Investigation of historical earthquake by seismic wave propagation simulation: Source parameters of the 1887 M6.3 Ligurian, north-western Italy, earthquake

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Hideo Aochi* — Ariane Ducellier* — Fabrice Dupros — Monique Terrier* — Jérôme Lambert***

** Bureau de Recherches Géologiques et Minières, Service Risques Naturels et Sécurité du Stockage de CO2*

3 avenue Claude Guillemin, BP36009, Orléans Cedex 2, 45060, France

h.aochi@brgm.fr

*** Bureau de Recherches Géologiques et Minières, Service Systèmes et Technologies de l'Information*

3 avenue Claude Guillemin, BP36009, Orléans Cedex 2, 45060, France

RÉSUMÉ. Les simulations numériques haute performance de la propagation des ondes sismiques de la source à la surface du sol sont un outil puissant pour l'étude d'un séisme. Comme la sismologie moderne basée sur les observations instrumentales n'existe que depuis quelques décennies, la simulation numérique est essentielle pour l'étude des séismes historiques ou l'estimation de futurs séismes pour lesquels il n'y a pas de données. Pour la France métropolitaine, le séisme ligure de 1887 est un des séismes les plus destructeurs, dont la position est estimée au nord-ouest de l'Italie, à proximité de la frontière avec la France, au large de la côte méditerranéenne. Nous effectuons des simulations numériques du mouvement du sol, à l'aide d'une méthode de différences finies (FDM) en 3D, basées sur des scénarios potentiels de séismes. En comparant l'extension spatiale des dommages (intensité), nous testons différents scénarios pour ce séisme basés sur des considérations sismotectoniques : (1) une faille normale superficielle proche de la côte, (2) une faille inverse superficielle au large et (3) une faille inverse plus profonde et plus proche de la côte. Les résultats de nos simulations améliorent nos connaissances des phénomènes passés et contribuent à l'évaluation de l'aléa sismique régional.

ABSTRACT. High performance numerical simulation of the seismic wave propagation from the earthquake source to the ground motion is a powerful approach to investigate the earthquake and its sequence. As the modern instrumental observational seismology has lasted only since a few decades, the numerical investigation is essential for studying the past historical earthquakes or assessing the future earthquakes for which there are no data. For French Metropolitan, the 1887 Ligurian earthquake is one of the most damaging earthquakes, whose position is estimated in the north-western Italy close to the border to France, off shore of the Mediterranean coast. We carry out numerical simulations of the ground motion, using a 3D Finite Difference Method (FDM), based on the supposed potential earthquake scenarios. Through testing earthquake scenarios and comparing to the spatial pattern of the damaging (intensity), we test different scenarios of this earthquake based on the seismotectonic insights, (1) a shallow normal faulting close to the coastline, (2) a shallow reverse faulting off shore and (3) a deep reverse faulting close to the coastline. Our simulation results improve our knowledge of past phenomena and contribute to the assessment of the regional seismic hazard.

MOTS-CLÉS : séisme ligure de 1887, mouvement du sol, méthode des différences finies, SisFrance

KEYWORDS: 1887 Ligurian earthquake, ground motion, finite difference method, SisFrance

1. Introduction

The high performance numerical simulations are actually powerful tools for studying the earthquakes and their sequences. The wave propagation in an elastic (sometimes anelastic) medium at large scale can be simulated from the earthquake source to the local ground motion, using for example finite difference scheme (Olsen *et al.*, 1997, Furumura and Chen, 2005, and many others) and spectral element scheme (e.g. Komatitsch *et al.*, 2004, and some others). Such fully numerical schemes allow us to introduce the complexity in the earthquake source description and/or in the medium property in higher resolution. This helps us to understand better the earthquake mechanism and analyze more quantitatively the sequential ground motion at sites of interest. The recent main damaging earthquakes are studied through such numerical simulations, such as the Mw7.3 1992 Landers, California (Olsen *et al.*, 1997), the Mw7.4 1999 Izmit, Turkey (Aochi and Madariaga, 2003), the Mw6.6 2000 Tottori, Japan (Furumura *et al.*, 2003), the Mw8.3 2003 Tokachi-oki, Japan (Aoi *et al.*, 2008), the Mw7.9 Wenchuan, China (Zhang *et al.*, 2008) and so on. Furthermore the numerical simulations are useful for the historical earthquake (before mid-20th century) for which we do not know well, for example, the 1855 M7 Ansei-Edo, Japan, the 1923 M7.9 Kanto, Japan (Furumura and Chen, 2005), the 1906 M7.9 San Francisco, California (Aagaard *et al.*, 2008), the 1944 M8 Tonankai, Japan (Furumura and Saito, 2009). For the earthquakes instrumentally well recorded, magnitude can be estimated based on the seismic moment (N.m) as moment magnitude Mw, while the historical events are not well constrained (sometimes by geodetic measurement, damage or paleoseismological observation) so that their magnitude are briefly expressed as magnitude M, without precision of the source. We do not aim to cite any more works about the applications for seismic hazard assessment, namely the earthquake scenarios for the future, as there are too many.

