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EARTHQUAKES IN THE VALMARECCHIA AREA (NORTHERN APENNINES, ITALY)

Caterina ZEI(*,**), Cecilia CIUCCIARELLI(*), Gabriele TARABUSI(*),
Cristiano GUERRA(***), Monica GHIROTTI(**) & Gianluca VALENSISE(*)

(*)*Istituto Nazionale di Geofisica e Vulcanologia*
(**)*University of Ferrara - Department of Physics and Earth Sciences - Ferrara, Italy*
(***) *University of Bologna - Department of Civil, Chemical, Environmental, and Materials Engineering - Bologna, Italy*
Corresponding author: caterina.zei@ingv.it

EXTENDED ABSTRACT

La Valmarecchia, situata tra l'Emilia-Romagna e le Marche, è un'area collocata in posizione marginale rispetto ai grandi lineamenti tettonici che interessano le zone appenniniche. Nonostante questo, nella storia ha risentito di terremoti avvenuti sia al di fuori che all'interno del suo territorio. Dal punto di vista geomorfologico e geotecnico la zona è caratterizzata da numerosi fenomeni franosi più o meno estesi. Sapendo che i terremoti sono una delle principali cause del manifestarsi di frane, in questo lavoro abbiamo indagato il possibile manifestarsi di frane sismoindotte, a partire dai terremoti del passato che hanno provocato scuotimento sensibile nell'area di studio.

Abbiamo così estratto tutti i terremoti presenti nelle banche dati nazionali per i quali i comuni della Valmarecchia hanno registrato intensità diverse da zero. Questi dati sono stati analizzati in base alla magnitudo e alla distanza dai confini esterni dell'area di studio. La distribuzione dei terremoti ha inoltre permesso di identificare le aree sismotettoniche che più facilmente provocano risentimenti. L'area della Valmarecchia può essere quindi divisa in due aree che risentono di terremoti diversi.

A partire da questa analisi abbiamo svolto un'ulteriore indagine, dapprima valutando per quale magnitudo e distanza epicentrale un terremoto avrebbe potuto e potrà causare frane sismoindotte nel territorio della Valmarecchia, e poi verificando le testimonianze di fenomeni gravitativi riportate nei portali online. Benché più della metà dei terremoti che hanno colpito la zona avrebbero potuto innescare tali fenomeni, il numero di eventi per i quali si ha un riscontro diretto tra scuotimento e frane è molto limitato. Si tratta verosimilmente di una carenza delle fonti informative, che può essere giustificata dal contesto storico, geografico e abitativo dell'area ma anche dalla marginalità sismotettonica in cui è collocata la Valmarecchia.

Questo studio vuole portare un contributo alla conoscenza della sismicità dell'area della Valmarecchia, allo stesso tempo proponendo una metodologia esportabile ad altre aree per l'individuazione di effetti sismo-indotti e delle aree predisposte al loro verificarsi.

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ABSTRACT

The Valmarecchia area, located between the Emilia-Romagna and Marche administrative regions, is characterized by numerous landslides and has been affected by earthquakes occurring both outside and inside its territory. As earthquakes are one of the main causes of gravitational phenomena, we investigated the occurrence of earthquake-induced landslides, starting from the events that were reported as felt in any of the Valmarecchia municipalities.

We analyzed their magnitude and distance from the area and identified the seismotectonic areas that generated them. We found that more than half of the earthquakes that hit Valmarecchia historically could have generated shaking-induced landslides; and yet, based on the ample documentation stored in online portals, we also found that the number of earthquakes for which there exists historical evidence for such phenomena is very limited. This is likely the result to lack of information on the correlation among earthquakes and landslides, possibly justified by the local historical and geographical context and by the seismotectonic marginality of Valmarecchia, located off the main seismogenic trends of the Italian peninsula.

We aim to improve knowledge on Valmarecchia seismicity and to illustrate a methodology for identifying both earthquake-induced effects and the areas that are prone to these phenomena

Keywords: *Valmarecchia earthquake, earthquake-induced landslides, historical earthquakes.*

INTRODUCTION

In this work we explore the landslide vulnerability to earthquake ground shaking of a 423.2 km^2 portion of the Italian northern Apennines; an area that we will consistently refer to as Valmarecchia. The area includes the entire drainage basin of the Marecchia River, located in the Italian Northern Apennines between the Emilia-Romagna and Marche administrative regions, but encompasses also selected portions of adjacent basins.

Valmarecchia includes the municipalities of Casteldelci, Sant'Agata Feltria, Pennabilli, Novafeltria, Talamello, Maiolo, San Leo, Poggio Torriana, Verucchio and Santarcangelo di Romagna all falling within the administrative province of Rimini (RN) (Fig. 1).

