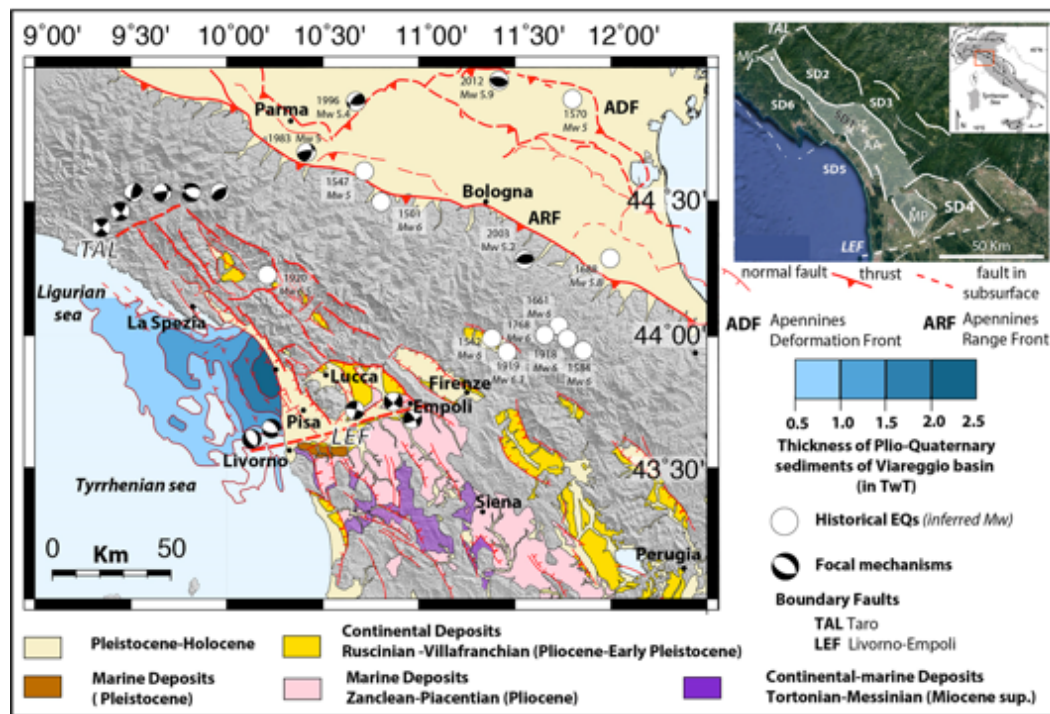


Active Fault Systems in the Inner Northwest Apennines, Italy: A Reappraisal One Century after the 1920 Mw 6.5 Fivizzano Earthquake

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1. INTRODUCTION AND GEOLOGICAL SETTING

Although large historical earthquakes, including the 1920 Fivizzano Mw ~6.5 event, have occurred in the investigated region, the catalogs (INGV and ISPRA CNR, [1,2]) currently used for the seismic hazard evaluation only report few active faults and only two seismic sources.

The Neogene-to-recent tectonic evolution of the Apennines, is characterized by contractional tectonic activity in the foreland, accompanied by extension in the internal domain [3,4,5]. The studied area, in the inner Northwest Apennines, is characterized by a lower frequency of earthquakes (compared to the external domains), yet of significant magnitude, with most of them showing a normal faulting slip mode. Among the several large earthquakes that have occurred in the region, there are the 1542 and the 1919 “Mugello” events (Mw 6.0 and Mw 6.4, respectively), the 1584, 1661, 1768, and 1918 events in the “Forlivese” region (all ~ Mw 6), and the 1920 ~Mw 6.5 Fivizzano earthquake [6,7,8], within the investigated area.

Simplified geological and structural map of the northern Apennines emphasizing the Neogene tectonics in the investigated area (shown in the Google Earth inset on the top right where the analyzed different structural domains, SDs are figured). AA: Alpi Apuane; LEF: Livorno–Empoli Fault; MG: Mt. Gottero; MP: Mt. Pisano; TAL: Taro Line. TAL and LEF bound the region of study. Offshore sediment thickness are after [9], and earthquakes and focal mechanisms are from the INGV archive [10,11,12].

