Source Mechanism of Long Period events recorded by a high density seismic network during the 2008 eruption on Mt Etna

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Abstract. 129 Long Period (LP) events, divided in two families were recorded by 50 stations deployed on Mount Etna within an eruptive context in the second half of June 2008. In order to understand the mechanisms of these events, we perform moment tensor inversion. Numerical tests show that unconstrained inversion leads to reliable moment tensor solutions because of the close proximity of numerous stations to the source positions. However, single forces cannot be accurately determined as they are very sensitive to uncertainties in the velocity model. These tests emphasize the importance of using stations located as close as possible to the source in the inversion of LP events.

Inversion of LP signals is initially unconstrained, in order to estimate the most likely mechanism. Constrained inversions then allow us to accurately determine the structural orientations of the mechanisms. Inversions for both families show mechanisms with strong volumetric components. These events are generated by cracks striking SW-NE for both families and dipping 70° SE (fam. 1) and 50° NW (fam. 2). The geometries of the cracks are different from the structures obtained by the location of these events.

The orientation of the cracks is consistent with the local tectonic context on Mount Etna. The LP events seem to be a response to the lava fountain occurring on the 10th of May, 2008.
1. Introduction

Mt Etna is an active 3330 m high stratovolcano located on the East coast of Sicily (Italy). An eruptive period began on the 10th of May 2008 with a powerful lava fountain in the South East Crater, one of the four main summit craters. An eruptive fissure opened on the 13th of May on the East flank of the volcano, in the “Valle del Bove” [see e.g., Cannata et al., 2009b]. The flank eruption stopped on July 7th 2009.

Long Period (LP) events recorded on Mount Etna have a frequency range between 0.2 and 1.3 Hz. In the last few years, they have been analysed and located in many studies [Falsaperla et al., 2002; Saccorotti et al., 2007; Lokmer et al., 2008; Patanè et al., 2008; Cannata et al., 2009a]. Sources of these events are found to be located a few hundred meters below the summit craters. They are usually repetitive, which suggests a repeating action of the same, non-destructive source process. Moment tensor inversion (MTI) has been performed on several volcanoes to quantify the source processes of these events. Most of these studies [e.g. Ohminato et al., 1998; Nakano et al., 2003; Chouet et al., 2003; Kumagai et al., 2002; Lokmer et al., 2007] suggest a fluid-filled crack mechanisms, often accompanied by single forces. Such a mechanism is supported by forward modelling of fluid filled resonator systems, with various geometries, such as crack or pipe. This resonance produces slow interface waves, also called crack waves, whose dispersive properties allow the generation of low frequency events from relatively small sources [Chouet, 1986; Ferrazzini and Aki, 1987]. The trigger mechanism for this excitation still remains uncertain, but they are usually related to instabilities in the fluid motion [Ohminato et al., 1998; Rust et al., 2008; Neuberg et al., 2006; Gilbert and Lane, 2008]. This fluid can be magma.
[Neuberg et al., 2006], water or steam [Casano et al., 2008; Kumagai et al., 2005], gas
[Lokmer et al., 2007] or mixtures of these fluids [Ohminato et al., 1998]. In the context of
the models outlined above the strong linkage between LP activity and fluid dynamics
implies that the characterisation of LP source mechanisms is of fundamental importance
in order to understand processes in magmatic systems.

While MTI is an efficient tool to characterize Very Long Period events [Chouet et al.,
2003], it is usually not stable for signals with periods of around 1s [Kumagai et al., 2010].
This is mainly due to the poor knowledge of the velocity structure [Bean et al., 2008;
Cesca et al., 2008], which induces uncertainties for the prediction of Green’s functions.
This issue can largely be solved by using stations located very close to the source positions
[Bean et al., 2008; Kumagai et al., 2010].

On Mt Etna, the first MTI was performed by Lokmer et al. [2007] complemented by
a full investigation of the LP properties [Saccorotti et al., 2007; Lokmer et al., 2008]
and MTI of synthetic data [Bean et al., 2008]. These authors suggest that the source
mechanism generating LP events consist of a subvertical crack striking NNW-SSE, with
a gas “pulsing” excitation. However, their data set contains only one station located in
the summit area. They suggested that a larger data set recorded in the close proximity
to the sources would help to better constrain the inversion.

For this reason, a joint Irish (University College Dublin), French (Université de Savoie,
Chambéry) and Italian (Istituto Nazionale di Geofisica e Vulcanologia, Catania and Pisa)
experiment was conducted on Mt Etna in early summer during the 2008 eruption. An
exceptionally high density network of 50 broad-band stations, 30 of them which were
located close to the summit, recorded LP events. De Barros et al. [2009] located the
source positions of 129 selected events belonging to two different families sharing similar
waveforms. They found shallow source locations with a temporal migration.

