The 2012 Ferrara seismic sequence: Regional crustal structure, earthquake sources, and seismic hazard

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[1] Inadequate seismic design codes can be dangerous, particularly when they underestimate the true hazard. In this study we use data from a sequence of moderate-sized earthquakes in northeast Italy to validate and test a regional wave propagation model which, in turn, is used to understand some weaknesses of the current design spectra. Our velocity model, while regionalized and somewhat *ad hoc*, is consistent with geophysical observations and the local geology. In the 0.02–0.1 Hz band, this model is validated by using it to calculate moment tensor solutions of 20 earthquakes ($5.6 \geq M_W \geq 3.2$) in the 2012 Ferrara, Italy, seismic sequence. The seismic spectra observed for the relatively small main shock significantly exceeded the design spectra to be used in the area for critical structures. Observations and synthetics reveal that the ground motions are dominated by long-duration surface waves, which, apparently, the design codes do not adequately anticipate. In light of our results, the present seismic hazard assessment in the entire Pianura Padana, including the city of Milan, needs to be re-evaluated.

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1. Introduction

[2] On May 20 2012, an event of M_L 5.9 (M_W 5.6) struck the southern edge of the Po river flood plain (Pianura Padana), approximately 30 km West of the town of Ferrara, and 10 km to the NW of the village of Finale Emilia (INGV). On 05/19/2012 at 23:13:27 the earthquake was preceded by a foreshock of M_L 4.1 (M_W 3.8). Hypocentral depths were 6.3 km for both events; centroid depths were 5 and 6 km (main and foreshock, respectively). Fault was a reverse one, dipping 45° to the South (Figure 1).

[3] The main shock started a complex seismic sequence, in which six more earthquakes with $M_L \geq 5$ struck the area, the latest one on June 3 2012. Aftershocks delineated a 50 km-long strip, 10–15 km wide, elongated in the EW direction (Figure 1). A total of 2100 events were located between May 19 and June 25 2012 by the INGV National Seismic Network. 80 of them (whose waveforms were gathered and used for this study) had $M_L \geq 3.5$.

[4] The widespread damage due to the seven M_L 5+ earthquakes was especially severe for historical towns and industrial infrastructures. However, a striking inconsistency exists between the relatively small main events of the sequence ($M_W \leq 5.6$), and the corresponding high level of shaking (a PGA of 9 m/sec^2 was recorded by the MRN strong-motion station on the vertical component of the ground motion, whereas a value of 3 m/sec^2 was observed on the horizontal motions), that, together with observed extreme durations, caused severe damage to houses and industrial structures, as well as the occurrence of widespread liquefaction phenomena [*EMERGEO Working Group*, 2012, http://emergeo.ingv.it].

[5] In this study we used the seismic profile *App_Orient_1* (see http://unmig.sviluppoeconomico.gov.it/videpi/) to define a velocity structure of the shallow crust beneath the Pianura Padana. The crustal model was validated using the broadband waveforms of our data set. Like for the L'Aquila case study presented by *Herrmann et al.* [2011], our goal was the inversion of waveforms in the frequency band between 0.02 and 0.1 Hz. Synthetic seismograms highlighted important implications for the seismic hazard in the Pianura Padana, because the shallow structure of the Po flood plain dramatically affects also the high-frequency ground motion, with which damage should strongly correlate.

2. Regional Velocity Structure and MT Solutions

[6] The study area (Figure 1a) includes the Ferrara arc: one of the northernmost portions of the Northern Apennines thrust front, that was active during late Pliocene - early Pleistocene times [*Scrocca et al.*, 2007]. The Ferrara arc lies under a thick sedimentary cover from the Po river with an average sediment thickness of 2–4 km. Thicknesses up to 8.5 km characterize the deepest depocenters of the valley [*Pieri and Groppi*, 1975].