1: Key points. On the base of a revision of the available stratigraphic, tectonic, morphological, geodetic, and seismological data, along with new structural observations, we present a reappraisal of the potential seismogenic faults and fault systems in the inner northwest Apennines, Italy.

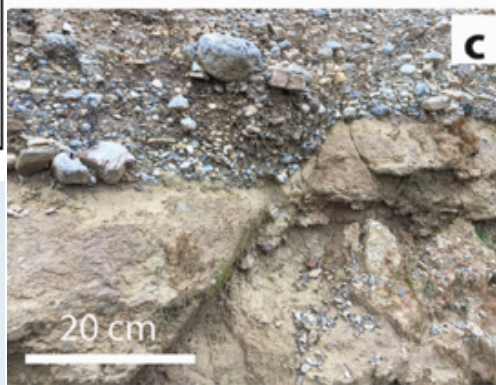
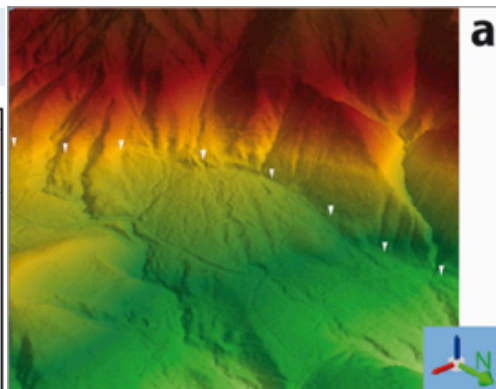
2. STRATIGRAPHIC CONSTRAINTS OF FAULTING

The study area is characterized by Plio-Quaternary stratigraphic units, sedimentary filling of the different intramontane or continental/marine domains. The Plio-Quaternary sedimentary records has been used to document the neotectonic activity of the principal faults and fault systems in each of the six structural domains and to constrain the slip-rate of the faults.

Schematic frame and correlations of continental–marine Plio-Quaternary sedimentary successions in the different structural domains described.

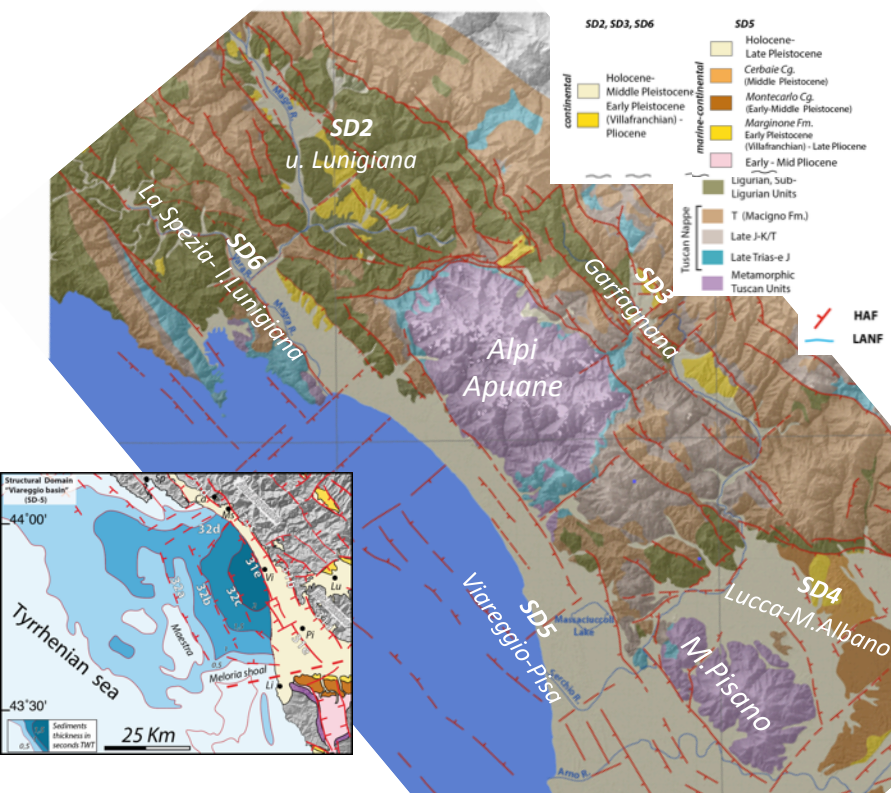
TIME		AGES My	STRUCTURAL DOMAINS					
CHRONOSTRATIG.	MAMMAL AGES		SD1 Alpi Apuane Mt. Pisano	SD2 upper Lunigiana	SD3 Lunigiana - Garfagnana Innaffage domain	SD4 Lucca - Mt. Albano	SD5 Pisa - Viareggio	SD6 La Spezia - lower Lunigiana
Quaternary		0.01 0.125 0.25 0.5 1 2 3 4 5	Alpi Apuane Cg	Pontremoli Cg MGV Cg Dozzano Cg	Lupicino Cg MAC Cg Barga Cg	Cerbale Cg Montecarlo Cg	Seq. 6b Seq. 6a Seq. 5 Seq. 4 Seq. 2+3	Sarzana Cg S. Godano Cg P.Borca Cg
Pleistocene								
Calabrian								
Gelasian								
Pliocene								
Zanclean								
Messinian								

