Originally published as:

Galland, O., Gisler, G. R., Haug, Ø. T. (2014): Morphology and dynamics of explosive vents through cohesive rock formations. - *Journal of Geophysical Research*, 119, 6, p. 4708-4728.

DOI: <http://doi.org/10.1002/2014JB011050>

RESEARCH ARTICLE

10.1002/2014JB011050

Key Points:

- Integrated laboratory and numerical modeling of explosive vents
- Phase diagram highlights the key parameters governing explosive vents
- Circular pipes result from plasticity-dominated yielding of rocks

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Citation:

Galland, O., G. R. Gisler, and Ø. T. Haug (2014), Morphology and dynamics of explosive vents through cohesive rock formations, *J. Geophys. Res. Solid Earth*, 119, 4708–4728, doi:10.1002/2014JB011050.

Received 19 FEB 2014

Accepted 3 JUN 2014

Accepted article online 7 JUN 2014

Published online 26 JUN 2014

Morphology and dynamics of explosive vents through cohesive rock formations

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Abstract Shallow explosive volcanic processes, such as kimberlite volcanism and phreatomagmatic and phreatic activity, produce volcanic vents exhibiting a wide variety of morphologies, including vertical pipes and V-shaped vents. In this study we report on experimental and numerical models designed to capture a range of vent morphologies in an eruptive system. Using dimensional analysis, we identified key governing dimensionless parameters, in particular the gravitational stress-to-fluid pressure ratio ($\Pi_2 = P/\rho gh$) and the fluid pressure-to-host rock strength ratio ($\Pi_3 = P/C$). We used combined experimental and numerical models to test the effects of these parameters. The experiments were used to test the effect of Π_2 on vent morphology and dynamics. A phase diagram demonstrates a separation between two distinct morphologies, with vertical structures occurring at high values of Π_2 and diagonal ones at low values of Π_2 . The numerical simulations were used to test the effect of Π_3 on vent morphology and dynamics. In the numerical models we see three distinct morphologies: vertical pipes are produced at high values of Π_3 , diagonal pipes at low values of Π_3 , and horizontal sills at intermediate values of Π_3 . Our results show that vertical pipes form by plasticity-dominated yielding in high-energy systems (high Π_2 and Π_3), whereas diagonal and horizontal vents dominantly form by fracturing in lower energy systems (low Π_2 and Π_3). Although our models are two-dimensional, they suggest that circular pipes result from plastic yielding of the host rock in a high-energy regime, whereas V-shaped volcanic vents result from fracturing of the host rock in lower energy systems.

1. Introduction

Explosive venting of high-pressure fluids through the Earth's crust leads to the formation of explosive vents through solid rocks [e.g., Grunewald *et al.*, 2007; Lorenz and Kurszlaukis, 2007; Nermoen *et al.*, 2010; White and Ross, 2011]. It occurs as a consequence of fast fluid pressure buildup, leading to underground explosions that blast the overlying rock formations [e.g., Gisler, 2009]. This phenomenon occurs in many geological settings and at various scales, and the fluids responsible for the rapid pressure buildup can have several origins: magmatic [Hawthorne, 1975; Sparks *et al.*, 2006; Gernon *et al.*, 2009], phreatomagmatic [Lorenz and Kurszlaukis, 2007; White and Ross, 2011; Valentine and White, 2012], and phreatic [Svensen *et al.*, 2006].

Magmatic explosive vents result from the rapid volatile exsolution of a rising volatile-rich magma. A good example is kimberlite magma, leading to kimberlite pipes (Figure 1) [e.g., Hawthorne, 1975; Sparks *et al.*, 2006]. In both phreatomagmatic and phreatic explosions, the pressure buildup is due to rapid vaporization of water (or ice) in direct or thermal contact with a nearby heat source, e.g., magma; the vaporization of water results in sudden volume increase, resulting in pressures that are high enough to pulverize rocks [e.g., Zimanowski *et al.*, 1991; Jamtveit *et al.*, 2004; White and Ross, 2011]. The main difference between these two latter types of explosions relates to the nature of the material filling the vents, i.e., magma and country rock for phreatomagmatic explosions and dominantly country rock for phreatic explosions. Good examples of phreatomagmatic vents are maar-diatremes [e.g., Lorenz and Kurszlaukis, 2007; White and Ross, 2011; Valentine and White, 2012]. Good examples of phreatic vents are hydrothermal vent complexes as described in, e.g., the Karoo Basin, South Africa, and resulting from the heating of fluids in sedimentary rocks by nearby sills [Jamtveit *et al.*, 2004; Svensen *et al.*, 2006; Aarnes *et al.*, 2012].

Despite their common occurrence, the mechanics of explosive vent structures is still unclear. So far, most studies on explosive eruption dynamics have focused on the processes within existing magmatic conduits, i.e., magma degassing and fragmentation, assuming that the walls were infinitely rigid [Melnik *et al.*, 2005; Starostin *et al.*, 2005; Dellino *et al.*, 2007]. While theoretical studies started considering the effect of the elastic

Figure 1. Geological examples of explosive vents in various geological settings. (a) Aerial photograph of the caldera of Mount Pinatubo, Philippines, which formed during the climactic eruption of June 1991. (b) Schematic drawing of maar-diatreme systems. The vents exhibit a conical shape opened toward the surface. (c) Photograph of the Big Hole, Kimberley, South Africa, corresponding to a mined kimberlite pipe. The excavated part highlights the subvertical structure of the pipe. (d) Geological cross section of the Wittkop III hydrothermal vent complex, Karoo Basin, South Africa [after Svensen *et al.*, 2006]. This figure shows an open conical crater at shallow level and a subvertical pipe at deeper levels. (e) Seismic profile illustrating the relationships between magmatic sills and hydrothermal vent complexes in the north central Vøring Basin, offshore Norway [after Jamtveit *et al.*, 2004]. Hydrothermal vents form from subvertical conduits rooted at the tips of sills. They pierce through several kilometers of sediments.

Figure 2. Sketch illustrating the typical geometrical and mechanical characteristics of explosive vents (modified after Nermoen *et al.* [2010]). The parameters indicated in this figure are those used in the dimensional analysis.

walls of magma conduits on volcanic eruptions, they assume that plastic or viscous behaviors do not play a role [e.g., Costa *et al.*, 2007]. Hence, these studies were not suitable for unraveling the formation of explosive vents.

Laboratory studies have been used to investigate the formation of explosive vents through loose material (sand or soil) [e.g., Woolsey *et al.*, 1975; Ross *et al.*, 2008a; Gernon *et al.*, 2009; Nermoen *et al.*, 2010]. In these experiments, explosive venting occurred by fluidization, due to the cohesionless properties of the model material. Natural rocks, however, exhibit substantial cohesion and elastic properties, which suggests that fluidization might not be the main mechanism controlling the formation of explosive vents. Conversely, fluid-induced deformation structures in cohesive and elastic rocks are expected to be planar fractures, like dikes or veins [e.g., Lister and Kerr, 1991; Rubin, 1995; Abdelmalak *et al.*, 2012; Galland, 2012], which is incompatible with the axisymmetrical pipe shapes of most explosive vents in nature

(Figure 1). This suggests that explosive venting does not result from fracturing either. Hence, the key question is as follows: what are the mechanisms governing the formation of explosive vents?

