Small magnitude earthquake sequences and seismic swarms in the Northern Apennines (central Italy): new observations from the analysis of Montefeltro seismicity

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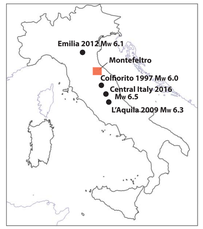
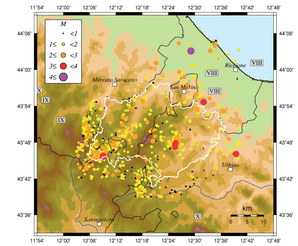
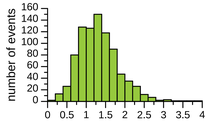
INTRODUCTION

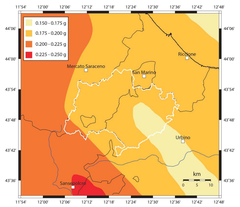
In this work we examine the seismicity of Montefeltro, a historical region of central Italy located between the northern Apennines and the Republic of San Marino towards the northern Adriatic coast. The seismicity of the northern Apennines region is mainly concentrated along the chain within a seismogenic layer that extends from about 5 to 15 km depth, commonly to other regions of the chain. Recently, important seismic sequences occurred in the central-northern Apenninic chain with magnitudes exceeding 5.5 (Colfiorito 1997, Mw 6.0; L'Aquila 2009 Mw 6.3; Emilia 2012, Mw 6.1; Central Italy 2016, Mw 6.5). Instead, the seismicity of Montefeltro, as recorded in the past three decades, appears quite widespread and discontinuous over time, except in some phases of intense activity. The magnitudes detected so far vary essentially from low to moderate, lower than 4.5 for the largest events. The seismic hazard is classified as moderate-to-high, with estimated maximum acceleration values ranging from 0.150g to 0.225g.



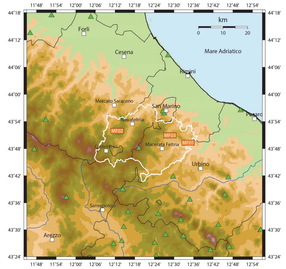


Seismicity of the Montefeltro region (white bounded area) and surrounding zones recorded by the Italian National Seismic Network (RSN) in the period 1/1/2005 - 30/9/2019 (database INGV). Rectangles display historical seismicity (I0 ≥ VIII) from the CPTI15 Parametric Catalogue of Italian Earthquakes [Rovida et al., 2016].





Seismic hazard of Montefeltro region (white bounded area) and surrounding zones (G.U. n.108 on 11/05/2006) with a probability of exceedence of 10% in 50 years.



Seismic stations of the RSN (green triangles) in the area of Central Italy including Montefeltro (white contoured area). MF01,MF02 and MF03 are the first three seismic stations of the temporary passive experiment.

station	site	sensor	recorder
MF01	Auditore	Lennartz 3D/5s	RefTek 130/SARA SL06
MF02	Sant'Agata Feltria	Guralp 3D/20s	RefTek 130
MF03	Montegrimano	Guralp 3D/40s	RefTek 130

Site location and instrumentation of the Montefeltro temporary stations.

Unfortunately, the region that includes the Montefeltro is still not adequately monitored, therefore a detailed analysis of the background seismicity, the calculation of focal mechanisms for low magnitude events, and a more reliable estimate of the b-value is limited. To better define these parameters, a temporary seismic network, consisting of mobile stations equipped with high dynamic digitizers and three-component extended/broad band seismometers, has been set up starting from December 2018 to integrate the instrumental coverage provided by the RSN. At present, the temporary network (Montefeltro passive experiment) is active with three stations in continuous recording mode at 100 sps.

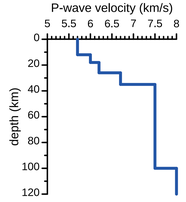
MF03 station site.
The station has been installed on the basement of the Monte San Lorenzo astronomical observatory.