[7] We compared geological data in literature [*Carminati et al.*, 2010; *Fantoni and Franciosi*, 2010] (see Figures 1b and 1c) against the seismic profile *App_Orient_1*, and constructed a 1D velocity model of the shallow crust for the area. We started from the deeper part of the model CIA [*Herrmann et al.*, 2011], and added shallow low-velocity layers based on the gathered information. We thus obtained a crustal model called PADANIA (Table 1) that, on a N-S path across the basin to stations SALO and MAGA, fitted well the dispersion curves of Love waves at periods as low as 10 sec (Figure 2). Rayleigh wave dispersion data are also

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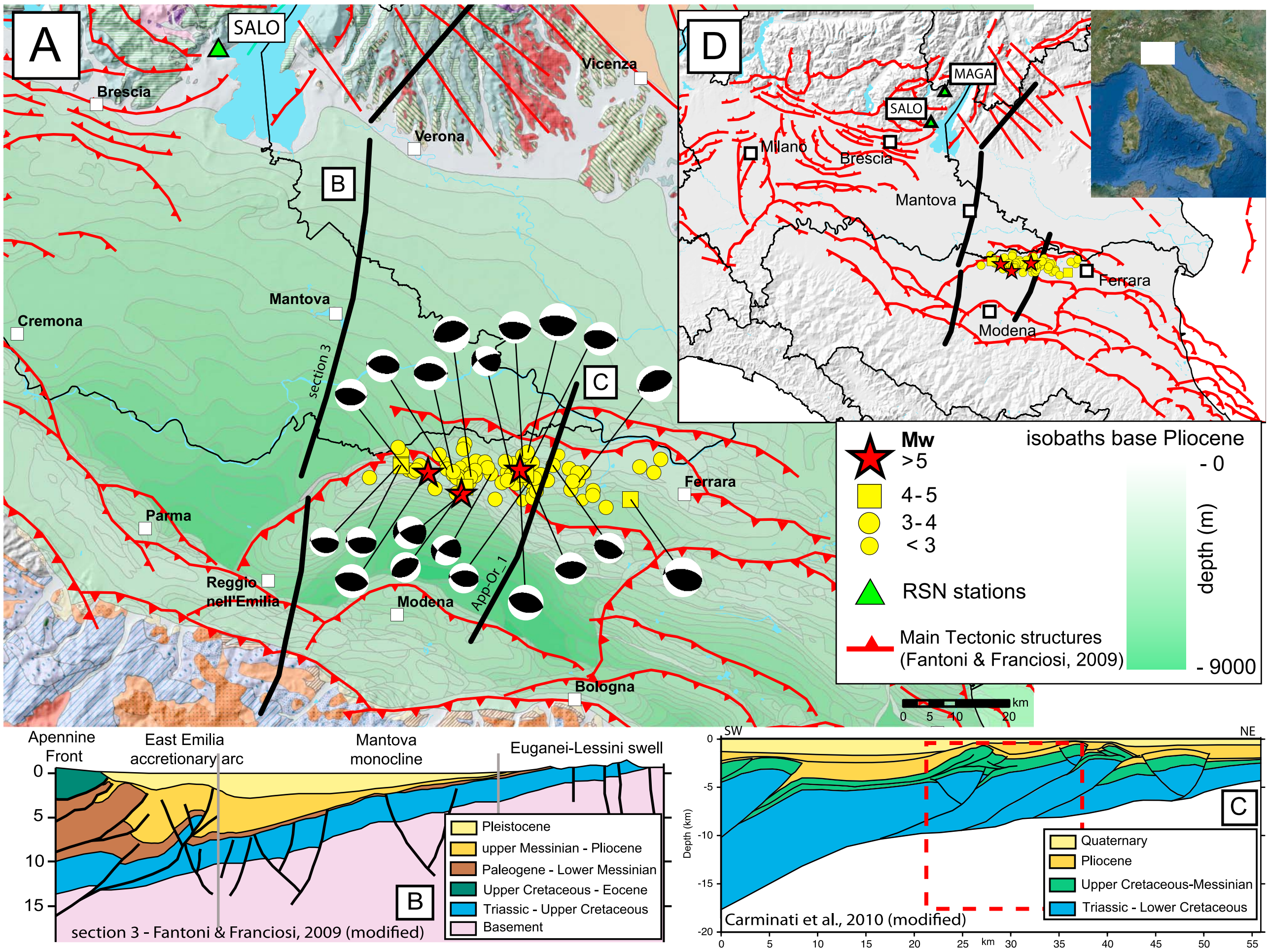

