The role of bubble formation in volcanic eruption

Eyal Goldmann

Division of Natural Sciences, El Camino College, Torrance, CA, 90506

Prepared for Geology 1 at El Camino College

Fall 2009

1. Introduction

Erupting volcanoes exhibit a wide range of visually spectacular phenomena, such as giant ash columns, "fire" fountains, in which glowing lava is projected several hundred meters into the air, and lava flows (see e.g. Schmincke, 1998). Besides their natural spectacle, many of these phenomena pose serious risk to human life and property. Both for the compelling interest they attract and the hazards they pose, there is a natural interest in understanding the physical principles underlying volcanic phenomenology.

The key physical factors which govern eruption phenomenology are the composition of the magma, the concentration and behavior of the volatiles dissolved in the magma, and the geometry of the volcanic conduit (Wilson and Head, 1981). In this article, we focus on the role played by volatile exsolution – i.e. the process by which dissolved gases leave the liquid magma to form bubbles – and the role that this plays in determining the nature of the eruption. We also discuss how similar bubble behavior in different types of magma may lead to very different styles of eruption.

2. Bubble dynamics in volcanic conduits: a synopsis

Magma originates in the earth's mantle, and is driven by buoyancy to rise through the mantle, enter the crust, and continue rising through the crust to collect in magma chambers connected to volcanic vents by conduits. (Parfitt and Wilson, 2008)

When magma arrives at the chamber (see Fig. 1), it carries with it a number of dissolved gases, most importantly H_2O and CO_2 (Schmincke, 1998). While in the chamber, the magma cools, and solid crystals begin to form, increasing the concentration of volatiles (i.e. dissolved gases) in the remaining liquid phase (Pinkerton et al., 2002). Eventually, a volatile species becomes saturated, and bubbles begin to form. The presence of bubbles reduces the space available for the liquid magma, stresses the surrounding rock, and ultimately forces open a conduit, allowing the magma to begin making its way towards the surface. (Pinkerton et al., 2002; Woods, 1995)

As the magma rises through the conduit, it experiences further depressurization, which eventually will cause further exsolution of the volatiles into bubbles. The collective behavior of the bubbles will cause the subsequent eruption to follow one of three basic patterns. A summary of these, based on the classifications used by Parfitt and Wilson (2008), follows:

Transient explosive eruptions: Transient explosive eruptions occur when the rising bubbles coalesce to make a small number of giant bubbles (Parfitt and Wilson, 1995) , possibly large enough to fill the cross-section of the conduit (Vergniolle and Mangan, 2000). The giant bubbles collect beneath magma which has cooled to form a viscous plug at the conduit exit, eventually accumulating enough pressure to burst the plug and explode outward. See Figure 2. This process leads to Strombolian eruptions in basaltic volcanoes (Fig. 3) and Vulcanian eruptions in silicic volcanoes (Fig.4). (Parfitt and Wilson, 2008)

Steady explosive eruptions: If the bubbles occupy a sufficiently large volume fraction of the magma, but cannot migrate through the magma rapidly enough to coalesce into large bubbles, the magma will fracture. The gas then becomes the continuous phase, and rapidly accelerates upward, carrying the fractured magma with it. Magma rising through the chamber continues to fracture, accelerates, and exits the vent, producing a steady eruption. See Fig. 5. Styles of eruption associated with this behavior include Hawaiian fire fountains (Fig. 6), which occur in basaltic systems, and Plinian eruptions (Fig. 7), which are associated with silicic magma. (Parfitt and Wilson, 2008)

Effusive eruption: Effusive eruption occurs when bubbles in the rising magma fail to form a continuous gas phase. The magma remains a continuous liquid, and exits the vent as a lava flow. This occurs either in magma with very low volatile content or very high viscosity. Since magma rising through the mantle nearly always has sufficient volatile content to drive an explosive eruption, the low volatile content scenario usually requires that a substantial amount of degassing occur either in the magma chamber or in the conduit (Parfitt and Wilson, 2008). The high viscosity scenario occurs in dacite and rhyolite magmas, and produces highly viscous lavas which cool to form steep-sided domes (Parfitt and Wilson, 2008).

