Exchange between Mafic Enclaves and Host Magma: Case of 1991-1995 Mount Unzen Eruption

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Received: October 18, 2011 / Accepted: November 15, 2012 / Published: November 20, 2012.

Abstract: Recent eruption of Unzen Volcano in 1991-1995 caught attention of scientists all over the world because of disastrous character of previous one in 1792. Intrusion of andesitic magma to the chamber with rhyolitic magma is proposed to be a trigger for these eruptions. T-P-X parameters of two end-member magmas have been estimated several times, but usually estimations are based on phenocrysts assemblages. New results of this research are based on mafic enclaves and groundmass. These results are significant for magma mixing and mingling theory.

Key words: Unzen Volcano, magma mixing, magma mingling, mafic enclaves, X-Ray tomography.

1. Introduction

Unzen Volcano is located behind the volcanic front and Wadati-Benioff zone related to the Phillipine Sea plate subduction (Ref. [1]). So eruption triggers are still under discussion. Unzen Volcano 1991-1995 eruption caught attention because of catastrophic consequences of previous eruption of 1792, when at about 15,000 people were killed [2].

Now almost all works involves magma mingling and mixing mechanism to explain 1991-1995 eruption, but clear systematic evidences of this process are poor or absent.

Nakada et al. [1] proposed mafic enclaves, which are abundant in products of the eruption, to be remnants of intruded mafic magma. Nakada et al. [3] used differences in K2O content between groundmass and bulk rock composition as evidence for external origin of phenocrysts. Sato et al. [4] proposed zoning in phenocrysts as an indicator of magma replenishment events and consequent mixing in volcanic chamber. Also they supposed change in fluid Cl/OH ratio to be a result of mixing. Browne et al. [5] provided some information about texture parameters of enclaves, but they are quiet brief; main topic of this work is Sr/Ba ratios of plagioclase.

Browne et al. [6] applied two-layer model of magma-magma interaction for mount Unzen with layer of mafic magma beneath felsic one, and explained generation of two groups of enclaves: Porphyritic and Equigranular. In this model interaction and matter exchange between enclaves and host magma is omitted.

Main goal of this work is to describe thermodynamic and kinetic features of interaction between small portions of hot mafic magma, encapsulated into relatively cool felsic one. Data about extensive matter exchange between chilled enclave and host magma is presented.

2. Materials and Techniques

Specimens with contacts between mafic enclaves and host rock from 1995 lava dome and 1991 pyroclastic flow were selected among samples, which were collected in field trip in 2007 at Unzen Volcano.

Chemical compositions of minerals were estimated
in thin sections with Jeol JSM-6480LV electron microscope with INCA-Energy 350 microprobe (petrology department of Lomonosov MSU, Russia).

X-Ray MicroCT for three samples was applied (Skyscan 1172, Lomonosov MSU, Russia). Three samples, including drilling core from enclave to host rock, were studied with resolutions of 0.85, 4 and 8.5 microns/voxel.

2.1 Petrological Overview

Host rocks are mainly dacitic, they contain abundant phenocrysts of plagioclase (with fine oscillatory zoning), hornblende, biotite, Fe-Ti oxides, rare quartz. Hornblende and biotite usually surrounded by opacitization rims. Groundmass contains a glass and small crystals of plagioclase, Fe-Ti oxides.

Mafic enclaves are composed of plagioclase, hornblende, Fe-Ti oxides and glass. So, they can be called spessartites. Studied enclaves vary from 1-10 cm in diameter. Porphyric enclaves (according to Browne et al. [6]) were studied to estimate early stages of interaction between host magma and enclaves.

2.2 Texture Features

Intruding of one magma in other magma results in several processes (Ref. [7, 9]). First of all, portion of intruded magma (usually, more mafic and hot) disintegrates into smaller parts, which cool rapidly. Mixing of two magmas is a result of further disintegration, and it can take place only after thermal equilibration [10].

Quenching character of enclaves crystallization may be estimated from CSD (crystal size distribution) plots. Noguchi et al. [11] published CSD data, estimated by Higgins [12] method. CSD was measured directly from X-Ray MicroCT. Results differ for the most small grains less than 11 mkm length, but for larger microlites they are exactly the same (Fig. 1). Such type of CSD curve indicates rapid crystallization of whole mafic enclave. Also a lot of glass (at about 10%) in central parts of enclaves proves quenching of enclaves.

Two types of enclave’s rims can be distinguished:

1) Smooth edges of enclaves have “chilled margins” structures. Major axis of microliths in margin is usually two times smaller, than in central parts;

2) “Chilled margins” near cusps (angular edges) are absent.

Enclaves are assumed to crystallize rapidly during thermal equilibration and form chilled margins. Absence of them near cusps can be explained by processes of fragmentation after cooling.

Confirmation of fragmentation hypothesis can be found in cracks in enclaves (Fig. 2). In some places chilled margin is found broken and host rock groundmass with phenocrysts can be found in cracks. According to these observations, chilled magrin’s microlites form after the enclave formation and before crack formation. It give a direct prove for magma-in-magma heterogeneity.

