Available online http:/amq.aiqua.it
ISSN (print): 2279-7327, ISSN (online): 2279-7335

Alpine and Mediterranean Quaternary, 25 (2), 2012, 105-123

MAY 2012 EMILIA EARTHQUAKES (MW 6, NORTHERN ITALY): MACROSEISMIC EFFECTS DISTRIBUTION AND SEISMOTECTONIC IMPLICATIONS

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ABSTRACT: We have carried out the macroseismic survey of both the May 20 (Mw 6.1) and May 29 (Mw 6.0) earthquakes in Emilia (Po Plain, northern Italy) by applying the Mercalli-Cancani-Sieberg scale, on 190 localities, mainly spread south of the Po River. Our data account for an Io 7 MCS evaluated for both earthquakes, with an Imax 7-8 assigned to the village of Rovereto after the mainshock of May 29. Damages were mainly focused on the historical buildings of the region, such as churches, castles, and towers, beside on the industrial warehouses, the collapse of which caused most of the victims of the two mainshocks. Churches and bell-towers were hit also in villages located far from the mesoseismic area, resulting often the only buildings affected by the earthquake. The seismic shaking induced also hundred of liquefaction phenomena that, in some places, have increased the damage level to buildings. By comparing macroseismic and instrumental data (i.e., hypocentres distribution, focal mechanisms, interferograms), to the deep geological structures of the region, it emerges that the May 20 mainshock was caused by a segment of the outer Ferrara thrusts front, whereas the May 29 mainshock by the Mirandola thrust. As these thrusts have been seismically silent in the past millennium, the current sequence fills partially a seismic gap along the seismogenetic structures of the buried outer Apenninic front.

Keywords: Macroseismic survey, 2012 Emilia earthquake, Po Plain, Buried thrusts, Active tectonics.

1. INTRODUCTION

At dawn of May 20, 2012, a moderate earthquake (Mw 6.1; QRCMT, 2012) hit a wide area of the eastern Po Plain, awakening most of the inhabitants of northern Italy. The mainshock was preceded in the night by a Mw 4.3 foreshock and it has been followed by dozens aftershocks with Ml>4 and at least 12 with Ml$\geq$4.5 (Tab. 1). In the morning of May 29, a second mainshock (Mw 6.0; QRCMT, 2012) struck roughly the same villages, causing, if possible, more panic in the population, scaring and awakening people from Florence and Pisa in the Apennines, to Venice and Milan in northern Italy. Unfortunately, due to this event, the death toll rose from 9 to 27, with most of the victims caused by the collapse of the industrial warehouses, as it was already happened during the first shock. Earthquakes are an unexpected event in this region, as testified by the lack of local epicentres in the seismic catalogues and by the consequent low level of the seismic classification (seismic zone 3: 10% probability of exceeding ag $\leq$0.15 in 50 years; ag, maximum horizontal acceleration; DPC, 2012).

Apart from the warehouses and hundreds of old, crumbling farmsteads spread all over the open country, the heavy damages focused on historical buildings, such as churches, bell-towers, castles, towers and palaces that were severely hit also in villages located very far from the epicentre, outside the mesoseismic area (i.e., 6 MCS). On the other hand, residential buildings suffered only light and/or moderate damage, apart from some exceptional cases.

The mesoseismic area is roughly WNW-ESE elongated, reflecting the geometry, kinematics and rupture dynamics of the seismogenetic structure, which is supposed to be a complex structural envelope of buried, ~N-verging, "Apenninic" thrusts, as testified by all the focal mechanisms of the sequence (QRCMT, 2012), and by the available oil-exploration seismic profiles (Pieri and Groppi, 1981; Cassano et al., 1986). Both mainshocks have been accompanied by an impressive amount of liquefaction phenomena (i.e., sand blows, sand volcanoes, surface breaks and lateral spread) which, in some case, caused also severe damage to buildings, pipelines and roads.

In order to provide the Civil Protection Department of Italy (DPC) with an expeditious, scientific and homogeneous pattern of the damaged localities, the macroseismic survey started few hours after the May 20 mainshock, proceeding continuatively until June 15. As in all the previous Italian earthquakes, it has been carried out by using the Mercalli-Cancani-Sieberg scale (MCS; Sieberg, 1930) accordingly to the methodology proposed by Molin (2003; 2009). We succeeded in visiting 52 localities affected by the May 20 mainshock before the second event of May 29, with a total of 190 visited by the end of the survey, and dozens villages visited two-three times, because of the progressive growth of damage during the sequence.

In this paper we present the results of this survey, together with the intensity datapoints distribution of both the May 20 mainshock and the cumulated distribution of May 20 and 29 earthquakes, hypothesizing also their

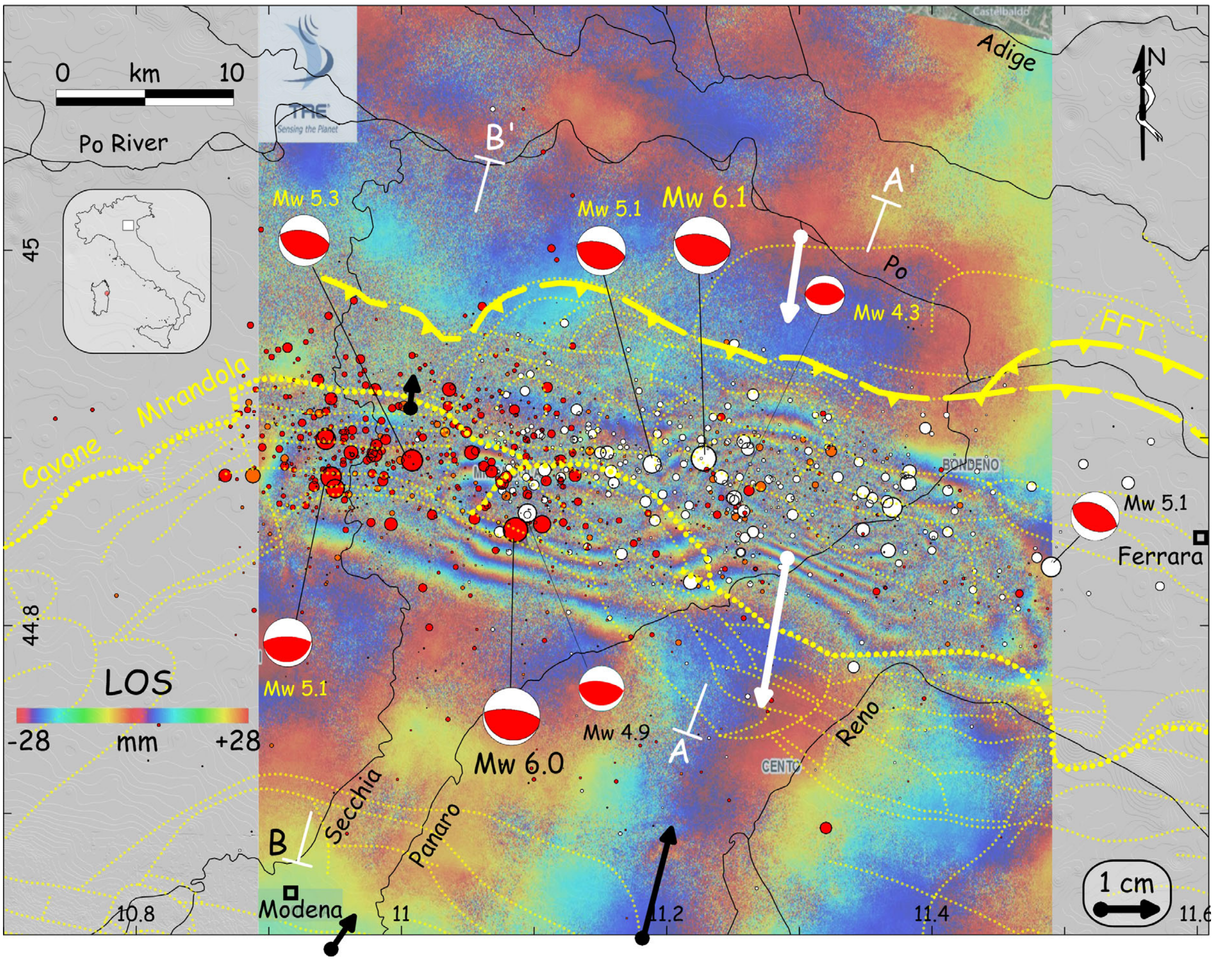

Fig. 1 - Structural map of the area affected by the 2012 seismic sequence (yellow dotted lines, buried thrusts, from Bigi et al., 1992; dashed line, front of Ferrara thrusts: FFT. Bold dots, front of Cavone-Mirandola thrusts. Circles, 2012 earthquakes, proportional to Ml>2.0. White, 19-28 May sequence; red, 29 May-5 June sequence; orange, up to July 5. ISIDe, 2012). Focal mechanisms from QRCMT (2012) and TDMT (2012). Black and white arrows are GPS horizontal coseismic offsets measured after the May 20 event, accounting for ~4 cm of shortening between Sermide (northernmost arrow) and San Giovanni in Persiceto (southernmost arrow; Anderlini et al., 2012). In background the differential interferogram elaborated by TRE (2012) from descending Radarsat satellite data (see line of sight color-scale: LOS. May 12-June 6), which magnificently shows the two “anticlines” grown on May 20 (~14 cm) and 29 (~11 cm), respectively. Sections A-A’ and B-B’ are in Figs. 2-3, respectively.

gg/mm/yr	h GMT	Lat-N	Long-E	depth km	Ml CNT	Mw RCMT	Io
20/05/2012	02.03.52.0	44.889	11.228	6.3	5.9	6.11	7
20/05/2012	02.06.30.0	44.886	11.189	7.7	4.8	-	-
20/05/2012	02.07.31.0	44.863	11.370	5	5.1	-	-
20/05/2012	03.02.50.0	44.860	11.095	10	4.9	5.05	-
20/05/2012	13:18:02.0	44.831	11.490	4.7	5.1	5.18	-
20/05/2012	17:37:14.0	44.876	11.382	3.2	4.5	4.52	-
29/05/2012	07.00.03.0	44.851	11.086	10.2	5.8	5.96	7
29/05/2012	08:25:51.0	44.901	10.943	3.2	4.5	4.69	-
29/05/2012	08:27:23.0	44.854	11.106	10	4.7	-	-
29/05/2012	10:55:57.0	44.888	11.008	6.8	5.3	5.53	-
29/05/2012	11:00:02.0	44.873	10.950	11	4.9	-	-
29/05/2012	11:00:25.0	44.879	10.947	5.4	5.2	-	-
03/06/2012	19:20:43.0	44.899	10.943	9.2	5.1	4.89	-

Tab. 1 - Events with Ml ≥ 4.5 recorded between May 20 and June 15 within the epicentral area of the Emilia earthquake of May 2012 (ISIDe, 2012). The last column provides the epicentral intensity (MCS) assigned to the two mainshocks in this paper.

