominantly, but not completely, caused by magmatic fragmentation and produced a thin pumice fallout deposit. Water regained access to the vent during the third phase to produce a very wet plume of highly fragmented ash. Ash was deposited as accretionary lapilli along with muddy rain. Violent explosions are indicated by the presence of pyroclastic surge deposits. These explosions rapidly widened the vent and an increase in the influx of water. The eruption discharge rate increased so that the column became unstable, collapsed, and fed extensive particle-laden pyroclastic currents resulting in a widespread ignimbrite during phase four. As the ignimbrite-forming phase came to a close the eruption returned again to a high standing plume with moderate magma-water interaction, producing a coarser grained fallout deposit (phase five). Toward the end of phase five magma-water interaction increased, leading to the final phase during which more ignimbrites were deposited.

Ash deposits from this eruption sequence are remarkably widespread, covering more than 10 million km^2 (~10% of the southern hemisphere) with 1 mm or more of ash. Most of the North Island of New Zealand received more than 15 cm of fallout ash. The Chatham Islands, 800 km downwind from Taupo, were blanketed with 12 cm of Wairakei ash. This wide dispersal indicates that the eruption plumes attained altitudes of 30 km or more. Ignimbrite-forming currents traveled up to 70 km radially away from the vent, overtopping mountains more than 600 m high, leaving deposits several meters to about 50 m thick. It is clear that a new eruption of this type would have catastrophic consequences.

2.2. Cana Creek Tuff

McPhie [9] described deposits from an ancient eruption that was probably similar in magnitude and dynamics to the Wairakei eruption. These deposits, called the Cana Creek Tuff, are of Late Carboniferous age (285-320 million years ago) and reside in New South Wales, Australia. Because of the formation's age and deformed nature, it is difficult to develop as detailed an understanding of the Cana Creek eruptive events as was possible for the Wairakei deposits. Nevertheless, McPhie [9] was able to distinguish five main eruptive events. First, water-rich eruptions produced wet pyroclastic debris that accumulated near the vent(s) and was subsequently carried toward medial regions by sheetfloods and debris flows to produce a basal sequence of water-lain volcanic debris. Thick (20-60 m), nonwelded ignimbrite, similar to those of phase four at Wairakei, were deposited next, indicating an increase in magma discharge rate. The eruption then shifted to a high-standing, buoyant phreatoplinian plume which deposited fine ash fallout layers, and was followed by a return to ignimbrite forming eruptions. The final eruptive phase was similar to the opening phase where debris piled up near the vent and was redeposited at more distant areas by floods and debris flows.

The most notable aspect of the Cana Creek Tuff eruption, compared to the Wairakei eruption, is predominance of water-driven sedimentary processes resulting from the wet eruptions. Hazard assessments at silicic volcanoes that may be prone to extensive magma-water interaction should account for the possibility of extensive mud flows and floods during the course of eruptions.

2.3. Whorneyside Tuff

The Wairakei and Cana Creek Tuff events were characterized by a predominance of extensive magma-water interaction during the eruptions, with perhaps only brief periods of dominantly magmatic eruption recorded in the Wairakei sequence. From this it can be implied that the vents were below or very close in elevation to the water level in the lakes through which they erupted. The Whorneyside Tuff eruption, which occurred between 450 and 475 million years ago in northwestern England, underwent a somewhat different evolution as described by Branney [13]. The eruption apparently was initially driven mainly be magmatic processes which produced large, welded ig-nimbrites. The eruption then became phreatoplinian, indicating that water gained access to the vent. Branney [13] suggests that this occurred as caldera collapse began in response to evacuation of large volumes of magma from the subsurface. The water probably came from either a lake which was filling a nearby volcanotectonic depression or from the nearby ocean. From this example we can see that the style of initial eruption can cause subsequent intense magma-water interaction, which in turn affects the eruption processes.

2.5. Larger eruptions in western United States

The western United States and Mexico have deposits from hundreds of mid- to late-Cenozoic caldera-forming eruptions of 100 km^3 to more than 3000 km^3 eruptive volume. Although many of these deposits have been studied for petrologic, geochemical, and economic reasons, there has been relatively little application of modern physical volcanological techniques or ideas to them. Detailed studies of the Peach Springs Tuff [14] and reconnaissance studies of other large eruptions in the San Juan (Colorado) and southern Nevada volcanic fields are suggesting that magma-water interaction has played an important role in many of these eruptions.

