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In Search of the 1654 Seismic Source (Central Italy): An Obscure, Strong, Damaging Earthquake Occurred Less than 100 km from Rome and Naples

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Abstract: The M6.3 earthquake that occurred in southern Lazio (Central Italy) in 1654 is the strongest seismic event to have occurred in the area. However, our knowledge about this earthquake is scarce and no study has been devoted to the individuation of its causative source. The main purpose of this study is putting together all of the information available for this shock to provide reliable landmarks to identify its seismic source. To this end, we present and discuss historical, hydrological, geological, and seismological data, both reviewed and newly acquired. An important, novel part of this study relies on an analysis of the coseismic hydrological changes associated with the 1654 earthquake and on the comparison of their distribution with models of the coseismic strain field induced by a number of potential seismogenic sources. We find more satisfactory results when imposing a lateral component of slip to the faults investigated. In particular, oblique left-lateral sources display a better fit between strain and hydrological signatures. Finally, the cross-analysis between the results from modeling and the other pieces of evidence collected point to the Sora fault, with its trend variability, as the probable causative source of the 1654 earthquake.

Keywords: historical seismicity; earthquake environmental effects; coseismic hydrological changes; earthquake source modeling; central Italy

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1. Introduction

Motivated by the limited knowledge concerning the M > 6 earthquake of 1654, this study is an attempt to understand the event that damaged the region of Lazio-Abruzzo in Central Italy, less than 100 km from Rome and Naples (Figure 1). Records on this earthquake are available but they are too old for seismogram data and are beyond the age limit for applying seismological analysis to robust historical documentation, including recognition of the causative fault that ruptured during the event. For these reasons, the approach used could not be solely based on direct data so validation through modeling was used as well.

The study area is located in the Central Apennines, an East verging, fold-and-thrust belt that developed during the Late Cretaceous to present Africa–Europe plate convergence [1,2]). The present-day landscape and tectonic setting of the region is the result of a long deformation history, characterized by cyclical extensional and contractional phases [3]. The regional seismicity and fault setting reflects the present-day NE–SW-oriented extensional regime characterizing the Central Apennines [4], with a broad and complex system of normal faults that dissect the belt and crosscut the pre-existing compressional structures.

Our analysis is based on the different typologies of direct historical coseismic data and geological/seismological data. Among the historical data, we utilize records extracted from the available seismic catalogues [5] and the hydrological and geological earthquake signatures newly acquired and derived from the archival research conducted in this study. Among the geological data, we take into account the active faults commonly considered as potential sources of the 1654 event. With regard to the seismological data, the distribution and the parameters of the present-day instrumental seismicity are considered.

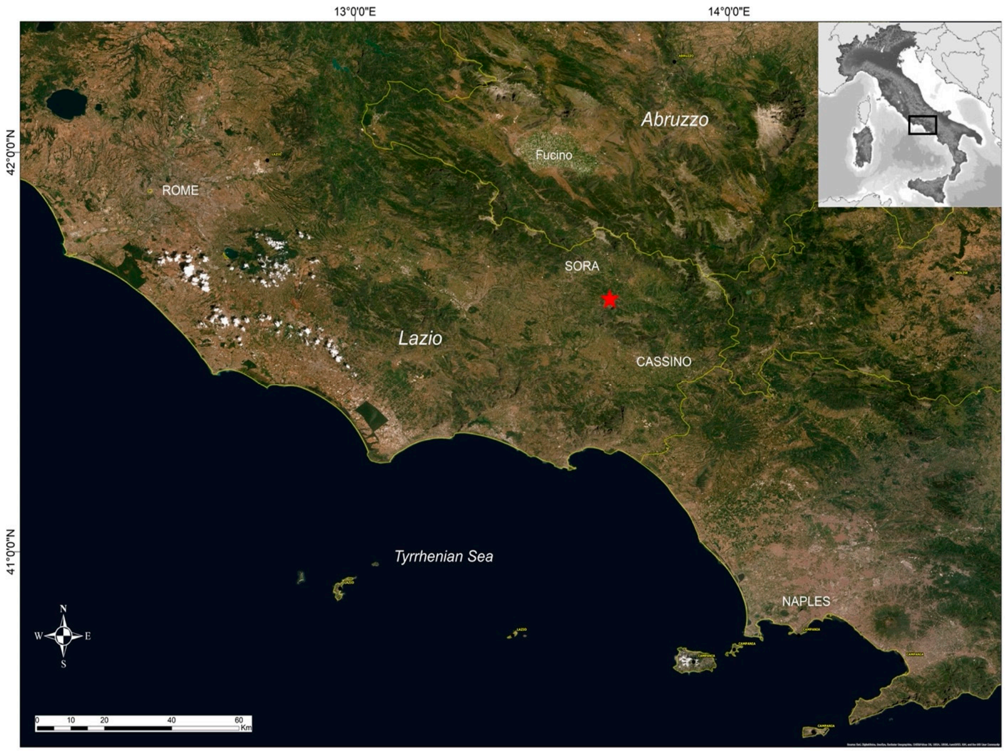

Figure 1. Epicentral location of the 1654 earthquake (red star). The cities of Rome and Naples are less than 100 km of distance from the source.