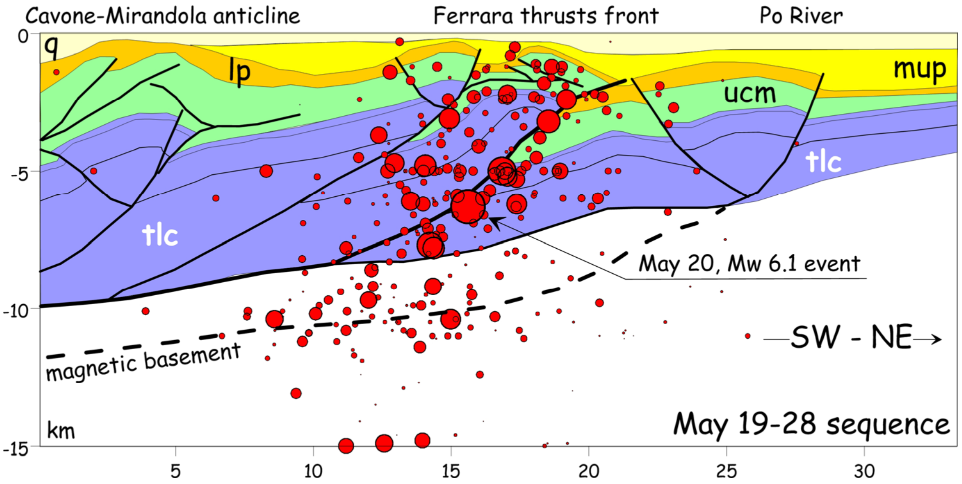

Fig. 2 - Geological cross section across the Cavone-Mirandola and outer Ferrara folds and thrusts front (modified from Carminati et al., 2010), showing the hypocentral distribution of the May 19-28 seismic sequence (events within 10 km from the section trace A-A' in Fig. 1. ISIDe, 2012). The Mw 6.1 mainshock and the successive sequence lay entirely at depth along the Ferrara thrust front. q, Quaternary; mup, Middle-Upper Pliocene; lp, Lower Pliocene; ucm, Upper Cretaceous-Miocene; tlc, Triassic-Lower Cretaceous.

possible seismotectonic framework. Moreover, we provide a brief description of the liquefaction phenomena and of their areal occurrence.

2. SEISMOTECTONIC FRAMEWORK OF THE MAY 2012 SEQUENCE

The villages struck by the May earthquakes are all founded in the Holocene-historical alluvial plain deposits of the Po River and of its dextral tributaries, mainly the Secchia, Panaro and Reno rivers, at elevation ranging 10-30 m a.s.l. In this part of the Plain, the soft post-Roman deposits (4th-6th cent. AD to Present) have a thickness ranging 5-10 m, depending from the presence of fluvial ridges or paleo-riverbeds, whereas the post Last Glacial Maximum-Holocene fluvial deposits reaches generally 20 m ("Subsintema di Ravenna", post 15-17 kyr BP calibrated age; CGI, 2009).

Since the Fifties, ENI-AGIP hydrocarbon exploration led to the discovery of a buried, imbricated fold and thrust system up to 40 km north of the outcropping Apenninic frontal margin (Pieri and Groppi, 1981), below the Quaternary deposits of the Po Valley) (see dotted and dashed yellow lines in Fig. 1). The thrust belt has developed during Neogene-Quaternary in the hangingwall of a westward subduction zone (Spakman, 1990), the eastward hinge-retreat of which probably caused the foreland flexure, and the consequent progressive thrusts front migration toward the eastward-moving foredeep basins (Patacca et al., 1990). In the investigated area, the buried Apenninic chain front matches with the Emilian and Ferrara Folds and Thrusts, which are generally sealed by thick Pleistocene-Holocene flat layers (Figs. 2-3).

According to Castellarin (2001, and reference

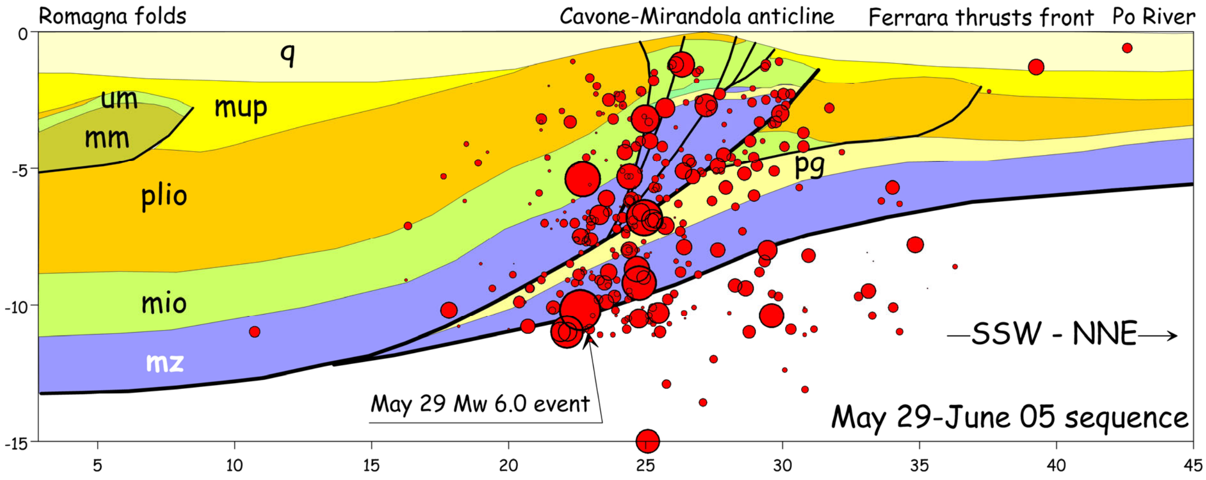

Fig. 3 - Geological cross section across the Cavone-Mirandola and outer Ferrara folds and thrusts front (modified from Pieri and Groppi, 1981), showing the hypocentral distribution of the May 29-June 05 seismic sequence (events within 10 km away from the section trace B-B' in Fig. 1. ISIDe, 2012). The Mw 6.0 mainshock and the successive sequence lay, in this case, along the Mirandola anticline frontal thrust and/or over the sole thrust. q, Quaternary; mup, Middle-Upper Pliocene; plio, Pliocene; um, Upper Miocene; mm, Middle Miocene; mio, Miocene; mz, Mesozoic.

therein), the structural growing at the front of both the buried thrusts and of the outcropping chain ceased with the Pleistocene, i.e. it was certainly active during the Late Pliocene-Early Pleistocene, with some structures growing also in middle to late Pleistocene times (e.g., Mirandola anticline; Scrocca et al., 2007). Indeed, according to Pierdominici and Heidbach (2012), in the area struck by the May 2012 sequence the present-day stress data records exhibit a constant NNE–SSW compression regime. This is also evidenced by the geodetic velocity solutions obtained from the analyses of GPS data (Serpelloni et al., 2005), accounting for ~0.8 mm/yr crustal shortening oriented along the same direction.

The May 2012 earthquakes confirmed this tectonic framework, as both the mainshocks and all the major aftershocks have a reverse faulting focal mechanism, striking roughly WNW-ESE – i.e. paralleling the different thrust system of the area (Fig. 1) – and hypocentral depth within the upper 10 km of crust (Figs. 2-3). Shortening due to May 20 event has been evaluated by GPS data analyses (Anderlini et al., 2012) at ~4 cm along a NNW-SSE direction, between the villages of Sermide (to the north) and San Giovanni in Persiceto (to the south; see bold arrows in Fig. 1). Moreover, the differential descending interferogram obtained by TRE (2012, Radarsat satellite) for both mainshocks (interval May 12-June 6) vividly represents the snapshot of the coseismic growing anticlines at surface (Fig. 1). Here the May 20 anticline matches with the hangingwall of the outer Ferrara thrusts (Fig. 2; see white epicentres in Fig. 1), and it is crossed just in the middle by the Panaro River where, according to the number of visible fringes (each one of 2.8 cm), it reaches the maximum uplift of ~14 cm. On the other hand, the May 29 anticline fits with the hangingwall of the Mirandola thrust (Fig. 3. See red epicentres in Fig. 1), with an uplift of ~11 cm, as inferable by the number of fringes.

Really, according to Scrocca et al. (2007), the structural and stratigraphical setting of this thrust-related fold suggests a syn-sedimentary growth also during the Middle-Late Pleistocene, with a decreasing rate of tectonic uplift during the last 1.4 Ma from 0.53 mm/yr to 0.16 mm/yr in the Late Pleistocene, which could be taken as a conservative vertical slip rate also for the Present.

As far as the historical seismicity of this region is concerned, according to all the available seismic compilations the area has not been affected by events with epicentral intensity Io>6 MCS (Mercalli-Cancani-Sieberg; Sieberg, 1930). This can be easily seen from Figure 4 which reports the Io>6 epicentres contained in the Italian seismic catalogue CPTI11 (Rovida et al., 2011), all falling at the eastern and western boundaries of the region hit in 2012.

