Ice in Volcanic Clouds – AE33B-0282

Arthur A Few
few@rice.edu; www.ruf.rice.edu/~few
Professor Emeritus of Physics and Astronomy, Rice University
Visiting Scientist, University Corporation for Atmospheric Research
700 Hill St; Gold Hill
Boulder CO 80302–8786

Plinian Volcanos

Plinian and Ultra Plinian volcanos are the most explosive types of volcanoes.

1. Plume heights typically exceed 25 km, some as high as 40 km.[2]
2. The explosive expansion is produced by exsolution of volatiles. One m^3 of magma expands to ~670 m^3 when the volatiles are released at 1 atm. See Figure 1 below.[2]
3. The magma is rhyolitic and contains mostly silicates.
4. Water is the dominant volatile; as much as 99% molar fraction[1], and up to 7% by mass in the molten magma.[2]
5. Other volatiles are CO_2 and compounds of S, Cl, and Fl, which form gases as the magma pressure decreases.[2]
6. Plinian plumes inevitably contain ice because of the height of the plume and the abundance of water. Other volcanic plumes topping out lower than the Plinian may also contain ice.

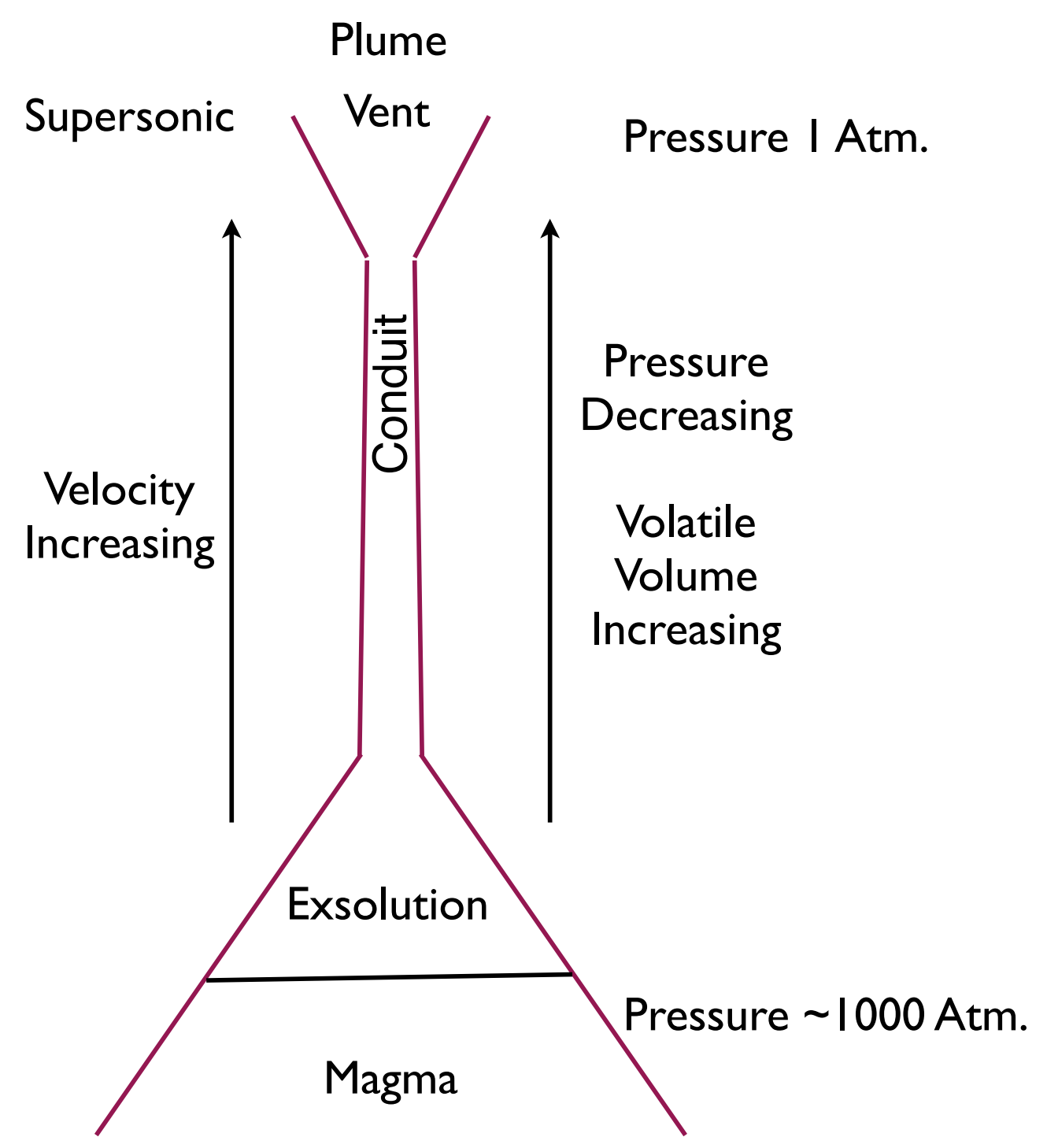

Figure 1

Drawing above is based upon Sparks et al [2].

The list below was complied primarily from references 2 and 3. W indicates the Alaska Volcano Observatory. All of the volcanos listed produced plumes equal to or greater than 10 km in height.

Ref	Name	Date	Height
2	Vesuvius	79	26-32 km
3	Krakatau	Aug 27, 1883	27 km
3	Etna	May 21,1886	14 km
2, 3	Soufriere	May 17, 1902	15.5-17 km
2, 3	Santa Maria	Oct 24, 1902	27-29 km
2	Komagatake	1928	13.9 km
2, 3	Quizapu	Apr 10, 1932	14-30 km
2, 3	Hekla	Mar 29, 1947	27.6 km
3	Spurr	Jul 9, 1953	22 km
2, 3	Bezymianny	Mar 30, 1956	36-45 km
3	Tokachidake	Jan 29, 1962	12 km
2, 3	Agung	Mar 17, 1963	10-22 km