From a geological point of view, the study area is marked by a unique geological occurrence, known as the Valmarecchia thrust sheet. The oldest Ligurian Units and the younger Epi Ligurian Units, which are related to different depositional cycles, overthrusted autochthonous units of the Umbro-Marchean-Romagna domain overlying the foreland units of the Adria continental microplate. The Epiligurian Units, which include more competent rocks such as sandstones and calcarenites, rest unconformably on the Ligurian Units (varicoloured clays, marls and limestones), creating high grounds named Epiligurian plates or slabs (Spreafico *et alii*, 2015). The slabs are often tectonized and crossed by several joint sets and faults, and are often tilted and affected by lateral spreading phenomena and associated rock topples and falls. In addition, the underlying clayey substratum

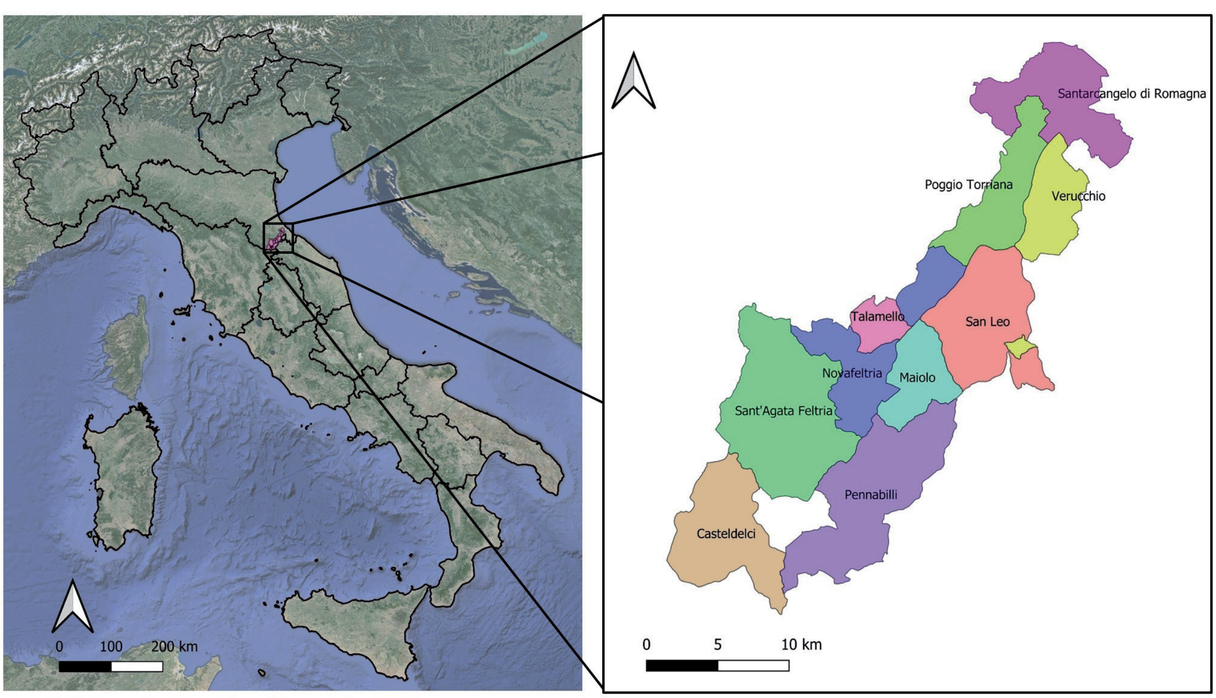

Fig. 1 - Overview of Valmarecchia, our study area, showing the 10 municipalities comprising it. Epicentral distances of earthquakes occurring outside Valmarecchia are calculated with reference to the external enevelope of all municipalities, whereas the distance of events falling within the study area is assumed to be zero

is involved in slow-moving landslides, giving rise to earth slides and flows (Casagli, 1994). The main cause of instability, which brings about these rather widespread phenomena, is the high deformability contrast between the plates and the underlying clays (D'Ambra *et alii*, 2004). Other factors leading to diffuse instability are the structural setting of these slabs, the groundwater flow inside the plates and the consequent destabilization of the basal clays; together with creep and flows in the underlying clay, these conditions undermine the foot of the rocky plates and causes the opening and widening of vertical fractures in the rock masses (Spreafico *et alii*, 2015).

Given this complex framework, we aim to explore the potential role of earthquakes in triggering instability phenomena, or in contributing to their evolution.

DATA AND METHODS

We extracted from the CPTI15 database (Rovida *et alii*, 2022) and carefully analyzed all earthquakes for which macroseismic intensities other than zero were reported in any of the Valmarecchia municipalities (Tab. 1).