In detail, the strongest event occurred in the vicinity of the May 2012 epicentres (~35 km far away), and the only one relevant for the villages struck by the current sequence, is the Ferrara earthquake (November 17, 1570; Io 7-8 MCS, Mw 5.46). Its mesoseismic area

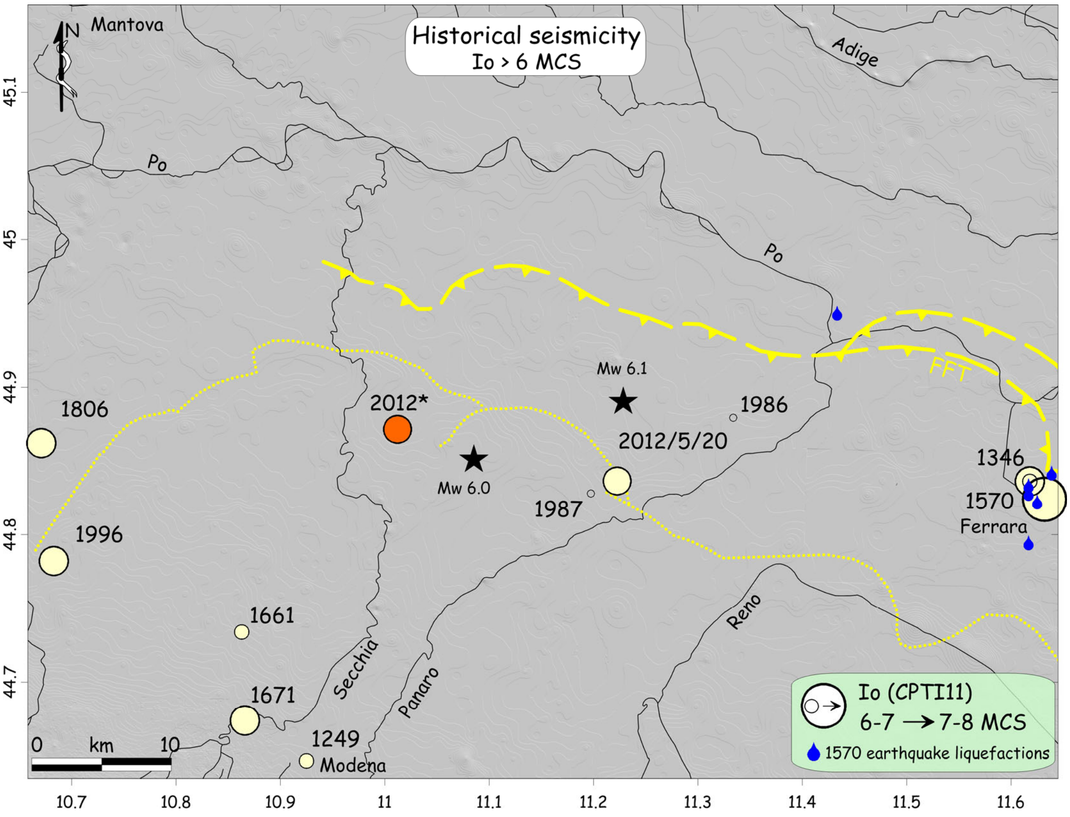

Fig. 4 - Distribution of the historical epicentres (CPTI11) within the area hit by the 2012 sequence (stars, instrumental epicentres of May 20 and 29; orange, macroseismic epicentre of the cumulated effects of May 20 and 29 events). Dotted and dashed yellow lines are the buried front of the Cavone-Mirandola and Ferrara folds and thrusts (see Fig. 1). 1570 earthquake-induced liquefactions are from Galli (2000). Note the absence of significant historical epicentres in the investigated area.

is NW-SE elongated (Postpischl, 1985), paralleling the local buried front of the Ferrara thrusts which are, in turn, the eastern prolongation of those activated in the current sequence. Also in this case, the sequence was characterized by more mainshocks, and it lasted at least until 1572. Among the localities hit by the 2012 events, the 1570-earthquake historical sources account for damages in Bondeno at the roof of the hospital and of the oratory; in Corpo Reno at the roof of Saint Antony church (in Marzola, 1976), while in Cento and Finale Emilia they report just the fall of some chimney (ASM, 1570a; 1570b), suggesting – in the whole – effects of 6 MCS (the Italian macroseismic database DBM11=Locati et al., 2011 reports 7 MCS to Bondeno, 6-7 MCS to Corpo Reno, and 6 MCS to Cento and Finale Emilia). Similarly to what happened in the 2012 events, also in the 1570 earthquake many liquefaction phenomena occurred in different localities, mainly surrounding Ferrara, and up to Ficarolo, on the left bank of the Po River (Galli, 2000; see Fig. 4).

Prior to 1570, a coeval chronicle (Giacomo da Marano, 14th cent.) suggests the existence of another strong earthquake in Ferrara in the year 1346 when, on February 22 "many houses fell down, palaces, towers… and, in the villages, tenements, barns… and other buildings". The event was felt also in Modena (even if Giovanni da Bazzano, 15th cent., records it on February 8) and likely in other places of the Po Plain. However, due to the scarcity of news, it is impossible to provide certain parameters or to associate it to a seismogenic structure. It could be really occurred everywhere around Ferrara and, for instance, also in the eastern part of the region hit in 2012.

DBMI11 reports also two minor earthquakes (Io 6 MCS) within the 2012 mesoseismic area. The first one occurred on December 6, 1986 (Mw 4.35), with effects of 6 MCS in Bondeno, Finale Emilia, Gavello and Scortichino; the second one on May 8, 1987 (Mw 4.56), with similar effects in Camposanto, Finale Emilia, Massa Finalese and San Felice sul Panaro. Taking into account their epicentral location (see Fig. 4), both could be related to the same seismogenetic structure of the 2012 events. It is worth noting that, due to the 1987 event, several fractures opened in the field of Rivara (San Felice sul Panaro), forming en-echelon linear settlements, 10-20 cm wide and 1-2 m deep which were not attributed to any liquefaction phenomena, but to mechanisms associated to sinkhole formation (Bianchi et al., 2008).

Finally, on October 15, 1996, at the western boundary of the investigated area, an earthquake with Mw 5.41 (CPTI11. Io 7 MCS: Massucci et al., 1996; De Canini et al., 1997) affected mainly Bagnolo in Piano and Correggio where severe damages were observed to few ancient buildings (i.e., the Torrazzo in Bagnolo and San Francesco church in Correggio), light cracks in many brick-masonry buildings, and also in two reinforced-concrete (r.c.) frame structure (i.e., cracks in the brick-infill of the pilotis), beside the fall of chimneys and tiles. At that time, the earthquake was associated to the rupture of the left-lateral ramp of the Cavone anticline (De Canini et al., 1997), i.e., the western prolongation of the Mirandola structure. Further north, in 1806 a similar earthquake caused damage in Correggio, and also in Brescello, Campagnolo Emilia, Novellara and Viadana (effects estimated as 7 MCS in ISMES, 1985), and also in other localities hit by the 2012 sequence, as Reggiolo and Carpi (6-7 MCS).

From all the above, we can conclude that at least in the past ~600 years (see the discussion of catalogue completeness in Stucchi and Albini, 2000), the epicentral area of the 2012 events:

1) has likely never generated earthquakes with energy similar to that associated to the 2012 sequence (i.e., Mw ≥ 5.8);
2) has likely never been affected by damage caused by external earthquakes, with the only exception of those related to the 1570 Ferrara event in the easternmost portion, and to the 1806 and 1996 events in the westernmost portion;
3) has been sometime affected by local, Mw ≤ 4.6 events, probably generated by the same 2012 seismogenetic structures.

Therefore, it is likely that the 2012 mainshocks is the real first, and somewhere the last, anti-seismic testing for all the historical buildings of the region.

3. THE MACROSEISMIC SURVEY

As aforementioned, the attribution of the site intensity (Is) has been achieved by applying the MCS macroseismic scale, that is the intensity scale of the whole Italian macroseismic database (DBMI11; ~86000 datapoints), and not the more recent European macroseismic scale (EMS; Grünthal, 1998). Indeed, as the MCS scale does not fully account for the vulnerability of each single building, it allows a more expeditious application during the survey, providing information directly correlated to the damage level, i.e. that of immediate interest to the civil protection purposes, both in terms of rescue planning and emergency management (Molin, 2009; Galli et al., 2009). In particular, we adopted the methodology proposed by Molin (2003; 2009), who differentiated five damage levels (1-5: light, moderate, severe, destruction, collapse), providing the percentages of damage level (5%, 25%, 50%, 75%, 100%) that are representative for each MCS degree (Fig. 5), as implicitly contained in the original scale (Sieberg, 1930).

Is MCS	Damage levels 1	2	3	4	5	percentages
5	[5]	-	-	-	-	
5-6	[25]	[5]				
6	[50]	[25]	[5]	-	-	
7	-	50	[25]	[5]	-	
8	-	-	50	25	5	
9	-	-	75	50	25	
10	-	-	-	75	50	
11	-	-	-	-	[75]	
12	-	-	-	-	[100]	

Tab. 2 - From left to right, damage progression (levels 1-5) to be adopted for an homogenous application of the MCS scale for Is ≥ 5 (from Molin, 2009).

For instance, the MCS 6 degree has to be assigned to those localities in which the ~50% of buildings presents level 1 damage, ~25% level 2, and where the 5% has bee affected by severe damage (level 3). Anal-

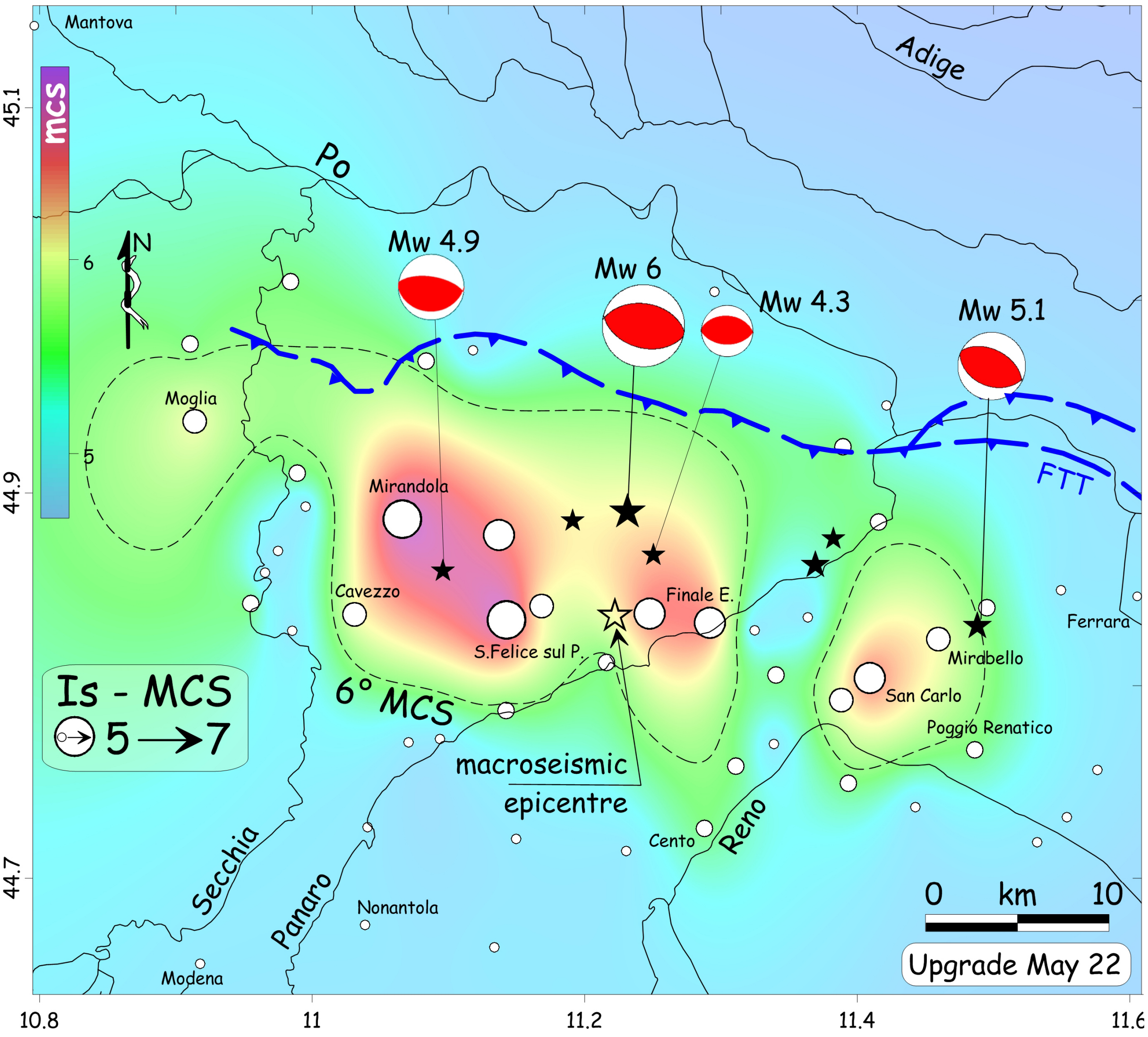

Fig. 5 - Intensity datapoint distribution of the May 20 mainshock (white circle, proportional to MCS degree). The background image roughly indicates the areal shaking in MCS terms. Dashed line is the interpolated 6 MCS isoseismal; dashed blue line is the buried front of Ferrara thrusts (see Fig. 1) to which the focal mechanisms are referred (TDMT, 2012 and QRCMT, 2012)°.