3	Trident	Apr 1, 1963	15 km
3	Surtsey	Nov 14, 1963	14.5 km
3	Taal	Sep 28, 1965	15-20 km
3	Redoubt	Feb 9, 1966	12-16 km
3	Deception Is.	Jul 5, 1967	10 km
3	Fernandina	Jun 11, 1968	22-24 km
2, 3	Hekla	May 5, 1970	14-16 km
2	Fuego	1971	10 km
3	Fuego	Oct 14, 1974	22 km
3	St. Augustine	Jan 23, 1976	11 km
2	Usu	1977	10-12 km
3	Soufriere	Apr 22, 1979	17-19 km
3	St. Helens	May 18, 1980	13-24 km
2	St. Helens	Jul 1, 1980	12-13 km
3	St. Helens	Aug 7, 1980	13 km
3	St. Helens	Oct 18, 1980	14 km
3	Alaid	Apr 28, 1981	15 km
3	Pagan	May 15, 1981	13.5 km
2, 3	El Chichon	Mar, Apr, 1982	22-30 km
2	Nevado del Ruiz	1985	24-29 km
W	Redoubt	1989	14 km
W	Redoubt	Mar 26, 1990	20 km
2	Mt. Pinatubo	Jun 15, 1991	34 km
W	Redoubt	Apr 21, 2009	> 15 km

Plinian Volcanos were named after Pliny the Elder or Pliny the Younger, hopefully both.

Pliny the Elder (Gaius Plinius Secundus, 23 AD – August 25, 79) was a natural philosopher and the author of *Naturalis Historia*, which was the first book written in the format of an encyclopedia. He was also a military commander of Rome and personal friend of Roman emperors. During the eruption of Mount Vesuvius, which had already destroyed the cities of Pompeii and Herculaneum, Pliny commissioned a ship to take him across the Bay of Naples not only to directly observe the volcano but to rescue family friends. In these his later years it is reported that he was quite obese requiring the assistance of two servants to stand up from a seated position. He was physically unable to return to the ship and stayed behind where he died. His body was found covered in pumice. Pliny had no children; he adopted his nephew (Pliny the Younger), helped raise and educate him, and left him his fortune and legacy.