3. Formation and growth of bubbles in the conduit

As magma rises through the magma chamber and then the conduit, its pressure decreases. When the pressure drops below the saturation vapor pressure for the dissolved volatiles, the magma becomes supersaturated. In itself, this does not lead to bubble formation, which requires either the presence of solid crystals to serve as nucleation sites, or or very large supersaturation pressures, as much as 100MPa (Parfitt and Wilson, 2008). The level at which bubble formation begins is called the exsolution level. See Figs. 2 and 5.

When nucleation sites are present, bubble formation occurs when a large number of gas molecules simultaneously converge on a nucleation site. Because the formation of any one bubble is thus a chance event, bubble formation will occur over a range of depths, with some bubbles forming at much lower depths than others (Parfitt and Wilson, 2008).

As bubbles rise through the conduit, they grow larger. Two different mechanisms drive this process. First, as the bubbles rise, the pressure of the surrounding magma decreases. This allows the bubbles to expand, decreasing their own pressure to match that of the magma. Second, the bubbles grow by diffusion as gas molecules from the surrounding magma migrate into the bubbles. (Cashman et al., 2000)

4. Transient explosive eruptions

Because bubbles grow as they rise, magma which has risen far past the exsolution level will contain bubbles with a range of sizes. Bubbles which formed at greater depths, and have had more time to grow, will be larger than more recently formed bubbles Since larger bubbles are more buoyant than smaller ones, they rise faster, and may "catch up" with smaller bubbles, allowing the bubbles to merge to form still-larger daughter bubbles. In a transient explosive eruption, this process dominates the bubble dynamics, allowing the bubbles become larger and fewer in number. The largest bubbles formed in this manner may have diameteres in excess of 10 meters (Parfitt and Wilson, 1995), and may be large enough to fill the cross-section of the conduit (Vergniolle and Mangan, 2000).

The arrival of large bubbles at the conduit exit occurs infrequently enough that magma at the exit can cool to form a plug of much greater viscosity than the rising magma. As bubbles arrive at the top of the conduit, they accumulate, increasing the pressure beneath the plug. When sufficient pressure builds, the plug fractures, allowing the accumulated, pressurized gas to expand rapidly, propelling fragments of the magmatic surface into the air.

In a Strombolian eruption, as occurs in basaltic systems, the magmatic plug takes the form of a plastic skin with a yield strength far less than that of solid basalt (Parfitt and Wilson, 2008). When the skin fractures, it breaks into pieces with a range of sizes, the largest of which have diameters greater than 0.2m, travel ballistically (Blackburn et al., 1976), and land within several hundred meters of the vent (Schmincke, 1998).

In Vulcanian eruptions, which occur in silicic systems, the greater viscosity of the magma leads to a much stronger, and more brittle plug forming at the top of the magma column. The pressure which must build up in the conduit to fracture such a plug is much greater, and leads to a much more explosive eruption known as a Vulcanian eruption. In a Vulcanian eruption, blocks a few meters in size can be ejected as far as 5 km from the vent, and tall plumes up to 20 km in height may form. (Parfitt and Wilson, 2008)

5. Steady Explosive Eruptions

If the bubbles are unable to merge in the manner of a transient eruption, the rising magma will eventually be dominated by a foam consisting of a large number of small bubbles separated from each other by thin liquid films

(Mader 1998). When the gaseous volume fraction reaches a sufficiently large value, the magma fractures, and gas becomes the continuous phase. The vertical level at which this occurs is called the fragmentation level (see Fig. 5). Fracture of the magma allows the gas phase to expand rapidly and accelerate upward, carrying the now-fragmented magma along with it. This scenario leads to a steady explosive eruption, as rising magma continues to fracture, supplying a steady stream of ash and pyroclasts to the vent. Most likely, the fragmentation level is fairly consistent throughout the course of the eruption. This may be inferred by the steady discharge rate typical of Plinian eruptions (Cashman et al., 2000).

The vesicularity (i.e. gaseous volume fraction) necessary for magmatic fracture has been inferred through study of the magmatic fragments, which land on the ground as (basaltic) scoria and (silicic) pumice. Typical vesicularities for scoria are in the range 70 – 85 % (Vergniolle and Mangan, 2000), and typical vesicularities for pumice are in the range 60 – 85 % (Mader, 1998).

