GEOPHYSICAL RESEARCH LETTERS, VOL. 21, NO. 18, PAGES 1959-1962, SEPTEMBER 1, 1994

Origin of the sound generated by Strombolian explosions

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Abstract. During strombolian eruptions, large bubbles break at the surface of the lava column and produce sound. Acoustic pressure recorded during several explosions on the Eastern vent of Stromboli volcano, shows a pattern consistent between explosions. The well-marked oscillation contains only very low frequencies (around 7 Hz), and is followed by a signal containing now both higher frequencies and lower frequency (less than 4 Hz). The generation of sound is explained by the vibration (7 Hz) and bursting (higher frequencies) of large bubbles, followed by the drainage of magma down in the conduit (less than 4 Hz). The interpretation suggests that: (1) the bubble vibrates before bursting and (2) the vibration prior to bursting yields more energy than the bursting itself. The radius of bubbles responsible for explosions is determined to be close to 1 meter, in agreement with observations of a few conduit sizes.

Introduction

At Stromboli volcano, eruptions are characterized by a series of explosions, each lasting a few seconds. For each explosion, the volume ratio of ejected gas to lava clots is very large, typically about 10^5 [*Chouet*, 1974]. The explosions are due to the bursting of large gas pockets, almost as large as the volcanic conduit [*Blackburn et al.*, 1976; *Wilson*, 1980]. Previous studies have shown that bubbles play an important role during volcanic eruptions, especially at Stromboli [*Chouet*, 1974; *Blackburn*, 1976; *Jaupart and Vergniolle*, 1988]. There, large bubbles are formed in a magma chamber by partial coalescence of a foam trapped at the roof of the magma chamber [*Jaupart and Vergniolle*, 1988], a few hundred meters deep [*Giberti et al.*, 1992]. They rise in a conduit, a few meters wide [*Giberti et al.*, 1992] and expand, inducing a two-phase flow regime, called slug-flow. Eventually, they break out at the surface within vents, a few meters wide [*Chouet et al.*, 1974; P. Allard, pers. comm, 1990; J.L. Cheminée, pers. comm. 1990].

P. Allard (pers. comm., 1993) has been able to observe bubbles of various diameters, up to one meter, at the lava surface inside the Western vent for small explosions. Bubbles reach the lava surface, where they stay for less than a few seconds showing a hemispherical shape. Then, they break, sending fragments into air and emitting sound at the same time. Similarly, for large explosions, bubbles may be responsible for both ejecting fragments of lava into air and producing sound, as was already suggested [*Blackburn et al.*, 1976]. This led us to monitor the acoustic activity during explosions, in order to gain information about these bubbles.

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Paper number 94GL01286
0094-8534/94/94GL-01286$03.00

Measurements

In September 1991, acoustic pressure and seismicity were continuously monitored at the summit at a distance of about 200 meters from the active Eastern vents (Fig 1). The ground motion was measured by a Lennartz seismometer (1-20 Hz), the acoustic pressure by a microphone and a sonometer (Brüel-Kjær type 4165 and 2230), with an attenuation of -3 dB at 4 Hz. Both the seismicity and the acoustic pressure were recorded on a Sony TCD-10 Pro Digital Audio Tape recorder (-3 dB at 1 Hz). Our acoustic measurements cover a much larger frequency range (from 4 Hz to 20 kHz) than the few studies performed 20 years ago (from 50 Hz to 5 kHz) by *Richards* [1963] and *Woulff and McGetchin* [1976].

We have selected nineteen explosions, with a good signal to noise ratio, for this study. Seismic activity is low during these explosions, and the air wave recorded on the seismometer is much more energetic than the ground waves. If the source of vibration is buried below the surface, its energy will go preferentially to the ground. Here the reverse happens, which suggests that the source of vibration is very shallow for the Eastern vent. For the Eastern and Western vents (Fig 1), lava was observed less than 10 m below the surface, 20 years ago [*Chouet et al.*, 1974], and is still probably at that level for the Eastern vent, which has not build up a cone as above the Western vent. Hence, for the Eastern vent, the sound is not produced by the volcanic tube, as was proposed before for strombolian eruptions [*Woulff and McGetchin*, 1976]. Here, we propose to explain the frequencies of the sound by a large bubble breaking at the magma-air interface.