EPICENTRAL AREA	Year	Month	Day (hour)	MwDef	Lat_Epicenter WGS84	Lon_Epicenter WGS84
Riminese*	1672	4	14	5,59	43,941	12,576
Cagliese	1781	6	3	6,51	43,596	12,512
Faentino*	1781	7	17	5,61	44,268	11,987
Riminese*	1786	12	25	5,66	43,991	12,565
Appennino marchigiano*	1873	3	12	5,85	43,089	13,244
Costa romagnola*	1875	3	17	5,74	44,209	12,659
Cesena	1881	9	28	4,71	44,142	12,189
Pianura Padana	1885	2	26	5,01	45,209	10,169
Liguria occidentale*	1887	2	23	6,27	43,891	7,992
Gargano	1889	12	8	5,47	41,83	15,688
San Piero a Sieve	1889	12	12	4,16	43,898	11,643
Valle d'Illasi*	1891	6	7	5,87	45,564	11,165
Fiorentino*	1895	5	18	5,5	43,703	11,264
Sant'Agata Feltria	1896	1	31	3,7	43,864	12,209
Marche settentrionali	1897	9	21	5,4	43,706	12,966
Alta Valtiberina*	1897	12	18	5,09	43,498	12,382
Bagno di Romagna	1899	7	8	4,02	44,01	11,822
Emilia Romagna orientale	1909	1	13	5,36	44,579	11,688
Crete Senesi	1909	8	25	5,34	43,15	11,403
Forlivese*	1911	2	19	5,26	44,117	12,074
Forlivese	1911	3	20	5,09	44,189	12,193
Riminese	1911	3	26	5,04	44,061	12,508
Casentino*	1911	3	26	4,54	43,811	11,816
Casentino	1913	7	29	4,54	43,814	11,89
Lucchesia	1914	10	27	5,63	43,912	10,598
Marsica	1915	1	13	7,08	42,014	13,53
Riminese*	1916	8	16	5,82	44,019	12,737
Riminese*	1916	5	17	5,82	44,119	12,748
Riminese*	1916	6	16	4,82	44,089	12,674
Alta Valtiberina*	1917	4	26	5,99	43,467	12,129
Appennino forlivese*	1918	11	10	5,96	43,917	11,933
Mugello*	1919	6	29	6,38	43,957	11,482
Garfagnana*	1920	9	7	6,53	44,185	10,278
Senigallia*	1924	1	2	5,48	43,737	13,138
Mugello	1929	7	18	4,96	43,988	11,507
Senigallia	1930	10	30	5,83	43,689	13,385
Alta Valtiberina*	1948	6	13	5,04	43,598	12,127
Appennino forlivese*	1952	7	4	4,94	43,98	11,883

EPICENTRAL AREA	Year	Month	Day (hour)	MwDef	Lat_Epicenter WGS84	Lon_Epicenter WGS84
Appennino forlivese	1953	12	14	4,7	44,064	12,061
Appennino forlivese*	1956	5	26	4,99	43,939	11,897
Appennino forlivese*	1956	6	3	4,51	44,003	11,876
Alta Valtiberina	1957	4	30	4,23	43,733	12,013
Montefeltro	1960	4	15	4,45	43,708	12,297
Forlivese	1961	5	8	4,37	44,134	11,962
Montefeltro	1962	8	30	4,76	43,877	12,144
Pianura Ravennate	1969	1	10	4,38	44,39	11,983
Appennino tosco-romagnolo	1969	8	9	4,2	43,76	11,962
Costa pesarese	1972	11	30	4,52	44,015	13,106
Irpinia-Basilicata*	1980	11	23	6,81	40,842	15,283
Monti della Meta*	1984	5	7	5,86	41,667	14,057
Umbria settentrionale	1984	4	29	5,62	43,262	12,525
Appennino forlivese	1985	11	24	4,29	43,844	12,017
Costa Marchigiana	1987	7	3	5,06	43,198	13,902
Montefeltro	1987	7	5	4,44	43,758	12,208
Montefeltro	1987	7	8	3,7	43,779	12,245
Montefeltro	1989	7	9	4,09	43,67	12,209
Alta Valtiberina	1990	5	8	3,77	43,576	12,18
Casentino	1991	1	14	4,26	43,781	11,853
Valle del Topino	1993	6	5	4,72	43,121	12,724
Forlivese	1995	12	27	3,97	44,156	12,113
Appennino umbro-marchigiano*	1997	9	26 (h 0.33)	5,66	43,022	12,891
Appennino umbro-marchigiano*	1997	9	26 (h 9.24)	5,97	43,014	12,853
Valnerina	1997	10	14	5,62	42,898	12,898
Alta Valtiberina	1997	10	2	4,42	43,627	12,172
Appennino umbro-marchigiano	1998	4	5	4,78	43,189	12,767
Appennino forlivese	1999	1	25	4,36	43,98	11,962
Faentino	2000	5	10	4,82	44,243	11,932
Faentino	2000	5	8	4,67	44,279	11,917
Montefeltro	2000	8	1	4,27	43,905	12,337
Casentino	2001	11	26	4,63	43,6	12,108
Casentino	2002	2	21	4,09	43,76	12,033
Appennino forlivese	2003	1	26 (h 19.57)	4,66	43,883	11,96
Appennino forlivese	2003	1	26 (h.20.25)	4,5	43,875	11,959
Forlivese	2003	12	7	4,18	44,162	12,18
Appennino forlivese	2003	1	29	4,06	43,898	11,926

*Tab. 1 - Full parameters of 75 earthquakes having reported macroseismic intensity >0 in at least one locality of the Valmarecchia area. Epicentral coordinates are expressed in WGS4 EPSG:4326. All data are from the CPTI database (Rovida et alii, 2022). Earthquakes with * have the CFTI5Med as the reference study*

The CPTI database shows that 75 earthquakes were felt within the study area, of which 27 use the CFTI5Med as the reference study (GUIDOBONI *et alii*, 2018). Only four of these 75 events fall within the territory of Valmarecchia. Table 2 shows their magnitude distribution.