The Peach Springs Tuff (approximate age - 18.5 million years) is an extremely widespread deposit that originally covered an area of 250 km (west to east) by 160 km, with the likely vent roughly in the center of the covered area [14, 15]. The deposit is dominated by a single ignimbrite of approximately 640 km^3 in volume [15]. In one sector of the Peach Springs Tuff distribution there is a thin (generally less than 1 m) sequence of deposits which records a complex interplay between magmatic and hydrovolcanic eruption mechanisms at the beginning of the eruption. Valentine et al [14] interpreted this sequence as consisting mainly of pyroclastic surges, but there is some debate that they may be minor fallout deposits [16, 17]. Variations in the abundance of hydrovolcanic components (poorly- to non-vesicular shards and lithic fragments) indicate that the eruption began with a brief phase of magmatic explosive activity which after a relatively short time experienced an abrupt increase in hydrovolcanic activity followed by a gradual return to magmatic activity. During this initial phase the erupted material was dominantly juvenile (fragments of quenched magma, as opposed to foreign rock fragments). The end of this phase and a period of quiescence lasting at least an hour are recorded by the presence of a thin layer of fine ash. Valentine et al. [14] inferred that the vent(s) had become blocked by slumping of the walls. During the quiet period magma-water interaction proceeded until a violent blasting event cleared the vent and deposited a layer rich in hydrovolcanic ash and pulverized foreign rock fragments. The vent(s) widened rapidly so that the eruption quickly evolved into a high-discharge rate, steady ash fountain which produced the main ig-nimbrite.

In the case of the Peach Springs Tuff, and possibly of other large-volume ignimbrites in the western U.S., magma-water interaction appears to have driven the eruption rapidly toward a fountain behavior, where most of the erupted material hugs the ground in pyroclastic currents and is deposited as ignimbrite or pyroclastic surge. This differs markedly from the other examples described above, where large-scale magma-water interaction enhanced the atmospheric dispersal of fine ash.

3. PROBLEMS

This section briefly points out some of the interesting problems associated with magma-water interaction in very large eruptions. All of these problems would benefit from experimental and theoretical studies.

3.1. Magma discharge and required water input rates

Large, caldera-forming eruptions discharge magma at rates of c. 10^6-10^9 kg/s for fallout events and c. 10^8-10^{10} kg/s or higher for ignimbrite-producing events. Wohletz and McQueen [18] suggested that maximum explosive efficiency occurs when the mass ration of water to magma is between 0.35-0.7. Thus for large-volume hydrovolcanic eruptions the water mass influx rate into the vent or conduit system is almost of the same order as the magma discharge rates. In terms of volume flux rates, phreatoplinian events require 10^3-10^6 m^3/s, and ignimbrite events require 10^5-10^7 m^3/s influx rates. These rates are probably not a problem for cases where the vent(s) are situated beneath standing bodies of water. For situations where groundwater dominates, such high flux rates may be difficult to attain by mechanisms of flow through porous or fractured media. Even for eruptions through bodies of surface water, though, the presence of nonvesicular ash particles indicates that the magma-water interaction was, at least in part, taking place at depths below the level of magmatic fragmentation, so that rates of groundwater flow must play a key role in most of these eruptions (it is assumed that surface water is not able to pour into the vent to great depths against erupting gas and ash that is flowing outward at speeds of a few hundred meters per second).

A related issue is the relative importance of magma-water interaction in the eruptive jet, after it has exited the vent, compared to interaction within the vent and conduit system. If the vent is under water then the jet must traverse some depth of water and it seems likely that some of it could be entrained. This water could quench and further fragment particles in the jet. Erupting mixtures of gas and ash in explosive silicic events typically have mixture densities ranging from 1-20 kg/m^3, thus the jet is substantially less dense than the water through which it erupts. Mixing dynamics of turbulent jets flowing into denser fluids could provide some important constraints on this problem.

3.2. Effects of magma properties

Most experimental research into explosive magma-water interaction has focused on cases where the magma has a Newtonian or near-Newtonian rheology and a relatively low viscosity (basaltic magmas). Silicic magmas, which characterize the eruptions discussed in this paper, have viscosities from 10^3-10^9 Pa·s, depending on temperature and volatile content, which are two to five orders of magnitude large than basaltic magmas. Wohletz [19] suggests that these high viscosities would require longer mixing times for explosive interaction. Given transit times on the order of 10-100 s for an erupting mixture to traverse the upper kilometer of the Earth's crust, what are the limits of explosive magma-water interaction in large eruptions?