In nature, magmatic, phreatomagmatic, and phreatic explosive vents are classically considered as distinct geological systems because both (i) the origins of the fluids leading to rapid pressure buildup and (ii) the nature of the fragmented and resulting infilling material are different. Nevertheless, kimberlite pipes, maar-diatreme systems, and hydrothermal vent complexes exhibit very similar structures [e.g., Nermoen *et al.*, 2010]. This similarity suggests that their formation may be governed by very similar physical processes, despite their distinct geological signatures.

In this paper, we integrate results from laboratory experiments and numerical simulations to address the dynamics of explosive vents resulting from a single-explosion event. The experimental models aim to simulate phreatic and phreatomagmatic explosive vents, whereas the numerical models aim to simulate magmatic explosive vents. Using dimensional analysis, we identify the key dimensionless parameters governing the dynamics of explosive vents and test their effects by running systematic laboratory experiments and numerical simulations. Finally, we compare the “phreatic” and “magmatic” explosive vent models and discuss their similarities.

2. Dimensional Analysis

Before running laboratory experiments and numerical simulations, it is important to establish a strategy, i.e., to identify which physical parameters are relevant and which ones can be tested. Establishing this strategy requires dimensional analysis of the physical system to be simulated. Dimensional analysis is a powerful tool to identify the relevant physical governing parameters of the system we are addressing. The principle is to define selected dimensionless numbers, which characterize the geometry, the kinematics, and the kinetics of the simulated processes. The dimensional analysis procedure is described in detail by Barenblatt [2003] and used, for example, by Merle and Borgia [1996], Galland [2012], and Galland *et al.* [2014].

The systems we are focusing on correspond to explosive venting due to a sudden pressure buildup induced by, e.g., vaporization of water in magma intrusion host rock (in experiments) or rapid degassing of volatile-rich magma (in simulations). In both our experiments and nature, the geometrical input parameters are the depth (h) of the pressure buildup, or the depth of the volcanic vent, and the diameter (d) of the pressure buildup source or of the vent (Figure 2). This size might correspond to the thickness of a dike tip or of a magma conduit intruding into water-rich country rock. In both simulations and experiments, the common known rock property is the density (ρ_r). In experiments, the mechanical behavior of the rock is characterized by its angle of internal friction (Φ) and cohesion (C). In the simulations, the mechanical behavior of the country rock is controlled by its yield stress (Y) and shear modulus (G). Note that the yield stress in the simulations is the strict equivalent to the cohesion in the experiments [Jaeger *et al.*, 2007]. However, Φ in experiments has no equivalent in the simulations and likewise G in the simulations has no equivalent in the

Table 1. List of Parameters Used for the Dimensional Analysis^a

	Experiments	Simulations	Nature
Values			
h (m)	0.01–0.13	1,000	10–3,000
d (m)	0.002	60	1–20
ρ_r (kg m ⁻³)	1,050	2,700	2,500–2,900
C (Pa)	350	30×10^6 to 100×10^6	10^6 – 10^8
g (m s ⁻²)	9.81	9.81	9.81
P (Pa)	5,000–120,000	80×10^6 to 360×10^6	4×10^7 – 10^{10}
Dimensionless numbers			
Π_1	5–65	16.7	0.5–3,000
Π_2	10–770	1.8–8	0.5 – 4×10^4
Π_3	14–343	0.8–12	0.4–1,000

^aSee Tables 2 and 3 for experimental and numerical parameters.

experiments. Given that (1) the range of values of Φ in natural rocks and granular materials is narrow and (2) G is constant in the simulations, we will not consider them further in the dimensional analysis. Another controlled input parameter is the gas overpressure (P). An external parameter, identical in both systems, is gravity (g).

We thus consider h , d , ρ_r , Y (or C), P , and g for the dimensional analysis. Among this list of six relevant parameters, three have independent dimensions. According to the Buckingham Π -theorem [Barenblatt, 2003], six variables minus three with independent dimensions lead to three independent dimensionless numbers that characterize the physical system.

At first, let us consider the geometric depth-to-size (lateral extent) ratio of the pressure source:

$$\Pi_1 = h/d. \quad (1)$$

Nermon et al. [2010] demonstrated that this geometrical ratio plays a governing role on the onset of venting. In nature, considering 1 to 20 m thick dikes intruding into water-rich rocks at depth (3000 m) or at very shallow level (10 m) [Lorenz and Kurszlaukis, 2007], Π_1 ranges between 0.5 and 3000 (Table 1). Overall, the values of Π_1 are mostly $<<1$.

We also define a dimensionless parameter that accounts for the gravitational forces with respect to the magma pressure:

$$\Pi_2 = \frac{P}{\rho_r g h}. \quad (2)$$

The values of Π_2 express whether the system is gravity dominated ($\Pi_2 << 1$) or pressure dominated ($\Pi_2 >> 1$). In natural systems, an average density for natural rocks is about 2500 kg m^{-3} , but it can reach 2700 to 2900 kg m^{-3} if the overburden consist of magmatic rocks. In natural systems, thermodynamic calculations predict that rapid vaporization of water in contact with hot magma has an explosive specific energy of $\sim 1000 \text{ kJ kg}^{-1}$, corresponding to pressures up to 1 GPa [Gisler, 2009; Thiéry and Mercury, 2009]. Considering that phreatic and phreatomagmatic explosions can occur typically between 10 and 1000 m depth yields values of Π_2 ranging from 0.5 to 4×10^4 (Table 1), meaning that explosive venting in nature is mostly pressure dominated, except for deep explosions.

Another dimensionless number is the ratio of the cohesion to the input pressure:

$$\Pi_3 = \frac{P}{C}. \quad (3)$$

This ratio scales the applied pressure with respect to the strength of the rock through which the vent forms and expresses whether the system is strength dominated ($\Pi_3 << 1$) or pressure dominated ($\Pi_3 >> 1$). The typical cohesions of natural rocks are between 10^6 and 10^8 Pa [Schellart, 2000]. Π_3 therefore ranges from 10^3 to 0.4 (Table 1), meaning that geological systems range from pressure-dominated regimes to regimes in which pressure is equivalent to cohesion forces.

Figure 3. Drawing of the experimental setup, consisting of a Hele-Shaw cell filled with compacted silica flour [Haug et al., 2013]. Pressurized air is injected through an inlet within the flour from a pressure tank of finite volume. A high-speed camera (4 kHz) monitors the development.

The aim of our study is to quantify the physical effects of the dimensionless parameters identified in the dimensional analysis on the explosive venting processes related to phreatic and phreatomagmatic systems (experiments) and magmatic systems (numerical simulations). Because it is easy to change the geometry of the system and the input pressure, we will test the physical effects of Π_1 and Π_2 using laboratory experiments. Conversely, varying the strength of the material is not an obvious task in laboratory experiments; we will thus test the mechanical effect of Π_3 through numerical simulations. Note that these dimensionless parameters are the main physical governing parameters of the studied systems, not the dimensional parameters they are calculated from Barenblatt [2003]. Both the laboratory and numerical models will be equivalent to natural systems if the values of Π_1 , Π_2 , and Π_3 are in the same range. This will be discussed in the following sections.

