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Seismicity related to the glacier of Cotopaxi Volcano, Ecuador

Jean-Philippe Métaxian,^{1,2} Sebastián Araujo,^{1,2} Mauricio Mora,^{2,3} and Philippe Lesage²

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[1] Significant seismic activity is generally recorded on volcanoes covered by an icecap. This work was carried out in order to quantify the role of the glaciers in the generation of seismicity for Cotopaxi volcano. We compared the seismic activity registered on the glacier and on the rock near the snout of the north flank glacier. We focused on the analysis of low frequency events (<5 Hz) similar to volcanic LP events when recorded on rock base. The particle motion analysis helps to estimate source locations, which are distributed in crevasses areas. High incident angles suggest a superficial origin. These events are interpreted as icequakes for which we propose as source mechanism a fluid-driven crack model triggered by ice cracking or hydraulic transients. The low quality factor values estimated are consistent with the resonance of an ice crack filled with water. This work shows that low frequency icequakes can be confusingly taken as volcanic LP events. *INDEX TERMS:* 7280 Seismology: Volcano seismology (8419); 8419 Volcanology: Eruption monitoring (7280); 9360 Information Related to Geographic Region: South America. *Citation:* Métaxian, J.-P., S. Araujo, M. Mora, and P. Lesage, Seismicity related to the glacier of Cotopaxi Volcano, Ecuador, *Geophys. Res. Lett.*, 30(9), 1483, doi:10.1029/2002GL016773, 2003.

1. Introduction

[2] Situated in the damp Cordillera Real of Ecuador, 60 km south of Quito, Cotopaxi volcano (5897 m) is an active andesitic stratovolcano covered by an icecap on the uppermost 1000 m of the cone. Seismic monitoring performed by the Instituto Geofísico of the Escuela Politécnica Nacional showed an unusual amount of long period events for a quiet volcano. This activity was located between 2 km and 14 km depth below the summit [Ruiz *et al.*, 1998]. The authors explained the continuous occurrence of LP events as the interaction of glacier thaw water and hot material at shallow depths. Using an additional seismic array operated near the summit, Métaxian *et al.* [1999] showed that most of the events originate at the top of the cone (depth <2 km under the summit). They suggested that the glacier could contribute directly to the seismic activity, for example by serac falls visually observed. There are few studies on seismicity related to glaciers in volcanic areas. Nevertheless, some experiments were carried out on Mount Saint Helens by setting up sensors over rock and over icecap [Weaver and Malone, 1976, 1979]. Observations showed a high frequency content for the near-field records on ice and a low frequency content for records

on rock base. The few located events had depths comparable with the glaciers' thickness. The authors suggested that the larger glacier events were the result of a stick-slip type of motion taking place at the bed of the glacier.

[3] The work on Cascades volcanoes pointed out the risk of confusion in volcano warning systems between icequakes and low frequency volcanic events. To address this problem on Cotopaxi, we proceeded to an experiment in a way similar to Weaver and Malone. Recordings made by two sensors set up one on rock base and one on icecap were compared by using several analysis criteria such as: time and spectral features, arrival times, wave polarization. This note yields to characterize a particular type of low-frequency icequakes, which we associate with resonances of water-filled pockets.

2. Data Acquisition

[4] We operated two RefTek stations with short-period seismometers Mark Products L4-3D with natural frequency at 1 Hz during 3 weeks in July 1998. One sensor was installed on the bedrock near the « Jose Rivas » Refuge at 4800 m height (C1 station) and the second one on the glacier (C2 station), 850 m horizontally to the south at a height of 5150 m and 1 km from the crater (Figure 1). The seismometer on the glacier was buried in ice at a depth of 0.5 m and was leveled once a week due to the glacier movement. GPS time receivers synchronized the recorders. They operated at 100 samples per second in a trigger mode using the STA/LTA algorithm with a low trigger threshold. Each record is one minute long.