The 1654 earthquake had an MCS intensity of 9–10 and an Me of 6.33+/−0.14 [5], with the uncertainty in its epicentral location being +/−2.5 km. Although which fault caused this earthquake is still unknown, the 1654 earthquake occurred in a highly seismogenic region in Central Italy, which has been struck by medium to large earthquakes in present and historical times [5], with a ~200-year M6+ earthquakes average regional recurrence time [6]. The main aim of this study is to identify the source of the 1654 earthquake and to provide suggestions regarding the kinematics of the 1654 rupture mechanism. To this aim, we (1) modeled the intensity data (Boxer 4.0 code by Gasperini et al. [7], deriving different types of macroseismic sources; (2) calculated the strain fields imposed by all the potential faults; (3) analyzed which sources best matched the coseismic hydrological/geological signals that we collected; and (4) discriminated among the resulting potential faults considering the seismological imprint of the region as defined by the instrumental seismicity and by the geometry of the active faults in the area.

2. The 1654 Earthquake: Geological, Seismological, and Macroseismic Context

The earthquake hit during the early hours of the 24th of July, producing destructive effects (I = 9–10, M = 6.3) [5] over a vast area of the Southern Latium region between Sora and Cassino and widespread damage on the southern side of the Fucino area (Figures 1 and 2).

The map of the macroseismic intensities extends approximately 25 km from the epicenter, and the effects are differentiated, mainly because of different geological and topographical conditions of the villages involved. Six localities were almost completely destroyed and another twelve were heavily affected by the shock that was felt as far as Rome and Naples (IV–V MCS intensity). The relatively limited spatial distribution of the intensities associated with the 1654 earthquake partly reflects the paucity of official documents and historical sources available for this event. The economic marginality of the affected area (scarce productive activities, far from the main roads, no relevant center damaged) did not encourage the authorities to send investigators (scientists and technicians) to produce detailed descriptions of the event, neither did the subsequent local historiography show interest in this seismic disaster. Additionally, the fact that this is a 'border' earthquake that occurred between the two former states of the Vatican and the Kingdom of Naples (Figure 2) may have played a role in the general knowledge of the event and further investigation could help to extend the map of damage. Despite this and except for the ancient 1349 M6.8 earthquake of which the location and magnitude are still debated [8,9], the 1654 Sora event is the most powerful earthquake to have occurred south of latitude 42° S and within 150 km southeast of Rome, representing the local seismic maximum for the study area (Figure 3).

