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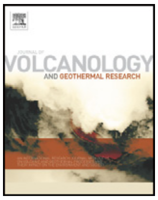

Origin of spurious single forces in the source mechanism of volcanic seismicity

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ABSTRACT

Single forces are often observed in the source mechanism of volcanic seismicity. However, their underlying causative processes are still doubtful. The reliability of single force observations must be assessed, prior to analyzing them in terms of physical mechanisms. Using numerical examples, we show that source mislocation and velocity mismodeling lead to strong spurious single forces. Layering in the velocity model produces converted S-waves and source mislocations modify the wavefield at the free surface (mainly through converted S- and surface waves). However, these waves can also be accurately reproduced in a homogeneous model by adding a vertical single force in the source mechanism, which mainly generates S-waves for large take-off angles. Hence approximate velocity models can lead to the appearance of strong single forces in source inversions. We conclude that, in moment tensor inversion, while single forces can be used in some cases to accommodate mismodeling errors, they cannot be reliably used to infer physical processes.

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1. Introduction

Moment tensor inversion (MTI) is an extensively used tool to characterize the source mechanism of seismic events. When applied to volcanic seismicity, such as Long Period events with dominant period of say 1 s (e.g. Kumagai et al., 2002; Lokmer et al., 2007; De Barros et al., 2011), Very Long Period events with a dominant period of say 20 s (e.g. Ohminato et al., 1998; Chouet et al., 2003) and tremors (Davi et al., 2012), the resulting mechanisms usually exhibit a strong volumetric component (see Chouet and Matoza, 2013, and references therein). In earthquake seismology, MTI is usually limited to the reconstruction of the 6 components of the Moment Tensor (MT) of the equivalent point source, but in volcanic applications the 3 components of Single Forces (SF) are usually added (Ohminato et al., 1998). The recovered SFs often have strong amplitude (e.g. Ohminato et al., 2006; De Barros et al., 2011).

As shown by theoretical considerations (e.g., Takei and Kumazawa, 1994) or by laboratory experiments (e.g., James et al., 2004), SFs can be generated by mass transfer or by viscous fluid movement in the volcano. They are usually interpreted in terms of magma upwelling in conduits when observed in volcanic seismicity (Chouet et al., 2003; Ohminato et al., 2006). SFs have therefore been used to strongly constrain the source processes of the volcanic seismicity. However, as shown firstly by Ohminato et al. (1998) and Chouet et al. (2003), and later by Bean et al. (2008) and De Barros et al. (2011), uncertainties in both source location and velocity structure can lead to the reconstruction of strong spurious SFs.

LP and VLP events are found to be shallow, in the first kilometer below the surface (see e.g. Chouet et al., 2003; De Barros et al., 2009; Inza et al., 2011). The upper part of the volcanic edifice is made of compliant and weathered materials, leading to low and highly heterogeneous seismic velocities (e.g., Chouet et al., 1998; Mora et al., 2006; Cauchie and Saccorotti, 2013). However, the detailed velocity structure is usually poorly known, hence homogeneous velocity models are commonly used when calculating Green's Functions (GFs) in MTI. This simplification is generally justified by the use of long wavelengths (especially for VLP), which are similar to the propagation distances. However, the lack of knowledge of the velocity structure leads to uncertainties in source location (particularly for the depth parameter) for joint location and MT inversion (Lokmer et al., 2007) or location only (De Barros et al., 2009). It is now well documented that MTI can suffer from a badly constrained velocity model (Jousset et al., 2004; Bean et al., 2008; Kumagai et al., 2011), especially for the highest frequency (LP). However, for both LP and VLP cases, it is not clear yet if SF should be included or not in the inversion, and if they can be unequivocally interpreted as physically present.

The aim of this paper is to numerically investigate why errors in the velocity model and in the source locations generate apparent source related SFs, and as a consequence, if it is meaningful to infer a physical process from SFs. We will first show on synthetic data computed in models of Mt Etna (De Barros et al., 2011) the effect on SFs of slight velocity modeling and sources location errors. We then simplify the problem in order to be able to identify the different waves

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responsible for the SF reconstruction, and generalize our findings to all frequency ranges.

2. Single forces in synthetic tests

Bean et al. (2008) showed that mismodeled complex media can have a detrimental effect on MT solutions for shallow volcanic sources. They suggest using stations as close as possible to the source. For this reason, a high-resolution experiment was undertaken on Mt Etna in 2008, including 30 stations within 2 km of the source area. De Barros et al. (2011) performed a MTI of the LP events recorded by this network. Here, using the same set-up, we compute synthetic data and GFs using the full wavefield elastic lattice algorithm of O'Brien and Bean (2004), including the topography of Mt Etna with a 40 m grid step. The GFs are calculated for a homogeneous model ($Vp_0 = 2000$ m/s, $Vs_0 = Vp_0/\sqrt{(3)}$, $\rho = 2300$ kg/m^3), for a 400 m deep source. Synthetic data are computed for two cases: 1) velocity mismodeling case: a 200 m layer ($Vp = 1600$ m/s) following real Mt Etna topography over a half-space with a 2400 m/s velocity; and 2) mislocation case: the homogeneous velocity model is used and the source location is misplaced by 120 m downward and by 90 m horizontally. The source has a 1 Hz Ricker wavelet time function and a vertical crack ($[3,1,1] \times 5 \cdot 10^{12}$ Nm) mechanism.