There are two main mechanisms by which the magma may fracture. One possibility is that the expansion of the bubbles with rising height causes the films of liquid magma *between* the bubbles to thin, eventually vanishing and allowing the bubbles to merge into a continuous gas phase. Another possibility is that the bubbles stop expanding before the fragmentation level, nevertheless causing the magma to become so brittle that the strain caused by the velocity difference between the rising magma and the conduit walls breaks the magma apart (Mader, 1998).

The plume of gas and fractured magma which exits the vent takes very different forms in the two principal types of steady explosive eruptions, which are Hawaiian fire fountains and Plinian eruptions. Fragments ejected from fire fountains are relatively large (centimeters to meters), are typically projected to heights of several hundred meters, and retain enough fluidity to form lava flows after falling to the ground (Schmincke, 1998). Plinian eruptions, by contrast, produce massive columns of ash and pumice that may reach as high as 40 – 50 km (Rosi et al., 2003; Fisher et al., 1997).

5.1 Why are fire fountains and Plinian eruptions different?

There are a number of ways to connect the differences between fire fountains and Plinian eruptions to the differences between their associated magmas, i.e. basalt and silicic magmas. However, only one of the references I read, Rosi et al. (2003), does this directly. We will discuss this explanation first, and then summarize explanations which may be inferred from other sources.

Rosi et al. point out that bubbles in silicic magma face far greater viscous resistance to expansion than bubbles in basaltic magma. Consequently, a bubble in silicic magma with a pressure far in excess of the surrouding magma may not be able to reduce this pressure through expansion. The fracture of a silicic magma therefore liberates far more gaseous pressure than the fracture of a basaltic magma, leading to much more violent explosions in silicic volcanoes.

Parfitt and Wilson (2008) discuss mechanisms which increase the explosiveness of volatile-rich magmas. First, exsolution tends to occur deeper in the conduit for more volatile-rich magmas. Thus, bubbles in these magmas form at higher pressure, and the gas inside will need to expand more to ultimately reach atmospheric pressure. Moreover, higher gas content causes fragmentation of the magma to occur deeper in the conduit. This reduces the distance the rising material must travel as a highly viscous liquid magma, decreasing the energy lost to friction with the conduit walls and increasing the energy available to drive the explosion. Since the volatile content of silicic magma is much greater than that of basaltic magma, these effects may contribute to the greater explosivity of silicic magmas.

A final reason for the different styles of steady explosive eruption can be inferred by contrasting bubble densities in basaltic scoria and silicic pumice. Typical bubble number densities in scoria are of the order $10^{10}/m^3$, while bubble densities in pumice are in the range $10^{14} – 10^{16}/m^3$ (Cashman et al., 2000). By implication, about-to-fracture silicic magmas will have much greater bubble densities than about-to-fracture basaltic magmas. This means that the liquid films separating bubbles in silicic magmas are thinner than those in basalic magmas, and can be expected to fracture into a finer suspension.

6. Summary

Much of the phenomenology of explosive volcanic eruptions can be explained by the behavior of bubbles formed in volcanic conduits as gases exsolve from the rising magma. In particular, we have seen that transient explosive eruptions, including Strombolian and Vulcanian eruptions, occur when the rising bubbles converge to make a small number of giant bubbles. We have also seen that steady explosive eruptions, including Hawaiian fire fountains and Plinian eruptions, occur when a foam of rising bubbles fails to converge in this manner, leading to fracture of the magma and explosive expansion of a continuous gas phase. Effusive eruption occurs when gas bubbles neither merge nor cause fragmentation of the magma.

REFERENCES CITED

Blackburn, E.A., Wilson, L., and Sparks, R.S.J., 1976. Mechanics and dynamics of Strombolian activity. *Journal of the Geological Society of London*, v. 132, pp. 429 – 440.

Cashman, K.V., Sturtevant, B., Papale, P., and Navon., O., 2000. Magmatic Fragmentation, in Houghton, B., McNutt, S., Rymer H., and Stix J. (eds.) *Encyclopedia of Volcanoes*, Academic Press, San Diego, pp. 421 – 430.

Fisher R.V., Heiken G., Hulen J.B., 1997. *Volcanoes*, Princeton University Press, Princeton, NJ.

Mader, H.M., 1998. Conduit Flow and Fragmentation, in Gilbert, J.S., and Sparks, R.S.J (eds.) *The Physics of Explosive Volcanic Eruptions*, Geological Society, London, pp. 51 – 71.

