ANNALS OF GEOPHYSICS, 55, 4, 2012; doi: 10.4401/ag-6131

2012 EMILIA EARTHQUAKES

Searching for the effects of the May-June 2012 Emilia seismic sequence (northern Italy): medium-depth deformation structures at the periphery of the epicentral area

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Article history
Received July 22, 2012; accepted August 27, 2012.
Subject classification:
Emilia 2012 earthquake, Seismic effect, Faulting, Seismic reflection survey.

1. Introduction

In 2012, a seismic sequence occurred in the lowlands of the Emilia-Romagna Region (northern Italy), between the borders of the Modena, Ferrara and Bologna Provinces. It consisted of seven mainshocks ($5.9 > M_L > 5$) that were recorded between May 20 and 29, 2012 [INGV 2012a] and 2,200 minor earthquakes [INGV 2012b]. An interferometric analysis [Bignami et al. 2012, Salvi et al. 2012, this volume] highlighted three main deformation areas, each of which was 12 km wide (from S to N) and 10 km to 20 km long in an ESE-WNW to E-W direction, thus affecting an area of about 600 km^2 (Figure 1). Field and aerial geological surveys recorded numerous surficial effects, such as: (i) sediment liquefaction [Crespellani et al. 2012]; (ii) localized ground fissures resembling surficial faulting [Fioravante and Giretti 2012] (Figure 2); (iii) groundwater levels rising up to 400 cm above the local ground level in phreatic wells during the mainshocks (lower values were observed in confined aquifers); and (iv) dormancy of previously known sinkholes [Borgatti et al. 2010, Cremonini 2010a, and references therein]. Some of the observed surface phenomena were previously recorded as coseismic effects during the earthquakes of Ferrara (1570) and Argenta (1624) [Boschi et al. 1995, Galli 2000], together with the early rising of the water level of the Po River in the Stellata section.

Apart from more than 700 liquefaction phenomena [Bertolini and Fioroni 2012, this volume] that were generated by shallow groundwater interactions with sandy fine sediments within 10-20 meter depth [Gruppo di Lavoro Liquefazione 2012], no significant tectonic faulting of the ground surface was detected [Galli et al. 2012].

In particular, there was no evidence of reactivation of previously reported tectonically generated faults in the area [e.g., Pellegrini and Vezzani 1978] or of possibly tectonically induced ground fissuring phenomena, like sinkholes [Bonori et al. 2000, Borgatti et al. 2010, and references therein]. To investigate the presence of possible, still undocumented, medium-depth fracturing and faulting phenomena, a high resolution seismic survey was carried out close to the site affected by the most significant ground fissure [Abu Zeid et al. 2012, this volume] and sand liquefaction phenomena [Gruppo di Lavoro Liquefazione 2012], on the outskirts of the village of San Carlo, near Sant'Agostino (Ferrara Province).

2. Geological and geomorphological setting

The study area is located on the buried front of the Apennine chain, which is characterized by a series of thrust-and-folds that resulted from the collision between the European (Corso-Sardinian block) and Adria plates. Since the Oligocene, the related chain foredeep is still in the process of evolving, according to a NE-directed compression that is causing external crustal shortening. At the end of the Lower Pleistocene, the chain began to grow, shaping the emerged mountain area of today, as a consequence of mantle wedging and crust rollback processes [Picotti and Pazzaglia 2008]. In the foredeep, the marine environment developed up to the beginning of the Middle Pleistocene, then it turned towards low marine to transitional conditions (Marine Quaternary Emilia-Romagna Subsyntheme), which finally (last major regional unconformity) became mainly continental during the Upper Pleistocene to Holocene (lower [AEI] and upper [AES] Emilia-Romagna synthemes). The minor unconformity separating the AEI and AES dates back to about 450 kyr BP [Boccaletti et al. 2010]. The continuous tectonic development of