In this study, we first present the data-set, and then use numerical tests to investigate the
resolution and robustness of constrained [Nakano and Kumagai, 2005] and unconstrained
inversion with the large number of stations available here. For real data we take a two step
approach. In step I, unconstrained inversion is performed on LP signals and allows us to
investigate the type of mechanism involved. In a second step, structural orientations are
determined by a constrained inversion based on the source type identified in step I. The
best solution is suggested to be a crack mechanism for both families. The interpretation
of these cracks, striking SW-NE, are discussed in relation to the volcanic activity.

2. Data

A total of 50 stations with three-component broadband sensors (30, 40 or 60 s cut-off
period), were installed on Mt Etna between the 18th of June 2008 and the 3rd of July 2008.
In particular, 30 of them were located at distance shorter than 2 km from the summit
area (see figure 1).

Before analyzing the data, we deconvolve the instrument response from the recorded
signals. 129 events are selected and classified into two families [De Barros et al., 2009].
The first family (63 events) is only recorded in the first day of the experiment (18th of
June), while the second family (66 events) is distributed over the first four days. After the
22nd of June, the amplitude of the LP events strongly decreases by an order of magnitude.
In the same period, the tremor amplitude increases. Since both LPs and tremor are in
the same spectral range, it is impossible to recognize additional LP events.
Most of the energy of the selected events is concentrated between 0.2 and 1.5 Hz, with a peak around 0.9 Hz. However, signal spectra show another peak around 2 Hz, and some signals have higher frequency (20-40 Hz) contents. For both families, the waveforms (unfiltered and filtered between 0.2 and 1.5 Hz) and the spectral contents are shown in figure 2. Although the waveforms are quite similar, the spectral peaks are not the same for the two families. Family 2 exhibits a sharper spectrum, with a peak frequency slightly higher than in the case of family 1.

De Barros et al. [2009] located the source of these events with a cross-correlation technique. The source positions are located below the summit craters at very shallow depth, between 0 and 800m from the summit for the first family and 0 and 400 m from the summit for the second family. The hypocenter positions are clustered into a subvertical, dike shape structure striking NW-SE (family 1) which branches into two pipe-like bodies (family 2). These two elongated structures belong to a same plane striking SW-NE and dipping 45° NW. Some events from the two different families share the same location, thus the waveform difference between the two families has to be ascribed solely to a different source mechanism. However, the similarities of waveforms indicates the action of the same source within individual families.

3. Method

3.1. Moment tensor inversion

We performed a moment tensor inversion in the frequency domain as previously used by Nakano et al. [2003], Kumagai et al. [2005] and Lokmer et al. [2007]. $u^s_n(r, \omega)$ denotes the $n^{th}$ component of the displacement field at station $s$, produced by a source located at
the position \( \mathbf{r} \). Considering single forces, it can be expressed as:

\[
\psi_n(r, \omega) = G_{np,q}^s(r, \omega) M_{pq}(\omega) + G_{np}^s(r, \omega) F_p(\omega), \quad \text{with } n, p, q = x, y, z, \tag{1}
\]

\( G_{np}^s(r, \omega) \) denotes the Green's functions (GF) and \( G_{np,q}^s(r, \omega) \) their spatial derivatives.

We do not consider rotational effect as we assume a symmetric moment tensor with

\( M_{pq}(\omega) = M_{qp}(\omega) \).

Equation 1 can then be rewritten in a matrix form. The data, merged in a column vector \( \mathbf{d} \), are expressed as a linear form:

\[
\mathbf{d} = \mathbf{Gm}, \tag{2}
\]

where \( \mathbf{G} \) is the matrix containing the Green's functions and their derivatives and \( \mathbf{m} \) is a column vector of the moment tensor components and/or single forces. As we assume that the moment tensor is symmetric, only 6 moment tensor components and 3 single forces have to be determined in order to recover the full mechanism and its Source Time Function (STF). The inversion problem is then linear, and the equation 2 is solved for each frequency by a classical least-square minimization. The associated misfit of the waveforms is defined by

\[
R = \frac{(\mathbf{d} - \mathbf{Gm})^T (\mathbf{d} - \mathbf{Gm})}{\mathbf{d}^T \mathbf{d}}. \tag{3}
\]

