Volcanic and stratospheric dustlike particles produced by experimental water-melt interactions

K. H. Wohletz
R. G. McQueen
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

ABSTRACT

Commercially available Thermit (Al + Fe_3O_4) was ignited, forming a molten mixture of Al_2O_3 + Fe. The subsequent mixing of this melt with water in steel containers produced explosive interactions that were used to model hydrovolcanic activity. Debris collected from the experiments consisted of quenched Thermit particles ranging in size from <1 μm to centimetres. Scanning electron microscopy of the debris showed spheroidal, irregular aggregates and blocky particle shapes that are very similar to hydrovolcanic ash, as well as some types of stratospheric dust and industrial fly ash.

INTRODUCTION

The pictures shown in Figure 1 illustrate two stages of an experiment simulating explosive hydrovolcanism (Wohletz and McQueen, 1981; Sheridan and Wohletz, 1983). Volcanic explosions that result from the interaction of magma with surface or near-surface meteoric water are the manifestation of a process termed Fuel-Coolant Interaction (FCI) (Colgate and Sigurgiersson, 1973; Peckover et al., 1973; Dullforce et al., 1976; Buxton and Benedict, 1979). In this process a fluid coolant (water) dynamically mixes and vaporizes during contact with a hot fluid, which we call fuel, melt, or magma. Its composition is not important, but its