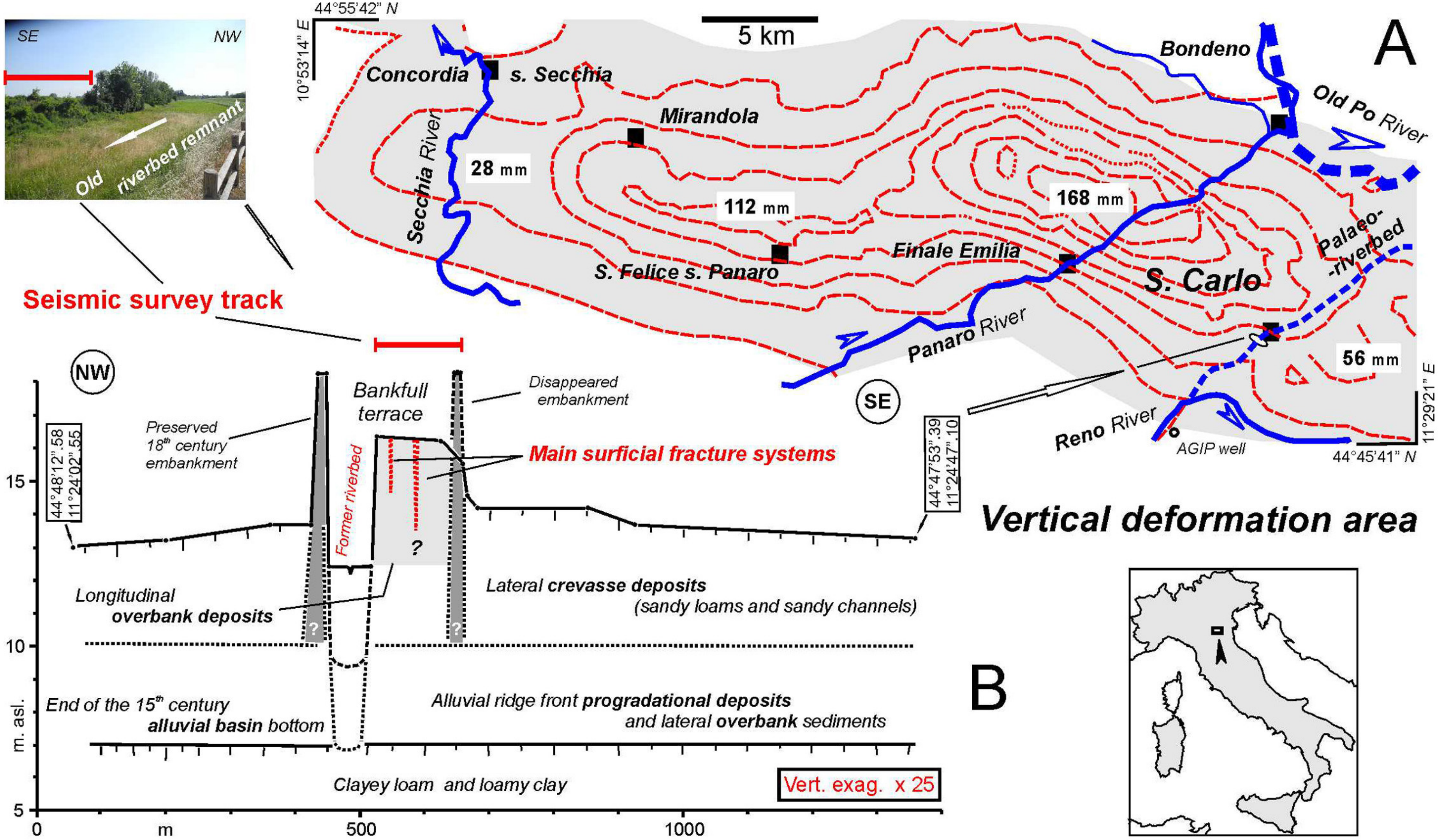

Figure 1. (A) Outline of the epicentral area. The gray shade highlights the real vertical deformation area. The shape contouring of the interferometric fringes (+28 mm each) [after Galli et al. 2012] is also shown: the related vertical displacement (in mm) is shown in the white labels. The main river courses and the most geomorphologically prominent palaeo-riverbeds are shown as well as the locations of the seismic survey and of the AGIP well *Pieve di Cento 1*. (B) Topographical section detail with the location of the surveyed seismic profile and related stratigraphic outline.