A very important issue that needs detailed study is the effect of gas bubbles in the magma on explosive interaction with water. By the time most silicic magmas reach the upper kilometer or so of the crust, where groundwater begins to be readily available, they can be expected to contain as much as 0.7 volume fraction of bubbles. (viscosity, vesicularity). Thus one end member of magma-water interaction that could be studied experimentally is the case where the magma is a compressible foam.

3.3. Climatic effects and hazards of large-scale hydrovolcanic eruptions

The case studies discussed above point out two opposite effects of magma-water interaction in large-volume eruptions. First, the formation of phreatoplinian eruption columns could result in very efficient dispersal of fine ash high in the atmosphere, which could have a range of climatic effects such as local cooling due to reflection of solar radiation. A plume such as that which accompanied the Wairakei eruption, leaving 1 mm or more of ash over 10% of the southern hemisphere, would likely cause a global climate perturbation due to reflection alone. Phreatoplinian eruption plumes could inject large quantities of water vapor into the stratosphere. The effects of this water, including effects on the formation of aerosols, are important topics for future study. The second, and opposite, effect of magma-water interaction is exemplified by the Peach Springs Tuff. In this eruption it appears that magma-water interaction acted to rapidly widen the vent(s) so that the eruption moved rapidly to an ignimbrite-producing fountain phase. This concentrated most of the erupted debris on the ground and may have actually decreased the climatic effect of the eruption.

Hazards that may be accentuated in large-volume, silicic hydrovolcanic eruptions include aviation hazards due to widely dispersed, fine grained ash at high altitude. Ash clouds produced by phreatoplinian eruptions may linger at high altitude for very long times because of the low settling velocities of the small particles. For people living in a region surrounding such an eruption the hazards from ash fallout and pyroclastic density currents would be serious. Additional hazards would be large-scale, syneruptive floods and mudflows and torrential muddy rains.

CONCLUSIONS

I have only scratched the surface in this paper on issues related to the identification of large-volume silicic hydrovolcanic eruptions, some case studies, and problems that need to be addressed. A large fraction of active or dormant silicic calderas in the world today either contain lakes or are situated on coasts. Thus it would be prudent to improve our understanding of this important class of explosive eruptions.

REFERENCES

[1] G. Heiken and K.H. Wohletz, Volcanic ash, Univ. Calif. Press, (1985), 246 pp.

[2] R.S.J. Sparks, The dynamics of bubble formation and growth in magmas: a review and analysis, J. Volcanol. Geotherm. Res. 3 (1978) 1-37.

[3] A. Toramaru, Vesiculation process and bubble size distributions in ascending magmas with constant velocities, J. Geophys. Res. 94 (1989) 17523-17542.

[4] K.H. Wohletz, Mechanisms of hydrovolcanic pyroclast formation: grain size, scanning electron microscopy, and experimental results, J. Volcanol. Geotherm. Res. 17 (1983) 31-63.

[5] S. Self and R.S.J. Sparks, Characteristics of widespread pyroclastic deposits formed by the interaction of silicic magma and water. Bull. Volcanol. 41 (1978) 196-212.

[6] R. Schumacher and H.-U Schmincke, Internal structure and occurrence of accretionary lapilli - a case study at Laacher See volcano, Bull. Volcanol. 53 (1991) 612-634.

[7] G.P.L. Walker, Characteristics of two phreatoplinian ashes, and their water-flushed origin. J. Volcanol. Geotherm. Res. 9 (1981) 395-407.

[8] S. Self, Large-scale phreatomagmatic silicic volcanism: A case study from New Zealand. J. Volcanol Geotherm. Res. 17 (1983) 433-469.

[9] J. McPhie, Primary and redeposited facies from a large-magnitude, rhyolitic, phreatomagmatic eruption: Cana Creek Tuff, Late Carboniferous, Australia, J. Volcanol. Geotherm. Res. 28 (1986) 319-350.

[10] R.A.F. Cas and J.V. Wright, Volcanic successions, modern and ancient, Allen and Unwin (1987) 529 pp.

[11] C.J.N. Wilson, A.M. Rogan, I.E.M. Smith, D.J. Northey, I.A. Nairn, and B.F. Houghton, Caldera volcanoes of the Taupo Volcanic Zone, New Zealand, J. Geophys. Res. 89 (1984) 8463-8484.

[12] C.J.N. Wilson, Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand, Phil. Trans. R. Soc. Lond. A (1993) 205-306.

[13] M.J. Branney, Eruption and depositional facies of the Whorneyside Tuff Formation, English Lake District: An exceptionally large-magnitude phreatoplinian eruption. Geol. Soc. Am. Bull. 103 (1991) 886-897.