EARTHQUAKE RELOCATION

We collected P and S phases from 516 earthquakes. Earthquakes were integrated with new pickings selected from the temporary array and relocated using the Hypoellipse code [Lahr, 1999].
The 1-D velocity model used in this work is based on the study by Santini et al. [2011], which was determinated for the solution of focal mechanisms of central-northern Marche.
To constrain the subcrustal seismicity of the area, we added the layers between 35 and 100 km to link the structure of crustal velocity with the superficial part of the upper mantle, as defined in the spherical global models such as iasp91, ak135 [Kennett et al., 1995]

Quality	SEH and SEZ errors	N	%
A	≤ 1.34	271	52.5
B	≤ 2.67	135	26.2
C	≤ 5.35	85	16.5
D	> 5.35	25	4.8
516 Earthquakes	Magnitude 0.5 ÷ 4.0	Depth 2 ÷ 57 km	
rms = 0.21s	V_p/V_s = 1.81 (476 eqks.)		

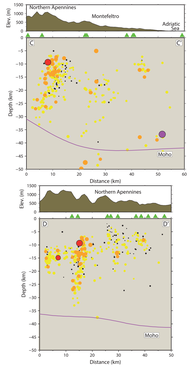
Summary of Hypoellipse relocation of the 2005-2009 dataset. SEH e SEZ give an estimate respectively of the major of the semi-axes horizontal and semi-vertical axis of the error ellipsoid hypocentral for a confidence level of 68% [Lahr, 1999]. N is the number of events which satisfy the error constraints.

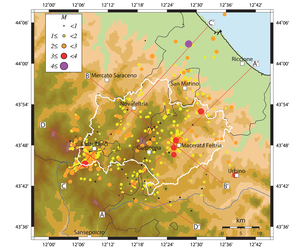


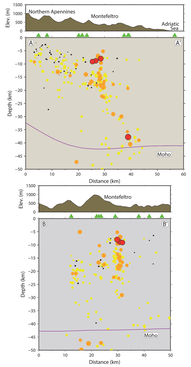
Velocity model among the various models tested, this model produced the best results in terms of quality of solutions and average rms.

Spatial distribution of the Montefeltro relocated seismicity for the period 2005-2019.

The map emphasizes the two main areas (around to Casteldelci and to Macerata Feltria) where the seismic activity has concentrated so far.





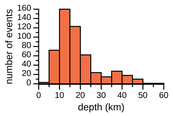


Cross-sections AA' to DD' show the extension in depth of the seismicity which permeates the entire crustal layer and part of the uppermost mantle. Moho profiles are from EuCRUST-07 model [Tesauro et al., 2008].

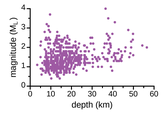
event date	focal mechanism	Lon	Lat	depth (km)	M_L	Strike (°)	Dip (°)	Rake (°)	n. pol.	n. distr.	azimuth plunge P axis	azimuth plunge T axis
18/09/2005		12.442	43.760	8.8	3.1	295	85	-40	16	4	246/ 19	342/ 15
07/10/2005		12.442	43.825	8.0	3.2	65	75	-160	12	5	287/ 15	197/ 2
30/08/2006		12.129	43.756	9.4	3.7	125	60	-30	21	6	90/ 30	357/ 2
11/11/2015		12.505	43.905	37.8	3.5	20	50	-20	43	8	330/ 28	247/ 10

Focal mechanisms calculated with the FPFIT code (Reasenberg and Oppenheimer, 1985) for the events with M_L > 3.1. Date of the events, focal mechanisms, longitudes, latitudes, depths, magnitudes, strikes, dips and rakes of the first nodal planes, number of the polarities, number of the discrepant observations, azimuths and plunges of P- and T-axes.

The focal mechanisms of the main events are of strike-slip type, similarly to those calculated by previous studies in the same area (Frepoli and Amato, 1997; Piccinini et al., 2009)



The seismicity is mostly concentrated within 25 km of depth.



The most of events have magnitudes between 0.5 and 2.0 at different depths.

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SEISMIC HAZARD MAP OF ITALY (riferimento: Ordinanza PCM del 28 aprile 2006 n.3519, All. 1b) (2006). http://zonesismiche.mi.ingv.it

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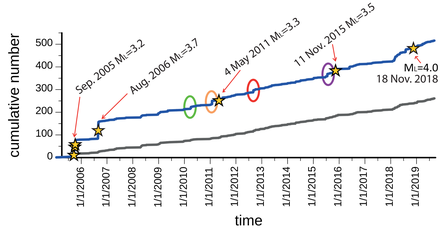
DECLUSTERING

The analysis by Zmap software [Wiemer, 2001] also showed the presence of sequences of small duration and with few events (bursts), which moreover have a hypocentral distribution rather superficial:

April 2010 (M_L 2.4, 6 events - Casteldelci),
January 2011 (M_L 2.2, 15 events - Casteldelci),
September 2012 (M_L 2.8, 6 events - Casteldelci) and
July 2015 (M_L 2.3, 10 events - Casteldelci).