ogously, the 8 MCS degree is reached when a quarter of the buildings has been destroyed (level 4), including a ~5% of total collapse (level 5), whereas half of the village presents severe damage (level 3). This means that in a locality with 1000 building, 500 should be severely damaged, 250 of which destroyed and 50 collapsed.

3.1. May 20 earthquake survey

The macroseismic survey started in the morning of May 20 from the epicentral area, reaching in the days after localities farther and farther in the provinces of Modena, Ferrara and Mantua, for a total of 52 visited localities belonging to 30 municipalities. Even if necessary incomplete, the results of this first survey have allowed to define the area of the most severe effects (Is ≥ 6 MCS), which is WNW-ESE elongated west to the instrumental epicentre, in full agreement with the focal mechanism of the mainshock (Fig. 5).

In detail, the area was extended less than 25 km in this direction, matching entirely the hangingwall of the

date	time GMT	Coord. Strum		Depth	M_l CNT	Mw RCMT	Coord. Macro		Io (MCS)
		Lat	Long				Lat	Long	
20/05/2012	02:03:52.0	44.889	11.228	6.3	5.9	6.11	44.836	11.222	7
29/05/2012	07:00:03.0	44.851	11.086	10.2	5.8	5.96	44.877	11.004	7

Tab. 3 - Instrumental (left), and macroseismic (right) parameters of the two mainshocks of the Emilia 2012 sequence (INGV source, and this paper).

outer Ferrara thrusts front (FTT in Figs. 1, 5, and associated focal mechanisms), i.e. the seismogenetic structure responsible for this part of the sequence.

Outside this area, both to the west and to the east, we observed a raising of the intensities, respectively in the Moglia area and Sant'Agostino, San Carlo and Mirabello.

The maximum intensity (Imax) estimated for this event is 7 MCS, assigned to Mirandola and San Felice sul Panaro (Fig. 5), with Is 6-7 observed at Finale Emilia, Canaletto, Mortizzuolo and San Carlo, and Is ≤ 6 MCS assigned to all the other localities. The epicentral intensity evaluated also through the Boxer4 algorithm (Gasperini et al., 1999) is Io 7 MCS, while the equivalent moment magnitude resulted much more low (Mw 5.1) than the instrumental value (Mw 6.11). The epicentral coordinate derived by Boxer4 identify a point located ~5 km south of the instrumental epicentre (Figs. 4, 5). Earthquake parameters have been summarized in Tab. 3.

Most of the heavy damages, including total and partial collapses, affected tall, historical buildings, as churches (Fig. 6), bell-towers, towers, castles (Figs. 7-8), palaces, ancient farmhouses, beside many industrial warehouses in the outskirts of Mirandola and Sant'Agostino (Fig. 9).

The residential housing estates, both in brick-masonry (reinforced and not) and in r.c., generally suffered low grade damage (levels 1-2), with sparse severe damages (level 3) and very rare partial collapses (usually of the roof-ledges, roofs and loading dock of crumbling houses) and destructions (level 4), beside diffuse fall of chimneys, tiles and plaster, almost everywhere focused within the old downtown. This fact explains why this earthquake, although it has happened in the night, has caused a limited number of victims (9), almost all night-shift workers in the industrial warehouses. Severe damages in r.c. buildings have been observed in one case inside Mirandola and in other three in its northern outskirts (light crushing of pillars and cracks on the brick-curtain walls), as in some apartment houses in Cavezzo (Fig. 10).

Fig. 6 - View of the Mirandola Cathedral (15th century) in the morning of May 20. At that time, only few architectural elements at the top of the façade were fallen down, beside the incipient façade detachment. Inside, not visible, also part of the roof has fallen down. The church was damaged again, more seriously, by the May 29 mainshock.

Fig. 7 - Partial collapse of the Estense castle (15th century) in Finale Emilia (Is 6-7 MCS) in the morning of May 20.

In some cases, more than the seismic waves, damages have been induced by the huge liquefaction phenomena affecting the deposits below the buildings, with consequent loss of the bearing capacity, and differential settlement and/or tilting of the foundations. Liquefaction occurred extensively in the villages located over the paleo-beds of the main rivers, as in Sant'Agostino, San Carlo and Mirabello, all founded along the abandoned Reno fluvial-ridge. Here, besides the damages to buildings, the surficial breaks related to the liquefaction settlement processes affected also roads and pipelines. By looking at Figure 5, it emerges that the intensity bulge at the eastern side of the mesoseismic area is merely due to the effects of liquefaction on.

In the far, main cities of the Plain, we did not observe severe damage, not even affecting isolated buildings. In Mantua and Modena everybody has awakened getting into a panic, and rushing out in the streets; however, damages were limited to levels 1-2 to very few houses. Ferrara, in turn, experienced levels 1-2 to several old houses downtown, mostly related to pre-existing cracks. We have recorded the fall or rotation of a dozen

Fig. 8 - Finale Emilia (Is 6-7 MCS): collapse of the Medieval clock-tower, and of the Cathedral tympanum in the May 20 morning. The tower collapsed definitely during the seismic sequence.

Fig. 9 - Collapse of the Sant'Agostino's ceramics warehouse.

Fig. 10 - Left, Cavezzo (Is 6 MCS), May 22: level 3-4 damage along the joint of a r.c. building inside the old-center; this building collapsed entirely because of the mainshock of May 29. Right, Mirandola (Is 7 MCS), May 21: crushing of a pillar of a r.c. building in the old-centre.

hanging on the churches façades, beside the partial collapse of a small tower over the Estense Castle.

Actually, we had trouble in evaluating the site intensity in many localities, because of the extreme difference of damage level existing between recent residential housing (usually 1-2 storeys, reinforced brick-masonry villas) and the historical-monumental buildings. As mentioned before, while on one hand many churches, castles, bell-towers, towers and ancient palaces experienced severe damage (levels 3-4) or collapse (levels 4-5), on the other hand, private houses generally were not damaged at all, especially all those outside the small old town-centre. As in the 2009, Mw 6.3 L'Aquila earthquake (Galli et al., 2009), we have choose to take more into account the effects recorded by the buildings inside the villages old-centre (almost all in brick unreinforced masonry), and to exclude entirely damages to industrial warehouses. In doing this, we think that the assigned intensities can be roughly comparable to those of the historical earthquakes contained in the Italian seismic database (DBMI11).

3.2. May 29 earthquake survey

Soon after the second mainshock (Mw 5.96), we re-started the macroseismic survey, visiting again the villages hit by the May 20 event, and extending it during the days after up to 190 localities belonging to 87 municipalities. In the whole, our observations cover the area of six Provinces of Emilia Romagna, Lombardy and Veneto Regions, i.e. 52 of Modena, 32 of Ferrara, 22 of Bologna, 14 of Reggio Emilia, 53 of Mantua and 11 of Rovigo (Fig. 11).

Generally speaking, we have observed a growth of the effects in the western part of the area, with an increase of 1-2 MCS degrees in some villages; severe damage in Reggiolo (Is 6-7 MCS), Novi di Modena (Is 7 MCS), Concordia sulla Secchia (Is 7 MCS; with some partial collapse and severe damage to the porch-buildings; Fig. 12), Moglia (Is 7 MCS), and Rovereto (Is=Imax 7-8 MCS; maximum intensity assigned in this earthquake) where several partial collapses and heavy damages occurred both in the brick-masonry houses of the old-centre and in some recent reinforced-masonry and r.c. buildings (Figs. 13-15). In the other localities, generally west of Mirandola, the intensity increase has been < 1 MCS degree.

In Mirandola, the mainshock of May 29 and the successive strong aftershock of the same morning (Mw 5.3) caused the collapse of the 14th century Saint Francis church, which was only slightly damaged by the May 20 shock. Moreover, it caused further collapses of the Cathedral and several heavy damages and partial collapses to the ancient houses downtown, besides to some r.c. buildings, the same already struck on May 20. In Cavezzo also, the increasing damage level has yield an higher intensity (at least Is 7 MCS), mainly justified by the col-