Papale, P., 2001. Volcanic Conduit Dynamics, in Freundt, A., and Rosi, M. (eds.) *From Magma to Tephra*, Elsevier, New York, pp. 55-89.

Parfitt, E.A., and Wilson, L., 1995. Explosive volcanic eruptions – IX. The transition between Hawaiian-style lava fountaining and Strombolian explosive activity. *Geophysical Journal International*, v. 121, pp. 226-232.

Parfitt, E.A., and Wilson, L., 2008. *Fundamentals of Physical Volcanology*, Blackwell Publishing, Oxford, UK.

Pinkerton, H., Wilson, L., and MacDonald, R., 2002. The transport and eruption of magma from volcanoes: a review. *Contemporary Physics*, v. 43, pp. 197 – 210.

Rosi, M., Papale, P., Lupi, L., and Stoppato, M., 2003. *Volcanoes*, Firefly Books, Buffalo, NY.

Schmincke, H.-U., 1998. *Volcanism*, Springer-Verlag, Berlin.

Vergniole, S., and Mangan, M., 2000. Hawaiian and Strombolian Eruptions, in Houghton, B., McNutt, S., Rymer H., and Stix J. (eds.) *Encyclopedia of Volcanoes*, Academic Press, San Diego, pp. 447 – 461.

Wilson L., and Head, J.W., 1981. Ascent and Eruption of Basaltic Magma on the Earth and Moon. *Journal of Geophysical Research*, v. 86, pp. 2971-3001.

Woods, A. W., 1995. The dynamics of explosive volcanic eruptions. *Reviews of Geophysics*, v. 33, pp. 495-530.

Pictures of volcanoes were taken from websites of the U.S. Geological Survey, http://www.usgs.gov

FIGURE CAPTIONS

Figure 1: Simple schematic of volcanic plumbing. Magma enters the magma chamber from below. A gradual buildup of pressure in the chamber eventually forces the magma to either open a conduit, or begin to rise through an existing conduit. Magma exits the conduit through an exit sometimes called the vent.

Figure 2: Bubble dynamics leading to transient explosive eruptions. As magma rises through the chamber and then conduit, it reaches a *saturation level* where the pressure of the magma equals the equilibrium vapor pressure of the dissolved volatiles. This level may occur either in the chamber or in the conduit. Actual bubble formation does not occur until the magma has risen somewhat higher, reaching the *exsolution level*. As the magma continues to rise, the bubbles merge into progressively larger bubbles, forming in the extreme case a giant bubble which fills the cross-section of the conduit (Vergniolle and Mangan, 2000).

Figure 3: Strombolian eruption. Strombolian eruptions are a type of transient explosive eruption most commonly occuring in basaltic volcanoes. Notice that the lava fragments follow ballistic trajectories which are parabolic in appearance. The picture shown is Stromboli Volcano erupting in December 1969. Picture taken by B. Chouet and downloaded from http://volcanoes.usgs.gov/images/pglossary/strombolian.php.

Figure 4: Vulcanian eruption. Vulcanian eruptions are a type of transient explosive eruption most commonly occuring in silicic volcanoes. The picture shown is Tavurvur Volcano in Papua New Guinea in October 1998. Picture taken by J.W. Ewert and downloaded from http://volcanoes.usgs.gov/images/pglossary/vulcanian.php.

Figure 5: Bubble dynamics leading to steady explosive eruptions. As magma rises through the chamber and then conduit, it reaches a *saturation level* where the pressure of the magma equals the equilibrium vapor pressure of the dissolved volatiles. This level may occur either in the chamber or in the conduit. Actual bubble formation does not occur until the magma has risen somewhat higher, reaching the *exsolution level*. As the magma continues to rise, more bubbles are formed, but the bubbles do not merge significantly, forming a foam of many small bubbles. At the fragmentation level, the foam fractures, releasing gas from the bubbles and allowing the gas to expand explosively. Above the exsolution level, the rising material consists of magmatic fragments entrained in a continuous gas phase. Based on a similar illustration in Papale (2001).