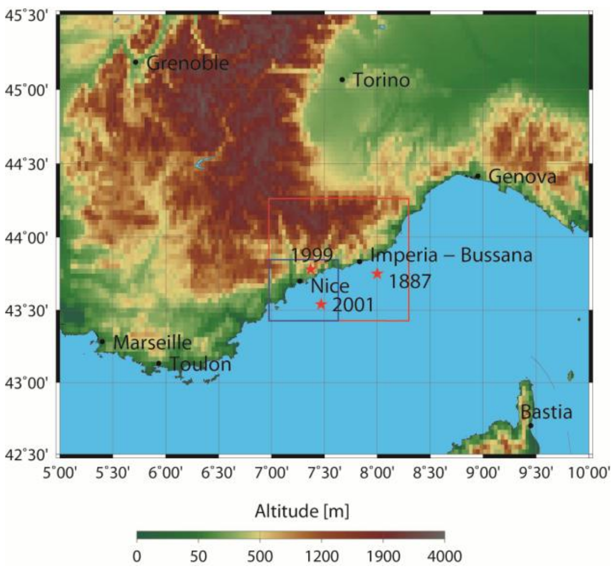

Figure 1. *Map of the Liguria region. The red rectangle corresponds to the area modeled for the numerical simulation of the 1887 earthquake (brief epicenter shown by star). The blue rectangle corresponds to the area for which we have originally a 3D structure model. For references, we show the recent earthquakes around Nice (1999 and 2001).*

The technique to simulate the wave propagation in an elastic medium was well established long time ago, although the improvement is always going on. One of the most popular methods is a finite difference method (FDM), whose framework in seismology is found in Madariaga (1976) and already on the textbook of Aki and Richards (1980). Many seismological applications are based on the staggered grid proposed in Madariaga (1976) and Virieux (1986), mainly because the scheme is very stable. Later comparing to this fully staggered grid, a partially staggered grid has been proposed (Saenger *et al.*, 2000). The classical FDM is based on the second order precision in space (Madariaga, 1976; Virieux, 1986) and then the fourth order precision becomes the most popular from the viewpoint of performance and precision (Levander, 1988), although higher order is still possible. The parallel computing became already casual in the mid-1990s (Olsen, 1994; Graves, 1996). The parallelization is relatively easier than other methods as the computing grids are in most cases structural. Thus the FDM is a very good example for high performance computing. In this paper, we adopt a 3D finite difference method and optimize it by equilibrating the charges on different processors. We demonstrate the numerical simulation for a historical event, the 1887 Liguria earthquake, which damaged the most in France Metropolitan and discuss its source mechanism.

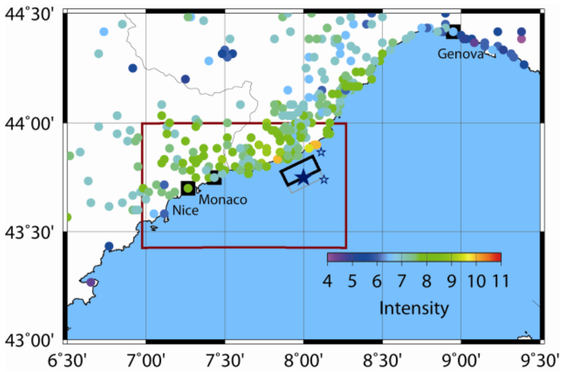

Figure 2. *Macroseismic intensity map of the 1887 earthquake. This map is provided by French earthquake database SisFrance. (http://www.sisfrance.net)*