Pliny the Younger (Galas Plinius Caecillus Secundus, 61 AD – ca. 112) was corespondent to emperors and the Roman historian Tacitus. He was 18 when his uncle died during the Vesuvius eruption of 79 AD. He started writing at 14 and is recognized for his letters; although they were written to people they were meant for publication. Of special interest here are two letters written to the Roman Historian Tacitus. There are several English translations of the two letters: (1) "a dreadful black cloud was torn by gushing flames and great tongues of fire like much-magnified lightning." http://quakeinfo.ucsd.edu/~gabi/erth15-06/lecture08/pliny.html; and (2) "In the other direction gaped a horrible black cloud torn by zigzag flashes and masses of flames, like lightning but much larger"; and (3) "Behind us were frightening dark clouds, rent by lightning twisted and hurled, opening to reveal huge figures of flame. These were like lightning, but bigger." This may be the first recorded description of lightning from "Plinian" volcanos.

Figure 2

Redoubt Volcano, Alaska – Alaska Volcano Observatory
Photograph by R. Clucas April 21, 1990, U. S. Geological Survey

The Plume rises through several thin stable layers before broadly spreading out just above the tropopause. The top of the cloud penetrates into the stratosphere. This plume is free of cross winds enabling us to see the turbulence on the edges of the plume.

Figure 3

Eyjafjallajökull volcano in Iceland
Photograph by Marco Fulle – April 17, 2010
This photograph appeared in Astronomy Picture of the Day 4/19/10
http://antwrp.gsfc.nasa.gov/apod/ap100419.html
Permission from Marco Fulle – www.stromboli.net

The photograph above is beautiful and also informative. In it we see both kinds of electrical discharges produced by volcanos: discharges produced near the vent and discharges emerging from the volcanic cloud higher in the plume. The upper discharges look exactly like negative cloud-to-ground lightning from thunderstorms. If this is the case then the lower plume near the terminus of the bright lightning channel would be charged positively. Many of the lower branches of this lightning flash are also moving toward the lower plume.

The discharges in the lower plume appear quite different. They are short and reddish in color; the plume has a very large optical thickness, so we only see the portions of the discharges that are close to the edge or may exit the plume for a short distance. The reddish emission extends beyond the discharge channel indicating that the discharge is heating the surrounding ash, which then radiates the reddish radiation.

Acknowledgment
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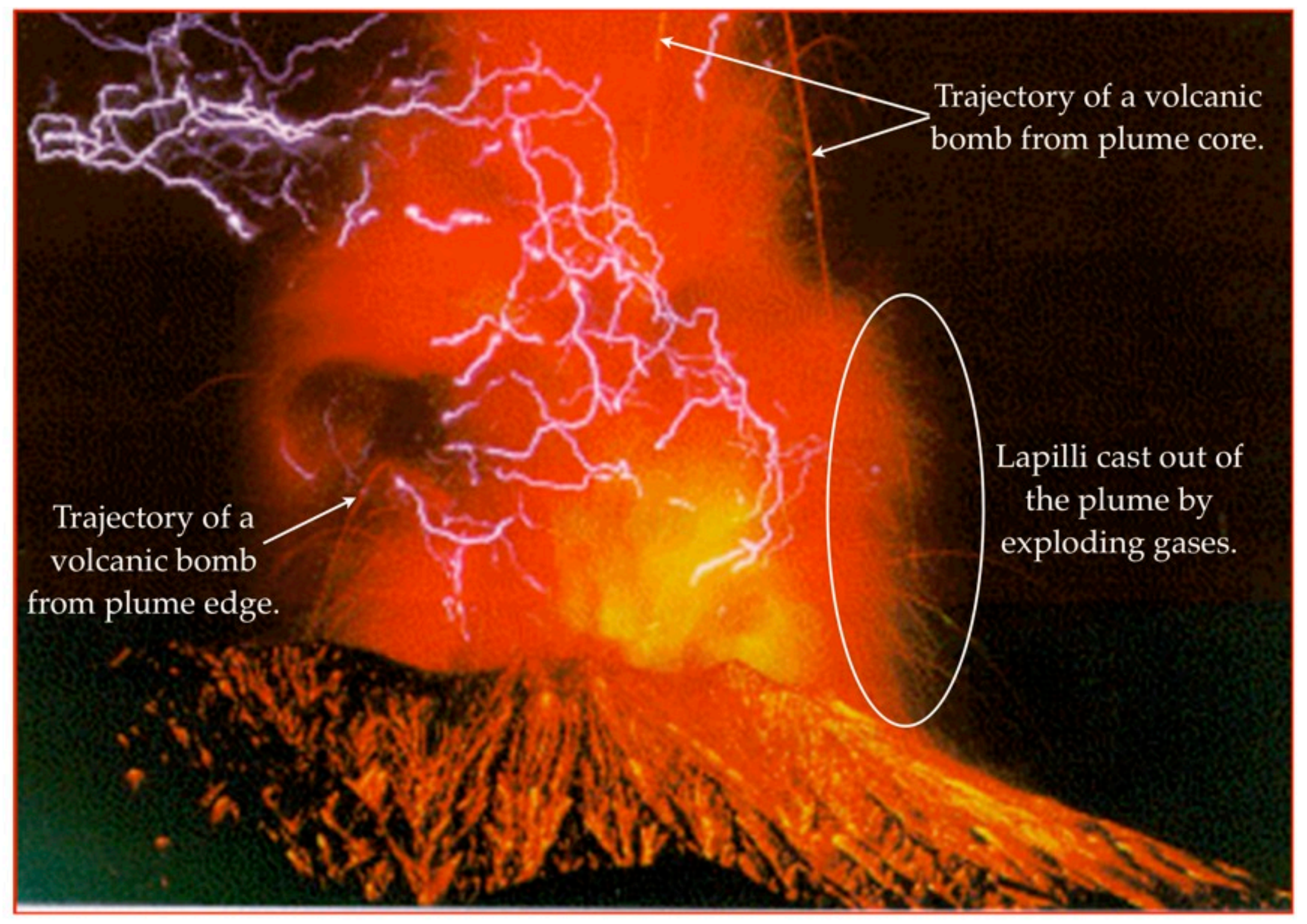
Cooling Volcano Plumes

