Earth and Planetary Science Letters 312 (2011) 401–410

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Fluid dynamics in explosive volcanic vents and craters

Darcy Ogden *

Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive MC 0225, La Jolla, CA 92092-0225, United States

ARTICLE INFO

Article history:
Received 28 April 2011
Received in revised form 17 October 2011
Accepted 18 October 2011
Available online 22 November 2011

Editor: Y. Ricard

Keywords:
explosive eruptions
volcanic vent
crater
numerical simulations
overpressure
jet

ABSTRACT

Explosive volcanic jets can transition to buoyant plumes or collapse to form pyroclastic density currents depending on their ability to entrain and heat the ambient air. Recent one-dimensional (1D) analysis shows that fluid acceleration through volcanic vents and craters changes the velocity and pressures within these jets sufficiently enough to be a first order control on plume dimensions and therefore air entrainment and column stability (Koyaguchi et al., 2010). These 1D studies are only applicable to craters and vents with angles of less than about 30° to vertical. Using analytical formulations and numerical simulations, this study describes 2D effects of shallowly dipping vents and craters on volcanic eruptions. The effect of vents on acceleration and expansion of eruptive mixtures of ash and gas is described as a force imparted on the fluid by the vent wall, the wall force (F_w). This force is a measure of the momentum coupling between an eruption and the solid earth that takes place in the vent. Rapid divergence of supersonic eruptive fluid within shallowly dipping vents occurs via Prandtl–Meyer expansion, which results in different pressure and velocity fields than those predicted by 1D analysis. This expansion decreases F_w and the vertical acceleration experienced by the eruptive fluid in the vent. For jets predicted by 1D analysis to exit the vent at supersonic velocities and at atmospheric pressure, this decrease in F_w will cause an increase in the predicted plume area, decreasing column stability. The complex 2D shape of volcanic vents can change jet structure (presence and location of shock waves) and preclude the development of jets that exit the vent supersonically with no internal standing shock waves (i.e., perfectly expanded or pressure balanced jets). These significant complications in jet structure and increase in plume radius may result in changes to air entrainment, plume stability, and tephra distribution.

1. Introduction

The stability and structure of explosive eruption columns are complex phenomena dependent on a number of important factors. Eruption columns enter the atmosphere as negatively buoyant jets. One-dimensional (1D) treatments of eruption dynamics show that these inertially driven columns (volcanic jets) can transition to buoyantly rising plumes with sufficient entrainment, heating, and expansion of ambient air. Alternatively, if the jet is unable to entrain and heat enough air, it forms a collapsing fountain and pyroclastic density currents (Sparks and Wilson, 1976). These 1D predictions are largely dependent on the mass eruption rate, mixing dynamics between the rising column and the atmosphere, and the initial radius of the column after entering the atmosphere.

Mass eruption rate influences eruption column behavior by controlling the amount of thermal energy available to heat the ambient air, the kinetic energy available for mixing, and the tephra mass that must be supported by buoyancy forces. Eruption rate is primarily dependent on the geometry of the conduit through which the magma erupts and the mass fraction of volatiles contained in the magma–gas mixture (Bower and Woods, 1997; Papale et al., 1998; Wilson et al., 1980). Volatile composition is a function of the chemical composition of the magma, the thermodynamic state of the magma before eruption, and the degassing history of the magma. Changing the mass fraction of volatiles influences both the density of the eruptive ash–gas mixture and its sound speed, which determines the maximum velocity reached within a narrowing or constant diameter conduit (Bercovici and Michaut, 2010; Kieffer and Sturtevant, 1984).

Upon entering the atmosphere, the behavior of the ash–gas mixture is influenced by the dynamics controlling the rate at which air is entrained into the column. Largely, this rate is controlled by the jet velocity and the area available for entrainment at the boundary, i.e., the initial column radius. Several studies, however, demonstrate that a host of other factors also influences the rate at which air mixes with the eruptive ash–gas jet. The density of the flow relative to the ambient atmosphere has recently been shown to produce results different than those predicted by neutrally buoyant self-similar laboratory jets (Carazzo et al., 2006; Kaminski et al., 2005; Suzuki et al., 2005). Atmospheric conditions and wind have been shown to change eruption column dynamics (Mastin, 2007; Tupper et al.,

* Tel.: +1 858 534 7386; fax: +1 858 534 5332.
E-mail address: dogden@ucsd.edu.

0012-821X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2011.10.032

2009). Several models and numerical simulations have demonstrated the influence of tephra particulate size and loading on air entrainment and column stability (e.g., Bercovici and Michaut, 2010; Dartevelle et al., 2004; Dufek and Bergantz, 2005; Neri and Dobran, 1994).