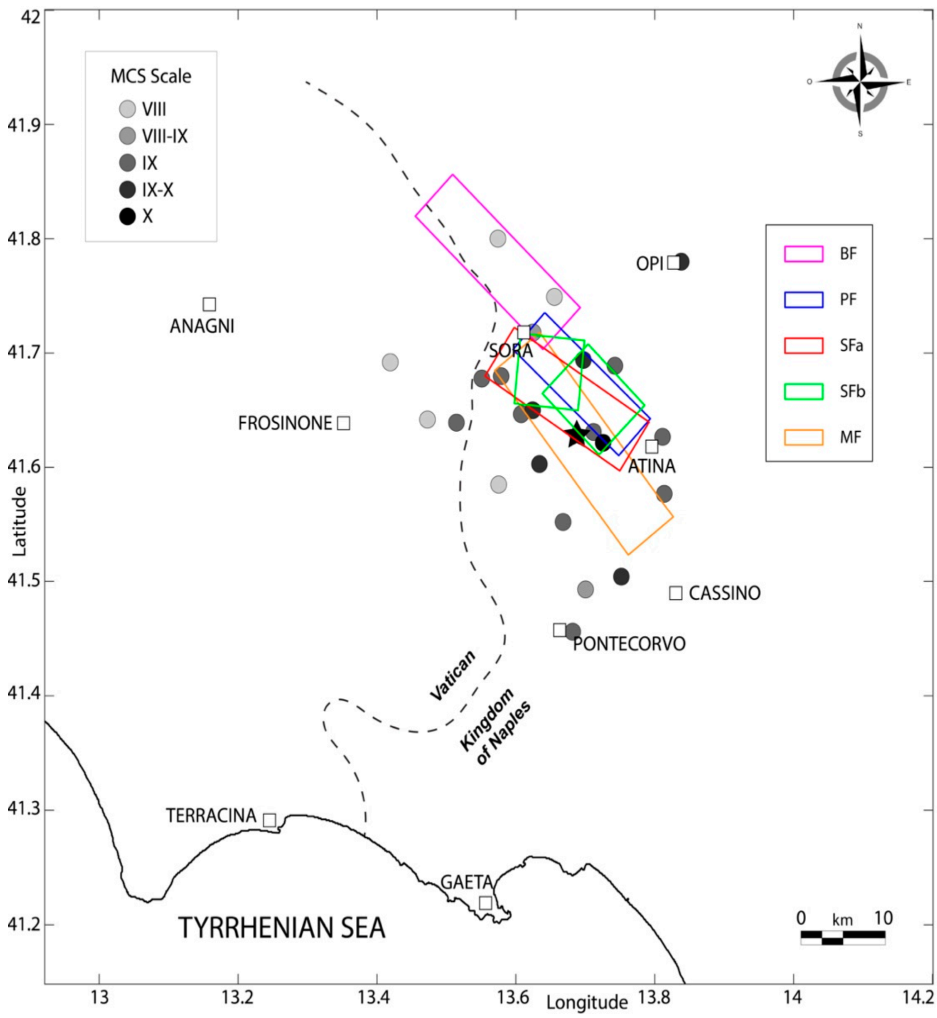

Figure 2. Map of the Mercalli–Cancani–Sieberg (MCS) intensities of the 1654 earthquake. A black star indicates the macroseismic epicenter of the event. The dashed line indicates the border between the two former states of the Vatican (West) and the Kingdom of Naples (East) in the XVII Century, at the time of the earthquake. Colored boxes are the modeled sources: BF, Balsorano fault; PF, Posta-Fibreno fault; SFa, Sora fault from ITHACA Working Group [12]; SFb, Sora fault from Boncio et al. [13]; MF, Macroseismic fault.

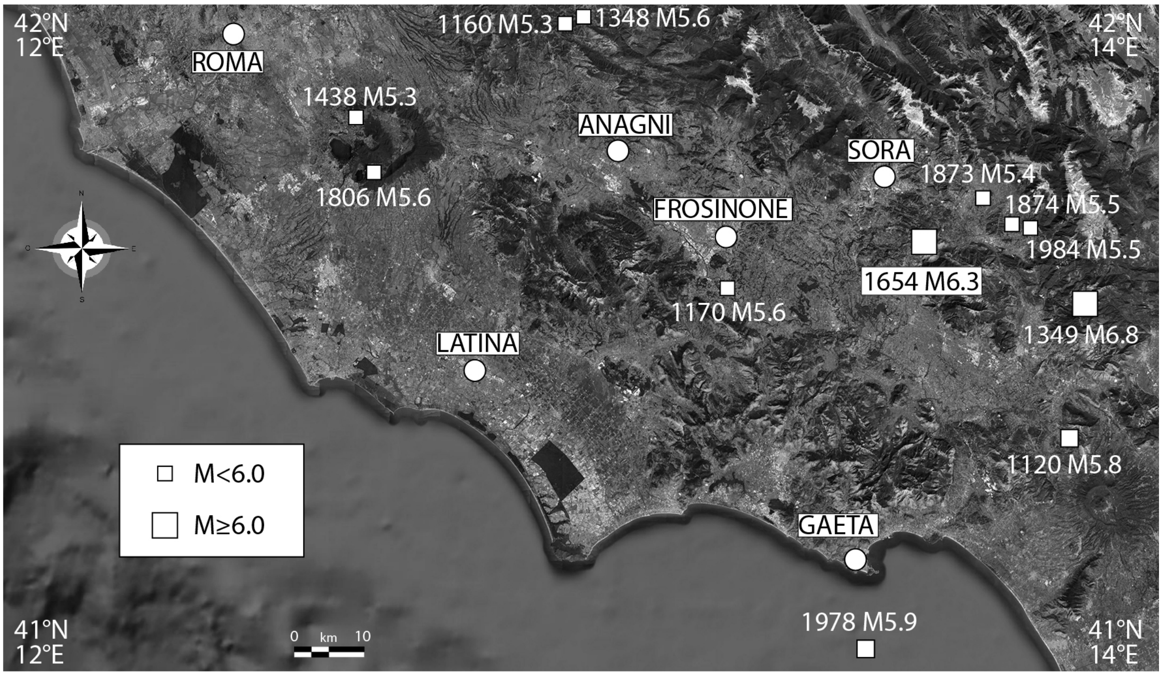

Figure 3. Historical seismicity [5] of the southern Lazio region. The 1654 earthquake is the strongest event to have occurred in this area, apart from the 1349 event.