3. Data Analysis

3.1. Seismicity

[5] We initially analyse the temporal evolution of the recorded seismicity. Figure 2 shows the histogram of seismicity and the mean amplitude of the seismic noise at both stations. It reveals an intense activity. The number of triggers can reach 60 per hour, which is almost equivalent to continuous recording. Moreover, several events can occur during one record as shown in Figure 3. The number of triggers at the ice station C₂ is twice that of the rock station C₁. Diurnal fluctuations of this number are observed at both stations and are clearly anti-correlated with the amplitude of the seismic noise. This is a consequence of the trigger algorithm, which detects fewer events when the noise level increases. On the other hand, the seismic noise is maximum during the warmer period of the day (18 UT). That time corresponds to the maximum water drainage and probably to an elevation of the water level in the glacier. Therefore part of the seismic noise could be related to water circulation in the glacier. Those observations suggest that most of the seismic activity comes from the glacier.

¹Institut de Recherche pour le Développement, Paris, France.

²Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, Le Bourget-du Lac, France.

³Escuela de Geología, Universidad de Costa Rica, San José, Costa Rica.

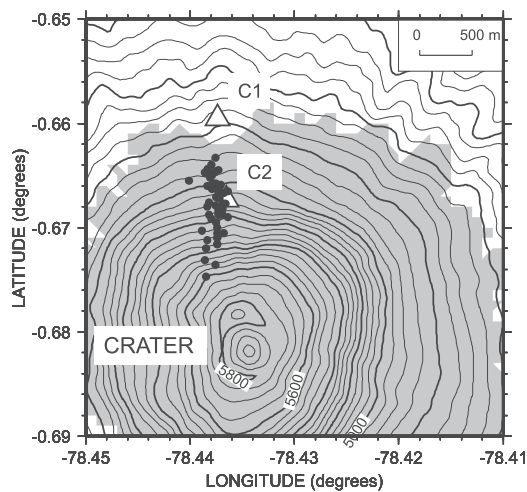


Figure 1. Map of the Cotopaxi volcano summit showing the location of the crater and the stations C_1 and C_2 (open triangles). The approximate contour of the glacier is represented in gray tint. Black circles represent the estimated location of the epicenters.

[6] Two types of event are differentiated by their spectral content and duration. The first type is characterized by high frequency content (>10 Hz) and a duration less than 1 sec (Figure 3). It represents respectively 85% and 95% of the triggers at C_1 and C_2 . Signals at frequencies higher than the Nyquist frequency probably exist. This type of event may be associated to ice crevassing or cracking [Neave and Savage, 1970; Deichmann et al., 2000]. The second type of event has lower dominant frequency (<5 Hz) and duration of the order of 10 sec (Figure 4). Both stations recorded an average of about 50 of these events per day. Our study focuses on the second type of event because they have similar features to LP volcanic events when they are observed by the monitoring array. Hereafter they will be called Long Period Ice (LPI) events.

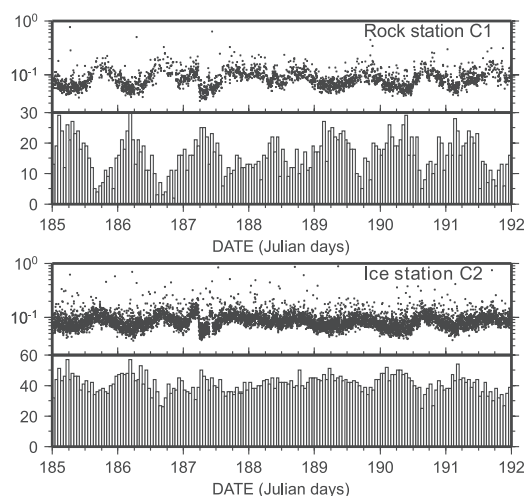


Figure 2. Mean level of seismic noise in $\mu.s^{-1}$ calculated in the 5 s time window preceding each trigger and histogram representing the number of triggers per hour at stations C_1 and C_2 for a period of one week. Time is UT.