Figure 6: Hawaiian fire fountain. Hawaiian fire fountains are a type of steady explosive eruption most commonly occuring in basaltic volcanoes. The picture shown is Pu`u `O`o erupting in Hawaii on September 19, 1984. Lava fragments are projected from the vent in to a 450 m fountain. Picture taken by C. Heliker and downloaded from http://hvo.wr.usgs.gov/gallery/kilauea/erupt/2553004_caption.html.

Figure 7: Plinian eruption. Plinian eruptions are a type of steady explosive eruption most commonly occuring in silicic volcanoes, characterized by tall columns of ash and pyroclasts. The picture shown is Mt. St. Helens erupting on May 18, 1980. Picture taken by Austin Post and downloaded from http://vulcan.wr.usgs.gov/Volcanoes/MSH/Images/MSH80/framework.html.

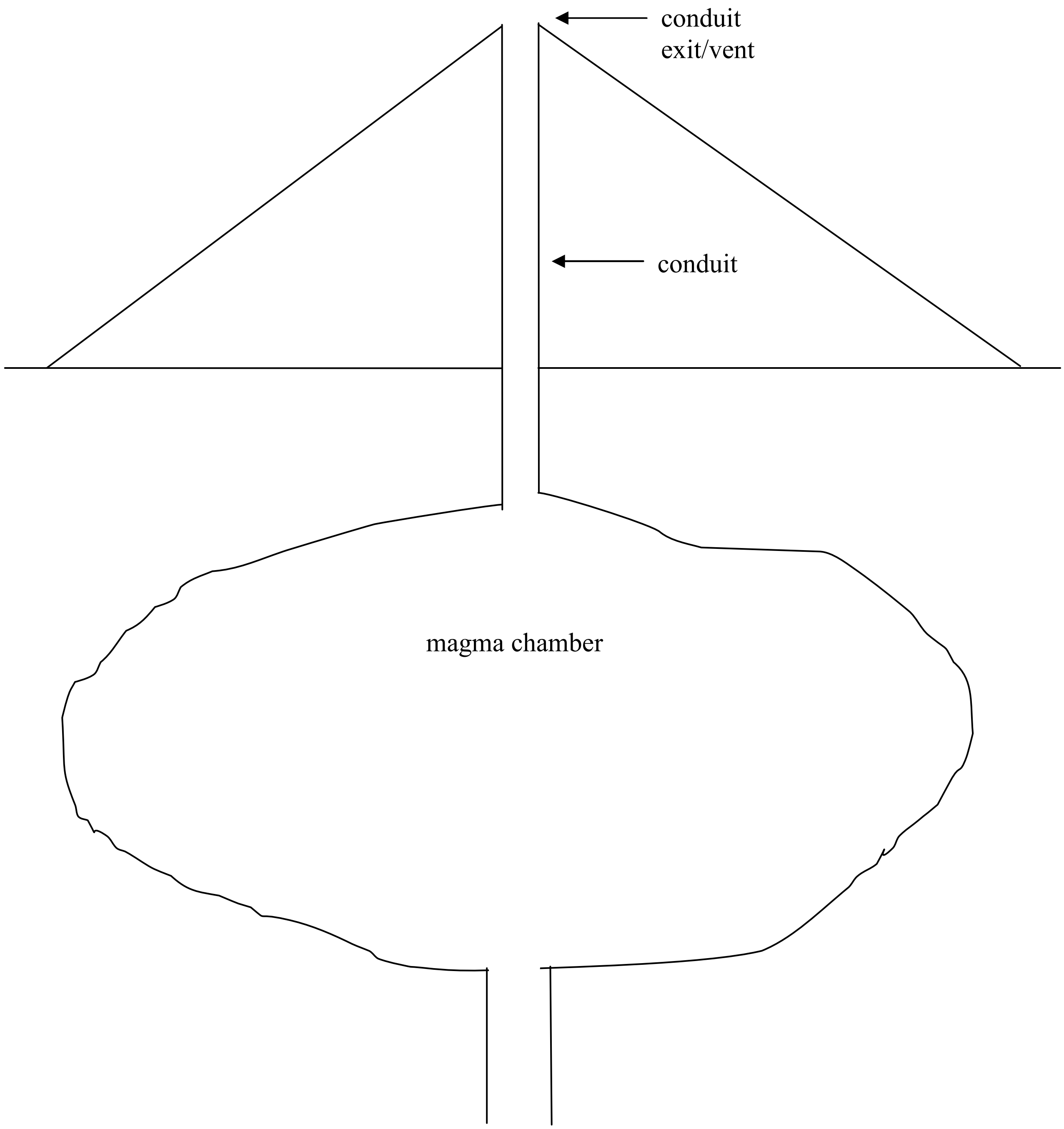

FIGURE 1

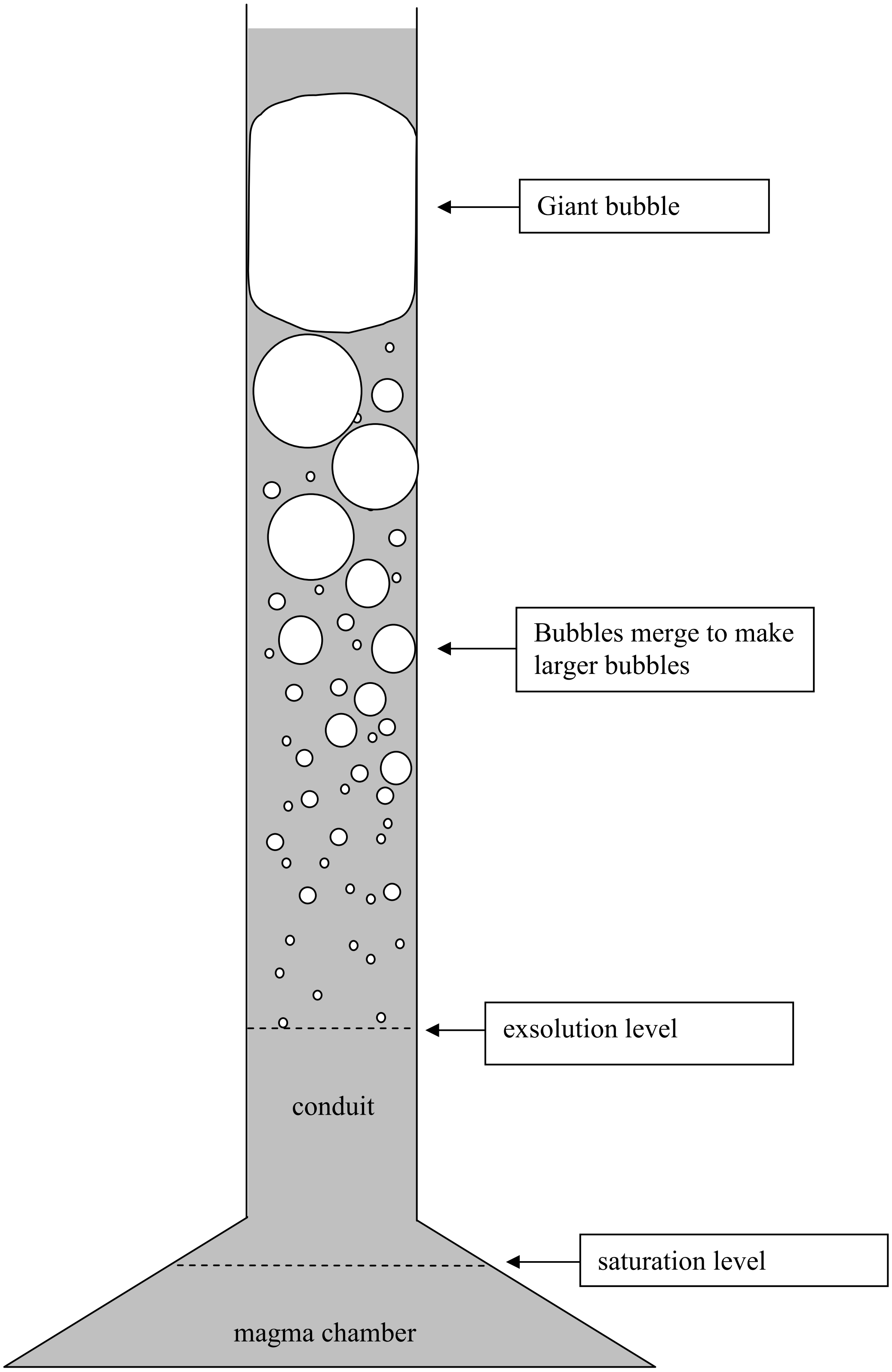
Giant bubble
Bubbles merge to make larger bubbles
exsolution level
conduit
saturation level
magma chamber