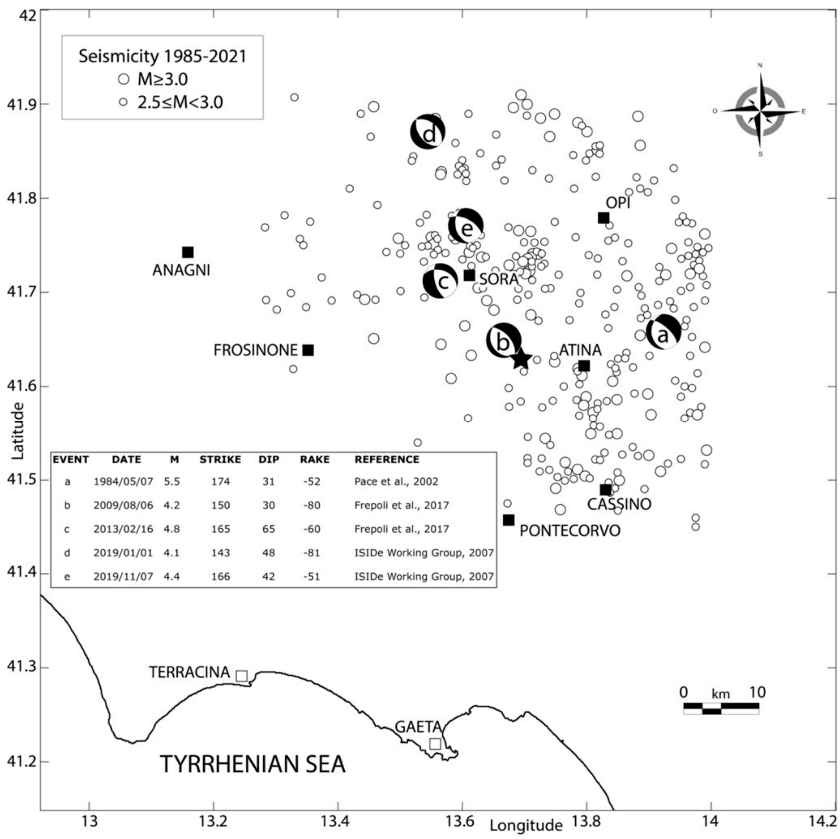

Figure 4. M $\geq$ 2.5 instrumental seismicity from 1985 [10] in the area of the 1654 earthquake (Latitude 41.45–41.90°, Longitude 13.30–14.00°). In the inset, we show the parameters of the five M > 4 instrumental earthquakes that occurred in the area since 1984. A black star indicates the macroseismic epicenter of the 1654 event.

The instrumental seismicity recorded in the area starting from 1985 [10] shows both low-to-moderate magnitude seismic sequences and diffuse swarm-like events, with the magnitude ranging from 0.4 to 4.8. Figure 4 reports the instrumental seismicity within 30 km from the 1654 epicenter, along with the focal mechanisms of the five most powerful ($M \geq 4.1$) seismic events in the study area that testify to a predominant normal faulting with an oblique left-lateral component [10,11].

The 1654 earthquake area contains at least three main active tectonic lineaments [12], hereinafter referred to as the Balsorano fault (BF), Posta-Fibreno fault (PF), and Sora fault (SFa and SFb) (Figure 2 and Table 1), that are generally indicated as potential sources for this event because of their location and geometry. The three faults are closely spaced and they belong to the western system of active faults of the Central Apennines [13]. They have a NNW–SSE average strike, dip towards WSW, and dip–slip to normal–oblique kinematics. They remain poorly investigated and are reported with differences in the mapping due to uncertainties on their longitudinal continuity, and their characterization is debated among the authors. Recently, evidence of Upper Pleistocene–Holocene activity has been collected along the BF and PF [14,15] while direct evidence of recent activity of the SF is unavailable.

Table 1. List of the five potential sources of the 1654 earthquake that represent the input to the modeling of the coseismic static strain.

Source	Length (km)	Width (km)	Min Depth (km)	Max Depth (km)	Strike°	Dip°	Rake°	Seismic Moment (Dyne cm)	Ref.
BF Balsorano	16.0	12.0	1	11.4	134	60	−50/−90/−130	2.9×10^{25}	[12]
PF Posta-Fibreno	13.0	10.4	1	10.0	133	60	−50/−90/−130	2.2×10^{25}	[12]
SFa Sora	16.6	11.5	1	11.4	125	60	−50/−90/−130	2.9×10^{25}	[12]
SFb Sora	17.0	14.4	1	13.5	115	60	−50/−90/−130	3.7×10^{25}	[13]
MF Macroseismic	19.6	10.3	5	13.9	142	60	−50/−90/−130	3.2×10^{25}	[7]

3. Effects of the Earthquake on the Natural Environment

The CFTI Catalogue of Strong Earthquakes in Italy [16] reports that this earthquake had two effects on the natural environment: a wide surface fracturing along Monte Corvo (M. Corvo) and a large landslide in Roccasecca (Figure 5 and Table 2). We re-positioned the fracture (number 4) that was misplaced in the Catalogue. In fact, Guidoboni et al. [16] located the fracture in Pontecorvo whilst the original source reports it at Monte del Corvo, 10 km NW of Sora. The landslide (number 7) reasonably occurred along the steep slope north of Roccasecca, where a scarf is still visible. We performed an in-depth round of investigation in local and national libraries and archives to seek new data of this type; the search in coeval chronicles, letters, and diaries and in later reports allowed us to add five new observations (Figure 5 and Table 2). Most of these new data concern hydrological changes that occurred immediately after the event. An increase in the discharge of the Gari River close to its springs in Cassino (number 1), a decreased and turbid flow of the Liri River in Isola Liri (numbers 2 and 3), and a decrease in discharge in the Fucino area (number 5) were reported. A fifth significant and previously unknown datum (number 6) derives from direct observation of fractures affecting the ancient structure of the Cathedral of Sora and it is indirectly inferred from the analysis of the church reconstruction history [17,18]. Some of the fractures of walls and the basement are preserved and appear aligned and adjacent to the trace of the SF. Moreover, an intriguing piece of evidence regarding the Cathedral is that its northwest end (presbyterium) is presently accessed through three steps as it is higher than the rest of the building [17,18]; however, according to the description of Bishop Giovannelli in 1618, it does not result in a higher position. This change possibly reflects a local ground deformation corresponding to the fractured zone.

