1   **Seismicity rate changes and geodetic transients in Central Apennines**

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12   **Key Points:**

13   • Sub-horizontal shear zone beneath the shallow normal faults of Central Apennines is
14   segmented into high and low seismicity rate strands

15   • Rate changes in seismicity are time-correlated with a transient deformation observed
16   before the 2016 Central Italy sequence

17   • Mw5+ earthquakes on the Campotosto fault highlight a connection between high rate
18   shear zone segments and locked fault patches

19

20

21 **Abstract**

22 Using template matching and GPS data, we investigate the evolution of seismicity and
23 observable deformation in Central Apennines. Seismicity appears more persistent at the base of
24 the seismogenic layer than in the shallower crust. Diffuse activity is reported on segments at
25 depth, alternating along strike with apparent quiescence on segments that experienced one or
26 more Mw6+ earthquakes in 1997, 2009 and 2016. Central Apennines are likely underlain by a
27 sizeable shear zone with areas of diffuse seismicity bounding shallow normal faults where
28 Mw6+ earthquakes occurred. The deformation observed at the surface seems to follow the
29 seismicity variations at the base of seismogenic layer along the Apenninic chain. Principal and
30 independent component analysis of GPS data exhibits a transient when the 2016 foreshock
31 sequence starts. This transient propagated northward from the Campotosto fault up to the Alto
32 Tiberina fault system and has likely loaded the Mw6+ 2016 earthquake sequence.

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34 **Plain Language Summary**

35 We use a non-standard method for the detection of microseismicity at depth augmenting the
36 available catalog. The enhanced seismicity distribution is coupled with the observable
37 deformation on a geodetic network of continuous GPS to infer a better comprehension of the
38 earthquake behaviour. The earthquake patterns in Central Apennines reveal a segmentation at
39 depth along an almost flat base of seismogenic layer with alternating low and high seismicity
40 rate segments. The deformation recorded at the surface seems to follow the seismicity variations
41 at the base of seismogenic layer along the Apenninic chain also determining a possible seismic-
42 aseismic mode. We suggest that aseismic deformation has a fundamental role in the tectonic
43 loading and that seismicity, even if heterogeneously distributed, could represent a tracer of it.
44 This conclusion is also supported by the evidence of a transient propagating from south to north
45 during the 2016 Central Italy sequence.
46

1 Introduction

Historical and recent destructive earthquakes in the Central Apennines, Italy (Amato et al., 1998; Chiaraluce et al., 2017; Rovida et al., 2011; Valoroso et al., 2013) occur mostly along the NW-SE trending system of normal faults, where 2 to 3 mm/year of extension perpendicular to the Apennines is accommodated (D'Agostino et al., 2011). The fault system is located above a delaminating Adria lithosphere (Aoudia et al. 2007; Chimera et al., 2003) within a complex tectonic setting (e.g. Calamita et al., 2003; Doglioni, 1991).

Central Apennines were recently struck by three destructive earthquake sequences, namely Umbria-Marche 1997, L'Aquila 2009 and Amatrice-Visso-Norcia 2016-2017. A large number of foreshocks and aftershocks was relocated using both continuous and temporary networks (Amato et al., 1998; Chiaraluce et al., 2003; Chiaraluce et al., 2011; Chiaraluce et al., 2017; Improta et al., 2019; Valoroso et al., 2013; Vuan et al., 2017) to depict the geometry of the system. The relocated catalogues of L'Aquila and Amatrice-Visso-Norcia sequences show a sub-horizontal and gently east-dipping Shear Zone (SZ) at the base of the seismogenic volume, between 8 and 12 km. The sub-horizontal geometry of SZ is confirmed by focal solutions of foreshocks and aftershocks at the base of Campotosto and Monte Vettore faults (Chiaraluce et al., 2017; Improta et al., 2019; Valoroso et al., 2013). Deep seismic profiles and geologic cross-sections show a horizontal SZ between 8 and 11 km as a transition from sedimentary into basement units (e.g. Porreca et al. 2018). This transition corresponds to the observed velocity changes underneath L'Aquila and Amatrice-Visso-Norcia sequences as inferred by local earthquake travel-time tomography (Buttinelli et al. 2018; Chiarabba et al. 2018).

Before the L'Aquila 2009 mainshock, a foreshock sequence started in the area adjacent to the nucleation point of the Mw6.3 mainshock along the Paganica normal fault (Valoroso et al., 2013). Sugan et al. (2014) identified three phases of foreshock migration towards the nucleation point of the April 6th 2009 mainshock, with one in mid-February interpreted as a slow-slip transient. The same transient was identified using GPS data by Borghi et al. (2016), who attributed it to a M6.1 slow-slip event. It was suggested that the transient took place over a sub-horizontal SZ at the base of Paganica and Campotosto faults involving the lateral extent of the aftershock sequence, causing stress loading close to the L'Aquila mainshock nucleation. Before the Amatrice, August 24th 2016 earthquake, Vuan et al. (2017) on the base of newly detected foreshocks, proposed that slip along the SZ increased the stress around the source area of the mainshock, therefore contributing to the unlocking of the overlying normal faults.
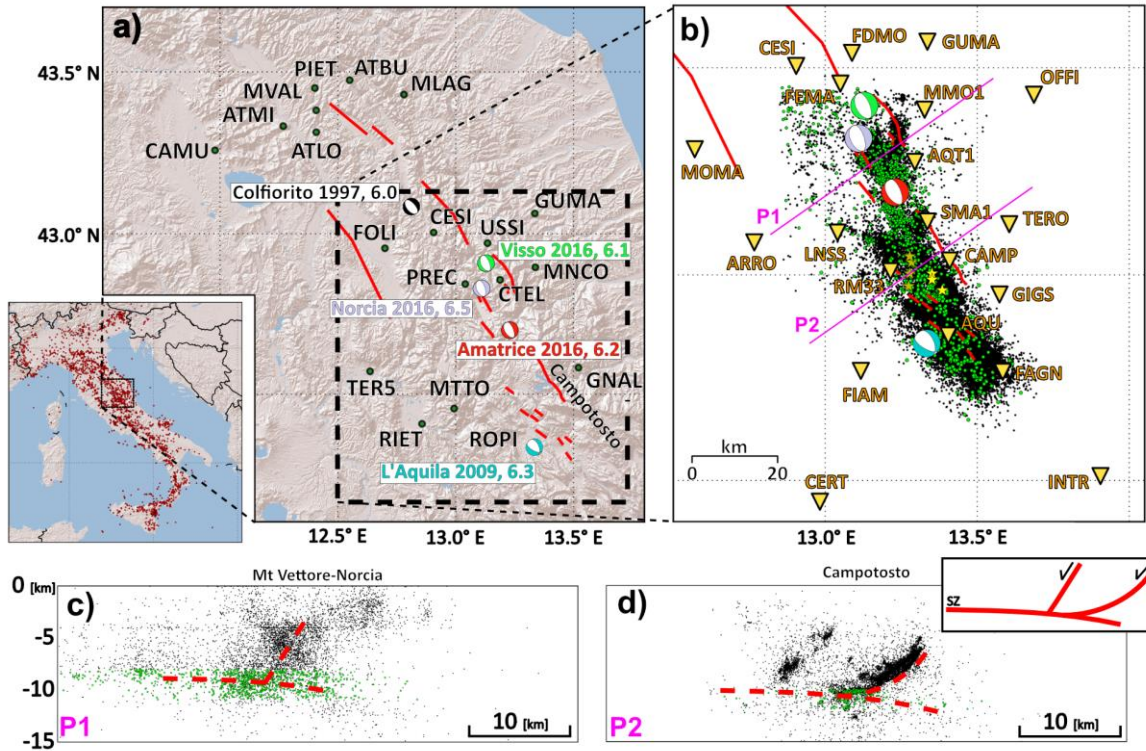
Figure 1: Studied area of Central Italy. a) Map of destructive earthquakes since 1997 in the studied area. Beach ball colours refer to the same events in figure 1a, b. Red lines represent causative faults responsible for the mainshocks. In green we plot the continuous GPS stations. b) Triangles represent seismic stations used in this study. Black dots are earthquakes of 2009 L'Aquila and 2016 Amatrice-Visso-Norcia sequences. With green we show selected template earthquakes. c) and d) are cross-sections over Amatrice-Visso-Norcia and L'Aquila epicentral areas. In d) we show an idealized profile over the area with normal faults, mature listric faults and shear-zone.