Figure 1. (a) Structural setting of the study area, as reported by *Consiglio Nazionale delle Ricerche* [1992]. Isobaths contours of Pliocene base surface below the whole Po Plain highlight the buried architecture of the area. Main tectonic lineaments are taken from *Fantoni and Franciosi* [2010]. 78 events of the entire seismic sequence and our 22 MT solutions are plotted. (b) Geological cross section modified from Fantoni and Franciosi (2010, three-pieces profile B of Figure 1a): gray vertical lines mark the discontinuities of the profile. (c) Geological cross section built on the interpretation of the App_Or_1 seismic profile (modified from *Carminati et al.* [2010], profile C in Figure 1a); dashed box indicates a section of the volume that is potentially interested by the seismic activity. (d) Location of the various elements, including the seismic stations SALO and MAGA, which were used to investigate the PADANIA model.

acceptably fitted by model PADANIA, down to 10 sec or less (Figure 2). However, small time shifts allowed to the synthetic seismograms of actual earthquakes permit very satisfactory fits, partially correcting distance- and azimuth-dependent model imperfections (see figures in the auxiliary material).[1] The locations of stations SALO and MAGA can be found in Figure 1d. Models CIA and PADANIA overlap below 4 km from the free surface.

Table 1. The PADANIA Model

Thickness (km)	V_P (km/sec)	V_S (km/sec)	ρ (kg/m^3)	Q_P	Q_S
1.0	1.9000	0.8000	2.25E + 03	50	25
1.0	2.6000	1.4300	2.60E + 03	80	56
2.0	3.8000	2.1350	2.65E + 03	200	200
0.5	4.4000	2.4400	2.85E + 03	250	250
0.5	4.9399	2.8210	2.85E + 03	250	250
3.0	6.0129	3.4336	2.85e + 03	250	250
7.0	5.5516	3.1475	2.85E + 03	600	300
15.0	5.8805	3.3583	2.85E + 03	600	300
6.0	7.1059	4.0081	3.00E + 03	600	300
8.0	7.1000	3.9864	3.01E + 03	600	300
0.0	7.9000	4.4036	3.28E + 03	600	300

[8] With the PADANIA crustal model, we attempted to compute stable moment tensor solutions for the 80 earthquakes with $M_L \geq 3.5$. Due to the high level of ambient noise that affect most stations within and around the Po valley, we were able to compute only 20 robust focal solutions (Figure 1a and Table 2). Focal mechanisms outline the existence of a thrust fault system that is in good agreement with the reconstructions by *Fantoni and Franciosi* [2010], and *Carminati et al.* [2010].

[9] We found that only three earthquake of the sequence had $M_W > 5$, and noted a systematic discrepancy between M_W and M_L for the events analyzed (Table 2).

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053214.

