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Total water contents in volcanic eruption clouds and implications for electrification and lightning*

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1. Introduction

The fundamental role of ice particle collisions in the separation of electric charge and generation of lightning in thunderclouds is now reasonably well established (Latham, 1981; Williams, 1985; Saunders, 1995). Charge separation and lightning are also prevalent in volcanic eruptions. A recent literature survey by McNutt and Davis (2000), and its recent extension, has shown more than 150 incidents of

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volcanic lightning. The efficacy of the ice-based process in thunderclouds has raised the interest in the possible applicability of the same process to a class of explosive volcanic eruptions. This study is concerned with an evaluation of volcanic eruptions as atmospheric ice factories.

The behavior of water in magma within the Earth is reasonably well understood in volcanology, and the behavior of water in the atmosphere is adequately understood in meteorology. The perceived gap in understanding lies in the transition from Earth to atmosphere. This study is aimed at bridging this gap.

2. Water content in explosive magma

Volatiles in magma have been well studied (Johnson et al, 1993; Wallace and Anderson, 2000; Wallace, 2004). The volatiles of greatest scientific interest have been H_2O, CO_2, and SO_2, but water is dominant in total mass by more than an order of magnitude. The solubility of water in magma is known to increase with pressure, and this physics is basic to explosive volcanism (Wilson et al, 1980). The water contents of magmas are traditionally estimated as a percent by weight of the magma. Numbers in the literature in a wide variety of studies, sampled in Table 1, are remarkably consistent.

The water contents in Table 1 are large from a meteorological perspective. For example, a cubic meter of magma at depth with mean magma density 2.5 gm/m^3 and with 4% water by weight contains 100 kilograms of water. In condensed form, this is 100 liters of liquid. Following the Clausius-Clapeyron relation, this amount in vapor form is sufficient to saturate 4000 m^3 of tropical atmosphere at a temperature T=30°C. At a temperature T= -50°C typical of conditions at the tops of Plinian eruption clouds, the same mass of water vapor is sufficient to ice-saturate more than 10^7 m^3 of atmosphere.

Table 1. Water Content of Explosive Magma

Volcano	Water Content (Wt %)	Investigator
Bezymianni (1955)	4	Markinen (1962)
Cerro Negro	3 – 6	Roggensack et al (1997)
Fuego	1 – 6	Sisson and Layne (1993)
Mt. St. Helens	4.6 – 6.1	Carey et al (1995) Gardner et al (1995)
Pinatubo (1991)	5	Wallace and Gerlach (2004)
Vesuvius (79 AD)	3.5 – 4.7	Cornell (1987)

3. Explosive eruptions and the relaxation volume

Water is widely recognized as the working substance of explosive volcanic eruptions. Water dissolved in magma at depth, and with typical weight % values given in Table 1, is exsolved to vapor in bubbles as the magma ascends and the pressure declines (Wilson et al, 1980). If the vapor phase remains disconnected in the magma, typical of isolated bubble inclusions in the magma matrix and typical of explosive eruptions over subduction zones, large confined gas pressures can develop. When the highly viscous magma fractures at a critical porosity (Gardner et al, 1996), the stored energy is released explosively, with an ultimate relaxation of the elevated pressure to ambient atmospheric pressure P_o.

Conservation of energy for a simple spherical explosion equates the available energy E and the pressure-volume work performed against the ambient atmospheric pressure P_o:

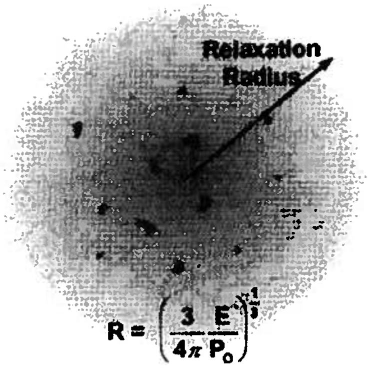
$$E = P_o\,(4\pi R^3/3) \qquad (1)$$

A rough estimate for the explosion radius R, the so called 'relaxation radius' (Few, 1980), is then given by:

$$R = (3E/4\pi P_o)^{1/3} \qquad (2)$$

This process is illustrated in Figure 1. Though ignored in this simple calculation, the relaxation volume will invariably be highly turbulent and involve a homogenization of the exploding material with the ambient atmosphere. Figure 1 also provides numerical estimates for different kinds of explosions. Detonations of small Chinese firecrackers have relaxation radii of centimeters, whereas energetic Fourth of July 'bombs' show relaxation smoke clouds of order meters. For a Krakatoa-level explosive eruption with estimated total energy 10^{17} joules, the relaxation radius is more than 4000 m. These scales are commensurate with the updraft widths of thunderstorm supercells (Williams, 2001), the largest and most violent form of convection known to terrestrial meteorology.