Evidence of Plio-Quaternary faulting and deformation: (a) LiDAR-derived DTM showing the fault scarp offsetting a Late Pleistocene–Holocene alluvial fan along the Mulazzo Fault in the structural domain SD2 (Lunigiana). This site has been recently trenched for paleoseismological studies [68,69]; (b) fault scarp offsetting Late Pleistocene alluvial fan deposit along the southernmost splay of the Corfino Fault, in structural domain SD3 (Garfagnana); (c) normal fault offsetting the Late Villafranchian Olivola Conglomerates, in structural domain SD2 (Lunigiana); (d) Ruscinian Sarzanella–Caniparola sands and clay tilted by the Sarzana–Carrara fault, in the northern part of the West Alpi Apuane Fault system in the structural domain SD6 (La Spezia–lower Lunigiana).

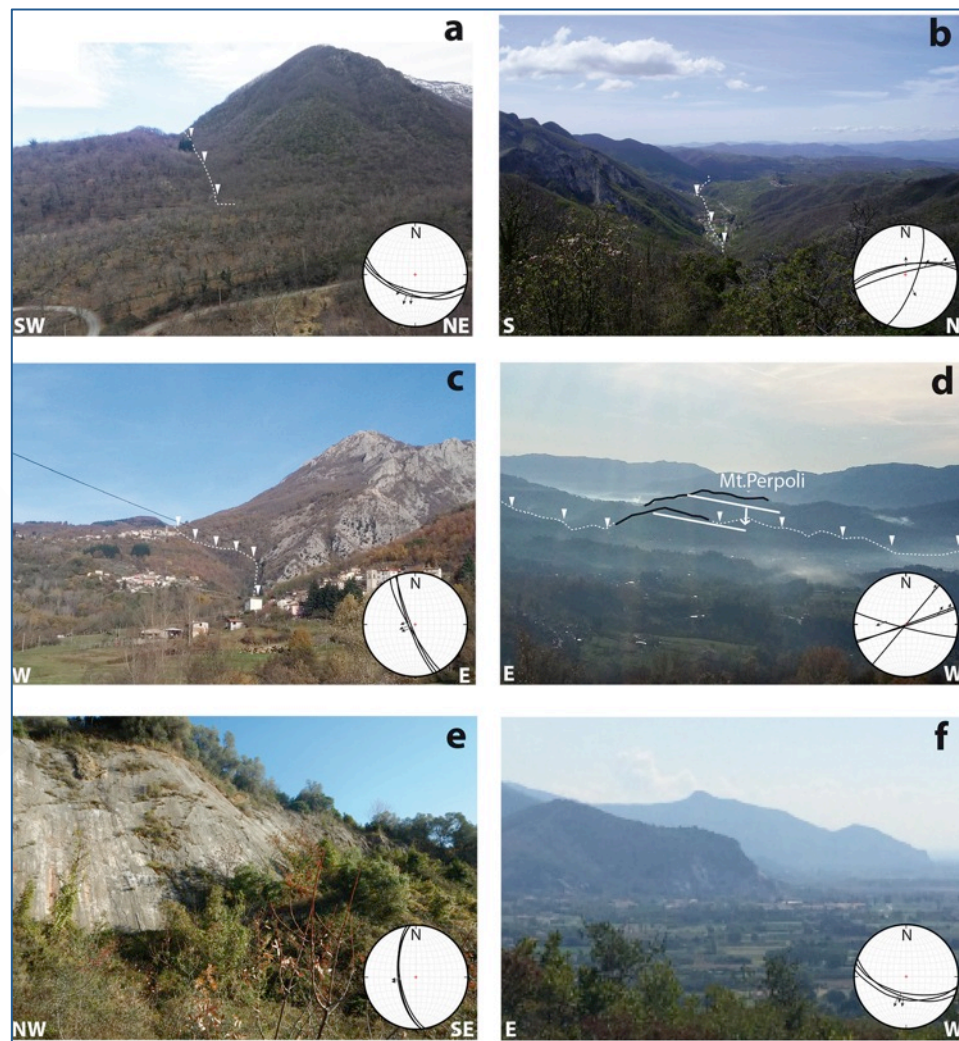


2: Key points. We document that the majority of faults described in the study have been active over the Quaternary. Most show displacements post-800 ka, and in some cases clear slips across Late Pleistocene and Holocene deposits [12,13].

3: FAULT SYSTEMS, KINEMATICS, TIME OF ACTIVITY AND DISPLACEMENT RATES