M_w range	Earthquakes
M_w<4.5	21
4.5≤M_w< 5.5	30
5.5≤M_w<6.5	20
M_w≥6.5	4

Tab. 2 - Number of investigated earthquakes for each magnitude class (see Tab. 1)

We then calculated the distance of all 75 earthquakes, from their epicenter to the closest point along the external boundary of Valmarecchia.We found that:

- 21 earthquakes of M_w < 4.5 fall at a maximum distance of 55-60 km from the Valmarecchia area. This magnitude class includes events located within the study area; these were felt in all municipalities. All the other shocks were recorded mainly in the municipalities of Pennabilli, Sant'Agata, Casteldelci, and Novafeltria, with intensity IV-V MCS or lower;
- 30 earthquakes in the range 4.5 ≤ M_w < 5.5 fall within 90 km of the study area, 14 of which are located 15-30 km from it. These earthquakes are rarely felt in the municipalities of Talamello, Verucchio, San Leo, Poggio Torriana, Maiolo. Pennabilli, Casteldelci, Novafeltria reported rather low intensities for some of these events, whereas all shocks were felt in Sant'Agata Feltria;
- out of 20 earthquakes in the range 5.5 ≤ M_w < 6.5, 15 fall at a distance up to 130 km from the study area. Six of them located 10-30 km from the study area. These earthquakes were felt in all municipalities, except for Maiolo and Talamello;
- four earthquakes of M_w ≥ 6.5 located within 100 km of Valmarecchia had intensity between VI and VII MCS in the study area. Other larger earthquakes located over 100 km from Valmarecchia were felt at some locations with intensity III to IV MCS;
- depending on distance from Valmarecchia, there are 35 earthquakes within a distance 30 km, and 20 distributed continuously over the range 30 to 100 km, and 12 over 100 km. The maximum concentration of earthquakes occurs within a distance of 10-30 km from the study area (Tab. 3).

Distance	Earthquakes	Magnitude
between 10 and 30 km	10	M_w<4.5
	14	4.5≤ M_w <5.5
	5	5.5≤ M_w <6.5

Tab. 3 - Magnitude distribution of earthquakes in the distance range 10 to 30 km from Valmarecchia (see Tab. 1)

Based on their location, all earthquakes were assigned to one of 11 seismotectonic districts, with the exception of 11 isolated events (Tab. 4).

Area	Earthquakes
Appennino Forlivese	10
Forlivese	7
Montefeltro	7
Riminese	7
Casentino	6
Alta Valtiberina	6
Appennino Umbro-Marchigiano	6
Mugello	3
Faentino	3
Senigallia	3
Distant or isolated earthquakes	8

Tab. 4 - Earthquake distribution by seismotectonic districts

The four main seismotectonic districts are described below (Tabb. 5-8, Fig. 2).

Epicentral area	Year	M_wDef
Bagno di Romagna	1899	4.02
Appennino forlivese	1918	5.96
Appennino forlivese	1952	4.94
Appennino forlivese	1956	4.99
Appennino forlivese	1956	4.51
Appennino forlivese	1985	4.29
Appennino forlivese	1999	4.36
Appennino forlivese	2003	4.66
Appennino forlivese	2003	4.5
Appennino forlivese	2003	4.06

Tab. 5 - Earthquakes falling in the Forlivese Apennines seismotectonic district (Fig. 2a)

The municipalities most affected by the earthquakes in the Forlivese Apennines seismotectonic district (Tab. 5, Fig. 2a), were Casteldelci, Sant'Agata Feltria, Pennabilli, and Novafeltria (Apennine area), although the intensity did not exceed V MCS.

Despite the larger magnitude of the 10 November 1918 earthquake, intensities were reported only for Casteldelci (VI MCS), Santarcangelo di Romagna (IV MCS), and San Leo (IV-V MCS). Conversely, the January 2003 earthquake sequence, having a lower magnitude but the same location and epicentral distance, was reported over the entire Valmarecchia Apennines area, probably as a result of more efficient means of transferring the information.