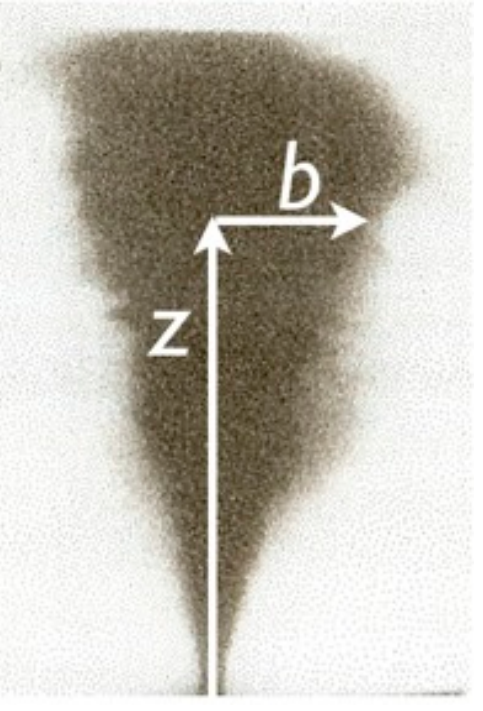
See the drawing, Figure 1, far left; the following discussion is based upon Sparks *et al.*[2] The conditions in the magma chamber at depths 3 km to 30 km below the surface are, for rhyolite magmas, ~ 900 °C and ~ 1000 atm. Volatiles are dissolved in the magma, principally water and CO_2. As the magma moves slowly (a few m/s) toward the surface the pressure decreases and at some pressure level the volatiles exsolve from the magma initially forming small gas bubbles. Further decreases in pressure accelerates the exsolution and the bubbles grow in size. At this intermediate stage the bubble volume may exceed that of the the molten magma, but the magma continues to envelop the bubbles. The upward flow is faster because of the increased volume. Upon reaching a pressure level of ~ 10 atm, which is probably within ~ 1 km of the surface, the volatile bubbles are large enough to break up the magma and become the dominant component of the fluid; until this stage the magma and gaseous components were in thermodynamic and dynamic equilibrium; from this stage to the surface vent the process is best described as a focused explosion. The gas and magma separate dynamically and thermodynamically; the magma with its mass and heat capacity maintains a temperature ~ 700 °C - 750 °C, while the explosive expansion of the gas cools rapidly. The expansion can cool the gas component to ~ 400 °C. The larger tephra fall out of the plume rapidly while the smallest lapilli and ash move with the plume gas and come into thermodynamic equilibrium probably somewhat above 400 °C.



