Is blind faulting truly invisible? Tectonic-controlled drainage evolution in the epicentral area of the May 2012, Emilia-Romagna earthquake sequence (northern Italy)

Pierfrancesco Burrato, Paola Vannoli, Umberto Fracassi, Roberto Basili & Gianluca Valensise
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Sismologia e Tettonofisica, Via di Vigna Murata 605, 00143 Roma, Italy. E-mail: pierfrancesco.burrato@ingv.it

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CORRESPONDING AUTHOR:
Pierfrancesco Burrato
Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605 Roma, Italy - 00143
Ph. +39 0651860492
Fax +39 0651860507
pierfrancesco.burrato@ingv.it

1. Introduction

For decades alluvial plains have been the areas of fastest population growth over most of the globe. Modern societies demand growing extensions of flat and easily accessible land to accommodate swelling urban areas, booming industrial districts, large power plants, and multi-runway airports. But how can we tell if one of such flat areas hides large active faults? How can we assign a significant pre-instrumental earthquake to its causative source? In other words, how can modern societies deal with buried, that is to say, *invisible* faults, and with the elusiveness of the hazard they pose?

The issue of blind faulting became widely debated in the Earth Science community in 1989, following the publication of a summary on a sequence of “hidden earthquakes" that hit central and southern California between 1983 and 1987 and following the 17 October 1989, Loma Prieta earthquake (M_w 6.9). These earthquakes shattered the accepted belief that large earthquakes are associated with large topographic contrasts - i.e. that they usually take place in mountainous terrains - and that their causative faults are expressed at the surface. Stein and Yeats (1989) spelled out clearly that “*...large earthquakes can take place not only on faults that cut the Earth’s surface but also on 'blind' faults under folded terrain*”. And due to the growing concentration of population and infrastructures in low topography areas, such earthquakes may pose a comparable hazard but a substantially larger risk than earthquakes that occur in hilly or mountainous terrains.

How can we make the invisible faults *visible*? Where are these faults hidden? Can we locate them through studies of the local geomorphology? We take on these challenges and show how continuing slip on the faults responsible for the May 2012 Emilia-Romagna, northern Italy earthquake sequence (two mainshocks of M_L 5.9 and 5.8 on 20 and 29 May, respectively) also controlled the drainage evolution of the southern Po Plain during the Holocene. Recent earthquakes worldwide show that the hazard posed by blind and hard-to-identify faults is a critical issue even in countries where active fault studies are advanced; such is the case of the 25 March 2007, Noto-Hanto, Japan earthquake (M_w 6.9) and of the 4 September 2010 (M_w 7.1) and 22 February 2011 (M_w 6.3) earthquakes near Christchurch, New Zealand, all of which came largely unexpected.

Not surprisingly, the identification of active faults in flat areas is fraught with conceptual and practical difficulties, some of which arising from the diffuse perception that "flat" equals "stable" and that "invisible" equals "absent". Whether or not a large active fault can be seen at the surface depends primarily on a combination of geodynamic circumstances, the local structural setting, the geometry of faulting (depth and dip), and the competition of tectonic vs sedimentation rates. In this respect, the Po Plain is especially challenging due to the combination of a) low strain rates, b) infrequent and moderate-size earthquakes, c) regional-scale tectonic strains being larger than those caused by localized faulting, d) sedimentary rates being much higher than tectonic rates, and e) locally, large man-induced elevation changes overshadowing those caused by genuine tectonic activity. More specifically, the blind nature of faulting in the Po Plain is a result of two fundamental geodynamic occurrences: a) Plio-Quaternary sedimentation rates (i.e. contemporary to the tectonic phases responsible for thrust development) induced by regional-scale uplift of the adjacent Apennines and Alpine belts are faster than the rate at which individual buried anticlines generate topographic relief (e.g. Bartolini et al., 1996), and b) progressive burial of active structures was favored by the creation of accommodation space due to the subsidence of the Northern Apennines foredeep, as shown by the dip of the foreland monocline beneath the Northern Apennines (Mariotti and Doglioni, 2000). As a result, the majority of the presently active structures are buried beneath a largely irregular sedimentary apron up to several thousand meters thick.