[14] G.A. Valentine, D.C. Buesch, and R.V. Fisher, Basal layered deposits of the Peach Springs Tuff, northwestern Arizona, USA, Bull. Volcanol. 51(1989) 395-414.

[15] D.C. Buesch, Incorporation and redistribution of locally derived lithic fragments within a pyroclastic flow, Geol. Soc. Am. Bull. 104 (1992) 1193-1207.

[16] C.J.N. Wilson and S. Self, Comment on "Basal layered deposits of the Peach Springs Tuff, northwestern Arizona, USA," Bull. Volcanol. 52 (1990) 562-564.

[17] G.A. Valentine, D.C. Buesch, and R.V. Fisher, Response to comment on "Basal layered deposits of the Peach Springs Tuff, northwestern Arizona, USA," Bull. Volcanol. 52 (1990) 565-569.

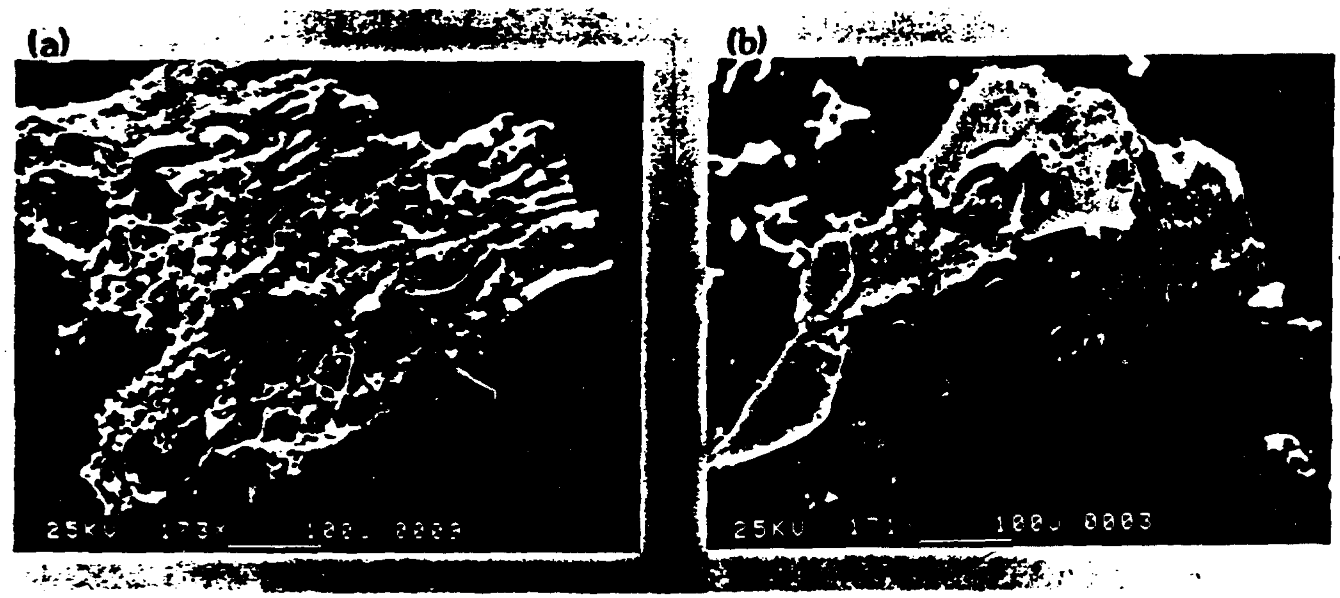
[18] K.H. Wohletz and R.G. McQueen, Experimental studies of hydromagmatic volcanism, in Explosive Volcanism: Inception, Evolution, and Hazards, National Academy Press, Washington, D.C. (1984) 158-169.

[19] K.H. Wohletz, Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies, Bull. Volcanol. 48 (1986) 245-264.

ACKNOWLEDGMENTS

This paper is supported by a grant from the Institute for Geophysics and Planetary Physics at Los Alamos National Laboratory.

Figure 1. Scanning electron microphotographs of ash particle from the Peach Springs Tuff, Arizona. (a) Ash particle produced by magmatic fragmentation. The particle consists of tube-shaped vesicles and has a very high porosity. (b) Ash particle produced by hydrovolcanic fragmentation. Notes that it is poorly vesicular, and vesicles are cross-cut b, curviplanar surfaces.


(a)
25KV
(b)
25KV
100U 0003