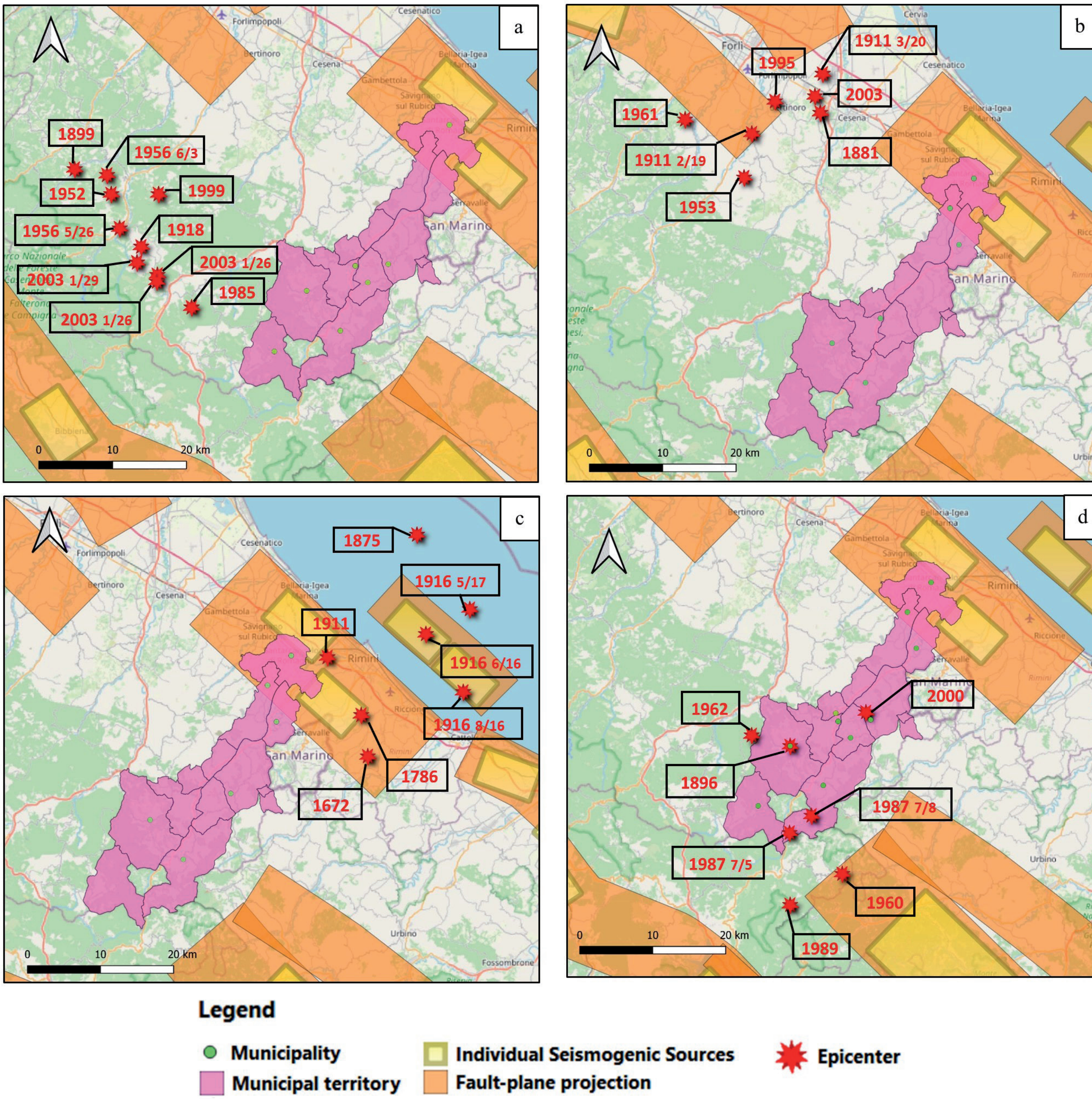

Fig. 2 - Distribution of the four main seismotectonic districts. Red stars and the associated labels indicate the earthquake location and date of occurrence, respectively. Green dots show the municipalities that reported intensity different from 0. Key: a) Forlivese Apennines (10 events); b) Forlivese piedmont area (7 events); c) Riminese area (6 events); d) Montefeltro area (6 events)

The earthquakes of the Forlivese piedmont seismotectonic area (Tab. 6, Fig. 2b) were recorded mainly in the municipalities of Sant'Agata Feltria, Santarcangelo di Romagna and Poggio Torriana with intensity betwen III-IV MCS. Sant'Agata Feltria, however, experienced a maximum intensity VI MCS during the 19 February 1911 earthquake (M_w 5.26). Some events were reported felt in Pennabilli, Verucchio, and Novafeltria.

The municipality most affected by the earthquakes in the Riminese seismotectonic area (Tab. 7, Fig. 2c) is Santarcangelo di Romagna (6 of 7 earthquakes). Verucchio (3 of 7), San Leo (3 of 7) and Poggio Torriana (1 of 7) were shaken less severely. Maximum reported intensities are in the range VI-VII to VII MCS. Sant'Agata Feltria and Pennabilli were marginally affected by some of these shocks (III-IV MCS).

Epicentral area	Year	M_wDef
Cesena	1881	4.71
Forlivese	1911	5.26
Forlivese	1911	5.09
Appennino forlivese	1953	4.7
Forlivese	1961	4.37
Forlivese	1995	3.97
Forlivese	2003	4.18

Tab. 6 - Earthquakes falling in the Forlivese piedmont seismotectonic area (Fig. 2b)

Epicentral area	Year	MwDef
Riminese	1672	5.59
Riminese	1786	5.66
Costa romagnola	1875	5.74
Riminese	1911	5.04
Riminese	1916	5.82
Riminese	1916	5.82
Riminese	1916	4.82

Tab. 7 - Earthquakes falling in the Riminese seismotectonic area (Fig. 2c)

Epicentral area	Year	M_wDef
Sant'Agata Feltria	1896	3.7
Montefeltro	1960	4.45
Montefeltro	1962	4.76
Montefeltro	1987	4.44
Montefeltro	1987	3.7
Montefeltro	1989	4.09
Montefeltro	2000	4.27

Tab. 8 - Earthquakes falling in the Montefeltro seismotectonic area (Fig. 2d)

The 1 August 2000 earthquake (Tab. 8, Fig. 2d), located within the municipal territory of San Leo, is the only one in the entire earthquake history of Valmarecchia for which intensities in all municipalities were reported. More specifically, the largest intensities were felt in San Leo (VI MCS, 1.2 km from the epicenter), Talamello and Maiolo intensity (both V-VI, both 4 km from the epicenter). The other earthquakes of the Montefeltro seismotectonic area (Tab. 8, Fig 2d) were felt in Casteledelci, Sant'Agata Feltria, and Pennabilli municipalities.