Under these conditions, identifying and characterizing seismogenic sources calls for an approach that integrates high-resolution subsurface geological and geophysical data with unconventional morphotectonic analysis that detects changes in local elevation or topographic gradient. Drainage patterns has been demonstrated to be the most sensitive landscape feature to subtle topographic gradient changes (e.g. Schumm and Khan, 1972; Holbrook and Schumm, 1999) and is therefore a key element in our approach. The combination of the lack of inherited landscape, since most of the plain formed during the Last Glacial Maximum or is of Holocene age, with the absence of significant lithological discontinuities makes the use of geomorphic analyses of the drainage evolution suitable for unveiling the subtle ongoing tectonic deformation.

Based on these principles, Burrato et al. (2003) mapped numerous drainage anomalies associated with buried active structures in the Po Plain. The main result of their investigation, later augmented by detailed studies of the subsurface stratigraphic and sedimentary configuration (Toscani et al., 2009), was the foundation for a seismogenic source model in the Po Plain (Fig. 1). These results have been incorporated in the Database of Seismogenic Sources (DISS; http://diss.rm.ingv.it/diss/; Basili et al., 2008; DISS Working Group, 2010). The 20 and 29 May 2012, Emilia-Romagna earthquakes (M_L 5.9 and 5.8, respectively) were most likely generated by two of the seismogenic sources identified through this approach; hence they support its reliability and its applicability on a wider scale and in similar tectonic contexts anywhere Quaternary folding is driven by active blind faulting (e.g. Andean adjacent foreland region; Costa et al., 2006). The Emilia-Romagna earthquakes also provided clear evidence that a fault-based model is of critical relevance in seismic hazard studies, especially in areas where earthquakes are dispersed and infrequent such as the Po Plain.

2. Geological and seismological framework

The Po Plain comprises the foreland of the S-verging central Southern Alps and of the N-NE-verging Northern Apennines fold-and-thrust belts, which developed in response to the continuous convergence of the African and European plates from the Cretaceous onward (Carminati and Doglioni, 2012, and references therein). Its physiographic boundaries correspond with the contact between the Quaternary alluvium of the plain and the pre-Quaternary rocks exposed along the mountain fronts.

The Plio-Quaternary sedimentary sequence filling in the Po Plain is characterized by an uneven thickness, ranging between several thousand meters and a few tens of meters atop the crest of the buried anticlines (Bigi et al., 1992). The relatively short wavelength variations (3-10 km) of the geometry of the sedimentary sequence due to the local tectonic activity are superimposed onto a much longer wavelength signal due to the larger subsidence of the Northern Apennines foredeep with respect to that of the Southern Alps (Mariotti and Doglioni, 2000). The main consequence of these relations is that the thickness of the clastic wedge generally increases southward, i.e. towards the Northern Apennines mountain front; similarly, the depth of the basal detachments of the thrust wedge increases going towards the southern margin of the Po Plain, where the outermost thrust fronts of the Northern Apennines belt are buried below Plio-Quaternary marine and continental deposits. These fronts are recognized as three complex fold systems: the Monferrato, Emilia, and Ferrara-Romagna arcs, from west to east (Fig. 1). Starting in the 1940s these buried structures were extensively explored by seismic reflection lines and deep well logs performed for oil exploration.

Ongoing deformation in the Po Plain as recorded by GPS data results in limited shortening with rates of few mm/y (e.g. Devoti et al., 2011). Borehole breakout data show Sh-max axes perpendicular to the trend of the buried thrust fronts (Montone et al., 2012). Evidence for earthquake activity of the frontal thrusts of the Northern Apennines and Southern Alps is supplied by macroseismic and instrumental data (Castello et al., 2006; Guidoboni et al., 2007; ISIDe Working Group, 2010; Rovida et al., 2011), the latter indicating dominant reverse faulting (e.g. Pondrelli et al., 2006). Accordingly, the 2012 sequence (consisting of more than 2,000 aftershocks) showed pure reverse faulting generated by the blind thrusts of the western Ferrara Arc, which activated a 50 km-long stretch of this buried thrust, and the Sh-max axes obtained from the focal mechanisms are perpendicular to the buried fronts. Most of the sequence occurred between 1 and 12 km depth, above the basal detachment of the outer thrust fronts of the Northern Apennines.

3. Method

Through the extensive analysis of the river network of the whole Po Plain, Burrato et al. (2003) identified several significant drainage anomalies. The wave-length of these anomalies was seen comparable to that of tectonic structures of crustal significance, and suggested the presence of buried growing folds beneath the river diversions. This analysis led to the compilation of a GIS database of anomalous river reaches to be compared with structural and earthquake data.

