Acoustic measurements of the 1999 basaltic eruption of Shishaldin volcano, Alaska
2. Precursor to the Subplinian phase

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Abstract

The 1999 eruption of Shishaldin volcano (Alaska, USA) displayed both Strombolian and Subplinian basaltic activity. The Subplinian phase was preceded by a signal of low amplitude and constant frequency (\( \approx 2 \) Hz) lasting 13 h. This “humming signal” is interpreted as the coalescence of the very shallow part of a foam building up in the conduit, which produces large gas bubbles before bursting. The acoustic waveform of the hum event is modelled by a Helmholtz resonator: gas is trapped into a rigid cavity and can only escape through a tiny upper hole producing sound waves. At Shishaldin, the radius of the hole (\( \approx 5 \) m) is close to that of the conduit (\( \approx 6 \) m), the cavity has a length of \( \approx 60 \) m, and gas presents only a small overpressure between (\( \approx 1.2 \times 10^{-3} \) and \( 4.5 \times 10^{-3} \) MPa). Such an overpressure is obtained by the partial coalescence of a foam formed by bubbles with a diameter from \( \approx 2.3 \) mm at the beginning of the episode towards \( \approx 0.64 \) mm very close to the end of the phase.

The intermittency between hum events is explained by the ripening of the foam induced by the \( \text{H}_2\text{O} \) diffusion through the liquid films. The two extreme values, from 600 to 10 s, correspond to a bubble diameter from 2.2 to 0.3 mm at the beginning and end of the pre-Subplinian phase, respectively. The extremely good agreement between two independent estimates of bubble diameters in the shallow foam reinforces the validity of such an interpretation.

The total gas volume lost at the surface during the humming events is at most \( 5.9 \times 10^6 \) m\(^3\). At the very end of the pre-Subplinian phase, there is a single large bubble with an overpressure of \( \approx 0.42 \) MPa. The large overpressure suggests that it comes from significant depth, unlike other bubbles in the pre-Subplinian phase. This deep bubble may be responsible for the entire foam collapse, resulting in the Subplinian phase.

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Keywords: Shishaldin; eruption dynamics; acoustics; Subplinian activity; bubble

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doi:10.1016/j.jvolgeores.2004.05.004
1. Introduction

Numerical modelling, laboratory experiments and geophysical measurements on active volcanoes have been the three main lines of geophysical investigation of eruption dynamics. Laboratory geology has also been very useful for the estimation of parameters such as the volatile content or the extent of magma mixing. Recent numerical modelling has included conduit flow (Massol and Jaupart, 1999; Massol et al., 2001; Kaminski and Jaupart, 2001), physical processes at the vent (Woods and Bower, 1995; Morrissey and Chouet, 1997a,b; Morrissey and Mastin, 2000), and development of eruption columns in the atmosphere (Woods, 1988; Sparks et al., 1997). The transition between dispersed turbulent flow at the surface and a viscous bubbly flow in the lowest part of the volcanic conduit is still poorly understood and very few numerical models have been proposed (Alidibirov, 1994; Melnik, 2000).

Laboratory experiments on explosive eruptions have mainly focused on fragmentation processes by studying the sudden decompression of a saturated liquid (Phillips et al., 1995; Zhang et al., 1997; Mader, 1998). For basaltic eruptions, laboratory experiments have reproduced the qualitative and quantitative behaviour of Hawaiian and Strombolian eruptions (Jaupart and Vergniolle, 1988, 1989) and have been combined with pressure sensors to explain seismic activity at real volcanoes (Lane et al., 2001; Ripepe et al., 2001a,b).

Eruption dynamics have also been examined via seismic studies, commonly focused on volcanic tremor. Tremor frequencies have been explained using models such as the resonant eigenfrequencies of a spherical liquid source (Crosson and Bame, 1985) or the vibration of a plexus of dikes in response to magma migration (e.g., Chouet, 1996; Neuberg, 2000). Alternatively, low frequencies may result from path effects (McNut, 2000). For example, oscillations of a magma column containing small gas bubbles can explain the tremor at ≈ 2 Hz observed at Stromboli volcano, Italy (Chouet, 1996). More generally, tremor on basaltic volcanoes has been shown to be associated with shallow degassing (e.g., Ripepe, 1996; Ripepe and Gordeev, 1999; Hagerty et al., 2000). Low-frequency seismic events have shown promising results for understanding eruption dynamics at volcanoes such as Soufrière Hills (Montserrat, West Indies) (Neuberg, 2000; Neuberg et al., 2000), Stromboli (Chouet et al., 1999), Popocatepetl (Mexico) (Arciniegas-Ceballos et al., 1999, 2003), and Aso (Japan) (Kawakatsu et al., 2000).

Recently, acoustic measurements of active eruptions have been made on volcanoes using permanent microbarograph networks for strong explosive eruptions (Morrissey and Chouet, 1997a,b) or with infrasonic microphones for less explosive activity. In general, two main classes of models of acoustic signals exist for basaltic volcanoes. The first class is based on resonant modes of the volcanic conduit (Garce`s and McNutt, 1997; Garce`s et al., 2000; Hagerty et al., 2000), whereas in the second class, the source is modelled by large bubble vibration at the top of the magma column, induced by a strong inner gas overpressure (Vergniolle and Brandeis, 1994, 1996; Vergniolle, 2003; Vergniolle et al., this issue).

Vent pressure during an eruption can vary significantly. It has been estimated between 0.2 and 5 MPa at Sakurajima volcano (Japan) (Morrissey and Chouet, 1997b) and reached a peak of 1.4 MPa at Shishaldin volcano (Vergniolle et al., 2004-this issue). Vulcanian explosions at Popocatepetl (Mexico) (Arciniegas-Ceballos et al., 1999) are roughly of similar size as Sakurajima explosions (Japan), which is 10 to 100 times larger than explosions at Stromboli, ≈ 0.1 MPa (Vergniolle and Brandeis, 1996). Estimates from microbarograph recordings of explosive volcanoes give between 0.1 and 1.0 MPa at Mount Tokachi (Japan) in 1988, between 0.2 to 5.0 MPa at Mount Ruapehu (New Zealand), between 5.0 and 6.0 MPa during the 1975 Ngauruhoe eruption (New Zealand), and ≥ 5.0 MPa at Mount Pinatubo (Philippines) in 1991 (Morrissey and Chouet, 1997b). The initial overpressure, responsible for removing more than half of the edifice at Mount Saint Helens (USA), is 7.5 MPa at the start of the 1980 eruption (Kieffer, 1981).