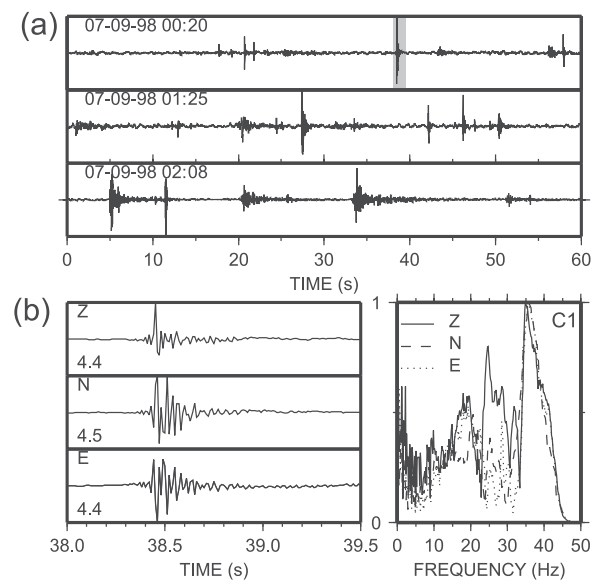


Figure 3. (a) Three examples of vertical records obtained at C_2 . The date and time (UT) of the first sample are indicated at the upper left of the record. (b) Three components seismograms of a typical icequake identified by the shaded zone in the first record, and corresponding normalized power spectra calculated on a 1.28 s long window.

3.2. Long Period Ice Activity

[7] The LPI events are characterized by onsets generally impulsive at C_2 and emergent at C_1 . The coda envelop decreases more quickly at C_2 (Figure 4). The spectra display complex contents with a low frequency dominant peak ($\sim 1-2$ Hz) and several peaks distributed up to 30 Hz (Figure 4). The high frequency peaks are attenuated at C_1 .

[8] In order to detect possible site effects, which could produce some of the observed spectral peaks, we applied the H/V spectral method [Mora et al., 2001]. Mean H/V ratios were calculated for a set of 25 LPI events (Figure 5).

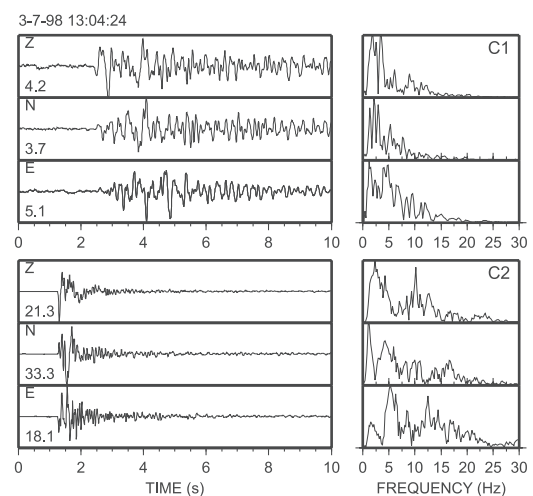


Figure 4. Three components velocity seismograms, and corresponding normalized spectra of a Long Period Ice (LPI) event recorded at C_1 and C_2 . The component and maximum amplitude ($\mu.s^{-1}$) are indicated at the left of the record.

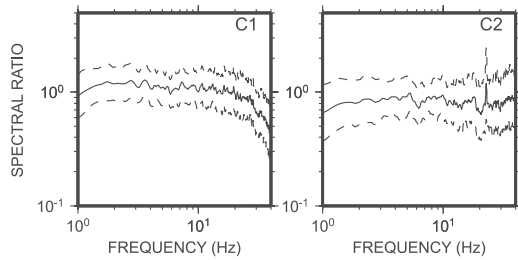


Figure 5. Mean H/V spectral ratios (solid lines), calculated for a set of 25 LPI events recorded at C_1 and C_2 stations, and mean ratios ± 1 standard deviation (dashed lines).

Almost no site effects are detected by this method, except a thin peak at 23 Hz at C_2 . This peak could be interpreted as a resonance of the glacier layer. The relation $f = V_s/2H$, where V_s is the velocity of S waves and H is the ice thickness, yields an estimation of the frequency of the fundamental resonance mode. Taking $V_s \sim 1.9 \text{ km.s}^{-1}$ [Deichmann et al., 2000] and $f = 23 \text{ Hz}$, we found $H = 41 \text{ m}$, which is consistent with the thickness of the glacier in this area.

[9] For almost all LPI events, the maximum amplitude is greater at C_2 with an amplitude ratio that can exceed 10. On the contrary, the amplitude ratio calculated for a set of 30 regional tectonic events is close to 1. This suggests that LPI events are closer to C_2 than to C_1 . This is consistent with P arrival times always smaller at C_2 . The maximal delay between both stations is 1.5 sec, which corresponds to an apparent velocity of 600 m.s^{-1} . This low value is consistent with propagation in a low consolidated medium.