Among the mentioned faults, the geometry and seismic potential of the Campotosto fault (Fig 1a, d) (hereafter Cf) for producing large earthquakes has been a matter of debate, especially after the occurrence of 2009 and 2016-2017 Mw5+ events (i.e. Chiaraluce et al., 2011; Cheloni et al., 2014; Cheloni et al., 2019; Falcucci et al., 2018; Gualandi et al., 2014; Valoroso et al., 2013). Cf is situated in the western flank of the Laga Mountains, oriented ~18km toward the northwest and dips toward the southwest with a listric geometry, as suggested from seismic data (Chiaraluce et al., 2011). This geometry was not retrieved from the GPS and InSAR studies (Cheloni et al., 2014; Cheloni et al., 2019; Falcucci et al., 2018; Gualandi et al., 2014) due to the quality of available data and methods used. Morpho-tectonic evidence confirms that Cf has different kinematics than its neighbouring Paganica and Mt Vettore-Norcia faults in its southeast and northwest, respectively, in term of fault slip rate (Falcucci et al., 2018). Cf is bounded at a depth of 10 km by SZ (Valoroso et al., 2013) and could be capable of producing an M6.4-6.6 earthquake (Falcucci et al., 2018). Two historical earthquakes on Cf were reported (Galadini and Galli, 2003) over the past ~8 ka, with ~1 m of minimum vertical slip.

Here we investigate both seismicity and deformation observed by the geodetic network of the Central Apennines. We exploit waveform similarity over 11 years from 2008 until the beginning of 2019 to define the spatial and temporal evolution of detected near-repeating earthquakes within the SZ and its relation to the reactivated normal faults. To better understand the geometry of Cf we invert the extended source ruptures of 8 (4.4≤M≤5.4) earthquakes during the 2009 and 2017 sequences (Fig 1b). We perform a principal component analysis and variational Bayesian

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106   Independent Component Analysis of all available continuous GPS (cGPS) stations in the broader
107   region of Central Apennines between January 1st 2015 until August 24th 2016 to detect possible
108   geodetic transients and investigate their significance together with variations in seismicity. We
109   study seismicity pattern of the SZ in the broader area of Central Apennines and compare it with
110   our results for the 2009 and 2016 seismic sequences.

111   **2 Methods**

112   **2.1 Template matching**

113   We analyse the period from 2008 to the beginning of 2019 using only well relocated foreshocks
114   and aftershocks of 2009 (Valoroso et al., 2013) and 2016 (Vuan et al., 2017) mainshocks (Fig
115   1b). These selected events nucleated beneath the computed slip distribution of the mainshocks
116   (Walters et al., 2018) within the SZ at depths between 10–12 km and 8–11 km for 2009 and 2016
117   respectively. The merged earthquake catalog (Supplementary Material Fig S2, S3) was used in
118   template matching (Gibbons & Ringdal, 2006; Ross et al., 2019; Shelly et al., 2007) to detect
119   collocated near-repeating earthquakes and transients (Vičič et al., 2019) within the SZ. Daylong
120   waveform data of selected stations (Fig 1b) are downsampled to 20 Hz and filtered between 2-8
121   Hz. For each event, we compute the theoretical S-wave arrival time (Krischer et al., 2015) using
122   a suitable velocity model (Herrmann et al., 2011) and trim the 3 component data in 5 seconds
123   waveforms centred on this arrival. We extract the templates for the four closest stations. To
124   detect new earthquakes we apply the template matching detection algorithm as described in
125   Vuan et al. (2018). For positive detection we set a threshold of 12 times median absolute
126   deviation of the daily stacked cross-correlation function. We only select detected events with
127   inter-event times > 3 seconds to not count same events as multiple events due to the detections
128   from multiple templates. Selected detection inside this time window is the one with highest
129   threshold value. The magnitude of the detection is calculated as the median value of the
130   maximum amplitude ratio for all channels between the template and detected event where a 10-
131   fold increase in amplitude corresponds to a unit increase in magnitude (Peng, et al. 2009).

132   **2.2 Extended source inversion**

133   We invert near-field three-component strong motion records of 8 earthquakes (4.4≤M≤5.4) that
134   occurred on the Cf during 2009 and 2017 sequences to study the kinematics of the ruptured area
135   and constrain the geometry of Cf and discuss its seismogenic potential. The elliptical sub-fault
136   approximation method (Di Carli et al., 2010; Twardzik et al., 2012; Ruiz & Madariaga, 2013;
137   Momeni et al., 2019) is used to retrieve the robust features of the ruptures. For each rupture we
138   look for the best waveform-fit to the observations (see Supplementary Material Figs. Sa1 to Sa7
139   in Appendix-A) and infer the geometry of the Cf along strike and dip. The details of our
140   inversions are presented in Appendix-A and B.

141   **2.3 GPS**

142   We perform a detailed analysis of the available cGPS stations along the Central Apennines from
143   the Alto Tiberina fault system (ATF) to the north and area of L'Aquila 2009 earthquake to the
144   south (Fig 1a). The 2015-2017 time series of the selected stations are analysed following the
145   procedure described in Barzaghi and Borghi (2018) that includes the estimate of discontinuities
146   due to station equipment changes, seismic events, periodic signals and a linear velocity term,
147   considering the time correlation between data. The data were spatially filtered to remove

148 correlated noise using the Principal Component Analysis (PCA), as suggested by Dong et al.
149 (2006) in order to search for transients (Borghi et al., 2016; Gualandi et al., 2016). After the
150 PCA, we apply variational Bayesian Independent Component Analysis (vbICA) (Choudrey et al.,
151 2003) to solve for a blind source separation problem and study discontinuities in the time series.
152 The methodology is described in the Supplementary Material (Appendix-C).
153

154 **3 The 2009 – 2016 sequences**

155 **3.1 Near-repeating earthquakes**

156 To evaluate spatial and temporal evolution of earthquake activity within the SZ, we used 1855
157 templates well distributed along strike and throughout the SZ beneath the causative faults of
158 2009 (10-12 km depth) and 2016-2017 (8-11 km depth) sequences (Fig 2a). We analyse the
159 continuous waveform series from 2008 to 2019, and detect 38229 near-repeaters in the SZ,
160 ranging between M-1.5 and M4.7 (Supplementary Fig S2).
161 Fig 2b shows the along-strike space-time distribution of the newly detected earthquakes (cross-
162 correlation values above 0.5). For the analysis, the whole SZ volume is divided into three sub-
163 volumes following the main normal faults: the Paganica fault (Pf), Cf and the Mt. Vettore-Norcia
164 fault (Vf) (e.g. Basili et al., 2018). Beneath Pf, we detect the foreshocks to the L'Aquila
165 mainshock as reported in Sugan et al. (2014). After the L'Aquila mainshock, the detections
166 exhibit a decay of aftershocks as in Chiaraluce et al. (2011). On the contrary, diffuse and
167 continuous near-repeating earthquakes are reported within the SZ under the Cf (Fig 1a, d). We
168 separate the templates of 2016 sequence into foreshocks and early aftershocks (Supplementary
169 Fig S4a,b) inherent to the August 24th earthquake covering an 80 km along-strike distance that
170 includes Cf and Vf. For Cf, the detections reveal a continuous rate of activity, independent of the
171 templates we use, over the 11-year time span. Underneath Vf (Fig 1a, c), very few near-repeaters
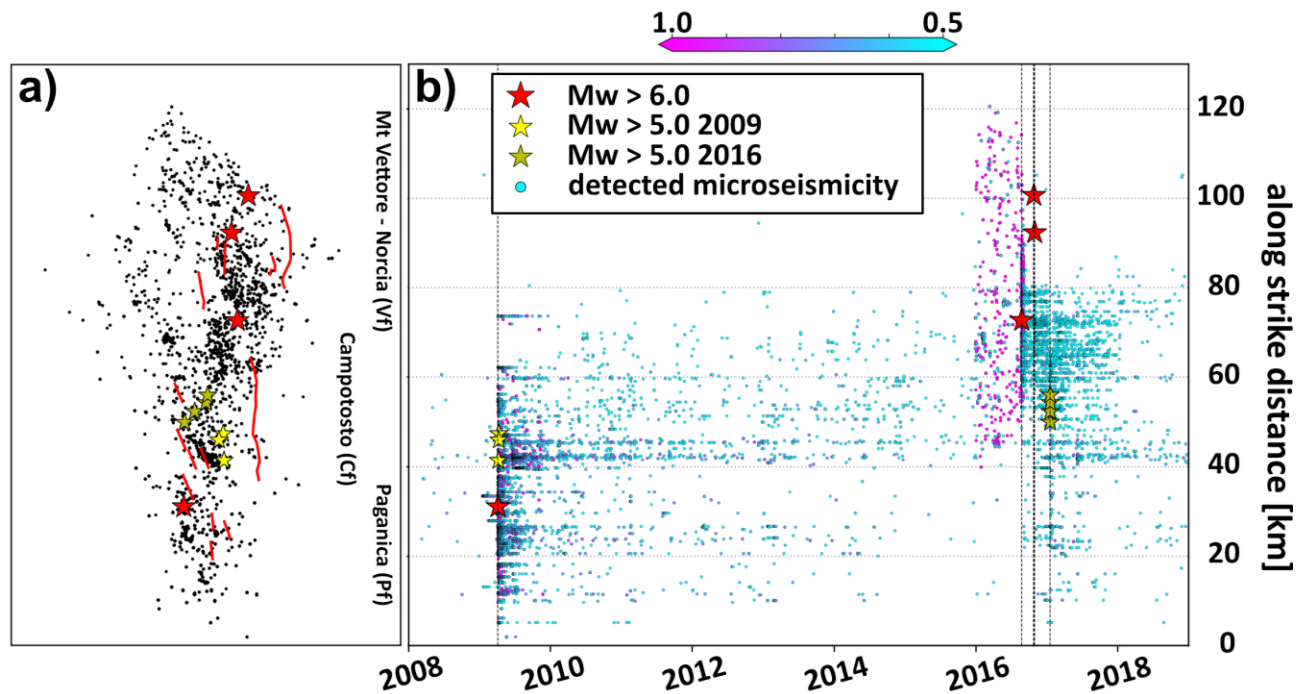172 are detected, except in its south-easternmost part, adjacent to Cf.