The excess pressure recorded in the air shows three distinct parts (Fig 2a, 2b): a very weak signal before the explosion (part 1), followed by a strong wave (part 2) and a weaker signal (part 3). Part 2 shows a well-marked oscillation of low frequencies around 7 Hz (Fig 2c) which starts by a compression of the air followed by an expansion. After that, the signal changes dramatically and higher frequencies appear on the acoustic pressure records (at 2.1 s, Fig 2a), superimposed on lower frequencies (less than 4 Hz) (Fig 2a). The spectral analysis shows that the dominant frequency of the large signal (Fig 2c), is also present before the first peak, albeit with a lesser amplitude (Fig 2d). This suggests that the source observed in the strong wave is already radiating energy before the main event.

To understand the origin of the acoustic pressure, it is necessary to separate source and path effects. This was achieved in April 1992 by recording simultaneously six explosions at approximately 200 m and 370 m from the Eastern vent (Fig 1). The waveform is similar at both sites (Fig 3a and 3c), distant by 600 m, and similar to explosion 129 (Fig 2a). Hence, the low frequency of the well-marked oscillation is related to the source. For these 6 explosions, the attenuation of

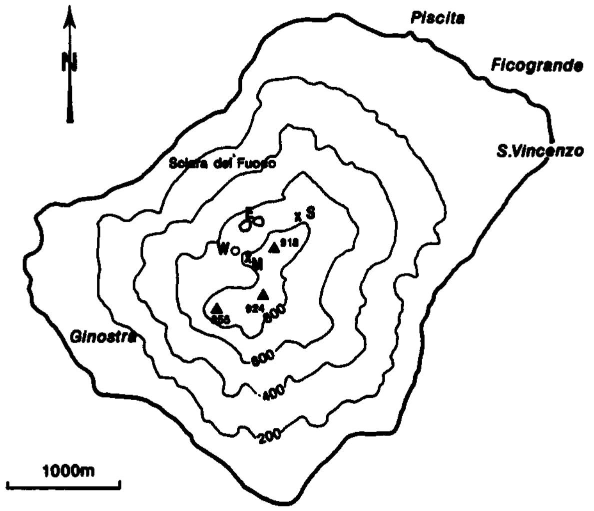

Figure 1. Map of Stromboli volcano, showing Western vent W and Eastern vent E. The topography of the volcano is such that the path of acoustic waves in air is free of solid obstacles from the vent to the sites of measurements (M and S).

the acoustic pressure with distance (Fig 3b and 3d) suggests that the source contains a strong monopole component [*Lighthill*, 1978].

Different mechanisms of sound production

We first consider breaking gravity waves at the surface of the lava because they can produce at the same time fragmentation of the lava surface and sound. In a tube, gravity waves may develop with a wavelength λ, for which the frequency f_g is [*Whitham*, 1974; *Temkin*, 1981; *Lighthill*, 1978]:

$$f_g = (2\pi)^{-1} (g/\lambda)^{1/2} \quad (1a)$$

where g is the acceleration of gravity. The wavelength λ is on the order of the conduit radius. The frequency is equal to 0.5 Hz for a radius of one meter. Hence, gravity waves can not explain the observed frequency of 7 Hz. Other sources of sound may be considered, such as resonant normal mode surface waves, but only one explosion among 25 shows more than one cycle before higher frequencies appear. Furthermore, they do not explain why the explosion produces ejecta. Any mechanism involving resonance to produce sound, like the acoustic resonance of the crater for example, seems therefore unlikely.

Measurements suggest that the source can be modelled as an isotropic point source, such as a bubble breaking at the magma surface. It is tempting to relate the sharp pressure rise at 1.66 s (Fig 2a) to the bursting of a bubble at the surface. A simple analogy of bubble bursting is the classical problem of balloon bursting due to overpressure [*Whitham*, 1974; *Temkin*, 1981]. The acoustic pressure recorded in air at a certain distance shows only one cycle, with a compression of air followed by an expansion of similar intensity. The period τ depends on the balloon radius R_0 and the sound speed in air c [*Lighthill*, 1978]:

$$\tau = 2 R_0 / c \quad (1b)$$

For c = 340 m/s and R_0 = 1 m as is assumed for bubbles at Stromboli from the vent size, the resulting frequency, 150 Hz, is much higher than the frequency observed in the well marked oscillation. In a previous study where low frequencies could not be recorded, *Richards* [1963] has shown that the peak frequency is around 150 Hz, within a broad spectrum, for a strombolian eruption of Mihara Yama volcano (Oshima, Japan, 1950). At Stromboli volcano, the source of the sound produced by an explosion, approximately 7 Hz, is also present before the first strong peak (Fig 2d). Therefore, bubble bursting is probably not the source of the powerful 7 Hz signal. Indeed, high frequencies appear 0.4 s into the event, but with a surprisingly low amplitude (Fig 2a, 2c). We suggest that these higher frequencies are caused by bursting. An alternate mechanism has to be called in order to explain the frequency of 7 Hz observed in parts 1 and 2 (Fig 2a).