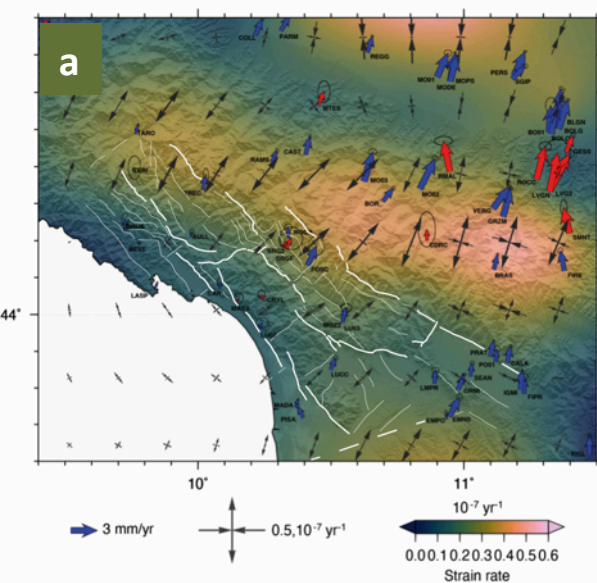


(a) Panoramic view (toward N/NW) of the Compione Fault (structural domain SD2); (b) panoramic view (toward W/SW) of the Aiola-Equi Terme fault part of the North Apuane Fault System. The village in the valley is Equi Terme, epicentral area of the 2013 Lunigiana earthquake. This fault has a possible role in the 1920 EQ too (see slides 4,5); (c) Corfino fault in structural domain SD3; (d) Monte Perpoli morphostructural high in SD3. White line indicates the base of the Late Pleistocene deposits in the hanging wall and footwall of the North Mt. Perpoli fault. The latter is taken to have produced the 2013 Garfagnana earthquake; (e) Pietrasanta fault (SD5), central southern segment of the West Alpi Apuane fault, the major bounding fault of the Viareggio basin; (f) basin and range landscape forming the western boundary of the Pisa plain (southernmost part of the structural domain SD5). Stereonets show microtectonic measurements we made on the faults (main and minor fault planes and slickensides, Schmid net, lower hemisphere).