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174 *Figure 2: a) Locations of selected SZ template earthquakes along strike the Central Italy faults activated in 2009 and 2016*
175 *sequences. b) Newly detected earthquakes from 2008 until the end of 2018. Colour represents the cross-correlation value of the*
176 *detection. 2009 sequence undergoes a decay of seismicity along the SZ of Paganica fault while the SZ underneath Campotosto*
177 *fault shows constant diffuse earthquake activity. At the beginning of 2016, foreshock activity of 2016 sequence start along the SZ*
178 *underneath Campotosto fault and SZ beneath Mt. Vettore fault system.*

179 The cumulative number of events over time and their yearly contributions are reported in Fig S5
180 and S6. We observe that soon after the 2009 mainshock and its aftershock sequence, earthquake
181 rate within the SZ beneath Cf overtakes (September 2009) the rate under the Pf. This is true

182 throughout the years 2010-2015, with few exceptions when a small sequence starts along Pf
183 (February 2011, February 2012, March 2013). The slope of earthquake rates beneath Cf is steady
184 over the years and characterizes the background seismicity with small increments over temporal
185 fluctuations (van den Ende et al., 2020).
186 At the end of 2015, the number of detections increased beneath Vf, starting the foreshock
187 sequence of the August 24th 2016 Mw6 earthquake. Beneath Cf an intensive swarm took place
188 during February 2016, located adjacent to the future termination of the mainshock slip
189 distribution (Chiaraluce et al., 2017). After the swarm, the SZ beneath Vf overtakes majority of
190 earthquake rate. The diffuse aftershocks that followed the August 24th mainshock are beneath Cf
191 and Vf, where most of the events took place. After the largest mainshock of October 30th, the
192 earthquake rate beneath Cf increases and by the end of 2016 seismic activity beneath Pf starts to
193 increase. Increased activity in late December 2016 beneath Cf signals the foreshock sequence of
194 the January 18th 2017 Mw5+ Campotosto earthquakes.
195 In Supplementary material (Fig S7) we plot earthquake activity in bins of 10 km along the strike
196 of the SZ beneath the fault system through time. We observe a slow (6 km/year) north-westward
197 migration of seismicity from the SZ beneath Pf towards the nucleation area of the August 24th
198 2016 mainshock. This is followed by a south-eastward migration (0.2 km/day) from the August
199 24th 2016 nucleation area towards the hypocentres of Campotosto 2017 earthquakes similar to
200 the observed migration of seismicity independent of the depth distribution reported by Sebastiani
201 et al. (2019).

3.2 Rupture history for the CF moderate earthquakes

203 The reported difference between coseismic and aseismic moment released along the Cf during
204 the 2009 and 2017 sequences (e.g. Cheloni et al., 2014; Cheloni et al., 2019) led to the detailed
205 investigation of the coseismic slip and source geometry of Mw5+ earthquakes on Cf.
206 Seven of the events (except the sub-horizontal June 22nd 2009 M_L4.4 event along SZ) occurred
207 on planes with strikes ranging from 142° to 190°, on average 157°, dipping to the southwest
208 (Supplementary Appendix-A Table A1). Our results confirm the listric geometry of Cf with dip
209 changing over depth from 50° to 30° (Supplementary Fig S1).
210 All slip models cover an area of ~18 km per 12 km on the Cf. The patches of maximum slip do
211 not overlap, and the ruptures evolved mostly up-dip. Similar to the migration observed along the
212 SZ after 2009 and 2016 sequence, also the 2009 and 2017 Campotosto Mw5+ events follow a
213 similar pattern and migrate from southeast towards northwest after 2009 and vice-versa after
214 2016. Unilateral ruptures are confirmed by directivity in the accelerograms.
215 Source parameters of the 2009 sequence show an average strike of 152° and dip of 48° for the
216 south-eastern part of the Cf. Scalar seismic moment of 1.73*10^17 Nm for the three large
217 aftershocks and the SZ event of 2009 are close to the value of 1.8*10^17 Nm, obtained using
218 point source inversion method by Scognamiglio et al. (2010). Using SAR and GPS data, Cheloni
219 et al., (2014) obtained a cumulative scalar seismic moment of 3.17*10^17 Nm for co and post-
220 seismic phases in 2009 and Gualandi et al., 2014 calculated an afterslip of a 2.9*10^17 Nm
221 released for 301 days after the 2009 mainshock. This suggests that most of the deformation was
222 aseismic with half as post-seismic considering negligible sum of the seismic moments released
223 by the rest of aftershocks (Falcucci et al., 2018).
224 Average strike for the 2017 events (north-western part of the Cf) is 161° while average dip is
225 35°, 13° less than Falcucci et al., (2018) from inversion of surface deformation measured from
226 cGPS and DInSAR. In their study, the rake angle would play an important role in obtaining the

227 dip angle, while in our inversions the rake was a well-retrieved parameter. The slip models
228 distribute from depths of 2.5 km to 10 km with a maximum slip of 0.49 m close to Falcucci et al.,
229 (2018). We obtain 7.98 *10^17 Nm of scalar seismic energy release during 2017 sequence close
230 to the obtained value by Falcucci et al. (2018). Considering 0.4*10^17 Nm of scalar seismic
231 moment released by 3.5<M<4.9 aftershocks and the cumulative geodetic moment of 9.29*10^17
232 Nm (Cheloni et al., 2019), we reach to the same 35% contribution of aseismic strain release
233 suggested by Cheloni et al., (2019).
234 The computed slip history of the Mw5+ events indicate that Cf is partially reactivated along its
235 deeper extent and a rupture up to the surface would require a larger magnitude earthquake as
236 reported by paleoseismologic observations (e.g. Galadini et al., 2003).
237