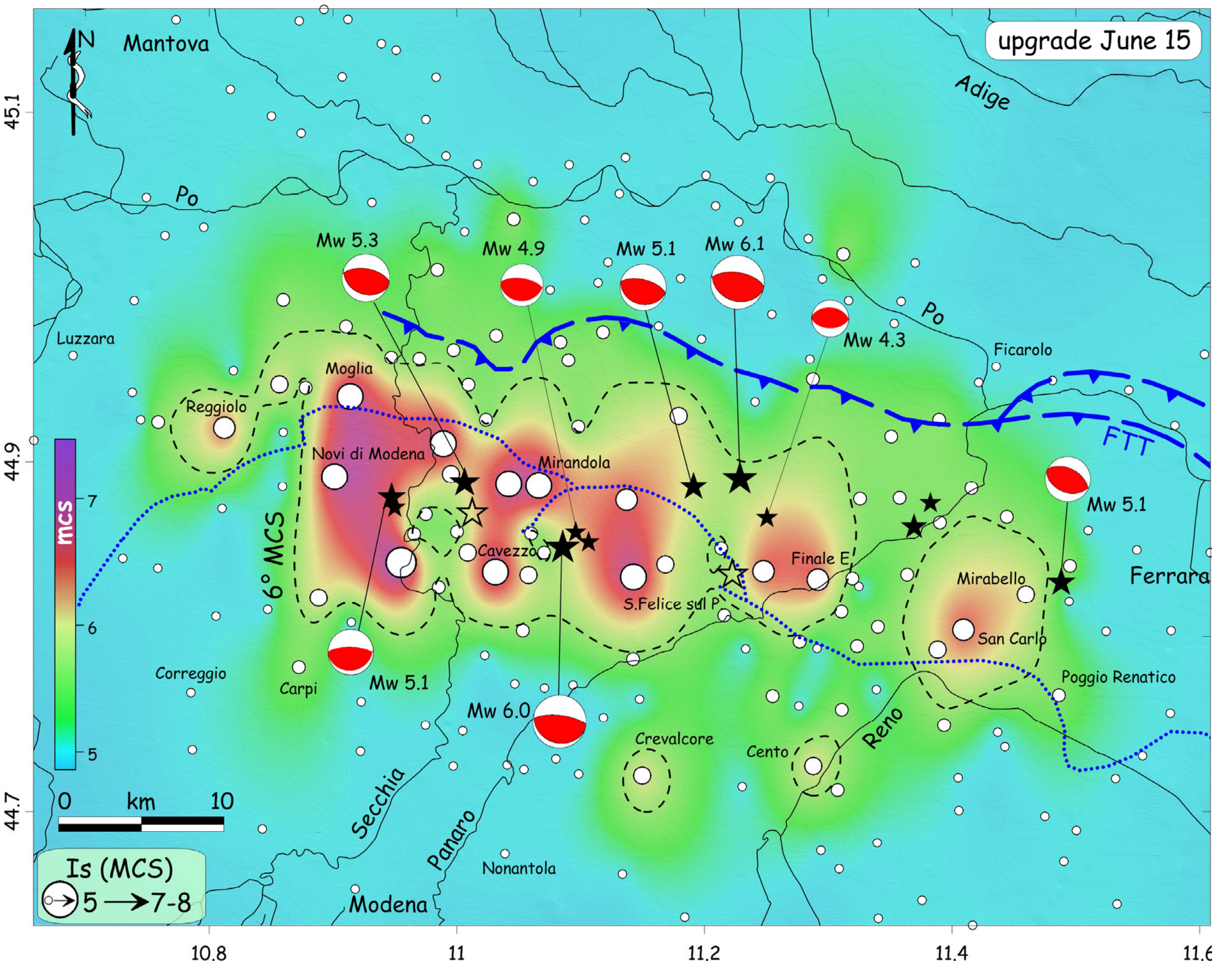

Fig. 11 - Intensity datapoints distribution of the whole 2012 sequence (June 15 updating; white circles, proportional to intensity). Also in this figure, the colour image in background suggests qualitatively the areal shaking in terms of MCS intensity. Black dashed line is the 6 MCS degree isoseismal as interpolated from the intensity data. Dashed and dotted blue lines are the Ferrara and Cavone-Mirandola thrust fronts, respectively, i.e. the structures responsible for the whole sequence. Black stars are the main events, with associated focal mechanisms (TDMT, 2012 and QRCMT, 2012). The two empty stars are the macroseismic epicentres of the May 20 (east) and of the cumulated May 20-29 mainshocks (west). Note the four intensity bulges located outside the mesoseismic area (Reggiolo, Crevalcore, Cento and San Carlo) which indicate as many possible local amplification areas.

lapse of the pilotis of three r.c. buildings and to the diffusion of level 3 damage to several brick-masonry houses in the old-centre.

Southward, outside the 6 MCS isoseismal (Fig.11), both Crevalcore and Cento suffered more effects within the old-centre which presents now diffuse level 2 damage at about a quarter of the buildings, with some heavy damage (level 3) and sparse partial collapse of underroof walls. In turn, the damage area substantially did not extended northward. Anyway, we have assigned Is 5-6 MCS to several localities near the Po River and, exceptionally, also north of it (Castelmassa). Heavy damage to isolated monumental structures (usually the churches or the bell-towers) have been observed in many villages to which we necessarily assigned Is 5 MCS. Indeed, these were the only buildings damaged by the seismic events that, instead, did not affect the remaining houses. However, the intensity datapoints listed in Table 4 keeps the memory of these effects in the column DJ, where labels A-B-C indicate heavy damage and/or collapse to buildings, towers/bell-towers and churches.

In the whole, the 6 MCS area extended westward, reaching a length of 35 km, i.e. 10 km more then the May 20 event. Also, two extreme intensity bulges exist to west and to east. The first one is now focused on Reggiolo (it was on Moglia, before), whereas the second is always that occupied by San Carlo and Mirabello. Considering also these areas, the 6 MCS is elongated WNW-ESE of ~55 km, with a N-S width of 15-20 km. By observing Fig. 11, and assuming a rough similar vulnerability in all the surveyed localities, it is probable that the mentioned intensity bulges represents as many cases of geological amplification. In one of these, we have recognized the strong contribution of the liquefaction phenomena occurred extensively all along the paleochannel of the Reno River, while in the others cases, only future geological analyses will hopefully reveal the causes of the seismic shaking increase. Also for this earthquake, our intensity estimate refer mainly to the old-centre of the surveyed localities, as almost everywhere the May 29 mainshock struck more these than the modern outskirts (generally affected by sparse 1-2 level damage), apart some impressive exceptions as the one of Rovereto (collapse of the pilotis of a new rein-

Fig. 12 - Concorda sulla Secchia (Is 7 MCS). Collapse of inhabited, old unreinforced brick-masonry buildings inside the old-centre (photo of June 6).

forced brick-masonry 3-storey villas; Fig. 15) or Fossoli (level 3 damage to the first-second storey of some r.c. buildings). In some villages (e.g., Cento, Concordia, Crevalcore, Moglia, Reggiolo, San Giacomo delle Segnate) damage is diffused in the porch-houses, i.e the typical building style of almost all the main streets of the Po Plain settlements. Here we often observed damage level 2 and 3 affecting the columns and/or the pillars of the arches, with consequent damage of the overlaying wall of the first-second storey.

We have tried to "close" the intensity points distribution both southward (Modena and Bologna Provinces) and northward (Ferrara, Rovigo and Mantua), identifying several localities affected by light damages in the Mantua Province, south to the Po River, with the exception of Castelmassa (left bank of Po River, Rovigo Province), where we have observed several level 2 cracks to the porch-houses of the old-centre and to the churches and the theatre.

On the other hand, we did not find significant damage increase east of San Felice sul Panaro, apart from the two quoted cases of Crevalcore and Cento, at southeast.

Fig. 13 - Left, Rovereto (Is=Imax 7-8 MCS): level 3 damage affecting a r.c. building. Right, Mirandola (Is 7 MCS): partial collapse of the under-roof walls of an unreinforced brick-masonry building of the old-centre (photos of May 29).

Fig. 14 - Cavezzo (Is 7 MCS). Total collapse of the *pilotis* of a r.c. building in the old-centre (photo of May 29). This building experienced level 2 damage because the May 20 mainshock, and was not inhabited when it crushed on May 29.

Fig. 15 - The impressive collapse of the brick-masonry *pilotis* of a new building in the outskirts of Rovereto (Is=Imax 7-8 MCS).