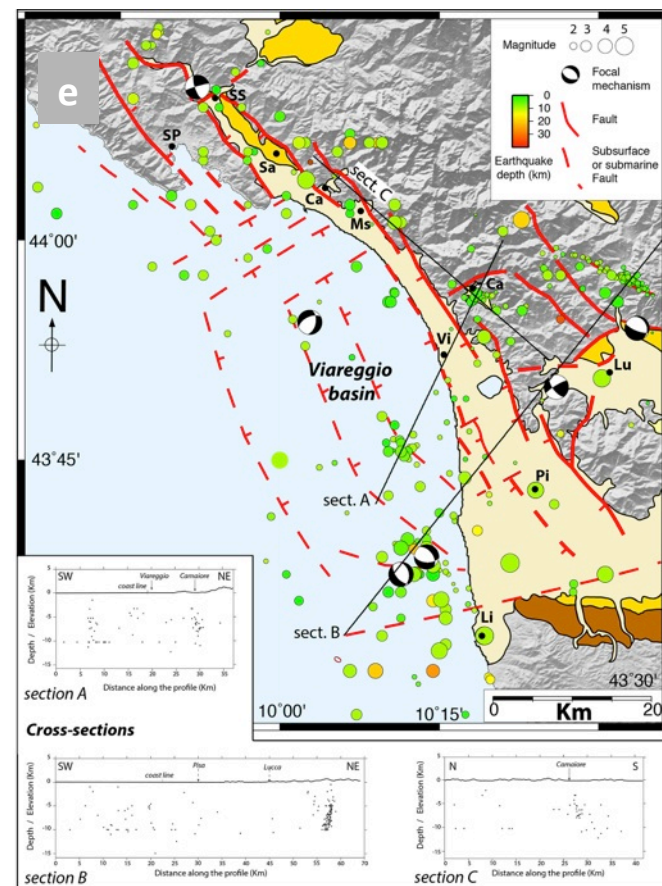
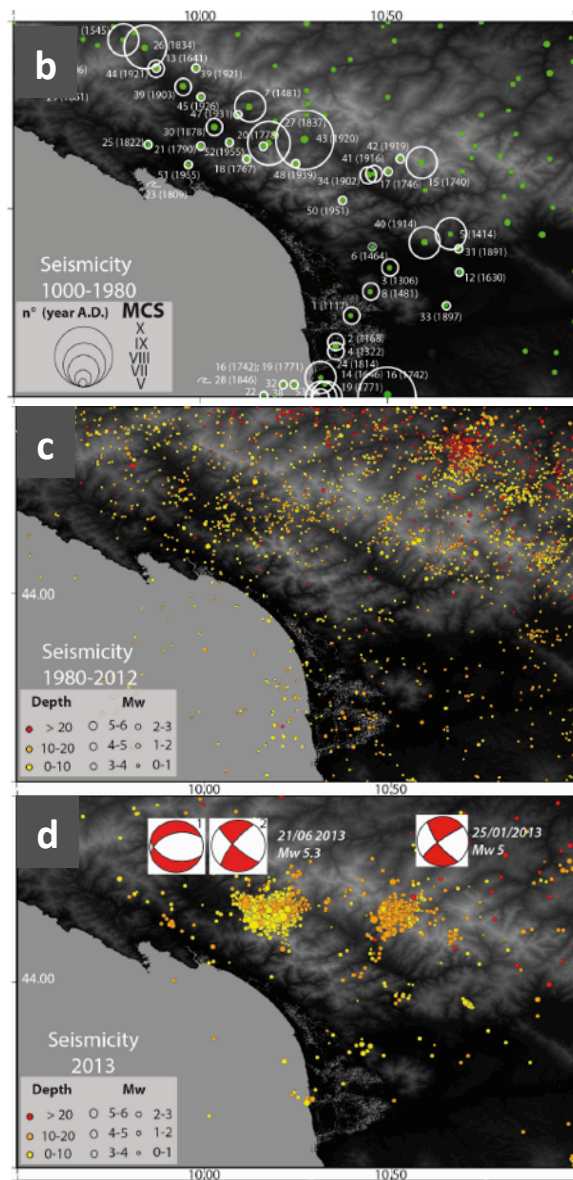


3: Key points. The dominant faulting trends NW-NNW, and has normal slip, locally with an additional component of left-lateral slip (in suborder right-lateral slip). The faults are steep and commonly combine in conjugate pairs of antithetic faults bounding grabens. Displacement rate ranges between 0,1 to 0,8 mm/y.