Credit: Sakurajima Volcananological Observatory
Caption: Sakurajima volcanic lightning, May 18, 1991.

Figure 4

Several important processes are evident in the above photograph. Just above the vent the explosive force of the expanding gas is forcing the lapilli out of the plume. That horizontal force with the addition of gravity is removing the larger components including volcanic bombs. The effluent from the vent (yellow) is hotter than the other parts of the plume (red). The core of the plume seen at the top of the photograph is moving upward very fast; this is the region of plume thrust where the upward velocity is a remanent of the focused explosive forces in the upper conduit and vent. Finally, the emission indicates that radiative cooling is another source of plume cooling.



During the thrust phase of the plume the boundary is very turbulent and the behavior can be approximated by that of jet flow; based upon experimental data[2], $b = z/8$. The turbulent flow at the edge produces mixing of the ambient air with the plume, which decelerates and cools the plume. Using this simple jet flow model with a vent radius equal 20 m, the radius of the jet will be approximately 125 m at 1 km above the vent. Assuming a vent radius of 20 m we estimate the momentum in a column in the core of the jet. By the entrainment mechanism this momentum is distributed throughout the entrainment cone; at 1 km above the vent the velocity of the expanded jet will be approximately 31 m/s, which is near the updraft velocity of an active thunderstorm. We estimate the heat content in the core of the Jet from the estimated temperature of 400 °C and the heat content of the entrained air from an assumed temperature of 10 °C; these are mixed and the total heat content is distributed over the entrainment cone giving us a temperature of 62 °C at 1 km. Admittedly, one has a lot of latitude in selecting values for the parameters used in these estimates, but it is evident that entrainment greatly reduces the velocity and temperature of the plume within a kilometer or so of the vent. The temperature remains very warm compared to the ambient air. The high-speed jet flow, which was produced by the thrust of the explosive volcano is replaced by buoyant plume dynamics; above the thrust region; modified cloud models can be used to describe subsequent development.

The plume continues its upward motion propelled now by its primitive heat. Entrainment continues to be a major source of cooling; simple models indicate that entrainment is proportional the upward velocity of the center of the plume[5]; adiabatic expansion also adds to the cooling. The plume is rising through a ambient atmosphere which is also cooling steadily with altitude, so the buoyancy remains the driving mechanism for most of the plume evolution. The reason that some Plinian plumes can reach heights of 25 km to 45 km, penetrating into the lower stratosphere, is that their temperatures never fall below the ambient atmosphere temperatures.

