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Key Points:
- How to use intensity to extend seismotectonic knowledge to preinstrumental times
- Source kinematics of the Ferrara destructive earthquake of 1570 in the Po Plain
- The role of the 1570 earthquake in the definitive diversion of the Po River is explained

Supporting Information:
- Data Sets S1 and S2
- Texts S1
- Bootstrap S1

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Source inversion of the 1570 Ferrara earthquake and definitive diversion of the Po River (Italy)

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Abstract An 11-parameter, kinematic-function (*KF*) model was used to retrieve the approximate geometrical and kinematic characteristics of the fault source of the 1570 M_w 5.8 Ferrara earthquake in the Po Plain, including the double-couple orientation (strike angle 127 ± 16°, dip 28 ± 7°, and rake 77 ± 16°). These results are compatible with either the outermost thrust fronts of the northern Apennines, which are buried beneath the Po Plain's alluvial deposits, or the blind crustal-scale thrust. The 1570 event developed to the ENE of the two main shocks on 20 May 2012 (*M* 6.1) and 29 May 2012 (*M* 5.9). The three earthquakes had similar kinematics and are found 20–30 km from each other en echelon in the buried chain. Geomorphological and historical evidence exist which suggest the following: (i) the long-lasting uplift of the buried Apenninic front shifted the central part of the course of the Po River approximately 20 km northward in historical times and (ii) the 1570 earthquake marked the definitive diversion of the final part of the Po River away from Ferrara and the closure of the Po delta 40 km south of its present position.

1. Introduction

The regional patterns of macroseismic intensity, *I*, contain information about earthquake sources. Over the years, the problem of extracting this information has been addressed in different ways. Most authors have used empirical relationships between the areas of isoseismals, or sparse observations, and their barycenters to infer magnitudes and epicenters [e.g., *Frankel*, 1994; *Johnston*, 1996; *Bakun and Wentworth*, 1997; *Gasperini et al.*, 1999; *Musson and Jiménez*, 2008] and treated the geographical distribution of high *I* degrees to infer the directions of the fault sources at depth [*Gasperini et al.*, 1999, 2010]; the approach by Gasperini *et al.* was also implemented in the catalogue of seismogenic sources in Italy that were larger than *M* 5.5 [*DISS Working Group*, 2010].

Suhadolc et al. [1988], *Zahradnik* [1989], and *Molchan et al.* [2004], however, attempted to include the source kinematics in a model. This approach is interesting but requires reliable *I* patterns, which are rare for historic earthquakes. The nonlinear intensity-based automatic inversion technique KF niching genetic algorithm (NGA) [*Sirovich and Pettenati*, 2004], which is used in the present work, was developed to exploit the extraordinary database of high-quality macroseismic observations in the Mercalli-Cancani-Sieberg (MCS) scale [*Locati et al.*, 2011]. These observations were made by seismologists and historians, who interpreted the reports that were written by the officers of various kingdoms of the time, the gazettes, and other sources. This KF-NGA algorithm roughly identifies the principal geometric and kinematic characteristics of the causative sources of destructive earthquakes from their regional *I* patterns (see section 2.1).

In previous papers, we performed geophysical nonlinear inversions by using a simple kinematic-function (*KF*) model [*Sirovich*, 1996] and a grid-search approach [*Pettenati and Sirovich*, 2003]. Since 2004, this kind of source inversion used a NGA algorithm. Because both the *KF* model and the NGA have been previously presented in this journal [*Sirovich and Pettenati*, 2004; *Sirovich et al.*, 2013], only a brief summary of these methods is given here. In particular, the KF-NGA technique was verified by using data from earthquakes in California [*Pettenati and Sirovich*, 2007], the Fennoscandian Shield-Caledonian Range transition [*Bungum et al.*, 2009] and Greece [*Pettenati et al.*, 2010]. In California and Greece, the fault sources of earthquakes that were retrieved by KF-NGA inversion were confirmed by those that were obtained from instrumentation. Recently, the source mechanism of the 1980 M_s 6.9 Irpinia earthquake was inverted, and the results agreed well with instrumental data and field observations of the rupture [*Sirovich et al.*, 2013]. In the same paper, the fault source of the 1694 M_w 7.0 earthquake was retrieved in the same region, and the result was confirmed by the paleoseismological study by *Galli et al.* [2014]. The vivid descriptions of

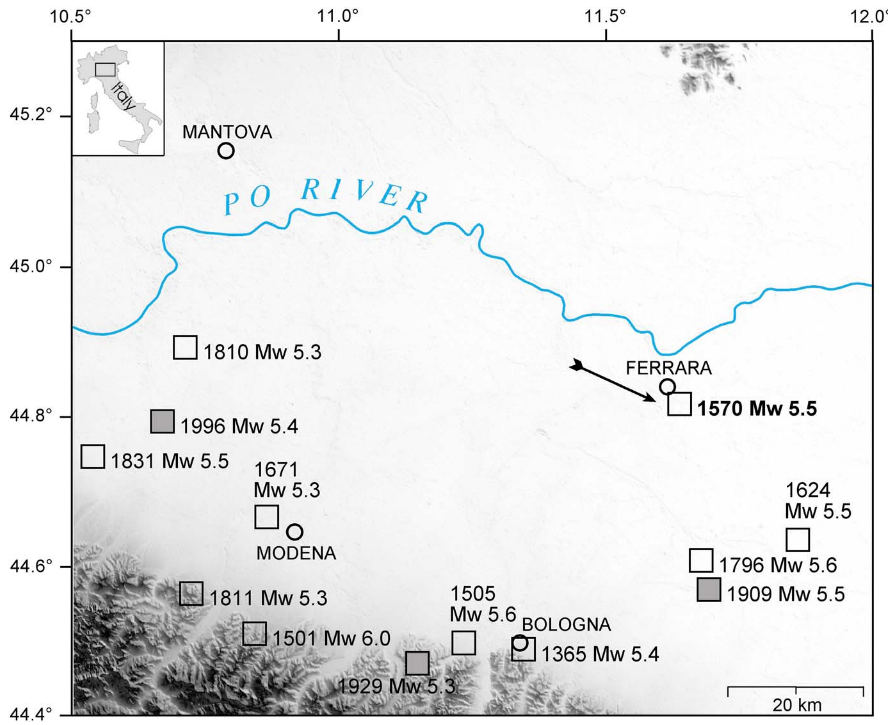

Figure 1. All earthquakes with $M_W \geq 5.3$ in the study area and in the parametric catalogue of Italian earthquakes CPTI11 by *Rovida et al.* [2011].

the surface rupture on 8 September 1694 and its changes during the following weeks, which were recorded by anonymous high officers from the Kingdom of Naples (printed in 1694), prove the correctness of the inversion results [see *Sirovich et al.*, 2013].

This paper shows that the KF-NGA source inversion of the *I* data by *Guidoboni et al.* [2007] for the Ferrara earthquake on 17 November 1570 (M_w 5.5 [*Rovida et al.*, 2011]) retrieves a fault source that is compatible with the regional seismotectonic setting and present evolution of the outer front of the Apenninic chain. This result also explains the role of the earthquake in the definitive diversion of the Po River course at Ficarolo (20 km NW of Ferrara). The study area is shown in Figure 1, and the point intensities that are used in this work are shown in Figure 2. This diversion dried the former principal branch of the river's delta and moved it from the area of "Valli di Comacchio" to its present position 40 km to the north.

First, the basic kinematic information of the fault source of the destructive earthquake that hit the southern Po Plain on 17 November 1570 is retrieved (including the double-couple, or DC, mechanism; see Figure 3). This earthquake had similar kinematics to the 20 May 2012 (*M* 6.1) and 29 May 2012 events (*M* 5.9; both magnitudes from *Ganas et al.* [2012] [see *Anzidei et al.*, 2012]). The three aforementioned events occurred at similar distances (20–30 km) en echelon (see Figures 4–6).

In a second step, the present paper reviews the existing geomorphological, archaeological, and historical information (Figure 4) on the regional uplift of the southern flank of the Po Plain over the last millennia. These pieces of data are intricate because the sedimentation and erosion rates, eustatic history, tectonic uplift, natural subsidence that is caused by consolidation and compaction and recent anthropogenic subsidence are superimposed onto the Po Plain. In this context, the hydrographic net is the most reliable reference, showing that the river course over the last millennia has shifted to the north by 20–40 km. The 1570–1591 seismic sequence appears to have been the last step in the tectonic process that caused the definitive diversion of the course of the Po River.

Incidentally, this geomorphological evidence solves the ±180° ambiguity of the KF-NGA algorithm in the calculated rake angle because the uplift of the southern Po riverbank is only compatible with a compressive mechanism of the Apenninic type. Therefore, we could draw the beach ball diagram in black

