Earth and Planetary Science Letters 460 (2017) 50–59

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Trapped bubbles keep pumice afloat and gas diffusion makes pumice sink

Kristen E. Fauria[a,*], Michael Manga[a], Zihan Wei[a,b]

[a] Department of Earth and Planetary Science, UC Berkeley, 307 McCone Hall, Berkeley, CA 94720-4767, United States
[b] Department of Earth and Space Sciences, Peking University, Beijing, China

ARTICLE INFO

Article history:
Received 14 September 2016
Received in revised form 26 November 2016
Accepted 29 November 2016
Available online xxxx
Editor: T.A. Mather

Keywords:
buoyancy
capillary processes
percolation theory
submarine volcanism
X-ray microtomography

ABSTRACT

Pumice can float on water for months to years – long enough for pumice to travel across oceans and facilitate the spread of species. Long-lived pumice floatation is unexpected, however, because pumice pores are highly connected and water wets volcanic glass. As a result, observations of long floating times have not been reconciled with predictions of rapid sinking. We propose a mechanism to resolve this paradox – the trapping of gas bubbles by water within the pumice. Gas trapping refers to the isolation of gas by water within pore throats such that the gas becomes disconnected from the atmosphere and unable to escape. We use X-ray microtomography to image partially saturated pumice and demonstrate that non-condensable gas trapping occurs in both ambient temperature and hot (500 °C) pumice. Furthermore, we show that the size distribution of trapped gas clusters matches predictions of percolation theory. Finally, we propose that diffusion of trapped gas determines pumice floatation time. Experimental measurements of pumice floatation support a diffusion control on pumice buoyancy and we find that floatation time τ scales as $\tau \propto \frac{L^2}{D\theta^2}$ where L is the characteristic length of pumice, D is the gas–water diffusion coefficient, and θ is pumice water saturation. A mechanistic understanding of pumice floatation is a step towards understanding how pumice is partitioned into floating and sinking components and provides an estimate for the lifetime of pumice rafts in the ocean.

1. Introduction

Pumice is a highly vesicular volcanic rock with a porosity high enough that it can float. Rafts of volcanic pumice can transit lakes and oceans and circle the globe (e.g., Richards, 1958; Risso et al., 2002; Bryan et al., 2004; von Lichtan et al., 2016). For example, pumice from the 1952 eruption of Volcán Barcena on Isla San Benedicto, 600 km west of Mexico, floated for at least 560 days and drifted over 8700 km (Richards, 1958). The 2012 eruption of Havre submarine volcano created a 1.5 km^3 pumice raft that spread over 550,000 km^2 within three months (Carey et al., 2014; Jutzeler et al., 2014). Pumice rafts have been shown to facilitate the dispersal of species such as barnacles, corals, algae, and gastropods (Bryan et al., 2012) because marine organisms grow on, and ocean currents advect, pumice (Richards, 1958; Jokiel, 1984; Bryan et al., 2004). While pumice rafts are relatively common and it is well known that ambient temperature pumice can float for long periods of time, the enduring buoyancy of pumice is surprising because pumice pores are almost entirely connected and water wets pumice (Whitham and Sparks, 1986; Vella and Huppert, 2007). Quantitative models for pumice saturation predict that ambient temperature pumice should sink orders of magnitude more rapidly than is observed (Vella and Huppert, 2007). The floatation time discrepancy between observations and the Vella and Huppert (2007) model suggests that simple gas displacement by an infiltrating water front is not sufficient to explain why ambient temperature pumice can float for years.

By comparison to ambient temperature pumice, hot pumice (e.g., >300 °C) sinks almost immediately and the tendency for air-filled pumice to sink increases with pumice temperature (Whitham and Sparks, 1986; Dufek et al., 2007; Allen et al., 2008; Jutzeler et al., 2016). Rapid water ingestion by hot pumice has been attributed to cooling-induced gas contraction (Whitham and Sparks, 1986; Cashman and Fiske, 1991; Allen et al., 2008) and hydrodynamic instabilities due to steam generation (Dufek et al., 2007). Air-filled hot pumice placed in water does not, however, completely saturate even at high (500 °C) temperatures (Allen et al., 2008). As a result, we wish to understand how gas remains within initially hot pumice and what differences and similarities exist between saturation of ambient temperature and hot non-condensable gas filled pumice.