Initial column radius is controlled by both the eruption rate and the degree of decompression that takes place in the vent and the atmosphere before significant air entrainment has begun. 1D models demonstrate how volcanic vents can change eruptive style by influencing decompression of the ash–gas mixture as it moves from the high pressure conduit to the atmosphere (Koyaguchi et al., 2010; Woods and Bower, 1995). Vent effects on volcanic jet expansion are shown to be a first order control on eruptive column stability, comparable in magnitude to the effects of volatile content (Koyaguchi et al., 2010). The low sound speed (c) (Table 1) in explosive volcanic eruptions enables eruptive mixtures to emerge from some vents at pressures that are greater than or less than local atmospheric pressure and velocities (u) that are greater than the fluid sound speed (i.e. supersonic flow, Mach numbers, $M = u/c > 1$). These imperfectly expanded jets must undergo further expansion or compression through a series of interior shock waves and rarefaction fans in the gas-thrust region before reaching atmospheric pressure and becoming well mixed (Chapman, 2000). Expansion or compression downstream of the vent changes the radius of the erupting plume. This change in radius changes the magnitude of entrainment that takes place in the plume, changing its stability. The vent therefore plays a key role in eruptive dynamics because it, along with conduit conditions, controls the degree of pressure mismatch that can occur at the vent exit, which in turn controls the fully expanded plume radius, air entrainment, and column stability (Koyaguchi et al., 2010; Woods and Bower, 1995).

Although 1D models have demonstrated the importance of volcanic vents on plume stability, their application is limited to steeply dipping vents with angles of less than about 30° to vertical and minimal curvature. The effects of many natural vents are therefore excluded from 1D analysis. In supersonic vent flow, 2D flow structures can have a significant influence on the overall effect of vents on the eruptive mixture. This study examines the effect of vents with shallowly dipping walls on perfectly expanded volcanic jets.

Table 1
Notation.

Symbol	Definition
P	Pressure
c	Sound speed
u	Fluid velocity
M	Mach Number (c/u)
Γ	Isentropic expansion coefficient for a pseudogas
γ	Isentropic expansion coefficient for an ideal gas
A	Area of vent or conduit
r	Radius
ρ	Fluid density
K	Overpressure ratio P/P_a
θ	Vent angle measured from vertical
F	Force from static pressure
F_w	Vent wall force
C_P	Heat capacity at constant pressure
C_V	Heat capacity at constant volume
C_s	Heat capacity of a solid
n	Volatile mass fraction
R	Specific gas constant for an ideal gas or pseudogas
Modifier	
*	At the throat or choke point
v	At the vent exit
p	Plume conditions near vent after equilibration to P_a
a	Ambient atmospheric conditions
in	Plumeria input parameter
1	Upstream
2	Downstream
'	Exit condition for perfect expansion predicted by 1D solution

2. Vent wall force and supersonic flow divergence

The effect of volcanic vents on the expansion of eruptive mixtures of ash and gas can be described by the vertical momentum balance for a control volume drawn over the vent and partway into the gas-thrust region for steady flow (Fig. 1). This approach remains valid when shock waves are present in the volume interior. The volume is defined by the jet boundary along the vent wall ($_w$), the jet boundary with the atmosphere ($_a$), a cross section through the jet located where the eruptive gas has reached atmospheric pressure ($_p$), and a cross section at the bottom of the vent, which is defined as the area minimum (or choke point) at the top of the conduit and base of the vent (*), see Fig. 1. For this simple analysis treatment of body and frictional forces are neglected. Air entrainment along the jet boundary is assumed to be negligible.

Conservation of momentum in the vertical direction across this control volume is

$$\rho_p u_p^2 A_p - \rho^* u^{*2} A^* = F^* - F_p + F_a + F_w \tag{1}$$

Momentum at the top and bottom of the control volume is represented by the product of the eruptive fluid density (ρ), vertical velocity (u) squared, and the cross sectional area (A) at each location. The forces (F) acting on the volume are the static pressure forces acting at the top (F_p) and bottom (F^*) of the volume, on the jet boundary with the air (F_a) and along the vent walls (F_w). F_p and F^* are expressed as the product of the pressure (P) and A on each surface. F_a is approximated by $P_a(A_p - A_v)$ where P_a is atmospheric pressure and A_p and A_v are the area of the plume when it fully reaches atmospheric pressure and the area of the vent top, respectively (Woods and Bower, 1995; Yuceil and Otugen, 2002). The pressure at the bottom of the vent, the choke pressure (P^*), is a function of upstream conduit dynamics which are beyond the scope of this paper. Here it is treated as a fixed value, the product of P_a and the non-dimensional choke overpressure ($K^* = P^*/P_a$).

The eruptive ash–gas mixture has a high heat capacity (relative to a pure gas), and its isentropic expansion coefficient is very close to 1 due to its ash content. Temperature can be approximated as constant,

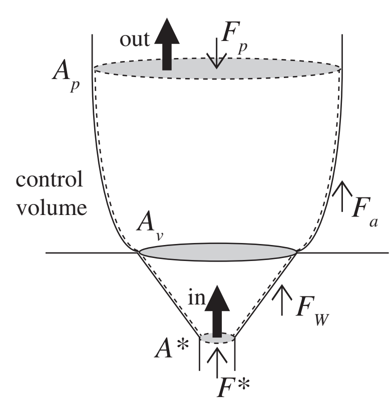

Fig. 1. Vertical momentum balance in a volcanic vent. A control volume is sketched across a schematic volcanic vent and into the gas-thrust region. Eruptive fluid flows in through the bottom, located at the base of the vent (top of the conduit). Fluid flows out only through the top of the volume, which is considered to be the height at which the eruptive fluid has reached atmospheric pressure. The sides of the control volume are drawn where the fluid intersects the vent wall and along the plume boundary. F indicates the forces acting on the boundaries from the static pressure at these locations. Body and frictional forces are neglected. A indicates cross sectional areas (shaded regions) at the top of the control volume ($_p$), vent exit ($_v$), and base of the vent (*).