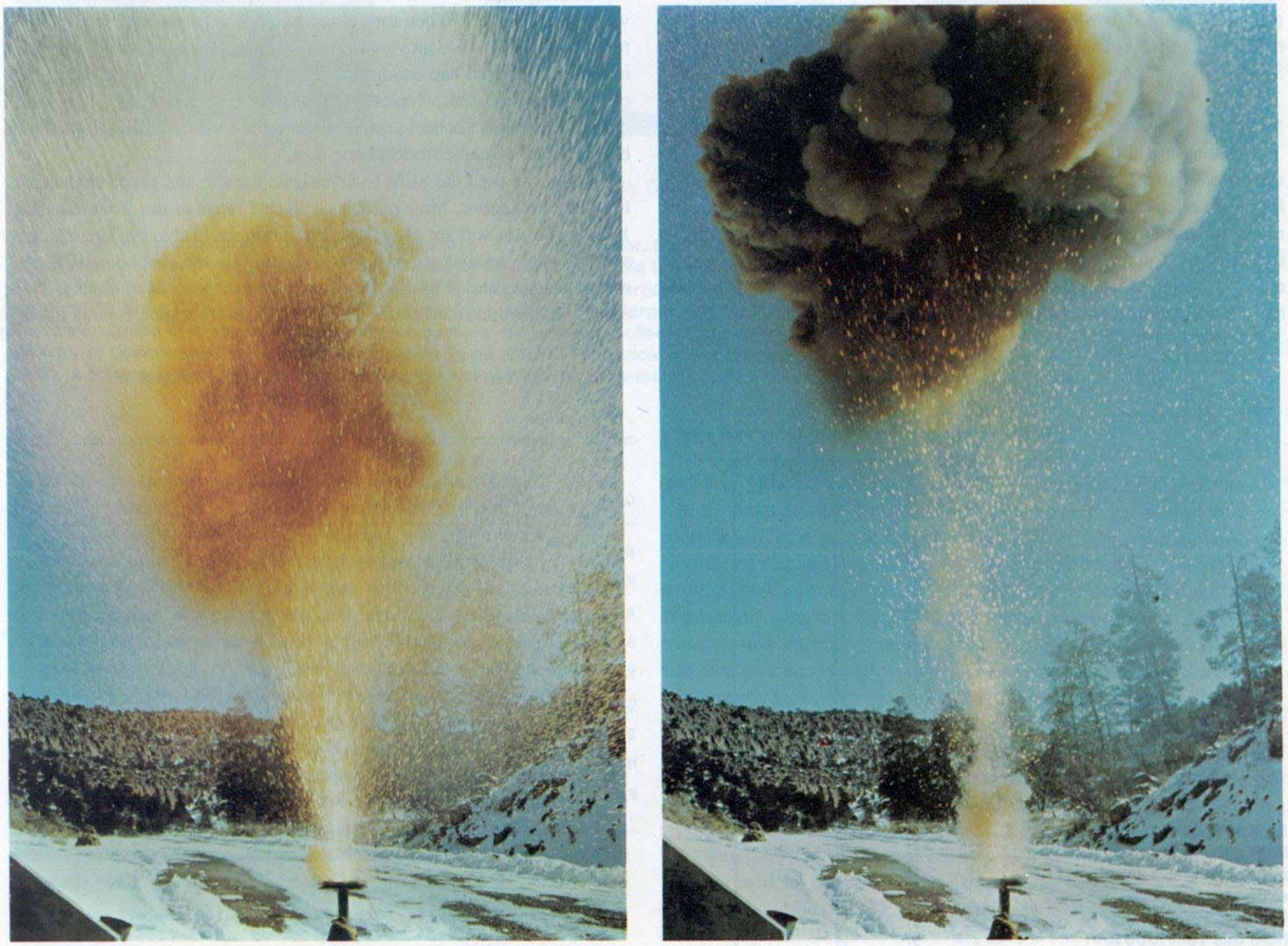

Figure 1. Photographs of top-venting experiment exhibiting explosive behavior. Left: Frame obtained ~1 s after burst time. Right: Frame obtained ~1.5 s after burst time.

temperature must be greater than the coolant's boiling temperature. Under certain conditions, the process results in fine particulation of the melt, which is ejected as a spray enclosed in superheated steam. This process is important in at least half of all explosive volcanic eruptions.

Interaction of magma with water is not always explosive. It encompasses a wide range of volcanic activities, including (1) Surtseyan-type eruptions of base surges (Fisher and Waters, 1970; Thorarinsson et al., 1964); (2) Vulcanian-type eruptions that are short, cannonlike bursts of ash; (3) Strombolian-type activity (McGetchin and Chouet, 1976) in which very little water interacts; and (4) submarine extrusion of lava forming pillow lava and hyaloclastite (Moore, 1975; Honnorez and Kirst, 1975); these result in the more passive behavior.

In general, as the interaction of the melt and water increases in explosivity, ejecta become finer grained. Typical sizes for hydrovolcanic particles range from 1 to 2 mm for weak interactions to 1 to 100 μm for strong explosive interactions. The rapid expansion of highly superheated steam and other volatiles produced in strong explosions may drive eruption columns to great heights (>30 km for El Chichón in 1982). Less explosive interactions produce wet steam that condenses on particle surfaces. Wet surfaces promote formation of aggregate particles and accretionary lapilli.

Understanding and characterizing the conversion of thermal to mechanical energy during volcanic events have been a focus of our experimentation. An outgrowth of this work has been scanning electron microscopic (SEM) analysis of the debris produced. The results of the SEM studies are reported here.

METHOD

A drawing of the confinement vessel used in the experiments is shown in Figure 2. The vessel contained Thermit, which, when reacted, forms a molten mixture of iron and aluminum oxide and is a suitable model of basaltic magma (Wohletz and McQueen, 1981). The internal energy of the reacted Thermit is several times greater than that of most magmas, which is fortunate, as sand and other materials added to the system are melted and hence make better silicate magma simulations. The higher temperatures also help to counteract heat losses in the system. Water was placed in the bottom and the Thermit supported above it by an aluminum disk. A loop of tungsten wire embedded in the Thermit about one-fourth of the way from the top was heated by an external low-voltage, high-current power supply. The wire was heated until the Thermit reacted. Reacted Thermit eventually melted the aluminum support plate and mixed with water. A calibrated high-pressure break valve installed in the top of the vessel ensured that the Thermit and water would not be ejected until considerable mixing occurred. Current studies (Wohletz and McQueen, 1984) show the importance of confinement in controlling explosiveness in these experiments. Sheets of plywood were placed 1 to 3 m from the vessel, and debris deposited on them was collected with a brush.

RESULTS

The two photographs in Figure 1 are representative of what we observe in top-venting experiments when explosive volcanism is exhibited. The first photo (Fig. 1, left) was taken ~1 s after burst time. Fairly large, about centimetre-size, particles (white lines at top of photo) were ejected ballistically from the container. Particles in the center of the ejecta plume were moving too rapidly, probably more than 100 m s^{-1}, to be resolved by the camera, whereas those at the sides were slower (~20 m s^{-1}). Colors ranging from white to yellow to orange suggest that temperatures were over 1000 °C. When the second photo was taken (Fig. 1, right) almost all particles were moving at much slower velocities, and the water in the central cloud had condensed. The brown color is due to the particles in the cloud, which typically just drift away. Several techniques are being developed to collect samples from these clouds, which undoubtedly best simulate volcanic stratospheric dust.

