Foreword and scope of work. This work draws inspiration from the discussion, taken during the final meeting of the DPC-INGV 2012-2013 projects (https://sites.google.com/site/progettisismologici/), about seismic strain rate variations in the area shocked by the 2012 Emilia seismic sequence. A further motivation for this work is the evident anomaly (with respect to the neighboring areas) shown in that area by the seismic strain rate map published by Barani et al. (2010), map which is presented also here (Fig. 1). The map clearly shows a deficit in the release of seismic deformation or, more precisely, a deficit in the distribution of the strain rate values in the area between Modena and Ferrara. This pattern is very similar to that observed by Chen et al. (2009) analyzing the distribution of the total amount of seismic moment in the Taiwan region before and after the 1999 Chi-chi earthquake ($M_w = 7.6$) and to that found by Barani and Eva (2011) in the area stricken by the 2009 L’Aquila earthquake ($M_w = 6.3$). Both studies have evidenced clear deficits in the total amount of seismic moment, deficits which were then filled following the occurrence of strong earthquakes. The major conclusion from both studies was that, for domains with similar tectonic settings, the analysis of deficit-then-fill patterns may be useful for the inference of future disastrous earthquakes.

In this study, the approach for seismic strain rate calculation proposed by Barani et al. (2010) is applied to the area of the 2012 Emilia sequence in order to investigate, in a retrospective way, the anomaly observed in the map in Fig. 1. The study is also important to further test the reliability of the method of Barani et al. (2010) to study seismicity patterns, such as seismic gaps and quiescence periods.

Seismotectonic framework. The area struck by the Emilia 2012 seismic sequence is located in the outermost portion of the northern Apennines. The Apennine chain is a post-collisional...
belt, the formation of which is related to the tectonic interaction between the African and European plates. Compressional deformation results from the westward subduction of the Adriatic lithosphere, causing the formation of compressional fronts migrating towards E and NE, thus progressively affecting the Adriatic foreland (Patacca et al., 1990; Chiarabba et al. 2005; Molli et al. 2010; Bignami et al., 2012).

The May-June 2012 seismic sequence was characterized by two strong events of $M_w$ 6.1 and 6.0 occurred on May 20 and 29, respectively. Both events were located close to the buried front of the Ferrara northward-verging active thrust belt. The two main earthquakes were then followed by six $M_w \geq 5.0$ events and by many weaker shocks. The aftershock distribution covers an area of 800 km$^2$ extending in the E-W direction for a total length of approximately 55km (Mirandola Earthquake Working Group, 2012). Compared to the May 20 event, the earthquake occurred on May 29 is located westward and the related aftershocks cover the western and central parts of the thrust front (Mirandola Earthquake Working Group, 2012).

As argued by some authors, the 2012 Emilia seismic sequence activated a portion of the buried outer thrust fronts of the northern Apennines (Bignami et al., 2012). More specifically, two N-NNE-verging segments of the blind thrust of the external Ferrara-Romagna Arc were activated (Serpelloni et al., 2012). Focal mechanisms indicate a prevalent compression (Pondrelli et al., 2012), which is in agreement with the regional compressional tectonics characterizing the Apennine structures buried below the Po Plain sediments (Boccaletti et al., 2004, Boccaletti et al., 2011, Pondrelli et al., 2012). Only in a few rare cases, a strike-slip component was observed. Of note is the rotation of the axis of maximum compression (P-axis). The major events show pure, low angle, thrust mechanisms with P-axis pointing towards north. Some aftershocks clearly present a rotation with respect to this dominant northward direction. In particular, those pointing towards NW are located close to the NE-striking part of the buried thrust front (Pondrelli et al., 2012).

Concerning past earthquakes, the seismicity was mostly concentrated along northeastern sector of the Apennine chain, at the border with the Po Plain. However, strong earthquakes also occurred in the blind thrust zone in the outer sector of the Apennines, such as the 1346 Ferrara ($M_w = 5.8$), 1570 Ferrara ($M_w = 5.5$), and 1688 Romagna ($M_w = 5.9$) earthquakes.