---

[*] Corresponding author.
E-mail address: kfauria@berkeley.edu (K.E. Fauria).

http://dx.doi.org/10.1016/j.epsl.2016.11.055
0012-821X/

Notation

v	velocity	p	volume–area coefficient
μ	dynamic viscosity	τ	pumice floatation timescale
γ	surface tension	D_{eff}	effective diffusion coefficient
ρ	density	θ	water saturation
g	gravity	D	liquid–gas diffusion coefficient
κ	permeability	d	mean pore throat diameter
ϕ	connected porosity	P	pressure
h	height	R	pore throat radius
V_w	volume of water absorbed	T	temperature
t	time	L_w	glass wall thickness
S_a	pumice surface area	D_w	water thermal diffusivity
n	number of occurrences	T_i	initial temperature
s	sites or pores	T_f	final temperature
β	power law coefficient	V_i	initial volume
a	spatial dimension	V_f	final volume
f	fractal dimension a cluster	ξ	gas saturation
s_{max}	maximum size of a trapped gas cluster	ξ_i	initial gas saturation
L	pumice diameter	ξ^*	neutral buoyancy gas saturation
A	surface area of trapped gas clusters	ρ_r	glass density
V	trapped gas volume	ρ_l	liquid density

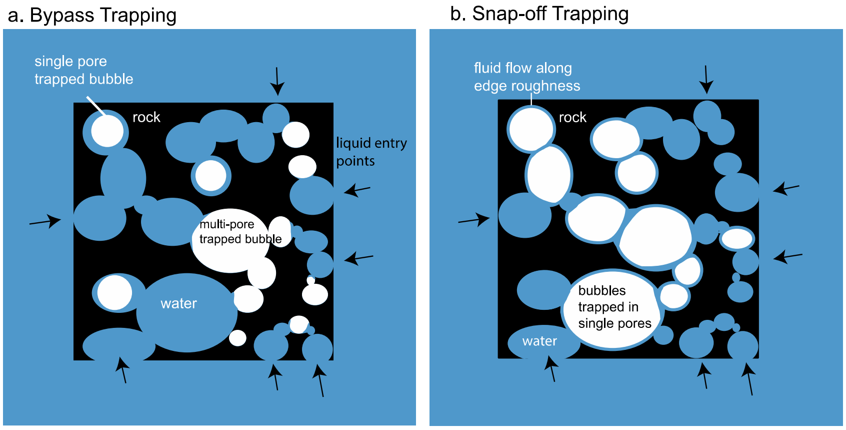

Fig. 1. Mechanisms of gas trapping. Illustrations of gas trapping by (a) bypass and (b) snap-off trapping in pumice with connected pores. In both cases capillary forces draw water into pores such that water completely surrounds the gas phase and the gas is unable to escape.

Pumice, with porosities of 50 to >90 percent, is a porous medium. Water saturation of pumice is an example of two-phase flow in porous media and requires the replacement of a defending fluid (air or magmatic gases) with an invading fluid (liquid water). Two-phase flow in porous media has been widely studied in the context of the vadose zone, oil recovery, CO_2 sequestration, and gas sparging. In addition, water infiltration of pumice is a manifestation of a particular type of two-phase flow, imbibition, because water is the wetting phase. During imbibition the arrangement of fluid, or wetting pattern, can range from one where nearly all the pores are filled with the invading fluid to one where the defending fluid remains trapped in clusters (e.g., Lenormand and Zarcone, 1984). Trapped gas clusters (Fig. 1), pockets of non-wetting fluid that are surrounded by the wetting fluid, are not only characteristic of two-phase flow in porous media but are very difficult to mobilize because of surface tension. Indeed, gas trapping is a mechanism employed for long term CO_2 sequestration (e.g., Ide et al., 2007; Benson and Cole, 2008).

We hypothesize that pumice floats for long periods of time because of the occurrence of gas trapping (either air or non-condensable magmatic gases) in isolated gas clusters during water infiltration. We use X-ray microtomography to test the hypotheses that gas trapping occurs in both hot and ambient temperature pumice, that gas trapping can result in a high enough residual gas saturations to keep pumice afloat, and that percolation theory can describe gas trapping in pumice. While trapped gas may buoy pumice, we hypothesize that the outward diffusion of gas trapped in bubbles eventually causes pumice to sink. We test this gas diffusion hypothesis by conducting experiments where we measure the floatation time of dry and ambient temperature pumice on artificial seawater in a controlled laboratory setting. We then compare our results and pumice floatation times from four other studies with a prediction for pumice floatation time based on gas-diffusion out of a porous medium.

1.1. Gas trapping in porous media

Gas trapping has been observed in experiments, dictates wetting patterns, and controls residual non-wetting saturation of porous media (e.g., Blunt and Scher, 1995; Iglauer et al., 2013; Geistlinger and Mohammadian, 2015). A key element that promotes gas trapping is the slow advance of the invading fluid such that capillary forces dominate over viscous forces. In other words, the Capillary number

$$\mathrm{Ca} = \frac{v\mu}{\gamma}, \quad (1)$$