Note that we did not test the thermal effects and the effects of chemical reactions. If we were aiming to do this, we would need to define more dimensionless parameters. Nevertheless, given that the simulated processes are very fast, we hypothesize that these thermal and chemical processes are too slow to have a substantial impact on the studied processes.

3. Laboratory Experiments

3.1. Experimental Setup

The experiments are described more thoroughly by Haug et al. [2013], where the focus is on the study of fragmentation processes and the resulting fragment size distributions. Here we provide a brief description and direct attention to the morphologies produced.

The experiments were performed in a vertically oriented Hele-Shaw cell, 60 cm in width and height with a gap between the glass plates of 0.5 cm (Figure 3). A layer of silica flour, with a density of 1050 kg m^{-3} , cohesive strength of 350 Pa, and tensile strength of 100 Pa [Galland et al., 2006, 2009; Galerne et al., 2011] is placed at the bottom of the cell. An inlet of 2 mm diameter at the cell's bottom is connected with a tube to a 5 L pressure tank filled with compressed air at a given pressure P . A rapid-action valve releases air

Table 2. List of Experimental Parameters

Experiment	P (Pa)	h (m)	P/h	Morphology
P1	5×10^3	0.05	10^5	V
P2	10×10^3	0.05	2×10^5	V
P3	20×10^3	0.05	4×10^5	V
P4	30×10^3	0.05	6×10^5	V
P5	40×10^3	0.05	8×10^5	V
P6	50×10^3	0.05	10×10^5	V
P7	60×10^3	0.05	12×10^5	I
P8	80×10^3	0.05	16×10^5	I
P9	100×10^3	0.05	20×10^5	I
P10	120×10^3	0.05	24×10^5	I
H1-1	20×10^3	0.01	20×10^5	I
H1-2	20×10^3	0.02	10×10^5	I
H1-3	20×10^3	0.03	6.7×10^5	I
H1-4	20×10^3	0.04	5×10^5	V
H1-5	20×10^3	0.05	4×10^5	V
H1-6	20×10^3	0.06	3.3×10^5	V
H1-7	20×10^3	0.07	2.9×10^5	V
H1-8	20×10^3	0.08	2.5×10^5	V
H1-9	20×10^3	0.09	2.2×10^5	V
H1-10	20×10^3	0.1	2×10^5	V
H2-1	80×10^3	0.01	80×10^5	I
H2-2	80×10^3	0.02	40×10^5	I
H2-3	80×10^3	0.03	26.7×10^5	I
H2-4	80×10^3	0.04	20×10^5	I
H2-5	80×10^3	0.05	16×10^5	I
H2-6	80×10^3	0.06	13.3×10^5	I
H2-7	80×10^3	0.07	11.4×10^5	I
H2-8	80×10^3	0.08	10×10^5	I
H2-9	80×10^3	0.09	8.9×10^5	V
H2-10	80×10^3	0.1	8×10^5	V
H2-11	80×10^3	0.11	7.2×10^5	V
H2-12	80×10^3	0.12	6.7×10^5	I
H2-13	80×10^3	0.13	9.1×10^5	V

from the tank into the Hele-Shaw cell, so that the air acts as an eruptive column capable of penetrating and fracturing the relatively weak silica flour layer. A high-speed camera records images of the experiments. Note that the experiments are designed to study the formation of explosive vents but not the post venting depositional processes.

In the experimental parameter study, we varied two quantities: the injection pressure (tank gauge pressure) P , ranging from 0.005 MPa to 0.12 MPa, and the depth h of the silica flour layer, ranging from 1 cm to 13 cm. The experiments were performed in three series (Table 2): (1) h is held at 5 cm, while P is varied from 0.005 MPa to 0.12 MPa (P series); (2) P is held at 0.02 MPa, while h is varied from 1 cm to 10 cm (H1 series); and (3) P is held at 0.08 MPa, while h is varied from 1 cm to 13 cm (H2 series).

In the experiments, $d = 2$ mm and h varies between 1 and 13 cm. Therefore, Π_1 varies from 5 to 65, i.e., it is much larger than 1 and in the same range as in natural systems (Table 1). P is varied between 0.005 and 0.12 MPa, yielding values of Π_2 between 10 and 770 (Table 1). These values imply that the process is pressure dominated, similar to natural systems. Finally, Π_3 in the experiments is between 14 and 343 (Table 1), which is again in the same range as in natural systems. Therefore, our experiments are equivalent to most natural systems we aim to simulate.

3.2. Experimental Results

Two distinct morphologies are observed in these experiments. Figures 4 and 5 present snapshots of two experiments with the same injection depth (5 cm) but different injection pressures. In Figure 4, we show an experiment with low injection pressure (experiment P3; 0.02 MPa, Table 2). An air pocket is produced early on, with fractures propagating laterally (Figure 4a). These fractures turn toward the surface, propagating

Figure 4. Snapshots of experiment P3 (also H1-5; Table 2) at (a) $t = 8.75$ ms, (b) $t = 20$ ms, and (c) $t = 36.25$ ms after beginning of experiment. Here $h = 5$ cm and $P = 0.02$ MPa. The vent developed a V shape.

diagonally (Figure 4b). When the fractures reach the surface, part of the layer directly above the inlet is lifted upward by the air, causing doming and tensional fractures at the surface (Figure 4c). The predominant morphology is diagonal, subsequently called V shaped.

Figure 5 shows an experiment with a higher injection pressure ($P = 0.08$ MPa; experiment P8; Table 2). Again, the experiment begins with a pocket of air with laterally propagating fractures. But before the lateral fractures turn upward, a vertical fracture develops (Figure 5a) and propagates rapidly upward in a channeling pipe (Figure 5b). When the air reaches the surface, a jet of dust and fragments is ejected from the pipe [Haug et al., 2013] (Figure 5c). The predominant morphology is vertical.

We represent the experimental results in a phase diagram by symbolically plotting the morphologies against the input parameters P and ρgh (Figure 6a). This phase diagram shows that the morphological types separate into two distinct regimes. The vertical morphology occurs when ρgh is small and/or P is high, whereas the oblique morphology (V shape) occurs when ρgh is large and/or P is small. This is somewhat surprising as it is opposed to what is observed in experiments of low viscosity magma intrusions [Galland et al., 2009, 2014] or in numerical models of hydraulic fractures in porous media [Rozhko et al., 2007]. In these less dynamic models, both vertical and cone sheets formed by fracturing of the country rock; but when injected at shallow level the magma lifts up its overburden, favoring the formation of cone sheets [Anderson, 1936; Phillips, 1974]. Obtaining the opposite results in our highly dynamic experiments suggests that processes other than fracturing occur. We will discuss these processes later.