The MTI is performed in the frequency domain, with a fixed source location. In both cases (see Fig. 1), and because of the exceptional number of stations in the close proximity of the source, the source time function (STF) and the mechanism of the MT are quite well reconstructed, unlike the amplitudes. The amplitudes are in fact inversely proportional to the velocity (Eq. (4.29), Aki and Richards, 2002). A slight time shift exists between the STFs of the different MT components, but the decomposition leads to a near perfect [3,1,1] solution in both cases. The accuracy of the MT solution is ensured here by the exceptionally dense network (De Barros et al., 2011). However, strong SFs appear, with amplitudes reaching more than $5.5 \cdot 10^9$ N. SFs are mainly in the vertical direction for the velocity mismodeling case, and are inclined for the source mislocation case. Note that an amplitude of 10^9 N from the SF source and of 10^{12} Nm for a MT source lead to seismic waves of the same order of magnitude when the radiation pattern is neglected (see Eqs. (4.27) and (4.28) in Aki and Richards (2002)). Hence, even in such a simple case, both location and velocity mismodelings give rise to strong spurious SFs.

3. Origin of single forces

To understand the relationship between the mismodeling and the spurious SFs, we simplify the problem even further: we calculate synthetic waveforms generated by a purely isotropic source (1 Hz Ricker wavelet signature) in a medium without topography. In this way, the source generates only a P-wave, and all complex signatures can be attributed to the propagation effects. The different waves can be easily identified, allowing us to determine which waves are responsible for the spurious SF generation. The synthetic data are computed using the SKB code (Dietrich, 1988) based on the reflectivity method of Kennett (1983), coupled with the wavenumber integration of Bouchon and Aki (1977).

Following the results from the previous section, we assume that the mechanism and the STF of the MT components are properly recovered, but not the amplitude. We therefore constrain the inversion to a fixed mechanism (explosion) and STF (1 Hz Ricker wavelet), and invert for the amplitudes of the explosion and of the SFs required to accommodate the modeling uncertainties. Hence, by constraining the mechanism, we focus exclusively on the SFs reconstruction due to the modeling errors.

Synthetic data $\boldsymbol{U}_{Ex}^{True}$ are calculated from an explosion in two models ("true" models, see Table 1): 1) a 2-layer model M_{True}^1 to investigate velocity mismodeling effects, and 2) a homogeneous model M_{True}^2, with a shallow-source location, to investigate mislocation effects. We also calculate a set of signals in a homogeneous model (hereinafter referred as "approximate" model M_{app}, see Table 1). This approximate model is equivalent to the model used in MTI in which Green's functions are computed. Similar to MTI of volcano data, this model is assumed to be the best model (usually homogeneous) we have to represent the complex structure of the volcano. The signals are generated by an explosion ($\boldsymbol{U}_{Ex}^{app}$) and SFs ($\boldsymbol{U}_{F}^{app}$). In all models, the amplitude of the isotropic source is 10^{12} Nm, and the amplitude of the SFs in the M_{app} model is 10^9 N.

The data computed in the approximate model ($\boldsymbol{U}_{Ex}^{app}$ and $\boldsymbol{U}_{F}^{app}$) are used to reconstruct the synthetic signals ($\boldsymbol{U}_{Ex}^{True}$) computed in the "true" models, such as:

$$\boldsymbol{U}_{Ex}^{True} = \alpha_{Ex}\ \boldsymbol{U}_{Ex}^{app} + \alpha_F\ \boldsymbol{U}_{F}^{app} \qquad (1)$$

α_{Ex} and α_F are the amplitudes of the explosion and of the SFs in the "approximate" model, respectively, needed to fit the synthetic data

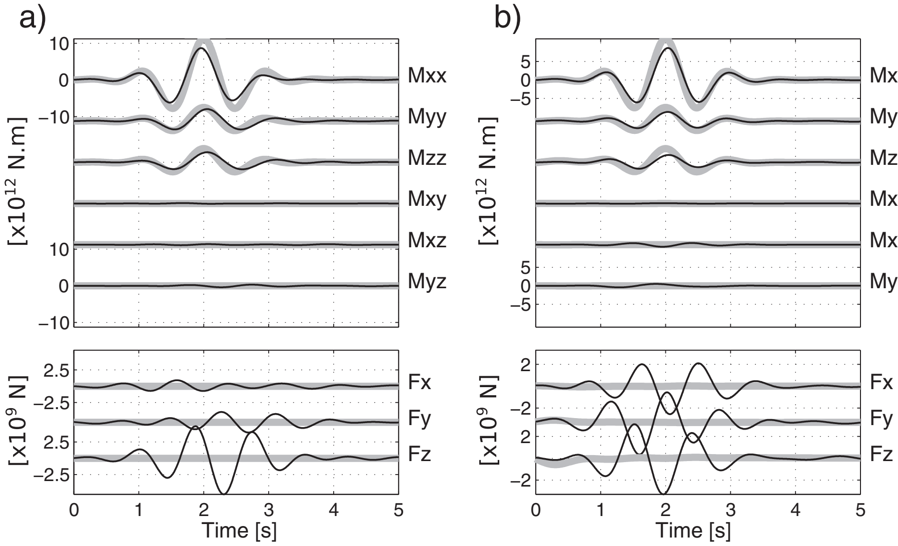

Fig. 1. Solutions of the moment tensor inversion of synthetic data computed for a vertical crack source (Mxx = 3*Myy = 3*Mzz) in the Mt Etna geometry. a) Data computed in a layered medium and inverted with GFs calculated in a homogeneous medium; b) Data computed in homogeneous medium and inverted with GFs calculated for a source mislocated by 120 m downward and 90 m horizontally. For both cases, gray thick lines are the true solutions and the black lines are the reconstructed solution for the 6 moment components and the 3 SFs.

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