The method adopted to identify an anomalous reach includes an analysis of the local topographic gradients and of the mean flow directions of the drainage network; it assumes that if the two vectors diverge beyond a given threshold, the river diversion must be driven by a force that is independent from the natural evolution of the stream channel (Fig. 2). Burrato et al. (2003) conventionally defined a drainage anomaly as a difference in the two vectors of > 10°. However, the length of the "anomalous reach" (adjusted to the river size), i.e. the distance over which the divergence persists must also be considered. This is important to avoid mistaking natural irregularities, such as large meanders, for anomalous reaches. Hence, an anomalous reach is further clarified and includes divergence between the two vectors that persists over a distance of 5 km or more. This minimum length is based on the average length of the longest meanders measured in the area.

The second step of their approach consists in comparing the position of the drainage anomalies with the location of known buried anticlines (taken from geological maps or the Structural Model of Italy; Bigi et al., 1992), to test the hypothesis of the tectonic nature of the anomalies. Such analysis led Burrato et al. (2003) to a) hypothesize a tectonic origin for a number of the drainage anomalies (shown in Figure 1 and listed in their Table I), and b) identify active structures in the subsurface (i.e., blind thrusts). Following the observation that some of these structures were also associated with historical earthquakes, Burrato et al. (2003) proposed that these blind thrusts may have been the potential sources of rather infrequent large earthquakes beneath the Po Plain. In selected cases, these analyses demonstrated the concomitance of 1) the location of a critical drainage anomaly, 2) the occurrence of a buried anticline, and 3) the location of significant past earthquakes – thus supporting a causative link among these factors. It was thus possible to characterize those faults that are likely responsible for the largest and comparatively better known historical earthquakes (e.g. the 17 November 1570, M_w 5.5, Ferrara; the 11 April 1688, M_w 5.8, Romagna; and the 12 May 1802, M_w 5.6, Valle dell’Oglio; ITIS090, ITIS100 and ITIS104 in Fig. 1). Likewise, other segments and fault systems in the area share geologic and geomorphic features with the faults responsible for known earthquakes. Although these faults were not associated with a known event, they likely will cause future earthquakes.

4. Drainage evolution of the southern Po Plain

The Po, Secchia, Panaro and Reno are the main rivers crossing the region hit by the 20 and 29 May 2012 earthquakes. These rivers exhibit unexpected trends and behavior (i.e. change of meander wavelength) as they cross the buried western portion of the Ferrara-Romagna Arc (Fig. 2). A geological section across the area (Fig. 3) shows from the SW to the NE an inner structure formed by buried, shallow, imbricated thrusts, known as the Pedeapenninic Thrust Front (PTF; Boccaletti et al., 1985), a deep thrust-top basin, and the outer buried thrusts and folds of the Ferrara-Romagna Arc. In turn, the Ferrara-Romagna Arc is a complex structure composed by an inner system of anticlines, which includes the Mirandola Anticline, and by the outer system of the Ferrara Folds.

The 20 and 29 May earthquakes ruptured two independent parts of these blind structures. Very little historical seismicity is reported for this region, with the notable exception of the 17 November 1570, M_w 5.5 Ferrara earthquake, located to the NE of the 2012 sequence and likely generated by one of the outermost shallow thrust of the Ferrara Folds (Fig. 1; DISS Working Group, 2010; Rovida, 2004; Toscani et al., 2009). The 1570 aftershocks were numerous and the largest comparable in size to the mainshock - much like the 2012 sequence.

The trend of the Po, Secchia, and Panaro river channels highlights a) an area of drainage attraction and b) an area of drainage avulsion (Figs. 2 and 4). The attraction is observed where the thrust-top basin is confined between the buried outer folds and the PTF, whereas the avulsion coincides with the buried outer anticlines. The Reno River shows a sharp diversion towards the SE that appears to be closely controlled by the growth of the Ferrara Folds (Figs. 2, 3 and 4). All these rivers flow in a sub-horizontal, aggradational alluvial plain of Holocene age. They exhibit meandering channels whose wavelength is controlled by the river stream-power (longer for larger rivers), and in some instances flow along suspended beds generated by the continuous aggradation caused by the slow subsidence of the area. The Po River is the longest river in Italy, draining longitudinally the entire Po Plain. The Secchia and Panaro are tributaries of the Po River, whereas the Reno River originally discharged into a paleo-channel of the Po that was abandoned in the 12th century, when the Po River changed course at Ficarolo and drifted northward (F in Fig. 4; Bondesan, 2001). Following this diversion, the Reno River began to discharge first in a marshy area (Valle Padusa), then directly to the sea after major reclamation works (Fig. 4).