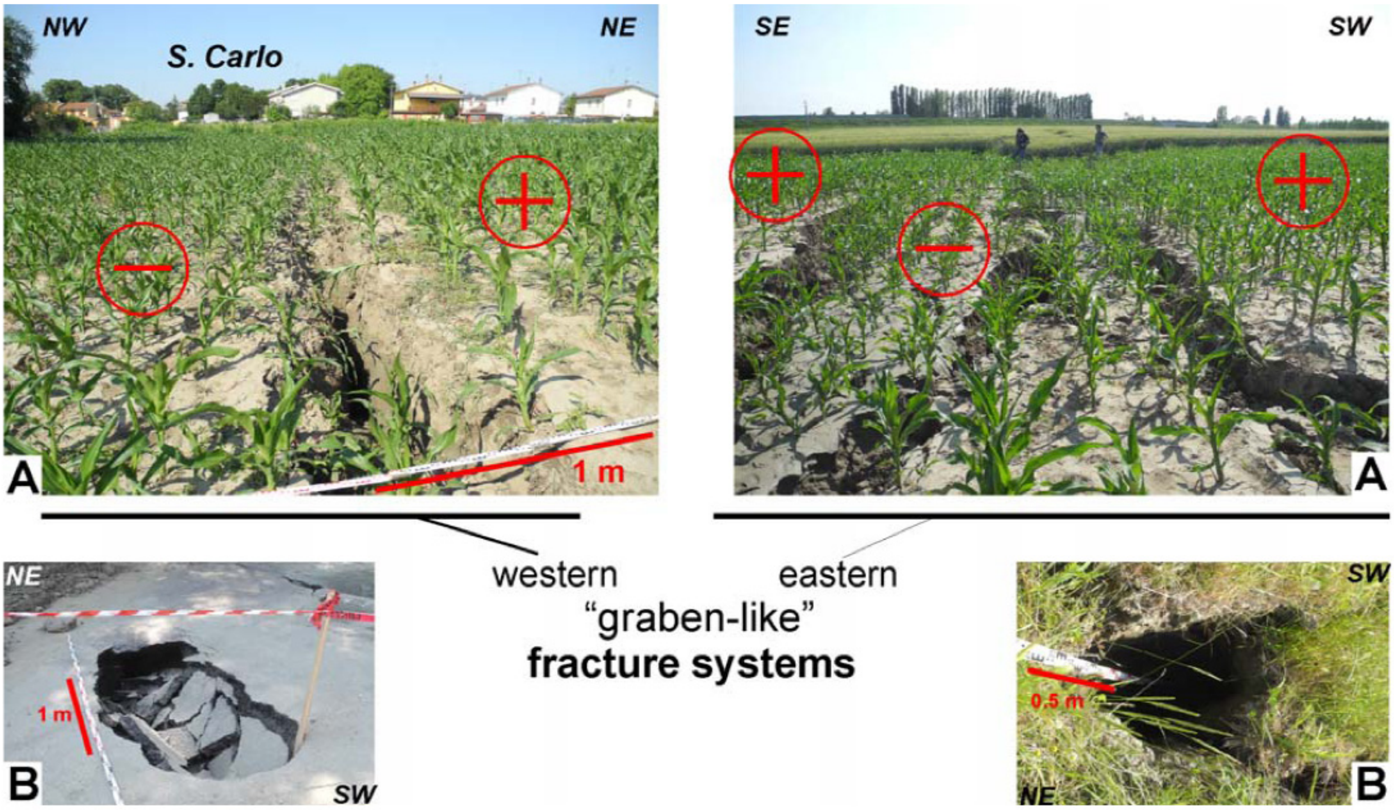

Figure 2. The graben-like surficial fracturing (A) at the San Carlo site, with small-scale sinkholes (B) at its tip. The location is the same as the surveyed seismic profile (see Figure 1).

the buried thrusts (*Dorsale Ferrarese* and *Pieghe Romagnole*) along its long axis (over a distance of 200 km) varies from place to place, in the time and depth domains, and deformed the Emilia-Romagna syntheme locally, affecting also the AES. The arc sector of the buried front involved in the May 2012 seismic sequence (almost 50 km long) is located in a central-western reach of the chain front, where it becomes more complex, displaying a double alignment of folds. Although published data are not available for the San Carlo area, the lower limit of the AEI could lie at an equivalent depth of about 360 m [ISPRA and R.ER 2009, sheet 2: profile F].

A medium depth stratigraphic outline for this area (Figure 3) can be obtained by the benchmark borehole *Pieve di Cento 1* that is located 6 km SW of San Carlo (Figures 1A, 3). It shows the top of the Pliocene deposit at about 315 m in depth [ENI 1972], whereas the overlying Pleistocene deposits can only be detailed according to an equivalent stratigraphic section [ISPRA and R.ER 2009, sheet 2: profile F]. Bearing in mind that the well lies near the top of an anticline structure after the projection of the San Carlo location, we can obtain the following stratigraphic outline (Figure 3). If the average ground elevation is kept as a reference, the thickness of the Holocene deposit (AES_8) can be estimated as in the order of 22 m to 25 m. The so-called AES_7 deposits of the last glacial age (clays and rare channel sediments) reach to about 80 m in depth. Between 80 m and 120 m, the interglacial (Riss-Wuerm) Po River channel sands and basinal fines (AES_6) are recorded. There are fluvio-deltaic or shelf Po River sands (AES undif) down to 216 m to 220 m, and finally pro-delta and shelf clays and loams (lower AE) reach to 320 m in depth, where the saltwater/freshwater boundary probably lies. At that depth, the base of the entire sequence is already gently folded [ISPRA and R.ER 2009, sheet 2] according to the general folding of the multiple and complex structural high that characterizes the outermost edge of the buried Apennine chain front [CNR 1992, Cerrina Feroni et al. 2002].