During the ≈ 13 h prior to the Subplinian phase of the 1999 eruption of Shishaldin volcano, Alaska, an unusual infrasonic “ humming” signal was recorded. In this paper, we study some aspects of this “Pre-Subplinian phase”, including the hum events and the trigger bubble, which by initiating the Subplinian phase (Vergniolle and Caplan-Auerbach, subm. 3 and 4), puts an end to that episode. We first model the source of sound of the hum events by local
coalescence of a magmatic foam accumulating in the conduit. We estimate the bubble diameter by two independent methods, one based on the intermittency between hum events and the other one by using the estimates on gas overpressure in the hum events. Gas velocity, estimated by this acoustic power, is validated by the estimates obtained from the synthetic waveforms of the hum events. We then deduce gas volume and gas flux for the duration of the pre-Subplinian phase.

2. Description of eruptive activity

Shishaldin volcano is among the most active volcanoes in Alaska, with \( \approx 40 \) eruptions in the past 200 years (Nye et al., 2002). Its historical eruptions have been primarily Strombolian in nature, producing steam and ash plumes of basalt and basaltic andesite. Although the Subplinian eruption of April 1999 is not typical of Shishaldin’s eruptive behaviour, Beget et al. (1998) note that 11 such eruptions have occurred in the past 9 ka.

Shishaldin is one of five volcanoes comprising Unimak Island, the easternmost island in the Aleutian arc, and at 2.85 km above sea level is the highest point in the Aleutian Islands. The two nearest population centers are False Pass, located \( \approx 60 \) km west of Shishaldin on the island’s eastern coast, and Cold Bay, located on the Alaskan peninsula \( \approx 92 \) km from Shishaldin (Fig. 1). Unfortunately, Shishaldin cannot be seen from False Pass due to the presence of the nearer volcanoes Round Top and Isanotski. The Alaska Volcano Observatory (AVO) is therefore dependent on observers in Cold Bay for visual confirmation of eruptive activity. As a consequence, visual observations are minimal and AVO relies heavily on telemetered seismic data and satellite imagery for volcanic monitoring.

In 1997, a six-station seismic network was installed near Shishaldin (Fig. 1). Five of the stations are short period Mark Products L-4C instruments with natural period of 1 s. Station SSLS is a Mark Products three component L-22 instrument with 0.5-s natural period. A Setra 239 pressure sensor is co-located with station SSLN on the volcano’s north flank. Details about the pressure sensor installation and response are included in a joined paper (Vergniolle et al., this issue). Data from all instruments are telemetered to Cold Bay or King Cove and then to AVO over analogue telephone.
lines. Finally the data are low-pass filtered with a corner frequency of 20 Hz and digitised at 100 Hz with 12-bit resolution.

The 1999 eruption of Shishaldin was preceded by several months of seismic tremor and weeks of thermal anomalies in satellite imagery. Low-level tremor was first recorded in January 1999 and remained at elevated levels throughout February, and March. Thermal anomalies became a regular feature in satellite imagery in early March (Dehn et al., 2002). On April 18 1999, AVO researchers performed an overflight of the volcano. Although a thick cloud obscured Shishaldin’s summit, infrared imagery acquired on the overflight with a Forward Looking Infrared Radiometer (FLIR) shows spattering activity with ejection of lava ≈ several tens of meters above the vent (Nye et al., 2002). This was the first confirmation of extrusive activity at Shishaldin. The largest phase of eruptive activity began at 19:39 h in April 19 based on increases in seismic and acoustic amplitude (Caplan-Auerbach and McNutt, 2003). Coincident with this increase in tremor amplitude, satellite images show the development of an ash plume to heights above 16 km. This Subplinian episode is believed to be responsible for the majority of ejecta produced by Shishaldin in 1999 (Stelling et al., 2002).

Data recorded by the pressure sensor in April 19 begin with a prolonged band limited signal between 2 and 3 Hz (Caplan-Auerbach and McNutt, 2003). Although the signal appears to be continuous, close examination of the waveforms shows that it is composed of discrete pulses of energy. While the spectrum of this “humming signal” remained constant during the ≈13 h, it was recorded, signal amplitude and signal occurrence rate increased with time. The humming signal stopped in April 19 at 19:30 h UTC, immediately prior to the major increase in tremor amplitude at 19h35 (Caplan-Auerbach and McNutt, 2003). The Subplinian eruption was recorded by the pressure sensor and by the seismic network as a diffuse, ≈ 47-min signal with energy between 0.5 and 5 Hz. Details of this signal are discussed in two other papers (Vergniolle and Caplan-Auerbach, subm. 3 and 4).

Following the Subplinian phase in April 19, the pressure sensor recorded a sequence of signals interpreted as Strombolian bubble bursts (Thompson et al., 2002; Caplan-Auerbach and McNutt, 2003). A final episode of bubble-burst signals was recorded in

Fig. 2. (a) Cumulative number of hum events from 07:00 to 19:30 h UTC, April 19, 1999, selected with a coherence threshold of 0.7. T indicates the approximate location of the thermal (Vergniolle and Caplan-Auerbach, subm. 3). (b) Event maximum amplitude as a function of time.
April 22–23. The interpretation of these explosions in terms of bubble radius, length and overpressure is the subject of a joined paper (Vergniolle et al., this issue). The eruption stopped at the end of May after the production of several additional small ash plumes. The interpretation of the entire eruption chronology, such as the transition between Subplinian and Strombolian activity is discussed in another paper (Vergniolle and Caplan-Auerbach, subm. 5).

3. The pre-Subplinian phase

The pre-Subplinian “humming phase” began on the 19th of April at \( \approx 06:30 \) h, after 30 h of acoustic silence, and lasted for 13 h (Caplan-Auerbach and McNutt, 2003). The acoustic pressure record is characterised by the occurrence of very repetitive signals of frequency \( \approx 2 \) Hz and amplitude of a few Pa (Figs. 2–4). Because signal amplitude is extremely

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**Fig. 3.** The intermittency (s) between hum events as a function of time (s) for the quasi-duration of the pre-Subplinian phase, i.e., from 07:00 to 19:30 h, April 19. T indicates the approximate time of the thermal (Vergniolle and Caplan-Auerbach, subm. 3).