The Liguria region, south-east coast of France along the Mediterranean Sea and close to the border to Italy (Figure 1), is one of the regions of metropolitan France where the necessity of studying seismic hazard and risk is more important. It is known that the region suffered several times from destructive earthquakes in 1494, 1564, 1618, 1644, 1887 after French historical earthquake catalogue (SisFrance, http://www.sisfrance.net) and there have been previously several studies concerning the regional and local seismic hazard and risk evaluation. For example, the European Risk-UE project (e.g. Mouroux and Le Brun, 2006) evaluated the seismic risk in the city of Nice for an earthquake scenario. In French national project, some earthquake scenarios are proposed according to the interpretation of the regional seismotectonics. In most cases, the reference earthquake is taken as a magnitude M6.3-6.4 which corresponds to the 23th February 1887 Ligurian earthquake (e.g. Salichon et al., 2010).

The 1887 event is the largest earthquake in the region. However its source mechanism is not well known. The epicenter of the 1887 Ligurian earthquake is found in north-western Italy, close to the border to France, in the Mediterranean Sea. Significant damage was reported at various towns from north-western Italy and south-eastern France (see Figure 2: macroscopic intensity after the database SisFrance). The macroseismic intensity at the epicenter is estimated at 9.5 in the MSK intensity scale (SisFrance, http://www.sisfrance.net), and the magnitude is estimated at around 6.2 – 6.5 (Barani *et al.*, 2007; Capponi *et al.*, 1985; Carrozo *et al.*, 1973; Ferrari, 1991). The epicenter is not so fairly determined because it is off-shore, probably at a distance of tenths kilometers from the Ligurian coast (see Figure 1). Table 1 summarizes epicenter location and magnitude proposed in previous studies. The fault mechanism is considered as a thrust fault as reverse mechanisms were observed for recent earthquakes in this area (Barani *et al.*, 2007 ; Baroux *et al.*, 2001; Béthoux *et al.*, 1988; Béthoux *et al.*, 1992). However, a tsunami with a negative first wave was observed at a large distance along the coast from Genova (Italy) to Cannes (France) (e.g. Eva and Rabinovich, 1997), which supports the assumption that the earthquake was produced by an off-shore normal fault. Both normal and reverse faultings were used in the previous studies (Eva and Rabinovich, 1997; Frisenda and Madariaga, 2004; Frisenda *et al.*, 2005; Pelinovsky *et al.*, 2002). Comparing to the detailed regional active fault maps and interpretation of the structural geology (Barani *et al.*, 2007; Bigot-Cormier, 2002; Terrier, 2004), both of them seem to be possible. Constraining better the mechanism of this earthquake is important for understanding not only the tectonics and the seismicity in the Liguria region but also the regional seismic hazard and for improving risk analyses. This is the main objective of this study.

Source	Latitude	Longitude	Intensity (MCS)	Magnitude	Depth
Capponi et al. (1985)	43°52'	8°07'	IX	5.6	15 km
Carrozo et al. (1973)	43°45'	8°00'	IX	6.2	unknown
Ferrari (1991)	43°45'	8°00'	IX	6.5	17 km
Barani et al. (2007)	43,74°	8,13°	IX	6.29	unknown

Table 1. *Summary of the source parameters of the 1887 earthquake proposed in the literature (after Ferrari, 1991).*

2. Numerical method and numerical performance

We adopt a finite difference scheme for simulating the ground motion from any assumed earthquake source model. The code Ondes3D (Dupros *et al.*, 2008; Dupros *et al.*, 2009), optimized for parallel computing, is based on the 4th-order staggered-grid framework (Madariaga, 1976; Virieux, 1986; Levander, 1988, Olsen, 1994). Any seismic source can be included as a moment distributed on grids (Olsen, 1994; Graves, 1996). A convolutional perfectly matched layer absorbing condition (Komatitsch and Martin, 2007) is introduced for avoiding the artificial wave reflection from the model volume border (Ducellier and Aochi, 2007). Our code can treat anelastic medium for introducing a realistic attenuation (Day and Bradley, 2001; Kristek and Mozco, 2003). However in this study, we limit our calculations to an elastic medium as the Liguria region is presented basically as a horizontally heterogeneous layered structure without any significant basin and anelastic parameter (quality factor Q) is not quantitatively known in this region. The simulations are carried out with a flat ground surface. This is usually enough for regional seismic hazard analyses since we discuss relatively low frequencies.