The geomorphological setting is characterised by fluvial activity and historical paleo-riverbeds. In particular, San Carlo village lies atop the bankfull terrace (18 m a.s.l.) of a paleo-bed of the Reno River that dates back to the Late Middle Ages (1460-1461). The river began to abandon this bed sector in the year 1738 (*Annegati* crevasse), and definitely ceased around the year 1751 (*Panfilia* crevasse) [Cremonini and Scarin 2007]. Because of this recent and sudden avulsion, the old riverbed is still well preserved and open (12.5 m a.s.l.); the external field ground lies at 13.3 m a.s.l. whereas the lateral bank is about 4 m higher (16.4 m a.s.l.) (Figure 1B). Due to the artificially controlled river progradation into the Late Medieval clayey alluvial basin, a local sedimentary sequence can be recognized, showing about 3 m of clayey loam and sand of the progradational front of the alluvial ridge. A further 3 m of lateral crevasse or incipient riverbed sands up to the field ground are finally covered by about 4 m of overbank deposits constrained by the old longitudinal embankment system. The sand belonging to the channel *facies* has a thickness of about 6 m [Cremonini 1981].

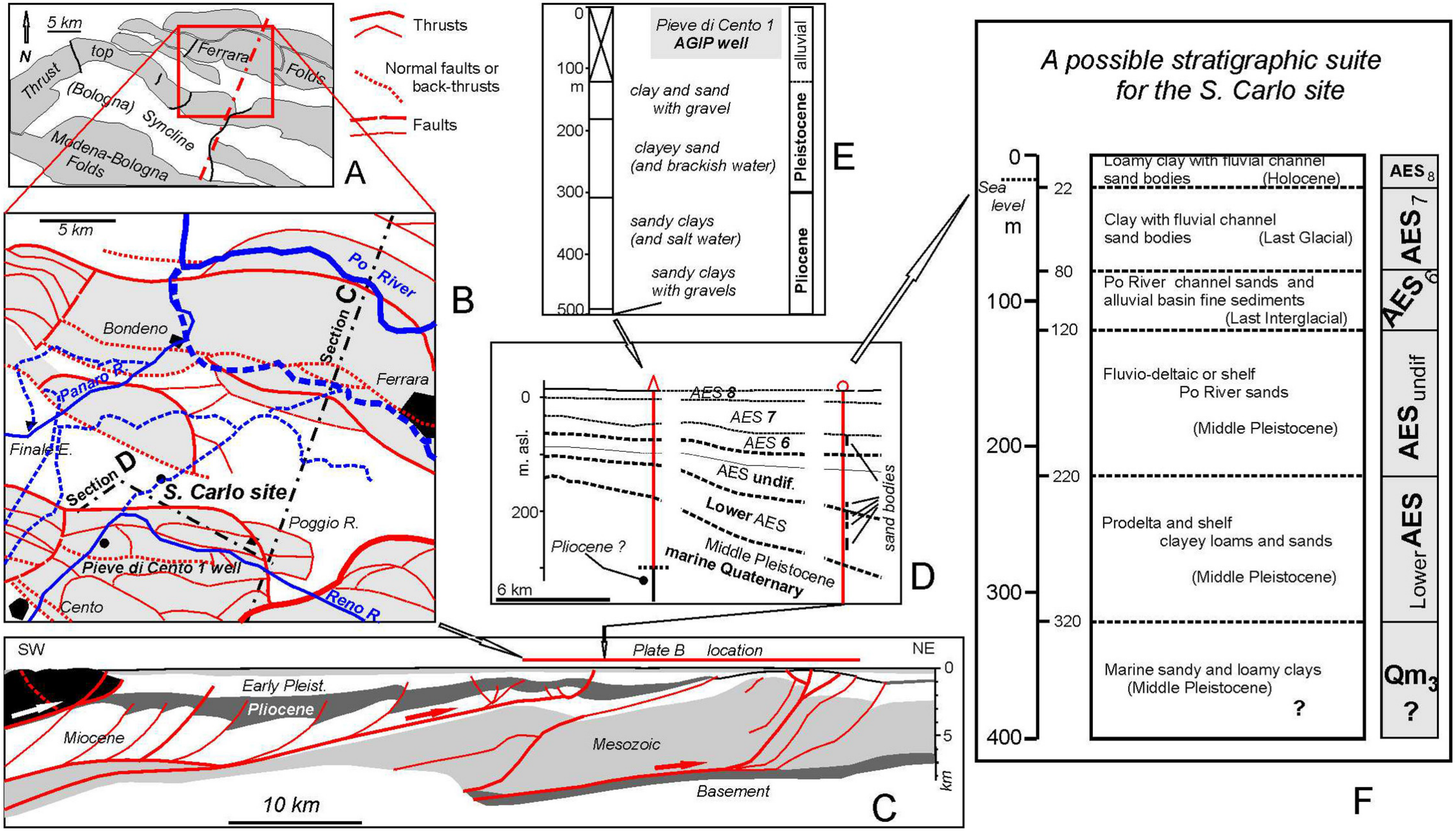

Figure 3. Geological outline of the San Carlo area. (A) Simplified sketch of the Apennine buried front [redrawn after CNR 1990]. (B) A detail of (A), with the location of sections C and D. The river and paleoriver courses are also shown (blue). (C) Geophysical section outline 7 km from the San Carlo site [redrawn after Boccaletti et al. 2010]. (D) A speculative, more suitable stratigraphical section for the San Carlo area [redrawn after ISPRA and RER 2009]. (E) AGIP well *Pieve di Cento 1* [1954] stratigraphy [redrawn after ENI 1972]. (F) A possible stratigraphic outline for the surveyed San Carlo area, derived from (D).