3.3. Particle Motion and Source Location

[10] A set of 50 events with good readability of the waveform was selected. The particle motions were plotted for the very first onset of signals (a quarter or a half of the wave cycle), filtered between 0.5 and 5 Hz. The particle motions are rectilinear in the horizontal and vertical planes (Figure 6). The polarization of the first arrival obtained at 2 stations can be used to locate the sources. In the horizontal plane, the direction of P-wave polarization coincides with the azimuth of propagation; their intersection yields an estimation of the epicenters. The corresponding error is obtained by using a probabilistic approach [Métaxian et al., 2002]. Taking a standard deviation for the polarization direction of 5° , we obtain a mean precision of 200 m. The epicenters are concentrated in a zone close to C_2 , which corresponds to a crevasse area (Figure 1).

[11] In the vertical radial plane, the particle motion indicates large incident angles at both stations. Apparent incident angles can be retrieved from the observed particle motion by taking the volcano slope (24° between C_1 and C_2) into account. At C_1 they are in the range $[55^\circ - 66^\circ]$ for the whole data. Those incident angles are then corrected of free surface effects [Neuberg and Pointer, 2000], which give values in the range $[60^\circ - 90^\circ]$ for all events. For 70% of them, the angles are greater than 80° . At C_2 , all the corrected angles are greater than 80° . Taking these values and the epicenter locations into account, we estimate that most source depths are less than 140 m below C_2 . These results suggest that sources are probably in the glacier or at

the interface between rock and ice. These source locations are consistent with amplitude analysis and confirm that the LPI events are icequakes.

3.4. Source Model

[12] In view of the previous results, we search for a source mechanism for LPI events. Several source mechanisms for glacier quakes are described in the literature. Serac collapses or ice avalanches produce signals [Weaver and Malone, 1979], but their duration is higher than LPI events and the frequency of occurrence is generally much lower. Ruptures in rock or ice may also provide possible sources of events observed in glaciers. Shallow tectonic events occurring close to the base of the glacier can induce resonances of the glacier itself as proposed by Wolf and Davies [1986] for the source of low frequency signals observed near Prince William Sound, Alaska. In the latter case, the resonance peak is at 1–2 Hz, which corresponds to an ice thickness of 1 km. At Cotopaxi, the 40 m thick ice layer produces a 23 Hz peak resonance. Thus, this mechanism cannot explain the low frequency spectral peaks. Weaver and Malone [1979] found evidence indicating that icequakes are the result of a stick-slip motion at the bed of the glaciers. Icequakes could be induced by the friction between stones carried by the glacier and the rock base or by brittle deformations (shear faulting or extension) of ice or between ice and bedrock [Neave and Savage, 1970; Deichmann et al., 2000]. These rupture mechanisms generate high frequency signals and they can probably not explain the dominant low frequencies of the LPI events. In order to explain the spectral features of these icequakes, it appears necessary to consider models based on the resonance of fluid-filled cavities (cracks and other glaciers conduits). St. Lawrence and Qamar [1979] attributed the seismic source observed in glaciers to hydraulic transients generated by abrupt changes in water flow through sub glacial conduits. For single-conduit geometries, the period of the oscillating displacement is given by $T = 4L/a$, where L is the conduit length and a the wave speed. If the conduit is filled with water, we obtain for $T = 1 \text{ s}$ a minimal length of 350 m, which is too long for a small Andean glacier.

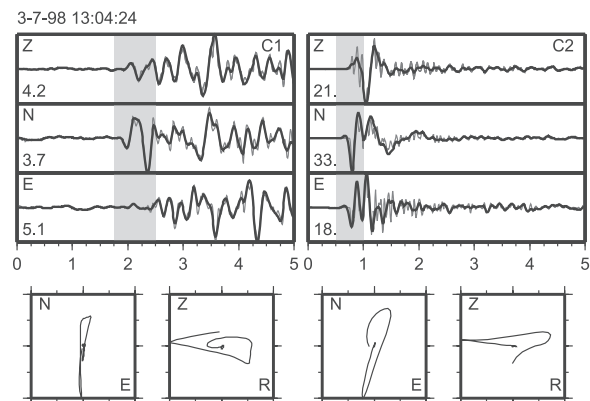


Figure 6. Original (thin lines) and filtered [0.5–5 Hz] (solid lines) three components records of a representative LPI event recorded at C_1 and C_2 . Normalized particle motions of the filtered records are displayed in horizontal (left) and radial-vertical (right) planes.