FIGURE 2

FIGURE 3

FIGURE 4

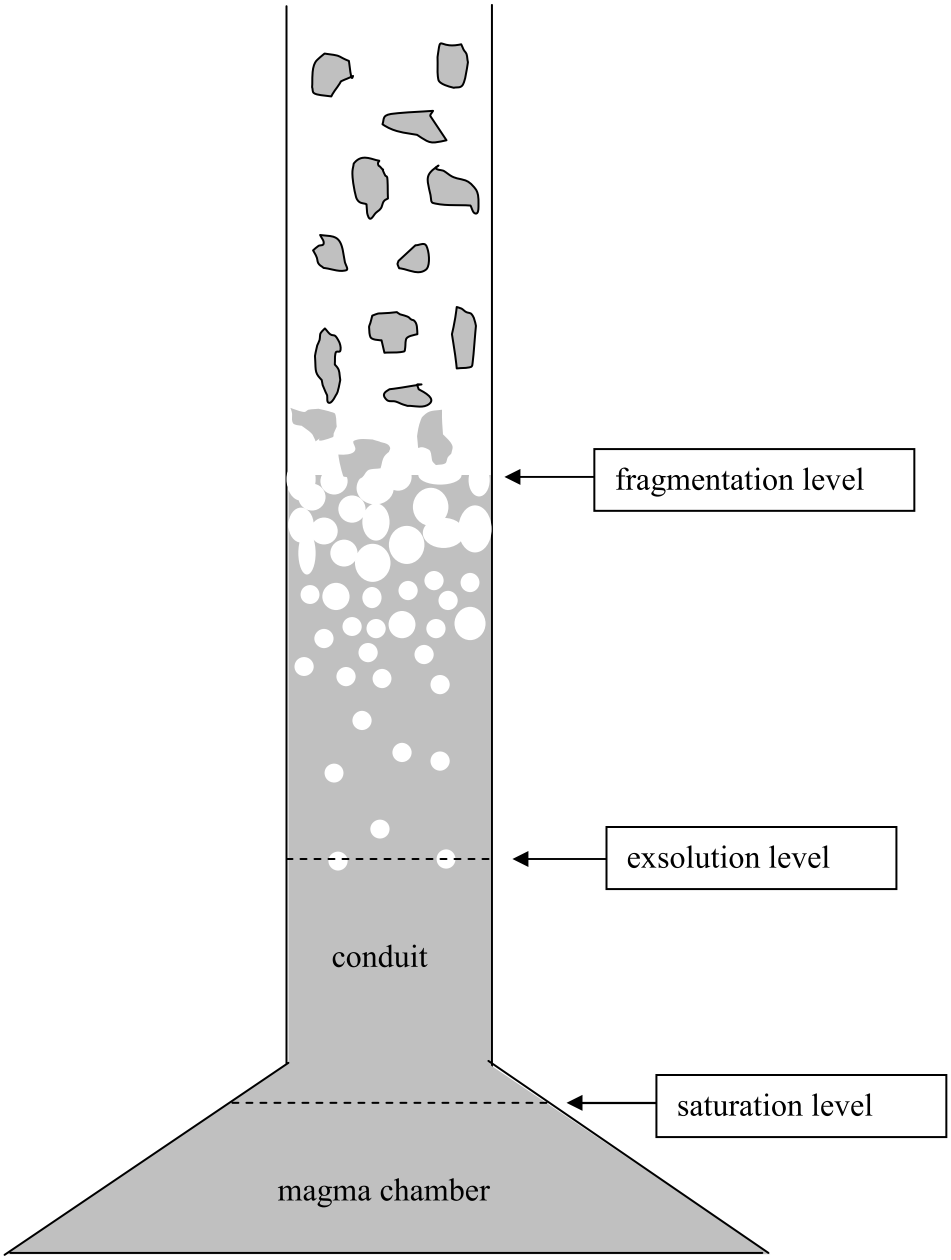
fragmentation level
exsolution level
conduit
saturation level
magma chamber

FIGURE 5

FIGURE 6

FIGURE 7