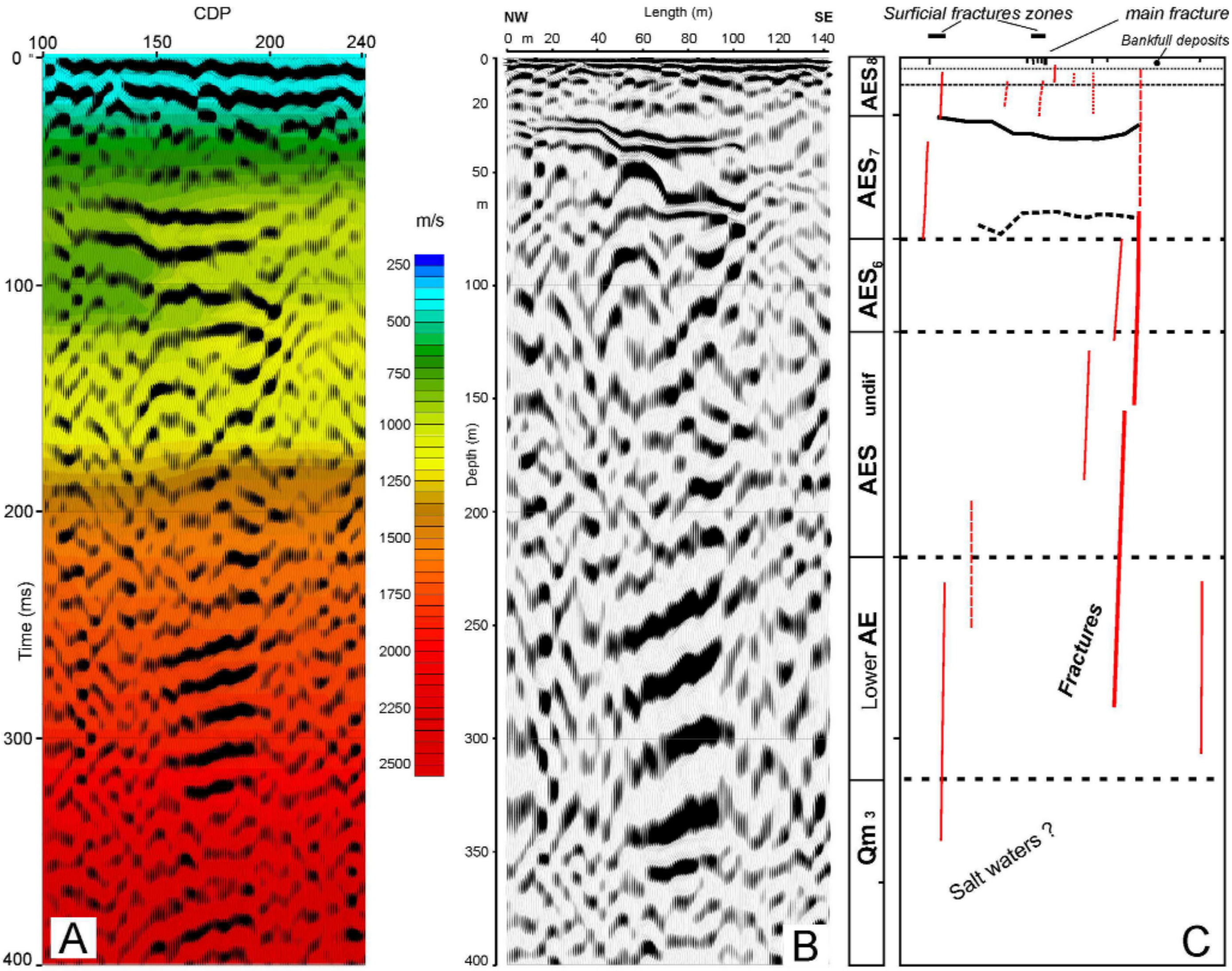

Figure 4. The surveyed seismic section. The velocity field (A): the stack section and the time/depth converted section (B) are shown. Sketch (C) suggests the possible interpretation of (B), mainly in terms of main faults/fractures. On the left of (C), the labels of the essential stratigraphy (see text) are recorded.

As a consequence of the ground shaking caused by the first mainshock (M 5.9, May 20, 2012), at the top of the right old river bank a parallel-coupled small graben-like system of fractures developed, with each 'graben' being about 3 m to 5 m in size, with the inner limb lowered by about 50 cm to 60 cm, with the border fractures up to 2.7 m deep and 0.5 m wide. Sporadic sinkholes were generated at the tip of some of the fractures (Figure 2). These are the only sinkholes known to have developed in the epicentral area.

3. Methods

A reflection seismic survey was performed as a transect crossing the wide right-hand terraced bank of the ancient river course, at an almost constant elevation of 16.4 m a.s.l. (Figure 1). The seismic line length was 142 m. Seventy-two geophones were used, with 2-m spacing. The chosen array was 1 geophone/channel, with frequency 10 Hz. The energy source was an 8 kg sledge-hammer impacting on a nylon plate, to reduce the effect of air blast noise. To complete a record, at least 3 blows were used for each shot point. The shot point location was at every geophone location, starting from geophone 1 through to geophone 72, thus resulting in a coverage of 3600% in the centre of the section. A 72 CHS Geometrics Geode recording instrument with 64,000 samples/channel was used, adopting a record length of 0.5 s. The sample interval was 0.125 ms, with filters out. The Moscow State University RadExPro QC configuration [MSU 2011] was adopted as the processing software, which involved the main subsequent processing steps of: data input, geometry assignment, amplitude corrections, deconvolution, trace interpolation, filtering, velocity analysis (using the 'interactive analysis of stacking velocities' option), NMO correction, CDP stacking, time-depth conversion, and F-K migration, which really improved the seismic imaging.

4. Results

Figure 4 shows the velocity field and the migrated section. No scale exaggeration is used. The horizontal resolution was 1 m (half way between the shot point and the geophones), whereas the vertical resolution varied from 1 m