The relaxation radius concept was developed initially to treat the cylindrical explosions around lightning channels (Few, 1980), with the aim of estimating the dominant acoustic frequency of thunder. The dominant acoustic wavelength is of the order of the relaxation radius. For this reason, Chinese firecrackers emit in the acoustic range for human hearing and exhibit a sharp 'crack', whereas much longer wavelengths are dominant for explosions in the category of volcanic eruptions, inaudible at distance. Hence there is current interest in detecting volcanic eruptions worldwide with infrasonic methods (Bass et al, 2004).



Source	E (joules)	R (m)
Chinese Firecracker	30 joules	2×10^{-2} m
Stick of Dynamite	2×10^{6} joules	0.6 m
1 kT Explosive	4.2×10^{12} joules	220 m
Krakatoa Eruption	10^{17} joules	4300 m

Energy E of explosion invested in expansion against ambient pressure P_0

$$P_0\left(\frac{4}{3}\pi R^3\right) = E$$

Figure 1. The eruption bomb based on water substance: illustration of the physical process of the relaxation radius, and some calculated values.

4. The water content and temperature in eruption clouds

The relaxation volume together with estimates of magma water content and temperature enable estimates of both the average water content and temperature of eruption clouds. In both cases, it is assumed that the magma property is distributed homogeneously within the ultimate relaxation volume.

The water content is considered first. A lower bound on cloud water content is considered by assuming the ambient atmosphere to be completely dry. The favorable assumption is also made that all of the water dissolved at depth is released to the atmosphere in the explosion. This assumption is supported by the observations that the porous (water vapor) phase is connected (Gardner et al, 1996) in post-explosive tephra. Under this assumption, the mean cloud water content (MWC) is simply:

$$\mathrm{MWC} = \frac{\text{total water in magma}}{\text{relaxation volume}} \tag{3}$$

$$= \frac{(\text{wt\%})(\text{total tephra mass})}{(E/P_0)} \tag{4}$$

$$= \frac{(\text{wt\%})M\,P_0}{E} \tag{5}$$

A useful reference point for total energy E is the design threshold for the Comprehensive Test Ban Treaty (CTBT) network (Sullivan, 1998): a bomb yield of 1 kiloton (1 kT = 4.2×10^{12} joules). The total energy on the scale of Volcanic Explosivity Index (VEI) (Simkin and Siebert, 1994) is not specified, but if the gravitational potential energy of the lofted tephra is 1% of the total energy, then a 1 kT event is at the low end of the VEI scale (VEI~0) where the tephra volume M ~10^4 m^3. Following Figure 1, the relaxation radius for a 1 kT total energy is ~220 meters.

If M is proportional to energy, the general assumption in considerations of VEI (Simkin and Siebert, 1994), and wt% is independent of eruption magnitude (broadly supported by the results in Table 1), then it follows that:

$$MWC = (wt\%)\,(620)\ gm/m^3 \qquad (6)$$

And for a representative value of wt% = 5 (based on Table 1):

$$MWC \sim 30\ gm/m^3 \qquad (7)$$

From a meteorological perspective, this number is again large. It exceeds by 50% the value needed to saturate air at 30°C. It exceeds by more than two orders of magnitude the value needed to saturate the upper troposphere at typical ambient temperatures. These comparisons suggest that the assumption of a dry entrained atmosphere is not a bad one, because the entrainment of a realistic moist atmosphere would not change the estimates appreciably. The magma water dominates the water budget.

Here it has been assumed that the eruption cloud will have the same temperature as the atmospheric environment in which it is mixed. Such is not strictly the case, but the cloud temperature can be estimated from similar considerations of the relaxation volume.