EARTHQUAKE-INDUCED ENVIRONMENTAL EFFECTS

CFTI5Med data show that all earthquakes of $M_w \geq 3.7$ are generally felt in one or more Valmarecchia municipalities, and that 56 events with intensity III-IV MCS and larger. Nevertheless, no landslides are reported in CFTI5Med (Guidoboni *et alii*, 2018), CFTIlandslide (Zei *et alii*, 2024; Zei *et alii*, 2024), CEDIT (Martino *et alii*, 2012) and EEECatalogue (http://eeecatalogue.isprambiente.it/; Guerrieri, 2012), although the geology of the area certainly makes it prone to such phenomena. Guerra (2014) conducted a systematic search of local parish and municipal archives and of the collections of the Archivio di Stato of Pesaro, looking for evidence of historical landslides in seven municipalities of Valmarecchia (Casteldelci, Maiolo Novafeltria, Pennabilli, San Leo, S. Agata Feltria and Talamello). The investigation brought to light 74 written sources from the interval 15th-20th century, relating to 20 well identified landslides and their (in some cases numerous) reactivations. Yet, none of them were explicitly reported as being caused by an earthquake. With the only exception of a 1875 document (see below), no evidence of landslide triggering or reactivation can be chronologically referred to any of the earthquakes felt in the area (Tab. 1).

Earthquake-Induced Landslides (EILs)

About 35% of the Valmarecchia territory is known to be affected by landslides: the Italian official landslide inventory (IFFI) (https://www.progettoiffi.isprambiente.it/) reports 3334 effects for the area., of which about 66% is active and 34% is quiescent (Regione Emilia-Romagna, 2024). 73% of the landslides has no specified movement typology, 19% are considered as rotational landslides, debris flows or lateral spreads, and 0.9% are listed as rockfalls. We decided to verify if the region is prone to landsliding due to earthquake activity. We first subdivided all earthquakes that are known to have affected Valmarecchia into three magnitude classes: Class 1: $M_w < 5.5$; Class 2: $5.5 \leq M_w < 6.5$; and Class 3: $M_w \geq 6.5$. Then, following Cinosi *et alii* (2023) we set circular search areas centered on the earthquake epicenter of each earthquake, using a 5 km moving window: for each area we then calculated the cumulative density of known Earthquake-Induced Landslides (EILs). We found that the cumulative density decreases with distance following a power law relationship, and that the distance that includes the 95th percentile of the landslide distribution increases for an increasing magnitude range. Tab. 9 shows the calculated distances for each M_w class.

We retained all the earthquakes for which the 95th percentile epicentral distance partially or completely includes the study area.

Earthquakes	M_w Class	95th percentile distance (km)
39	M< 5.5	42
10	5.5≤M<6.5	66
1	M≥6.5	77

Tab. 9 - Distribution of earthquakes by magnitude classes and corresponding 95th percentile distance

This procedure returned 50 earthquakes, all of which positively affected Valmarecchia. Notice that the only earthquake having $M_w \geq 6.5$ occurred on 3 June 1781 in the Appennino marchigiano, at a minimum distance of 26 km from the Valmarecchia area.

In remote and sparsely inhabited areas, such as most of the Apennines, landslides are commonly testified when they affect buildings, communication routes or productive landfields. For this reason we selected the 57 landslides reported in IFFI that affected SS 258, the main state road crossing the study area. To determine if they were related to ground shaking, we analyzed the triggering of each landslide as reported in the database. Pennabilli is the municipality that suffered the largest number of landslides (23). For only one of these landslides IFFI described the triggering mechanism, which was not earthquake shaking.
We also searched the Landslide Inventory Map and Historical Landslide Archive of the Emilia Romagna Region portal (Regione Emilia-Romagna, 2024) for any reported landslide in any of the Valmarecchia municipalities. This inventory includes the results obtained by Guerra (2014). The Soanne landslide (Fosso della Rupina) (Regione Emilia-Romagna, 2024), in the municipality of Pennabilli, is the only landslide mentioned that could be indirectly related to an earthquake. It is an active landslide of indeterminate type, and the cause of its activation in autumn 1875 is not specified.

RESULTS AND DISCUSSION

The 75 earthquakes that were reported with a sizable intensity in Valmarecchia allowed us to identify two main areas of earthquake impact, which we refer to as western and eastern. The first is of a purely Apennines relevance and caused comparable intensity levels in the municipalities of Casteldelci, Novafeltria, Pennabilli and Sant'Agata. The latter town is the most sensitive to earthquakes, which cause consistently higher intensity. The eastern quadrant includes the municipalities of Maiolo, Poggio Torriana, San Leo, and Santarcangelo di Romagna, Talamello and Verucchio. For thesewe can make a more accurate distinction among the localities based on two dominant behaviors. Maiolo, Poggio Torriana, Talamello and Verucchio rarely report earthquakes, whereas San Leo and especially Santarcangelo di Romagna are more likely to report shaking. This distinction rests on the available historical evidence and probably related to the size and historical importance of these municipalities. Those of the first subgroup are smaller and less populated; the other two were more urbanized and developed, therefore are more likely to have reported information on earthquake shaking. The municipalities of Sant'Agata Feltria and Santarcangelo di Romagna are most susceptible to earthquake shaking, whereas in Maiolo, Poggio Torriana, Verucchio – and above all, Talamello – earthquakes are hardly ever felt, and hence reported.