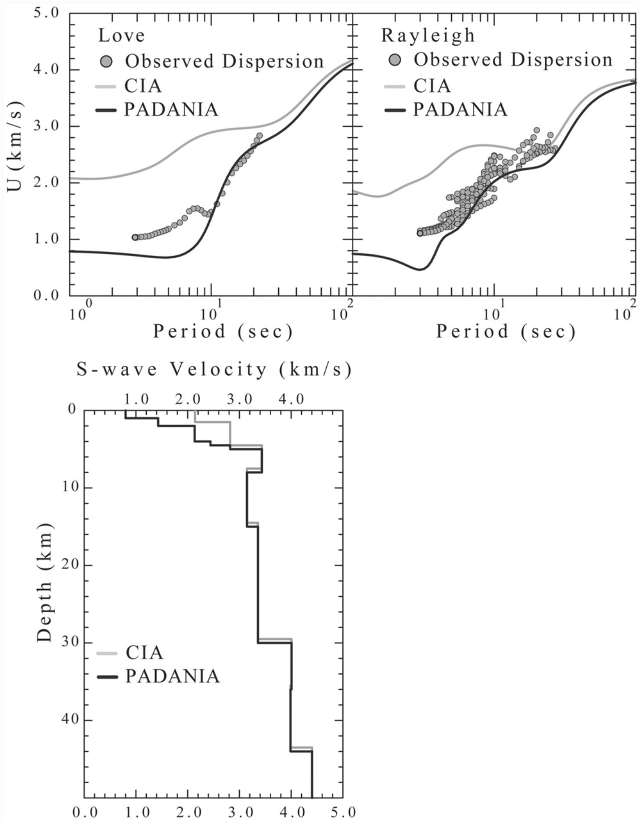

Figure 2. Love and Rayleigh dispersion observations obtained at stations MAGA and SALO (circles), compared to theoretical predictions from the crustal models CIA (gray curves) and PADANIA (black curves). Most of the source-receiver paths are within the sediments. The events used for the dispersion analysis are the ones indicated with footnote a in Table 2, as well as the seismograms from two events occurred on 06/01/2012 at 12:22:44, and on 06/01/2012 at 23:07:15.

[10] A regression yielded the following relationship, for the INGV network M_L, and the corresponding M_W:

$$M_L = M_W + 0.29; \quad 3.5 \leq M_L \leq 5.9. \tag{1}$$

We will analyze the reasons for the discrepancy described in (1) by comparing time histories calculated using models PADANIA and CIA. For earthquakes in the Appennines, we usually observe that $M_L = M_W$ [*Herrmann et al.*, 2011]. The difference indicated in equation (1) may be a direct consequence of the fact that the Ferrara earthquakes occurred underneath a very thick layer of low-velocity sediments.

3. Synthetic Seismograms

[11] In order to compare synthetic seismograms generated using models CIA and PADANIA (up to a 5 Hz maximum frequency), we simulated an M_W 4 earthquake with the following source parameters: Strike = 105, Dip = 40, Rake = 100, Depth = 5 km, representative of the typical event of the sequence (depths of the events are well constrained, see the auxiliary material). We are aware of the fact that we cannot use model PADANIA for successfully reproduce the individual wiggles of the recorded seismograms in the frequency band between 0.1 Hz and 1 Hz, but we strongly believe that the new crustal model may be used to understand the general properties of the ground motion in Pianura Padana.

[12] Seismograms of Figure 3a (Transverse and Vertical components of the ground motion) are calculated at an epicentral distance of 40 km, and an azimuth of 330 (i.e., along the path to station SALO). Upper waveforms (in red) in each frame of Figure 3a refer to model PADANIA, whereas lower seismograms (in black) refer to model CIA. Figure 3a shows that surface waves dominate the seismograms in the PADANIA crustal structure.

[13] Large amplitudes and durations of the ground motion are documented in Figure 3b, where the seismograms observed at SALO during five earthquakes (black shading) are compared with synthetic time histories calculated with the source parameters and azimuth used for Figure 3a. Observed and synthetic waveforms are normalized to their peak values after they are bandpass-filtered in the indicated frequency bands.

[14] We satisfactorily reproduce the low-frequency characters of the observed seismograms of Figure 3b, together with the extreme duration of the ground motion at all frequencies. The extreme durations that characterize the ground motion at high frequencies, at least between 0.02 Hz and 1.0 Hz (bottom frames in Figure 3b), are due to the strong dispersion characteristics of the seismic waves trapped in the thick sedimentary layer at the surface, and may also be influenced by the attenuation characteristics of the crust in the region [*Del Pezzo et al.*, 2011]. Finally, anomalous durations of the ground motion may be one of the main reasons for the anomalous level of damage observed in the epicentral area, and for the widespread occurrence of liquefaction phenomena as well (Emergeo Working Group, 2012).