If the pre-explosive hot porous magma causing a volcanic explosion has temperature T_M and volume V_M, then the average temperature of the eruption cloud can be estimated from the volume mixing law:

$$V_M T_M + V_A T_A = (V_M + V_A)\, T_C \qquad (8)$$

$$T_C = \frac{V_M T_M + V_A T_A}{(V_M + V_A)} \qquad (9)$$

V_M is directly related to the VEI (Simkin and Siebert, 1994) and V_A is essentially the relaxation volume. Taking values for the nominal 1 kiloton explosion, VEI = 0 case, we have $V_M = 10^4\ m^3$, VA $=4.2 \times 10^7\ m^3$, T_M = 1000°C, T_A = 30°C, we obtain a mean cloud temperature from equation (1):

$$TC \sim 30.2^{\circ}C \qquad (10)$$

which is only 0.2°C warmer than the atmospheric environment. This modest temperature perturbation is expected in general because $V_M << V_A$, despite the large temperature contrast between magma and atmosphere.

This result suggests that the rapidly rising cumuliform towers in explosive eruptions are caused primarily by the kinetic energy of the explosions (on the way to the relaxation radius), rather than by cloud buoyancy forces set up by cloud-atmosphere temperature contrasts. This conclusion must be considered tentative however, as it is based on a thorough mixing of the explosion emission over the entire relaxation volume. In the case of the 1980 Mt St Helens eruption, the lateral blast that initiated the eruption was clearly NOT well mixed with environmental air (Kieffer, 1981), and substantial enhancements of temperature (>100°C) were documented. Modelling studies of eruptions (e.g., Woods and Self, 1992) show 20-30°C temperature contrasts between plume and environment. Furthermore, Pack et al (2000) have documented thermal anomalies from space indicative of strong temperature perturbations in Plinean eruptions, but more interpretation of these anomalies is needed. For the calculations here, we are not concerned with the short time scales of the initial blast, however, but rather the disposition of temperature and water substance at the time of 'relaxation'.

5. Supporting observations of water substance in volcanic eruption clouds

The foregoing calculations suggest that condensation of water vapor to the liquid and solid phase should be a common occurrence in explosive volcanic eruptions. How do these simple predictions square with available observations?

Regarding the evidence for liquid water in volcanic eruptions, Clarke (1821) describes observations of the May 31, 1806 eruption of Vesuvius in Italy: "two places were deluged with a thick black rain, consisting of a species of mud filled with sulphureous particles". In the case of the more recent Mt St Helens eruption in 1980, Waitt (1981) reports, "...dark gray pisolitic mud fell from the second high-level cloud", and Thompson (2000) notes "...mud balls the size of a half-dollar fell like rain for several minutes". In tropical eruptions, wet conditions have also been documented, though in these cases the interpretation is less clear-cut, owing to the abundance of moisture and the prevalence of natural precipitating convection that may be processing atmospheric water vapor rather than magma water. Nevertheless, the reports form the tropics are worth noting in light of the predictions. In the case of the Rabaul volcano, Rose et al (1995) reported, "some of the ash fallout was very wet, and a 'rain of mud' occurred in some areas around Rabaul". For the Pinatubo (Philippines) eruptions in 1991, Oswalt et al (1996) reported:

"Tephra fall continued throughout the day…varying from completely dry ash through a cement-like mud, to muddy water". Paladio-Melosantos et al (1996) document Pinatubo conditions as follows: "An area of about 2000 square kilometers was blanketed by 10 to 25 centimeters of rain-soaked tephra." Note that a typhoon accompanied the Pinatubo eruption so some of the water came from the typhoon.

In addition to this evidence for liquid water, ice has been reported in volcanic eruptions in a few instances. Owing to the lower saturation thresholds and the prevalence of subfreezing conditions in the upper troposphere, ice is expected to be the most prevalent fate of magmatic water. In the case of the Surtsey volcano in Iceland, Thorarinsson (1966) reported, "…fallout of icy pyroclasts onto local ships was described as hail showers with a grain of ash within each hailstone". Using remote sensing methods on the Rabaul volcano, Rose et al (1995) "…report the detection, using a satellite-borne infrared sensor, of >million tons of ice in the cloud". For the 1980 eruption of Mount St. Helens, Hoblitt (2000) states, "upon the arrival of the yellow cloud, ice and ice-cold mudballs began to fall…". Of the same eruption, Thompson (2000) notes: "ice-cube sized chunks of glacier ice began pelting the ground…". In the latter case, the interpretation is again fuzzy, as the ice particles could have originated from glacial ice on the volcano slope, rather than from magmatic water. Note the small number of cases cited here. Ironically, these observations, which are key for lightning studies, are not made systematically for volcanoes.