Methodology. The calculation method proposed by Barani et al. (2010) is based on the zone-less, smoothed seismicity approach used by Frankel (1995) for the seismic hazard assessment of the Central and Eastern United States. The method of Barani et al. (2010) consists of calculating moment rates, $\dot{M}_o$, for each cell of a homogeneous grid covering the entire study area. Then, an elliptical kernel (here applied with smoothing parameters $\tau_1 = 30$ km and $\tau_2 = 20$ km) with the major axis ($\tau_1$ is the major semi-axis) oriented parallel to the prevalent direction of compression characterizing the outer Apennines is applied on them to determine smoothed $\dot{M}_o$ values. Based on this approach, the elliptical smoothing function allows for both the epicentral location error (quantified by $\tau_1$ and $\tau_2$) and the prevalent orientation of active faults within a region. $\dot{M}_o$ values are then converted into strain rates, $\dot{\epsilon}$, by applying the Anderson formula (Anderson, 1979):

$$\dot{\epsilon} = \frac{\dot{M}_o}{(2 / k) \mu V}$$

where $k (= 0.66)$ is an empirical constant that depends on the regional stress field, $\mu$ is the shear modulus (taken as $3.6 \cdot 10^{10}$ N/m$^2$), and $V = Ah$ is the seismogenic volume ($A$ indicates the area of a grid cell and $h$ is the thickness of the seimogenic layer).

In this application, $\dot{M}_o$ values are calculated by summing the moments $M_o$ of all events with $M_w \geq 4.0$ (and then dividing the cumulative moment by the observation period to obtain the rate per year) included in the catalog used by Barani et al. (2010) updated to year 2013 (to this...
end, the ISIDE database is used; http://iside.rm.ingv.it). The catalog collects both historical [the CPT104 catalog is used (Gruppo di Lavoro CPT1, 2004)] and instrumental earthquake data. Note, finally, that a Monte Carlo simulation procedure is adopted to allow for the uncertainty affecting earthquake magnitude and seismogenic thickness. Strain rate maps presented here display average results from 500 randomizations. For further details regarding the overall procedure, the reader can refer to the article of Barani et al. (2010).

**Results and discussion.** Fig. 2 shows the distribution of the seismic strain rate values before (Fig. 2a) and after (Figs. 2b and 2c) the 2012 sequence. While the maps in Figs. 2a and 2b are based on earthquake data sets collecting independent events [analogously to Barani et al. (2010)], Fig. 2c includes also the contribution of aftershocks and foreshocks recorded between year 2007 and 2013. Compared to the map in Fig. 1, the maps in Fig. 2 are computed using a finer grid, of 0.025° spacing in latitude and longitude. Comparing the three maps not only seems to confirm our suspicion about the presence of a seismicity gap (precisely, a spatial gap) between Modena and Ferrara but would also indicate that this gap was completely filled in by 2012 crisis. Note the non-negligible contribution from the stronger aftershocks following

![Fig. 2 – Comparison of seismic strain rate distributions before (a) and after (b and c) the 2012 Emilia crisis. The maps in Figs. 2a and 2b use declustered catalogs. Clusters from year 2007 to 2013 are retained to produce the map in Fig. 3c. Red circles indicate M5.5+ earthquakes occurred since 1740 (year of completeness for M5.5+ events). The major events belonging to the 2012 sequence are indicated by red stars.](image-url)
the May 20 shock, which produce an increase in the strain rate from about 1-1.5 yr\(^{-1}\) (Fig. 2b) to 2.5-3.5 yr\(^{-1}\) (Fig. 2c).