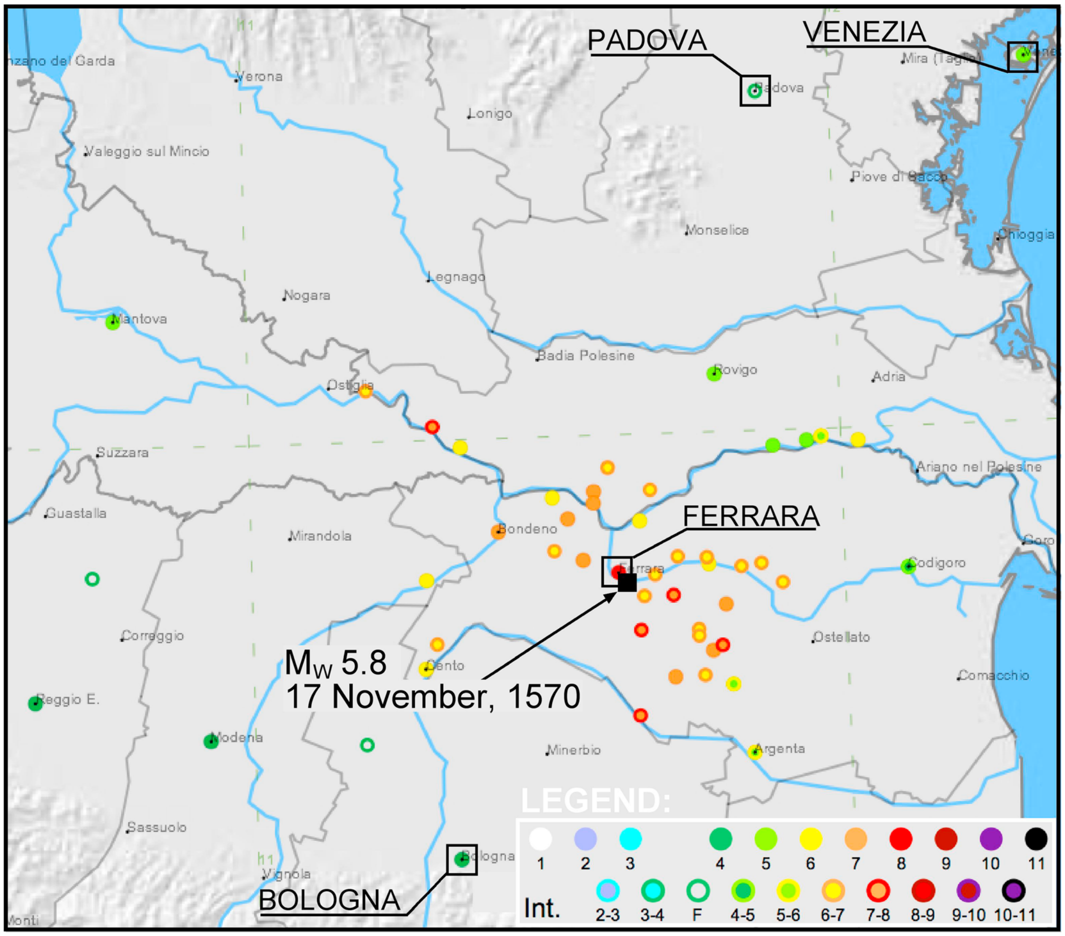

Figure 2. Field intensities of the M_w 5.5 17 November 1570 Ferrara earthquake in 51 towns and villages (dots), which were used in the present paper. The values in the MCS scale are from the Italian database DBMI11 of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), courtesy of *Locati et al.* [2011] (modified, see text).

and white; however, the diagram remains white to emphasize the limitation of the standard procedure that was used. This work continues a multiyear project to obtain quantitative seismological information on preinstrumental earthquakes from their regional *I* patterns.

2. Methods

Two algorithms are used: (i) the *KF* geophysical inversion of intensities, which applies the NGA genetic approach and (ii) the natural-neighbor (n-n) bivariate interpolation scheme, which contours point *I* data and draws isoseismals [*Sirovich et al.*, 2002]. For the present purposes, we only recall here that the interpolation algorithm uses the n-n coordinates for weighting, interpolating, and contouring the *I* points. The interpolation is local because the weight of an observed *I* brought to a new neighbor point is proportional to the area of the intersection of their Voronoi polygons. In the n-n approach, the interpolant (a) fits the data exactly at the observation sites, (b) is isoparametric and bounded by the data values, and (c) is continuously differentiable at all points except the data sites. Moreover, the n-n isoseismals do not require (contouring) parameters and act as a compromise between the crude objectivity of the Voronoi tessellation and intuitive appeal of the somewhat subjective classical isoseismals. Thus, the values of the point intensities in this paper are given by the colors of the isoseismal areas.

2.1. The KF-NGA Inversion Procedure

The 11-parameter *KF* inversion procedure considers the total horizontal component of the body wave radiation from a rupture plane of unit width in an elastic half space within a distance range from

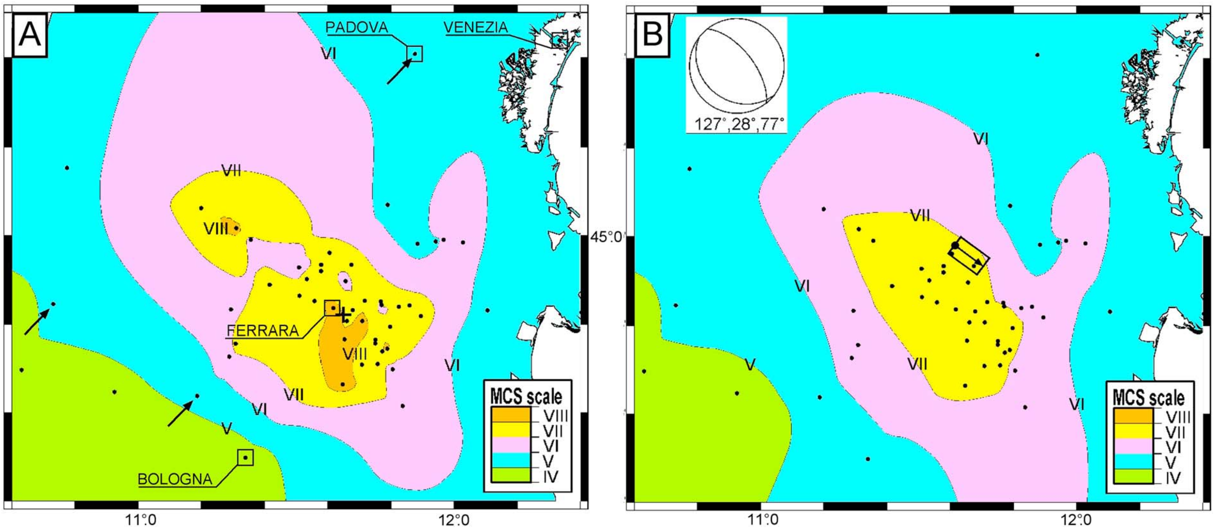

Figure 3. (a) Same as in Figure 2; however, the 25 intermediate values were rounded to the upper values. The isoseismals were traced with the n-n bivariate interpolation scheme [*Sirovich et al.*, 2002]. (b) Synthetic intensities and the beach ball diagram that was produced by the minimum variance model from the data in the third column of Table 2 and interpolated as in Figure 3a (the projection of the source is unilateral toward the SE from the nucleation that is marked by a black circle).

approximately 10 to 80–100 km from the source. Incidentally, the nonparametric regression analyses of the attenuation of the peak ground acceleration (PGA) from moderate-sized earthquakes in the Po Plain by *Bragato et al.* [2011] demonstrated that the PGA in the present study area is systematically enhanced for distances between 80 and 200 km by postcritically reflected *S* waves and multiples from the Moho discontinuity. This situation has been suggested to hold for the PGA and pseudo-acceleration at various frequencies and for the intensities of strong earthquakes [*Sugan and Vuan*, 2013].

The 11 parameters that are inverted are the hypocentral latitude and longitude, the DC (strike, dip, and rake angle), the seismic moment (M_0), the depth (H) of the line source, the shear wave velocity (V_s), the rupture velocities (V_r) along strike and antistrike, and the along-strike percentage of the total rupture length (L). The L and source width parameters are derived from the M_0 by using the empirical relationships given by *Wells and Coppersmith* [1994]. Moreover, L is the sum of the absolute values of the along-strike (considered positive, $L+$) and the antistrike source segments ($L-$). The signs of the V_r/V_s ratios (i.e., Mach numbers) follow the same logic (Mach+ and Mach−).

The nondimensional values produced by the *KF* are transformed into intensities through the empirical relationship that was developed by *Sirovich et al.* [2001, equation (2)] from 1720 *I* values of Californian earthquakes. These 1720 observations were more often taken in sedimentary basins where people tend to live; consequently, the aforementioned empirical correlation between the *KF* and *I* values is likely to implicitly incorporate site effects that are similar to those in the Po Plain.

The inversion is performed by an NGA sharing technique with four independent subpopulations, which are used to search for the absolute minimum variance model in the 11-source parameter model space. Each initial subpopulation has 1000 random sources and evolves independently from the others. One selection and three evolutionary (stochastic) steps are applied within every generation. First, the best individuals (90% of the initial source models) are chosen in the Selection step and are then “married” in the Crossover step (with 90% fertility). In the Mutation step, 6% of the 500 new individuals (450 “sons” plus 50 nonfertile parents) receive a new value for one parameter by chance. In the Crowding step, identical individuals are deleted and each subpopulation is prevented from quickly converging to a false minimum. The genetic process continues for N generations to ensure that the virtual space of the parameters is properly explored. In particular, the best source of each generation that is transmitted to the new generation is included in the evolution logic. The NGA also involves the sharing step, which allows subpopulations of sources to survive within parameter subspaces (niches) so that each source of each subpopulation is not in competition with the sources of other subpopulations that live in other niches. In this step, each subpopulation of sources evolves independently from the others, and the normalized distance between

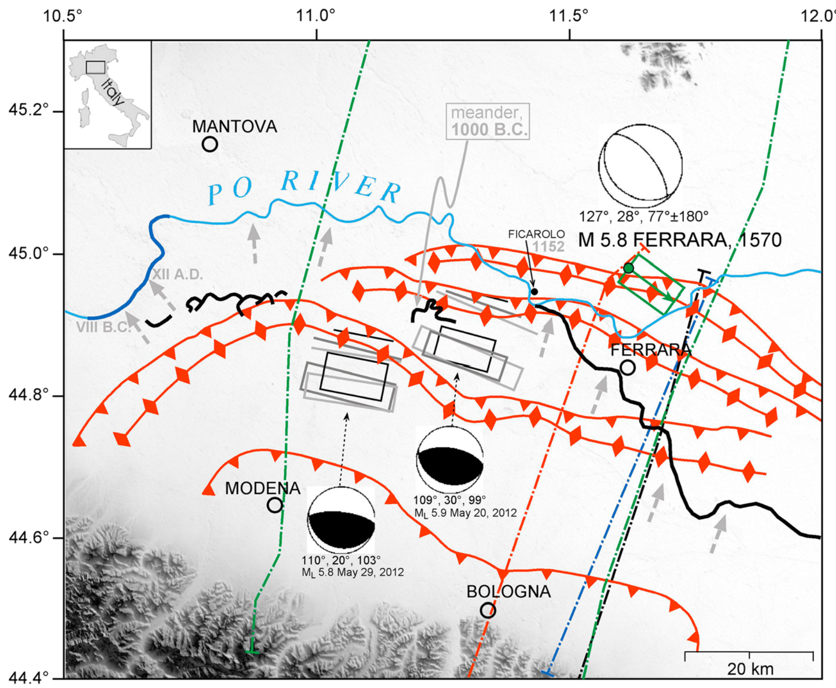

Figure 4. The dark green rectangle north of the city of Ferrara is the projection of the best fitting source from Table 2 (third column), with the arrow indicating unilateral rupture propagation toward the SE. The gray and black rectangles are the fault sources of the main events on 20 May 2012 (middle) and 29 May 2012 (left), which were obtained by three independent groups at the INGV [from *Serpelloni et al.*, 2012]; their virtual intersections with the Earth's surface (the segments NNE of the rectangles) follow the same color key. The dark blue river course segment on the left is the main drainage anomaly found by *Castaldini* [1989]. The short and sparse black river course segments are some of the southernmost abandoned course remnants found by *Castaldini* [1989]. The black river course that abuts Ferrara to the south is the Po river course until the 1570–1591 seismic crisis. The gray arrows indicate river diversions of seismotectonic origin; the present river course is in light blue.

each source of a subpopulation and each source of all the other subpopulations obeys a certain condition [*Koper et al.*, 1999, equation (1)].