We have used the SEM to investigate the size and shape characteristics of ejected debris. Most particles collected range in size from less than 1 μm to 50 μm and are of variable compositions (Table 1). The majority are either spheres that are similar to industrial fly ash (Gibbon, 1979) or mosslike aggregates (Figs. 3a, 3b). Other particles consist of blocky, equant shapes and small plates. Hollow spheres (cenospheres) and filled

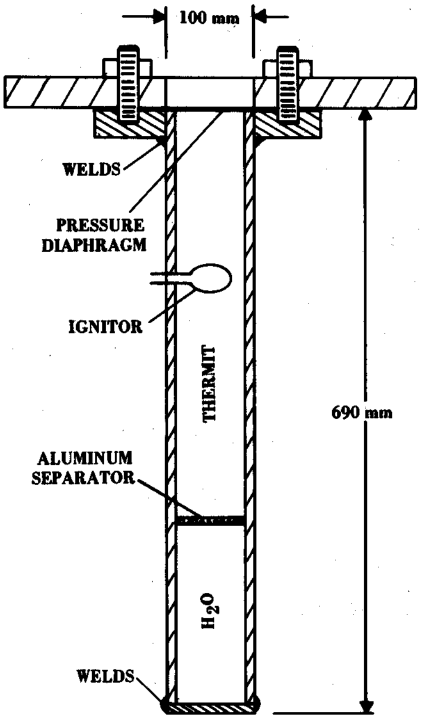

Figure 2. Sketch of confinement vessel used in top-venting Thermit experiment. Large flange on top is used to hold this vent tube in larger container for large top-venting experiments.

TABLE 1. REPRESENTATIVE CHEMICAL ANALYSES OF THERMIT MELT PRODUCTS

	Sample*				
Oxide	82-1-34	82-1-35	82-1-13	82-1-17	82-1-26
Na_2O	-	-	3.1	2.0	3.2
MgO	-	-	6.4	3.7	5.8
Al_2O_3	31.2	25.1	11.4	34.4	23.3
SiO_2	10.1	10.7	14.3	36.5	18.3
K_2O	0.3	-	1.9	2.0	1.8
CaO	0.4	-	2.1	1.7	1.9
TiO_2	-	-	2.2	1.4	1.9
MnO	-	-	1.6	1.0	1.3
FeO	58.0	64.2	57.0	17.3	42.5

Note: Normalized standardless energy dispersive spectral (EDS) analyses.

* Experiment Sample: 82-1-34 - Iron-aluminum sphere, large (Figure 2); 82-1-35 - Iron-aluminum sphere, small; 82-1-13 - Iron particle; 82-1-17 - Coating on iron particle; 82-1-26 - Iron-aluminum spindle.