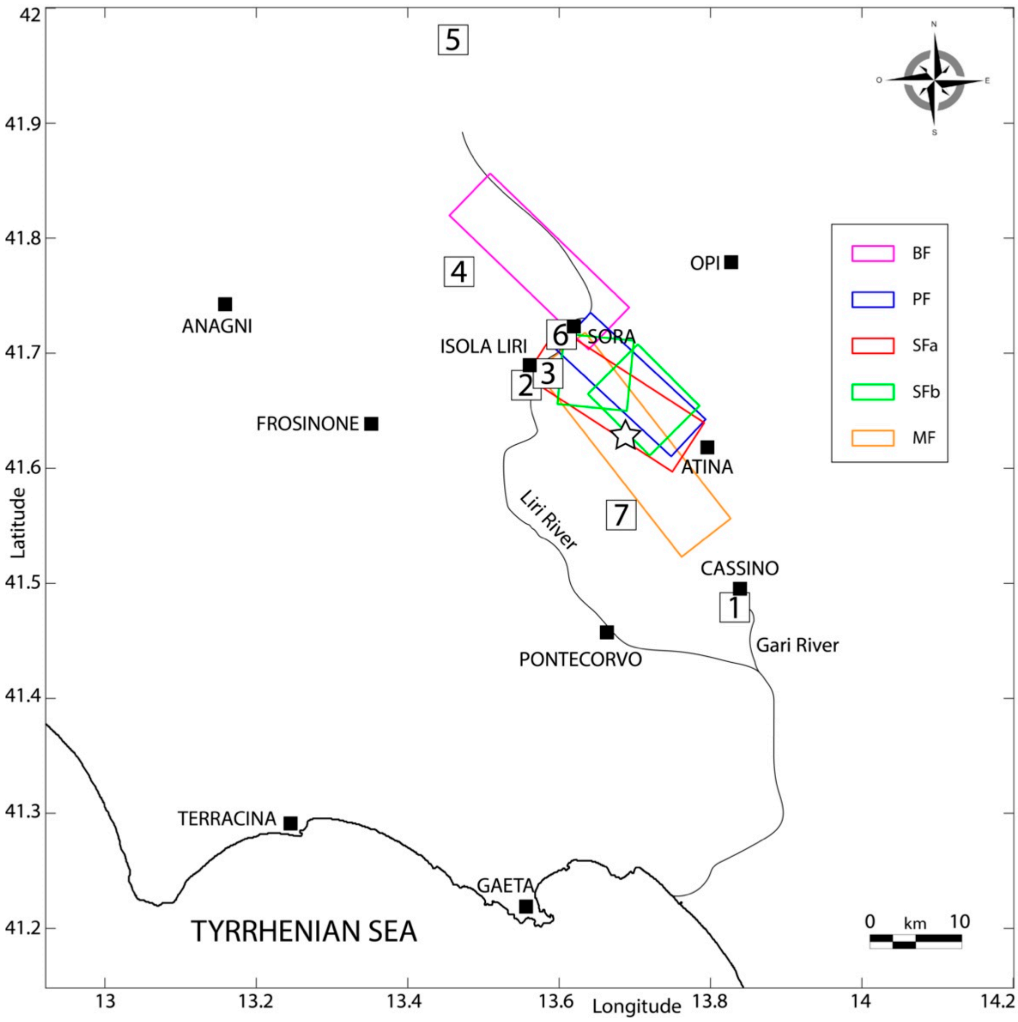

Figure 5. Distribution of the effects of the 1654 earthquake on the natural environment (see Table 1 and text for the description of the effects). Colored boxes are the modeled sources: BF, Balsorano fault; PF, Posta-Fibreno fault; SFa, Sora fault from ITHACA Working Group [12]; SFb, Sora fault from Boncio et al. [13]; MF, Macroseismic fault.

Table 2. List of the effects observed in the natural environment following the 1654 earthquake (progressive number corresponds to Figure 5). The epicentral distance is calculated from the location of the Italian seismic Catalogue (red star in Figure 1) [5].

No	Locality	Lat°	Lon°	Epic. dist. (km)	Effects	References
1	Cassino	41.480	13.832	21.2	Increase in discharge of Gari springs	[19,20]
2	Isola del Liri	41.680	13.574	10.5	Decrease in flow from Liri River	[21]
3	Isola del Liri	41.678	13.571	10.6	Turbid water from Liri River	[21]
4	M. Corvo	41.772	13.468	23.5	Wide surface fracturing	[16,19,20]
5	Luco dei Marsi	41.973	14.461	41.8	Chasms and lowering of waters in the Fucino Lake area	[22]
6	Sora	41.723	13.615	11.3	Inferred coseismic fracturing in the flooring of the Cathedral	[17,18]
7	Roccasecca	41.554	13.669	9.1	Landslide	[16,23]

4. Source Modeling

The scarcity of records belonging to the 1654 event is reasonably due to the ca. 350-year age of the earthquake itself, more than due to the real absence of effects on the landscape and villages. However, we are still able to use the collected records to infer the 1654 source parameters. Indeed, an analysis of the geographic distribution and the type of earthquake effect (i.e., building damage, ground failures, and hydrological change) is a way to provide constraints on both the fault location and the deformation style.