The dimensional analysis described in section 2 identified two potential governing parameters of the modeled processes, $\Pi_1 = h/d$ and $\Pi_2 = P/\rho gh$. We plot the experiments in a dimensionless phase diagram with Π_1 as y axis and Π_2 as x axis to test their respective effects (Figure 6b). This diagram shows that vertical vents form preferentially for large values of Π_2 , whereas V-shaped vents form for low values of Π_2 . This result means that vertical vents correspond to a pressure-dominated regime, whereas V-shaped vents correspond to a regime where gravitational force plays a significant role. In the diagram of Figure 6b, the transition between

Figure 5. Snapshots of experiment P8 (also H2-5; Table 2) at (a) $t = 5$ ms, (b) $t = 16.75$ ms, and (c) $t = 36.25$ ms after beginning of experiment. Here $h = 5$ cm and $P = 0.08$ MPa. The vent developed a vertical shape.

Figure 6. (a) Phase diagram of vent morphologies obtained in experiments as functions of P and ρgh . Dark gray squares represent vertical morphologies, light gray inverted triangles represent V-shaped morphologies, and the transition between the two regimes is marked by a solid line. Vertical pipe-like morphologies occur at high P and low ρgh , while diagonal morphologies occur for low P or high ρgh . (b) Phase diagram of vent morphologies of the same experiments as in Figure 6a but plotted with respect to the dimensionless numbers Π_1 and Π_2 identified in the dimensional analysis (section 2). Symbol legend is the same as in Figure 6a. A dashed line roughly locates the transition between the vertical and V-shaped vent regimes.

the vertical and the V-shaped regimes is not very well constrained. Nevertheless, it appears that this transition is marked by a line in a log-log plot of slope larger than 2. This suggests that the vertical-to-V-shaped transition is dominantly governed by Π_2 rather than Π_1 , i.e., the balance between the fluid overpressure and the lithostatic stress dominantly governs the dynamics of explosive vents, when the strength (cohesion) of the host rock remains constant. The following sections describe numerical simulations that tested the effect of the strength (cohesion) of the host rock.

4. Numerical Simulations

4.1. Numerical Model: The Sage Code

The hydrocode used in this work is Sage (a subset of RAGE; see Gittings *et al.* [2008]). It was originally developed at Science Applications International and subsequently adopted and further developed by Los Alamos National Laboratory under the auspices of the Department of Energy's program in Advanced Simulation and Computing. We have used the Sage code previously to study tsunami generation [Gisler, 2008] and asteroid impacts [Gisler, 2011; Gisler *et al.*, 2011] and to examine venting situations in which supercritical water penetrates a deformable homogeneous medium [Gisler, 2009]. This last reference contains additional details relevant to the present paper. In this paper, Sage is adapted to simulate the penetration of a hot, volatile-rich magma into a homogeneous, compactible, and brittle medium representing undisturbed country rock.

In order to simulate geological materials in a realistic manner, Sage includes several analytical equations of state and strength models and can also make use of tabular equations of state that are available for a variety of materials through the Los Alamos National Laboratory Sesame library [Holian, 1984; Lyon and Johnson, 1992]. There are five different materials used in the present calculations:

- (1) The atmosphere above the surface, with a density of 1.29 kg m^{-3} at standard temperature and pressure, is modeled as dry air, Sesame material #5030 [Graboske, 1976; Holian, 1984].
- (2) We use Sesame material #7530, basalt [Barnes and Lyon, 1987], for the country rock in its solid, brittle state. The compact solid density is 2870 kg m^{-3} , but we adopt the crush-porosity model, or p - α crush model [Herrmann, 1968; Kerley, 1992; See also Gisler, 2009], to reduce its density in most of the domain. The model relationship between pressure and distension is linear between the start of crushing and full crush, and the pdV work done during the crush is accounted for in a straightforward manner. We use $\alpha = 1.4$, corresponding to a porosity $\Phi = 0.29$ at 0.1 MPa, crushing to solid density at 100 MPa. An elastic-plastic strength model with adjustable yield strength, shear modulus, and fail pressure (for tensional cracking) is invoked for this material.
- (3, 4, and 5) The eruptive magma consists of molten basalt (Sesame #7530), mixed with 1% carbon dioxide (Sesame #5210; Shaw *et al.* [1993]) and 5% water by mass. The equation of state for water is built into the Sage code and derived from the National Bureau of Standards/National Research Council of Canada (NBS/NRC) Steam Tables [Haar *et al.*, 1984].

Figure 7. Equations of state for (left) basalt and (right) water as used in the simulations presented here. Basalt (at left) is Sesame material #7530, and water is calculated internally in Sage, from the NBS/NRC Steam tables. The top row is density as a function of temperature and pressure, with the dry melt line indicated for basalt and the phases indicated for water (phases of ice designated by Roman numerals). The very high latent heat of vaporization for water is easily read from the bottom right frame, as is the high-energy density of the supercritical regime.

The simulations are relevant to simulate magmatic explosive venting when volatile-rich magma exsolves during its ascent, as in kimberlite vents. The simulations do not intend to simulate the exsolution process, given that at the beginning of the calculations, we assume that exsolution has already taken place, and that the eruptive material therefore consists of a simple mixture of the volatiles and molten basalt in local thermodynamic equilibrium at a temperature of 1500 K and a chosen pressure of injection. The unmixed density of molten basalt at this temperature is 2.69 kg m^{-3} , but mixing in the volatiles reduces the density to 1.3 kg m^{-3} at our lowest injection pressure (80 MPa) or to 2.14 kg m^{-3} at the highest injection pressure (360 MPa).

The equations of state for basalt and water are illustrated in Figure 7, with basalt at left and water at right. The top row shows density as a function of temperature and pressure, and the bottom row shows internal energy as a function of the same variables. The equation of state for basalt is illustrated at full crush state. In the equation of state for water, the high latent heat of vaporization, $\sim 2260 \text{ J g}^{-1}$ at STP, comparable to the energy density of gunpowder, is readily seen. It is also possible to deduce from these diagrams that the energy density of supercritical water, $\sim 1000 \text{ J g}^{-1}$, is explosive [Thiéry and Mercury, 2009].

The atmosphere and the hot, volatile-rich magma are treated as nearly inviscid fluids. The country rock is treated as an elastic-plastic material using the method first described by Wilkins [1964]. The method requires input of the yield stress, the shear modulus, and a tensile failure stress. For the crushable basalt country rock, we use a constant tensile failure stress of -5 MPa , a constant shear modulus of 100 MPa , and yield stresses of 30 MPa and 100 MPa for two different series of runs (Table 3).

The elastic-plastic material responds elastically to compressional stress until the yield stress is reached, and then it deforms plastically. When the (negative) tensional stress exceeds the negative failure stress in a material, cracks develop and propagate. Propagation of cracks occurs through the propagation of mesh

Table 3. List of Parameters Used in the Simulations

Simulation	<i>P</i> (MPa)	<i>Y</i> (MPa)	Morphology
F4Ci	360	30	Vertical
F4Di	360	100	Horizontal
F4Cf	240	30	Vertical
F4Df	240	100	Horizontal
F4Cd	160	30	Vertical
F4Dd	160	100	Horizontal
F4Cc	120	30	Horizontal
F4Dc	120	100	V-shape
F4Cbm	100	30	Horizontal
F4Dbm	100	100	V-shape
F4Cb	80	30	Inverted T shape
F4Db	80	100	V-shape

refinement in regions of high stress. When a given cell reaches the stress failure criterion and its size is above the minimum cell size, it subdivides until the minimum cell size is reached or the stress across the daughter cells is insufficient for failure. Failure is allowed to occur only at minimum cell size. Failed cells are fluid cells and do not support tensional or shear stresses. The transmitted stresses must therefore be supported by neighboring cells, which may similarly subdivide until they fail themselves; a crack thereby results. If the tensional stress in the material surrounding a crack is not sustained, the crack can numerically anneal as failed cells combine with cells that have not failed.