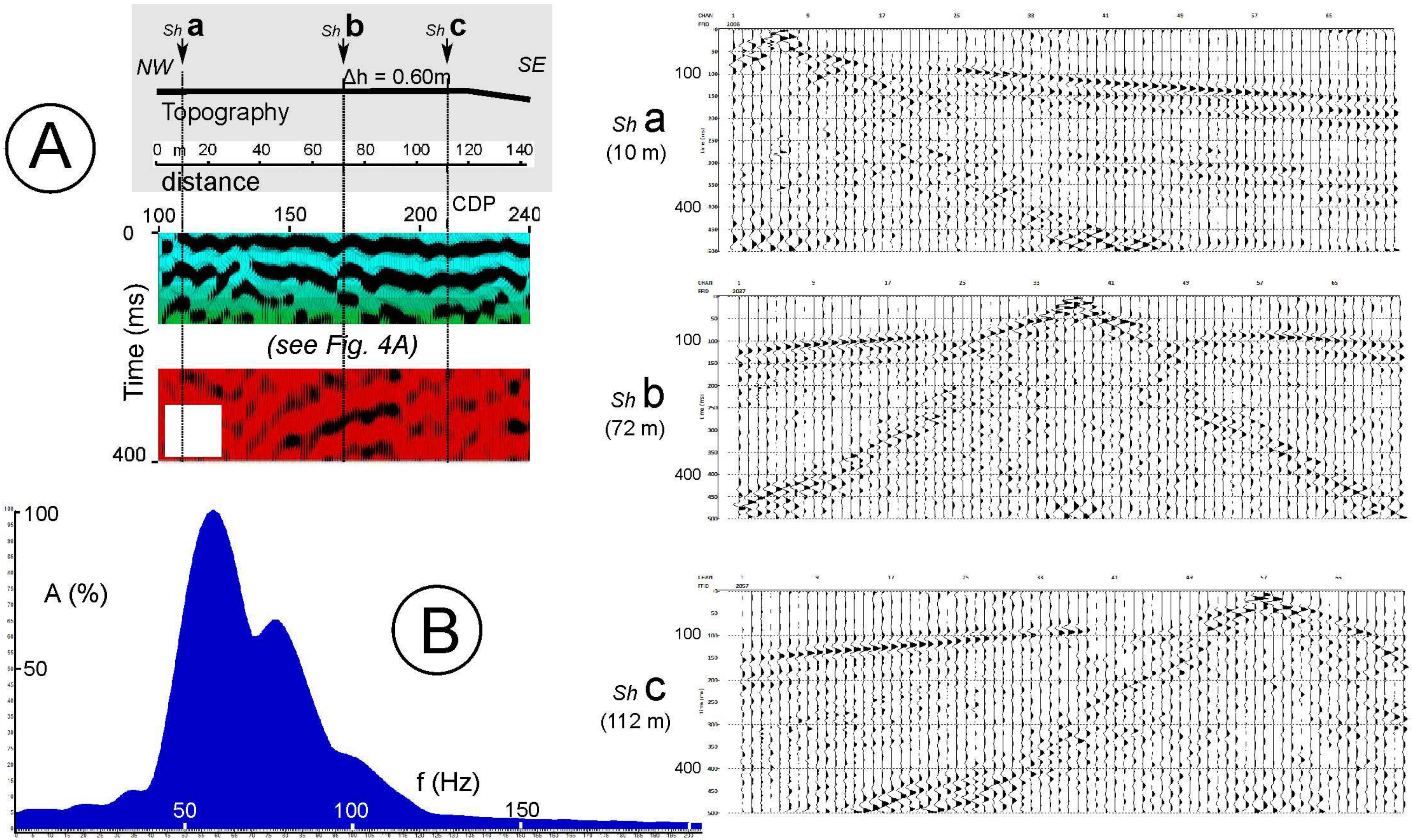

Figure 5. A representative shot gather (A) for the surveyed seismic section and related frequency spectrum of the seismic wave reflection (B).

to 8 m, depending on the reflected signal frequency content and velocity (according to the equation: Resolution = V/4f). Most of the reflectors are sharp. Figure 5 shows a shot gather and the frequency spectrum of the seismic waves reflection, to better check the signal quality. A signal attenuation appears at around 110 m to 130 m horizontal distance. The unusual aspect ratio of the section and its resolution can generate some difficulties in the interpretation of the general pattern, which might be expected to show mainly a nearly horizontal bedding. The general pattern is instead extremely complex. The uppermost part (Holocene) is clearly disturbed by a series of almost vertical disruptions, apparently involving the whole thickness of the unit. The first two reflectors are the equivalent of the bankfull terrace deposits. Even if the vertical resolution is not yet adequate, in this part of the section the disturbances are clear and there appears to be a good fit between them and the surficial fractures. The Late Pleistocene–Holocene stratigraphic boundary is marked by two coupled reflectors lying at 25 m to 30 m (i.e., 21 m to 26 m below the mean ground level), and lowered in the central part by ca. 6 m to 7 m. A second, irregular couplet lies at 60 m to 70 m, which probably represents the AES6/AES7 boundary [ISPRA and R.ER. 2009]. At depth, the reflector convolutions are partly due to a series of subvertical discontinuity planes (fractures or faults, often characterized by clear vertical displacement), such as the one lying at 100 m to 105 m towards the East. A suggestion leading towards a pockmark morphology is exerted by some recurrent V-shaped forms, such as that at 40 m E, although these are probably just artefacts arising from a local scattering phenomena, instead of diffractions, which usually characterise faults in rocky environments.