In particular, the coseismic hydrological changes (increase or decrease in the discharge of springs and streamflows, the water level in wells, turbid flow from springs and rivers, and liquefaction) can be a valid alternative method to provide further constraints to estimate (or to confirm related hypotheses) the faulting style of major historical earthquakes of which the seismogenic source is unknown or in dispute, as is the case of the 1654 earthquake. The basic rationale is that such hydrological variations are explained by the coseismic static strain and pore pressure changes predicted by the poroelastic theory, as first proposed by Wakita [24]. Following this theory, an earthquake imposes a coseismic strain field that causes rocks to dilate or contract; the opening or closing of saturated cracks in rocks result in decreases or increases in the ground water discharge from springs and streams. The amplitude of the hydrological changes is proportional to the volumetric strain field, so that the groundwater discharge increases in areas that contract and decreases in areas that extend. Following this rationale, in recent decades, the character of the coseismic hydrological changes has often been found to be related to the style of faulting (Cucci [25] and references therein). The most important caveat regarding the use of hydrological changes in this kind of study is that local precipitation can influence the effect that is observed and it must be carefully investigated. In the case of the 1654 earthquake, the available reports confirm the absence of rainfall in the days preceding the event, which is reasonable as the earthquake occurred at the end of July—the driest period in peninsular Italy. For a complete review of the application and of the limits of this theory in seismogenic studies, see Cucci [25]. It is possible now to perform the calculations of the coseismic strain for the 1654 earthquake produced by the potential sources listed in Table 1 to verify the best fault solution fitting with the observed hydrological and geological effects. The static strain change induced by an earthquake can be calculated using a fault dislocation model. The calculations of the strain were made in an elastic half-space with uniform isotropic elastic properties following Okada [26], and using Coulomb 3.4 [27,28]. In particular, we investigated the deformation imposed by the BF, SFa, and PF [12] and by the Sora fault as proposed by Boncio et al. [13], referred to as SFb. The fifth modeled source (macroseismic fault, referred as MF) is derived from Boxer 4.0 [7], a code that computes the quantitative parameters of earthquakes from the inversion of macroseismic intensity data, which is routinely used for the parametrization of the historical events of the Catalogue. The considered faults are generally reported by the authors with dip–slip to normal–oblique kinematics; this is also confirmed by the focal mechanisms displayed in Figure 4. Thus, we first performed our modeling on pure normal sources (rake -90°, Figure 6a–e); then, a second round of calculation was carried out considering left-lateral oblique slip (rake -50°, Figure 6f–i,l). Finally, we tested the strain calculations on a set of normal sources with oblique right-lateral slip component (rake -130°, Figure 6m–q). The outputs of our calculations are plots of the volumetric strain at the free surface on the five selected individual sources; the plots are shown in Figure 6. We expect to find an increase in discharge in areas of compressional strain and a decrease in discharge in areas of dilatational strain.