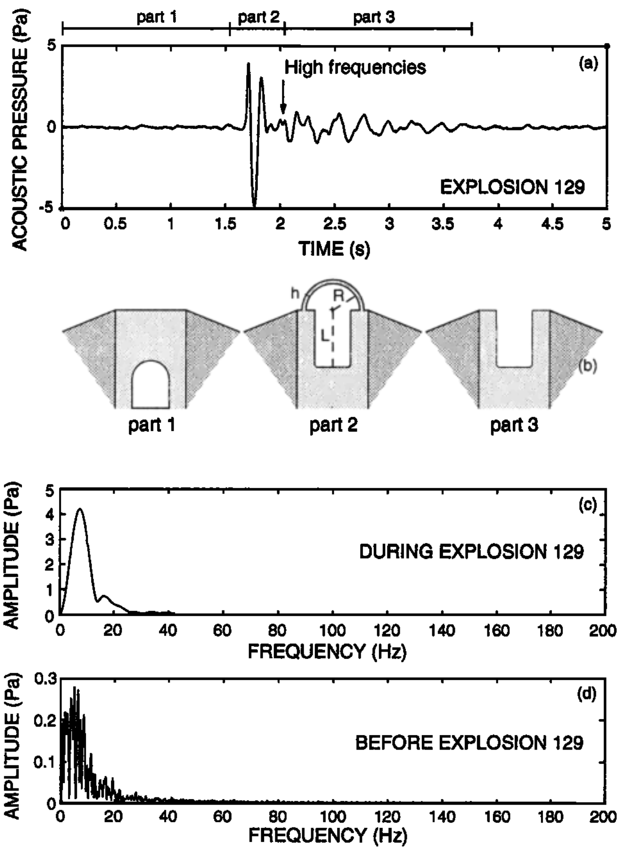

Figure 2. Recorded acoustic pressure during explosion 129 at M, 200 m from Eastern vent (a) as bubble rises in conduit (b). (c) Spectrum between 1.66 and 1.87 s with maximum amplitude at 7 Hz. (d) Spectrum 1.6 s before the explosion with maximum amplitude at 6 Hz.

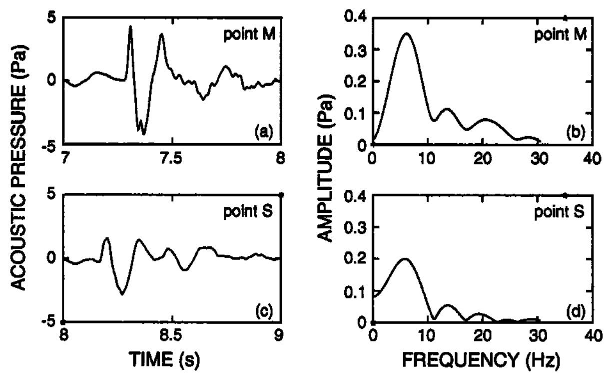

Figure 3. (a) Acoustic pressure recorded during explosion 610 at M. (b) Spectrum at point M between 7.28 and 7.49 s. (c) Acoustic pressure measured at point S, 370 m from eastern vent. The Brüel-Kjær microphone, type 2231, used in 1992 at S, is much more sensitive to low frequencies (-3 dB at 1 Hz) than the microphone used at M in 1991 and 1992 (-3 dB at 4 Hz). (d) Spectrum at point S from 8.16 to 8.37 s.

If the source of sound is below the lava surface, like a rising bubble (part 1, Fig 2b), the small amplitude of acoustic pressure before the main event can be a consequence of low transmission efficiency between liquid and gas [*Temkin*, 1981]. During the main event, the bubble is static at the lava surface and radiates a lot of energy (part 2, Fig 2b). When the gas escapes from the bursting bubble, the lava level drops quickly from a few meters (part 3, Fig 2b). Echos inside the crater and drainback of magma down into the conduit contribute to the last part of the recorded acoustic pressure .

Modelling bubbles as oscillators

Small bubbles floating at the liquid-air interface have been observed to vibrate for a few cycles before bursting [*Lu et al.*, 1989]. Here, we propose that the first low-frequency signal is due to such vibrations. Spherical bubbles in an infinite liquid have 3 different modes of oscillations involving shape and volume [*Lu et al.*, 1989]. The shape is constrained by surface tension and oscillates about the spherical form in various modes [*Lighthill*, 1978]. The frequency, f_σ, of surface-tension mode of wavelength R is [*Lu et al.*, 1989] :

$$f_\sigma = (2\pi)^{-1}\,\sigma^{1/2}\,\rho_{liq}^{-1/2}\,R^{-3/2} \quad (2a)$$

where ρ_{liq} is liquid density, σ is surface tension, approximately 0.4 $N.m^{-1}$ in basalts [*Walker and Mullins*, 1981], and R the bubble radius.