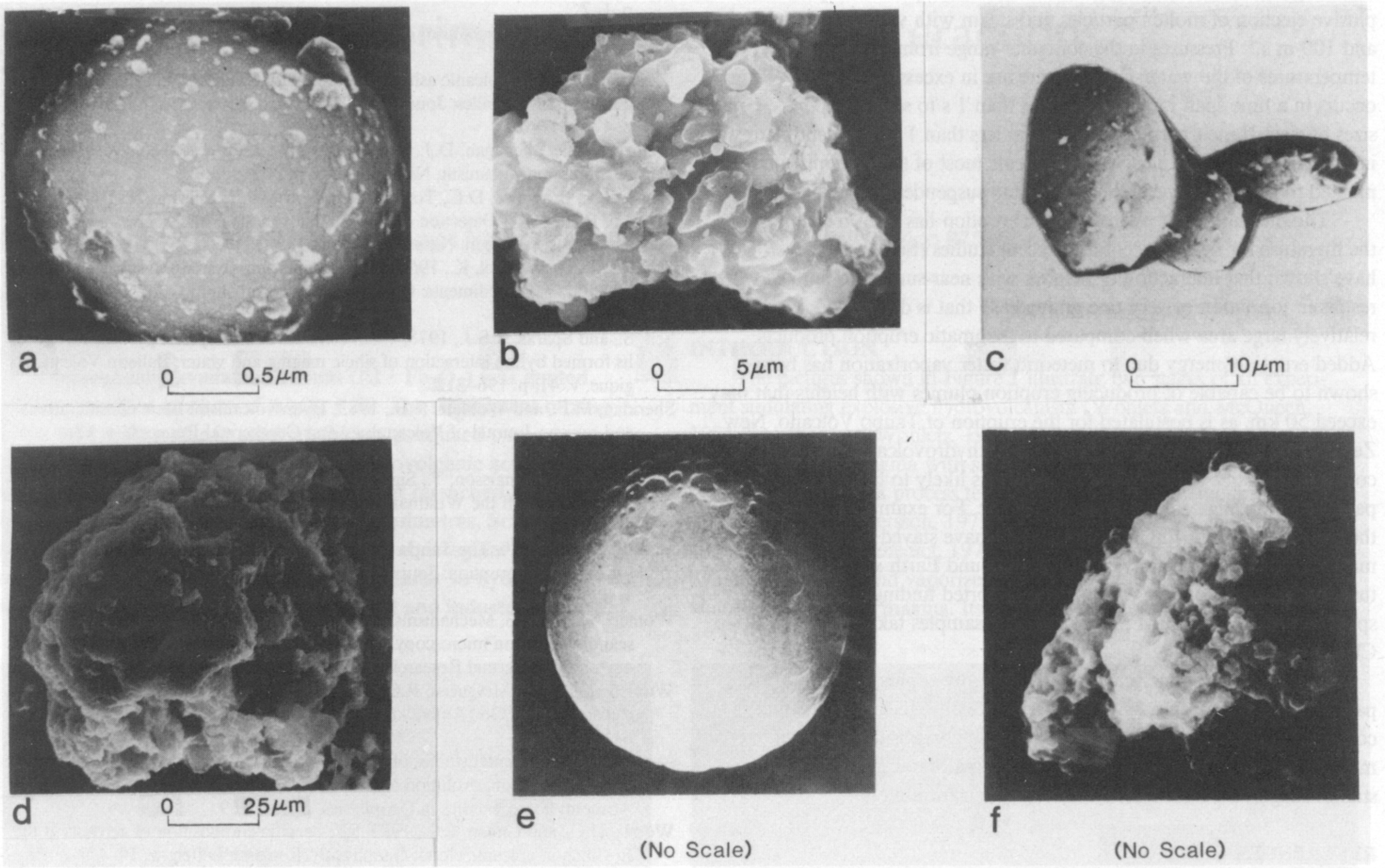

Figure 3. a: Photomicrograph of Thermit melt sphere ~2 μm in diameter. Surface is pitted and covered with irregular-shaped particles. b: Photomicrograph of mosslike aggregate of Thermit melt particles. This sample is ~15 μm long and consists of spheres and irregular shapes that appear to be fused together. c: Photomicrograph of spherical volcanic particle ~10 μm in diameter collected from phreatomagmatic ash deposits surrounding Koko Crater, Hawaii. Note that this sphere is attached to larger particle, a typical occurrence of spherical volcanic particles. d: Photomicrograph of irregular-shaped volcanic particle ~50 μm wide collected from phreatomagmatic ash deposits around Kilbourne Hole, New Mexico. e: Cosmic Dust Preliminary Examination Team (CDPET) spherical-shaped cosmic dust particle (see cover of *EOS*, v. 63, no. 11, March 1982). f: Example of an irregular-shaped cosmic dust particle investigated by CDPET (see cover of *EOS*, v. 63, no. 11, March 1982).

hollow spheres (plerospheres) were also observed. (See Wohletz, 1983, for a comparison of particles produced experimentally with those from volcanoes.) A wide variety of shapes of most 1- to 100-μm-size particles are quite similar to particles of volcanic ash formed in basaltic hydrovolcanic eruptions. This was not unexpected, as we feel production mechanisms for creating these particles are quite similar. Two typical types of particles produced experimentally (Figs. 3a, 3b) can be compared with volcanic particles (Figs. 3c, 3d). These two types have been chosen for comparison because they are similar in morphology to (but totally different in elemental composition from) some particles classified as cosmic dust collected in high-altitude atmospheric sampling flights (as shown on the cover of *EOS*, v. 63, no. 11, March 1982). The pictures are reproduced in Figures 3e and 3f, but they are not totally representative of cosmic dust particles. Debris produced in industrial and solid-fuel rocket exhaust also contain spherical particles that are found in the stratosphere (Cosmic Dust Preliminary Examination Team, 1982).