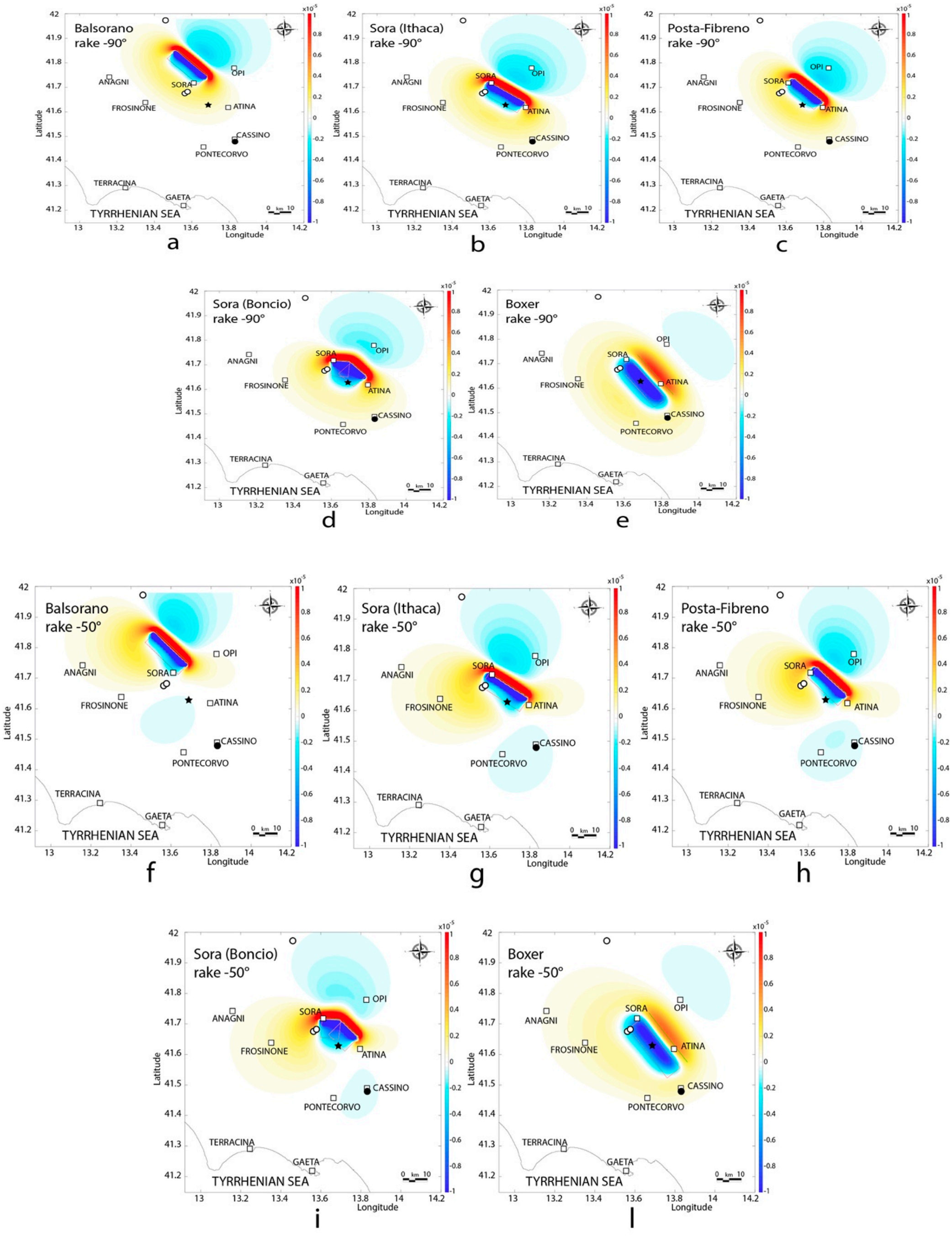

Figure 6. *Cont.*

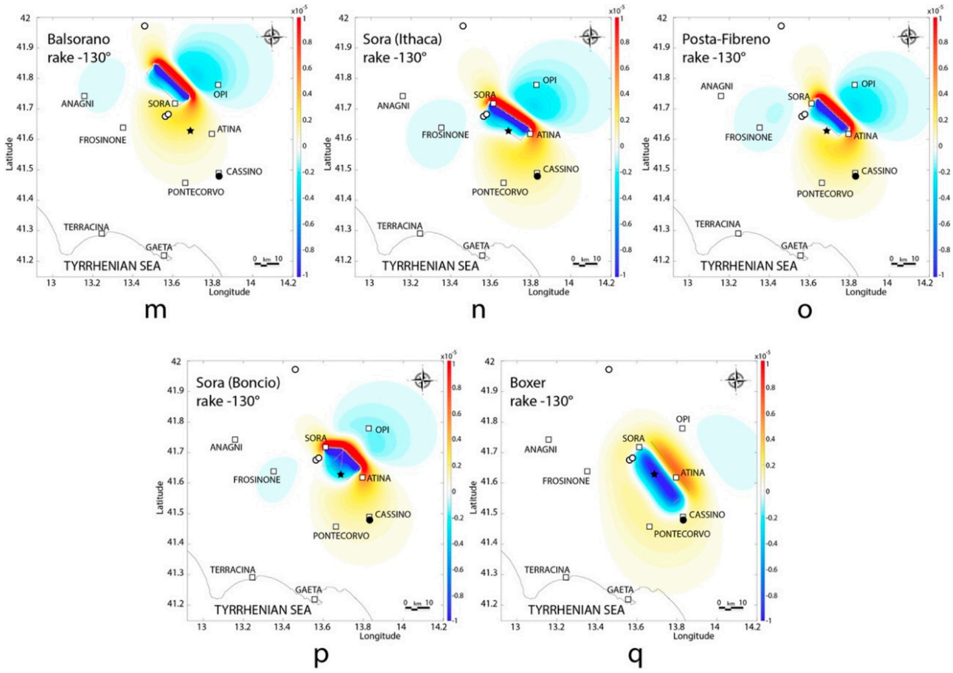

Figure 6. Comparison between the calculated coseismic strain fields along five potential sources and the observed hydrological effects produced by the 1654 earthquake. The calculation of strain was made using Coulomb 3.4 [27,28]. Plots '(**a**–**e**)' show the calculations for normal sources (rake −90°), plots '(**f**–**i**,**l**)' show the calculations for oblique left-lateral sources (rake −50°), and plots '(**m**–**q**)' show the calculations for oblique right-lateral sources (rake −130°). In the plots of strain, blue shading indicates areas in compression and red shading indicates areas in dilatation. Units: 10^{-5}. A red rectangle indicates the surface projection of the fault plane; a green line is the intersection of the updip projection of the fault with the surface. Streamflow changes are indicated by circles (black/discharge increase; white/discharge decrease).