The objective function during the inversion is Σr_s^2, where r_s is the intensity calculated at a site minus the field intensity (obtained by historians and seismologists; the suffix denotes the sites). Each parameter space is explored with the sampling steps and within the ranges given in Table 1. The resolutions of the uncertainties of the parameters obtained by the inversion coincide with the widths of the steps shown in the table. The width of the fault source that is used by the *KF* is also obtained with the aid of *Wells and Coppersmith* [1994] (using empirical relationship number 4 in Table 2A on p. 990 and "Slip type" "All") from the M_0 via the relationship $M_w = 2/3(\log M_0 - 9.1)$, which was suggested by *International Association of Seismology and Physics of the Earth's Interior* [2005], where M_w is the moment magnitude. The inversion errors are calculated by inverting randomized sets of data and following the standard by *Pettenati and Sirovich* [2007] and *Sirovich et al.* [2013] (see later).

As mentioned in the presentation of the *KF* model, the source depth is not well constrained when using the *KF* technique given the half-space condition [*Sirovich*, 1996]. Additionally, a specific reason exists for the low reliability of the depths that are often obtained in Italy. In fact, as touched upon before, the KF values in other regions can be transformed into intensities by using a number of local earthquakes that are well documented by instruments. However, this is not yet possible in Italy because of the small number of well-known strong earthquakes in regions that are sufficiently homogeneous from a geologic perspective. Because the decrease of intensity with epicentral distance is affected by several factors, including crustal characteristics and depth of the source, different behaviors are often found in different regions. For example, the mutual distances between isoseismals of decreasing intensities in Figure 3a could be due to either the crust rheology or to the hypocentral depth. This interaction spuriously influences the depth determination of Table 2.

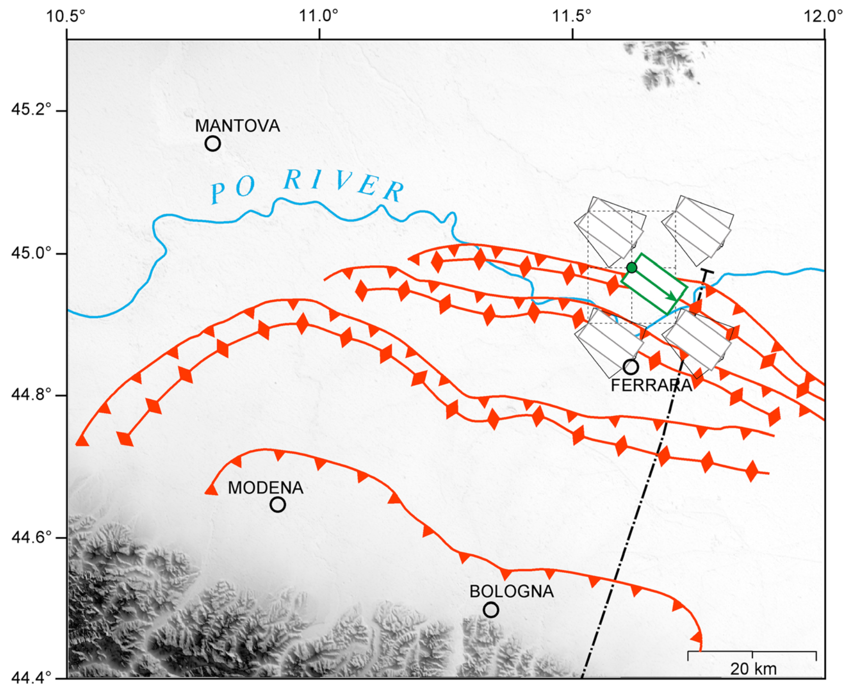

Figure 5. Effects of the inversion errors of the epicentral coordinates and strike angles on the position of the fault source that was retrieved for the 1570 earthquake, taken from the same area as Figure 4.

3. Seismotectonic Context

The study area is in the region where the northern Apennines override the subducting Adria Plate to the north, which produces uplift. However, disagreement exists concerning the tectonic activity rate of the Apenninic thrust-fold system. The activity may have strongly decreased in the whole area from the early Pleistocene [e.g., *Castellarin*, 2001; *Di Bucci and Mazzoli*, 2002; *Argnani et al.*, 2003], or the tectonic activity could be concentrated in the frontal part of the northern Apennine accretionary wedge, producing deformation mostly in the outermost—and likely youngest—thrusts. For example, *Meletti et al.* [2000], *Burrato et al.* [2003], and *Scrocca et al.* [2007] suggested that this activity is concentrated in the external thrust fronts that are buried under the Po Plain's alluvial deposits.

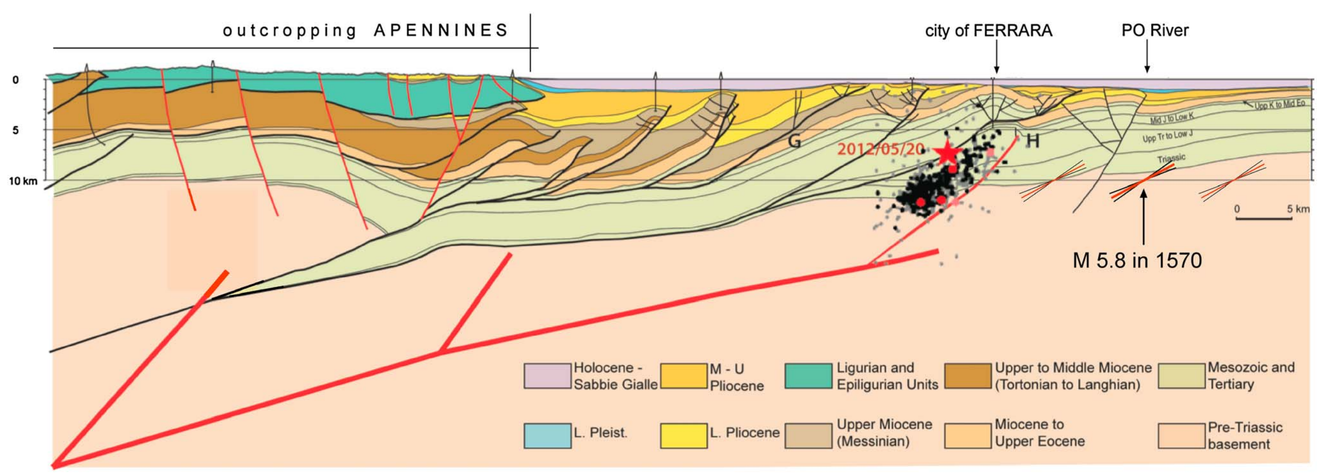

Figure 6. Projections of the best fitting fault source for the 1570 M_w 5.8 earthquake (Table 2, third column), plus and minus the latitude and dip errors, on a modified geological section by *Picotti and Pazzaglia* [2008], which was updated by *Picotti* [2012] (SSW is on the left, NNE on the right). The nucleation depth was fixed to 10 km.

Table 1. Sampling Steps and Ranges of the Space of the 11 Source Parameters That Were Explored

Parameter	Explored Range	Sampling Step
Nucleation latitude N (deg)	44.50–45.20	0.01
Nucleation longitude E (deg)	11.20 – 12.00	0.01
Strike angle (deg)	0 – 359	1
Dip angle (deg)	20 – 90	1
Rake angle (deg)	0 – 179	1
Nucleation depth (km)	4 – 50	0.1
V_S (km/s)	3.50 – 3.96	0.01
Mach in along-strike direction	0.50 – 0.95	0.01
Mach in antistrike direction	0.50 – 0.95	0.01
M_0 (N m) 10^{17}	1.0 – 8.0	0.01
Percentage of L along-strike	1 – 100	1

The growth of the Apenninic mountain front has occurred through uplift of approximately 1 mm/yr with shortening of 1 to ~2.5 mm/yr, both of which are driven by subduction. During the Pleistocene, the slip rates (measured along the fault planes; thus, dip parallel) would have decreased on average between 0.1 and 1.0 mm/yr [*Maesano et al.*, 2015]. During the middle-late Pleistocene, the rate of uplift would have been no more than 0.16 mm/yr, and this value could be a reference for the Present [*Scrocca et al.*, 2007]. According to *Picotti and Pazzaglia* [2008], the subduction occurs in the context of a slab rollback. The upper plate retreat process is cored by a midcrustal flat-ramp structure that accommodates the ongoing movements and the resulting earthquakes (see Figure 6). The area is characterized by the alternation of arcuate thrust systems and growth folds. We refer, for example, to the milestone Structural Model of Italy by *Bigi et al.* [1990]. In Figure 4, the point-dashed lines are the traces of geologic sections by *Cassano et al.* [1986] in green, by *Pezzo et al.* [2013] in red, by *Toscani et al.* [2009] in blue, by *Benedetti et al.* [2003], and by *Picotti and Pazzaglia* [2008] in black (the last is reproduced in Figure 6 as updated by *Picotti* [2012]).

In Figure 4, the red lines with diamonds indicate the anticlinal axes, and those with triangles are the top traces of the main Apenninic thrust fronts (triangles point to the upthrown front), both from *Boccaletti et al.* [2010], *Picotti* [2012], and *Bigi et al.* [1990] as modified by *Pezzo et al.* [2013].