R	P	Municipality	Locality	Is May 20	Is final	DJ	Long	Lat	pop	blds
LOMBARDIA	MANTOVA	Bagnolo San Vito	Bagnolo San Vito		5.0		10.8744	45.0879	1740	447
		Bagnolo San Vito	San Biagio		5.0		10.8503	45.0977	1521	343
		Borgoforte	Borgoforte		5.0		10.7492	45.0511	977	240
		Borgofranco sul Po	Borgofranco sul Po		5.0		11.2089	45.0464	477	171
		Carbonara di Po	Carbonara di Po		5.0		11.2278	45.0372	847	273
		Felonica	Felonica		5.0		11.3534	44.9790	1162	453
		Gonzaga	Gonzaga		5.0		10.8197	44.9520	4556	1050
		Gonzaga	Zocca		5.5	C	10.8778	44.9423	126	42
		Gonzaga	Bondeno		6.0	C	10.8567	44.9442	872	248
		Magnacavallo	Magnacavallo		5.0		11.1808	45.0046	1149	326
		Mantova	Mantova	5.0	5.0	C	10.7733	45.1526	40398	5073
		Moglia	Moglia	6.0	7.0		10.9139	44.9372	3700	967
		Moglia	Bondanello		5.5	B C	10.9470	44.9595	633	173
		Motteggiana	Motteggiana		5.0		10.7642	45.0294	453	138
		Motteggiana	Villa Saviola		5.0		10.7957	45.0343	515	152
		Ostiglia	Ostiglia		5.0	C	11.1361	45.0740	5808	1557
		Pegognaga	Pegognaga		5.5	A C	10.8597	44.9926	4092	931
		Pegognaga	Galvagnina	5.5	5.5		10.9105	44.9773	108	26
		Pieve di Coriano	Pieve di Coriano		5.0		11.1035	45.0383	672	233
		Poggio Rusco	Poggio Rusco	5.0	5.5	B C	11.1181	44.9740	5476	1332
		Poggio Rusco	Dragoncello		5.0		11.1975	44.9703	178	38
		Poggio Rusco	Avia		5.0		11.1628	44.9775	36	19
		Quingentole	Quingentole		5.5	C	11.0458	45.0388	931	468
		Quistello	Quistello	5.5	5.5	A C	10.9841	45.0096	3710	1014
		Quistello	Zambone		5.5		10.9697	44.9589	39	13
		Quistello	Nuvolato		5.0	C	11.0062	45.0317	259	120
		Revere	Revere		5.0		11.1314	45.0532	2019	576
		Roncoferraro	Roncoferraro		5.0		10.9511	45.1353	2481	626
		Roncoferraro	Barbassolo		5.0		10.9390	45.1390	0	
		Roncoferraro	Barbasso		5.0		10.9073	45.1200	650	177
		Roncoferraro	Cadè		5.0		10.8926	45.1585	135	43
		Roncoferraro	Casale		5.0		10.9750	45.0958	340	122
		Roncoferraro	Governolo		5.0	B C	10.9616	45.0848	1063	320
		Roncoferraro	Nosedole		5.0		10.9831	45.1200	295	89
		Roncoferraro	Villa Garibaldi (Breda)		5.0		10.9119	45.1529	18	5
		San Benedetto Po	San Benedetto Po		5.0		10.9314	45.0482	4973	1907
		San Giacomo delle Segnate	San Giacomo delle Segnate		5.5	A C	11.0318	44.9722	1184	514
		San Giacomo delle Segnate	Malcantone		5.5		10.9975	44.9638	91	29
		San Giorgio di Mantova	Villanova de Bellis		5.0		10.8726	45.1520	468	129
		San Giovanni del Dosso	San Giovanni del Dosso	5.5	5.5	C	11.0837	44.9684	727	228
		Schivenoglia	Schivenoglia		5.0		11.0753	44.9981	1059	372
		Sermide	Sermide	5.0	5.0		11.2954	45.0044	3613	1002
		Sermide	Porcara		5.0		11.2852	44.9588	70	21
		Sermide	Santa Croce		5.0		11.2544	44.9843	318	121
		Sermide	Caposotto		5.0		11.3165	44.9921	412	150
		Serravalle a Po	Serravalle a Po		5.0	A	11.0907	45.0698	653	209
		Serravalle a Po	Libiola		5.0		11.0616	45.0602	806	337
		Sustinente	Sustinente		5.0		11.0167	45.0699	1142	385
		Sustinente	Sacchetta-Ca' Vecchia		5.0	C	10.9913	45.0748	511	184
		Suzzara	Suzzara		5.0	B	10.7395	44.9922	13761	2877
		Villa Poma	Villa Poma		5.0		11.1142	45.0024	1650	465
		Villa Poma	Ghisione		5.0	B	11.1221	45.0140	0	
		Virgilio	Virgilio		5.0		10.8172	45.1130	716	1057
VENETO	ROVIGO	Bergantino	Bergantino		5.0		11.2533	45.0622	2026	645
		Calto	Calto		5.0	C	11.3588	44.9917	755	297
		Castelmassa	Castelmassa		5.5	A C	11.3122	45.0187	3395	928
		Castelnovo Bariano	Castelnovo Bariano		5.0		11.2838	45.0276	1280	430
		Ceneselli	Ceneselli		5.0	C	11.3702	45.0135	976	348
		Ficarolo	Ficarolo		5.0	B C	11.4357	44.9544	2071	532
		Fiesso Umbertiano	Fiesso Umbertiano		5.0	C	11.6039	44.9615	3458	941
		Gaiba	Gaiba		5.0		11.4809	44.9463	796	246
		Melara	Melara		5.0		11.2012	45.0638	1332	557
		Occhiobello	Occhiobello		5.0		11.5800	44.9208	2004	368
		Stienta	Stienta		5.0		11.5428	44.9410	1647	416
EMILIA ROMAGNA	REGGIO EMILIA	Campagnola Emilia	Campagnola Emilia		5.0		10.7584	44.8392	3928	826
		Correggio	Correggio		5.0		10.7850	44.7679	13480	2333
		Fabbrico	Fabbrico		5.0	C	10.8102	44.8732	4879	802
		Guastalla	Guastalla		5.0		10.6584	44.9122	11087	2339
		Luzzara	Luzzara		5.0		10.6899	44.9608	4090	942
		Luzzara	Villarotta		5.0		10.7446	44.9240	1291	328
		Luzzara	Casoni		5.0	C	10.7380	44.9396	418	150
		Novellara	Novellara		5.0		10.7303	44.8447	9198	1922
		Reggiolo	Reggiolo		6.5		10.8121	44.9194	6243	1284
		Reggiolo	Villanova		5.0		10.8598	44.9167	387	108
		Reggiolo	Brugneto		5.5	C	10.7587	44.9227	781	225
		Rio Saliceto	Rio Saliceto		5.0		10.8054	44.8116	4442	776
		Rolo	Rolo		5.0	C	10.8592	44.8857	3188	779
		San Martino in Rio	San Martino in Rio		5.0		10.7863	44.7353	4963	863
	MODENA	Bastiglia	Bastiglia		5.0		10.9972	44.7259	3005	427
		Bomporto	Bomporto	5.0	5.0		11.0407	44.7265	2265	422
		Bomporto	Sorbara		5.0		11.0047	44.7460	2683	451
		Bomporto	Gorghetto	5.0	5.0		11.0709	44.7706	350	89
		Bomporto	Solara	5.0	5.0	A B	11.0939	44.7722	1096	234
		Campogalliano	Campogalliano		5.0		10.8429	44.6900	5890	793
		Camposanto	Camposanto	5.5	5.5	A B C	11.1422	44.7871	2264	490
		Camposanto	Ca' Bianca	5.5	5.5		11.2160	44.8120	21	11
		Carpi	Carpi Centro		5.5	C	10.8724	44.7825	49658	6631
		Carpi	San Marino		5.0		10.9148	44.8081	1354	291
		Carpi	Migliarina		5.0		10.8471	44.8154	1485	337
		Carpi	Fossoli		6.0		10.8884	44.8222	2756	479
		Cavezzo	Cavezzo	6.0	7.0		11.0310	44.8369	4964	1027
		Cavezzo	Motta	5.0	5.5	B	10.9855	44.8284	19	13
		Cavezzo	La Bottega		6.0		11.0089	44.8481	159	46
		Cavezzo	Disvetro		5.5	C	11.0003	44.8600	128	40
		Concordia sulla Secchia	Concordia sulla Secchia	5.5	7.0		10.9890	44.9103	4414	991
		Concordia sulla Secchia	Fossa		5.5		11.0235	44.9240	1298	388
		Concordia sulla Secchia	Vallalta		5.5	C	11.0094	44.9440	503	137

R	P	Municipality	Locality	Is May 20	Is final	DJ	Long	Lat	pop	blds
EMILIA ROMAGNA	MODENA	Finale Emilia	Finale Emilia	6.5	6.5		11.2917	44.8326	8567	1711
		Finale Emilia	Reno Finalese		5.5	C	11.3197	44.8333	148	57
		Finale Emilia	Canaletto	6.5	6.5		11.2477	44.8373	48	?
		Finale Emilia	Massa Finalese		5.5	C	11.2135	44.8503	4061	934
		Medolla	Medolla		5.5	B C	11.0704	44.8480	4189	999
		Medolla	Villafranca		6.0		11.0578	44.8352	172	66
		Medolla	San Giacomo Roncole		5.5	B C	11.0602	44.8589	72	29
		Mirandola	Mirandola	7.0	7.0		11.0660	44.8864	15414	2814
		Mirandola	Mortizzuolo	6.5	6.5		11.1370	44.8781	729	246
		Mirandola	San Martino Carano		7.0		11.0420	44.8873	168	56
		Mirandola	Quarantoli		5.5	C	11.0982	44.9202	981	302
		Mirandola	Gavello		6.0		11.1793	44.9261	343	110
		Mirandola	San Martino Spino		5.0		11.2409	44.9341	763	214
		Mirandola	Tramuschio		5.5	C	11.0902	44.9580	313	105
		Modena	Modena	5.0	5.0		10.9177	44.6559	156717	13735
		Nonantola	Nonantola	5.0	5.0		11.0389	44.6758	8918	1053
		Novi di Modena	Novi di Modena		7.0		10.9014	44.8915	5330	1273
		Novi di Modena	Rovereto	5.5	7.5		10.9551	44.8425	3207	860
		Ravarino	Ravarino		5.0	B C	11.0985	44.7213	3391	602
		Ravarino	Rami		5.0		11.0801	44.7300	0	
		Ravarino	Casoni		5.0		11.0541	44.7240	335	64
		Ravarino	Stuffione		5.0		11.1185	44.7536	301	90
		San Felice sul Panaro	San Felice sul Panaro	7.0	7.0		11.1425	44.8341	6421	1357
		San Felice sul Panaro	Rivara	6.0	6.0		11.1684	44.8413	755	189
		San Possidonio	San Possidonio	5.0	6.0		10.9953	44.8929	2948	760
		San Possidonio	Forcello	5.0	5.5		10.9751	44.8700	0	
		San Possidonio	Pioppa	5.0	5.5		10.9654	44.8586	81	35
		San Prospero	San Prospero		5.0	B	11.0226	44.7893	1794	375
		San Prospero	San Pietro		5.0	A B	11.0467	44.7730	559	158
		San Prospero	Staggia		5.5	B C	11.0534	44.8034	298	78
		Soliera	Soliera		5.0		10.9221	44.7343	7586	1166
		Soliera	Sozzigalli		5.0		10.9746	44.7494	761	149
		Soliera	Limidi		5.0		10.9226	44.7628	2253	436
	BOLOGNA	Argelato	Argelato		5.0		11.3404	44.6393	2335	265
		Argelato	Volta Reno		5.0		11.3088	44.6673	306	?
		Baricella	Baricella		5.0		11.5333	44.6473	2944	566
		Bentivoglio	Bentivoglio		5.0		11.4167	44.6353	1069	123
		Castello d'Argile	Castello d'Argile		5.0		11.2940	44.6776	2964	373
		Castello d'Argile	Venezzano		5.0		11.3395	44.6820	1166	149
		Crevalcore	Crevalcore	5.0	6.0		11.1497	44.7205	7570	1430
		Crevalcore	Bolognina		5.0	B	11.1475	44.7644	222	46
		Crevalcore	Palata Pepoli		5.0	B C	11.2332	44.7930	572	116
		Crevalcore	Galeazza		5.5	A C	11.2769	44.7971	150	28
		Galliera	Galliera	5.5	5.5	B C	11.3936	44.7493	483	89
		Galliera	San Venanzio		5.0		11.4369	44.7452	1747	253
		Galliera	San Vincenzo	5.0	5.0		11.4427	44.7370	1632	213
		Malalbergo	Malalbergo	5.0	5.0		11.5320	44.7187	1269	220
		Malalbergo	Altedo		5.0		11.4903	44.6714	3512	696
		Malalbergo	Pegola		5.0		11.5003	44.6891	609	140
		Malalbergo	Ponticelli		5.0		11.4737	44.6972	108	25
		Pieve di Cento	Pieve di Cento		5.5	C	11.3075	44.7123	5946	1011
		San Giorgio di Piano	San Giorgio di Piano		5.0		11.3756	44.6495	4565	589
		San Giovanni in Persiceto	San Giovanni in Persiceto	5.0	5.0		11.1840	44.6400	12974	2017
		San Giovanni in Persiceto	San Matteo della Decima	5.0	5.0		11.2304	44.7142	4585	?
		San Pietro in Casale	San Pietro in Casale		5.0		11.4054	44.7004	6357	843
		San Pietro in Casale	Sant'Alberto		5.0		11.4049	44.7192	135	35
		Sant'Agata Bolognese	Sant'Agata Bolognese	5.0	5.0		11.1339	44.6642	4540	814
	FERRARA	Bondeno	Bondeno	5.5	5.5	B C	11.4157	44.8849	7618	1965
		Bondeno	Santa Bianca		5.5	B C	11.3903	44.8653	185	68
		Bondeno	Ponte Rodoni		5.5	C	11.4442	44.8684	355	109
		Bondeno	Borgo Piva		5.5		11.3576	44.8794	59	20
		Bondeno	Scortichino		5.5		11.3257	44.8788	1487	454
		Bondeno	Burana		5.5	B C	11.3509	44.9145	348	112
		Bondeno	Ponti Spagna	5.5	5.5		11.3895	44.9240	120	36
		Bondeno	Stellata	5.0	5.0	C	11.4214	44.9453	408	143
		Bondeno	Pilastri		5.5	A B C	11.2875	44.9473	751	224
		Cento	Cento	5.5	6.0		11.2880	44.7259	14720	2291
		Cento	Corpo Reno	5.5	5.5	C	11.3110	44.7581	916	161
		Cento	Renazzo		5.0		11.2764	44.7605	3481	770
		Cento	Bevilacqua		5.5	C	11.2551	44.7661	431	135
		Cento	Dodici Morelli		5.0		11.2909	44.7931	1908	491
		Cento	Pilastrello		5.5		11.3233	44.7943	210	70
		Cento	Buonacompra	5.5	5.5	B C	11.3403	44.8056	264	67
		Cento	Alberone		5.5	C	11.3106	44.8141	613	204
		Cento	Reno Centese	5.0	5.0	B	11.3249	44.8287	881	247
		Cento	Casumaro	5.0	5.5	B C	11.3637	44.8355	1957	554
		Ferrara	Ferrara	5.0	5.0		11.6086	44.8481	94307	12731
		Ferrara	Chiesuol del Fosso		5.0		11.5768	44.8034	0	?
		Ferrara	Montalbano	5.0	5.0		11.5762	44.7562	688	198
		Ferrara	Porotto	5.0	5.0	C	11.5494	44.8496	4400	874
		Mirabello	Mirabello	6.0	6.0		11.4595	44.8242	3160	902
		Poggio Renatico	Poggio Renatico	5.5	5.5	A B C	11.4863	44.7666	3958	796
		Poggio Renatico	Gallo	5.0	5.0		11.5537	44.7316	1201	299
		Poggio Renatico	Coronella		5.0		11.5244	44.8029	676	280
		Poggio Renatico	Madonna dei Boschi		5.0		11.4947	44.8200	21	11
		Sant'Agostino	Sant'Agostino	6.0	6.0		11.3883	44.7926	2384	511
		Sant'Agostino	Dosso	5.0	5.0		11.3389	44.7697	1106	240
		Sant'Agostino	San Carlo	6.5	6.5		11.4093	44.8039	1713	434
		Vigarano Mainarda	Vigarano Mainarda	5.5	5.5	B C	11.4951	44.8403	3265	947
		Vigarano Mainarda	Vigarano Pieve		5.0	B C	11.5100	44.8606	1755	443