We use the 3D geological model constructed by compiling different geophysical profiles so as to be consistent with the geological interpretation in the framework of the French national project (QSHA, http://qsha.unice.fr/). Although the initial model is constructed for a dimension of about 50 km around the city of Nice, it lacks some extension toward Italy and the source region of the 1887 event. Thus we extend the available 3D model outside to the direction of N60°E supposing a 2D structure along the axis N30°W (e.g. Bertrand and Deschamps, 2000), briefly perpendicular to the coastline of the region. For the first part of the simulation of the 1887 earthquake, the model volume is therefore given by 100 x 70 x 26 km3. The model parameters used in the simulations are given in Table 2.

The frequency limit in the finite difference scheme is controlled by the grid spacing and the wave velocity in the material. The upper limit is described as

$$f_{max} = v_{min} / (g \cdot \Delta s) \,, \qquad [1]$$

where v_{min} is the minimum velocity in the medium (1400 m/s in the model used in this study), Δs is grid size and a constant *g* which stands for the number of points per wavelength. For 3D calculation with the 4th order scheme, the computation of 5 points per wavelength is usually taken to avoid numerical dispersion (e.g. Levander, 1988). The calculation up to high frequency requires finer grids. Theoretically Equation (1) gives f_{max} = 1.4 Hz for Δs = 200 m.

For our discussion, we focus on values of Peak Ground Velocity (PGV) among various engineering parameters. PGV is numerically a reliable parameter in the current numerical scheme, as it represents relatively low frequencies comparing to, for example, PGA (Peak Ground Acceleration). The correlation between the PGV and damage (or macroseismic intensity) has been discussed mainly in the United States (e.g. Trifunac and Brady, 1975; Wald et al., 1999) or Japan (e.g. Miyakoshi et al., 1998). More discussions and applications are found for example in Bommer and Alarcon (2006).

Layers	P-wave velocity Vp [m/s]	S-wave velocity Vs [m/s]	Density ρ [kg/m^3]
Sediment	3000	1400	1730
Crust	5720	3300	2600
Moho	6930	4000	2990

Table 2: Model parameters of the numerical simulations in this study. Elastic property of each layer in the model.

3. Source models for the 1887 Ligurian earthquake

As explained in the previous sections, for the 1887 Ligurian earthquake, two different faulting mechanisms are inferred from seismo-tectonic interpretation. Figure 3 shows a schematic view of these possibilities: reverse faultings, relatively shallower and far from the coast (A) or deeper and close to the coast (B), and normal

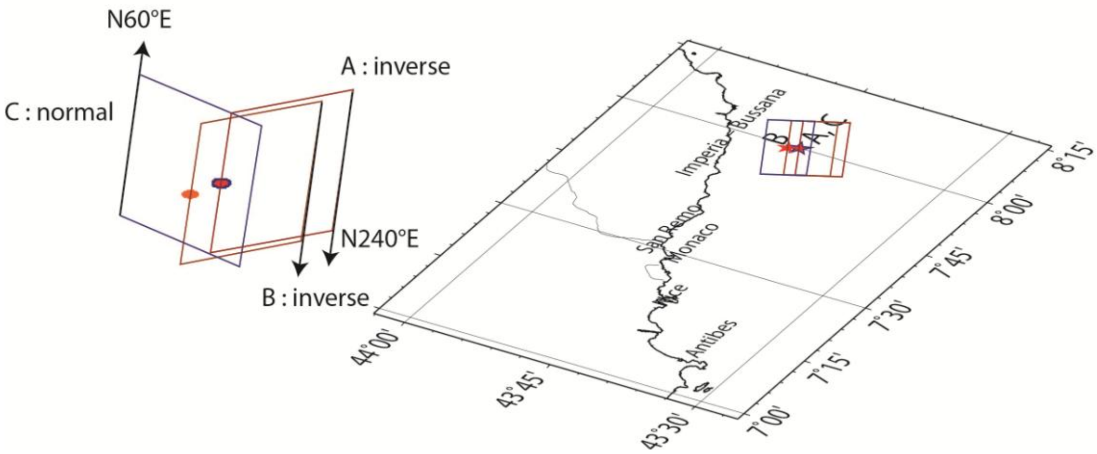

Figure 3 : *Projection of fault geometries tested in this study and 3D schematic illustration shown at corner from the same view azimuth. The hypocenters are also marked. A: reverse faulting off-shore with the hypocenter at center bottom (strike=N240°E, dip=30°). B: deeper reverse faulting closer to the coastline with the hypocenter at center bottom (strike=N240°E, dip=30°). C: normal faulting still closer to the coastline with the same hypocenter as Model A (strike=N60°E, dip=60°). Fault dimension is 18 km length by 9 km width.*