![Fig. 1 CSD data for mafic enclave from 1995 extrusive dome show rapid crystallization of groundmass. Note, that data from X-Ray MicroCT (this work) and data from thin sections studying are in a good agreement.](image-url)
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2.3 Interaction between Enclave and Host Magma (Matter Exchange)

Crack in Fig. 2 was formed during chilled margin crystallization, because margin covers partially “walls” of crack. Host rock groundmass with relatively large phenocryst penetrated in the crack. Enclave will breakup to smaller xenoliths without textural evidences of mingling, or preserve with host magma material.

Two different types of glass are estimated in enclaves: high-potassium glass usually form amorphous drops in low-potassium. Average compositions of these two types are presented in Table 1. High-potassium glass is proposed to be a result of mafic magma quenching, and low-potassium glass was a captured and quenched host magma melt.

Several gas bubbles are observed near the edge of enclave. Their form show, that they left mafic enclave. It also provides direct evidence for fluid introduction. MicroCT estimated pore volume up to 5-8 vol.% of enclave.

2.3 Influence of Mafic Magma on Host Magma Minerals

Mafic magma intrusion results in several petrographic features of host rock:

1. Biotite opacitization rims are up to 100 mkm thick;
2. Hornblende with absent to very narrow rims;
3. Pyroxene rims around quartz phenocrysts;
4. Absence of quartz microlithes in groundmass.

These features are accounted as a result of sudden change of chamber thermodynamic parameters during magma hybridization processes.

2.4 Thermodynamic Parameters of Magmatic Chamber

Previous investigations provided the following thermodynamic conditions:

1. For host rhyolite magma: 100 ÷ 300 MPa, 775 ÷ 875 °C, 4 ± 1 wt. % H₂O, fO₂ = NNO [13]; 790 ± 20 °C, 160 MPa [14]; 770 °C, 300 - 400 MPa, 7 ÷ 8 wt. % H₂O [15];
2. For intruded andesite magma: 1,050 ± 75 °C, up to 8 wt. % H₂O [13]; 1,030 ÷ 1,130 °C [14]; 1,050 °C [15];
3. For magma after mixing: 870 ÷ 900 °C, 6 ± 1 wt. % H₂O [13]; 850 ÷ 930 °C [14]; 930 °C [15].

The geothermometry data (two pyroxenes by Wells...
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[16], hornblende and plagioclase by Holland et al. [17], Fe-Ti oxides by Andersen et al. [18]) gave 750 ± 850 ºC for host magma, 1,050 ± 1,100 ºC for intruded one and 850 ± 950 ºC for magma after mixing. It is more than 150 ºC, predicted by Browne et al. [6] according to elongation of enclave’s microliths.

2.5 Quantity of Intruded Mafic Magma and Time of Equilibration

According to temperatures before and after mixing, density values by Lange et al. [19], heat capacity values by Leth-Miller [20] and assuming heat influence of mafic magma crystallization to 50 K [10], a simple heat balance equation could be written. Calculation gives 16 vol.% of mafic magma.

Maximum observed size of the enclaves is 20 cm. Time of thermal equilibration had not exceeded 32 hours (according to Plechov [10]).

On the other hand, time of effective interaction can be estimated by altering of host minerals. Following to Plechov [21], time of horblende opacitization in Unzen 1991-1995 magma was not exceeded first days. It can be the result of delay between mafic magma intrusion and 1995 spine growth.

3. Discussion

Calculation of quantity of intruded magma give 16 vol.% of mafic magma. It is much more than is predicted (Ref. [22]). Probably, that not all volume of magma chamber was involved in hybridization processes, so the estimation represents effective mixing volume.

Also host magma could be heated by intruded material before enclave formation. This proposition is consistent with two layers hypothesis.

Chilled margins are supposed to isolate enclave material from host magma, because of their rigidity (Ref. [23]), but two contrast glasses, distributed in enclaves, contradicts it. Angular cusps and crack, described in this work, are the result of crumbling and further fragmentation processes during and after chilled margins formation. Cracks are the effective transport channels for gaseous, liquid and solid phases in both directions.

Effective mechanism of interaction after chilled margin formation is not considered by Browne et al. [6], but it is essentially important for fluid extraction and migration.

4. Conclusions

In the paper, direct evidences for magma chamber replenishment event under Unzen Volcano are provided.

New data about effective matter exchange (gas, liquid and crystals) during and after chilled margin formation is presented. This result make scheme of enclave-host magma interaction much more complicated, and the moment of phenocrysts or melt capturing or gas extraction should be considered as independent parameter. A full 3D analyse should be applied to estimate crack-induced matter exchange.

Acknowledgments

Authors are grateful for important remarks and advices of A.E. Tsay and D.V. Korost.

The authors acknowledge partial support from Lomonosov Moscow State University Program of Development and Russian Foundation for Basic Research (project 12-05-00941-a for P. Plechov).

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