The earthquakes felt in the Valmarecchia area are much variable in sizes, from $M_w < 4.5$ to $M_w \geq 6.5$, with a greater frequency of $4.5 \leq M_w < 5.5$. Their epicenters, except for those located within Valmarecchia, concentrate between 10 and 30 km from the boundaries of the study area. The earthquakes falling in this distance range tend to have magnitude lower than 5.5 and concentrated to the west of our study area, while the few having magnitude between 5.5 and 6.5 concentrate to the east of it, in the Rimini area. Therefore, for an equal distance from the study area, the seismogenic district capable of generating the largest earthquakes is that of Rimini.

Various seismogenic districts may shake Valmarecchia. The main ones are:

- the Forlì Apennines, which may cause earthquakes of magnitude up to 6.0 that are felt entirely in the western quadrant with intensity not exceeding V MCS;
- the Forlì area, that rarely generates tremors exceeding magnitude 5.0;
- the extreme eastern quadrant of the study area (earthquakes felt in Santarcangelo di Romagna and Poggio Torriana) and the extreme western quadrant (earthquakes felt in Sant'Agata Feltria);
- the Rimini area, that may generate earthquakes larger than M_w 5.5, causing up to intensity VII MCS in the eastern part of Valmarecchia.

The other seismotectonic districts did not cause significant effects in Valmarecchia, except for the 29 June 1919 earthquake in Mugello. Among all earthquakes of magnitude larger than 6.0, this is the event located closest to Valmarecchia (about 50 km), causing shaking of intensity VI to VII particularly in its western portion.

Earthquakes rarely reach magnitude 5.5 within the Valmarecchia area, and only occasionally they produced shaking of intensity up to VI MCS at specific locations.

Nevertheless, the 17 March 1875 earthquake (https://storing.ingv.it/cfti/cfti5/quake.php?10615IT) was widely and strongly felt along the Romagna coast and had an intensity III-IV MCS in Pennabilli. Knowing that pulses of increased landslide frequency may last for 10 years after an earthquake (Fan *et alii*, 2019), this landslide may well be related to the 17 March 1875 event.

Despite the absence of information on earthquake-induced effects, the magnitude of the 75 investigated earthquakes (see Tab. 1) and their reported intensities were large enough to cause at least some effect on the environment. In particular, based on the combination of magnitude and epicentral distance (Tab. 9), our analysis suggests that 50 out of 75 earthquakes were capable of causing earthquake-induced landslides.

The absence of information on earthquake-induced effects may indeed be justified by a combination of historical, territorial, and geomorphological circumstances. All municipalities, with the exception of Santarcangelo di Romagna, hardly ever