Fantoni and Franciosi [2010] wrote that the frontal Plio-Pleistocene accretionary wedge of the northern Apenninic margin became active in the upper Miocene (late Messinian) on the southern side of the Po Plain (the foreland) with second-order arcs and lateral ramps. In particular, these authors stressed that a large spread in the accretionary system is encountered along the inner and outer Ferrara arcs, as shown in Figures 4 and 5.

The situation is complicated because the present tectonic uplift in the area is partly masked by anthropogenic subsidence [*Carminati and Martinelli*, 2002; *Teatini et al.*, 2011]]. *Maesano et al.* [2015], however, were able to eliminate secondary effects such as the differential compaction of sediments across structures from their calculations and for the Mirandola thrust (related to the earthquake on 29 May 2012 in Figure 4). The authors accredit a slip rate of 0.86 ± 0.38 mm/yr during the last 0.4 Myr (all due to thrust activity). Anthropogenic subsidence, however, was absent at the time of the river diversions that are discussed below.

Table 2. Source Parameters (±Inversion Errors) of the Best Fitting Solutions for Data Sets With Half Degrees and All Integers[a]

Parameter	With half degrees	All integer Values
Nucleation latitude N (deg)	44.97 ± 0.07	**44.97 ± 0.08**
Nucleation longitude E (deg)	11.55 ± 0.10	**11.63 ± 0.09**
Strike angle (deg)	121 ± 16	**127 ± 16**
Dip angle (deg)	26 ± 6	**28 ± 7**
Rake angle (deg)	73 ± 18	**77 ± 16**
Nucleation depth (km)	35.3 ± 4.8	**34.9 ± 5.4**
V_S (km/s)	3.96 ± 0.06	**3.90 ± 0.09**
Mach in along-strike direction	0.71 ± 0.10	**0.63 ± 0.10**
Mach in antistrike direction	0.53 ± 0.05	**0.60 ± 0.06**
$L+$ (km)	1.8	**8.9**
$L-$ (km)	5.8	**0.0**
M_0 (N m) 10^{17}	3.21 ± 1.7	**4.95 ± 1.05**
Objective function $\left(\Sigma r_s^2\right)$ (n. data)	11 (51)	**13 (51)**

[a]Probability errors = 95%, 2 standard deviations. Bold numbers refer to the results shown in Figures 3b, 4, 5, and 6.

The matter of river diversions is introduced by quoting *Burrato et al.* [2003], who stated that the activity of the buried thrust fronts seems to have controlled the course of the Po River, which exhibits shifts in channel patterns near the city of Ferrara. Additionally, in Figure 5 in that study, these authors suggested that the buried anticlines correspond to surface evidence but that no historical earthquakes were reported. The present study completes their observation because the 1570 earthquake possibly was produced by the outermost external front.

The study area has moderate seismicity. Figure 1 shows the epicenters of the earthquakes with $M_w \geq 5.3$ in the parametric catalogue of Italian earthquakes CPTI11, which was produced by *Rovida et al.* [2011] with version 3.3 of the Boxer algorithm by *Gasperini et al.* [1999]. CPTI11 lists six additional earthquakes with M_w that are close to 5 in the Ferrara area, with epicenters that are not well constrained because of the lack of sufficient historical information. However, the event on 11 July 1987 is not shown in Figure 1 because the International Seismological Centre largely overestimated its single-station magnitude (from La Paz, Bolivia), which was based on an earthquake that occurred several minutes prior in Costa Rica (written communication from P. Gasperini, 2014). These earthquakes (M_w in parentheses) occurred in 1234 (5.1), 1285 (5.1), 1346 (4.9), 1410 (4.9), 1411 (5.1), and 1743 (4.9). M_w is the moment magnitude from the intensity data [*Rovida et al.*, 2011]. The earthquake in 1346 is controversial and is considered a fake event by *Camassi and Castelli* [2013] and a true event by *Guidoboni et al.* [2015].

3.1. Tectonic Control of the Course of the Po River

In their pioneering paper, *Castaldini et al.* [1979] related the river courses of the Po Plain with the active tectonics of the region. In particular, the literature currently agrees that the course of the Po River moved progressively northward during the Holocene because of the progressive uplift of the orographic rightside (south) of the river, which was caused by the uplift of the Apenninic chain under the alluvial deposits [e.g., *Panizza and Castaldini*, 1987; *Castiglioni et al.*, 1997; *Castiglioni and Pellegrini*, 2001; *Burrato et al.*, 2003, 2012]. Additionally, the N-S course of the Adige River rotated approximately 90° to the east when entering the Po Plain. *Castaldini* [1989] showed that the Po River experienced two course diversions approximately 30 km SSW of Mantova: in the eighth century B.C. and in the twelfth century A.D. (refer to the two gray arrows that are close to the dark blue segment of the river on the leftside of Figure 4). See *Castiglioni and Pellegrini* [2001] and *Burrato et al.* [2003] regarding these drainage anomalies. Many more remnants of the Po River that are south of its present course were documented by *Castaldini* [1989], *Castiglioni et al.* [1997], and *Castaldini et al.* [2009]. Figure 4 was inadequate to reproduce all these data; thus, only certain southernmost abandoned meanders that were found by *Castaldini et al.* [2009] were drawn (in black). The river course shifted northward by approximately 20 km from the eighth century B.C. to 1152 A.D., from the left border of Figure 4 to the hamlet of Ficarolo (20 km NW of Ferrara). The present course of the river is shown in light blue in Figure 4.

In particular, the abandoned meander that was found by *Pellegrini* [1969] (see the gray label "meander 1000 B.C." in Figure 4), which is situated approximately 11 km south of the present course of the river, is a reference for the present study. *Castaldini et al.* [2009], who also used archaeological remains, demonstrated that this segment of the paleocourse of the Po River was active during the Bronze Age (approximately 1000 B.C.), became a small watercourse during the Iron Age, maintained a degree of vitality throughout the Roman Period, and became extinct at an unknown time.

To the east, the course of the Po River washed the southern margin of the city wall of medieval Ferrara (see Figure 7) until approximately the middle of the twelfth century A.D. and then divided into two branches immediately south of the city. The southern branch, the so-called Po "Primaro" (i.e., the first or principal one), flowed toward the southeast, and the Po Volano flowed toward the east. At approximately, the middle of the twelfth century (1152 is often credited as the date and will be used here for simplicity), the river broke its left bank 20 km NW of Ferrara, close to the hamlet of Ficarolo (Figures 4 and 7). This event is still remembered as the "Rotta di Ficarolo" (the leak of Ficarolo). Thus, the river divided into three branches after 1152, and the new and northernmost branch (approximately the present one, "Po di Venezia" in Figure 7) progressively became the principal course.

However, in 1554, which was 16 years before the studied earthquake, post boats could still use the Po Primaro from Bologna to the Adriatic Sea. Historic chronicles confirm that fluvial commercial transportation was also still possible on the Po Primaro between Ferrara and the Adriatic harbor of Ravenna during the second half of the sixteenth century.

4. Data

The point intensities of the 1570 earthquake that are listed in the Italian database DBMI11 by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) [*Locati et al.*, 2011] were used (see Figure 2). As touched upon in the Introduction, *Guidoboni et al.* [2007] collected the data for this specific earthquake through a

Figure 7. The branches of the Po River in 1568 based on the descriptions by G. Sardi, the famous erudite that lived in Ferrara in the sixteenth century [*Facci*, 1729] (from the municipal library "Ariostea" of Ferrara, geographical archives "Crispi", 15th series, plate 7).

historical and seismological study and also examined many contemporary primary sources, including three manuscript diaries [*Ferrari et al.*, 1985].

Guidoboni et al. [2007] classified five sites as "felt." For the present inversion, intensities of V were assigned to the felt sites inside the area of Figure 3a (the three arrows indicate San Giovanni in Persiceto, Novellara, and Padova). Thus, 51 total data points were used. *Guidoboni et al.* [2007] classified 25 sites with intermediate field *I* values (e.g., VI–VII; see the double-color circles in Figure 2). Unfortunately, the literature does not agree on the use and interpretation of these intermediate values. Some experts interpret them as uncertainties between the lower and the upper values; others view them as half degrees, such as "higher than VI but lower than VII." For many years, we followed the prevalent practice and rounded the intermediate values to the upper values. Here however, two data sets from *Guidoboni et al.*'s [2007] intensities were produced, one with rounded values and one with half degrees that were treated as real numbers (e.g., 6.5), and both data sets were inverted.

The legend (Figure 2) of *Locati et al.*'s [2011] catalogue shows the intensities in the 51 towns and villages, but the figure does not help the reader grasp the shape of the regional intensity patterns. These patterns are visible in Figure 3a, where the data (rounded to upper values) were contoured with the n-n bivariate interpolation scheme [*Sirovich et al.*, 2002]. From this figure, the intensities tend to be distributed in the NW-SE elongated areas. The black cross in Figure 3a is the macroseismic epicenter, which was estimated by *Locati et al.* [2011] and is close to the barycenter of the intensities. All traditional approaches that use intensity place the epicenter and/or the source close to the barycenter. Note the "finger" of the degree VI area toward the NNE that is visible in Figure 3a. One could hypothesize that this pattern was caused by site effects at the five nearby locations, such as amplification in the two easternmost locations and/or deamplification in the three western locations. However, the discussion below will show that the simplicity principle (the so-called Occam's razor) suggests a source effect instead. The n-n isoseismals obtained from the intermediate values, which are treated as real numbers, are similar to those in Figure 3a and are not shown for brevity.

In previous works in California, South Los Angeles, Sicily, Norway, Greece, central Italy, and Slovenia-Croatia, we investigated site effects in point intensity catalogues such as the one used here. The only case where a strong, statistically reliable difference between deep, soft sites, and stiff, rocky sites was observed was in Slovenia and northern Croatia, where hundreds of point intensities came from small agricultural villages and hamlets in hilly areas with different site geologies [*Sirovich et al.*, 2012].

The database that was employed in this work was composed of intensities in towns and villages on the Po Plain that have largely similar geologic conditions. No homogeneous information was available on the site effects in all these localities, if any. In general, grouped site effects would obviously bias the inversion; isolated site effects increase the noise of the inversion but are not expected to heavily condition the results. No objective criterion was available to correct all the data for site effects. Thus, we inverted the original values so as not to risk being criticized for having corrected some data to drive the inversions toward the desired results.