Inversion can be unconstrained, i.e. performed considering only the 6 moment components (MT) or the 6 moment components and 3 single forces (MT+F). In these cases, we have 6 or 9 independent parameters to determine. Nakano and Kumagai [2005] and Lokmer et al. [2007] constrained the inversion to the particular mechanisms that are considered the most likely source mechanisms generating the LP events: a Crack (Cr), a Pipe (Pi) and an Explosion (Ex). We use the sets of equations given by Nakano and Kumagai [2005]
to express the Cartesian components of the moment tensor as functions of the azimuth angle $\phi$ and dip angle $\theta$. Equation 2 becomes:

$$d = G_{M0}f(\lambda/\mu, \theta, \phi) + G_F m_F,$$

(4)

where $M_0$ denotes the Source Time function (STF), $\lambda$ and $\mu$ are the Lamé’s constants. $G_F$ and $m_F$ are the Green’s functions and the source properties associated with the single forces, respectively. The last term of this equation refers to the inversion for single forces, and can either be included or omitted. If omitted, as the vector $f$ is independent of the frequency, the inversion procedure reduces to an inversion for a single parameter, $M_0(\omega)$, for given values of $\lambda/\mu$, $\theta$ and $\phi$. We search for the most likely solution by performing a grid search over the $\theta$-$\phi$ domain. If single forces are considered (inversion denoted $Cr+F$, $Pi+F$ and $Ex+F$), forces are determined for every $\phi$ and $\theta$. For this constrained inversion, the number of unknowns to be determined varies from 1 (without single forces) to 4 (with single forces).

Herein, azimuth $\phi$ and dip $\theta$ are defined using the convention of Lokmer et al. [2007, fig. 2], i.e. $\phi$ is measured between 0 and 360° anticlockwise from East and $\theta$ is defined between 0 and 90° from the upward direction. $X$, $Y$ and $Z$ refer to the East, North and vertical upward direction, respectively.

### 3.2. Green’s functions (GF) computations

The Green’s functions are computed using the elastic lattice algorithm of O’Brien and Bean [2004]. The model is three-dimensional and includes topography. It is centered on the volcano summit and has an area of 21.5x16.4x7 km with a 40 m grid size. Absorbing boundaries (6 km wide) are applied at the bottom and the edges of the model in order...
to prevent reflections from the model boundaries. As the topography strongly distort
waveforms [Cesca et al., 2008; O’Brien and Bean, 2009], a free surface based on the Dig-
itital Elevation Model (DEM) of Mt Etna is used. The source function used for the GF
computation is a Gaussian pulse with a 10 Hz cut-off frequency to insure a flat response
below 2 Hz.

Bean et al. [2008] show that the moment tensor is very sensitive to incorrect velocity
models, and particularly to shallow, low velocity structures. However, they also show that
the effect of a wrong velocity model is stronger for stations further from the source. For
stations close to the source, the near field effects are correctly taken into account in our
simulation. Since 30 stations are located in the source near field (they are less than one
wavelength away) and we do not have any information on the shallow velocity properties,
we then choose to use a homogeneous model. Velocities for P− and S−wave are 2000 m
s−1 and 1175 m s−1, respectively. These velocities are similar to the results of the recent
tomographic study of Mount Etna [Monteiller et al., 2009] and to those determined in
the location process of the LP events considered in this study [De Barros et al., 2009].
Attenuation is also unknown in the shallowest part of the volcano. It is not as important
as scattering and topographic effects [O’Brien and Bean, 2009] and it is not considered
here.

As shown by Lokmer et al. [2007], in the presence of a poorly resolved shallow velocity
model the coupled inversion of LP signals for both position and mechanism is ambiguous
and can lead to an erroneous solution. Moreover, the GF calculation for multiple sources
with such a large number of receivers is computationally expensive, for both direct and
reciprocal approaches. We use the source location from De Barros et al. [2009]. As the events do not share exactly the same source location, we define an average source position for both families. We then use these positions for the inversion of all LP events. The average source positions have UTM coordinates of (499.4, 4178.76, 2.84) for family 1 and (499.5, 4178.45, 3.0) km for family 2, i.e. 490 and 330 m below summit level.

4. Inversion of synthetic data

As shown by Bean et al. [2008] and Cesca et al. [2008], moment tensor inversion is very sensitive to shallow velocity structure. Chouet et al. [2003] show the importance of a correct source location. The homogeneous velocity model is too simple to accurately reproduce the complexity of the waveforms. To assess the sensitivity of our inversion to uncertainties in the velocity structure, source mislocation and noise, we perform inversion of noisy numerical data computed with a velocity model and a source location different from those used in the Green’s functions calculation. We also intend to assess: 1) if a constrained inversion gives more reliable results than an unconstrained inversion, and 2) if single forces have to be considered in the inversion.