Ice in Volcanic Clouds

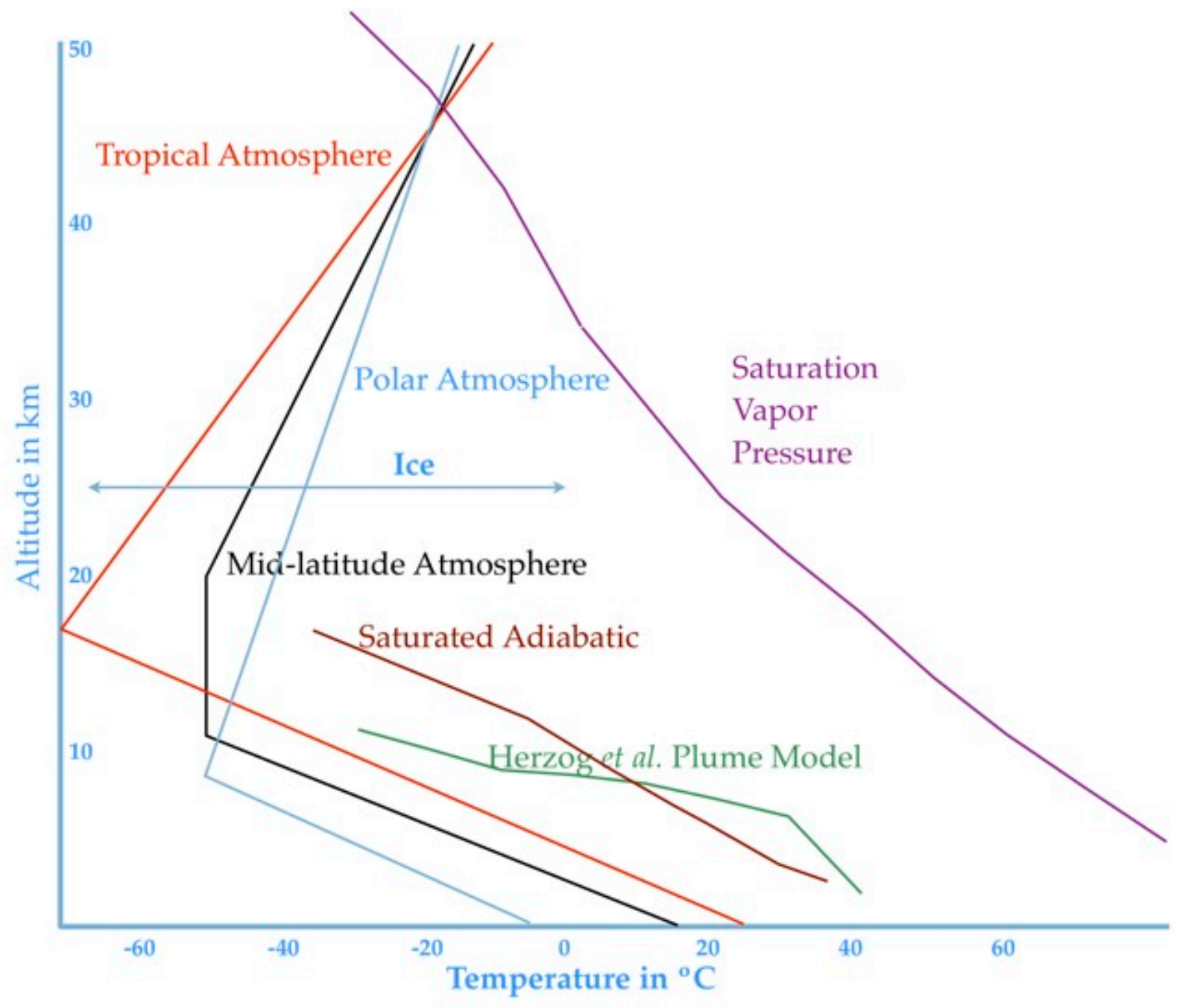


Figure 5

Several curves are plotted in Figure 5 above on linear Altitude versus Temperature diagram. On the left side are schematic representations of the environmental profiles for tropical, mid-latitude and polar atmospheres. As long as a volcanic plume/cloud remains to the right of the appropriate profile it will remain buoyant. The "Saturated Adiabatic" curve is an extension of the conditions computed above for the top of the thrust region of the jet from the vent; a thermodynamic diagram was used to plot this curve. The curve labeled "Herzog *et al.* Plume Model" is derived from their Figure 5.[6] Their model is a cloud physics model including microphysics that is placed in a moist tropical environment. Among their conclusions are the significance of moisture entrainment and latent heat releases to the cloud evolution. Finally, the right-most curve "Saturated Vapor Pressure" was computed using the Clausius-Clapeyron equation. This curve represents the upper boundary for clouds because it assumes that the vapor is providing the total pressure in the cloud.