6. Implications for microphysics in volcanic clouds

The evidence for an abundance of water in all three phases in eruption clouds has important implications for the cloud microphysics occurring therein. Textor et al (2003) have already treated some of these processes in numerical simulations of volcanic clouds.

Firstly, the fine volcanic ash particles will serve as nuclei for condensation—cloud condensation nuclei for the liquid phase of water and ice nuclei for the solid phase (Mason, 1971; Hobbs, 1975). The high concentrations of such nuclei in volcanic clouds in comparison to the concentration of natural aerosol in thunderclouds will likely serve to keep the nucleated cloud droplets and ice crystals small, thereby suppressing the precipitation process (by either coalescence or by riming).

Secondly, the classical Bergeron process involving the liquid and solid phases of water is expected to be active in the mixed phase region of volcanic eruptions where the in situ temperature lies between 0°C and –40°C. This process will stimulate the growth of ice crystals at the expense of the liquid droplets.

Thirdly, given the presence of supercooled water droplets and ice particles, the riming process should occur for the larger, faster-falling tephra particles, with consequent accretion of ice on the surfaces of these particles, so long as the supercooled droplets are not too small. In eruptions clouds with extreme updrafts, substantially larger than those in thunderclouds, the available time for riming is expected to be shorter. Nevertheless, the collection action of nucleation and riming are expected to coat the volcanic particles with water substance in ether liquid or solid form, with considerable efficiency. This widespread coating of the volcanic debris would seem to preclude mechanisms for charge separation based on tribo-electrification of silicate mineral surfaces. At least within the mixed phase region, often half the depth of the troposphere, ice particle collisions need to be considered in the electrification process.

7. Gross electrical dipole structure of volcanic eruptions

A characteristic feature of ordinary thunderstorms is their gross positive dipolar structure—positive charge in upper levels and negative charge at lower levels of the ice region. A weak test of whether ice is responsible for the charge separation in volcanic eruptions is the inquiry into the gross charge structure of eruptions. The available observations summarized in Table 2, show gross positive dipole structure and so pass this weak test. The test is 'weak' because one has a 50-50 chance of being correct.

Eruptions such as Mt St. Helens in May 1980 (Cobb, 1980) grow to heights greater than the tallest thunderclouds, and given the foregoing calculations, are expected to be rich in ice in upper levels. Some of the eruption clouds documented in Table 2, however, have insufficient depth to penetrate the cold part of the troposphere, and in this case, their inclusion in the table may not be appropriate. It is however useful to consider in this context a meteorological entity composed of dry silicate minerals—the small vigorous vortices developing in desert environments called 'dust devils'. The desert conditions typically involve dry air (20% relative humidity or less), and deep boundary layers in which condensation and cloud do not occur. There can be little doubt that dust devils involve collisions between dry silicate minerals only—no liquid water and no ice is available. Electrical measurements show that the gross dipole polarity of dust devils is negative—i.e., negative charge in upper levels and positive charge at lower levels (Freier, 1960; Crozier, 1964; Ette et al, 1971). Freier (1960) refers to the dust devil dipole as an 'inverted thunderstorm'. This dust devil polarity is not consistent with any of the results in Table 2, even for the smaller eruptions (i.e., Sakurajima volcano) that are most likely NOT to contain ice.

Table 2. Gross Dipole Polarity of Eruption Clouds

Anderson et al (1965), Surtsey volcano
"...downwind, there is a region of negative charge beneath the region of positive charge."