faulting (C). For all the models, we suppose a magnitude Mw6.3 with a fault dimension of 18 km length and 9 km width. The dip is taken as 30° for the reverse faultings (A and B) and 60° for the normal faulting. The hypocenters are located at the bottom center of each fault model. The hypocenter depth is taken at 7 km depth for A and C (full star in Figure 3), but is shifted to 9 km for B (open star). We first apply a uniform source model (slip distribution) and then introduce a characteristic source model based on Miyake *et al.* (2003) and Irikura and Miyake (2011). In all cases, we suppose a very simple, but typical form of the source time function represented by a rectangular pulse of duration (rise time) of 1 second. We choose a rupture velocity of 2.700 km/s. It is possible to introduce sophisticated source time function and spatial heterogeneity, but the simple

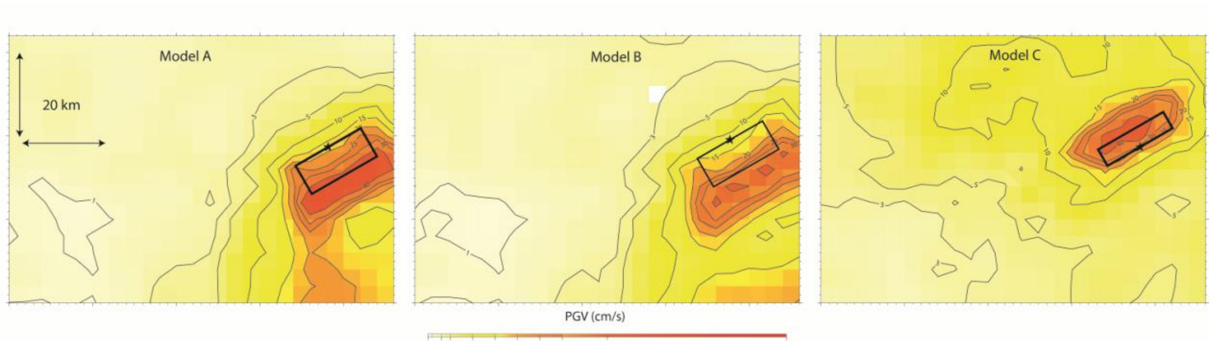

Figure 4. *Horizontal PGV (peak ground velocity) in cm/s for models A, B and C. The geometrical map is shown in Figure 3.*

parameterization is enough for our discussion.

We first compare the homogeneous models A, B and C. The difference in the resultant ground motions is clearly shown in the spatial distribution of horizontal peak ground velocity (PGV) values in Figures 4. It is not easy to compare the PGV distribution and the macroscopic intensity reported at this period. However it is evident that a wide area of high intensity spreads along the coast from Italy to France. For explaining this feature, the source is required geographically to be near the coastline. Indeed, the reverse faulting does not affect significantly the coastline, because the directivity effect of earthquake rupture goes away from the coast. In this meaning, it is model C which can easily generate strong ground motion (e.g. 10 cm/s) on the land. Although model C does not sufficiently supply the strong ground motion (e.g. Figure 2), this fault geometry is necessary to consider for further discussion. For model C, we try to simulate a different hypocenter position, for example as like in model C-unilateral in Figure 5, where the eastern-bottom corner is chosen so as to be the most severe scenario to the west, French Liguria. Although this scenario leads to a wide area of strong ground motion to the west because of the rupture directivity, this instead weakens it to the east. This does not match the wide spread of intensity map, either. Thus, a bilateral rupture scenario should be required in any case.

As long as we consider a homogeneous fault model, the strong ground motion is localized just around the fault and its peak value is not so high so that it is not transported at distance. Then a heterogeneous model is introduced based on the Miyake *et al.* (2003) and Irikura and Miyake (2011)'s recipe. The asperity (large fault slip) area is 20% of the total rupture area. The number of asperities is assumed to be 2, both of which have the same area and twice the fault slip than the background fault area. Figure 5 also shows this characteristic source model (C-asperities1) and the resultant PGV map. This scenario allows a wide area of strong ground motion along the coast, although the epicenter area is slightly eased.