Numerical studies of natural systems are inherently limited by the approximations that must be used, the physical processes that are ignored, the errors of truncation and round-off, and the limitations of computational resources and time. The particular simulations we present here are further limited because they present a two-dimensional view of a three-dimensional world and because they deal with uniform and homogeneous media while the real world is irregular and inhomogeneous. Thermal conduction is not included, nor are chemical reactions. The volatiles within the magma are simply *mixed*, not dissolved, so complete exsolution is considered to have taken place before the calculation begins.

4.2. Numerical Setup

We performed simulations in which a homogenous, compactible, and brittle medium representing undisturbed country rock is penetrated by a hot, volatile-rich magma. The medium suffers tensile failure under the stresses produced by the inserted magma. To have this occur in Sage simulations, we have set the tensile failure criterion for the medium to a value artificially low to allow cracks to appear and propagate. We made a parameter study by running two series of runs: in each series, we fixed the value of the yield stress (*Y*) and we varied in a systematic manner the injection pressure (*P*) between 80 and 360 MPa (Table 3).

All the runs considered in this paper are of the same configuration. In the *x-y* Cartesian geometry, there is a half plane of dry air for $y > 0$ and a half plane of elastic, compactible, and brittle basalt for $y < 0$. Earth gravity is used, and the assembly is initialized with a pressure gradient that assures gravitostatic equilibrium with a pressure of 0.1 MPa at $y = 0$. The dimensions of the computational box are 4 km in *y* (vertical), from -2 km in rock to $+2$ km in air, and 8 km in *x* (horizontal). The maximum cell size is 100 m in each direction, and mesh refinement proceeds in four binary stages to a minimum cell size of 6.25 m.

In the middle of the box at the bottom there is an inlet pipe of width 60 m containing a volatile-rich magma (94% basalt, 5% supercritical water, and 1% carbon dioxide by mass) at a temperature of 1500 K and a certain given injection pressure, varied among the runs of the parameter study. The injection pressure is always higher than the lithostatic pressure of the overburden, which in all these calculations is 44 MPa. The volatile-rich mixture is thus pressurized and buoyant; both these attributes cause the column to rise and eventually erupt. The volatile-rich magma in the inlet pipe is not depleted during the eruption; the cells within the pipe are restored to initial conditions at each time step. There is a constant supplied pressure at the pipe, which is not relieved during the calculation.

Similar to our experiments, the simulations are designed to study the formation of explosive vents, not the post venting deposition processes.

In the simulations, $\Pi_1 = 16.7$, i.e., within the experimental range and within the range observed in nature, so the geometry of the numerical setups is consistent with geological systems. The values of Π_2 are between 1.8 and 8, meaning that gravitational forces are not negligible with respect to magma pressure. This is the main difference with the experiments. Finally, Π_3 in the simulations exhibits values ranging between 0.8 and 12, meaning that the system varies from slightly pressure dominated to systems in which gravitational and pressure forces are equivalent. Overall, the values of Π_1 , Π_2 , and Π_3 in our simulations are in the same range as in natural systems. Therefore, the simulations are equivalent to the natural systems they aim to simulate.

Figure 8. Density plots for the 12 runs of our parameter study. The pressure within the injected volatile-rich magma is indicated at left, increasing upward, and the material properties of the background medium are indicated at the top, with the yield stress lower in the left column, higher for the right. The color scale for density is shown at the top. Three regimes are apparent here: diagonal development at bottom right, central vertical pipe at top left, and initial horizontal development at bottom left and top right. The bottommost run in the right column began with a horizontal development followed by the very slow growth of a central vertical pipe.

4.3. Numerical Results

The numerical parameter study we performed is illustrated in Figure 8, which shows the density state of each calculation in 12 different runs at a time well before breakout. Pressure at the inlet in the eruptive magma column increases from 80 MPa to 360 MPa upward in this figure, and the yield stress within the background medium differs between the left (30 MPa) and right (100 MPa) columns. The physical time, in seconds, for the snapshots in this figure are shown in the top right corner of each frame, and the run names in the top left corner.

Figure 9. Evolution of (left) density and (right) deviatoric stress state for the run F4Ci. Frames (a) through (d) illustrate successive stages in the development of the vent, as described in the text. A hot (1500 K) mixture of basalt, water, and carbon dioxide is injected at the bottom of the computational domain into a background medium of elastic-plastic deformable basalt. The background medium has a shear modulus of 100 MPa, yield stress of 30 MPa, and fail pressure of -5 MPa. The pressure in the injection region is 3600 MPa (see F4Ci in Table 3). The dimensions of each frame is 4 km vertical by 8 km horizontal, and the color bars for the density and stress state scales are shown at the top of the first frame.

The simulations show three separate regimes (Figure 8). Diagonal developments, i.e., V-shaped vents, and off-axis eruptions dominate for the three runs at bottom right (low magma pressure and high background yield stress). In the three runs at top left (high magma pressure and low background yield stress) the development is predominantly vertical, or pipe-like, resulting eventually in eruptions near the initial axis.

For the three runs at top right (high magma pressure and high background yield stress) and the three runs at bottom left (low magma pressure and low background yield stress), initial horizontal developments are present.

In the simple phase diagram of Figure 8, the different morphologies can be separated by lines of slopes P/Y , which is the definition of Π_3 . Therefore, Figure 8 highlights the controlling effect of the parameter Π_3 identified in the dimensional analysis: vertical vents form only when $\Pi_3 \geq 5$, V-shaped vents form when $\Pi_3 \leq 1.5$, and a combination of horizontal and vertical structures form for intermediate values.

Figure 10. Evolution of (left) density and (right) deviatoric stress state for the run F4Db. Frames (a) through (d) illustrate successive stages in the development of the vent, as described in the text. A hot (1500 K) mixture of basalt, water, and carbon dioxide is injected at the bottom of the computational domain into a background medium of elastic-plastic deformable basalt. The background medium has a shear modulus of 100 MPa, yield stress of 100 MPa, and fail pressure of -5 MPa. The pressure in the injection region is 80 MPa (see F4Db in Table 3).

The interesting case at the bottom of the left column (Figure 8) bears special mention. The initial horizontal development, common to the two runs above it, is arrested after tensional cracks above the cavity allow the slow development of a vertical pipe. This run will be discussed in more detail later.

The contrasting regimes of diagonal propagation and vertical development seen from top left to bottom right (Figure 8) are broadly consistent with the experimental results. The main difference is that the depth h of the inlet is varied and the cohesion (i.e., strength) of the country rock is fixed in the experiments, and vice versa in the simulations. Interestingly, the horizontal developments at bottom left and top right are apparently an intermediate regime that is not accessible with the current experimental setup. All three regimes are present in natural volcanic and venting systems as discussed in section 1.