238 **4 Central Apennines**

239 **4.1 Seismicity**

240 We compare our newly constrained catalog with the Italian Seismic Bulletin (Fig 3). We remove
241 earthquakes shallower than 12 km (removing fixed depth and shallow events) along the Central
242 Apennines. We observe alternating high and low seismicity rate strands along the strike, showing
243 similarities to our own findings in the SZ beneath Pf, Cf and Vf. The areas of last moderate
244 earthquakes in 1997, 2009 and 2016 correspond to strands where seismicity is less diffuse. The
245 high seismicity rate segments are located in between, namely Campotosto segment, North Mt.
246 Vettore segment (NVf), and Alto Tiberina segment (Anderlini et al., 2016).
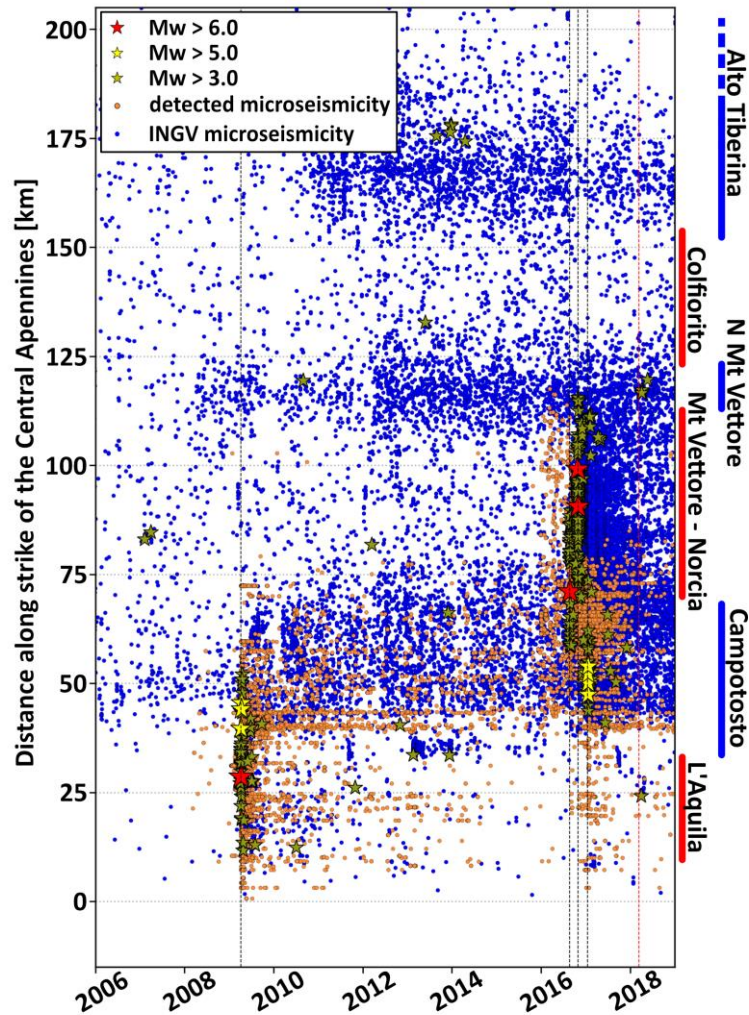
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249 *Figure 3: Seismicity along the strike of Central Apennines. Orange dots represents the near-repeating earthquakes obtained in*
250 *this study while blue dots represent earthquakes deeper than 12 km from INGV earthquake catalog. We observe good spatial*
251 *correlation between our enhanced catalog in the 2009 and 2016 epicentral areas and INGV catalog. Additionally, similar*
252 *behaviour is observed along strike of the Central Apennines. Along the segmented SZ we observe segments of high rate seismicity*
253 *(Campotosto, N. Mt. Vettore, Alto Tiberina – blue vertical lines on the right) and segments with low rate of seismicity (L'Aquila,*
254 *Mt. Vettore-Norcia, Colfiorito – red vertical lines on the right). Later correspond to the SZ beneath the faults, that ruptured with*
255 *recent Mw 6+ events.*

4.2. GPS analysis

256

257 The analysed GPS network is reported in Fig. 1a. The central part of the network, where the
258 2016 M6+ events nucleated represents an empty zone since no stations were installed in that
259 period or we do not have access to the data. Although the vbICA method has resulted efficient in
260 finding the signal along the Alto Tiberina fault (ATF) (Gualandi et al., 2017), we also applied the
261 PCA method, as it allows finding the average behaviour of the stations and avoids local effects.
262 We show the results (Fig. 4) in terms of the second Principal Component (PC2) of the East
263 component. We observe an increase of values starting at the beginning of 2016 with both
264 northern (ATF) and southern (Campotosto) GPS station cluster contributing to the PC2. We
265 repeat the analysis splitting the stations in the ATF and in the Campotosto part. Analysing the
266 two clusters separately allowed us to point out a similar behaviour of the ATF and Campotosto
267 stations but shifted in time: the Campotosto stations present this discontinuity in the first vbICA
268 component on January 7th 2016, with a probability around 94% as detected by the Bayesian test
269 inference (Appendix-C), whereas the ATF stations present an analogous behaviour seven months
270 later on July 7th with a probability of 98% (Fig 4). The last analysis involves the cGPS stations
271 set up after the Mw6.5 October 30th 2016 earthquake. The time-series show (Appendix-C Fig
272 Sc2) the non-linear effect of the post-seismic deformation. Accordingly we preferred not to fit
273 the data using any functional models but applied the PCA to describe the deformation. In
274 Appendix-C Fig Sc2 the first and second principal components are reported. All the stations are
275 affected by a common signal represented by the linear tectonic rate and the post-seismic
276 deformations, as shown by the first PC (Appendix-C Fig Sc2), however a discontinuity is present
277 at the beginning of 2018. Soon after the discontinuity, the northern extension of the area affected
278 by 3 Mw6+ earthquakes is hit by a series of Mw3.5+ earthquakes with the strongest Mw4.5 on
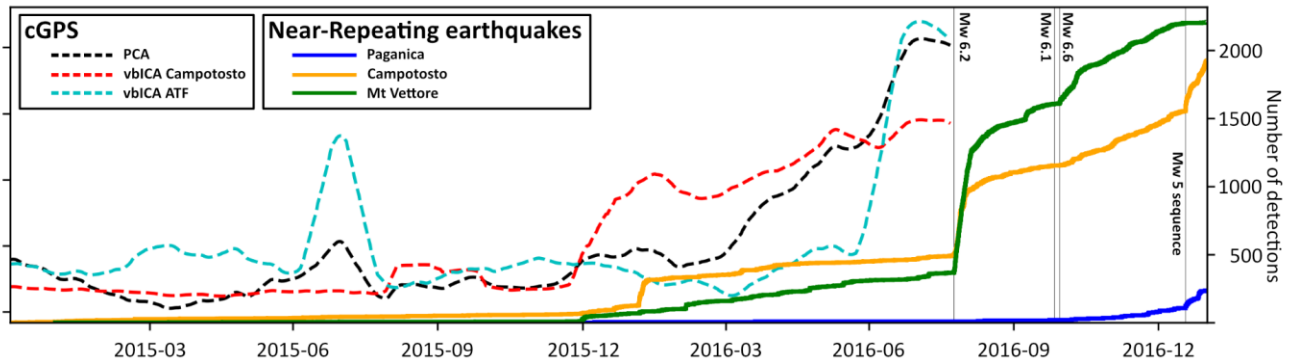279 April 10th 2018.

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281
282 *Figure 4: Cumulative number of newly detected near repeating earthquakes between 2015 and 2017 and a geodetic transient.*
283 *Different colours represent different segments of SZ under the shallow normal faults. Dashed black line represents 2nd principal*
284 *component over all the GPS stations used while red and magenta represent independent components of spatially grouped cGPS*
285 *stations, around Campotosto and ATF respectively. We observe that deformation is migrating from the south of the system*
286 *towards north.*