Table 4 - MCS intensities (Is) evaluated for the May 20 and for the May 29 (cumulated) Emilia earthquakes. DJ, severe damage to isolated buildings (Is<6 MCS). Pop and blds, number of inhabitants and buildings, respectively. Through Table 3, the latter column may suggest the quantity and level of damaged buildings for each locality.

Finally, it is worth noting that also during the May 29 seismic shaking, several liquefaction phenomena occurred, some of them in the same place as May 20, others in localities that were not previously affected. However, the strength of the phenomenon was certainly lower than the first case, and none further damage has been reported.

We have found unreliable estimating the macroseismic parameters of the only May 29 shock, because of the cumulated effects with the preceding events. Therefore, the epicentral intensity of the cumulated sequence (mainly May 20 and 29), calculated also through Boxer4 algorithm, is Io 7 MCS, with an equivalent magnitude always lower (Mw 5.23) with respect to the instrumental one (Mw 6.11 + Mw 5.96). The final epicentral coordinates (Tab. 3) identify a point located more than 15 km west of both the instrumental and macroseismic epicentre of May 20, and 5 km west of the instrumental one of May 29 (Fig. 11). This westward drift of the barycentre of the macroseismic effects with respect to the instrumental ones may roughly indicate the rupture direction along the structures responsible at depth for the sequence, i.e. from east to west.

3.3. Liquefaction

As aforementioned, both mainshocks - and mainly the first one – have induced hundred liquefaction phenomena all over the mesoseismic area. Liquefaction is the transformation of a granular deposit from a solid state into a liquefied state as a consequence of the increased pore-water pressure determined by cyclic shaking (Youd, 1977). The associated features may vary from place to place in geometry, type, and dimension, due to the different propagation and amplification of the seismic waves at the surface and to the differing site conditions (grain size and density of deposits, position of the ground-water level). In the eastern Po Plain region, liquefaction processes have already happened, and in particular during the quoted 1570 event, when in Ferrara and in some neighbouring localities (San Paolo bridge, San Pietro church area, Giara del Po, La Punta, Polesino di San Giovanni Battista, Polesino di San Giorgio, Torre della Fossa), up to Ficarolo, on the left bank of Po River, several sand boils, volcanoes and ground settlements occurred (see in Galli, 2000). Indeed, on the basis of its geological properties and seismicity level, this sector of the Po Plain was long since classified as “liquefaction

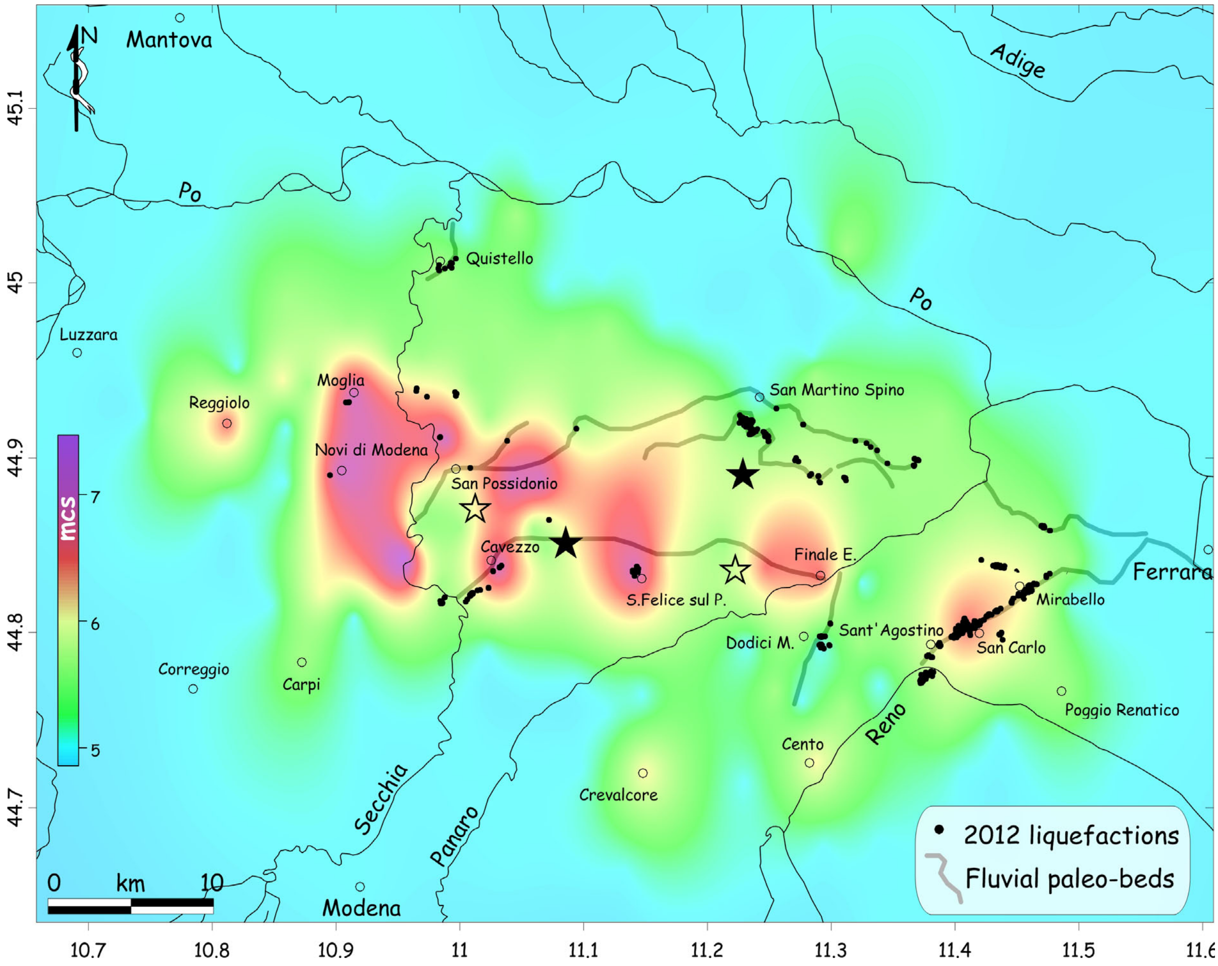

Fig. 16 - Distribution of the liquefactions generated by the 2012 earthquakes vs MCS intensity (empty and black stars, macroseismic and instrumental epicentres, respectively). Almost all the liquefaction cases fall within the 6 MCS area, with the exception of the May 29 cluster in Quistello. Note that liquefactions affect systematically the sandy deposits related to the abandoned paleo-bed of the main rivers (gray lines, from Castaldini e Raimondi, 1985), as the case of the paleo-Reno, toward Mirabello, of the paleo-Secchia, toward Cavezzo-San Felice sul Panaro and san Possidonio, or as the case of the abandoned paleo-beds of Po River, further north.

Fig. 17 - San Carlo: left, differential settlement of a mixed r.c. and masonry building, due to huge liquefaction phenomena below part of the foundation. Right, sand ejected from a water-manhole (photo of May, 20).

susceptible zone" (Galli, 1991; Galli and Meloni, 1993; Galli and Ferreli, 1995). Nevertheless, recently, it has been surprisingly defined as scarcely or not prone to liquefaction by Fioravante (2008).

In May 2012 earthquakes, the most diffuse features typology (e.g. in Galli, 2000) that we have observed can be related both to ground fissuring ("dry" ground fissures; with water emission; water and sand ejection: i.e. sand boils, sand volcanos. Figs. 17-18) and to related ground deformation (linear settlement and lateral spread). All of these occurred in the agricultural fields and below buildings, roads and pipeline causing, in the latter cases, from light to severe damages (i.e., differential settlement; fig. 17). The most impressive phenomena are surely those happened in the easternmost side of the area, between Sant'Agostino, San Carlo and Mirabello (Fig. 16), all villages built up over the paleo-channel of the Reno River, a fluvial ridge emerging ~5 m above the plain. Here, the liquefaction processes caused huge lateral spread mechanisms all along the fluvial ridge, with hundred meters long fractures arranged in complex en-echelon geometry, with synthetic and antithetic systems (e.g., graben-like features) and offsets reaching some decimetres (Fig. 19). Cracks affected also buildings, walls, pipelines and roads, causing severe damage and throwing over 1-m-thick layer of greyish, fine sand (Fig. 20). Water and sand have been ejected from ground fissures, but also from any preferential path met during the upward rising, as wells, shafts, piping systems, manhole, underground structures (car-box, cellars), and even phone booth and toilet bowl.