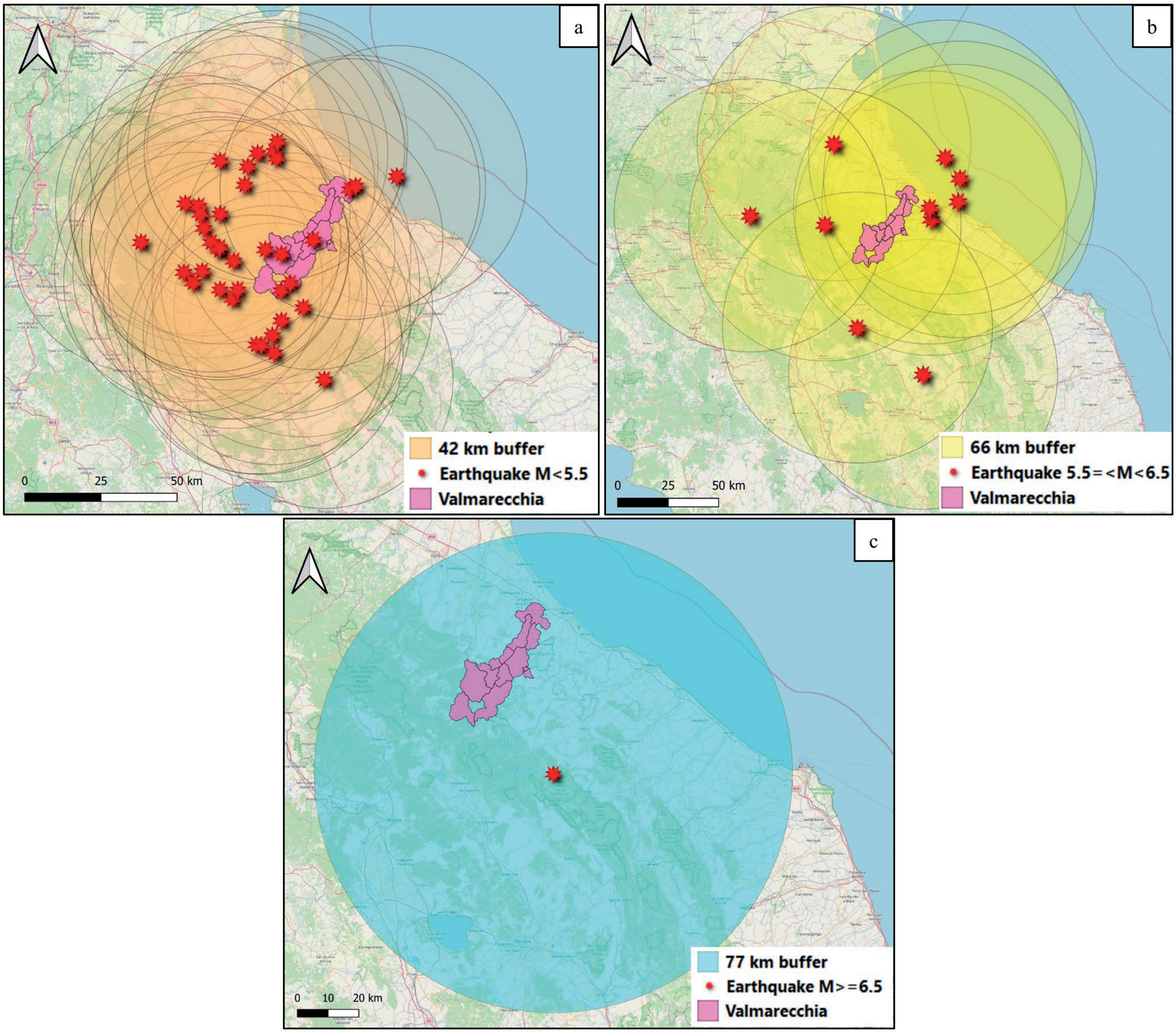

Fig. 3 - 95th percentile distance buffers for three selected Mw classes (see text for details). The figure shows the earthquakes whose distance buffer overlaps fully or partially the Valmarecchia area: a) earthquakes of M_w < 5.5 (42 km, orange buffer); (b) earthquakes of 5.5 ≤ M_w < 6.5 (66 km, yellow buffer; c) earthquake of M_w ≥ 6.5 (77 km, light blue buffer)

exceeded a population of 5.000 inhabitants, and population density is very low, especially in Apennines areas. From an historical-administrative point of view, up until the unification of Italy in 1861 Valmarecchia was a peripheral area of the Papal State, located at the border with the Grand Duchy of Tuscany; a rugged mountainous area, much less developed than its coastal counterpart. The only reliable communication route used for commercial purposes was the current national road SS 258, which connects Valmarecchia with Tuscany through Passo di Viamaggio (983 m above sea level).

The apparent lack of data on earthquake-induced landslides may be justified also by the nature of post-earthquake surveys, especially for historical events such as the 10 November 1918 and 29 June 1919 earthquakes, when Valmarecchia suffered shaking of intensity up to VII MCS. The documentation produced by central administrations was based on reporting the damage to dwellings and paid little attention to environmental effects, which were briefly mentioned only when they involved buildings. For this reason, evidence of historical landslides in Valmarecchia exists only in relation to damage caused by hydrogeological instability to buildings and communication routes. More specifically, the historical sources available for the 1918 and 1919 earthquakes mention only damage to buildings, often mixing the effects of the two events due to their chronological proximity and to the overlap of their epicentral areas. Under these circumstances, the lack of information from the epicentral areas of these two earthquakes is inevitable, in particular for marginal areas such as Valmarecchia.

We already remarked that the causal factors of landslides reported by IFFI as having affected state route SS 258 are unknown. As a result, it cannot be ruled out that some of these landslides were triggered by earthquakes. The new CFTIlandslides database (Zei *et alii*, 2024; Zei *et alii*, 2024) shows that the most common earthquake-induced landslide type is rockfall; yet, for 73% of Valmarecchia landslides the type of movement is undefined, whereas 19% are considered as rotational landslides, debris flows or lateral spreads, and only 0.9% are listed as rockfalls. This evident mismatch might explain the apparent low frequency of occurrence of genuine earthquake-induced landslides.

CONCLUSIONS

Knowing that earthquakes are one of the main causes of gravitational phenomena, we investigated the occurrence of earthquake-induced landslides through the history of the broader Valmarecchia area.

Our main finding is that the magnitude and intensity of at least 75 of the earthquakes we investigated were large enough to cause at least some effect on the environment, and yet the information available on earthquake-induced effects throughout the entire Valmarecchia is very limited. We found that this substantial lack of information may be justified by a combination of historical, territorial, and geomorphological circumstances.

Valmarecchia may be adversely affected by the activity of multiple, highly productive seismogenic areas: the most hazardous are those referred to as Riminese and Appennino Forlivese, both of which may generate rather frequent and relatively large earthquakes. From the point of view of historical earthquake shaking, Valmarecchia can be subdived into two distinct portions: a western area, that is closer to the Apennines proper and for which several events are reported, and an esatern area, closer to the Adriatic shoreline, that has been primarily affected by Riminese earthquakes.

The historical witnesses for severe ground shaking, whose availability is primarily controlled by differences in the density of population, play a key role in the understanding of the effects of past earthquakes and in the assessment of their impact, both on the built and on the natural environment. Larger and more densely populated municipalities, such as Sant'Agata Feltria and Santarcangelo di Romagna, generally reported a larger number of felt earthquakes, whereas more sparsely populated areas remained largely silent.

The administrative and economic setting of different parts of Valmarecchia also played a role in reducing the number of available witnesses: this variability is probably the main reason for the lack of evidence of earthquake-induced effects on the environment. In addition, the contrast between the most common type of movement of earthquake-induced landslides and the type of movement detected for the majority of the Valmarecchia landslides may further reduce the quantity of shaking-induced landslides we may expect.

Finally, we wish to stress that this work was primarily based on historical data, whose availability definitely suffered from the limited consideration of environmental phenomena in most post-earthquake surveys. More targeted research on specific earthquakes and their effects is needed to improve the understanding of historical earthquake-induced effects in Valmarecchia, and prepare for future ones.

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