As the map of intensity (Figure 2) seems to give a slightly larger affected zone at the west of the model than at the east, a last scenario (C-asperities2) is defined with two asperities of different sizes: the western asperity represents 15% of total rupture area and the eastern 5% of total rupture area (this variation is allowed by Irikura and Miyake's recipe). In Figure 5, we also show this characteristic source model and the resultant PGV map. Using two different sizes for the two asperities leaded to eliminate the symmetry which appeared in the previous model and generated more ground motion in the western part than in the eastern part, which can correspond better to the spatial extension of intensity map.

4. Discussion and summary

Through the simulations performed in this study, preferred source models, explaining the macroseismic intensity observed in the Liguria region, are inferred. However, without more information on the ground motion, it is difficult to improve more the source models proposed here. In fact, the intensity data may not be homogenized between France and Italy for this earthquake and may include any local effect (site and/or vulnerability). It is not completely assured that it indicates the intensity of ground motion. We fixed a magnitude to 6.3 according to the literature, but it is also under debating. If we had more precise ground motion indication

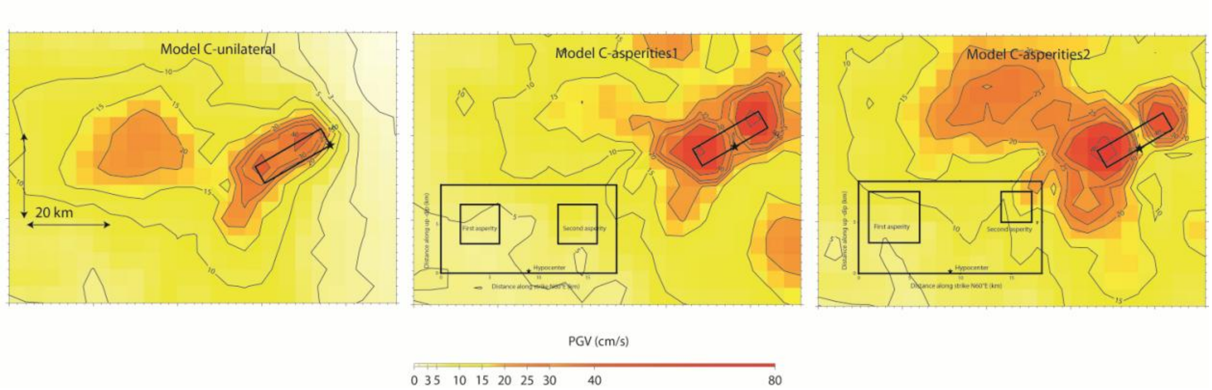

Figure 5. *Horizontal PGV map for the derivative models based on fault geometry model C. ModelC-unilateral: Hypocenter is chosen eastern bottom corner of fault, and fault slip is uniform. ModelC-asperities1: Hypocenter is center bottom. Two asperities of equal dimension (10% each) are given. ModelC-asperities2: Hypocenter is center bottom. Two asperities of large (15%) and small areas (5%) are given.*

for this earthquake, we could constrain more the source parameters, too. About this earthquake, we should not forget that two large aftershocks followed in a day (http://www.sisfrance.net). It is probable that some historical record were confused between the mainshock and aftershocks, so we need to read it carefully. All these topics should be considered in future works.

The 3D geological model we use in this study remains 2D profile over the whole scale with only three layers and the minimum wave velocity of 1400 m/s. Therefore, our calculation represents the ground motion for the basement at each point. The real ground motion at the ground surface can be amplified by a significant factor. It is expected anyway to improve the geological model so as to include surface layers of at least 700-800 m/s. Our calculation is based on the frequency of 1 Hz. In order to discuss the damages of this era, we will need to refine both the structure and source models until 2-3 Hz.

Regardless of the limits of data and available models, such numerical simulation approaches are useful to discuss the historical earthquakes and their better understanding is important for seismic hazard analysis. In this study, we have tested different scenarios of both reverse and normal faulting, taking into account of tectonic interpretation of this region. Our simulations infer a preference of normal faulting for this earthquake, which differs from some previous studies. All the discussion is still open.

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