**Fig. 4.** Power spectra for 2 h before the proposed thermal (10:30–12:30 h) and 2 h following the thermal (14:30–16:30 h). Power spectra were calculated using a 8192 point fft with 50% overlap and compared to a rms reference pressure \( P_e \) of 20 \( \mu \)Pa. The Sound Pressure Level (SPL), i.e., the amplitude, is given in dB by \( \text{SPL}=20 \times \log \left( \frac{P_e}{P_{\text{ref}}} \right) \), where \( P_e \) is the measured effective pressure of the sound wave (Kinsler et al., 1982; Leighton, 1994). Although the number of “hum events” increased with time, the strongest spectral peak remained at \( \approx 2.2 \) Hz throughout the pre-Subplinian phase.
low for the first 30 min of the humming phase, our analysis of this phase begins with signals recorded at 07:00 h. Note that there is the formation of a thermal, i.e., a Vulcanian plume, occurring between 12:19 and 12:25 h (see shaded areas in Figs. 2 and 3). Since many measured and interpreted parameters during this phase appear similar to that of the Subplinian plume, despite a much smaller scale, the proposed thermal is presented in another paper together with the Subplinian event (Vergniolle and Caplan-Auerbach, subm. 3).

3.1. Modelling the hum events

To evaluate changes in the pre-Subplinian phase, we extracted pulses of the humming signal over the course of its duration, starting at 07:00 h. The extraction was achieved by first selecting a 3-s reference signal against which other pulses of signal would be compared. The last 12.5 h of the humming signal was divided into 3-s segments, each of which was cross-correlated with the reference event, and the coherency in the frequency band of the signal (1–4 Hz) was estimated at the point of maximum cross-correlation. Any portion of the signal that achieved coherency estimates exceeding 0.7 with the reference event was considered a pulse of the humming signal, and a 10-s segment around the event was extracted for analysis. The cumulative number and maximum amplitude of these events with time is shown in Fig. 2. There is an increase in the number of events and their amplitude as the pre-Subplinian phase (Fig. 2), approaches the Subplinian phase at approximately 19:31 h.

To reduce the noise level, the 12 h and a half period beginning at 07:00 h is divided into 25 parts, each lasting ≈ 30 min and all of the hum events during that time period are stacked (Fig. 5). Stacked waveforms of acoustic pressure show about three cycles of approximately the same frequency ≈ 2.2 Hz (Figs. 4 and 5). Such a frequency could be obtained by the resonance of a tube (Temkin, 1981) of length ≈ 40 m, however, the signal does not have any harmonics as would be expected in such a tube (Fig. 4). Furthermore, it is very unlikely that the level of magma would remain constant over 13 h, particularly as the humming signal immediately preceded the Subplinian eruption. Consequently, we exclude this model and consider instead a bubble source. Note that the magma is probably very close to the surface during the

Fig. 5. Stacks of 30-min worth of hum events selected using a coherence threshold of 0.7. They start at time 09:00, 11:00, 14:30 and 17:00 h and have 33, 115, 94 and 143 events, respectively.
Strombolian phases (Dehn et al., 2002; Vergniolle et al., this issue); thus, we neglect amplification by the conduit or the crater.

Waveforms such as the ones shown in Fig. 5 are similar to the appearance of a sound wave produced by a small bubble bursting at the ocean surface (Spiel, 1992; Leighton, 1994). The formation of a small hole on the upper part of a bubble connects the inner gas to the atmosphere outside (Fig. 6). The outer shell of the bubble is still in the liquid, which is assumed to behave rigidly. This assumption, which also supposes that the hole is set instantaneously at its final value, is validated by acoustic measurements on the bubbles in the ocean (Spiel, 1992; Leighton, 1994). The large viscosity of magma, which slows down the drainage in the liquid shell (Vergniolle et al., this issue), makes that assumption even more valid for Shishaldin magma. Sound is then produced by the motion of gas rushing from a small tube, the length of which is equal to the thickness of the liquid layer, into an infinite space. Sound emission is approximated by that of a piston mounted on an infinite baffle, which produces sound as a monopole source in the far field (Temkin, 1981; Spiel, 1992). The mass flow rate $q(t)$ through a circular hole of radius $R_{\text{hole}}$ is:

$$q(t) = \rho_{\text{air}} \pi R_{\text{hole}}^2 U$$

where $U$ the velocity of magmatic gas through the small aperture. The excess pressure in air, $p_{\text{ac}} - p_{\text{air}}$, produced at distance $r$ is related to the rate of mass outflow from the source by (Lighthill, 1978):

$$p_{\text{ac}} - p_{\text{air}} = \frac{\dot{q}(t - r/c)}{4\pi r}$$

For a piston emitting sound in a halfspace, acoustic pressure is:

$$p_{\text{ac}} - p_{\text{air}} = \frac{\rho_{\text{air}} \xi \pi R_{\text{hole}}^2}{2\pi r}$$

where $\xi$ is the displacement of air. If the dimensions of the resonator are small compared to the wavelength, here, 140 m for a $\approx 2$ Hz frequency, the behaviour of an element of air in the neck of an undriven Helmholtz resonator is:

$$m_{\text{helm}} \ddot{\xi} + R_{\text{helm}} \dot{\xi} + s_{\text{helm}} \xi = 0$$

where $m_{\text{helm}}$, $R_{\text{helm}}$ and $s_{\text{helm}}$ are the mass, the resistance coefficient leading to damping and the stiffness coefficient of the oscillator, respectively:

$$m_{\text{helm}} = \frac{\rho_{\text{air}} \varepsilon S_{\text{hole}}}{c}$$

$$R_{\text{helm}} = \frac{\rho_{\text{air}} \omega^2 S_{\text{hole}}^2}{2\pi c}$$

$$s_{\text{helm}} = \frac{\rho_{\text{air}} c^2 S_{\text{hole}}^2}{V_{\text{helm}}}$$

where $S_{\text{hole}}$ is the hole area, $V_{\text{helm}}$ is the volume of the resonator, $\varepsilon$ is the effective length of the orifice and $c$ is the sound speed in air, $\approx 340$ m/s (Lighthill, 1978). We look for a damped harmonic solution like:

$$\xi = A \exp(-t/\tau) \cos(\omega t + \phi)$$

where $A$ and $\phi$ are arbitrary constants to be determined by initial conditions. The relaxation time $\tau$ and the radian frequency $\omega$ are:

$$\tau = \frac{2m_{\text{helm}}}{R_{\text{helm}}}$$

$$\omega = \left[ \frac{s_{\text{helm}}}{m_{\text{helm}}} - \left( \frac{R_{\text{helm}}}{2m_{\text{helm}}} \right)^2 \right]^{1/2}$$

$$= \left[ \omega_0^2 - 1/\tau^2 \right]^{1/2}$$

$$\omega_0 = \left( \frac{s_{\text{helm}}}{m_{\text{helm}}} \right)^{1/2}$$

Fig. 6. The Helmholtz resonator is a rigid cavity of radius $R$ and length $L$. Gas can escape through a small hole of radius $R_{\text{hole}}$ with a velocity large enough to produce sound waves. $h_{\text{eq}}$ is the thickness of magma layer above bubble.
where \( \omega_0 \) is the radian frequency without damping. Calculations suggest that the effect of damping on the frequency can be ignored and it is confirmed by the results discussed below. It gives:

\[
\tilde{\xi} = -\omega_0^2 A \exp(-t/\tau) \cos(\omega t + \phi) \tag{12}
\]

\[
\omega = \omega_0 = \frac{c}{V_{\text{helm}}} (4\pi)^{1/2} \tag{13}
\]

If the gas overpressure is \( \Delta P \), the initial force on the mass of air will be \( \Delta P S_{\text{hole}} \). The initial speed of the mass is zero. Implicitly the mass of the rupturing film is ignored. This conditions lead to:

\[
\dot{\phi} = \arctan \left[ -\frac{1}{\omega_0 t} \right] \tag{14}
\]

\[
A = -\frac{\Delta P}{\rho_{\text{air}} \omega_0^2 \cos \phi} \tag{15}
\]

We adapt equations given by Temkin (1981) and Spiel (1992) for a cylindrical bubble of length \( L \), which has a volume \( V_{\text{helm}} \):

\[
V_{\text{helm}} = \pi R^2 L + 2\pi R^3/3 \tag{16}
\]

\[
S_{\text{hole}} = \pi R_{\text{hole}}^2 \tag{17}
\]

where \( R_{\text{hole}} \) and \( S_{\text{hole}} \) are radius and area of the hole, which is assumed both to be set at its value instantaneously and not to change in time. We shall see later that these assumptions are drastic at the beginning of the oscillation.

The velocity, \( \dot{\xi} \), within the orifice is:

\[
\dot{\xi} = -A \exp(-t/\tau)[\omega \sin(\omega t + \phi) + \cos(\omega t + \phi)/\tau] \tag{18}
\]

The effective length \( \epsilon \) of the oscillator is longer than the geometrical length, i.e., the thickness of magma layer above the bubble (\( h_{\text{eq}} \) in Fig. 6), because some of the air beyond the end of the neck also moves (Spiel, 1992). For the bubble at the surface, there is almost no neck, except the thickness of the magma layer above the bubble \( h_{\text{eq}} \), which is small compared to the bubble size (Vergniolle et al., this issue). The effective length \( \epsilon \) corresponds essentially to end corrections of a flanged piston, which are difficult to estimate since the behaviour of the gas about the orifice is nonlinear. Temkin (1981) suggests a value of \( \epsilon = 8R_{\text{hole}}/3\pi \) and Spiel (1992) a value of \( 8R_{\text{hole}}/3\pi \leq \epsilon \leq 16R_{\text{hole}}/3\pi \).

A synthetic waveform is calculated for each of the 25 stacks and the best fit between theoretical and measured waveforms is used to find the characteristics of the gas pocket bursting. Once the bubble has burst, the hot magmatic gas reaches atmospheric temperature very quickly due to strong turbulence within the gas. For simplicity, we shall assume that the sound speed to be used in the model is the sound speed in air, \( \approx 340 \text{ m/s} \).

### 3.2. Results from synthetic waveforms

We have only two equations for the magmatic gas rushing through the hole and three unknowns, namely the radius of the hole \( R_{\text{hole}} \), the bubble length \( L \) and its initial overpressure \( \Delta P \). However, the gas velocity through the hole (Eq. (18)) cannot exceed the sound speed and is probably less than during the Strombolian phase, \( \leq 80 \text{ m/s} \) (Vergniolle et al., this issue). For a hole smaller than 2.5 m, gas velocities through the aperture are unrealistic, above 200 m/s. The radius of the hole \( R_{\text{hole}} \) has to be smaller than the conduit, \( \approx 6 \text{ m} \), so we chose \( \approx 5 \text{ m} \), which is also the bubble radius during Strombolian phases (Vergniolle et al., this issue), and gives velocities between 10 and 40 m/s. The comparison between observations and a synthetic waveform calculated for a hole radius \( R_{\text{hole}} \approx 5 \text{ m} \) gives a very good overall agreement (Fig. 7). In these conditions, the effective length \( \epsilon \) varies between 8.5 and 4.3 m for \( \epsilon = 16R_{\text{hole}}/3\pi \) and \( \epsilon = 8R_{\text{hole}}/3\pi \), respectively.

However, there is a finite time during which the hole expands to its average radius \( R_{\text{hole}} \). This time cannot be included in the model and, consequently, the model is unable to match perfectly the first initial positive peak (Spiel, 1992). This is the same for the small bubbles in the ocean (Spiel, 1992) and various mechanisms have been proposed for the physics of bubble rupture. For a soap bubble with a very thin film, the rupture occurs in the inertial regime and gives a constant velocity as high as 10 m/s (Pandit and Davidson, 1990). More recent studies have discussed both the viscous regime leading to a lower velocity...
Debregeas et al., 1995) and a viscoelastic regime in which the rupture, much faster, occurs as a transverse wave (Debregeas et al., 1998). Because the physics of bubble rupture is extremely complex, the validation of the model is done by comparing with the bubbles in the ocean, which display a very similar waveform than the hum events.