The velocity model used to compute the numerical data is a gradient with a $V_p$ increase from 1600 m s$^{-1}$ to 2.5 m s$^{-1}$ from the surface to 500 m below the summit level. The source location is misplaced by 90 m in the horizontal plane and 120 m vertically compared to the position where the GF’s are computed. The source function is a Ricker wavelet, with 1 Hz central frequency. Synthetic data are computed for two cases: 1) Vertical crack $(3,1,1)$ with the crack-normal oriented along $X$–axis and amplitude $M_0 = 310^{12}$ N m; 2) Same as case 1 adding a single force with components $(F_X, F_Y, F_Z) = (9, 9\sqrt{2})\times10^9$ N.
Random noise is band-pass filtered in the same spectral range as that used for the waveforms. It is then added to the synthetics in order to achieve a noise level similar to the one present in the data (20% of maximum amplitude at etsm station in the considered frequency band). As for real data, for stations further than 2.5 km from the summit LP signals and noise have similar amplitude.

For case 1 (i.e. true source is a crack without single forces), the moment tensor is well reconstructed by unconstrained inversion with, and without, single forces (see fig. 3 and table 1). The reconstructed moment however has a higher amplitude than the true solution. This is an expected result as the GF source is deeper (120 m) than the data source location. We then invert the synthetic data for a Crack, Pipe and Volumetric constrained mechanism (see tab. 1). Minimum residual is obtained for the correct mechanism, i.e. for the crack, its orientation and the STF are correctly recovered. As the solutions with and without noise are similar (not shown in figure), MTI does not appear to be very sensitive to the noise in this case.

However, the wrong velocity model, and the mislocation, produce spurious forces. Converted waves are generated by the gradient velocity model. As the radiation pattern of converted waves are comparable to the radiation patterns of the single forces, the inversion process leads to spurious single forces to accomodate the reconstruction of these waves. Moreover, for all stations, arrival times of the waveforms are different when waveforms are computed with mislocation and wrong velocity models. Moment tensors do not seem to be strongly affected by these time shifts for such a near-field deployment. This effect is once again accomodated by the singles forces as their STF appear shifted compared to
those of the moment. Because of these effects (converted waves, arrival time shifts), the amplitudes of the spurious single forces are comparable to the amplitudes of the moments. The spurious forces are very similar for both inversions presented in figure 3, as they are representative of the model errors. Constrained, or not, the inversion does not help to determine if single forces are real or due to mismodeling in the GF computations. However, the RMS difference between inversion, with and without single forces, is very small.

The same inversions are carried out for case 2 where the true source is a crack and a strong single force (see fig. 4 and table 1). The inversion for moment only (MT) gives a mechanism similar to a pipe (1,2,2.3) which is far from the true solution. However, the moment tensor components reconstructed by the unconstrained inversion (MT+F) are very close to the true solution. The same results are obtained for crack-constrained inversions (Cr and Cr+F): moment is not reliable when forces are not considered as the reconstructed crack appears to be horizontal instead of vertical. The inversion constrained for crack and single forces (Cr+F) gives very good results. For the constrained inversion for different geometries (Pi, Cr and E), the RMS minimum is not necessarily obtained for the correct mechanism. As shown by Lokmer and Bean [2010], radiation patterns for Crack and Pipe mechanisms are very close, and can appear similar if the data coverage is not perfect. When including single forces, the RMS minimum leads to a crack mechanism, but the RMS differences is still very small.

Similarly to case 1, the forces found in case 2 inversion tests are not properly reconstructed as they include spurious forces due to velocity mismodeling and mislocation. The difference in RMS values between inversion with and without single forces is larger than for
case 1, but it is not large enough to assure that forces are real.

Moment tensor inversions do not allow single forces to be properly reconstructed and to estimate if they are real or the result of mismodeling and mislocation. However, numerical tests show that the moment is more reliable if the inversion is carried out considering free single forces. Consequently, herein we allow single forces in the inversion, to compensate for the errors coming from the velocity model and the source location. These single forces are not considered for the interpretation of the mechanism. A similar conclusion has been reached by Šílený [2009], who shows that, for earthquakes with double-couple mechanisms with a small non-shear component, and in the presence of mislocation and mismodeling, solutions are more stable when considering the 6 MT components than for a constrained double-couple inversion. Therefore, it can be sometimes better to have more unknowns in an inversion process, in order to accommodate the errors. However, synthetic tests, like the ones presented here, are always necessary to choose an inversion strategy (constrained MTI?, single forces?), as results will strongly depend on station density and topography. In agreement with Bean et al. [2008], MTI appears to be very sensitive to shallow velocity structures, but this is balanced here by using stations very close to the source.