Cobb (1980) Mt. St. Helens volcano
"the measurements always indicated a positively charged plume"

Hobbs and Lyons (1983), Mt. St. Helens volcano
"negatively charged particles at lower altitudes, and positively charged particles higher up"

Hoblitt (1994), Redoubt volcano
"the flash polarity tended to change through time from negative to positive"

Lane and Gilbert (1992), Sakurajima volcano
"positive charges develop in the gas-rich top and negative charges in the ash-rich part of plume"

Gilbert and Lane (1994), Sakurajima volcano
"positive charges dominate at the top of the plume and negative charges dominate at the base"

McNutt and Davis (2000), Mt Spurr volcano
"thunderstorms...and eruptions...both show the same sequence of first negative, then positive..."

The polarity behavior noted for cloud-to-ground lightning discharges from volcanic eruptions also bears a similarity with thunderstorms, as noted also in Table 2. Both Hoblitt (1994) and McNutt and Davis (2000) have noted a sequence of activity involving ground flashes of negative polarity followed by ground flashes with positive polarity. This behavior is characteristic of thunderclouds as they transition from their mature phase to their dissipating stage (Moore and Vonnegut, 1977; Williams and Boccippio, 1993).

8. Implications of predictions for the satellite-detection of eruption clouds

Satellite remote sensing of volcanic ash clouds has focused on the split window technique (Prata, 1989), based on the differential infrared response of dry volcanic ash. Ice is well known to show the opposite response (Prata, 1989). Ice-coated ash particles are expected to respond as ice. Given the calculations in the present study, one can expect difficulties with the split window technique in distinguishing thunderclouds from explosive volcanic eruptions. This expectation is borne out by the observations (Simpson et al, 2000; Tupper et al, 2004), and in many instances the dry ash signature will not appear strongly until the ice near the tops of eruptions clouds has sublimated to expose the dry ash.

'Dry' eruptions are referred to in the literature (Ellrod et al, 2002), but this is a relative term only. Given the water-based physics believed responsible for explosive eruptions, it is difficult to see how any eruption can be dry. Further observations of volcanic eruptions with fine time resolution from the earliest stages are needed to throw more light on this issue.

9. Conclusions

Calculations have been presented which treat the transferal of magma water in the Earth to eruptions clouds in the atmosphere. Volcanic lightning appears to be widespread, and the high water contents of magmas may be key to electrification processes. Under favorable assumptions, water in both its condensed phases is expected to be abundant in large Plinean eruptions. Further evidence involving gross electrical structure and lightning behavior is identified for a fundamental role for ice and lightning production in large eruptions. However, basic information on water and ice contents in volcanic plumes is poorly known. Instrumental electrical data and direct sampling of the water contents of ash columns and adjacent atmosphere are needed for at least a few case studies.

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References

1. Anderson, R., S. Bjornsson, D.C. Blanchard, S. Gathman, J. Hughes, S. Jonasson, C.B. Moore, H.J. Survilas, and B. Vonnegut, Electricity in volcanic clouds, Science, 148, 1179-1189, 1965.
2. Bass, H., M. Garces, D. McCormack, P. Chen and M. Jean, Evaluation of a prototype infrasound system for enhancing volcanic ash warnings, The 2nd International Conference on Volcanic Ash and Aviation Safety, Alexandria, VA, June 21-24, 2004.