287

288   **5 Conclusions**

289

290   Analysing 11 years of continuous waveforms recorded at multiple seismic stations in Central
291   Italy allowed us to detect more than 38.000 near-repeaters within the shear zone (SZ). The
292   detected events and their locations give us insight on the space-time behaviour of the SZ
293   underneath Paganica fault (Pf), Campotosto fault (Cf) and Monte Vettore fault (Vf) before, after
294   and in-between the recent Central Italy earthquake sequences. Pf and Vf are related to the 2009
295   Mw6.1 L'Aquila earthquake and the 2016 Amatrice-Visso-Norcia Mw6+ earthquakes
296   respectively, which ruptured shallow, SW dipping normal faults. Cf, located in between Pf and
297   Vf, is affected in the aftermath of both 2009 and 2016 sequences with earthquakes of Mw5+.
298   We observe different spatial and temporal patterns of earthquakes within the SZ underneath Pf,
299   Cf and Vf.
300   The seismicity rate within the SZ appears to be segmented from south to north along the strike of
301   the fault system (Fig 3). SZ beneath Pf is experiencing an expected decay in its activity after the
302   2009 earthquake reaching a lower rate with very few events after 2014 while the adjacent SZ
303   beneath Cf exhibits a far higher rate in its activity that is continuous over time. The SZ beneath
304   Vf shows a very low rate between 2009 up to the end of 2015 when it starts exhibiting a large
305   foreshock sequence, also affecting SZ beneath Cf and Vf as well as the above normal faults,
306   prior to the 2016 Mw6+ earthquakes.
307   Our study suggests that Central Apennines are underlain by a sizeable sub-horizontal shear zone
308   that is segmented in its frictional and/or mechanical properties accommodating therefore low and
309   high rates of seismicity at the base of the seismogenic layer. The low rate seismicity segments
310   are beneath high-angle normal faults responsible of the 1997, 2009 and 2016 earthquake
311   sequences. The high rate seismicity segments are beneath listric faults (e.g. Campotosto), and
312   low-angle normal faults (e.g. Alto-Tiberina).
313   Analysing 19 cGPS stations show that the start of the 2016 foreshock sequence coincides with a
314   clear geodetic transient that first affected Cf-Pf and later expanded northward affecting ATF. The
315   foreshock near-repeaters likely correspond to creeping patches accommodating aseismic slow-
316   slip in the foreshock period (e.g. Meng et al., 2014) combined with a gradual unlocking within
317   the plate boundary (e.g. Schurr et al., 2014). The space-time correlations between the seismicity
318   and the geodetic transient and their northward along strike migrations are thus most likely due to
319   an expanding/propagating slow-slip along strike. Our results show that the northward expanding
320   transient was accommodated differently by the segmented system where less-coupled and
321   creeping segments connect areas of future large earthquakes. Similar behaviour is described in
322   subduction zones (e.g. Rolandone et al., 2018; Radiguet et al., 2016). Furthermore, we argue that
323   the geometry and the frictional properties of the segmented system affects the degree of
324   interseismic coupling. This likely leads to differences in recurrence intervals and maximum
325   magnitude between mature listric faults and younger high-angle normal faults as exhibited by the
326   historical seismicity and paleoseismology across Central Apennines (e.g. Cinti et al., 2018;
327   Falcucci et al., 2018; Galadini et al., 2003, Galli et al., 2019; Guidoboni et al., 2018).

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338 **References**

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340 Amato, A., Azzara, R., Chiarabba, C., Cimini, G. B., Cocco, M., Di Bona, M., ... & Basili, A.
341 (1998). The 1997 Umbria-Marche, Italy, earthquake sequence: A first look at the main shocks
342 and aftershocks. *Geophysical Research Letters*, *25*(15), 2861-2864,
343 https://doi.org/10.1029/98GL51842

344

345 Anderlini, L., Serpelloni, E., & Belardinelli, M. E. (2016). Creep and locking of a low-angle
346 normal fault: Insights from the Altotiberina fault in the Northern Apennines (Italy). *Geophysical*
347 *Research Letters*, *43*(9), 4321-4329, https://doi.org/10.1002/2016GL068604

348

349 Aoudia, A., Ismail-Zadeh, A. T., & Romanelli, F. (2007). Buoyancy-driven deformation and
350 contemporary tectonic stress in the lithosphere beneath Central Italy. Terra Nova, 19(6), 490-
351 495, https://doi.org/10.1111/j.1365-3121.2007.00776.x

352

353 Barzaghi, R., & Borghi, A. (2018). Theory of second order stationary random processes applied
354 to GPS coordinate time-series. GPS Solutions, 22(3), 86, https://doi.org/10.1007/s10291-018-
355 0748-4

356

357 Basili, R., Burrato, P., Fracassi, U., Kastelic, V., Maesano, F., Tarabusi, G., ... & DISS Working
358 Group. (2018). Database of Individual Seismogenic Sources (DISS), Version 3.2. 1: A
359 compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas,
360 https://doi.org/10.6092/INGV.IT-DISS3.2.1

361

362 Borghi, A., Aoudia, A., Javed, F., & Barzaghi, R. (2016). Precursory slow-slip loaded the 2009
363 L'Aquila earthquake sequence. *Geophysical Journal International*, *205*(2), 776-784,
364 https://doi.org/10.1093/gji/ggw046

365

366 Buttinelli, M., Pezzo, G., Valoroso, L., De Gori, P., & Chiarabba, C. (2018). Tectonics
367 inversions, fault segmentation, and triggering mechanisms in the central Apennines normal fault
368 system: Insights from high-resolution velocity models. *Tectonics*, *37*(11), 4135-4149,
369 https://doi.org/10.1029/ 2018TC005053

370

371 Calamita, F., Paltrinieri, W., Pelorosso, M., Scisciani, V., & Tavarnelli, E. (2003). Inherited
372 mesozoic architecture of the Adria continental palaeomargin in the Neogene central Apennines
373 orogenic system, Italy. *BOLLETTINO-SOCIETA GEOLOGICA ITALIANA*, *122*(2), 307-318.

374

375 Cheloni, D., Giuliani, R., D'Anastasio, E., Atzori, S., Walters, R. J., Bonci, L., ... & Deninno, F.
376 (2014). Coseismic and post-seismic slip of the 2009 L'Aquila (central Italy) Mw 6.3 earthquake
377 and implications for seismic potential along the Campotosto fault from joint inversion of high-
378 precision levelling, InSAR and GPS data. *Tectonophysics*, *622*, 168-185,
379 https://doi.org/10.1016/j.tecto.2014.03.009

380

381

382

383 Cheloni, D., D'Agostino, N., Scognamiglio, L., Tinti, E., Bignami, C., Avallone, A., ... &
384 Mattone, M. (2019). Heterogeneous Behavior of the Campotosto Normal Fault (Central Italy)
385 Imaged by InSAR GPS and Strong-Motion Data: Insights from the 18 January 2017
386 Events. *Remote Sensing*, *11*(12), 1482, https://doi.org/10.3390/rs11121482

388 Chiarabba, C., De Gori, P., Cattaneo, M., Spallarossa, D., & Segou, M. (2018). Faults geometry
389 and the role of fluids in the 2016–2017 Central Italy seismic sequence. Geophysical Research
390 Letters, 45, 6963–6971. https://doi.org/10.1029/ 2018GL077485

392 Chiaraluce, L., Ellsworth, W. L., Chiarabba, C., & Cocco, M. (2003). Imaging the complexity of
393 an active normal fault system: The 1997 Colfiorito (central Italy) case study. Journal of
394 Geophysical Research: Solid Earth, 108(B6), https://doi.org/10.1029/2002JB002166

396 Chiaraluce, L., Valoroso, L., Piccinini, D., Di Stefano, R., & De Gori, P. (2011). The anatomy of
397 the 2009 L'Aquila normal fault system (central Italy) imaged by high resolution foreshock and
398 aftershock locations. *Journal of Geophysical Research: Solid Earth*, *116*(B12),
399 https://doi.org/10.1029/2011JB008352

401 Chiaraluce, L., Di Stefano, R., Tinti, E., Scognamiglio, L., Michele, M., Casarotti, E., ... &
402 Lombardi, A. (2017). The 2016 central Italy seismic sequence: A first look at the mainshocks,
403 aftershocks, and source models. *Seismological Research Letters*, *88*(3), 757-771,
404 https://doi.org/10.1785/0220160221

406 Chimera, G., Aoudia, A., Saraò, A., & Panza, G. F. (2003). Active tectonics in Central Italy:
407 constraints from surface wave tomography and source moment tensor inversion. *Physics of the*
408 *Earth and Planetary Interiors*, *138*(3-4), 241-262, https://doi.org/10.1016/S0031-
409 9201(03)00152-3

411 Choudrey, R. A., & Roberts, S. J. (2003). Variational mixture of Bayesian independent
412 component analyzers. *Neural computation*, *15*(1), 213-252,
413 https://doi.org/10.1162/089976603321043766

415 Cinti, F. R., Civico, R., Blumetti, A. M., Chiarini, E., La Posta, E., Pantosti, D., ... & Pinzi, S.
416 (2018). Evidence for surface faulting earthquakes on the Montereale fault system (Abruzzi
417 Apennines, central Italy). *Tectonics*, *37*(9), 2758-2776, https://doi.org/10.1029/2017TC004780

419 D'Agostino, N., Mantenuto, S., D'Anastasio, E., Giuliani, R., Mattone, M., Calcaterra, S., ... &
420 Bonci, L. (2011). Evidence for localized active extension in the central Apennines (Italy) from
421 global positioning system observations. *Geology*, *39*(4), 291-294,
422 https://doi.org/10.1130/G31796.1

424 Di Carli, S., François-Holden, C., Peyrat, S., & Madariaga, R. (2010). Dynamic inversion of the
425 2000 Tottori earthquake based on elliptical subfault approximations. *Journal of Geophysical*
426 *Research: Solid Earth*, *115*(B12), https://doi.org/10.1029/2009JB006358

428 Doglioni, C. (1991). A proposal for the kinematic modelling of W-dipping subductions-possible
429 applications to the Tyrrhenian-Apennines system. *Terra Nova*, *3*(4), 423-434,
430 https://doi.org/10.1111/j.1365-3121.1991.tb00172.x

432 Dong, D., Fang, P., Bock, Y., Webb, F., Prawirodirdjo, L., Kedar, S., & Jamason, P. (2006).
433 Spatiotemporal filtering using principal component analysis and Karhunen-Loeve expansion
434 approaches for regional GPS network analysis. *Journal of geophysical research: solid*
435 *earth*, *111*(B3), https://doi.org/10.1029/2005JB003806.