5. Moment tensor inversion of Mt Etna data

We invert data from both families to determine the moment tensor using 16 stations (see section 6 for a justification of the number of stations) with the best azimuthal distribution and signal-to-noise ratio. Since some stations were not available at the beginning of the experiment, the set of stations is different for each family. Individual events are contaminated by noise and do not share exactly the same source position [De Barros
et al., 2009]. The GF’s are however computed for fixed positions (see section 3). We carried out inversion for 44 and 39 events for family 1 and 2, respectively. The mean STF is obtained by averaging all the reconstructed STF and the standard deviation gives us errors associated with noise and mislocation. Errors for family 1 (fig. 5) are larger than for family 2 (fig. 6), but the calculated STF does not show any strong variations for either family. The reconstruction of the STF is not very sensitive to the noise and to the mislocation. As expected for LP multiplets, the source process is perfectly repetitive.

For both families we use a two-step approach: 1) we invert for an unconstrained solution, in order to determine the most reliable mechanism type (Crack, Pipe), and 2) we use results of step 1 to constrain the inversion and to quantify the structure details (e.g., dip, azimuth).

5.1. Family 1

For family 1, the STF reconstructed by unconstrained inversion with and without single forces are very similar (fig. 5a and b). The RMS value (see table 2) is however considerably lower when forces are considered. Forces, whether physical or an artefact, do not change the moment tensor solution in this case. Waveform matches between data and reconstructed waveforms are shown in figure 7 for the 16 stations used for the unconstrained inversion with single forces for an individual event. Fits are very good for most of the stations very close to the source position. They disimprove for stations with lower amplitude signals, due to the lower signal-to-noise ratio and because inversion give more weight to the signals with largest amplitude.

The STF for unconstrained inversion (MT and MT+F) can be interpreted as a crack (e.g., 1,1,1.2,3 for MT+F inversion). In the second step, we invert for a crack solution, with
and without single forces, and search for the azimuth and dip (fig. 5c and d). Whereas
STF functions are slightly different for the four inversion results, they show a very similar
amplitude and orientation of the crack mechanism. These results are in close agreement
with the numerical tests shown in figure 3. We can therefore assume that the single forces
are probably not real or too weak to be reconstructed. The moment tensor components
are well reconstructed in each of the inversions used and show a crack whose normal is
oriented with azimuth $\phi = -40^\circ$ and dip $\theta = 70^\circ$.

5.2. Family 2

The moment tensor solution for inversion with and without single forces are very differ-
ent, both for the mechanism and for the STF (see figure 6). The RMS difference between
these two inversions is very large. The waveforms cannot be properly explained without
forces, though they are very well reconstructed when forces are considered (see figure
8). Analogous to the numerical tests shown in figure 4, we are more confident with the
solution reconstructed with single forces. However, the strong time shifts between the
different moment components and single forces do not allow an easy interpretation of
the mechanisms. If we use a Principal Component Analysis (PCA) for the moment part
[Vasco, 1989], the first principal component shows eigenvalues of (1,1.1,1.6), with more
than an 80% isotropic component. However, in this case, the deviatoric part of the mo-
ment is practically neglected because of the time shift between the different components.

By removing the isotropic component first, the PCA analysis leads to a CLVD dominant
mechanism (70 %) with the major axis pointing in the ($\phi = 110^\circ$, $\theta = 50^\circ$) direction. If we
use only the absolute maximum of the STF, we find a source mechanism of (1,1.5,2.2)
with same orientation for the major axis.

To solve this uncertainty, we perform constrained inversion for a crack, a pipe and an explosion (see table 2). Smaller RMS values are obtained for the crack mechanism. The orientation of the crack is $\phi=110^\circ$ and $\theta=50^\circ$. The pipe and the explosive constrained inversion show slightly higher RMS. We choose to discard these mechanisms as they do not show a major axes with orientation consistent with the one obtained by the unconstrained inversion. Both the unconstrained inversion and the constrained crack inversion show a mechanism with strong volumetric components and a major axes in the $(\phi=110^\circ, \theta=50^\circ)$ direction.

This case is similar to the inversion of synthetic data computed for a crack and single forces (fig. 4). The amplitude of the forces is quite strong and at least part of these forces may be real. However, as shown by synthetic tests, it is impossible to accurately reconstruct the forces. For this reason, the single forces will not be quantitatively described and discussed.