The volume varies only in a mode for which the bubble remains spherical. For this volume-mode, the bubble expands when the gas is overpressurized, pasts the equilibrium radius with a non-zero expansion velocity and then overshoots. When the bubble is larger than equilibrium, the gas becomes underpressurized and the bubble contracts, generating an oscillation. For the volume-mode, the restoring force is due to the compressibility of gas [*Batchelor*, 1967; *Lighthill*, 1978] and the frequency f_v, assuming isothermal heat transfer inside the gas at pressure p_g, is [*Lu et al.*, 1989] :

$$f_v = (2\pi)^{-1}\,p_g^{1/2}\,\rho_{liq}^{-1/2}\,R^{-1} \quad (2b)$$

For a semi-infinite liquid, bubbles distort the interface when they reach it. Hence, a third mode of vibration exists, due to gravity, producing gravity waves. They are driven by a balance between the fluid's inertia and its tendency under gravity to return to a stable equilibrium, with heavier fluid underlying a lighter one [*Lighthill*, 1978]. The frequency f_g of gravity waves is given by equation (1a), taking the bubble radius R for the wavelength [*Lu et al.*, 1989].

For a small bubble oscillating at a liquid-air interface, the frequencies of different modes are scaled to those of an infinite liquid [*Lu et al.*, 1989]. If we assume that a bubble of 1 m in radius, as strombolian bubbles, stays spherical and vibrates mainly in liquid, the above relation gives frequencies of 2 10^{-3} Hz for the surface-tension mode, 0.5 Hz for the gravity mode, and from 1 to 3 Hz for the volume mode if the internal pressure inside the gas varies from 10^5 Pa to 10^6 Pa. Surface tension is very weak for large bubbles and the corresponding mode may be neglected. Because the bubbles in strombolian explosions are overpressurized during rise in the volcanic tube, the volume mode is the most energetic.

We have considered a bubble vibrating at the surface of an infinite liquid. Here, the bubble is very close to the conduit. *Prosperetti* [1986] has shown that the effect of solid boundaries on the frequency is small. The bubble is oscillating in a viscous liquid which could damp the vibrations and change the frequency. Therefore, we compare the observed frequency ω (given in radian, i.e. $\omega = 2\pi f = 44$) to the viscous damping coefficient β_v,which has the dimension of a frequency, and depends on the bubble radius R [*Prosperetti*, 1986] :

$$\beta_v = 2\,\mu\,\rho_{liq}^{-1}\,R^{-2} \quad (2c)$$

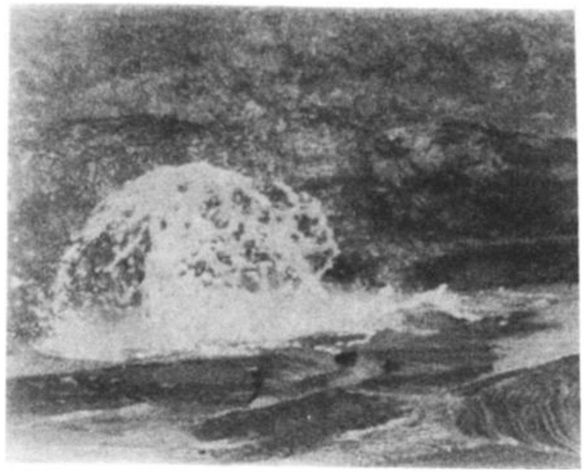

Figure 4. Photograph of a large bubble bursting at the surface of a lava pond (Puu o'o eruption, Hawaii, 1988).

Magma at Stromboli has a viscosity μ of 100 Pa.s [*Williams and Mc Birney*, 1979]. For a bubble of 1 m in radius, the damping coefficent β_v, 7.4 10^{-2}, is small compared to the radian frequency ω. Therefore, the real pulsation is hardly affected by the viscosity of magma [*Temkin et al.*, 1981].