After that finite time, however, the fit is very good between the synthetic waveform and the measured one although there is a slight phase lag at the second cycle, which may be due to either the enlargement of the hole beyond \( R_{\text{hole}} \) or emptying the gas in the cavity. We have chosen to optimise the fit at the beginning of the oscillations in case there are other sources of damping not considered in the model. The results are not significantly different from those obtained by fitting the model to the coda. Bubble lengths are found to be between 60 and 120 m and gas overpressure between \( \approx 4.2 \times 10^3 \) Pa and \( \approx 2.1 \times 10^3 \) Pa, respectively, for a hole radius of 5 m and the two limits on the effective length \( \varepsilon \) are 8.5 and 4.3 m, respectively. If the hole is only 4 m in radius, gas velocity and bubble length become 41 m/s and 50 m, respectively, for \( \varepsilon = 16R_{\text{hole}}/3\pi \). Gas velocity, estimated from synthetic waveforms, is not strongly dependent on \( \varepsilon \). Although both values of length and overpressure are acceptable, we prefer to take \( \varepsilon = 16R_{\text{hole}}/3\pi \) because this model yields bubble lengths that are very similar to the those used to model the Strombolian phases (\( \approx 80 \) and \( \approx 24 \) m; Vergniolle et al., this issue).

The hole radius (\( \approx 5 \) m) is small compared to the bubble length (\( \approx 60 \) m). Gas overpressure roughly increases between \( \approx 1.2 \times 10^3 \) Pa at the beginning of the pre-Subplinian phase to \( \approx 4.5 \times 10^3 \) Pa just before the Subplinian phase (Fig. 8). Although Shishaldin is a basaltic volcano and the intensity of the hum events very tiny, this gradual buildup in intensity is also observed on more silicic explosive eruptions such as Mount Pinatubo (Kanamori and Mori, 1992). This gas overpressure is small, in comparison to overpressure estimated for the large bubbles responsible for Strombolian explosions, with an average between \( \approx 0.83 \times 10^5 \) and \( \approx 1.5 \times 10^5 \) Pa (Vergniolle et al., this issue). This difference in gas overpressure between Strombolian explosions and hum events may explain why the waveforms for the two phases are so different. Gas overpressure during Strombolian explosions (Vergniolle et al., this issue) has been related to the significant depth of bubble formation (Jaupart and Vergniolle, 1988, 1989; Vergniolle, 2001). Since we shall interpret the Subplinian phase by a sudden disruption of a foam accumulated in the conduit (Vergniolle and Caplan-Auerbach, subm. 4), we suggest that these gas pockets results from the local coalescence on the top of the foam (Fig. 9).

The pre-Subplinian phase is divided into four main periods, for which histograms of the intermittency have been calculated (Fig. 10). There is a significant decrease in the maximum intermittency combined with a large increase in the number of events as the eruption approaches the Subplinian phase (Fig. 10). There are two long periods where the intermittency is small, less than 100 s, and two short periods where the intermittency can be as high as 10 min (\( \approx 08:00 \) and \( \approx 13:50 \) h) (Fig. 3). Histograms do not show any characteristic time scale, suggesting that the local coalescence of the foam does not occur as a simple layer by layer process as suggested for sudden decompression of a porous sample, used as an laboratory analogue of fragmentation during Plinian columns (Alidibirov and Panov, 1998).

Fig. 7. Comparison between a measured acoustic pressure (plain line) and a synthetic waveform (dashed line). The discrepancy on the first positive peak is attributed to initial enlargement of the hole, not instantaneously set at its average radius \( R_{\text{hole}} \). After that finite time, \( \leq 0.1 \) s, the fit is very good and the bubble radius, length and overpressure, are 5 m, 60 m and 4200 Pa, respectively. The radius of the hole is equal to the bubble radius, \( \approx 5 \) m, and the gas velocity is 36 m/s with an effective length \( \varepsilon = 16R_{\text{hole}}/5 \pi \approx 8.5 \) m.

(Debregeas et al., 1995) and a viscoelastic regime in which the rupture, much faster, occurs as a transverse wave (Debregeas et al., 1998). Because the physics of bubble rupture is extremely complex, the validation of the model is done by comparing with the bubbles in the ocean, which display a very similar waveform than the hum events.

After that finite time, however, the fit is very good between the synthetic waveform and the measured one although there is a slight phase lag at the second cycle, which may be due to either the enlargement of the hole beyond \( R_{\text{hole}} \) or emptying the gas in the cavity. We have chosen to optimise the fit at the beginning of the oscillations in case there are other sources of damping not considered in the model. The results are not significantly different from those obtained by fitting the model to the coda. Bubble lengths are found to be between 60 and 120 m and gas overpressure between \( \approx 4.2 \times 10^3 \) and \( \approx 2.1 \times 10^3 \) Pa, respectively, for a hole radius of 5 m and the two limits on the effective length \( \varepsilon \) are 8.5 and 4.3 m, respectively. If the hole is only 4 m in radius, gas velocity and bubble length become 41 m/s and 50 m, respectively, for \( \varepsilon = 16R_{\text{hole}}/3\pi \). Gas velocity, estimated from synthetic waveforms, is not strongly dependent on \( \varepsilon \). Although both values of length and overpressure are acceptable, we prefer to take \( \varepsilon = 16R_{\text{hole}}/3\pi \) because this model yields bubble lengths that are very similar to the those used to model the Strombolian phases (\( \approx 80 \) and \( \approx 24 \) m; Vergniolle et al., this issue).

The hole radius (\( \approx 5 \) m) is small compared to the bubble length (\( \approx 60 \) m). Gas overpressure roughly increases between \( \approx 1.2 \times 10^3 \) Pa at the beginning of the pre-Subplinian phase to \( \approx 4.5 \times 10^3 \) Pa just before the Subplinian phase (Fig. 8). Although Shishaldin is a basaltic volcano and the intensity of the hum events very tiny, this gradual buildup in intensity is also observed on more silicic explosive eruptions such as Mount Pinatubo (Kanamori and Mori, 1992). This gas overpressure is small, in comparison to overpressure estimated for the large bubbles responsible for Strombolian explosions, with an average between \( \approx 0.83 \times 10^5 \) and \( \approx 1.5 \times 10^5 \) Pa (Vergniolle et al., this issue). This difference in gas overpressure between Strombolian explosions and hum events may explain why the waveforms for the two phases are so different. Gas overpressure during Strombolian explosions (Vergniolle et al., this issue) has been related to the significant depth of bubble formation (Jaupart and Vergniolle, 1988, 1989; Vergniolle, 2001). Since we shall interpret the Subplinian phase by a sudden disruption of a foam accumulated in the conduit (Vergniolle and Caplan-Auerbach, subm. 4), we suggest that these gas pockets results from the local coalescence on the top of the foam (Fig. 9).