The Holocene evolution of the Po, Secchia, Panaro and Reno rivers was reconstructed thanks to existing mapping and dating of alluvial deposits and paleo-channels (e.g. Castaldini et al., 1979; MURST, 1997a; Castiglioni et al., 1999; Fig. 4). The oldest known course of the Po River between Guastalla and Ficarolo (G and F in Fig. 4, respectively) initially followed a straight E-W direction across the buried folds of the Northern Apennines outer front, then progressively migrated northward through repeated sudden diversions. Eventually it adopted the present-day convexity that parallels the Ferrara-Romagna Arc bordering it along its outer (northern) side. With an average SW-NE trend, the Secchia and Panaro rivers instead cross at a high angle the outer tectonic structures of the Northern Apennines, in doing so sharing their evolutionary destiny. Crossing the thrust-top basin south of Mirandola, over time the two rivers deflected one toward the other and both towards the present-day active depocenter. Downstream this area, their channels have been diverted in opposite directions as they cross the buried folds of the Ferrara-Romagna Arc (Figs. 2 and 4).

5. Discussion and conclusions

The Holocene evolution of the drainage network in the central sector of the Po Plain north of Bologna followed a consistent pattern through time, highlighting areas of relative slight subsidence and uplift that spatially correspond with the buried basin and anticlines of the outer Northern Apennines fronts.

What controls the drainage pattern in this flat alluvial area? Fault dislocation theory shows that active blind faulting contributes to changing topographic gradients and so drainage is a) drawn to subsiding areas, and b) diverted from uplifting areas. This circumstance is testified by the coexistence of drainage anomalies with buried anticlines all around the Po Plain

(Figs. 1 and 3). Historical earthquake activity generated by the active thrusts, however, peaks at magnitude ca. 6, with the only notable exception of the 3 January 1117, M_w 6.7 Veronese event. As shown by the coseismic elevation changes caused by the M_L 5.9 and 5.8 mainshocks of the 2012 Emilia-Romagna sequence (see Bignami et al., this volume), blind faulting earthquakes in this magnitude range cause uplift up to 10-30 cm, which is probably insufficient to induce coseismic channel diversions. Therefore, the evolution of the drainage network must be interpreted in a long-term perspective (10,000-50,000 y) and must take into consideration regional-scale tectonic and non-tectonic processes, including local structural and kinematic variations and localized compaction effects. The uneven thickness of the Plio-Quaternary sedimentary sequence controls ground elevation changes induced by differential compaction, in their turn controlled by the thickness of the sediments involved (among other factors). Young, water-rich sediments thicken in the synclines and get thinner over the anticlines; hence the subsurface geometry of the recent sediments alone is able to induce relative differential vertical ground variations, mimicking those produced by the tectonic activity and in fact amplifying them significantly. A detailed study of the Mirandola Anticline using back-stripping of high resolution Middle Pleistocene stratigraphic data highlighted that differential compaction may account for up to 50% of the relative vertical separation between the anticline high and the syncline low (Scrocca et al., 2007; Maesano et al., 2011).

In spite of these difficulties, the analysis of the drainage network showed to be a powerful tool for identification of buried growing anticlines and, together with fault dislocation modeling, characterizing the geometry of the blind thrusts driving them. This approach led to the inclusion of the Mirandola thrust in the DISS database since its first published version (Valensise and Pantosti, 2001: see also Fig. 1). We propose to use the experience gained with the identification and parameterization of the Mirandola seismogenic source to investigate other blind seismogenic sources in the Po Plain and in other alluvial plains worldwide.