DISCUSSION

Besides SEM imaging and optical properties, a major criterion for determination of the origin of atmospheric particles is chemistry. Cosmic particles commonly contain metallic oxide phases. Recent and ongoing studies of small volcanic particles show that similar metallic oxide and sulfide phases are also present in some of these particles. This result is not surprising, as basaltic magmas may contain 10 wt% or more iron, nickel, chromium, titanium, zinc, and copper oxides that form a distinct phase(s) in the magma prior to eruption. Also of interest is the recent discovery of unusually large concentrations of iridium and other rare metals from emissions of Kilauea Volcano (Zoller et al., 1983). A hydrovolcanic eruption mechanism may separate these phases as individual particles that are subsequently lofted into the atmosphere. Presolidification viscosities and differences in surface tension between glassy silicate and metallic oxide particles result in the latter being typically much smaller (1–10 μm; Del Monte et al., 1975; Woods and Chuan, 1983). The smaller particles can attain higher altitudes and stay aloft longer than larger silicate glass particles. Hydrovolcanic explosions occur with both silicic and basaltic magmas; therefore, a mechanism exists by which the small and poorly known volcanic particles can penetrate the tropopause. Much work has been done on discrimination of cosmic particles by measuring isotopic abundances (Rajan et al., 1977; Esat et al., 1979). The origin of stratospheric dust has been studied extensively for the past 20 years (Fredriksson and Martin, 1963; Mutch, 1964; Wright and Hodge, 1965; Schmidt and Keil, 1966).

SUMMARY AND CONCLUSIONS

In general, our molten Thermit and water experiments produce explosive ejection of molten particles and steam with velocities between 20 and 100 m s^{-1}. Pressures in the container range from 10 to 40 MPa, and temperatures of the water-melt mixture are in excess of 500 °C. Venting occurs in a time span ranging from less than 1 s to several seconds. Grain sizes of ejected melt particles range from less than 1 μm to centimetres in diameter. In very explosive experiments most of the Thermit is fragmented to fine, dust-size particles that stay suspended in the air.

The mechanism of hydrovolcanic eruption has been recognized in the literature for nearly a century. Recent studies (Self and Sparks, 1978) have shown that interaction of magma with near-surface or surface water results in formation of very fine grained ash that is distributed over a relatively large area when compared to magmatic eruption products. Added eruption energy due to meteoric water vaporization has been shown to be capable of producing eruption plumes with heights that may exceed 50 km, as is postulated for the eruption of Taupo Volcano, New Zealand, in A.D. 130 (Walker, 1980). The hydrovolcanic mechanism is common at many volcanoes and therefore is likely to be important in the particulate loading of the upper atmosphere. For example, products of the 1982 eruption of El Chichón, Mexico, have stayed suspended for many months, and they have circulated around Earth in northern latitudes. However, Gooding et al. (1983) reported finding no volcanic spherical particles in SEM probes of many samples taken from the El Chichón eruption.

Thermit-water experiments that are highly explosive produce particles quite similar in shape and surface texture to those classified as cosmic dust. Although chemical and isotopic composition and not morphology is the positive indication of origin of cosmic particles, these studies suggest a possible mechanism for their formation.

REFERENCES CITED

Buxton, L.D., and Benedict, W.B., 1979, Steam explosion efficiency studies: Sandia National Laboratories, SAND-79-1399, NUREG/CR-0947, 62 p.

Colgate, S.A., and Sigurgiersson, T., 1973, Dynamic mixing of water and lava: Nature, v. 244, p. 552–555.

Cosmic Dust Preliminary Examination Team, 1982, Cosmic dust catalogue 3-1: NASA Planetary Materials Branch Publication 63, 95 p.

Del Monte, M., Nanni T., and Tagliazucca, M., 1975, Ferromagnetic volcanic particulate matter and black magnetic spherules: A comparative study: Journal of Geophysical Research, v. 80, p. 1880–1884.

Dullforce, T.A., Buchanan, D.J., and Peckover, R.S., 1976, Self triggering of small-scale fuel-coolant interactions: 1, Experiments: Journal of Physics D: Applied Physics, v. 9, p. 1295–1303.

Esat, T.M., Brownlee, D.E., Papanastassiou, D.A., and Wasserburg, G.J., 1979, Magnesium isotope composition of interplanetary dust particles: Science, v. 206, p. 190–197.

Fisher, R.V., and Waters, A.C., 1970, Base surge bed forms in maar volcanoes: American Journal of Science, v. 268, p. 157–180.

Fredriksson, K., and Martin, L.R., 1963, The origin of black spherules found in Pacific islands, deep-sea sediments and Antarctic ice: Geochimica et Cosmochimica Acta, v. 27, p. 245–248.

Gibbon, D.L., 1979, Microcharacterization of fly-ash and analogs: The role of SEM and TEM: Scanning Electron Microscopy 1979-1 (AMF O'Hare, Illinois, SEM Inc.), p. 501–510.