6. Discussion

6.1. Station distribution and density

Only 16 stations are used in the inversion. However, 30 stations close to the summit recorded signals with amplitudes above the noise level for family 2 and part of family 1. To investigate the influence of the number of stations, we invert events from family 2 gradually changing the number of stations from 30 to 6. Using between 10 and 30 stations, we find that the number of stations does not change the solution as long as: 1) a correct azimuthal distribution is respected and 2) some stations closest to the sources are used. This is mainly because the stations closest to the source strongly constrain the solution.
Using less than 8 stations, MTI leads to a different and certainly erroneous solution. However, this result cannot be directly generalised to any other station distributions and any other volcano.

Moreover, we do not use the same set of 16 stations for family 1 and family 2. We also verify that the difference between the solutions obtained for the two families is not produced by this dataset difference. Inversion of family 2 events leads to a similar result when using either set of stations.

Lokmer et al. [2007] show that the stations closest to the source help to constrain the source time function, while the others can be used to determine the mechanism. Here, the STF does not resemble the waveform recorded at the closest station (summit station etsm). Signals from this station show a complex waveform (see fig. 8) probably due to near field effects and strong site effects. However, the other stations with small offset from the source display a signal very similar to the STF. In general, for stations close to the source, LP waveforms are not strongly distorted by propagation effects, which stabilizes the STF reconstruction. In this case, numerical tests show that unconstrained inversion allows a correct reconstruction of the mechanisms if the velocity model is consistent with reality. As this was not possible with the station distribution used by Bean et al. [2008], moment tensor inversion is sensitive to the station distribution.

In conclusion, MTI requires stations in close proximity to the source (near summit stations in our case) to be accurate, but not necessarily a large density of stations (i.e. a minimum of 8 near summit stations in our case).
6.2. Source mechanisms

Solution for moment tensor inversion for both families suggests a crack mechanism. Figure 9 graphically summarizes the orientation of the solution for the moment components, with the orientation of the main location structures found by De Barros et al. [2009]. We are confident of the crack solution found for family 1, as it appears stable for all of the inversion tests. For family 2, the unconstrained solution shows a high volumetric component with a mechanism between a crack and an explosion. Even if the geometry is not clearly defined, the crack solution appears to be the most likely solution.

The principal moment component for both families are around (1,1,2). To obtain these values for a crack, we need a Poisson’s ratio of $\nu = 1/3$, which implies $\lambda = 2\mu$. This high ratio is classically related to the high temperature in volcanic rocks [Chouet et al., 2003]. Fractured and unconsolidated media can also present high Poisson’s ratio [e.g. Bourbié et al., 1986], which is most likely the case in the near subsurface on volcanoes. Another possible explanation of the difference with the theoretical crack mechanism (1,1,3) is that the latter is computed for an idealised point source with no realistic boundary conditions between the cracks perimeter and the surrounding medium. We also note the presence of strong single forces and time shift between the moment components, specially for family 2. If some of these forces are real this might mean that the mechanism is more complex than can be solved by the MTI as used here as 1) the source can comprise several time delayed mechanisms, 2) it can have a spatial extend with complex geometry, and 3) it may not be described by a first-order moment tensor. Numerical experiments have yet to be conducted to investigate how to recover complex sources such as pressure dipole,
torque effects, etc.

Orientations of crack normals are \((\phi=-40^\circ, \theta=70^\circ)\) and \((\phi=110^\circ, \theta=50^\circ)\) (see figure 9), which correspond to cracks in the SW-NE and WSW-ENE directions. Uncertainty due to the inversion process is \(\pm 10^\circ\). Cracks of both families are roughly orthogonal but their strikes show a similar orientation (between N40\(^\circ\) E and N70\(^\circ\) E).

The orientation of those cracks are different from the crack found by Lokmer et al. [2007] \((\phi=35^\circ \text{ and } \theta=72^\circ)\). However, these events were recorded during the 2004 eruption and showed different waveforms and spectral characteristics. They are certainly associated with different source mechanisms.

For family 1, De Barros et al. [2009] found that the source locations of the events describe a dike-like structure with normal oriented in the \((\phi=60^\circ, \theta=85^\circ)\) direction. The crack obtained by moment tensor inversion is approximately orthogonal to this location structure. The source locations of family 2 events form into two pipe-like volumes. For both families, the crack mechanism and the source location structures are thus different, i.e. the events are not directly produced by the structure in which they are located. However, for family 2, the two pipe-like bodies belong to a same flattened structure, with a normal orientation of \((\phi=120^\circ, \theta=50^\circ)\) as shown in figure 9. This structure has the same orientation as the crack solution of the MTI, i.e. the pipes and the cracks belong to the same plane.

As expected, the inversion of all the individual events (see fig. 5 and 6) shows that the mechanism is perfectly repetitive. As the source location of the events within the two
family change, different structures have to produce the same signals.