The pre-Subplinian phase is divided into four main periods, for which histograms of the intermittency have been calculated (Fig. 10). There is a significant decrease in the maximum intermittency combined with a large increase in the number of events as the eruption approaches the Subplinian phase (Fig. 10). There are two long periods where the intermittency is small, less than 100 s, and two short periods where the intermittency can be as high as 10 min (\( \approx 08:00 \) and \( \approx 13:50 \) h) (Fig. 3). Histograms do not show any characteristic time scale, suggesting that the local coalescence of the foam does not occur as a simple layer by layer process as suggested for sudden decompression of a porous sample, used as an laboratory analogue of fragmentation during Plinian columns (Alidibirov and Panov, 1998).
Gas velocity can be directly estimated from synthetic waveforms (Eq. (18)) or from acoustic power (Woulff and McGGetchin, 1976; Vergniolle et al., this issue). In the latter case, sound is radiated by the flat circular area of radius \( R \) hole and is a monopole source. Estimates of gas velocity from acoustic power, when using \( K_m = 1/16 \) (Vergniolle et al., this issue), gives very similar values, \( \approx 10-40 \) m/s, to those determined from synthetic waveforms. The difference between the two estimates (Fig. 8) is related to the initial mismatch between the first positive peak in synthetic waveforms and the measurements (Fig. 7). However, Fig. 8 shows that measuring acoustic power on remote volcanoes can provide quantitative information on gas velocity during an eruption.

Gas volume released at atmospheric pressure increases over the 12 h, from \( 5.0 \times 10^4 \) to \( 1.4 \times 10^5 \) m\(^3\), while gas flux increases from 50 to 750 m\(^3\)/s (Fig. 8). The mass flux varies from 20 to 300 kg/s for a composition of pure CO\(_2\) and has its lowest value, between 8.2 and 120 kg/s, for the end-member case of a pure H\(_2\)O phase. The total volume of gas lost through the hum events of the pre-Subplinian phase is \( 9.9 \times 10^6 \) m\(^3\), which is almost four times smaller than the amount lost during the first Strombolian phase and 10 times smaller than the gas volume of the second Strombolian phase (Vergniolle et al., 2004-this issue).

All these estimates have been determined for events selected with a coherency estimate of 0.7 to detect similar events in acoustic pressure. If we do the same analysis with a coherence threshold of 0.9, the total gas volume lost during the hum phase reduces to \( 1.4 \times 10^6 \) m\(^3\), due to the lower number of detected events, \( \approx 245 \) versus \( \approx 2000 \). All the waveforms picked up with a coherence threshold of 0.9 are definitively proper “hum” events, but there is ambiguity over some of them for the lower 0.7 coherence threshold. Therefore, \( 9.9 \times 10^6 \) m\(^3\) represents the maximum gas volume and \( 1.4 \times 10^6 \) m\(^3\) its minimum value. However, \( \approx 1100 \) events have been detected with an estimated coherency exceeding 0.8, and the
gas volume of each hum, \( \approx 5.3 \times 10^3 \text{ m}^3 \), is almost constant and independent of the threshold. Therefore, we suggest that the best estimate of the total gas volume lost during the pre-Subplinian phase is \( 5.9 \times 10^6 \text{ m}^3 \). The rationale for using a threshold of 0.7 is twofold. First, the number of detected events is large giving convincing stacked waveforms and showing a reliable time evolution of the hum characteristics during the pre-Subplinian phase (Fig. 8). Second, since the gas volume and gas flux have also been overestimated during the two Strombolian phases, comparison between the two regimes using the approximate average gas volumes and gas flux will be more reliable. These calculations show that there was a significant amount of degassing prior to the Subplinian phase, consistent with arguments put forth by Stelling et al. (2002).

### 3.3. Origin of overpressure within the hum events

In another paper (Vergniolle and Caplan-Auerbach, subm. 4), we show that the Subplinian phase can be modelled as a massive coalescence of a very long foam. In this light, the hum events of the precursory phase could also result from a series of partial collapses of the shallowest part of a foam trapped in the conduit. Foams in industry have been extensively studied and they can be produced, under certain conditions, in high-viscosity liquids, regardless of the properties of the gas–liquid interface (Prud’homme and Kahn, 1996). This is a consequence of the extreme slow drainage of the liquid separating the bubbles, which also prevents the films from breaking once the foam is established. Spontaneous disruption of foams can also be the consequence of the gas diffusion down the
concentration gradient (Prud’homme and Kahn, 1996). This gas diffusion exists between two bubbles if their diameters are different: large bubbles tend to grow at the expense of small bubbles, a process called the ripening of the foam (Prud’homme and Kahn, 1996). A diffusive time scale $\tau_d$ can be calculated (Navon and Lyakhovsky, 1998) by using the bubble diameter $d$ as a measure of the thickness of the liquid film between two adjacent bubbles and the diffusion constant $D_{H_2O}$, giving:

$$\tau_d = \frac{d^2}{4D_{H_2O}} \quad (19)$$

Although the bubbles in the foam come from the depth of the reservoir and are CO$_2$-rich (Vergniolle and Caplan-Auerbach, subm. 4), H$_2$O exists at a very shallow depth, less than a few hundreds meters, and may produce tiny bubbles within the liquid film close to the surface. Therefore the diffusion constant $D_{H_2O}$ may be that of H$_2$O, known to be a highly volatile specie in silicate melts (Dingwell, 1998). In a basaltic melt at 1200 C, the diffusion constant $D_{H_2O}$ is equal to $2 \times 10^{-9}$ m$^2$/s (Zhang and Stolper, 1991; Proussevitch and Sahagian, 1996). If the intermittency between hum events is associated with the spontaneous disruption of the foam by gas diffusion, the diffusive time scale can be used as a rough measure of the time separating two successive events of local coalescence. In that case, the two extreme values of intermittency, 10 and 600 s (Figs. 3 and 10), corresponds to bubble diameters between 0.3 and 2.2 mm. Note that the intermittency is $\approx 200$ s when the proposed thermal starts at 12:19 h (Vergniolle and Caplan-Auerbach, subm. 3), which corresponds to a bubble diameter of $\approx 1.3$ mm.