437 Falcucci, E., Gori, S., Bignami, C., Pietrantonio, G., Melini, D., Moro, M., ... & Galadini, F.
438 (2018). The Campotosto seismic gap in between the 2009 and 2016–2017 seismic sequences of
439 central Italy and the role of inherited lithospheric faults in regional seismotectonic
440 settings. *Tectonics*, *37*(8), 2425-2445, https://doi.org/10.1029/2017TC004844

442 Galadini, F., & Galli, P. (2003). Paleoseismology of silent faults in the Central Apennines (Italy):
443 the Mt. Vettore and Laga Mts. faults. *Annals of Geophysics*, https://doi.org/10.4401/ag-3457

445 Galli, P., Galderisi, A., Peronace, E., Giaccio, B., Hajdas, I., Messina, P., ... & Polpetta, F.
446 (2019). The awakening of the dormant Mount Vettore fault (2016 central Italy earthquake, Mw
447 6.6): paleoseismic clues on its millennial silences. *Tectonics*, *38*(2), 687-705,
448 https://doi.org/10.1029/2018TC005326

450 Gibbons, S. J., & Ringdal, F. (2006). The detection of low magnitude seismic events using array-
451 based waveform correlation. *Geophysical Journal International*, *165*(1), 149-166,
452 https://doi.org/10.1111/j.1365-246X.2006.02865.x

454 Gualandi, A., Serpelloni, E., & Belardinelli, M. E. (2014). Space–time evolution of crustal
455 deformation related to the M w 6.3, 2009 L'Aquila earthquake (central Italy) from principal
456 component analysis inversion of GPS position time-series. *Geophysical Journal*
457 *International*, *197*(1), 174-191, https://doi.org/10.1093/gji/ggt522

459 Gualandi, A., Serpelloni, E., & Belardinelli, M. E. (2016). Blind source separation problem in
460 GPS time series. *Journal of Geodesy*, *90*(4), 323-341, https://doi.org/10.1007/s00190-015-0875-
461 4
462 Gualandi, A., Nichele, C., Serpelloni, E., Chiaraluce, L., Anderlini, L., Latorre, D., ... & Avouac,
463 J. P. (2017). Aseismic deformation associated with an earthquake swarm in the northern
464 Apennines (Italy). *Geophysical Research Letters*, *44*(15), 7706-7714,
465 https://doi.org/10.1002/2017GL073687

467 Guidoboni, E., Ferrari, G., Mariotti, D., Comastri, A., Tarabusi, G., Sgattoni, G., & Valensise, G.
468 (2018). CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 aC-1997) e nell'area
469 Mediterranea (760 aC-1500), https://doi.org/10.6092/ingv.it-cfti5

471 Herrmann, R. B., Malagnini, L., & Munafò, I. (2011). Regional Moment Tensors of the 2009
472 L'Aquila Earthquake SequenceRegional Moment Tensors of the 2009 L'Aquila Earthquake

Sequence. *Bulletin of the Seismological Society of America*, *101*(3), 975-993, https://doi.org/10.1785/0120100184

Improta, L., Latorre, D., Margheriti, L., Nardi, A., Marchetti, A., Lombardi, A. M., ... & Moretti, M. (2019). Multi-segment rupture of the 2016 Amatrice-Visso-Norcia seismic sequence (central Italy) constrained by the first high-quality catalog of Early Aftershocks. *Scientific reports*, *9*(1), 1-13, https://doi.org/10.1038/s41598-019-43393-2

Krischer, L., Megies, T., Barsch, R., Beyreuther, M., Lecocq, T., Caudron, C., & Wassermann, J. (2015). ObsPy: A bridge for seismology into the scientific Python ecosystem. *Computational Science & Discovery*, *8*(1), 014003, https://doi.org/10.1088/1749-4699/8/1/014003

Meng, L., Huang, H., Bürgmann, R., Ampuero, J. P., & Strader, A. (2015). Dual megathrust slip behaviors of the 2014 Iquique earthquake sequence. *Earth and Planetary Science Letters*, *411*, 177-187, https://doi.org/10.1016/j.epsl.2014.11.041

Momeni, S. M., Aoudia, A., Tatar, M., Twardzik, C., & Madariaga, R. (2019). Kinematics of the 2012 Ahar–Varzaghan complex earthquake doublet (M w6. 5 and M w6. 3). *Geophysical Journal International*, *217*(3), 2097-2124, https://doi.org/10.1093/gji/ggz100

Peng, Z., & Zhao, P. (2009). Migration of early aftershocks following the 2004 Parkfield earthquake. *Nature Geoscience*, *2*(12), 877-881, https://doi.org/10.1038/ngeo697

Porreca, M., Minelli, G., Ercoli, M., Brobia, A., Mancinelli, P., Cruciani, F., ... & Cannata, A. (2018). Seismic reflection profiles and subsurface geology of the area interested by the 2016–2017 earthquake sequence (Central Italy). *Tectonics*, *37*(4), 1116-1137, https://doi.org/10.1002/2017TC004915

Radiguet, M., Perfettini, H., Cotte, N., Gualandi, A., Valette, B., Kostoglodov, V., ... & Campillo, M. (2016). Triggering of the 2014 M w 7.3 Papanoa earthquake by a slow slip event in Guerrero, Mexico. *Nature Geoscience*, *9*(11), 829-833, https://doi.org/10.1038/ngeo2817

Rolandone, F., Nocquet, J. M., Mothes, P. A., Jarrin, P., Vallée, M., Cubas, N., ... & Font, Y. (2018). Areas prone to slow slip events impede earthquake rupture propagation and promote afterslip. *Science advances*, *4*(1), eaao6596, https://doi.org/10.1126/sciadv.aao6596

Ross, Z. E., Trugman, D. T., Hauksson, E., & Shearer, P. M. (2019). Searching for hidden earthquakes in Southern California. *Science*, *364*(6442), 767-771, https://doi.org/10.1126/science.aaw6888

Rovida, A., Camassi, R., Gasperini, P., & Stucchi, M. (2011). Catalogo parametrico dei terremoti italiani, https://doi.org/10.13127/CPTI/CPTI15.2

Ruiz, S., & Madariaga, R. (2013). Kinematic and dynamic inversion of the 2008 Northern Iwate earthquake. *Bulletin of the Seismological Society of America*, *103*(2A), 694-708, https://doi.org/10.1785/0120120056

519 Schmedes, J., Archuleta, R. J., & Lavallée, D. (2010). Correlation of earthquake source
520 parameters inferred from dynamic rupture simulations. *Journal of Geophysical Research: Solid*
521 *Earth*, *115*(B3), https://doi.org/10.1029/2009JB006689

523 Schurr, B., Asch, G., Hainzl, S., Bedford, J., Hoechner, A., Palo, M., ... & Oncken, O. (2014).
524 Gradual unlocking of plate boundary controlled initiation of the 2014 Iquique earthquake.
525 Nature, 512(7514), 299-302, https://doi.org/10.1038/nature13681

527 Scognamiglio, L., Tinti, E., Michelini, A., Dreger, D. S., Cirella, A., Cocco, M., ... & Piatanesi,
528 A. (2010). Fast determination of moment tensors and rupture history: What has been learned
529 from the 6 April 2009 L'Aquila earthquake sequence. *Seismological Research Letters*, *81*(6),
530 892-906, https://doi.org/10.1785/gssrl.81.6.892

532 Sebastiani, G., Govoni, A., & Pizzino, L. (2019). Aftershock Patterns in Recent Central
533 Apennines Sequences. *Journal of Geophysical Research: Solid Earth*, *124*(4), 3881-3897,
534 https://doi.org/10.1029/2018JB017144