The main question arising from both the experiments and the numerical simulations is the following: why are there different regimes, and what are the mechanics behind them? The advantage of the numerical simulations is the access to mechanical information, the stress field for example, during the development of the simulated processes. In the next section, we will thus compare the stress developments of four characteristic runs, each corresponding to one of the observed morphologies.

Figure 11. Evolution of (left) density and (right) deviatoric stress state for the run F4Df. Frames (a) through (d) illustrate successive stages in the development of the vent, as described in the text. A hot (1500 K) mixture of basalt, water, and carbon dioxide is injected at the bottom of the computational domain into a background medium of elastic-plastic deformable basalt. The background medium has a shear modulus of 100 MPa, yield stress of 100 MPa, and fail pressure of -5 MPa. The pressure in the injection region is 240 MPa (see F4Df in Table 3).

4.4. Detailed Results From Four Characteristic Runs

We now consider separately the evolution of a characteristic run of each morphology identified in Figure 8 (see Figures 9–12). In these figures, time progresses from top to bottom. The left-hand images are color plots of density, and the right-hand images are plots of the deviatoric stress state w defined by

$$w = \sqrt{s_{xx}^2 + s_{yy}^2 + 3s_{xy}^2 - s_{xx}s_{yy}}, \quad (4)$$

where s represents the deviatoric stress tensor,

$$s_{ij} = \sigma_{ij} - p\delta_{ij}, \quad (5)$$

and p is the isotropic pressure given by one third the trace of the stress tensor σ . These quantities are plotted at four different times during each of the calculations.

In the run shown in Figure 9 (F4Ci), the vent developed vertically. The background medium was set to have a shear modulus of 100 MPa and yield stress of 30 MPa. The pressure within the volatile-rich magma is set to 360 MPa (Table 3), which is almost a factor of 10 greater than the lithostatic pressure of 44 MPa, giving an effective overpressure of 316 MPa. This is the highest pressure used in our runs.

Figure 12. Evolution of (left) density and (right) deviatoric stress state for the run F4Cb. Frames (a) through (d) illustrate successive stages in the development of the vent, as described in the text. A hot (1500 K) mixture of basalt, water, and carbon dioxide is injected at the bottom of the computational domain into a background medium of elastic-plastic deformable basalt. The background medium has a shear modulus of 100 MPa, yield stress of 30 MPa, and fail pressure of -5 MPa. The pressure in the injection region is 80 MPa (see F4Cb in Table 3).

Early on (Figure 9a), the induced stress causes a round cavity to open up at the top of the pipe. The injection pressure is more than 10 times greater than the yield stress, so the country rock dominantly deforms plastically, and the cavity elongates vertically (Figure 9b). The dominant plastic behavior of the country rock is illustrated on the stress plot of Figure 9, where the deforming domain at the tip of the conduit is substantial in size. Additionally, a little pair of leading void cracks arise ahead of the cavity, where the tensional stress is highest. Stress waves impinging on the interface with the atmosphere cause a slight flexing of the surface. The tensional cracks above the cavity merge and propagate toward the surface (Figure 9c), opening up communication between the rising column and the atmosphere. Ears of lower density magma begin to form plastically on opposite sides of the opening crack and eventually (Figure 9d) penetrate toward the surface. The wide-open central channel develops further to become the principal conduit for magma to the surface, although the initial eruption is off axis.

In the run shown in Figure 10 (F4Db), a typical V-shape morphology developed. The yield stress of the background medium has been increased to 100 MPa from 30 MPa, and the injection pressure of the volatile-rich magma is reduced to 80 MPa (Table 3), an overpressure of 36 MPa over the lithostatic pressure and the lowest pressure we consider. All other parameters are identical to the run of Figure 9.

The cavity at the top of the pipe in this case takes on a butterfly shape early on (Figure 10a). From this, the volatile-rich magma carves out upward leading diagonal cracks (Figure 10b). The ratio between injection pressure to yield stress is less than 1, and the failure mode in this case is not plasticity-dominated deformation but rather elasticity-dominated fracturing. The stress state plot at right illustrates the concentration of tensile stress in bow tie patterns at the crack tips and the relief from stress in the medium behind the propagating crack front. A weaker stress concentration is seen at the surface directly above the inlet pipe, where the surface is bowed slightly upward. A deep tensional crack forms at the surface and propagates downward but does not meet the diagonal cracks. The upward leading diagonal cracks eventually flatten out (Figure 10c), probably under the influence of the boundaries at left and right. The surface bows upward everywhere above the spreading cracks, forming a plateau. Strong tensile stresses at the plateau's edge produce vertical downward propagating cracks. Eventually (Figure 10d), one of these cracks reaches the upward and sideways moving eruptive column, and the eruption occurs in a supersonic jet through that crack, with velocities exceeding 600 m s^{-1} . Once again, an off-axis eruption is observed, but in this case the possibility of a central vent is foreclosed. The density gradients visible within the cracks in Figures 10c and 10d give evidence of the separation of the volatile component of the magma mixture.

In the run of Figure 11 (F4Df), the conduits develop horizontally. We used the same background medium yield stress as in Figure 10 (100 MPa), but the pressure of the volatile-rich magma is increased to 240 MPa (Table 3). With a ratio of injection pressure to yield stress $\Pi_3 = 2.4$, this is in a regime intermediate between the runs of Figures 9 and 10.

In this case, the early configuration above the vent (Figure 11a) is lozenge shaped, with no hint of the butterfly pattern seen in the run of Figure 10. Horizontal cracks open in both directions (Figure 11b), and there is a hint of an upward projection pushing upward by plasticity-dominated deformation above the vent, but this does not develop further until much later. The concentration of tensional stress is much lower around the vertical tip compared to the higher levels around the ends of the horizontal crack, so the horizontal cracks grow by fracturing. A downward propagating crack that opened in tension at the surface fails to make contact with the cracks spreading from the magma inlet. The horizontal cracks turn upward toward the surface (Figure 11c) and eventually flatten downward again as they approach the boundaries. Tensional cracks from the surface develop above the tips of the magma-filled dikes, but no surface eruption occurs before the diagonal branches reach the boundary (Figure 11d). After this, the vertical projection above the vent grows and eventually penetrates to the surface via plasticity-dominated deformation, becoming the dominant eruption channel. Separation of the volatile component of the magma mixture can be seen from the density gradient within the cracks.

The run shown in Figure 12 (F4Cb) is at the bottom left of Figure 8, with the lowest injection pressure (80 MPa) and the lowest yield stress (30 MPa) for the background medium (Table 3) and thus a ratio of pressure to yield stress $\Pi_3 = 2.7$.

