CIRCULATION OF MAGMA IN THE VOLCANIC CONDUIT AS A MECHANISM FOR PASSIVE DEGASSING AT VOLCÁN POPOCATÉPETL, MÉXICO

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The mechanism by which some volcanoes are able to passively degas large quantities of volatiles while others explode catastrophically is a fundamental question in volcanology. Over the past 5½ years, Volcán Popocatépetl (México) has non-explosively degassed ~14 Mt SO_2 to the troposphere. This compares with the ~17 Mt SO_2 injected into the stratosphere in a single day during the climactic eruption of Pinatubo on June 15, 1991.

The current eruptive phase of Popocatépetl began in December 1994 with elevated levels of degassing, seismicity, and phreatic explosions. Juvenile dacite magma first appeared in the crater in March 1996 as a lava dome. Since unrest began, Popocatépetl has been characterized by continuous, high rates of degassing. This non-explosive degassing activity at Popocatépetl continues to the present. Measurements of SO_2 degassing by correlation spectrometry give emission rates of ~2000 to ~14,000 tons/day SO_2 (Delgado and Cárdenas-G, 1997, CENAPRED, unpubl. data). On rare occasions, SO_2 emissions have reached 30-50,000 tons/day SO_2 (Goff et al., 1998, CENAPRED, unpubl. data). For comparison, Mt. St. Helens (USA) emitted 100-2500 tons/day SO_2 during the dome growth period of 1980-86 (Gerlach and McGee, 1994) and Galeras (Colombia) emitted 20-880 tons/day SO_2 during an explosive and passive degassing phase from December 1992 to March 1993 (Fischer et al., 1994). Only minor eruptive activity accompanies the high rates of passive degassing at Popocatépetl. This minor activity includes: transient Vulcanian-type explosions that eject lithic and juvenile ash and rock debris up to 8 km above the vent; transient ash-poor "exhalations" of volcanic gas; and periodic lava dome growth, subsidence, and explosive destruction.

We analyzed pumices and dome rocks erupted on June 30, 1997 and January 1, 1998 to define the magmatic variables (T, P, X, f_{O_2}, f_{S_2}) relevant to degassing and assess potential sources of volatiles. Evidence for magma mixing is abundant. Hand samples show bands and lenses of light and dark material suggesting the mechanical mixture of magmas of differing composition. Disequilibrium textures and mineralogy include: resorbed olivine (Fo_{90}) in a dacitic to rhyolitic matrix glass, sieve-textured plagioclase, reverse zonation in pyroxene, normal zonation in olivine and chromite, co-existing quartz and olivine, and orthopyroxene reaction rims on olivine. These observations are consistent with other studies that suggest magma mixing is a common process at Popocatépetl (Kolisnik, 1990). Two-pyroxene and Fe-Ti oxide geothermometry as well as thermodynamic modeling using the MELTS algorithm suggest that the erupted magma is the result of variable degrees of mixing of basalt (50 wt.% SiO_2, ~1200 °C) and dacite (64 wt.% SiO_2, ~950 °C). Mixing produced a hot, (~1050-1130 °C) and oxidized (f_{O_2} of ΔNNO = +1.0±0.3 log units) magma. We infer that variations in calculated T and f_{O_2} in the mixed magma reflect variable degrees of mixing and incomplete thermal re-equilibration. Melt inclusions in olivine phenocrysts from the mafic end-member contain 715±1 ppm S

(n=2). Melt inclusions in pyroxene phenocrysts from the silicic end-member contain 79±30 ppm S (n=7). Matrix glass contains 27±11 ppm S (n= 3).

We explore five hypotheses to explain the high rates of degassing that occur at Popocatépetl without explosive eruption: direct degassing from erupted magma, breakdown of sulfur-bearing phases, fumarolic remobilization, shallow degassing of non-erupted magma, and circulation of magma in the volcanic conduit.

Direct degassing from erupted magma is perhaps the most obvious source of volatiles. During the first two years of magmatic activity (1996-97), ~1.5 x 10^7 m^3 of magma was erupted. If we assume triple this amount has been erupted to date (~4.5 x 10^7 m^3) and 60 vol.% melt degasses (i.e. 40 vol.% crystals in the magma), a concentration of ΔS =1100 ppm would need to degas from the melt to produce the amount of SO_2 observed by COPSEC. Matrix glass compositions of recent eruptives of Popocatépetl are dacite to high silica rhyolite (63-77 wt.% SiO_2). Solubility limits for sulfur in dacitic melts at oxygen fugacities similar to Popocatépetl are more than five times too low assuming 100% S-degassing from the melt (Carroll and Rutherford, 1985). The solubility of sulfur in rhyolitic melts is more than eighteen times too low (Gerlach et al., 1996). We estimated the amount of sulfur degassing from recent eruptives of Popocatépetl by measuring the difference in sulfur contents in melt inclusions and matrix glasses (ΔS). For the silicic end-member ΔS=52 ppm and for the mafic end-member ΔS=688 ppm. If we assume equal proportions of the two end-members mix at depth then the measured amount of sulfur degassing is ΔS=370 ppm. This value, combined with the aforementioned volumes of magma erupted will produce ~4½ Mt SO_2 which is less than a third of the ~14 Mt SO_2 total measured by COSPEC over the last 5½ years. Direct degassing from the erupted magma is clearly inadequate to account for the SO_2 emission measured by COSPEC.