For a spherical bubble in a liquid, the frequency of the volume mode is determined by a balance between inertia of liquid and compressibility of gas. A large bubble arriving at an interface, distorts it, and produces a hemispherical cap [*Lu et al.*, 1989], as was observed at Hawaii (Fig 4) and at Stromboli (P. Allard, pers. comm., 1993). The bottom part of the bubble is still immersed in the liquid and should vibrate at a frequency close to that produced by a bubble in an infinite liquid (part 2, Fig 2b). The hemispherical cap pushes simultaneously the liquid film around the nose of the bubble and the air surrounding the bubble. The bottom part and the hemispherical cap belong to the same bubble and hence, their vibrations are coupled. Because the magma is much more viscous than air (10^{-5} Pa.s [*Batchelor*, 1967]), the motion is far easier in air than in liquid. For small bubbles, strong deformations of the hemispherical cap have been observed [*Lu et al.*, 1989]. This suggests that the vibration is concentrated in the liquid film above the bubble. The sound is thus generated by the vibration of a membrane, the film of magma.

We can obtain the frequency of the volume mode from the general oscillation theory [*Lighthill*, 1978] by evaluating the kinetic and potential energy. The kinetic energy E_{kin} for a liquid film of thickness h small before the radius R can be written as:

$$E_{kin} = 0.5\,(2\,\pi\,\rho_{liq}\,R_1^2\,h_1)\,\dot{R}^2 \quad (3a)$$

where $\dot{R} = dR/dt$ is the radial velocity of the liquid film and index 1 corresponds to equilibrium values. At Stromboli, the thickness of the liquid film is probably on the order of the average size of ejecta thrown out during an explosion, approximatively 2.5 cm [*Chouet*, 1974], indeed small compared to the average bubble radius. The term in round brackets in (3a) is called the generalized inertia. The potential energy, for small oscillations, is related to the relative changes in gas density ρ_g inside the bubble:

$$(\rho_g - \rho_{g1})\,/\,\rho_{g1} = -\,2\,\pi\,R^2\,(R - R_1)\,/\,V_{g1} \quad (3b)$$

where the volume of gas V_g depends on the length of the cylinder L. The potential energy per unit volume, e_{pot} becomes:

$$e_{pot} = 0.5\,(\rho_g - \rho_{g1})^2\, c_g^2\, \rho_{g1}^{-1} \qquad (3c)$$

where c_g the sound speed in gas, is a function of the ratio of adiabatic heats γ [*Lighthill*, 1978] and of the pressure inside the gas p_g, assumed to be close to atmospheric pressure p_{air}:

$$c_g^2\, \rho_{g1} = \gamma\, p_g \qquad (3d)$$

The generalized stiffness is the term in square brackets in the expression of the total potential energy of the bubble E_{pot}:

$$E_{pot} = 0.5\left[4\,\pi^2\,\gamma\, p_{air}\, R^4\, V_{g1}^{-1}\right](R - R_1)^2 \qquad (3e)$$

The frequency f_{cyl} is then the ratio between generalized stiffness and inertia [*Lighthill*, 1978] :

$$f_{cyl} = \frac{1}{2\,\pi}\sqrt{\frac{2}{2 + 3\,(L / R_1)}}\,\sqrt{\frac{3\,\gamma\, p_g}{\rho_{liq}\, h_1\, R_1}} \qquad (4)$$

where γ is equal to 1.1 for hot gases [*Lighthill*, 1978].

For bubbles whose length is twice the radius, a minimum value for well-developed slug-flow [*Wallis*, 1969], a frequency between 4 and 7 Hz corresponds to a bubble radius between 0.6 and 1.9 m. If the length is four times the radius, these values become 0.4 and 1.1 m. Because the bubble radius is limited by the conduit size, variations in length may explain the variability in the low frequency content.

Conclusion

Acoustic measurements yield constraints on the physics of strombolian explosions, especially on the geometry of bubbles, and on the size of the vent. Measurements suggest that most of the acoustic energy is released prior to the bubble bursting itself. We propose that these bubbles oscillate weakly during their rise and strongly at the air-magma interface. These oscillations are driven by an overpressure inside the bubbles, when they rise in the conduit. The radius derived from the frequency analysis is in good agreement with observations.

Aknowledgments. We thank the help of J-C. Marechal, X. Hill, S. Tait, C. Jaupart, S. Sparks, G. Sartoris, J. Lister, A. Woods, R. Bonnecaze, H. Igel, V. Ferrazini, H. Lyon-Caen, P. Briole, M. Martini, P. Allard, C. Bercy, G. Bienfait, D. Breford, R. Verhille, F. Barberi and the Italian Civil protection. This work was supported by CNRS-INSU-DBT Instabiltés and Cordet 1992 programs. INSU contribution number 701.

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(Received: December 20, 1993; revised: April 5, 1994; accepted: May 16, 1994)