4. Seismic Hazard

[15] Figure 4 shows the spectral acceleration of the closest waveform registered at a Joyner-Boore distance R_{jb} = 5 km at the Mirandola (MRN) strong-motion station (used in engineering seismology to take into account the finite dimensions of a seismic source, R_{jb} indicates the distance to the nearest point of the vertical projection to the surface of a fault rupture). MRN is classified as a C-type soil in the EC8 classification [*European Committee for Standardization*, 2003].

[16] During the main event of May 20 2012 (M_W 5.63, see Table 2) site MRN recorded a horizontal Peak Ground Acceleration (PGA) of 3 m/sec^2 [*Dolce et al.*, 2012]. We compared the observed spectral acceleration of the radial and transverse component at MRN (5% damping) with the Italian building code spectra (Uniform Hazard Spectra - UHS) relative to soil class C, and two different return periods: 475 and 2475 years (Figure 4). UHS estimates are obtained from the official website of the Consiglio Superiore dei Lavori Pubblici (http://www.cslp.it/cslp/), and are based on the recently developed National Probabilistic Seismic Hazard Maps for Italy (http://esse1.mi.ingv.it/).

[17] We argue that, if compared with the maximum magnitude expected for the area (M_{Wmax} = 6.14 [see *Stucchi et al.*, 2011]), the main earthquake of the Ferrara sequence is characterized by a small moment magnitude (M_W = 5.63). Yet, Figure 4 shows that the spectral acceleration observed during the main event at station MRN largely exceeds the design spectra (the UHS) in a broad frequency range around

Table 2. The 20 Events for Which We Could Obtain an MT Solution and Other Events Used for the Dispersion Analysis

	From INGV Network Location				From MT Solution				
Date	Time	Latitude	Longitude	Ml	Depth	Mw	Strike	Dip	Rake
05/19/2012	23:13:27	44.898	11.258	4.10	5.0	3.79	284	52	102
05/20/2012	02:03:53	44.889	11.228	5.90	6.0	5.63	285	45	90
05/20/2012	03:02:50	44.860	11.095	4.90	13.0	4.72	245	65	45
05/20/2012[a,b]	09:13:21	44.879	11.241	4.20	7.0	4.13	265	55	85
05/20/2012	12:50:24	44.866	11.366	3.90	6.0	3.60	235	35	75
05/20/2012	13:18:02	44.831	11.490	5.10	7.0	4.78	275	55	75
05/21/2012	08:01:36	44.911	11.235	3.20	7.0	3.24	275	65	90
05/21/2012	18:02:26	44.847	11.259	3.60	11.0	3.28	245	65	40
05/22/2012	06:11:15	44.850	11.074	3.70	5.0	3.40	245	45	95
05/23/2012	21:41:18	44.868	11.251	4.30	7.0	3.69	265	50	75
05/24/2012	14:34:38	44.868	11.293	3.30	7.0	3.26	297	61	99
05/25/2012	13:14:05	44.883	11.108	4.00	5.0	3.62	260	30	99
05/27/2012	18:18:45	44.882	11.158	4.00	6.0	3.74	117	66	141
05/29/2012	07:00:03	44.851	11.086	5.80	5.0	5.44	270	45	85
05/29/2012	08:25:51	44.901	10.943	4.50	7.0	4.34	270	65	80
05/29/2012	08:40:58	44.892	10.962	4.20	7.0	3.98	282	56	97
05/29/2012[a,b]	09:30:21	44.892	11.053	4.20	5.0	3.48	104	52	102
05/29/2012[a,b]	10:55:57	44.888	11.008	5.30	6.0	5.10	282	50	94
05/29/2012[a,b]	14:39:40	44.882	11.068	3.90	5.0	3.56	280	41	102
06/03/2012	19:20:43	44.899	10.943	5.10	10.0	4.61	265	65	75

	Other Events				
Date	Time	Latitude	Longitude	Ml	Depth
05/29/2012[a,b]	11:07:05	44.876	11.076	15.0	4.00
05/30/2012[a]	6:00:33	44.931	10.937	5.0	3.80
05/31/2012[a]	4:21:56	44.872	11.262	4.5	3.60
06/01/2012[a]	12:22:44	44.877	10.986	6.7	3.1
06/01/2012[a]	23:07:15	44.948	10.914	2.3	3.5

[a]Events used in Figure 2.
[b]Events used in Figure 3b.