Early on (Figure 12a), the induced stress causes a lozenge-shaped cavity to open up at the top of the pipe. A little later (Figure 12b), the volatile-rich magma has opened horizontal cracks in both directions and a vertical crack that moves upward via plastic deformation, ever more rapidly as it encounters lower pressure. A leading void crack can be seen in this frame a little ahead of the volatile-filled crack, where the tensional stress is highest. Stress is relieved in the quadrants between the vertical and horizontal cracks. The upper surface is bowed very slightly upward as stress waves impinge on the interface with the atmosphere. As the volatile-rich magma column nears the surface (Figure 12c), tensional cracks open up communication between the rising column and the atmosphere. The opened pipe assumes the converging-diverging form of a deLaval nozzle (Figure 12d), and horizontal cracks appear off the side of the column. A supersonic gaseous eruption ensues, with the outflow speed over 500 m s^{-1} on breakout. The gradient in density within the pipe in Figures 12c and 12d is evidence that the volatile components, water and carbon dioxide, have separated from the heavier molten magma. The start of the eruption is almost entirely gaseous. The subsequent evolution of this system involves pulsations in the channel width and outflow speed.

The early termination of the horizontal channels and subsequent development of the vertical one appears to be robust; small changes in the input parameters resulted in configurations that were broadly similar.

4.5. Interpretation of the Numerical Results

As illustrated by the preceding section, we have three, or possibly four, different regimes appearing. From the phase diagram in Figure 8, we observe that the morphology of the vents is controlled by the value of Π_3 . The stress plots of Figures 9–12 show contrasting mechanical behaviors between the distinct regimes, i.e., for different values of Π_3 . Large values of Π_3 result in plasticity-dominated failure of the country rock leading to the propagation of a wide, vertical vent (Figure 9). In contrast, for low values of Π_3 , large stress concentrations at conduit tips indicate that failure rather occurs by elasticity-dominated fracturing through tensile failure

5. Integration and Discussion

5.1. Relation to Experimental Work

Although the experiments and numerical simulations correspond to different scales and pressure buildup mechanisms, they produced very similar features. In both we obtained two different conduit morphologies: vertical and V-shaped channels. In both numerical and experimental work, the formation of vertical channels occurs at higher input pressure, suggesting that the physical regimes related to the V-shaped and vertical vents are the same. Therefore, the quantitative and dynamic data from the numerical simulations can be used to interpret the experimental results. Consequently, according to the simulations (Figures 9 and 10), the experimental vertical vents dominantly result from plasticity-dominated yielding of the silica flour, whereas the V-shaped vents dominantly result from elasticity-dominated fracturing of the flour. This interpretation is in agreement with the morphologic features observed in the experiments: the V-shaped vents exhibit oblique fracture-like structures (Figure 4), whereas the vertical vents do not (Figure 5).

An important difference between the experiments and the numerical simulations is the tested parameter, i.e., $\Pi_1 = h/d$ and $\Pi_2 = P/\rho gh$ in the experiments and $\Pi_3 = P/Y$ in the numerical simulations. Π_2 and Π_3 compare the input energy, expressed by the pressure P , with initial conditions of the models, i.e., gravitational stresses and host rock strength, respectively. In both experiments and numerical simulations, vertical vents (i.e., plasticity-dominated yielding of the host rock) occur when P is large (i.e., high input energy, large Π_2 and Π_3) with respect to the gravitational forces and host rock strength, respectively. This implies that the plasticity-dominated yielding regime corresponds to high-energy systems, as intuitively expected. Conversely, V-shaped vents (i.e., elasticity-dominated fracturing of the host rock) occur when the values of Π_2 and Π_3 decrease, i.e., for lower energy systems. Note that the gravitational forces and the host rock strength act in the same direction, i.e., they tend to impede the plasticity-dominated yielding regime. This result is intuitive, as larger or stronger systems require more energy to be deformed. This interpretation is also in agreement with the qualitative experiments of Ross *et al.* [2008a, 2008b], who show that rapid injection of pressurized air in cohesionless dry sand triggers distributed deformation in the sand, resulting in a pipe, whereas rapid injection of pressurized air in cohesive wet sand triggers focused deformation along conical fractures. This interpretation is also in good agreement with the experiments of Valentine *et al.* [2012], who show that the morphology of explosive craters differ depending on the explosion energy and depth.

The systematic occurrence of both V-shaped and vertical vents appears very similar to the recent 3-D laboratory experiments of igneous intrusions of Galland *et al.* [2009, 2014]. These authors identified the physical parameters that govern the formation of conical (cone sheets) and vertical (dikes) igneous sheet intrusions. There are, however, important mismatches between our results and those of Galland *et al.* [2009, 2014]. For example, the experiments of Galland *et al.* [2014] show that conical features form at shallower depth, whereas our results show the opposite (Figures 6 and 8). Such differences suggest that the vertical conduits of Galland *et al.*'s [2014] experiments and our experiments correspond to distinct physical regimes. This is in very good agreement with our conclusions, given that in the experiments of Galland *et al.* [2014] vertical dikes are inferred to form by fracturing, whereas our simulations suggest that the vertical vents produced in our experiments and simulations result from plastic yielding of the host rock.

The main limitation of both the experiments and simulations is that they are two-dimensional, whereas natural systems and the experiments of Galland *et al.* [2009, 2014] are three-dimensional. In 2-D models, both vertical sheets (dikes or fractures) and pipes would appear as vertical conduits. A key question is thus the following: how is it possible to decipher whether a vertical conduit produced in 2-D experiments and simulations corresponds to a cross section of a sheet or of a pipe in 3-D (see for example simulations F4Ci and

F4Cb; Figures 9 and 12)? The discussion in the above paragraph brings some insights to this question, as sheets and pipes correspond to different physical regimes: sheets result from fracturing, whereas pipes do not. In simulation F4Cb, the deviatoric stress map shows that stresses concentrate in a relatively small zone at the tip of the conduit (Figure 12). This suggests that F4Cb rather simulates fracturing process, so that the conduit may correspond to the cross section of a sheet. In contrast, the deviatoric stress maps of simulation F4Ci show that stresses induced by the conduit propagation is broadly distributed ahead of the conduit tip, which is not in agreement with fracturing. This suggests instead that this plastic yielding regime may be related to pipe formation. Thus, the simulations F4Ci, F4Cf, and F4Cd might represent cross sections of subcylindrical pipes but not of sheets.

The occurrence of vertical and V-shaped vents in both the experiments and simulations suggest that comparable phenomena can arise from different triggering mechanisms. This result has implications for our understanding of phreatic, phreatomagmatic, and magmatic explosive vents: while these result from different triggering mechanisms of pressure buildup and produce different geological deposits, the process is nevertheless similar. In both cases, the explosive vents form through solid overburden rocks. Differences arise from the contrasting nature of the fragmented material at the pressure source: in phreatic and phreatomagmatic explosions, the fragmented material is dominantly the solid host rock, whereas in magmatic explosive vents, the fragmented material is the fluid magma. However, fragmentation occurs so rapidly that Zimanowski *et al.* [2003] and Dürig *et al.* [2012] argue that the magma fragments in a brittle manner, similar to the solid host rock. Therefore, phreatic, phreatomagmatic, and magmatic explosive venting might correspond to equivalent mechanical systems.