536 Shelly, D. R., Beroza, G. C., & Ide, S. (2007). Non-volcanic tremor and low-frequency
537 earthquake swarms. *Nature*, *446*(7133), 305-307, https://doi.org/10.1038/nature05666

539 Soldati, G., Zaccarelli, L., Faenza, L., & Michelini, A. (2015). Monitoring of crustal seismic
540 velocity variations in the L'Aquila fault zone inferred from noise cross-correlation. *Geophysical*
541 *Journal International*, *202*(1), 604-611, https://doi.org/ 10.1093/gji/ggv172

543 Sugan, M., Kato, A., Miyake, H., Nakagawa, S., & Vuan, A. (2014). The preparatory phase of
544 the 2009 Mw 6.3 L'Aquila earthquake by improving the detection capability of low-magnitude
545 foreshocks. *Geophysical Research Letters*, *41*(17), 6137-6144,
546 https://doi.org/10.1002/2014GL061199

548 Twardzik, C., Madariaga, R., Das, S., & Custódio, S. (2012). Robust features of the source
549 process for the 2004 Parkfield, California, earthquake from strong-motion
550 seismograms. *Geophysical Journal International*, *191*(3), 1245-1254,
551 https://doi.org/10.1111/j.1365-246X.2012.05653.x

553 Valoroso, L., Chiaraluce, L., Piccinini, D., Di Stefano, R., Schaff, D., & Waldhauser, F. (2013).
554 Radiography of a normal fault system by 64,000 high-precision earthquake locations: The 2009
555 L'Aquila (central Italy) case study. *Journal of Geophysical Research: Solid Earth*, *118*(3), 1156-
556 1176, https://doi.org/10.1002/jgrb.50130

558 van den Ende, M. P., & Ampuero, J. P. (2020). On the statistical significance of foreshock
559 sequences in Southern California. *Geophysical Research Letters*, *47*(3), e2019GL086224.

561 Vičič, B., Aoudia, A., Javed, F., Foroutan, M., & Costa, G. (2019). Geometry and mechanics of
562 the active fault system in western Slovenia. *Geophysical Journal International*, *217*(3), 1755-
563 1766, https://doi.org/10.1093/gji/ggz118
564

565 Vuan, A., Sugan, M., Chiaraluce, L., & Di Stefano, R. (2017). Loading rate variations along a
566 midcrustal shear zone preceding the Mw6. 0 earthquake of 24 August 2016 in Central Italy.
567 *Geophysical Research Letters*, *44*(24), https://doi.org/10.1002/2017GL076223
568
569 Vuan, A., Sugan, M., Amati, G., & Kato, A. (2018). Improving the Detection of Low‐Magnitude
570 Seismicity Preceding the M w 6.3 L'Aquila Earthquake: Development of a Scalable Code Based
571 on the Cross Correlation of Template Earthquakes. *Bulletin of the Seismological Society of*
572 *America*, *108*(1), 471-480, https://doi.org/10.1785/0120170106
573
574 Walters, R. J., Gregory, L. C., Wedmore, L. N. J., Craig, T. J., McCaffrey, K., Wilkinson, M., ...
575 & Iezzi, F. (2018). Dual control of fault intersections on stop-start rupture in the 2016 Central
576 Italy seismic sequence. *Earth and Planetary Science Letters*, *500*, 1-14,
577 https://doi.org/10.1016/j.epsl.2018.07.043
578