1 Hz. In fact, at 1 Hz, the observed transverse component of the ground motion is a factor of two larger than the estimate for the 475 years return period, and almost 30% larger than that relative to a return period of 2475 years. The considerations just made clearly demonstrate the need for an update of the reference hazard map of northern Italy, in which the regional characteristics of the ground motion are to be included.

5. Conclusions

[18] We calibrated a 1-D crustal structure (model PADANIA) for seismic paths going across the Pianura Padana, allowing the inversion of moment tensor solutions for 20 events of the Ferrara seismic sequence, from M_W 5.63 (the largest main event, occurred on May 20 2012), down to M_W 3.2.

[19] Due to a high noise level at low frequency, we were not able to obtain acceptable moment tensor solutions for all the 80 events of the sequence with $M_L \geq 3.5$. Nevertheless, PADANIA represents a major improvement for the investigation of the seismicity along the southern edge of the Pianura Padana.

[20] We also used model PADANIA in order to perform a numerical study on the characteristics of the ground motion in the thick sediments of the flood plain, in the frequency band between 0.02 and 1.0 Hz. Our synthetic seismograms correctly reproduced the anomalous durations of the ground motion observed on the sediments at high frequencies, at least up to 1 Hz, and Figure 3 shows how the seismograms in the Po flood plain are dominated by surface waves, that may have played a major role in enhancing the damage observed on industrial structures.

[21] Predicted Spectral Accelerations (SA) at 5% damping for a return period of 2475 years (see Figure 4) were exceeded at station MRN by the spectral acceleration observed during the largest main event of May 20 2012. Note that predicted SAs are somehow controlled by the maximum magnitude chosen for the area (M_{Wmax} = 6.14 [see *Stucchi et al.*, 2011]), which is 0.5 magnitude units larger than that of the main event that struck Ferrara.

[22] The inconsistency pointed out in Figure 4, between observed SA and UHS, indicates the necessity of including the regional characteristics of the ground motion into the tools used for the calculation of the UHS, at least in this region of Italy. Although the work on regional Ground Motion Predictive Equations (GMPEs) in Italy was included in the logic tree of the hazard map [*Montaldo et al.*, 2005], no high-quality digital waveforms from substantial earthquakes in the Pianura Padana were available until now, and no regional GMPE from this specific area could be included in the logic tree.

[23] Because the fundamental characteristics of earthquake-induced ground motion are not taken into account in current estimates of seismic hazard, it is likely that, within the thick sedimentary body of the Pianura Padana, seismic hazard got substantially underestimated until now. The issue may be especially important at low-frequencies, with a substantial impact on the expected response of very tall structures, even in Milan.