Gooding, J.L., Clanton, U.S., Gabel, E.M., and Warren, J.L., 1983, El Chichón volcanic ash in the stratosphere: Particle abundances and size distributions after the 1982 eruption: Geophysical Research Letters, v. 10, p. 1032–1036.

Honnorez, J., and Kirst, P., 1975, Submarine basaltic volcanism: Morphometric parameters for discriminating hyaloclastites from hyalotuffs: Bulletin Volcanologique, v. 34, p. 1–25.

McGetchin, T.R., and Chouet, B.A., 1976, Energy budget for the volcano, Stromboli, Italy: Los Alamos National Laboratory Informal Report LA-6308-MS, p. 1–7.

Moore, J.G., 1975, Mechanism of pillow formation: American Scientist, v. 63, p. 269–277.

Mutch, T.A., 1964, Volcanic ashes compared with Paleozoic salts containing extraterrestrial spherules: Journal of Geophysical Research, v. 69, p. 4735–4740.

Peckover, R.S., Buchanan, D.J., and Ashby, D.E., 1973, Fuel-coolant interactions in submarine volcanism: Nature, v. 245, p. 307–308.

Rajan, R.S., Brownlee, D.E., Tomandl, D., Hodge, P.W., Farrar, H., IV, and Britten, R.A., 1977, Detection of ^{4}He in stratospheric particles gives evidence of extraterrestrial origin: Nature, v. 267, p. 133–134.

Schmidt, R.A., and Keil, K., 1966, Electron microprobe study of spherules from Atlantic Ocean sediments: Geochimica et Cosmochimica Acta, v. 30, p. 471–478.

Self, S., and Sparks, R.S.J., 1978, Characteristics of widespread pyroclastic deposits formed by the interaction of silicic magma and water: Bulletin Volcanologique, v. 41, p. 196–212.

Sheridan, M.F., and Wohletz, K.H., 1983, Hydrovolcanism: Basic considerations and review: Journal of Volcanology and Geothermal Research, v. 17, p. 1–29.

Thorarinsson, S., Einarsson, T., Sigvaldson, G., and Elisson, G., 1964, The submarine eruption off the Westman Islands 1963–64: Bulletin Volcanologique, v. 27, p. 1–11.

Walker, G.P.L., 1980, The Taupo Pumice: Product of the most powerful known (ultra plinian) eruption: Journal of Volcanology and Geothermal Research, v. 8, p. 69–94.

Wohletz, K.H., 1983, Mechanisms of hydrovolcanic pyroclast formation: Size, scanning electron microscopy, and experimental results: Journal of Volcanology and Geothermal Research, v. 17, p. 31–63.

Wohletz, K.H., and McQueen, R.G., 1981, Experimental hydromagmatic volcanism [abs.]: EOS (American Geophysical Union Transactions), v. 62, p. 1085.

—— 1984, Experimental studies of hydromagmatic volcanism, *in* Explosive volcanism: Inception, evolution and hazards: Washington, D.C., National Academy Press, Studies in Geophysics, p. 158–169.

Woods, D.C., and Chuan, R.L., 1983, Size-specific composition of aerosols in the El Chichón volcanic cloud: Geophysical Research Letters, v. 10, p. 1041–1044.

Wright, F.W., and Hodge, D.W., 1965, Studies of particles for extraterrestrial origin: Journal of Geophysical Research, v. 70, no. 16, p. 3889–3898.

Zoller, W.H., Parrington, J.R., and Kotra, J.M.P., 1983, Iridium enrichment in airborne particles from Kilauea Volcano: January 1983: Science, v. 222, p. 1118–1121.

ACKNOWLEDGMENTS

Supported by the U.S. Department of Energy. Technical and physical support was given by the Shock Wave Physics group at the Los Alamos National Laboratory. Michael Sheridan of Arizona State University helped in analysis of experimental results and the SEM investigation, which was supported by NASA and by Institutional Supporting Research and Development at Los Alamos National Laboratory. Grant Heiken of Los Alamos provided considerable information on atmospheric sampling of volcanic ash as well as strong support of our experimental work. James Gooding of the Johnson Space Center aroused our interest in cosmic-dust characteristics and supplied results of the Cosmic Dust Preliminary Examination Team for our consideration; however, he does not agree with our statements having inferences about cosmic dust.

Manuscript received September 19, 1983
Revised manuscript received May 21, 1984
Manuscript accepted June 15, 1984