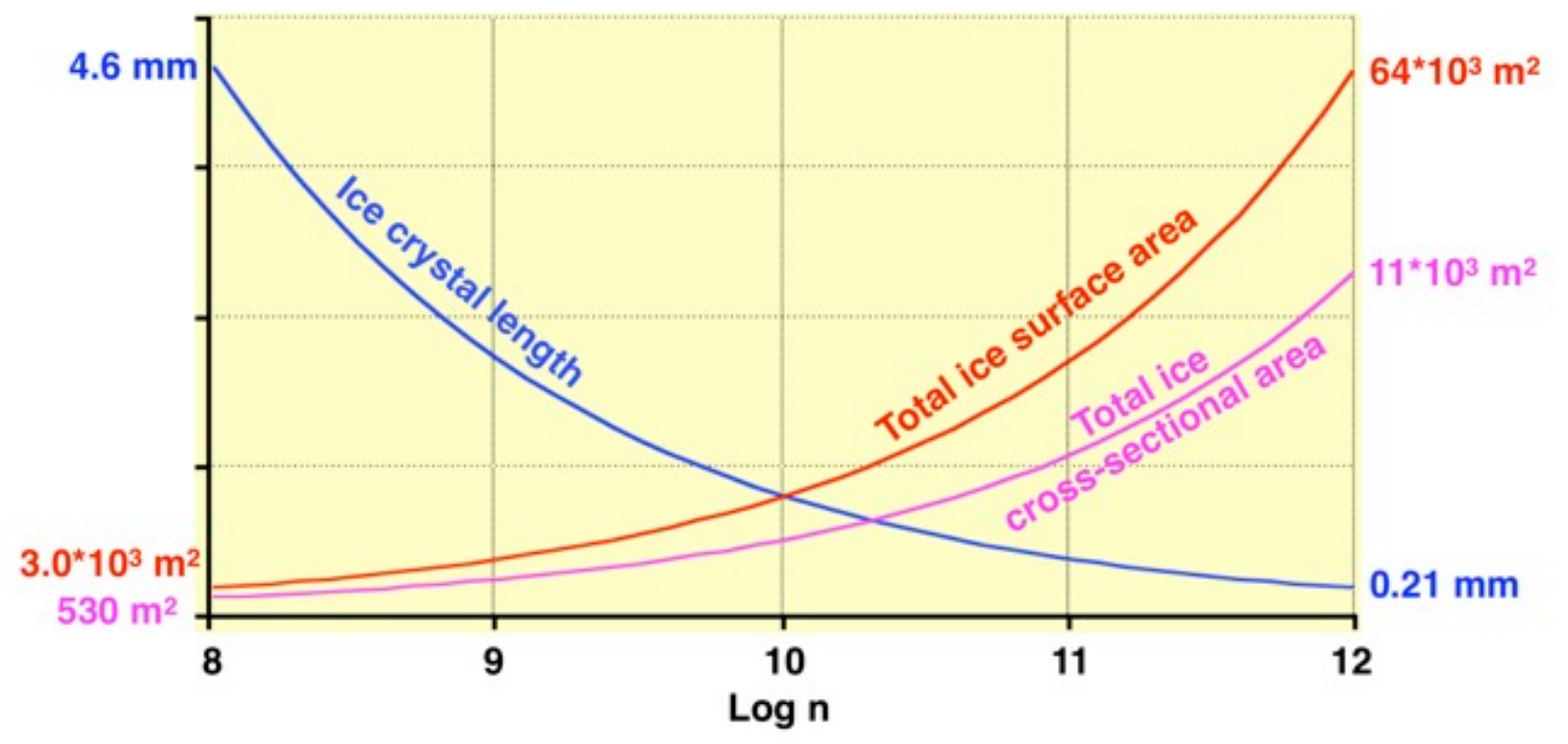


Figure 6

The curves in Figure 6 above are useful to understanding the consequences of the overseeding of ice in volcanic clouds.[4] In summary, ice nuclei are sparse in thunderstorm clouds; hence, there are few ice particles but they can grow large on the available vapor. In contrast volcanic clouds contain numerous ice nuclei particularly silicates, and they can develop as many small ice particles. This great difference in ice behavior between the thunderstorm clouds and the volcanic clouds can have significant impact on electrification, cloud evolution and chemical transport into the stratosphere.

To produce Figure 6, I took 1 m^3 of water and distributed it into "n" hexagonal rod crystals each having a side dimension "a" and length "5a". I then computed for each value of n the total surface area and cross-sectional of the whole collection of crystals. The results are displayed in the figure. We easily see that increasing the number of crystals, increases the total surface and the cross-sectional areas of the system even when the volume is constant.

1. Electric charge resides on the surface of ice particles; hence, the more numerous but smaller ice particles have a greater electrical capacity.
2. The adsorption capability of ice particles for chemicals in the volcanic plumes is also proportional to total surface area.
3. The smaller ice particles are more easily lofted into the stratosphere transporting the volcanic chemicals.
4. Ice-ice contact is a source of electrical charging and the frequency of particle collisions is increased with increased total cross-sectional area.