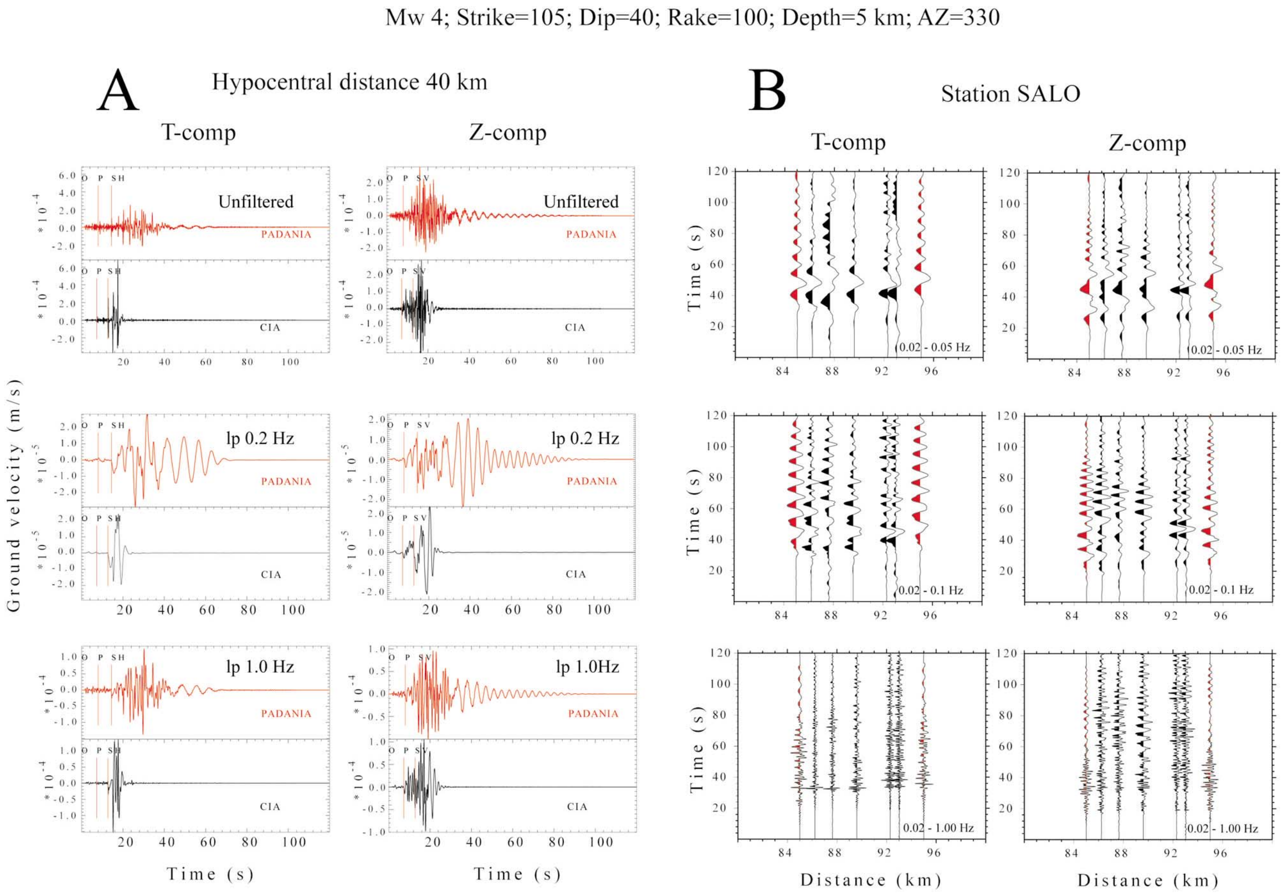

Figure 3. (a) Synthetic seismograms (left: transverse components; right: vertical components) calculated at 40 km distance and at an azimuth of 300° over the PADANIA and CIA crustal models (red and black, respectively), for an earthquake of M_W 4, strike = 105°; dip = 40°; rake = 100°. From top to bottom: i) unfiltered; ii) bandpass filtered between 0.02 and 0.2 Hz; iii) bandpass filtered between 0.02 and 1.0 Hz. (b) Waveforms recorded at SALO (T and Z components of the ground motion, black shading) during five earthquakes (events marked with footnote b in Table 2), compared with synthetic waveforms (red shading) calculated around the same hypocentral distances. Parameters are the same as before. Amplitudes are normalized to their peak values. Waveforms are bandpass-filtered in the following frequency bands: top 0.02–0.05 Hz; middle 0.02–0.1 Hz; bottom 0.02–1.0 Hz.

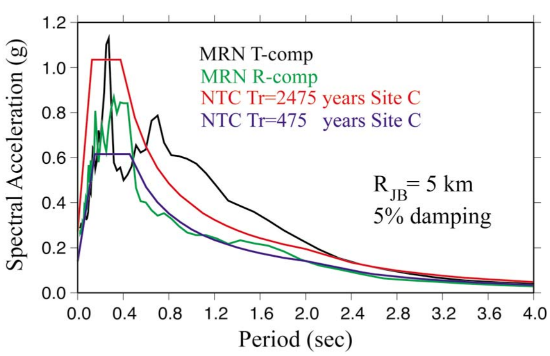

Figure 4. Transverse and radial Spectral Acceleration (black and green, respectively) recorded at station MRN (Mirandola, EC8 site C) during the main event of 05/20/2012 (M_W 5.63, 5 km Joyner-Boore distance). SAs are plotted against 475 and 2475 years return time estimates (blue and red, respectively) for an EC8 C site.