3. Carey, S., J. Gardner, and H. Sigurdsson, The intensity and magnitude of Holocene Plinian eruptions from Mount St. Helens volcano, J. Volcanol. Geotherm. Res., 66, 185-202, 1995.
4. Clarke, C.C., The Hundred Wonders of the World and the Three Kingdoms of Nature, printed for Sir Richard Phillips and Co., London, 1821, 668 pp.
5. Cobb, W.E., Electric fields and lightning in the Mt. St.Helens cloud, EOS, 61, 978, 1980.
6. Cornell, W.C., Petrology and ash dispersal studies of products of the Neapolitan volcanic area, PhD thesis University of Rhode Island, Narragansett, 255 pp., 1987.
7. Crozier, W.D., The electric field of a New Mexico dust devil, 69, 5427-5429, 1964.
8. Ellrod, G.P., R.L. Helz, and G. Wadge, Volcanic Hazards Assessment, Committee on Earth Observation Satellites, Disaster Management Support Project, NOAA Report, 2002.
9. Ette, A.I.I., The effect of Harmattian dust on atmospheric electric parameters, J. Atmos. Terr. Phys., 33, 295-300, 1971.
10. Few, A.A., Acoustic radiations from lightning, 257-290, Handbook of Atmospherics, Vol. II, Ed., H. Volland, CRC Press, 1980.
11. Freier, G.D., The electric field of a large dust devil, J. Geophys. Res., 65, 3504, 1960.
12. Gardner, J.E., R.M.E. Thomas, C. Jaupert, and S. Tait, Fragmentation of magma during Plinian volcanic eruptions, Bull. Volcanol, 58, 144-162, 1996.
13. Hobbs, P.V., Ice Physics, Clarendon, Oxford, 1975, 837 pp.
14. Hobbs, P.V. and J.H. Lyons, Electrical activity associated with the May 18, 1980 eruption of Mount St. Helens, Unpublished report, September, 1993.
15. Hoblitt, R.P., Was the 18 May lateral blast at Mt St Helens the product of two explosions?, Phil. Trans. R. Soc. Lond. A, 358, 1639-1661, 2000.
16. Johnson, M.C., A.T. Anderson, Jr., and M.J. Rutherford, Pre-eruptive volatile content of magmas, Chapter 8 in Volatiles in Magmas, Reviews in Mineralogy, Vol 30, Eds., M.R. Carroll and J. R. Holloway, Mineralogical Society of America, Washington, D.C., 1993.
17. Kieffer, S.W., Fluid dynamics of the May 18 blast at Mount St. Helens, in The 1980 Eruptions of Mount St. Helens, Washington, 379-400, Geological Survey Professional Paper 1250, (Ed. P.W. Lipman and D.R. Mullineaux), U.S. Government Printing Office, Washington, D.C., 1981.
18. Latham, J., The electrification of thunderstorms, Quart. J. Roy. Met. Soc., 107, 277-298, 1981.
19. Markinen, E.K., On the possibility of estimating the amount of juvenile water participating in volcanic explosion, Bull. Volcanol. 24, 187-191, 1962.
20. Mason, B.J., *The Physics of Clouds*, Clarendon, Oxford, 1971.
21. McNutt, S.R. and C.M. Davis, Lightning associated with the 1992 eruptions of Crater Peak, Mount Spurr Volcano, Alaska, J. Volcanology and Geothermal Res., 102, 45-65, 2000.
22. Melson, W.G. and C.A. Hopson, Preeruption temperatures and oxygen fugacities in the 1980 eruption sequence, 641-648, Geological Survey Professional Paper 1250, (Ed. P.W. Lipman and D.R. Mullineaux), U.S. Government Printing Office, Washington, D.C., 1981.