In order to identify a possible quiescence period (often named as temporal gap or gap of 2\(^{nd}\) kind) preceding the May 20 earthquake, we have analyzed the variation of the seismic moment release rate with time. More specifically, we plot 50-year running averages of the (smoothed) seismic moment release rate as a function of time (Fig. 3a) accounting for the contribution of earthquakes with magnitude \(M_w \geq 5.0\) since 1825 [which corresponds to the year of catalog completeness for M5+ events as determined by Barani et al. (2010)]. In such a way, quiescence periods are identified by minima in the \(\dot{M}_o\) curve which are attributable to seismic inactivity (particularly concerning the occurrence of moderate to large earthquakes). The temporal variation of the cumulative seismic moment (again calculated using the smoothed seismicity approach) is also shown (Fig. 3b). In this latter plot, quiescence periods are identified by “plateau” in the cumulative curve. In this study, we compare the curves for two sites, one (site S1) located close to the May 20 event and one (site S2) between the two larger aftershocks occurred on May 29 (see Fig. 2c).

Similarly to the case study of the 2009 L’Aquila earthquake, Fig. 3a evidences that the occurrence of the main shock is preceded by a minimum in the running average of \(\dot{M}_o\). The minimum in the \(\dot{M}_o\) curve, which presents a rise in the latter stages (last 15 years) before the occurrence of the main shock, corresponds to a period of time during which the seismic activity in the region surrounding the seismic gap is sporadic (i.e., earthquakes of \(M_w \geq 5.0\) are almost absent). Only five events of \(M_w\) greater than or equal to 5.0 occurred in the study region (dashed square in Fig. 1) from year 1923 to 2012, at distances greater than 30 km from the gap area.

Fig. 3 – Evolution of seismic activity (\(M_w \geq 5.0\)) in the area shocked by the Emilia 2012 seismic sequence from 1825 to 2013: 50-year running averages of the seismic moment release rate versus time (data points in the running average curve are plotted at the end of each time interval) (a); cumulative seismic moment versus time (b); distribution of earthquake magnitude versus time (c). The horizontal dashed line in Fig. 3a indicates the average moment rate calculated in the seismicity gap area. Blue circles in Fig. 3c indicate the earthquakes belonging to the 2012 sequence; the May 20 main shock is displayed by a red star.
They concentrated in a period of time of about 30 years close to the 2012 sequence, from July 1971 to January 2012. As such, this pattern may be an index of preseismic quiescence (e.g., Kanamori, 1981; Ellsworth, 1981; Scholz, 1988). Defining the length of the preseismic quiescence stage is not an easy task. One could assume the time frame going from year 1909 (occurrence of the Bassa Padana earthquake, $M_w = 5.5$) to 2012, corresponding to the “plateau” in Fig. 3b (dashed line). However, considering the average moment rate for the area under study (horizontal dashed line in Fig. 3a), it is not unreasonable to assume a wider period of time (which is not considered in the calculation due to catalog incompleteness), possibly extending from the 1570 Ferrara ($M_w = 5.5$) or 1688 Romagna ($M_w = 5.9$) earthquakes to 2012. To verify this second hypothesis, one should analyze the variation of the seismic moment release rate with time taking into consideration the contribution of the seismic activity since 1500 (despite the possible incompleteness of the catalog). Finally, comparing the results for site S1 and site S2, it is evident that the curves relevant at site S2 in Figs. 3a and 3b are influenced by the higher seismic activity characterizing the northeastern sector of the Apennine chain, at the border with the Po Plain.

Concluding, this study has revealed that the 2012 Emilia seismic crisis occurred in an area characterized by a seismicity gap and was preceded by a quiescence period of at least 100 years (or possibly wider, going back to 1570) during which the moment rate and the cumulative moment trends indicate a deficit in the release of seismic deformation. Furthermore, the study has confirmed the effectiveness of the smoothed seismicity method of Barani et al. (2011) for the detection and analysis of peculiar seismicity patterns, such as seismic gaps and quiescence periods. This makes the method useful for the monitoring of the evolution of the seismic activity in a region, as it may help in inferring the areas of occurrence of future disastrous earthquakes.

References