In the experiments, only two morphological regimes were recognized (vertical and V-shape), whereas three (or even four) were produced in the simulations. In particular, the horizontal regime seen in the simulations (Figure 11) was not observed in the experiments. This difference might be explained in the light of the dimensional analysis. While the experimental values of Π_1 perfectly overlap with those in the simulations, the values of Π_2 and Π_3 do not, though they are close. These differences can result in slightly different dynamics, resulting in other physical regimes not identified in the laboratory experiments. Many more simulations and experiments would be required to overlap the parameter space between the experiments and the numerical simulations.

Note that in the simulations, the tensile strength is constant while the yield stress varies. In reality, this is not the case as the tensile strength is a function of the yield stress [Galland *et al.*, 2006; Jaeger *et al.*, 2007]. According to the Griffith's criterion, the yield stress is twice the tensile strength [Jaeger *et al.*, 2007]. Therefore, in the simulations, the tensile strength is very low, favoring the propagation of tensile fractures. The simplifications of keeping the tensile strength constant and independent of yield stress and of keeping the yield strength independent of local overburden were both made to avoid additional complications in our phenomenological study. It is possible that these simplifications could explain the occurrence of the fourth regime in the lower left corner of Figure 8.

5.2. Geological Implications

Explosive vent structures observed in nature show remarkable similarities to our experimental and numerical results. Both vertical pipes and conical conduits have been described in various geological settings (Figure 1). In hydrothermal vent complexes, some systems exhibit both morphologies, as deep vertical pipes are often connected to shallow conical vents, as revealed by field [Svensen *et al.*, 2006] and seismic observations [Planke *et al.*, 2005; Hansen, 2006].

Our experimental and numerical phase diagrams show that the morphology of explosive vents depends upon the dynamics of their formation (Figures 6 and 8). Vertical pipe morphologies arise when the pressure of the injected fluid dominates with respect to the gravitational forces and the strength of the host rock, overcoming the plastic yielding limit. In contrast, when the pressure of the injected fluid is not high enough, the plastic yielding limit is not reached, so that the country rock fails by fracturing. These results are consistent with our knowledge of volcanic and nonvolcanic vents. In many kimberlite pipes, the explosions must have been highly energetic as their morphology is nearly vertical (Figure 1) [Hawthorne, 1975], like the high-energy experiments and simulations. In hydrothermal vent complexes, mafic sills penetrate into sedimentary basins and spread out over large distances, cooking their aureoles [Aarnes *et al.*, 2011, 2012] and developing extensive

high-pressure reservoirs of overpressured volatiles. Although the mechanism for localization is not understood, the combination of high pressure and a large reservoir likely results in plastic yielding of the host rock, i.e., vertical pipes [Jamtveit *et al.*, 2004; Planke *et al.*, 2005; Svensen *et al.*, 2006].

Hydrothermal vent complexes and certain other systems exhibit both deep vertical pipes and shallow conical vents [Svensen *et al.*, 2006]. If our analysis is correct, these systems are highly energetic at depth and less near the surface. This is to be expected if we observe that the energy of the working fluid is consumed as it penetrates and deforms the host rock. The local energy available at the working surface can decrease so much that the penetration mechanism changes from plastic deformation to fracturing. An example from our numerical simulation is shown in Figure 9, and similar behavior is also seen in some of the experiments (Figure 5).

One can notice the morphological difference of the vents simulated in our experiments and simulations (vertical or gently dipping V shapes) compared to those of, e.g., maar-diatremes (steeply dipping conical vents; Figure 1). Whereas in natural systems, maar-diatremes result from successions of numerous explosions [Lorenz and Kurszlaukis, 2007; White and Ross, 2011; Valentine and White, 2012], our experiments and simulations model a single venting event, similar to many existing laboratory and numerical models [Ross *et al.*, 2008a, 2008b]. Our work should be expanded to simulate successive explosions to address the full dynamics and evolution of explosive vents such as maar-diatremes.

A key question associated with volcanic pipes remains unsolved: what are the processes leading to the formation of circular vents in solid rocks (Figure 1)? Such a morphology does not result from fracturing, which should generate sheet, planar structures, such as dikes, cone sheets, and sills [e.g., Lister and Kerr, 1991; Rubin, 1995; Galland, 2012]. As mentioned above, vertical circular vents in nature are associated with high-energy dynamics or venting through loose material, i.e., for high values of Π_2 and Π_3 . Under those conditions, according to our results, the country rock is expected to yield in a plasticity-dominated manner. Therefore, we conclude that the formation of circular pipes in nature occurs because the input energy is such that the country rock dominantly yields plastically rather than by elasticity-dominated fracturing.

This conclusion is in good agreement with geological observations in hydrothermal vent complexes. In the Karoo basin, for example, mapping of internal structures of the Wittkop I-III hydrothermal vent complexes show intense brecciation, even fluidization [Svensen *et al.*, 2006]. In addition, the strata of the country rock outside the vent exhibits substantial inward dipping structures, which cannot be explained by elastic behavior of the rocks. These observations thus suggest that the rock likely behaved plastically when the vents formed, as in the experiments of Gernon *et al.* [2008], Ross *et al.* [2008a], and Nermoen *et al.* [2010].

This last conclusion, however, should be drawn with caution. Indeed, pipes are three-dimensional structures whereas the numerical and experimental models are two-dimensional. Thus, vertical conduits in the models can represent either a section of a vertical planar or a circular structure. In order to confirm that circular pipes result due to plasticity-dominated yielding of the country rock above critical values of Π_2 and Π_3 , one needs to perform systematic three-dimensional models.

6. Conclusions

This contribution presented experimental and numerical models of explosive vents. We draw the following conclusions.

The experiments show that two vent morphologies develop: vertical and V-shaped vents.

In a phase diagram with the dimensionless geometric parameter $\Pi_1 = h/d$ and the dynamic parameter $\Pi_2 = P/\rho gh$ as y and x coordinates, respectively, the experimental vertical and V-shaped vents define two distinct regimes. Vertical vents form for high values of Π_2 , i.e., when the injection pressure P is high with respect to the lithostatic stress. In addition, the effect of Π_1 is less prominent than that of Π_2 .

The simulations also produced vertical and V-shaped vents. A third horizontal morphology was also produced.

In a phase diagram with the yield stress (Y) and pressure (P) as x and y coordinates, the numerical vertical, horizontal, and V-shaped vents define three distinct regimes separated by lines of critical slope $\Pi_3 = P/Y$. Vertical vents form when the injection pressure P is high and/or the yield stress Y is low, i.e., when Π_3 is high.

The simulations show that vertical vents form due to plasticity-dominated yielding of the country rock, whereas horizontal and V-shaped vents form due to elasticity-dominated fracturing.

Our results suggest that the circular vertical volcanic vents result from plasticity-dominated yielding of the rocks rather than elasticity-dominated tensile fracturing. For lower energy systems, we expect fracturing to occur, leading to conical or fissural vents.

Acknowledgments

This work was supported by Center of Excellence grant from the Norwegian Research Council to PGP. The authors gratefully acknowledge the technical support of Olav Gundersen. The staff of the workshop of the Physics Department at the University of Oslo built the experimental box. The authors gratefully thank Knut Jørgen Måløy for lending the high-speed camera to Ø. Haug. The manuscript benefited from constructive reviews of T. Gernon, an anonymous reviewer, and the associate editor M. Todesco.

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