5. The 1570 Earthquake

The main shock of 1570 was preceded by foreshocks that caused damage in Ferrara [*Ferrari et al.*, 1985] and was followed by a number of relatively strong aftershocks during 1570–1574 [*Boschi et al.*, 1995]. However, the total seismic sequence would have lasted from 1570 to 1591 [*Bottoni*, 1872].

Eleven thousand of the 32,000 total inhabitants left the city [*Ferrari et al.*, 1985]. From 1573 to 1575 Min Haadumim, a physician and scientist that is known in Italy as Bonaiuto dei Rossi, one of the leaders of the Ferrara Jewish community, wrote in Hebrew a series of reports that we consulted from an Italian translation [*Shalem*, 1938]. Min Haadumim wrote that the total number of deaths in Ferrara was approximately 70 (see Appendix A). *Boschi et al.* [1995] used this translation but erroneously quoted its date as 1932. Min Haadumim also mentioned the following relevant seismological observation: "…first, [in Ferrara] the earthquake moved the Earth in the east-west direction, then also north-south" [from *Shalem*, 1938].

5.1. Inversion Results

The results shown in Table 2 were obtained on the first inversion attempt; no adjustments were made whatsoever to improve them. The NGA evolution continued for more than 200 generations; in particular, the trend of the objective function during the inversion of integer values (third column in Table 2) became flat after 223 iterations. The second and third columns in Table 2 show the 10 source parameters that were directly obtained from the inversion and the L+ and L− derived from the 11th inverted parameter (which is the along-strike percentage of the total rupture length). Columns two and three show the results obtained from the intensities treated as real numbers and those rounded to the upper integer, respectively.

The scored objective functions are also shown. The Σr_s^2 values in columns two and three are not comparable because Σr_s^2 increases intrinsically when integer intensities are used. Note the strong similarity of the two solutions. However, the opposite directions of the rupture propagations (the values of L+ and L−) and Mach numbers have low reliability. In our experience, the stability of the epicenter, fault plane solution, M_0 (and derived total length) in columns two and three in Table 2 represents stability in the KF-NGA method. The second solution was chosen only because rounded intensities were inverted in previous papers to obey the original definition (I values expressed in a discrete and bounded scale). The magnitude M_w, derived from M_0 in Table 2, is 5.8, higher than the M_w 5.5 value from *Rovida et al.* [2011]. The depth values that are close to 35 km in Table 2 are not reliable, but this is not surprising in the KF-NGA inversion. Depth determination is sometimes a weak point also of catalogues based on instrumental measurements. For example, *Bolton et al.* [2006] suggested using the half depth of the crust (averaged for geographic region) for the International Seismological Centre when the determination of a free depth is not possible. Given the Moho depth in the area [*Dezès et al.*, 2004], this choice would very roughly lead to 15 km depth.

However, a series of inversions was performed for the 1570 earthquake with depth constraints from 35 to 5 km. Its goal was to find the depth range within which the DC solutions still belonged to the family of the minimum variance DC solution in Table 2 (third column: 127°, 28°, and 77°). The minimum disorientation angle γ [*Kagan*, 1990, 1991] can be used for this goal. The γ is the minimum 3-D rotation such that the pairwise orthogonal unit vectors of a DC coincide with those of a benchmark DC. The new algorithm from *Sirovich et al.* [2013] was used to calculate γ. According to these authors, a certain DC belongs to the same tectonic family of a benchmark DC if its disorientation γ is less than an acceptable value; 40° was proposed for this limit on an empirical basis. The present inversions with depth constraints showed that the DC solutions are still acceptable up to approximately 20 km depth. In fact, for 21.6 km $< H \leq$ 34.9 km, $0° \leq \gamma <$ 30.8°, and for $H <$ ~20 km, $\gamma > 40°$. However, H was fixed to 10 km, as sometimes used by international seismological agencies in the area.

Figure 4 is the core of the present paper because it summarizes the seismological, tectonic-geological, geomorphological, and historical data. This figure suggests that the results in Table 2 are coherent with the geological and tectonic-geological evidence (see the Discussion). The dark green rectangle, which is north of the city of Ferrara in Figure 4, is the projection of the best fitting source of the third column in Table 2; its beach ball diagram is also shown.

Figure 4 indicates the following: (i) from 20 to 29 May 2012, the seismic rupture migrated from an outer Apenninic front to an inner one and (ii) the projection of the mean source obtained by KF-NGA inversion almost coincides with the outermost front. Then, if one takes the inversion errors of column three in Table 2 into account, the 1570 rupture spans from the fronts that are north of Ferrara in Figures 4 and 5 to a fault more toward the NE, which is only shown in Figure 6 (see the next paragraph and the Discussion).

5.2. Errors

The KF-NGA inversion is a typical example where the calculations of uncertainties are mathematically intractable because different sets of experimental values are not available and one cannot estimate the observational errors. Thus, inversion errors were calculated by using a randomization from the Monte Carlo technique, as was done for three earthquakes in California [*Pettenati and Sirovich*, 2007] and two in Italy [*Sirovich et al.*, 2013]. A random number N ($50 < N < 250$) of artificial intensity data sets was created for each source parameter. New intensity values were then assigned to all sites, and each artificial set was compiled with the following conditions.

The artificial values had to fall within the I–XI limits. Starting from a normal distribution that was centered on the data value I_{obs} with a standard deviation of 1°, the maximum difference between the artificial value and I_{obs} was two degrees. However, one exception was allowed because the limit between the V and VI degrees (i.e., between nondamage and damage) is particularly reliable: intensities less than V could not exceed the VI value, and intensities greater than VI could not be less than the V value. In setting these limits, an average of 37% of the observed intensities was substituted for the two sets. In Table 2, we applied 2 standard deviations as the 95% probability errors. In 2004, we erroneously referred to this randomization as a type of bootstrap technique ([*Sirovich and Pettenati*, 2004] this wrong explanation was corrected in *Pettenati and Sirovich* [2007]).

An increasing number of papers have shown that homogeneous elastic models are inappropriate for use in simulations of earthquake ruptures. The inelastic behavior of crustal media around faults might affect ground motions and intensities; however, this subject is beyond the scope of the present work. Figure 5 explains the effects of the inversion errors in the epicentral coordinates and strike angles of the 1570 fault source in Table 2 (third column); only the 95% confidence limits of the source positions are shown.

Figure 6 shows the effects of the inversion errors in the latitude and dip angle on the trace of the 1570 fault source, which was projected on the geological section that was interpreted by *Picotti and Pazzaglia* [2008] (modified by *Picotti* [2012]). The upper edge of the outermost Apenninic front, drawn in red in Figure 4, almost coincides with the front that is shown in the section of Figure 6 approximately 7 km NNE of the city of Ferrara under the alluvial sediments (pink, "yellow sands of Holocene"). However, Figure 6 shows one more tectonic structure 14 km NNE of Ferrara (just under the arrow that points to the Po River), with its principal fault scarp dipping SSW (toward the left in the figure), and two secondary planes that were interpreted as antithetic by *Picotti and Pazzaglia* [2008]. According to *Benedetti et al.* [2003; Figure 2b], this fault scarp that dips SSW is the outermost thrust front that is buried in the northern Apennines. Finally, this figure shows the midcrustal flat ramp that would accommodate the orogenic uplift and shortening in the area (see the Discussion).

6. Discussion

Notwithstanding, the use of the *KF-I* calibration on California data, evident shape similarity exists between the yellow and pink areas in Figures 3a and 3b, and the green area is almost in the right position in Figure 3b. In Figure 3b, the finger of *I* VI in Figure 3a was properly reproduced without evoking path or site effects in the cause-effect logic chain from the source to the site. Thus, according to the logic principle of simplicity (Occam's razor), this finger is most likely produced by the source (confirmed by the radiation pattern).

The testimony by Min Haadumim in 1570 on the first east-west oscillation, which was followed by north-south movement [*Shalem*, 1938], can be interpreted as an *SH*-wave onset followed by a Rayleigh wave, which is compatible with the best fitting epicenter in Table 2 that is north of the city (see Figures 3–5). However, this interpretation is not unique. Then, the dominant direction of rupture propagation for six of the eight events in the Emilia sequence in May 2012, which was studied by *Convertito et al.* [2013], was from WNW to ESE, as in Table 2 (third column). This agreement should not be emphasized because this peculiar result of the inversion is unstable.

The retrieved epicenter (Table 2 and Figure 3b) is some kilometers north of the macroseismic epicenter of Figure 3a. This result is rational because (i) the macroseismic epicenter is mostly based on the barycenter of the intensities, whereas the *KF* algorithm includes a source model, and (ii) the dip-slip mechanism of 1570 mostly radiates *S* body waves toward the side of the fault roof.

The best fitting strike angle for 1570 was 17°–18°, rotated clockwise from the two angles of the mechanisms for 20 and 29 May (see Figure 4). This rotation agrees with the clockwise rotation of the Apenninic fronts approaching the Adriatic Sea (the rotation starts approximately east of Ficarolo in Figure 4). Then, the aforementioned fault plane that dips SSW—with two antithetic planes—14 km to the NNE of Ferrara (i.e., to the right of the town in Figure 6) still does not have a consensual interpretation.

This final observation deserves a comment. From seismic soundings, this fault plane is a pop-up structure and could either be the outermost front of the buried Apennines (beyond the northeasternmost front mapped in Figure 4), as in *Benedetti et al.* [2003], or a transpressive structure. In the second case, the structure would accommodate both the Apenninic overthrusts and the N-NW movement of the Adria plate. As seen in Figure 6, *Picotti and Pazzaglia* [2008] did not resolve the issue. Recently, *Tortora* [2013] noticed that in the seismic sections, the structure in question seems to be deeply rooted and has transpressive characteristics (S. Tortora, private communication, 2014). Thus, the mixed behavior of the 1570 fault source in Table 2 cannot be ruled out, and therefore, the rake angle of $77 \pm 16°$ is fully compatible with the tectonics.