For both families, the source time function is very short (i.e. less than 4s), which suggests a pulsing rather than an oscillating mechanism. Amplitudes of the seismic moment are about 43 and 25 \(10^9\) N m for family 1 and 2. Volumetric change \(\Delta V\) can be estimated from \(M_0 = \mu \Delta V\). From the velocity of the medium we compute a rough approximation of the shear modulus: \(\mu = 2.9\) GPa. The volume changes are 15 and 9 m\(^3\) respectively. These volumes are smaller than the one found by Lokmer et al. [2007], but they are in agreement with the lower amplitude of the signals and the shallower source positions. These volumes correspond to a normal displacement of 1 mm for a 100 meter sided square crack and 10 cm for a 10 m one.

### 6.3. Relationship to the eruption

De Barros et al. [2009] and this study show that 1) LP events are spread out along structures located between 800 m and the surface; 2) Their source mechanisms are related to cracks, not necessarily similar to the location structures; 3) Crack strikes are roughly similar while dips are orthogonal; 4) Signals and source mechanisms are perfectly similar within each family.

Following the lava fountain of the 10\(^{th}\) of May 2008, an eruptive fissure opened on the eastern flank of the volcano below the LP source locations. Lava flowed a distance of 1.5 km. It is unlikely that magma was uprising to the upper part of Mount Etna and more likely that only gases were being released from the summit craters. This suggests that LP
events are not directly related to magma movements. Moreover, gases are the most likely fluids present in the main conduits and in the fractures surrounding them.

The lava fountain is associated with high fluid pressure. This can destabilize the edifice, by opening fractures in the upper part of the volcano. After this event, the fracture lava flow and the summit degassing certainly drained the cone producing a decrease of the pressure. The LP events may be linked to this decompressive phase. The decrease of pressure can lead to the closure of those fractures, as the volcano settled due to its own weight. Patané et al. [2008] analysed a family of LP events (called family 2 in Patané et al. [2008]) occurring only after the lava fountains of 2007, which have similar characteristics to the events studied here. They lasted for approximately one month after the lava fountain and were interpreted as the response to the volcano deflation. This is also confirmed by Falsaperla et al. [2002] who linked the LP activities to the collapses of the crater floor. In this case, the fluids involved can be gases or steam. Gases contained in the cracks are suddenly expelled to the main conduits. This can produce LP events with mechanisms similar to hydraulic transients [Ferrick et al., 1982] or hydrodynamic instabilities of nonlaminar flows [Rust et al., 2008]. This hypothesis can be linked to the laboratory studies performed by Benson et al. [2008], who show that decompression phase in rock samples can generate LP events in complex-shape fractures belonging to the damage zone of the main conduits.

Cracks for both families are striking SW-NE. To generate these events, a set of parallel and similar fractures are required for family 1. The upper part of the volcano appears to be a highly fractured medium. The orientation of the cracks and of the location structures are consistent with the tectonic setting, which generate faults in the NW-SE and NE-SW.
direction [Bonacorso and Davis, 2004]. However, as they are in the shallowest part of
the volcano, they are more likely due to gravity effects. In particular, the East flank of
the volcano is collapsing and successive eruptions strongly destabilize this area.

The cessation of the LP events after the 22nd of June suggests that the upper part of the
volcano reached an equilibrium, where pressure and stress return to a static state. The
decompression phase, following the lava fountain of the 10th of May, 2008, lasts about 40
days, which is in agreement with the conclusion of Patanè et al. [2008].

7. Conclusion

Two families of LP events, comprising 63 and 66 events respectively, are selected from
the first four days of a seismic experiment on Mount Etna (18/06/2008-03/07/2008). 50
stations, including 30 stations located in close proximity to the summit were used for this
study.

Moment tensor inversion of numerical data shows that, for this deployment, it is more
reliable to use forces in the inversion to correctly describe the moment. However, the
forces cannot be correctly reconstructed as they strongly reflect the errors coming from
the velocity mismodeling and the mislocation. As MTI appears strongly sensitive to sta-
tion distribution, numerical tests are hence required before every MTI. In general, stations
close to the source positions are required to correctly invert Long Period events.

We perform moment tensor inversion in two steps. First, we determine the type of mech-
anism involved using unconstrained inversion. We then constrain the inversion to this
particular mechanism to accurately find its characteristics, such as dips and strike. Inver-
sions of the events of the two families show mechanisms with high volumetric components,
most likely generated by cracks. For both families, cracks are striking in the SW-NE di-
rection, while their dip is roughly orthogonal. The crack orientations are thus different
from the location structures obtained by De Barros et al. [2009]. This suggests that the
LP events are generated by the faults which belong to the damaged zone around the main
conduits of the volcano. We hypothesize that these events are related to the decompres-
sion phase following the lava fountain of the 13th of May, and not to the lava flow from
the flank eruption.