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Figure captions

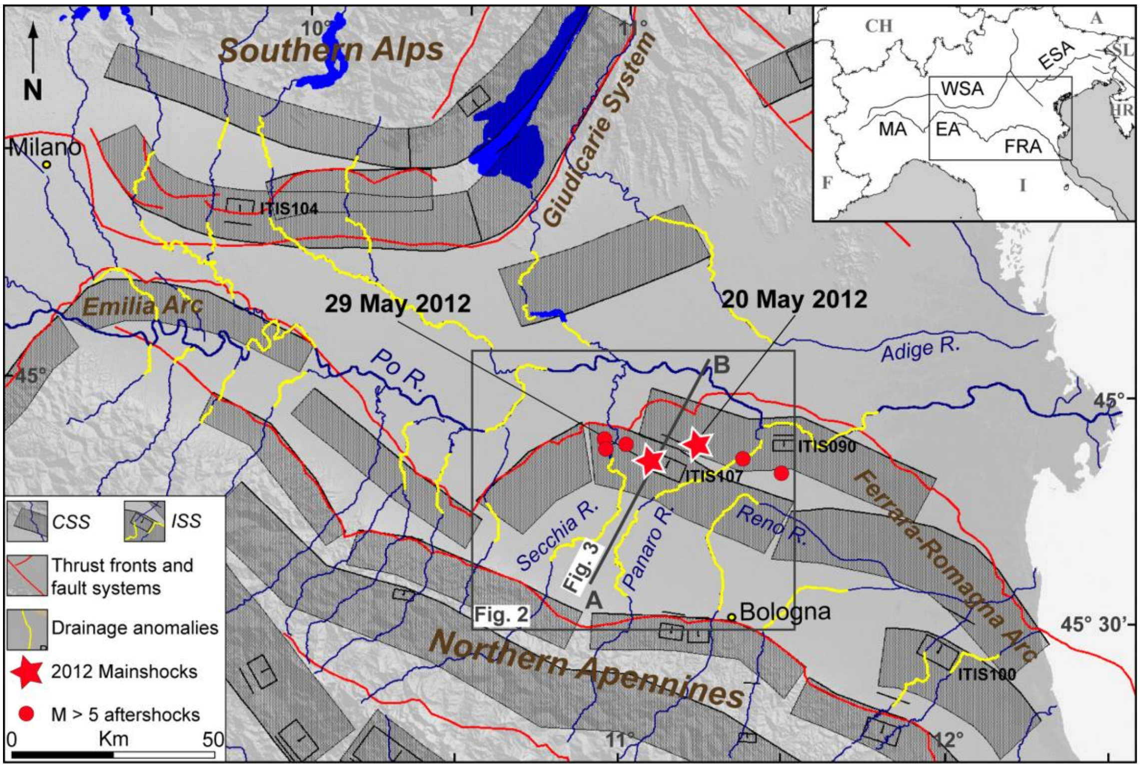

Figure 1: Seismotectonic sketch of the Po Plain and its fluvial system. Drainage anomalies are highlighted in yellow (from Burrato et al., 2003). *Individual Seismogenic Sources* (ISS) and *Composite Seismogenic Sources* (CSS) are from DISS 3.1.1. Keys: ITIS090, Ferrara Individual Source (http://diss.rm.ingv.it/dissHTML/ITIS090INF.html); ITIS107, Mirandola Individual Source (http://diss.rm.ingv.it/dissHTML/ITIS107INF.html); MA, Monferrato, EA, Emilia and FRA, Ferrara-Romagna arcs; WSA, Western Southern Alps; ESA, Eastern Southern Alps.