The observation of these bursts confirms the evidence of a strongly clustered seismicity.

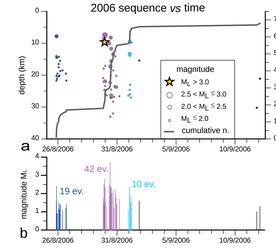


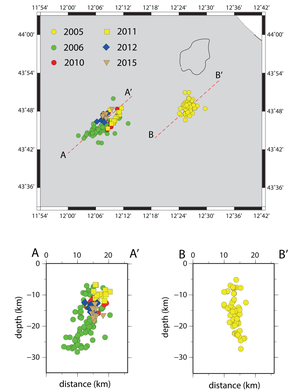
Cumulated number of the events versus time for the relocated catalogue (blu line) and for the declustered catalogue (grey line) in the area of Montefeltro.
The stars are the events of magnitude M≥ 3.0.

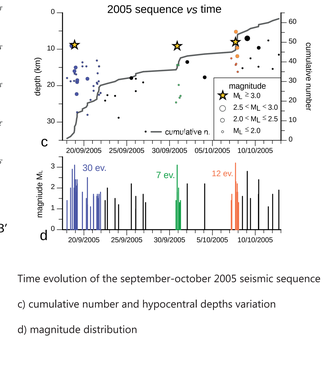
value	τ_{min} (day)	τ_{max} (day)	P	x_{meff}	R_{fact} (km)	ERH (km)	ERZ (km)
starting	1	20	0.95	1.4	5	1.0	2.0
minimum	1	10	0.90	1.4	5	1.0	2.5
maximum	1	20	0.99	1.5	30	2.0	5.0
selected	1	20	0.95	1.4	30	1.5	2.0

Starting values and ranges of parameters used in applying the Reasenberg's algorithm [Reasenberg E.A.; 1985] on the relocated earthquakes catalog. τ_{min} and τ_{max} indicate the minimum and maximum wait time for observing the next event in the sequence with a certain probability P, X_{meff} is the completeness magnitude, R_{fact} is the scale length to identify the area in which an event is considered belonging to the cluster, ERH and ERZ are the horizontal and vertical errors of the hypocentric coordinates. In the last row the parameters selected for declustering.

The most important seismic sequences, occurred in September-October 2005 (M_L = 3.2) close to Macerata Feltria and in August-September 2006 (M_L = 3.7) closer to Casteldelci. They show a complex space-time trend, presence of sub-sequences and a distribution hypocentral that extends about 25 km of depth.







Time evolution of the august-september 2006 seismic sequence:

a) cumulative number and hypocentral depths variation

b) magnitude distribution

Time evolution of the september-october 2005 seismic sequence

c) cumulative number and hypocentral depths variation

d) magnitude distribution

CONCLUSIONS

- The analysis of the seismic activity occurred in the period January 2005 – up to now shows a sporadic, rather diffuse background seismicity marked by small magnitude seismic sequences strongly clustered in time and space.
- The most important sequences occurred in September-October 2005 (M_L=3.2) and August-September 2006 (M_L=3.7), nearby the towns of Macerata Feltria and Casteldelci, respectively.The spatio-temporal evolution of these main episodes highlights an energy release consistent with swarm-like activity.
- The notable migration of the hypocentres observed for the two main sequences, suggests the possible rise of fluids as a conceivable mechanism for generating micro-seismicity at high pressure from the lower layers.
- Others minor clusters were observed in April 2010 (M_L 2.4, 6 events), January 2011 (M_L 2.2, 15 events), September 2012 (M_L 2.8, 6 events), and July 2015 (M_L 2.3, 10 events). These bursts are confined in the upper crust contrary to the swarm-like seismicity that extends up to ~25 km depth.
- The focal mechanisms of the main events are of strike-slip type, similarly to those calculated in the same area from previous studies.
- Another major feature of the seismicity pattern is represented by the occurrence of events even in the lower crust and in the upper mantle down to about 60 km depth.