Laboratory experiments shows that a foam layer at the top of a bubbly liquid of viscosity 0.1 Pa s can be locally unstable and can partially coalesce producing large gas pockets (Fig. 11). These are perfect laboratory analogue of the hum events recorded at Shishaldin. One can note that the diameter of the analogue hum, i.e., the large bubble on the top of the foam, is slightly less than the diameter of the conduit (Fig. 11), as assumed above for calculating the length of the gas pocket.

If the hum events correspond to the coalescence of the upper part of the foam, their overpressure is...
related to the overpressure existing in each of the small bubbles composing the foam. The overpressure \( \Delta P_{\text{hum}} \) existing in small bubbles is mainly related to their capillary pressure, i.e., to their diameter \( d_{\text{foam}} \) and surface tension \( \sigma \) by (Spiel, 1992):

\[
\Delta P_{\text{hum}} = 8\sigma / d_{\text{foam}} \tag{20}
\]

The factor 8, instead of the more commonly used factor 4, reflects the fact that bursting the foam occurs at a free surface, distorted by the updoming of individual bubbles (Fig. 11) and therefore two curved interfaces, between the magmatic gas and air, are broken at coalescence (Bikerman, 1973). If the hum event is the result of a series of coalescence events each involving two small bubbles, the overpressure in the resulting large bubble can be approximated by the capillary pressure (Eq. (20)). For a surface tension, \( \sigma \approx 0.36 \text{ kg s}^{-2} \) for a basaltic magma at 1200 °C and 0.1 MPa (Proussevitch and Kutolin, 1986; Proussevitch and Sahagian, 1996), an overpressure \( \Delta P_{\text{hum}} \) from \( 1.2 \times 10^{-3} \) to \( 4.5 \times 10^{-3} \) MPa corresponds to a bubble diameter between \( \approx 0.64 \) and \( \approx 2.3 \) mm. This is also in the range of bubble diameters, between 0.3 and 2.2 mm, deduced by associating the intermittency with gas diffusion in the foam. Thus, we see that the largest bubbles, with diameters of \( \approx 2.3 \) mm, correspond to the beginning of the pre-Subplinian phase, also the time with largest intermittency. Similarly, the smallest bubbles, \( \approx 0.64 \) mm, correspond to the shortest intermittency, approaching the onset of the Subplinian phase. Further note that the gas overpressure between 12:00 and 12:30 h, corresponds to a bubble diameter of 1.1 mm (Eq. (20)), very similar to the value found from the intermittency, \( \approx 1.3 \) mm (Eq. (19)). This excellent agreement between overpressure in the hum and intermittency, both at the beginning and at the end of the pre-Subplinian phase, suggests that the shallow foam collapse is controlled by the gas diffusion. The measured intermittency between hum events also shows that the same phenomenon probably exists for the two periods, from 07:30 to 12:00 h and from 14:00 to 19:30 h (Figs. 3 and 10). Because the latter period culminated with a Subplinian plume, the similarity in intermittency reinforces the model of a thermal, i.e., a small ash burst, at the end of the first period (Vergniolle and Caplan-Auerbach, subm. 3). Further note that our estimates of bubble diameter at the top of the magma column are in agreement with observations of bubbles in Shishaldin scoria, which ranges from tiny, i.e., submillimetric, to several centimeters for those with coalescence just after expulsion (P. Stelling, personal communication, 2003).

Since the hum events correspond to partial foam coalescence, the length of the unstable foam can be estimated from its gas volume. Each hum has a gas volume of \( \approx 5.3 \times 10^3 \text{ m}^3 \) and is compressed under its own weight towards its base. The length of the upper foam which regularly collapses is \( \approx 28 \) m for a gas volume fraction in the conduit of 0.6 (Vergniolle and Caplan-Auerbach, subm. 4). It has a characteristic length between two and three times the diameter of the conduit, \( \approx 12 \) m (Vergniolle et al., this issue), whereas it was about half of the radius in laboratory experiments (Fig. 11).

A time series of gas overpressure (Fig. 8a) shows that for the second fourth of the pre-Subplinian phase, gas overpressure undergoes a few very large oscillations with a period of \( \approx 6800 \) s (\( \approx 01:54 \) h). The fact that this feature is not seen at other times during the eruption strongly suggests that it results from the

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![Fig. 11. Foam formed at a top of a bubbly liquid, here, a silicone oil (Rhodorsil 47V100) of viscosity 0.1 Pa s. The foam is partially unstable and produces large gas pockets, which is the laboratory equivalent of the hum events recorded at Shishaldin. Note that the upper part foam on the left-hand side contains bubbles which are both not spherical and larger than below. These small bubbles correspond to next coalescence event that will happen on the top of the foam, and this region is the future hum event in formation. Note that the interface is distorted by the updoming of individual bubbles.](image-url)
eruption dynamics of the pre-Subplinian phase. This period of \( \approx 6800 \) s is much longer than that observed at Popocatepetl either for Vulcanian explosions, \( \approx 28 \) s (Arciniega-Ceballos et al., 1999) or for long-period events, from 0.04 to 90 s (Arciniega-Ceballos et al., 2003). It is also two orders of magnitude above the period of Strombolian explosions, with spectral peaks at \( \approx 3, \approx 6 \) and up to 20 s at Stromboli (Chouet et al., 1999) and at \( \approx 20, \approx 11 \) and \( \approx 7 \) s at Erebus (Rowe et al., 1998). It is also longer than acoustic and gravity modes of the atmosphere, \( \approx 300 \) s, as detected during large explosive eruptions such as Mount St Helens, Krakatao, Pinatubo and El Chichon (Kanamori et al., 1994). However, at Soufrière Hills, swarms of hybrid events precede major dome collapse and occur with periodicities of 4 to 12 h, which correlate very well with the radial tilt of the flank of the volcano (Neuberg et al., 1998). Repetitive Vulcanian eruptions have been reported at intervals between 0.5 to 1 h at Mount Ngauruhoe (Nairn and Self, 1978), around 10 h at Soufrière Hills (Druitt et al., 2002). At Mount Pinatubo, a sequence of explosions with periodicity ranging from 10 to 28 h occurred just prior to the climactic eruption (Hoblitt et al., 1996).