5. Discussion

Within the framework of the Emilia geological and hydrogeological setting [Pellegrini et al. 1976, ISPRA and R.ER 2009], previous studies have shown an anomalous concentration of NaCl in soils in the area affected by the seismic sequence [Puppini et al. 1955, Calzolari and Ungaro 2011]. Martinelli et al. [1998, and references therein] and Conti et al. [2000] described the occurrence of brackish groundwater in the same area, possibly attributable to deeper geological units. Scicli [1972], Martinelli [2007], and Martinelli et al. [2012] also discuss the origins of the deep fluid emissions in this area. Cassano et al. [1986] reported that there are faults in Miocenic and pre-Miocenic layers of the Po Valley that can cross, in principle, Quaternary deposits [see also Castellarin et al. 2006, Cremonini 2010a, Cremonini 2010b, Cremonini et al. 2010, and references therein]. Thus, geophysical surveys should reveal the eventual fault structures involved in the tectonic pumping phenomena [e.g., Sibson, 1981] of deeper Mio-Pliocenic sediments, and be able to induce geochemical anomalies in groundwater hosted in the Quaternary sediments and saline soil anomalies recorded by Puppini et al. [1955] and Calzolari and Ungaro [2011]. Data obtained in the San Carlo seismic survey show the possible faulting/fracturing at least in the interval from 0 m to 400 m in depth. No seismic profiles that were obtained during oil prospecting are available in this area to date, and thus caution should be taken in the data interpretation. In particular, the observed geometric features might be tectonically originated or due to gas and water uprising, as well as to gravitative phenomena. Indeed, some of the most surficial features might be related to liquefaction-induced lateral spreading [Obermeier et al. 2001]. This is defined as the finite, lateral displacement of gently sloping ground (mild slopes of 0.3% to 5% underlain by loose sands and a shallow water table; see Bartlett and Youd [1992]), as a result of pore pressure build-up or liquefaction in a shallow underlying deposit during an earthquake. On this issue, it is still unclear why the local response to the seismic shaking was so strong 20 km from the May 20, 2012, epicenter; at the same time, along many other riverbeds and paleo-riverbeds that cross the epicentral area (the Secchia, Panaro and Reno rivers), the recorded surficial effects were not so striking.

The whole compressive setting of the buried Apennine outer arc that is highlighted by the Emilia seismic sequence [Galli et al. 2012] shows the triggering of both longitudinal and transverse structural elements of minor order all along the buried arc, which are partly still not documented in detail [INGV 2012c]. The eastern wing of the epicentral area where San Carlo also lies is constituted by two relative structural highs, with an interposed small syncline (Figure 3). If the Ramsey stress model is adopted [Ramsey 1967, Carminati et al. 2010], a series of longitudinal fractures develop along the top of the thrust folds in the uppermost hundreds of meters, and contemporary tension structures can appear along the syncline axis. Thus, the medium depth fractures found at San Carlo might be extradossal structures. Furthermore, the observed fractures (Figure 4C) might also be related to a possible transverse shear zone. Indeed, the interferometric survey [Galli et al. 2012, Bignami et al. 2012, Salvi et al. 2012] shows a 1-km-wide, sharp-cut band (evidence of coherence loosening) in the eastern wing of the uplifted epicentral area, almost following the path of the old Reno riverbed, particularly near San Carlo. This separates (Figure 1A) a western area that is characterized by a higher vertical displacement rate (168 mm), from an eastern area that has a lower rate (56 mm). An alternative model might be to link the existence of the medium depth fault to sediment compaction, which is still ongoing along the thrust sides [Carminati et al. 2010]. Ultimately, the possible existence of faulting phenomena that can cross Quaternary layers should be considered.

6. Conclusions

The analysis of the seismic survey performed at the San Carlo site shows that the whole local sedimentary column is cut by a set of faults/fractures. The observed medium-depth geometric features might have had a role in the development of surface fracturing that occurred in the surveyed area after the May 20, 2012, event. In the near future, only a few geological pieces of evidence of coseismic surface phenomena will be preserved, and the San Carlo fracture system should be better investigated, to understand whether it should be considered as a mere site-effect due to the 4-m-high river bank surficial morphology, or whether other possible conditioning factors might exist.

Acknowledgements. Our thanks go to Geoexploration Srl (namely Giuseppe Mainardi and Diego Peraccini), for cooperation in the field survey and the data processing. Thanks are also due to anonymous reviewers for their thoughtful suggestions, which contributed to the improving of the overall quality of our manuscript.

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