5. Results and Discussion

A total of 15 plots of the volumetric strain at the free surface have been computed for the modeled faults, inferring a different sense of slip (Figure 6a–q). Being inferred by inversions of intensity data, the source MF (Figure 6e,l,q) obviously shows a good fit with the map of intensities and the location of the earthquake. However, the performance of the strain modeling of this source is limited, with no agreement between observed hydrological changes and the expected pattern of strain, independent of the style of faulting adopted. Additionally, there is no close association between the location of this source and the distribution of the other effects observed following the earthquake, all located northwest of the fault. When we impose pure normal kinematics to all of the seismogenic sources investigated (Figure 6a–e), we obtain a limited agreement between the predicted pattern of strain and the location of the hydrological changes. In particular, the noticeable increase in discharge of the Gari springs observed in Cassino constantly falls in an area of expected dilatation. Conversely, if we impose a lateral component of the slip on the five sources, we find more satisfactory solutions for data merging. In general, oblique left-lateral sources display a better fit between strain and hydrological signatures; in particular, PF (Figure 6h) and SF (Figure 6g,i) show the best fit for the observations in Cassino (increase in discharge/expected compression) and Isola Liri (decrease in discharge/expected dilatation).

The potential source of the 1654 earthquake is inferred through the cross-analysis between the results from modeling and the other pieces of evidence described above (see chapter 3). Though there is a fairly good fit from strain modeling shown by the Balsorano fault with rake −130° (only for the two observations in Isola Liri, Figure 6m), we exclude this source from the group of most likely causative faults of the 1654 earthquake because (1) there is no agreement between its location and the map of the intensities (see Figure 2);

(2) oblique-right lateral source seems to be an infrequent style of faulting in this sector of the Central Apennines based on seismological and geodetic data [11,29]; and (3) the epicenter of the 1654 quake is located 15 km from the southern tip of the BF. With regard to the Posta-Fibreno fault, its location fits better than the Balsorano fault when compared with the 1654 epicenter and distribution of macroseismic intensities, and an oblique left-lateral sense of slip along this fault (Figure 6h) displays a good fit with the distribution of the hydrological changes (effects 1, 2, and 3 in Figure 5 and Table 1). However, given the present mapping, the magnitude of a seismic event along this fault (M6.1–6.2, see also Table 2) would be underestimated when compared with the M6.3 magnitude presently reported for the 1654 event in the Catalogue (see Table 2). The results from the strain calculations suggest that the Sora fault, when modeled with a left-lateral component of slip, is the most probable candidate fault of the 1654 earthquake. In particular, the SFb source as traced in Boncio et al. [13] fits the most outstanding hydrological observations at Cassino and Isola del Liri as well as the evidence of fractures (effects 1, 2, 3, 4, and 6 respectively, in Figure 5 and Table 1). It is worth noting that the fractures we newly found at the Sora Cathedral would be located in the very near fault. Moreover, the magnitude of a seismic event along this source would coincide with the magnitude 6.3 quoted in the Catalogue for the 1654 earthquake.

6. Conclusions

As stated at the beginning of this manuscript, this study represents a first effort to search for new data, to merge the available information for an earthquake never studied despite its magnitude and heavy effects on the territory, and to provide some reliable landmarks for the individuation of its seismic source.

We collected five novel 1654 coseismic effects on the natural environment concerning hydrological changes (increase in discharge from a spring in Cassino and decrease in flow from Liri river in Isola Liri) and coseismic fracturing in Sora. We also shifted almost 40 km farther NNW and re-positioned one of the effects already documented (coseismic fracturing in Monte Corvo), thus enriching the picture of the natural and anthropic coseismic impact. Though it is a difficult task, due to the age of the event, the retrieval of further data on damage and natural effect as well as detailing of the fracturing would possibly consolidate the earthquake scenario and then support the source modeling.

In summary, the scenarios modeled on the basis of the collected evidence point to the Sora fault, with its trend variability, as the most probable candidate as the causative source of the 1654 event. However, the results of our model do not rule out the possibility of a complex fault rupture during the 1654 event, such as fault linkage between the Sora fault and the adjacent Posta-Fibreno fault, and possible slip along this latter source. The 1654 earthquake would be the most recent $M \geq 5.5$ event along the Sora fault since no earlier damaging earthquake is reported in the historical catalogue for this area of study. Based on these reasons and on our results, the Balsorano fault would be silent for similar energetic events, raising its potential to generate a damaging earthquake in the area. Finally, this study confirms that the hydrological signatures of earthquake strains and field observations are valid supplemental data for estimating geometry and fault style even for early earthquakes limited by historical memory and historical reports, and they help to isolate the fault source within an active dense and complex system such as that of the Central Apennines.

Author Contributions: L.C.: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Data Curation, Writing—Original Draft Preparation, Writing—Review and Editing, F.R.C.: Conceptualization, Methodology, Validation, Investigation, Writing—Original Draft Preparation, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

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