By comparing the areal distribution of the surveyed liquefaction cases (e.g. in Gruppo di Lavoro Liquefazione, 2012) with the MCS intensity assigned in this paper (Fig. 16), it emerges that all the cases fall within the 6 MCS degree area, with the only exception of those happened in Quistello (Is 5-6 MCS), near the Po River, whereas all happened less than 20 km from the two epicentres. This is in full agreement with the empirical relationships between Io/Is/Mw and distance for liquefaction (Galli, 2000) that foresee a boundary limit for Mw 6 earthquake of ~40 km (N.B., this limit is respected also assuming the value of the equivalent magnitude calculated through Boxer4 – Mw 5.23 – which yields a distance of 17 km).

However, the most striking fact emerging from Figure 16 is that all the liquefaction cases do not match with the maximum intensities; on the other hand, they

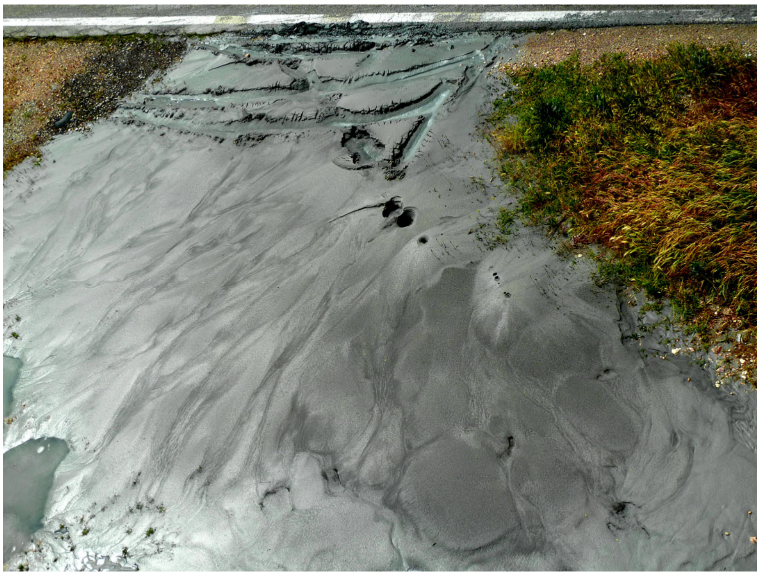

Fig. 18 - Road San Carlo-Sant'Agostino: sand volcanoes aligned on a ground fissure (photo of May 21).

Fig. 19 - San Carlo. Coseismic surficial breaks associated to liquefaction (linear ejection of sand and water). Note the echelon geometry of fractures that mimic a graben-like feature (i.e., lateral spreading of the paleo-Reno River ridge). Buildings, roads, walls and pipelenes located above this fractures have been seriously damaged the night of May 20.

Fig. 20 - San Carlo. Sand ejection inside a car-box. Remarkably, that the car has been by raised by ~80 cm up to the ceiling of the box due to the powerful push of the liquefied sand below during the night of May 20. This side of the house (see Fig. 17, left) has been severely damaged by differential settlement.

systematically follow the paths of the paleo-river beds (Castaldini and Raimondi, 1985), as the case of the paleo-Reno, toward Mirabello, of the paleo-Secchia, toward Cavezzo-San Felice sul Panaro and san Possidonio, or as the case of the abandoned paleo-beds of Po River, further north (San Martino Spino). Likely, in our opinion, the sandy deposits associated to the depositional facies of river-channel s.s. are dramatically the most liquefaction susceptible among all the other alluvial sediments of the plain. Therefore, as many settlements have been founded along the abandoned fluvial ridges that emerge few meters above the level of the whole Po Plain, this fact might represent a general risk than need to be mitigated by means of appropriate geotechnical tools, both in the 2012 mesoseismic area and elsewhere in the Plain.

4. DISCUSSION AND CONCLUSIONS

We applied the MCS scale (Sieberg, 1930) during the survey of the effects induced by the 2012 Emilia seismic sequence to 190 localities around the epicentres, in the Provinces of Mantua, Rovigo, Ferrara, Modena and Reggio Emilia. The intensities were estimated by using the methodology proposed by Molin (2009), which roughly quantifies the percentage of buildings affected by each of the five level of damage. In this way, as in the 2009 L'Aquila earthquake (see in Galli et al., 2009), we believe to have released a comprehensive intensity datapoints distribution (IDD) of the earthquake which, on one hand, meets the primary purposes of the civil protection intervention (rescue and emergency planning based on real damages, living vulnerability out of consideration), and on the other can be promptly compared to the historical earthquakes, i.e. to the IDD contained in the Italian seismic database (e.g., DBMI11), all expressed in terms of MCS intensities.

In doing this, owing both to the early onset of the MCS survey on May 20 morning, and to its intrinsic expeditiousness, we succeed in compiling the IDD also for the first mainshock, which has resulted composed by 52 datapoints (Tab. 4). The highest IDD (HIDD) for both mainshocks fits with the hangingwall of the two seismogenetic structures that, in turn, have been individuated by matching instrumental (hypocentres, interferograms, focal mechanisms) and geological (maps of the buried structures, seismic reflection profiles) data. As a matter of facts, May 20 HIDD lays entirely south of the outer Ferrara thrusts front, while May 29 HIDD lays south of the Mirandola-Cavone thrust (Figs. 5, 11). Both mainshocks look associated to the frontal thrust rupture of each of the two mentioned structures (Figs. 2-3), even though we can not exclude the involvement of the sole thrust, as suggested also by the fault dip provided by the focal mechanisms (Fig. 1). On the other hand, the macroseismic epicentre of the cumulated sequence falls west to the instrumental ones, suggesting a rough rupture directivity from east toward west, at least for the May 29 shocks (Fig. 11).

Therefore, considering 1) the entire extension of the arched, outer Ferrara thrusts front and of the intermediate Cavone-Mirandola buried folds and thrusts (Fig. 11), and 2) the historical seismicity of the same region (Fig. 4), this sequence has partially filled the seismic gap existing between the earthquakes in the Ferrara area to the east (i.e., 1570), and those around Correggio to the west (1806, 1996), confirming the supposed residual activity of these buried structures (Galli, 2005). Indeed, this activity has been recently quantified by Scrocca et al. (2007) at 0.15 mm/yr for the Mirandola structure (Late Pleistocene), and this value is consistent with the amount of surface coseismic vertical uplift (11-15 cm) measured by the differential interferograms during the current earthquakes (TRE, 2012). Taking into account the lack of seismic events comparable to the 2012 sequence in the last ~1 kyr, or even hypothesizing that the quoted 1346 earthquake might represent a possible 2012 predecessor (i.e., the literary sources record its effects only for Ferrara, and not for smaller villages), that slip rate could really represent an average value for these structures (11-15 cm every 700-1000 yr yield ~ 0.15 mm/yr), and, in particular, relatable to Mw $\leq$ 6 earthquakes.

Anyway, it is worth noting that this tectonic slip rate, and its related surficial deformation, are from 10 to 50 times lower that the rough sedimentation rate in this region of the Po Plain. By considering the mentioned thickness of the post LGM and post Late Roman deposits, the sedimentary rates has grown from 1.3 to 6.7 mm/yr in the past thousands years. Thus, at least in the eastern part of the Plain, the supposed diversion of the rivers around the growing anticlines - which some scholars claim to be an evidence of active tectonics (Burrato et al., 2003) - seems unreliable. Conversely, it is probable that fluvial paths are here influenced by other geological/hydrogeological causes that have much higher rates. For instance, the huge general subsidence affecting wide areas of the Po Plain (1-5 mm/yr, with local peaks of 3-4 cm/yr; Bitelli et al., 2010; Carminati et al., 2010), and/or – within this subsidence - the differential rates affecting the areas subtending deep synclinal (e.g., 8000 m of Plio-Quaternary deposits NE of Modena) vs shallow, sub-outcropping anticlines (few hundred meters below Novi di Modena, Concordia, Mirandola, San Felice sul Panaro), that have been quantified at 1 mm/yr by Arca and Beretta (1985) for the period 1897-1957 (i.e., -4 mm/yr vs -3 mm/yr). Indeed, from this point of view, the dominant geomorphic processes are not the moderate, 1-kyr spaced earthquakes, but the hundred, often catastrophic alluvial floods occurred continuatively in the past centuries in the Po Plain (see in CNR-SICIS, 2012).

Living aside this specific issue, we want to evidence another aspect linked to the 2012 event. The equivalent magnitude estimated through Boxer4 algorithm (i.e., the one on which the whole CPTI11 is based) is, in facts, much lower than the instrumental values. On the basis of our HIDD, we calculated Mw 5.23 vs an instrumental Mw 6.1 (or Ml 5.8). Probably, if we really had considered only the damage affecting the ancient houses in each villages, excluding at all not only the recent outskirts, but also the new buildings inside the old-centres, our intensities would have been likely higher by 0.5-1 degree (N.B., not everywhere! For instance in Cavezzo it would have been lower). Anyway, this increase is not yet enough to rise the equivalent magnitude to the instrumental one. This "anomaly" is evidenced also by the measured acceleration peaks (e.g., 0.29 g, PGA in Mirandola; 0.23 g, PGA in San Felice sul Panaro and Cento; 0.25 g, PGA in Moglia; accelerometric data of DPC-RAN), that would theoretically account for much more damage with respect to those really occurred (i.e., according to the existing regression laws, the peak acceleration in Mirandola account for 9 MCS; Faccioli and Cauzzi, 2006). Moreover, until 2004 the area affected by the current seismic sequence was not classified as seismic, and therefore was not subject to compliance with specific technical standards for construction.

However, as aforementioned, most of the settlements have small old-centres with brick-masonry buildings (where damage mostly focused on high and wide structures), and vast residential outskirts, consisting of low and regular buildings (2-3 storeys), realized with reinforced composite masonry (manufactured bricks) or, rarely, in reinforced concrete. Moreover, even in downtowns, the quality of ancient buildings is higher than that observed in many other areas of Italian territory, such as in Abruzzo (hit by the 2009 earthquake), where it is common to observe houses made with rubble stones or field stones with poor mortar (class of vulnerability A, according to EMS scale). Therefore, the quality of constructions and, likely, the role played by the deep alluvial deposits on filtering the earthquake frequency contents, might have concurred in mitigating the shaking effects on buildings, despite both the relative high magnitude values and the acceleration peaks.

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Ms. received: July 13, 2012
Final text received: July 20, 2012