An other interpretative model is the fluid-driven crack model [Chouet, 1986]. The resonant period of the fluid-filled crack is much longer than that expected from acoustic resonance because of the presence of slow waves called crack waves. This allows explaining low frequencies with reduced source dimensions. The presence of crack waves can also explain several resonant modes in the spectrum, as it is observed for LPI events. Moreover, crack geometry is common in glaciers, with the form of either crevasses at the surface, fractures or water conduits within the glacier or at the bed [Paterson, 1994]. The crack could be excited by nearness ruptures in ice or by perturbations in water flow.

[13] Here after, we estimate the source parameters of the icequake events assuming a shallow ice crack filled with a fluid that we will determine. The stacked spectrum of 50 LPI events recorded at C₂ shows a dominant peak at 1.2 Hz. We estimate the quality factor Q describing the damping of oscillations by autoregressive analysis [Lesage et al., 2002]. We obtain values of Q between 1 and 3. The impedance contrast between ice and fluid is defined by $Z = \rho_i/\rho_f \cdot \alpha/a$, where ρ_i (916 kg.m⁻³) and ρ_f are the densities of ice and fluid, respectively, $\alpha = 3500$ m.s⁻¹ is the speed of compressional waves in ice and a is the acoustic speed of the fluid. Aki et al. [1977] formulated the energy loss due to radiation by: $Q_r^{-1} = 1/\pi \cdot \ln[(Z + 1)/(Z - 1)]$. In the context of a glacier, the fluid in a crack is either air or water. In the case of air, the density and the acoustic speed are at 0°C $\rho_f = 1.3$ kg.m⁻³ and $a = 331$ m.s⁻¹, respectively, therefore $Z = 7450$ which yields a very high value of Q. In the case of pure water at 0°C, $\rho_f = 1000$ kg.m⁻³ and $a = 1400$ m.s⁻¹. The resulting impedance contrast is $Z = 2.3$ and $Q_r = 3.4$. The quality factor describing the damping of oscillations is expressed by: $Q^{-1} = Q^{-1} + Q_i^{-1}$. Q_i^{-1} can be neglected as attenuation of acoustic waves in water is weak. Consequently, Q has a value of 3.4, which corresponds to the observations. This result indicates thus that the fluid involved in the source of icequakes is water.

[14] The properties of the fluid and solid are fixed by the dimensionless ratios α/a , ρ_f/ρ_i and b/μ , where $b = 2.2 \cdot 10^3$ Mpa and $\mu = 3.8 \cdot 10^3$ Mpa are respectively the bulk modulus of water and the ice rigidity. The crack stiffness is defined by $C = bL/\mu d$, where L is the crack length, d the crack thickness and b/μ has a value of 0.58. Thus, the value of C mainly depends on the ratio L/d . C has a low value for a widely opened crevasse and conversely a high value for a narrow crack. In the following, we suppose that C is between 100 and 500. To estimate the geometrical parameters of the crack, we used the dispersion curves calculated by Chouet et al. [1994]. The wavelengths of the longitudinal modes allowed in the fluid-driven crack model are given by $\lambda = 2L/n$, $n = 2, 3, 4, \dots$. Taking $f_1 = 1.2$ Hz as the fundamental mode frequency, the dispersion curves give the ratio v/a , v being the phase velocity, between 0.04 and 0.1 for values of crack stiffness between 100 and 500. This leads to a phase velocity $v = 56 - 140$ ms⁻¹. The wavelength of the crack wave (v/f_1) associated to these velocities, ranges between 47 and 117m ($\lambda = L$ for the fundamental mode). The ratio b/μ being 0.58, the crack thickness is in the range $d = 5.5 - 68$ cm. Lower values of L and d can be obtained by taking higher values of C.

4. Conclusions

[15] While most of the activity is related to ice cracking high frequency events, we have shown that low frequency icequakes also occur. We interpret these events in term of resonant water-filled ice cavity. Ice cracking could generate LPI events when occurring in the vicinity of a cavity filled with water. A sudden change in water flow is another possible excitation mechanism.