579 **References From the Supporting Information**
580
581 Blewitt, G., Hammond, W. C., & Kreemer, C. (2018). Harnessing the GPS data explosion for
582 interdisciplinary science. *Eos*, *99*, 1-2, https://doi.org/10.1029/2018EO104623.
583
584 Borghi A., Aoudia A., Riva R., Barzaghi R. (2009). GPS monitoring and earthquake prediction:
585 a success story towards a useful integration. Tectonophysics, 465, pp 177-189, ISSN 0040-1951,
586 doi: 10.1016/j.tecto.2008.11.022
587
588 Borghi, A., Cannizzaro, L., & Vitti, A. (2012). Advanced techniques for discontinuity detection
589 in GNSS coordinate time-series. An Italian case study. In *Geodesy for Planet Earth*(pp. 627-
590 634). Springer, Berlin, Heidelberg , https://doi.org/10.1007/978-3-642-20338-1_77
591
592 Cotton, F., & Coutant, O. (1997). Dynamic stress variations due to shear faults in a plane-layered
593 medium. *Geophysical Journal International*, *128*(3), 676-688, https://doi.org/10.1111/j.1365-
594 246X.1997.tb05328.x
595
596 Hyvärinen, A., & Oja, E. (2000). Independent component analysis: algorithms and
597 applications. *Neural networks*, *13*(4-5), 411-430, https://doi.org/10.1016/S0893-6080(00)00026-
598 5
599
600 Sambridge, M. (1999). Geophysical inversion with a neighbourhood algorithm—I. Searching a
601 parameter space. *Geophysical journal international*, *138*(2), 479-494,
602 https://doi.org/10.1046/j.1365-246X.1999.00876.x
603
604 Sambridge, M. (1999). Geophysical inversion with a neighbourhood algorithm—II. Appraising
605 the ensemble. *Geophysical Journal International*, *138*(3), 727-746,
606 https://doi.org/10.1046/j.1365-246x.1999.00900.x
607
608 Silverii, Francesca, et al. "Transient crustal deformation from karst aquifers hydrology in the
609 Apennines (Italy)." *Earth and Planetary Science Letters* 506 (2019): 23-37,
610 https://doi.org/10.1016/j.epsl.2018.10.019
611
612 Spudich, P., & Miller, D. P. (1990). Seismic site effects and the spatial interpolation of
613 earthquake seismograms: results using aftershocks of the 1986 North Palm Springs, California,
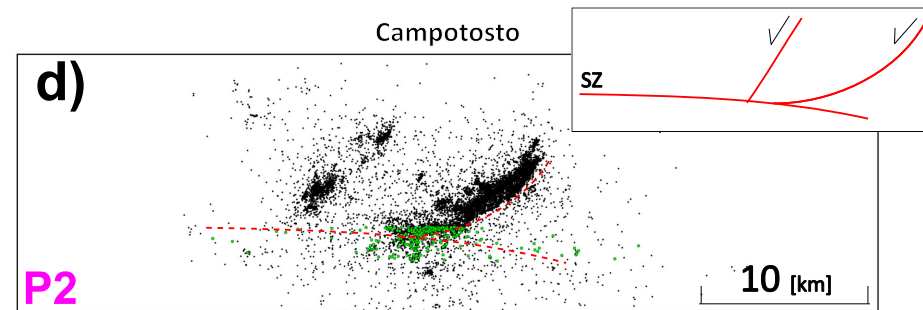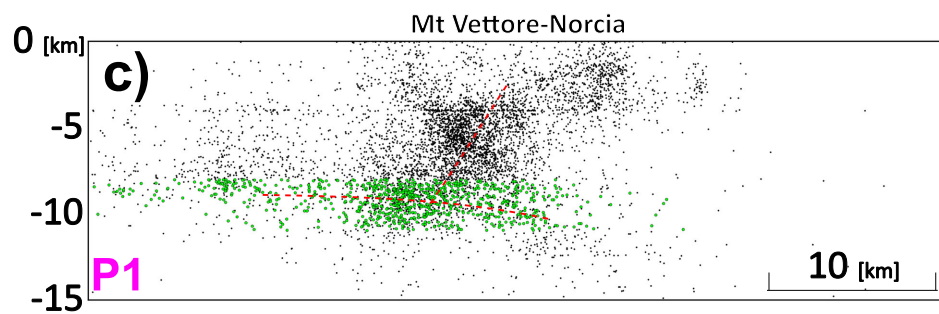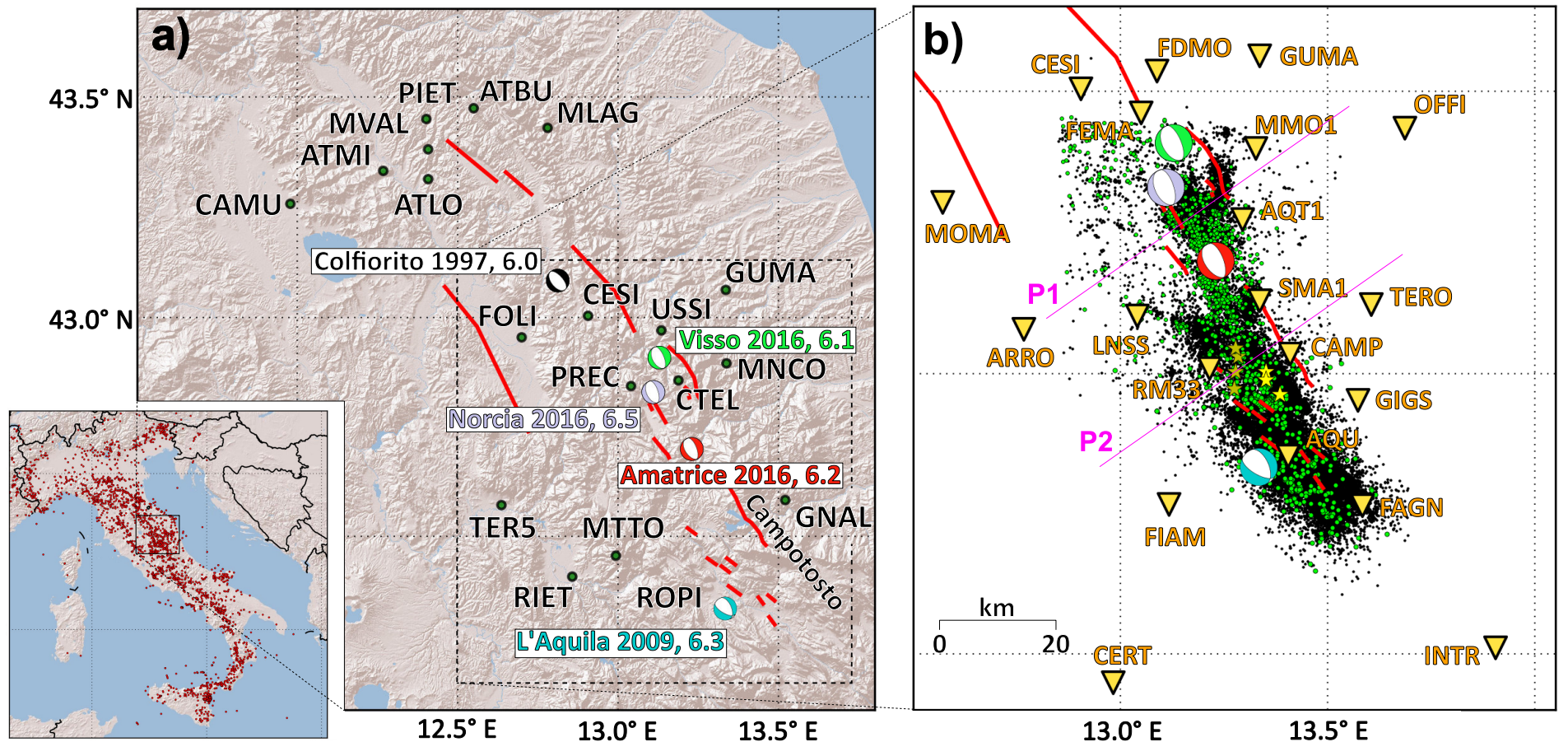614 earthquake. *Bulletin of the Seismological Society of America*, *80*(6A), 1504-1532.
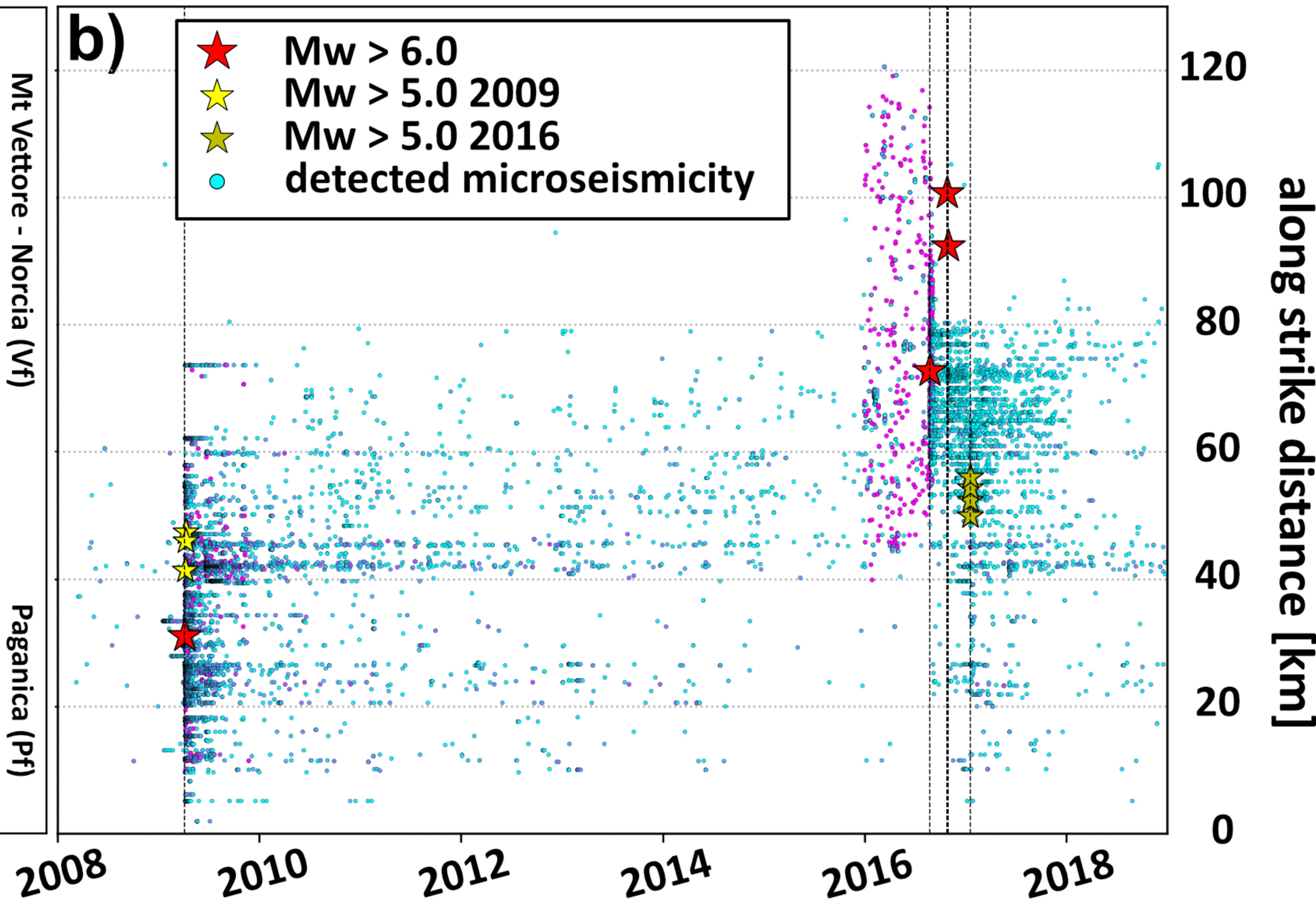615

Figure 1.

a)

PIET ATBU
MVAL   MLAG
ATMI
CAMU   ATLO

Colfiorito 1997, 6.0

FOLI   CESI   GUMA
                USSI
PREC   MNCO
        CTEL

Visso 2016, 6.1

Norcia 2016, 6.5

Amatrice 2016, 6.2

TER5   MTTO   GNAL
                          Campotosto

RIET   ROPI

L'Aquila 2009, 6.3

b)

CESI   FDMO   GUMA
                        OFFI
FEMA   MMO1
MOMA   AQT1
                        TERO
         P1   SMA1
ARRO   LNSS   CAMP
         RM33
      P2   AQU   GIGS
                        FAGN
         FIAM
km
0   20
         CERT   INTR

Mt Vettore-Norcia

0 [km]

-5

-10

c)
P1   10 [km]

-15

Campotosto

d)
P2   10 [km]

Figure 2.

a)

Mt Vettore - Norcia (Vf)

Campotosto (Cf)

Paganica (Pf)

b)

- ⭐ Mw > 6.0
- ⭐ Mw > 5.0 2009
- ⭐ Mw > 5.0 2016
- ● detected microseismicity

1.0   0.5

along strike distance [km]

120

100

80

60

40

20

0

2008   2010   2012   2014   2016   2018

Figure 3.

Figure 4.