Finally, the relationship between the 1570–1591 seismic crisis and the definitive diversion of the Po River is discussed. As stated previously, the Po River divided into three branches in 1152, and the new branch (Po di Venezia) reached its present mouth 40 km to the north. However, its principal branch (Primaro, drawn in black next to Ferrara to the south in Figure 4) still abutted the Ferrara city walls some months before the studied earthquake. In fact, a historical essay [*Tozzi Fontana*, 2001] says that Duke Alfonso II d'Este made the last attempt to keep the city's river trade by closing the Po di Venezia some months before the study earthquake. The 17 November earthquake occurred after the completion of the Duke's works, which failed [*Tozzi Fontana*, 2001]. The dating of the definitive diversion of the Po River to the decade 1570–1580 comes also from the fact that in 1580 Pope Gregorio XIII asked a painter to immortalize the recent happenings of the Ferrara region in the Gallery of Geographical Maps for the Vatican museums. The painting was completed in 1580–1581 [*Gambi et al.*, 1994; *Touring Club Italiano*, 1977; *Paolucci*, 2010]. Then, we know that Duke Alfonso II d'Este resigned himself in 1592 to permanently shut the Primaro branch, which could no longer be used, and to try to retain at least some water in the Volano branch (which lost importance, however) [*Tozzi Fontana*, 2001].

Then, when a geographer of the eighteenth century wanted to hand down to posterity the favorable fluvial situation of Ferrara in the old days, he referred to 2 years before the 1570 earthquake and drew the map in Figure 7 [*Facci*, 1729]. He based his reconstruction upon the findings of famous erudites that lived in Ferrara in the sixteenth century. Figure 7 shows that the Po Primaro was still the principal river course in

1568, while the branch that opened in 1152 was still a minor branch (now the mainstream). Finally, the map of the Bologna Plain by *Magini* [1710] shows historical evidence that neither the Primaro nor the Volano branches no longer received water from the Po River in 1710 (figure not shown for brevity).

Unfortunately, the KF-NGA inversion is not able to quantify the coseismic uplift, and we do not know if the 1570–1591 seismic crisis produced creep movements. The data sets by *Wells and Coppersmith* [1994] and *Wesnousky* [2008] listed few surface displacements for reverse earthquakes, and the limited data yield poorly fit regressions. We can have an idea of the amount of the 1570–1592 coseismic uplift from that measured in the area after the two earthquakes in 2012, which had similar kinematics and magnitude. The c-band coseismic interferogram and deformation maps of the two earthquakes that were produced by *TRE* [2012] show that the fault roofs of the 20 and 29 May events uplifted ~14 cm and ~11 cm, respectively [see *Galli et al.*, 2012]. The fault sources that are able to uplift the southern Po riverbank in 1570 should be looked for in Table 2 among those with negative errors in latitude, longitude, strike angle, and positive errors in the dip angle; the fault sources in column 2 are even better than those in column 3 (shown in Figures 3b, 4, and 5), because the epicenter of the best-fitting solution is 6.3 km further west.

Of course, the small vertical displacements produced by the 1570–1591 seismic sequence were not sufficient to change the Po's course; the diversion was the result of the long-lasting tectonic uplift of the basement of the Po Valley's sedimentary basin. The cumulative displacement during 1570–1591 represented a snapshot of this long-lasting phenomenon, which had already shifted the central part of the course of the Po River approximately 20 km northward. Regarding the possible delay between the main shock in 1570 and the river's diversion, small uplifts in an almost flat area are unable to produce instantaneous diversions. Instead, diversion occurs during subsequent floods.

7. Conclusions

The source parameters of the 1570 earthquake are fully compatible with the known seismotectonic setting of the area and with the kinematics of the region's two main shocks in 2012. The 1570 earthquake was produced by a fault that was located NE of the two faults that activated in 2012. Its geometry and kinematics were consistent with the uplift of the buried Apenninic chain in the Ferrara area. The main shock from 1570 and the two main shocks from 2012 are en echelon, but our knowledge of the 1234-1285-1346-1410-1411-1570-1743-2012 sequence is relatively poor and making any deterministic hypothesis regarding its evolution is impossible. During the complex evolution of this thrust system, an earthquake broke its buried (perhaps youngest) outermost thrust front in 1570, and two earthquakes broke two inner front segments in 2012 en echelon.

The northward shift of the course of the Po River during the Holocene had a turning point in the eighth century B.C. when the river abandoned its west-east course (gray arrows in the left part of Figure 4). Until that time, the river passed through the black meanders that are visible in the same figure. The continuous tectonic uplift of the southern side of the plain caused the river to fork at Ficarolo in 1152. Then, as this uplift continued, the southern river branch was finally abandoned in 1570–1580, leaving Ferrara dry at the end of the sixteenth century. We are reasonably confident that the 1570 earthquake contributed to the last catastrophic diversion in the history of the Po River.

Appendix A: Seismology and Superstition Between the Sixteenth and Eighteenth Centuries in Ferrara

Ferrari et al. [1985] wrote that the historical research on this earthquake was favored by the preservation of the archives of the Este Dukes and by the resonant effects that the consequences of that seismic sequence on the Ferrara duchy had on the Italian and European Courts. Similar to many small Italian states at the end of the sixteenth century, Ferrara was experiencing a climate of political and cultural tension (accompanied by some territorial claims by the Pope). Both Catholic and Hebrew orthodoxies encouraged the supernatural interpretation of earthquakes and disasters, whereas rationalists of both sides were looking for their natural causes and remedies.

In Ferrara, the emerging rational personality in the Catholic environment was the architect Pirro Ligorio, the successor of Michelangelo in directing the "Fabbrica" (building) of St. Peter's Basilica in Rome from 1564 to 1568. Then, having fallen into disfavor, he moved to Ferrara 2 years before the earthquake and experienced the event.

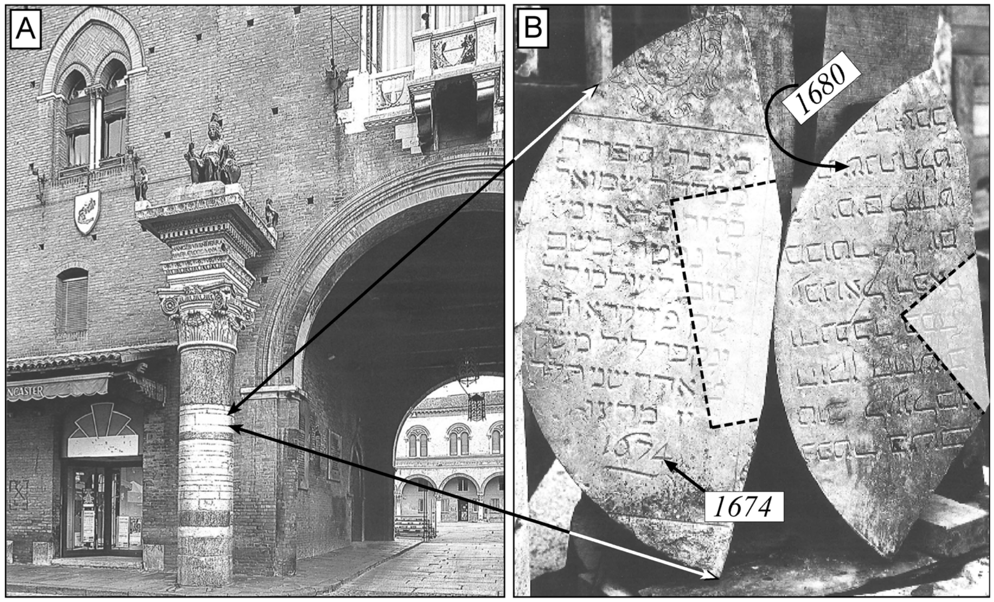

Figure A1. (a) The present condition of the column-shaped monument of Duke Borso D'Este (fifteenth century) in Ferrara. (b) Tombstone of Min Haadumim's family (dated to 1674) and another dated to 1680 (shown up-side down) [from *Ravenna*, 2003].

In his manuscript [*Ligorio*, 1571], he wrote that "the defense against earthquakes is a duty of the human intellect" and proposed the first well-devised design for an aseismic house in Western countries. His text was published in 2006 by *Guidoboni* [1997]. The most prominent figure in the Jewish field was Min Haadumim, who described the east-west and subsequent north-south oscillations [*Shalem*, 1938].

Following the destructive 1570 earthquake, Pope Pius V sent letters to the duchy of Ferrara that informed the Ferrara subjects of Alfonso II D'Este that God sent the earthquake to punish their Duke because Alfonso II had given hospitality to a community of Jews and even Marranos, who had escaped from Spain [see *Bonito*, 1691; *Guidoboni*, 1984]. Whether the causes were natural or supernatural, the 1570 earthquake and the following loss of fluvial trade brought on the decline of the city. However, the Vatican's instigations and long-lasting persecutions of the Jews worsened the dukedom's crisis.

We know from *Ravenna* [2003] that these events (mixed with superstition and prejudices) had consequences. During the restoration of the column-shaped monument of Duke Borso D'Este in 1960 (Figure A1a), the municipal administration of Ferrara found that the monument had already received a special restoration in 1718, perhaps to exorcise new seismic punishments of divine origin. In fact, the column (previously made with reddish, massive marly limestone from the Jurassic "Rosso Ammonitico Veronese") was rebuilt that year in part by using small whitish blocks, which were the tombstones of important Jewish families (Figure A1b), including that of Min Haadumim, who described the 1570 damage. All the mortal remains were transferred from the cemetery, which was in full use, to certain agricultural fields. This new cemetery is depicted in a drawing from that time with silhouettes of devils floating around [*Ravenna*, 2003].

As shown in Figure A1b, in 1718, the tombstones were reworked for insertion into the column. Unfortunately, they were not given back to the Jewish community or rendered available for public exhibition in 1960. Instead, the inscriptions were reworked again, as depicted by the dashed segments in Figure A1b, to allow for the construction of an aseismic column core of reinforced cement. In conclusion, anti-Jewish prejudice and seismic superstition were still prevalent in Ferrara in 1718, and modern ideas regarding defense against earthquakes were not contemplated for at least another two centuries.

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References

Anzidei, M., A. Maramai, and P. Montone (Eds.) (2012), The Emilia (northern Italy) seismic sequence of May–June, 2012: Preliminary data and results, *Ann. Geophys.*, *55*(4), doi:10.4401/ag-6146.

Argnani, A., G. Barbacini, M. Bernini, F. Camurri, M. Ghielmi, G. Papani, F. Rizzini, S. Rogledi, and L. Torelli (2003), Gravity tectonics driven by Quaternary uplift in the Northern Apennines: Insights from the La Spezia-Reggio Emilia geo-transect, *Quat. Int.*, *101-102*, 13–26.