Breakdown of sulfur-bearing phases has been suggested as a source of sulfur emissions at other volcanoes (Baker and Rutherford, 1992). The primary sulfur-bearing phases in volcanic rocks include sulfides under reducing conditions and sulfates such as anhydrite under oxidizing conditions. Igneous anhydrite has not been observed in recent eruptives from Popocatépetl either as a phenocryst phase or as inclusions. Sulfides are very rare in these rocks. They occur primarily as small inclusions in pyroxene where they appear to have suffered little (Larocque et al., 2000) to no breakdown. The observed oxidation state of Popocatépetl magma is below the boundary of anhydrite stability and above the stability limit of Fe-rich sulfides. It is possible that this oxidation state was achieved during the mixing process, liberating sulfur according to the mechanism proposed by Kress (1997). There is, however, little petrographic evidence for substantial redox modification during mixing. Breakdown of sulfur-bearing phases is, therefore, an unlikely source for the large quantities of SO_2 emitted by Popocatépetl.

Some sulfur emissions may be derived by fumarolic remobilization of pre-existing sulfur deposits within the volcanic edifice (Garcia, M.O., pers. comm., 1998). Such sulfur deposits may take the form of fumarolic precipitates filling cracks in wall rocks as native sulfur and a variety of other sulfur-bearing minerals. Intrusion of fresh magma could provide the heat necessary to liberate sulfur from these deposits. Native sulfur and other low temperature precipitates may be liberated with relatively modest heating in the presence of oxygen, but many important vein filling minerals will require temperatures of 500 °C or more to liberate their sulfur. Furthermore, a portion of this re-mobilized sulfur can be expected to re-precipitate in the cooler margins of the volcanic edifice. The relative contribution of this mechanism to the total sulfur budget at Popocatepetl is difficult to assess on the basis of available data. Isotopic investigation of evolved sulfur would be very useful in this regard.

Shallow degassing of non-erupted magma is another potential source of the observed SO_2 emission. Using the measured sulfur contents in melt inclusions and matrix glasses from recent eruptives of Popocatépetl and assuming a cylindrical conduit with a radius of 50 m, the volume of magma needed to produce 14 Mt SO_2 would occupy a conduit ~17 km long. Exsolution and transport of volatiles from these depths is unlikely. Alternatively, this same volume of magma would occupy a sphere ~640 m in diameter. A volume of magma this large emplaced into the upper two kilometers of the volcanic edifice where degassing is most efficient would likely cause substantial deformation of the slopes of the volcano. Monitoring of Popocatépetl using precise leveling and GPS have reported little to no deformation of the edifice (Cabral-Cano et al., 1999, CENAPRED, unpubl. data). Though we cannot rule this mechanism out at the present time, it is difficult to imagine a scenario by which sufficient magmatic material is degassed in the shallow crust to produce the observed SO_2 output without the degassed products being observed either in the volcanic output, or through inflation of the volcanic edifice.

We propose an alternative hypothesis to explain the continous, high rates of degassing at Popocatépetl. Substantial quantities of SO_2 could be derived through processing of large quantities of magma, initially stored at depth, brought to shallow levels by circulation of magma in the volcanic conduit followed by permeable, vertical gas flow through the volcanic edifice (Witter and De la Cruz-Reyna, 1998). Kazahaya et al. (1994) were the first to propose convection in a volcanic conduit as a passive degassing mechanism at Izu-Oshima (basaltic) and Sakurajima (andesitic) volcanoes. Kazahaya et al. (1997) extended the hypothesis of conduit convection to the rhyolitic system of Satsuma-Iwojima.

The conceptual model for conduit circulation at Popocatépetl is as follows. Magma ascends to shallow levels through a cylindrical or dike-shaped conduit from a larger magma body at depth. Rising magma obtains its buoyancy from the significant density decrease that is associated with gas exsolution and bubble growth as pressure decreases. At a vesicularity of ~60%, Eichelberger et al. (1986) argue that bubbles become interconnected and the magma becomes a "permeable foam." Permeability development in magma allows expanding gases to travel through an interconnected network of vesicles and escape, leading to foam collapse. Over some vertical interval above the "permeability level" of ~30-60% vesicularity, exsolved magmatic gases travel out of the magma and into presumably highly permeable wall rocks (Jaupart and Allègre, 1991). The relatively dense, degassed magma descends back down into the volcano's plumbing system making room for influx of fresh, low-density, volatile-rich magma. Following magma-gas separation, gases ascend vertically through permeable wall rocks to be emitted from the crater walls or margins of the dome.

The potential for conduit circulation at Popocatépetl is enhanced by several factors. High magmatic temperatures (~1050-1130 °C) reduce magma viscosity and enhance circulation of magma in the volcanic conduit. In addition, the calculated oxygen fugacity ($\Delta NNO = +1.0 \pm 0.3$ log units) is near the solubility minimum for sulfur in dacite leading to early partitioning of this component into the vapor phase. The presence of a low-density, gas phase at depth would serve to further enhance circulation.

The proposed potential sources for Popocatépetl sulfur are not mutually exclusive. The total gas budget at Popo probably involves contributions from many sources. Nevertheless, we suggest that the high and sustained levels of SO_2 output observed at Popocatépetl are most easily accounted for through the mechanism of conduit convection. This mechanism allows the processing of very large volumes of magma without requiring excessive volumes of erupted material or inflation of the volcanic edifice.

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