MTI reveals strong forces, especially for family 2, but we are not able to determine if
they are real or due to artefacts in the moment tensor inversion. We also observe time
shifts between the moment components. These effects can be due to uncertainties in
the velocity model or to complex sources (e.g., dual sources, torque...) that can not be
accurately reconstructed by first-order MTI as used here. To solve this problem, a better
knowledge of the velocity model is needed. To be able to unambiguously explain both
moment and forces, a more general approach must take into account: i) extended sources,
ii) multiple sources, and iii) rotational effects.

References

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Figure 1. Broadband station positions on Mt Etna. Left: Mt Etna location (top panel) and all stations on Mt Etna between the 18th of June and the 3rd of July 2008 (bottom panel). Contour interval is 250 m. Right: Summit area of the volcano with stations located within 2 km from the summit. Contour interval is 100 m.
Figure 2. Data of a single event from a) family 1 and b) family 2, recorded at et81 station, vertical component. Top panels: Waveforms (raw data and filtered data between 0.2 and 1.5 Hz) and lower panels: spectral content.
Figure 3. Source Time Function (black thin lines) reconstructed using a) unconstrained inversion for moment only (MT), b) unconstrained inversion for moment and single forces (MT+F), c) constrained inversion for crack only (Cr), d) constrained inversion for crack and single forces (Cr+F). Synthetic data are computed for a vertical crack (9,3,3) without single forces, whose mechanism is shown by the thick grey lines. Noise is then added to the synthetic data. Amplitude is $10^{12}$ N m for the moment and $10^9$ N for the single forces.
Figure 4. Source Time Function (black thin lines) reconstructed using a) unconstrained inversion for moment only (MT), b) unconstrained inversion for moment and single forces (MT+F), c) constrained inversion for crack only (Cr), d) constrained inversion for crack and single forces (Cr+F). Synthetic data are computed for a vertical crack (9,3,3) and single force (9,9,9√2), whose mechanism is shown by the thick grey lines. Noise is then added to the synthetic data. Amplitude is 10^{12} N m for the moment and 10^9 N for the single forces.
Table 1. Results for different constrained (Cr, Pi, Ex) or unconstrained (MT) inversion with and without single forces. N represents the number of free parameters during the inversion process. Case 1 corresponds to synthetic data computed for a vertical crack only, case 2 is for synthetic data for a crack mechanism plus a strong single force.
Figure 5. MTI results for family 1: Mean solution and error bars for unconstrained inversion of 44 events for a) moment only (MT) and b) moment and single forces (MT+F); Constrained inversion of a single event for c) crack constrained inversion (Cr); d) crack constrained inversion with single forces (Cr+F). Amplitude is $10^9$ N m for the moment and $10^6$ for the forces.
Figure 6. MTI results for family 2: Mean solution and error bars for unconstrained inversion of 39 events for a) moment only (MT) and b) moment and single forces (MT+F); Constrained inversion of a single event for c) crack constrained inversion (Cr); d) crack constrained inversion with single forces (Cr+F). Amplitude is $10^9$ N m for the moment and $10^6$ N for the forces.
Figure 7. Waveform fit between the data (continuous lines) and the synthetic seismograms (dashed lines) for an individual event of family 1. Three single forces and 6 moments are considered in the inversion (MT+F). The RMS value is 27% (see tab. 2).
<table>
<thead>
<tr>
<th>Family</th>
<th>Inv</th>
<th>N</th>
<th>RMS (%)</th>
<th>MTE</th>
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<tr>
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<td>9</td>
<td>27</td>
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<td>6</td>
<td>61</td>
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<tr>
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<td>84</td>
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</table>

Table 2. RMS value, moment tensor eigenvalues (MTE) for both families and different inversion. N is the number of unknowns.
Figure 8. Waveform fit between the data (continuous lines) and the synthetic seismograms (dashed lines) for an individual event of family 2. Three single forces and 6 moments are assumed in the inversion (MT+F). The RMS value is 21% (see tab. 2).
Figure 9. Source mechanisms obtained for a) family 1 and b) family 2 events, for the crack constrained inversion (Cr+F). Lines represent the normalized eigenvectors. The circular areas are the crack orientation. The light grey areas show the location structures obtained by De Barros et al. [2009], i.e. a) a sub-vertical dike striking WNW-ESE for family 1 and b) a 45° inclined plane striking SE-NW containing the two pipe bodies of family 2.