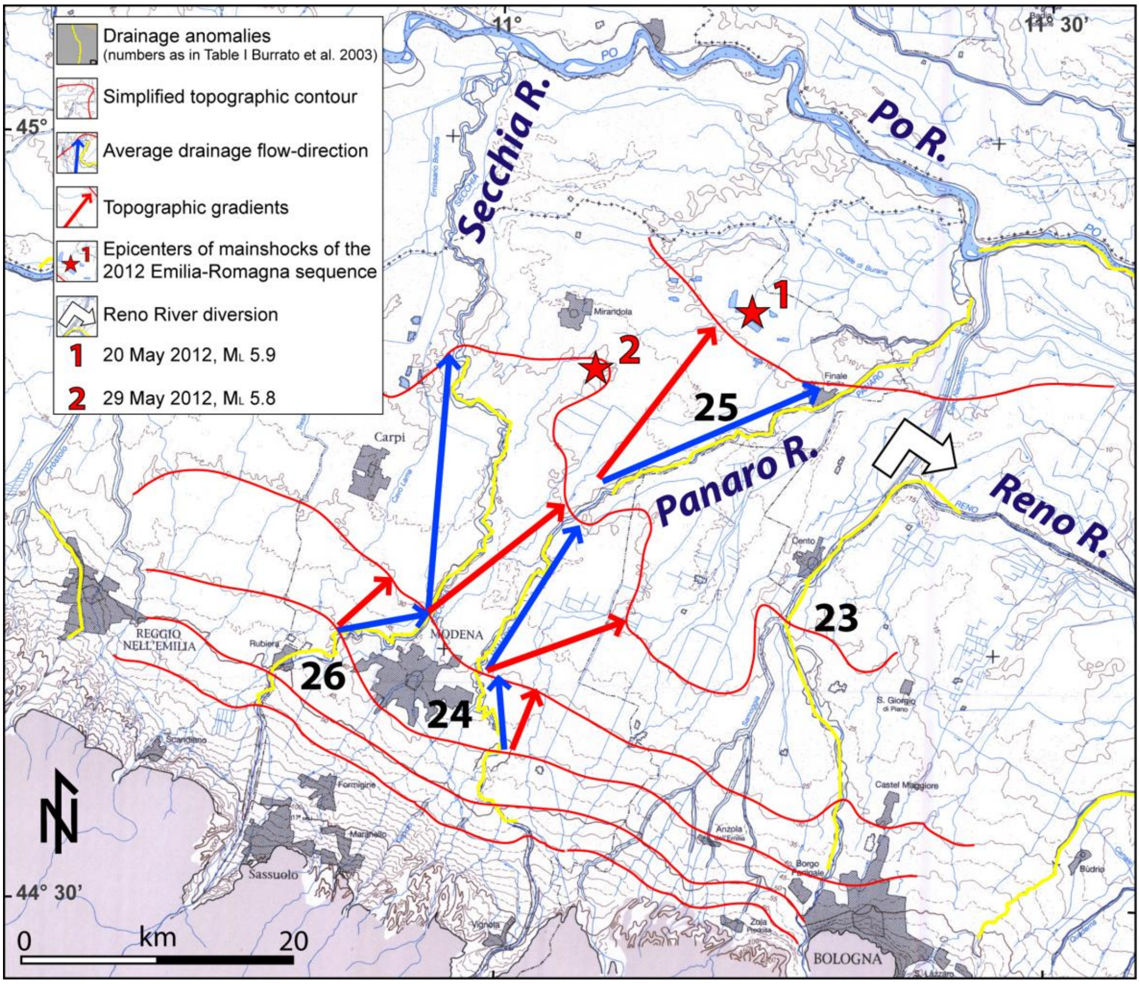

Figure 2: Drainage anomalies in the epicentral area of the 2012 Emilia-Romagna seismic sequence. The drainage should flow following the maximum regional topographic gradient, i.e. in a direction perpendicular to the smoothed topographic contour lines. The mean flow direction of each river is calculated between contour lines. An anomaly is identified when the drainage and the topographic vectors diverge > 10° along a > 5 km-long section of the river course. Basemap is from MURST (1997b).

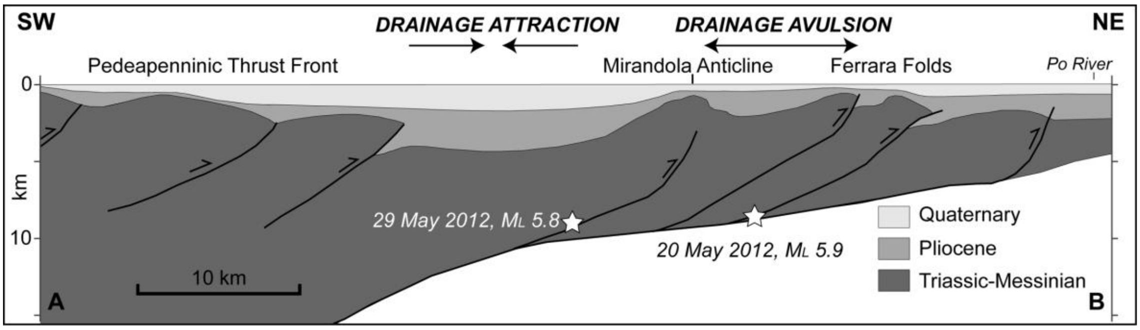

Figure 3: Simplified SW-NE geological section across the Northern Apennines thrust fronts in the epicentral area of the 2012 sequence (after Carminati et al., 2010, redrawn).