23. Moore, C.B. and B. Vonnegut, The thundercloud, in The Physics of Lightning, ed. R.H. Golde, pp. 51-98, Academic, New York, 1977.
24. Oswalt, J.S., W. Nichols and J.F. O'Hara, Meteorological observations of the 1991 Mount Pinatubo eruption, in *Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines*, Ed. C.G. Newhall and R.S. Puynongbayan, pp. 513-535, Philippines Institute of Volcanology and Seismology and University of Washington Press, Quezon City and Seattle, 1996.
25. Pack, D.W., C.J. Rice, B.J. Tressel, C.J. Lee-Wagner and E. Oshika, Civilian uses of surveillance satellites, Crosslink (The Aerospace Corporation magazine of advances in aerospace technology), Winter issue, 2000.
26. Peladio-Melosantos, Ma. Lynn O., R.U. Solidium, W.E. Scott, R.B. Quiambao, J.V. Umbal, K.S. Rodolfo, B.S. Tubianosa, P.J. Delos Reyes, R.A. Alonso, and H.B. Ruelo, Tephra falls of the 1991 eruptions of Mount Pinatubo, in *Fire and Mud, Eruptions and Lahars of Mount Pinatubo, Philippines*, Ed. C.G. Newhall and R.S. Puynongbayan, pp. 513-535, Philippines Institute of Volcanology and Seismology and University of Washington Press, Quezon City and Seattle, 1996.
27. Prata, A.J., Observations of volcanic ash clouds using AVHRR-2 radiances, International Journal of Remote Sensing, 10, 751-761, 1989.
28. Rose, W.I., D.J. Delene, D.J. Schneider, G.J.S. Bluth, A.J. Krueger, I. Sprod, C. McKee, H.L. Davies, and G.G.J. Ernst, Ice in the 1994 Rabaul eruption cloud: implications for volcano hazard and atmospheric effects, Nature, 375, 477-479, 1995.
29. Rose, W.I., G.J.S. Bluth, and G.G.J. Ernst, Integrating retrievals of volcanic cloud characteristics from satellite remote sensors: a summary, Phil. Trans. R. Soc. London A, 358, 1585-1606, 2000.
30. Roggensack, K.R., R.L. Hervig, S.B. McNight and S.N. Williams, Explosive basaltic volcanism from Cerro Negro Volcano: Influence of volatiles on eruptive style, Science, 277, 1639-1642, 1997.
31. Saunders, C.P.R., Thunderstorm electrification, in Handbook of Atmospheric Electrodynamics, H. Volland, Ed., CRC Press, 61-92, 1995.
32. Simkin, T. and L. Siebert, *Volcanoes of the World*, 2nd Edition, Geoscience Press, Tucson, AZ, 1994.
33. Simpson, J.J., G. Hufford, D. Pieri and J. Berg, Failures in detecting volcanic ash from satellite-based technique, Remote Sensing of the Environment, 72, 191-217, 2000.
34. Sisson, T.W. and G.D. Layne, H_2O in basalt and basaltic andesite glass inclusions from four subductionrelated volcanoes, Earth Planet Sci Lett., 117, 619-635, 1993.
35. Sullivan, J.D., The Comprehensive Test Ban Treaty, Physics Today, 24-29, March, 1998.
36. Textor, C., H.-F. Graf and M. Herzog, Injection of gases into the stratosphere by explosive volcanic eruptions, J. Geophys. Res., 108, 4606, doi:10.1029/2002JD002987, 2003.
37. Thompson, D., *Volcano Cowboys—The Rocky Evolution of a Dangerous Science*, Thomas Dunne Books, St. Martins Press, New York, 2000, 326pp.
38. Tupper, A., S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata, and M. Tokuno, An evaluation of volcanic cloud detection techniques during recent significant

eruptions in the western 'Ring of Fire', Remote Sensing of the Environment, (in press), 2004.

39. Thorarinsson, S., *Surtsey: the new island in the North Atlantic*, Reykjavik: Almenna Bokateloged, 1966.
40. Waitt, R.B., Jr., Devastating pyroclastic density flow and attendant air fall of May 18—Stratigraphy and sedimentology of deposits, 439-458, in Geological Survey Professional Paper 1250, (Ed. P.W. Lipman and D.R. Mullineaux), U.S. Government Printing Office, Washington, D.C., 1981.
41. Wallace, P., Volatiles in subduction zone magmas: Concentrations and fluxes based on melt inclusion and volcanic gas data, JVGR Special Volume on State of the Arc (SOTA), Eds., W. Leeman and J. Davidson, submitted, 2004.
42. Wallace, P. and A.T. Anderson, Jr.. Volatiles in magmas, in *Encyclopedia of Volcanoes*, Academic Press, 2000.
43. Wallace, P.J. and T.M.Gerlach, Magmatic vapor source for sulfur dioxide released during volcanic eruptions: evidence from Mount Pinatubo, Science, 265: 497-499, 1994.
44. Williams, E.R., Large scale charge separation in thunderclouds, J. Geophys. Res., 90, 6013-6025, 1985.
45. Williams, E.R., The Electrification of Severe Storms, Chapter 13 in *Severe Convective Storms*, Ed., C.A.Doswell, III, Meteorological Monograph, Vol. 28, No. 50, 527-561, 2001.
46. Williams, E.R. and D.J. Boccippio, Dependence of cloud microphysics and electrification in mesoscale air motions in stratiform precipitation, 17 Conf. on Severe Local Storms and Conf. on Atmos. Elec., 825-831, American Meteorological Society, Oct. 4-8, St. Louis, MO, 1993.
47. Wilson, L., R.S.J. Sparks, and G.P.L. Walker, Explosive volcanic eruptions—IV. The control of magma properties and conduit geometry on eruption column behavior, Geophys. J. R. Astr. Soc., 63, 117-148, 1980.
48. Woods, A.W. and S. Self, Thermal disequilibrium at the top of volcanic clouds and its effect on estimates of the column height, Nature, 355, 628-630, 1992.