[16] When recorded on the rock base, LPI events are similar to long period volcanic quakes. Some of them can be registered beyond the limits of the glacier, at distances of at least several hundred of meters. Confusion is therefore possible and could explain the high level of seismic activity usually observed on apparently quiet volcanoes covered by icecap. One way to identify icequakes in such a situation is to set up a seismic station as close as possible to the glacier.

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References

- Aki, K., M. Felher, and M. Das, Source mechanism of volcanic tremor: fluid-driven crack models and their application to the 1963 Kilauea eruption, *J. Volcanol. Geotherm. Res.*, 2, 259–287, 1977.
- Chouet, B., Dynamics of a fluid-driven crack in three dimensions by the Finite Difference Method, *J. Geophys. Res.*, 91, 13,967–13,992, 1986.
- Chouet, B., R. A. Page, C. D. Stephens, J. C. Lahr, and J. A. Power, Precursory swarms of long-period events at Redoubt volcano (1989–1990), Alaska: Their origin and use as a forecasting tool, *J. Volcanol. Geotherm. Res.*, 62, 95–135, 1994.
- Deichmann, N., J. Ansorge, F. Scherbaum, A. Aschwanden, F. Bernardi, and G. H. Gudmundsson, Evidence for deep icequakes in an Alpine glacier, *Annals of Glaciology*, 31, 85–90, 2000.
- Lesage, P., F. Glangeaud, and J. Mars, Applications of autoregressive models and time-frequency analysis to the study of volcanic tremor and long-period events, *J. Volcanol. Geotherm. Res.*, 114, 391–417, 2002.
- Métaxian, J.-Ph., M. Ruiz, A. Necessian, S. Bonvalot, P. Mothes, G. Gabalda, F. Bondoux, P. Briole, J. L. Froger and D. Rémy, Geophysical Studies of Cotopaxi volcano, Ecuador: Seismicity, Structure and Ground Deformation, ISAG 1999, Symposium on Andean Geodynamics, October 4–6, 1999, Ed. IRD.
- Métaxian, J.-Ph., P. Lesage, and B. Valette, Locating sources of volcanic tremor and emergent events by seismic triangulation: Application to Arenal Volcano, Costa Rica, *J. Geophys. Res.*, 107(B10), 2243, 2002.
- Mora, M. M., P. Lesage, J. Dorel, P.-Y. Bard, J.-Ph. Métaxian, G. E. Alvarado, and C. Leandro, Detection of seismic site effects by using H/V spectral ratios at Arenal volcano (Costa Rica), *Geophys. Res. Lett.*, 28(15), 2991–2994, 2001.
- Neave, K. G., and J. C. Savage, Icequakes on the Athabasca Glacier, *J. Geophys. Res.*, 75, 1351–1362, 1970.
- Neuberg, J., and T. Pointer, Effects of volcano topography on seismic broad-band waveforms, *Geophys. J. Int.*, 143, 239–248, 2000.
- Paterson, W. S. B., The physics of glaciers, Elsevier Science, 1994.
- Ruiz, M., B. Guillier, J.-I. Chatelain, H. Yepes, M. Hall, and P. Ramon, Possible causes for the seismic activity observed in Cotopaxi volcano, Ecuador, *Geophys. Res. Lett.*, 25(13), 2305–2308, 1998.
- St. Lawrence, W. S., and A. Qamar, Hydraulic transients: a seismic source in volcanoes and glaciers, *Science*, February 16, 654–656, 1979.
- Weaver, C. S., and S. D. Malone, MT. Saint Helens seismic events: Volcanic earthquakes or glacial noises?, *Geophysical Research Letters*, 3(3), 197–200, 1976.
- Weaver, C. S., and S. D. Malone, Seismic evidence for discrete glacier motion at the rock-ice interface, *Journal of Glaciology*, 23(89), 1979.
- Wolf, L. W., and J. N. Davies, Glacier-generated earthquakes from Prince William Sound, Alaska, *Bull. Seismol. Soc. Am.*, 76(2), 367–379, 1986.

S. Araujo, P. Lesage, J.-P. Métaxian, and M. Mora, Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, 73376 Le Bourget-du-Lac, Cedex, France. (metaxian@univ-savoie.fr)