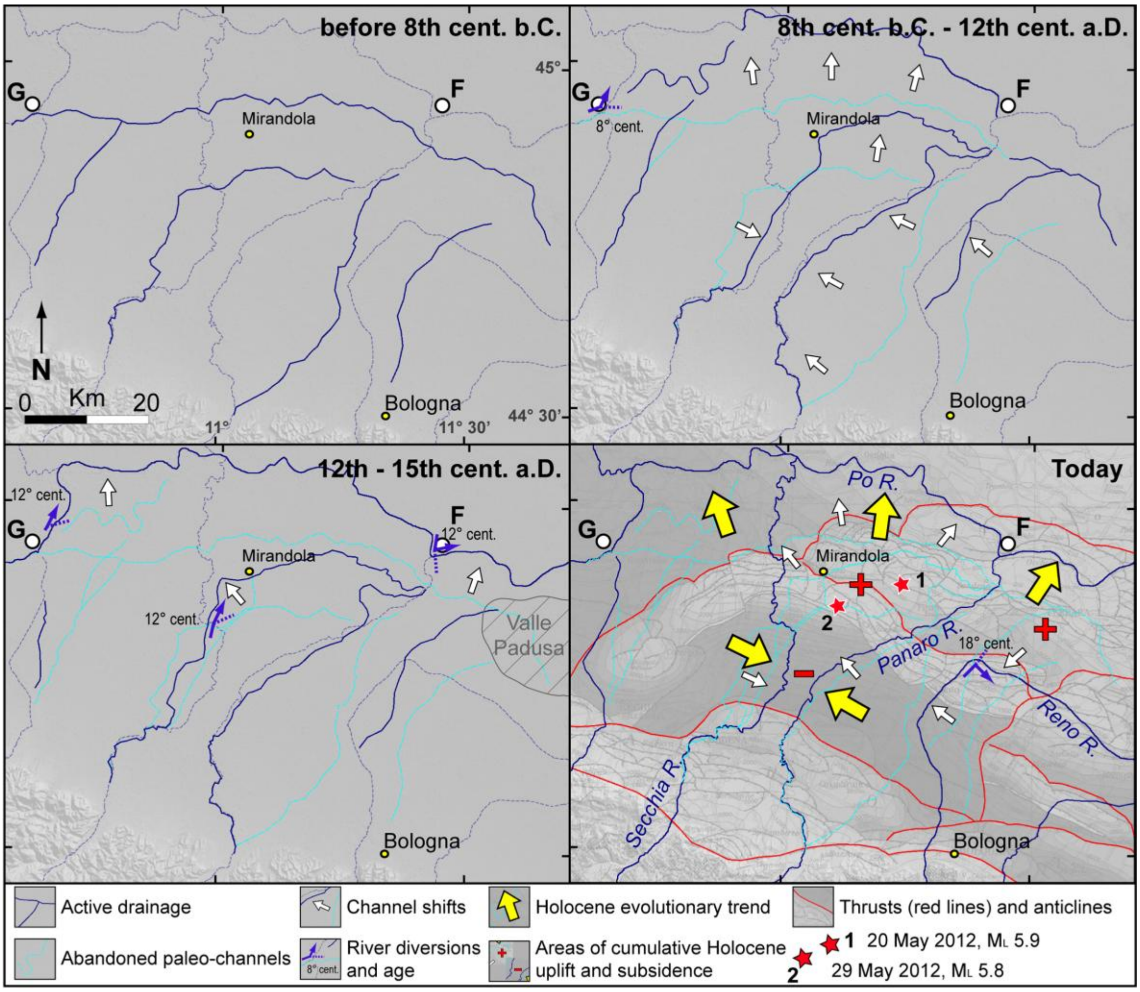

Figure 4: Drainage network evolution in the central part of the southern Po Plain north of Bologna, modified after Castaldini et al. (1979) and MURST (1997a). Modern drainage pattern is reproduced in the background of all panels. Basemap of lower-right panel is from Bigi et al. (1992). The coseismic elevation changes detected by the DInSAR technique (see Bignami et al., this volume) fit well the buried syncline-anticline pair. Rivers are attracted towards areas of relative subsidence, e.g. synclines and thrust-top basins, and diverted away from the buried growing anticlines. Age of diversions from MURST (1997a). Key: F, Ficarolo; G, Guastalla.