[24] Due to the large discrepancy between the relatively small moment magnitudes of the sequence's main events, and the widespread heavy damage that they caused, we feel that the size of the historical earthquakes in the region, and so their recurrence times, may need to be re-evaluated in the light of our results.

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References

Carminati, E., D. Scrocca, and C. Doglioni (2010), Compaction-induced stress variations with depth in an active anticline: Northern Apennines, Italy, *J. Geophys. Res.*, *115*, B02401, doi:10.1029/2009JB006395.

Consiglio Nazionale delle Ricerche (1992), Structural model of Italy and gravity map, scale 1:500000, in *Progetto Finalizzato Geodinamica*, *Quad. Ric. Sci.*, vol. 114, 1 pp., Rome.

Del Pezzo, E., F. Bianco, S. Marzorati, P. Augliera, E. D'Alema, and M. Massa (2011), Depth-dependent intrinsic and scattering seismic attenuation in north central Italy, *Geophys. J. Int.*, *186*, 373–381, doi:10.1111/j.1365-246X.2011.05053.x.

Dolce, M., et al. (2012), The Emilia thrust earthquake of 20 May 2012 (northern Italy): Strong motion and geological observations, *Rep. 1*, Dip. Della Prot. Civ., Rome. [Available at http://www.protezionecivile.gov.it/resources/cms/documents/Report_DPC_1_Emilia_EQSd.pdf.]

EMERGEO Working Group (2012), Technologies and new approaches used by the INGV EMERGEO Working Group for real-time data sourcing and processing during the Emilia Romagna (northern Italy) 2012 earthquake sequence, *Annals of Geophysics*, *55*(4) doi: 10.4401/ag-6117.

European Committee for Standardization (2003), Eurocode 8: Design of structures for earthquake resistance part 1: General rules, seismic actions and rules for buildings, draft 6, *Doc. CEN/TC250/SC8/N335*, Brussels.

Fantoni, R., and R. Franciosi (2010), Tectono-sedimentary setting of the Po Plain and Adriatic foreland, *Rend. Fis. Accad. Lincei*, *21*, suppl. 1, 197–209, doi:10.1007/s12210-010-0102-4.

Herrmann, R. B., L. Malagnini, and I. Munafò (2011), Regional moment tensors of the 2009 L'Aquila earthquake sequence, *Bull. Seismol. Soc. Am.*, *101*, 975–993, doi:10.1785/0120100184.

Montaldo, V., E. Faccioli, G. Zonno, A. Akinci, and L. Malagnini (2005), Treatment of ground-motion predictive relationships for the reference seismic hazard map of Italy, *J. Seismol.*, *9*, 295–316, doi:10.1007/s10950-005-5966-x.

Pieri, M., and G. Groppi (1975), The structure of the base of the Pliocene-Quaternary sequence in the subsurface of the Po and Veneto Plains, the Pedeapennine Basin and the Adriatic Sea, *Quad. Ric. Sci.*, *90*, 409–415.

Scrocca, D., E. Carminati, C. Doglioni, and D. Marcantoni (2007), Slab retreat and active shortening along the central-northern Apennines, in *Thrust Belts and Foreland Basins: From Fold Kinematics to Hydrocarbon Systems, Frontiers in Earth Sciences*, edited by O. Lacombe et al., pp. 471–487, Springer, Berlin, doi:10.1007/978-3-540-69426-7_25.

Stucchi, M., C. Meletti, V. Montaldo, H. Crowley, G. M. Calvi, and E. Boschi (2011), Seismic hazard assessment (2003–2009) for the Italian building code, *Bull. Seismol. Soc. Am.*, *101*(4), 1885–1911, doi:10.1785/0120100130.