4. End of the pre-Subplinian phase

At 19:31:03 h in April 19, the humming signal that defines the pre-Subplinian phase abruptly ends. At this time, the acoustic record shows a waveform with an initial positive peak followed by a larger negative one (Fig. 12). The waveform for this event is very similar to the ones generated during Strombolian activity (Vergniolle et al., 2004-this issue) and is modelled by the strong vibration of a large and highly overpressurised bubble at the top of the magma column (Vergniolle and Brandeis, 1994, 1996). Approximately 9 min later, both the acoustic and seismic records show a strong broadband signal that has been interpreted as the beginning of the Subplinian phase (Caplan-Auerbach and McNutt, 2003). Because it appears to mark the transition between the pre-Subplinian phase and the Subplinian, we refer to this waveform as the “trigger bubble” (Vergniolle and Caplan-Auerbach, subm. 3 and 4).

Details of the modelling of this type of event can be found in a joined paper (Vergniolle et al., this issue). By analogy to the results found during the two Strombolian phases, the thickness of the layer of magma above the about-to-break bubble is taken to be \( \approx 0.15 \) m. The fit is excellent between the model of bubble vibration and the measured acoustic pressure. Bubble radius, length and overpressure are very similar to estimates from the two Strombolian phases (Vergniolle et al., 2004-this issue). However, the bubble length at the vent \( (L \approx 15 \) m) is much shorter for this large bubble than for the rest of the pre-Subplinian phase \( (L \approx 60 \) m). Gas overpressure is very large in this trigger bubble, \( \Delta P \approx 0.42 \) MPa, and much higher than other bubbles produced during the rest of the pre-Subplinian phase, from \( \Delta P \approx 1.2 \times 10^{-3} \) to \( 4.5 \times 10^{-3} \) MPa. At Stromboli, the large overpressure, \( \approx 0.10 \) MPa (Vergniolle and Brandeis, 1996) still present in the large bubbles breaking at the top of the magma column is acquired at their formation at the depth of the reservoir (Vergniolle, 2001). By analogy, we suggest that this final bubble of the pre-Subplinian phase is formed at.

![Fig. 12. Comparison between the measured acoustic pressure (solid line) and the synthetic waveform (dashed line) for the “trigger bubble”, a Strombolian bubble signal recorded immediately prior to the Subplinian eruption. The waveform is characteristic of a large overpressurised bubble, whose radius, length and overpressure are 5 m, 15 m and 0.42 MPa, respectively. Magma thickness over the bubble, \( h_{\text{eq}} \), is 0.15 m, magma viscosity, \( \mu \), is 500 Pa s. Time \( t=0 \) is 18:00 h, the April 19, 1999.](image-url)
the depth of the shallow reservoir (Fig. 9d), unlike bubbles producing the hum at \( \approx 2 \, \text{Hz} \) (Fig. 9a and c). Although this gas overpressure is within the average overpressure obtained for the two Strombolian phases, it is above the “normal” value, \( \approx 0.083 \) and \( 0.15 \) MPa for the first and second phase and closer to the peak value \( 1.4 \) MPa (Vergniolle et al., this issue).

The Subplinian phase initiates when the trigger bubble breaks at the top of the magma column (Fig. 9). The exact time that the explosive phase begins is uncertain; it has been cited as 19:35 h based on seismic tremor amplitudes (Thompson et al., 2002) and at 19:39 h based on the spectral content of the acoustic record (Caplan-Auerbach and McNutt, 2003). This suggests that there is a minimum of 4 min between the arrival of the bubble and the collapse of the foam in the conduit. Furthermore, the formation of the trigger bubble at the depth of the reservoir must have occurred before that, since the bubble rises at a finite velocity, \( \approx 26 \) min, from the reservoir at 5-km depth through the foam to the surface with the last 14 min within the foam itself (Vergniolle and Caplan-Auerbach, subm. 3 and 4). During the time that the bubble rises through the conduit, however, the acoustic record shows no sharp change in either the amplitude or number of hum events. Thus, there is no evidence at the surface that the trigger bubble, while rising, induces more local coalescence in the shallowest part of the foam. We therefore propose that the Subplinian phase is instigated by the arrival of the trigger bubble at the surface, at 19:31 h, and that there is a small finite time in which this event triggers foam collapse. The detailed modeling of the trigger bubble and its relationship to the Subplinian phase is discussed by Vergniolle and Caplan-Auerbach, (subm. 4).

However, the timing between the end of the humming phase, the arrival of the bubble and the onset of the Subplinian activity confirms that there is a clear relationship between the rise of the trigger bubble through the foam-filled conduit and the onset of the Subplinian eruption (Vergniolle and Caplan-Auerbach, subm. 4).

5. Conclusion

Acoustic measurements provide a quantitative understanding of the eruption dynamics. Modelling the source of the sound during the pre-Subplinian phase shows that large \( (L \approx 60 \, \text{m}) \) and weakly overpressurised bubbles, \( 1.2 \times 10^{-3} \) and \( 4.5 \times 10^{-3} \) MPa, break regularly at the surface. These bubbles correspond to local coalescence of the upper part of the foam, which is slowly building up in the volcanic conduit during the pre-Subplinian phase. The bubble diameter at the top of the foam in the conduit decreases from \( \approx 2.3 \) to \( \approx 0.64 \, \text{mm} \), right before the Subplinian phase. The intermittency of the hum events, which is explained by \( \text{H}_2\text{O} \) diffusion in the liquid film separating the bubbles, leads to an estimate of bubble diameters between 2.2 and 0.3 mm at the beginning and the end of the pre-Subplinian phase, respectively. This excellent agreement existing between these two independent estimates of bubble diameter reinforces the interpretation of hum events as the shallow collapse of a foam.

At the very end of the pre-Subplinian phase, there is a single large overpressurised bubble, \( (L \approx 15 \, \text{m}) \). The large overpressure, \( \approx 0.42 \) MPa, suggests that it comes from the depth of the magma chamber, unlike other bubbles in the pre-Subplinian phase (Vergniolle et al., this issue). This bubble may be responsible for the entire foam collapse, resulting in the Subplinian phase (Vergniolle and Caplan-Auerbach, subm. 4).

Acknowledgments

We thank Milton Garce`s for taking the initiative to install a pressure sensor at Shishaldin. We are grateful for the support of the Alaska Volcano Observatory, as well as the support of our colleagues, notably P. Stelling and S. R. McNutt. We also thank Matthias Hort and two anonymous reviewers. This work was supported by CNRS-INSU (ACI and PNRN: contribution number 324) and by the french Ministère de l’Environnement (number 122/2000). This is a IPGP contribution number 1946.

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