Bakun, W. H., and C. M. Wentworth (1997), Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seismol. Soc. Am.*, *87*, 1502–1521.

Benedetti, L. C., P. Tapponnier, Y. Gaudemer, and I. Manighetti (2003), Geomorphic evidence for an emergent active thrust along the edge of the Po Plain: The Broni-Stradella fault, *J. Geophys. Res.*, *108*(B5), 2238, doi:10.1029/2001JB001546.

Bigi, G., D. Cosentino, and M. Parotto (1990), in *Structural Model of Italy and Gravity Map (1:500.000)*, CNR Prog. Final. Geodin., Quad. Ric. Sci., *114*(3), 6 sheets, edited by R. Sartori and P. Scandone, S.E.L.C.A., Firenze, Italy.

Boccaletti, M., G. Corti, and L. Martelli (2010), Recent and active tectonics of the external zone of the Northern Apennines (Italy), *Int. J. Earth Sci. (Geol. Rundsch.)*, *100*, 1331–1348, doi:10.1007/s00531-010-0545-y.

Bolton, M. K., D. A. Storchak, and J. Harris (2006), Updating default depth in the ISC bulletin, *Phys. Earth Planet. Inter.*, *158*, 27–45.

Bonito, M. (1691), Terra tremante,overo continuatione de' terremoti dalla creatione del mondo fino al tempo presente [in Italian], Napoli, ristampa anastatica Sala Bolognese, Forni, 1981, p. 709.

Boschi, E., G. Ferrari, P. Gasperini, E. Guidoboni, G. Smriglio, and G. Valensise (1995), *CFTI Catalogo dei Forti Terremoti in Italia dal 461 a. C. al 1980* [in Italian], 973 pp., Istituto Nazionale di Geofisica, SGA Storia Geofisica Ambiente, Bologna, Italy.

Bottoni, A. (1872), *Appunti Storici sulle Rotte del Basso Po* [in Italian], 223 pp., Tipografia Sociale, Ferrara, Italy.

Bragato, P. L., M. Sugan, P. Augliera, M. Massa, A. Vuan, and A. Saraò (2011), Moho reflection effects in the Po Plain (northern Italy) observed from instrumental and intensity data, *Bull. Seismol. Soc. Am.*, *101*(5), 2142–2152, doi:10.1785/0120100257.

Bungum, H., F. Pettenati, J. Schweitzer, L. Sirovich, and J. I. Faleide (2009), The MS 5.4 23 October 1904 Oslofjord earthquake: Reanalysis based on macroseismic and instrumental data, *Bull. Seismol. Soc. Am.*, *99*, 2836–2854.

Burrato, P., F. Ciucci, and G. Valensise (2003), An inventory of river anomalies in the Po Plain, Northern Italy: Evidences for active blind thrust faulting, *Ann. Geophys.*, *46*, 865–882.

Burrato, P., P. Vannoli, U. Fracassi, R. Basili, and G. Valensise (2012), Is blind faulting truly invisible? Tectonic-controlled drainage evolution in the epicentral area of the May 2012, Emilia-Romagna earthquake sequence (northern Italy), *Ann. Geophys.*, *55*(4), 525–531.

Camassi, R., and V. Castelli (2013), The curious case of the 1346 earthquake recorded only by very young chroniclers, *Seismol. Res. Lett.*, *84*(6), 1089–1097, doi:10.1785/0220130063.

Carminati, E., and G. Martinelli (2002), Subsidence rates in the Po Plain, northern Italy: The relative impact of natural and anthropogenic causation, *Eng. Geol.*, *66*, 241–255.

Cassano, E., L. Anelli, R. Fichera, and V. Cappelli (1986), *Pianura Padana: Interpretazione Integrata di Dati Geofisici e Geologici, 73° Congresso Società Geologica Italiana [in Italian], Roma, 29 September - 4 October*, 27 pp., Societá Geologica Italiana, Rome.

Castaldini, D. (1989), Evoluzione della rete idrografica centropadana in epoca protostorica e storica, in *Proceedings of the National conference "Insediamenti e Viabilità nell'alto Ferrarese dall'Età Romana al Medioevo," Cento May 8–9, 1987* [in Italian], pp. 115–134, Accademia delle Scienze di Ferrara, Ferrara, Italy.

Castaldini, D., G. Gasperi, M. Panizza, and M. Pellegrini (1979), Neotettonica dei Fogli 74 (Reggio nell'Emilia) p.p. e 75 (Mirandola) nell'intervallo da 18.000 B.P. all'Attuale (Interv. V), in *Nuovi Contributi alla Realizzazione della Carta Neotettonica d'Italia* [in Italian], Pubbl., vol. 251, pp. 317–332, P. F. Geodinamica, Napoli, Italy.

Castaldini, D., M. Marchetti, and A. Cardarelli (2009), Geomorphological and archaeological aspects in the central Po Plain (Northern Italy), in *Ol'man River. Geo-Archaeological Aspects of Rivers and River Plains (ARGU 5)*, edited by M. De Dapper et al., pp. 193–211, Univ. Gent Academia Press, Belgium.

Castellarin, A. (2001), Alps-Apennines and Po Plainfrontal Apennines relations, in *Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins*, edited by G. B. Vai and P. Martini, pp. 177–196, Kluwer Acad., Dordrecht, Netherlands.

Castiglioni, G. B., and G. B. Pellegrini (Eds.) (2001), *Illustrative Notes of the Geomorphological Map of Po Plain* [in Italian], Suppl. Geogr. Fis. Dinam. Quat., vol. IV, Brigati, Genova.

Castiglioni, G. B., et al. (1997), *Geomorphological Map of the Po Plain, 3 Sheets at 1:250,000 Scale*, S.E.L.C.A., Firen, Italy.

Convertito, V., F. Catalli, and A. Emolo (2013), Combining stress transfer and source directivity: The case of the 2012 Emilia seismic sequence, *Nat. Sci. Rep.*, *3*, 3114, doi:10.1038/srep03114.

Dezès, P., S. M. Shmid, and P. A. Ziegler (2004), Evolution of the European Cenozoic Rift System: Interaction of the Alpine and Pyrenean orogenes with their foreland lithosphere, *Tectonophysics*, *389*, 1–33.

Di Bucci, D., and S. Mazzoli (2002), Active tectonics of the Northern Apennines and Adria geodynamics: New data and a discussion, *J. Geodyn.*, *34*, 687–707.

DISS Working Group (2010), Database of Individual Seismogenic Sources (DISS), version 3.1.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, INGV - Istituto Nazionale di Geofisica e Vulcanologia, doi:10.6092/INGV.IT-DISS3.1.1. [Available at http://diss.rm.ingv.it/diss/.]

Facci, A. F. (1729), Stato di Ferrara al tempo dell'antica Padusa descritto dal signor Gio. Battista Benetti perito ferrarese su l'idea dei più antichi ed accreditati auttori citati da Gasparo Sardi istorico degl'antichi siti di questo Stato l'anno 1568 [in Italian], Roma, 1729, Biblioteca Comunale Ariostea, Ferrara, fondo Cartografico Crispi, series 15, tav. 7.

Fantoni, R., and R. Franciosi (2010), Tectono-sedimentary setting of the Po Plain and Adriatic foreland, *Rendiconti Fisici Accad. Lincei*, *21*(suppl. 1), S197–S209, doi:10.1007/s12210-010-0102-4.

Ferrari, G., E. Guidoboni, and D. Postpischl (1985), The Ferrara earthquake of November 17, 1570, in *Atlas of Isoseismal Maps of Italian Earthquakes*, edited by D. Postpischl, pp. 164, P. F. Geodinamica, C. N. R., Roma.

Frankel, A. (1994), Implications of felt area-magnitude relations for earthquake scaling and the average frequency of perceptible ground motion, *Bull. Seismol. Soc. Am.*, *84*, 462–465.

Galli, P., S. Castenetto, and E. Peronace (2012), May 2012 Emilia earthquakes (MW 6, Northern Italy): Macroseismic effects distribution and seismotectonic implications, *Alp. Mediter. Quat.*, *25*, 105–123.

Galli, P., E. Peronace, B. Quadrio, and G. Esposito (2014), Earthquakes fingerprints along fault scarps: The case of the Irpinia 1980 earthquake fault (southern Apennines), *Geomorphology*, *206*, 97–106.

Gambi, L., A. Pinelli, A. Chiggiato, and C. Franzoni (1994), *Galleria delle Carte Geografiche (Vaticano)* [in Italian], 595 pp., Panini, Modena, Italy.

Ganas, A., Z. Roumelioti, and K. Chousianitis (2012), Static stress transfer from the May 20, 2012, M 6.1 Emilia-Romagna (northern Italy) earthquake using a co-seismic slip distribution model, *Ann. Geophys.*, *55*(4), doi:10.4401/ag-6176. [Available at http://www.annalsofgeophysics.eu/index.php/annals/article/view/6176.]

Gasperini, P., F. Bernardin, G. Valensise, and E. Boschi (1999), Defining seismogenic sources from historical felt reports, *Bull. Seismol. Soc. Am.*, *89*, 94–110.

Gasperini, P., G. Vannucci, D. Tripone, and E. Boschi (2010), The location and sizing of historical earthquakes using the attenuation of macroseismic intensity with distance, *Bull. Seismol. Soc. Am.*, *100*, 2035–2066.

Guidoboni, E. (1984), Riti di calamità: Terremoti a Ferrara nel 1570-74 [in Italian], *Quad. Stor.*, *55*, 107–136.

Guidoboni, E. (1997), An early project for an antiseismic house in Italy: Pirro Ligorio's manuscript treatise of 1570–74, *Eur. Earthquake Eng.*, *4*, 1–18.
Guidoboni, E., G. Ferrari, D. Mariotti, A. Comastri, G. Tarabusi, and G. Valensise (2007), CFTI4Med, Catalogue of Strong Earthquakes in Italy from 461 B.C. to 2000 and in the Mediterranean area, from 760 B.C. to 1500, An Advanced Laboratory of Historical Seismology. [Available at http://storing.ingv.it/cfti4med/.]
Guidoboni, E., P. Gasperini, G. Valensise, and G. Ferrari (2015), Comment on "The Curious Case of the 1346 Earthquake Recorded Only by Very Young Chroniclers" by Romano Camassi and Viviana Castelli, *Seismol. Res. Lett.*, *86*(4), 1–7, doi:10.1785/0220140074.
International Association of Seismology and Physics of the Earth's Interior (2005), *Summary of Magnitude Working Group Recommendations on Standard Procedures for Determining Earthquake Magnitudes from Digital Data*, edited by J. W. Dewey, pp. 6. [Available at www.iaspei.org/commissions/CSOI/summary_of_WG_recommendations_2005.pdf; last accessed 8 Sept. 2014].
Johnston, A. C. (1996), Seismic moment assessment of earthquakes in stable continental regions - I. Instrumental seismicity, *Geophys. J. Int.*, *124*, 381–414.
Kagan, Y. Y. (1990), Random stress and earthquake statistics: Spatial dependence, *Geophys. J. Int.*, *102*, 573–583.
Kagan, Y. Y. (1991), 3-D rotation of double-couple earthquake sources, *Geophys. J. Int.*, *106*, 700–716.
Koper, K. D. L., M. E. Wysession, and D. A. Wiens (1999), Multimodal function optimization with a niching genetic algorithm, *Bull. Seismol. Soc. Am.*, *89*, 978–988.
Ligorio, P. (1571), *Libro di Diversi Terremoti (Manuscript), Code 28 Ja II 15 State Archive of Torino* [in Italian], Ital. Ed. of the Works by Pirro Ligorio, with Hist. and Crit. Appar., edited by E. Guidoboni, De Luca, Roma, 2006.
Locati, M., R. Camassi, and M. Stucchi (Eds.) (2011), *DBMI11, the 2011 Version of the Italian Macroseismic Database*, Istituto Nazionale di Geofisica e Vulcanologia, INGV, Milano, Bologna, doi:10.6092/INGV.IT-DBMI11. [Available at http://emidius.mi.ingv.it/DBMI11.]
Maesano, F. E., C. D'Ambrogi, P. Burrato, and G. Toscani (2015), Slip-rates of blind thrusts in slow deforming areas: Examples fromthe Po Plain (Italy), *Tectonophysics*, *643*, 8–25.
Magini, G. A. (1710), *Carta della Pianura Bolognese*, Domenico De Rossi, Bologna, Italy [in Italian]. [Available at http://www.bonificarenana.it/gallerie/CartografiaStorica/.]
Meletti, C., E. Patacca, and P. Scandone (2000), Construction of a seismotectonic model: The case of Italy, *Pure Appl. Geophys.*, *157*, 11–35.
Molchan, G. M., T. L. Kronrod, and G. F. Panza (2004), Shape of empirical and synthetic isoseismals: Comparison for Italian $M \leq 6$ earthquakes, *Pure Appl. Geophys.*, *161*, 1725–1747.
Musson, R. M. W., and M. J. Jiménez, (2008), Macroseismic estimation of earthquake parameters, EC project # 026130, NERIES Technical Report NA4-D3, 38 pp.
Panizza, M., and D. Castaldini (1987), Neotectonic research in applied geomorphological studies, *Z. Geomorphol. N. F., Suppl.-Bd.*, *63*, 173–211.
Paolucci, A. (2010), Giro d'Italia senza uscire dal Vaticano [in Italian], L'Osservatore Romano, 27–28 Sept.
Pellegrini, M. (1969), La pianura del Secchia e del Panaro [in Italian], *Atti Soc. Nat. Mat. Modena*, *100*, 1–51.
Pettenati, F., and L. Sirovich (2003), Test of source-parameter inversion of the U.S. Geological Survey intensities of the Whittier Narrows, 1987 earthquake, *Bull. Seismol. Soc. Am.*, *93*, 47–60.
Pettenati, F., and L. Sirovich (2007), Validation of intensity-based source inversion of three destructive Californian Earthquakes, *Bull. Seismol. Soc. Am.*, *97*, 1587–1606.
Pettenati, F., L. Sirovich, D. Sandron, and C. Papaioannou (2010), Earthquake sources retrieved from intensities: Seven successes in Greece, in *Proceedings 14th European Conference on Earthquake Engineering ECEE*, Aug. 30–Sept. 3, 2010. CD Paper #1809, pp. 7, Ohrid, FYROM-Macedonia.
Pezzo, G., et al. (2013), Coseismic deformation and source modeling of the May 2012 Emilia (Northern Italy) earthquakes, *Seismol. Res. Lett.*, *84*, 645–655, doi:10.1785/0220120171.
Picotti, V. (2012), La crisi sismica in Emilia del Maggio - Giugno 2012 e la tettonica attiva in Appennino settentrionale [in Italian], *Geol. Emilia Romagna*, *45*, 7–11.
Picotti, V., and F. J. Pazzaglia (2008), A new active tectonic model for the construction of the Northern Apennines mountain front near Bologna (Italy), *J. Geophys. Res.*, *113*, B08412, doi:10.1029/2007JB005307.
Ravenna, P. (2003), *Le Lapidi Ebraiche nella Colonna di Borso d'Este a Ferrara*, 86 pp., Gabriele Corbo Editore, Ferrara, Italy.
Rovida, A., R. Camassi, P. Gasperini, and M. Stucchi (Eds.) (2011), *CPTI11, the 2011 Version of the Parametric Catalogue of Italian Earthquakes*, Istituto Nazionale di Geofisica e Vulcanologia, INGV, Milano, Bologna. [Available at http://emidius.mi.ingv.it/CPTI.]
Scrocca, D., E. Carminati, C. Doglioni, and D. Marcantoni (2007), Slab retreat and active shortening along the Central-Northern Apennines, in *Thrust Belts and Foreland Basins Frontiers in Earth Sciences*, edited by O. Lacombe et al., pp. 471–487, Springer, Berlin, doi:10.1007/978-3-540-69426-7.
Serpelloni, E., et al. (2012), GPS observations of coseismic deformation following the May 20 and 29, 2012, Emilia seismic events (northern Italy): Data, analysis and preliminary models, *Ann. Geophys.*, *55*(4), doi:10.4401/ag-6168. [Available at http://www.annalsofgeophysics.eu/index.php/annals/article/view/6168.]
Shalem, N. (1938), Una fonte ebraica poco nota sul terremoto di Ferrara del 1570 [in Italian], *Riv. Geogr. Ital. Firenze*, *45*, 66–76.
Sirovich, L. (1996), A simple algorithm for tracing out synthetic isoseismals, *Bull. Seismol. Soc. Am.*, *86*, 1019–1027.
Sirovich, L., and F. Pettenati (2004), Source inversion of intensity patterns of earthquakes: A destructive shock in 1936 in northern Italy, *J. Geophys. Res.*, *109*, B10309, doi:10.1029/2003JB002919.
Sirovich, L., F. Pettenati, and C. Chiaruttini (2001), Test of source-parameter inversion of intensity data, *Nat. Hazards*, *24*, 105–131.
Sirovich, L., F. Pettenati, F. Cavallini, and M. Bobbio (2002), Natural-neighbor isoseismals, *Bull. Seismol. Soc. Am.*, *92*, 1933–1940.
Sirovich, L., F. Pettenati, and P. Jamsek (2012), Searching for regional and site effects in intensity data sets (one intensity per town), in *Proceedings 31st National Conference Gruppo Nazionale di Geofisica della Terra Solida GNGTS, Potenza, 20-22 November 2012*, vol. 2, pp. 252–256.
Sirovich, L., F. Pettenati, and F. Cavallini (2013), Intensity-based source inversion of the destructive earthquake of 1694 in the southern Apennines, Italy, *J. Geophys. Res. Solid Earth*, *118*, 6241–6257, doi:10.1002/2013JB010245.
Sugan, M., and A. Vuan (2013), On the ability of Moho reflections to affect the ground motion in northeastern Italy: A case study of the 2012 Emilia seismic sequence, *Bull. Earthquake Eng.*, *12*, 2179–2194, doi:10.1007/s10518-013-9564-y.
Suhadolc, P., L. Cernobori, G. Pazzi, and G. F. Panza (1988), Synthetic isoseismals, in *Seismic Hazard in Mediterranean Regions*, edited by J. Bonnin et al., pp. 205–228, Kluwer, Dordrecht, Netherlands.
Teatini, P., L. Tosi, and T. Strozzi (2011), Quantitative evidence that compaction of Holocene sediments drives the present land subsidence of the Po Delta, Italy, *J. Geophys. Res.*, *116*, B08407, doi:10.1029/2010JB008122.
Tortora, S. (2013), Evoluzione Tettonico-Stratigrafica delle successioni terrigene mio-plioceniche sepolte nella Pianura Padana emiliana-romagnala in base ai dati di sottosuolo disponibili [in Italian], MS thesis, 125 pp., 17 plates, Engineering and Geology Dep., G. D'Annunzio Univ., Chieti, Pescara.
Toscani, G., P. Burrato, D. Di Bucci, S. Seno, and G. Valensise (2009), Plio-Quaternary tectonic evolution of the Northern Apennines thrust fronts (Bologna-Ferrara section, Italy): Seismotectonic implications, *Ital. J. Geosci. (Boll. Soc. Geol. Ital.)*, *128*, 605–613, doi:10.3301/IJG.2009.128.2.605.

Touring Club Italiano (1977), *Roma; Guida d'Italia* [in Italian], 1045 pp., Touring Club Italiano, Milano, Italy.
Tozzi Fontana, M. (Ed.) (2001), *Bologna e l'Invenzione delle Acque* [in Italian], 199 pp., Editrice Compositori, Bologna, Italy.
TRE (2012), TRE produces first C-band co-seismic interferogram of Italian earthquakes, June 7. [Available at http://treuropa.com/news/tre-produces-first-c-band-co-seismic-interferogram-of-italian-earthquakes/ last accessed 22 January, 2015].
Wells, D. L., and K. J. Coppersmith (1994), New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seismol. Soc. Am.*, *84*, 974–1002.
Wesnousky, S. G. (2008), Displacement and geometrical characteristics of earthquake surface ruptures: Issues and Implications for seismic-hazard analysis and the process of earthquake rupture, *Bull. Seismol. Soc. Am.*, *98*, 1609–1632, doi:10.1785/0120070111.
Zahradnik, J. (1989), Simple method for combined studies of macroseismic intensities and focal mechanisms, *Pure Appl. Geophys.*, *130*, 83–97.