4. GEODETIC DATA, HISTORICAL AND INSTRUMENTAL SEISMICITY: SHORT TERM CONSTRAINTS



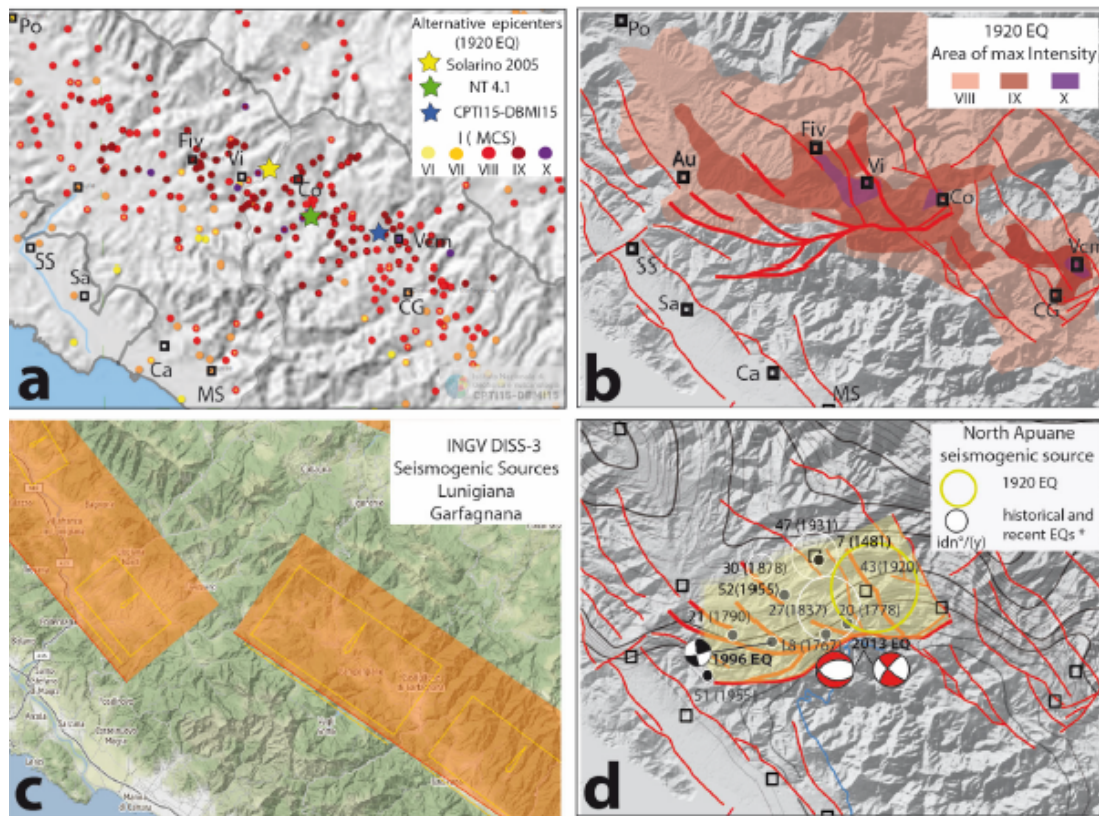
(a) Horizontal GPS velocity field (blue and red vectors are continuous and campaign stations, respectively, with 95% confidence error ellipses) and total strain-rate field (color scale). The diverging and converging grey arrows show the axes of the principal strain rates, indicating extensional and contractional deformation, respectively.



4: Key points. GPS data and the shallow EQs of low to moderate magnitude and normal to oblique focal mechanisms characterized all the investigated area which is currently in active deformation. The instrumental and historical seismicity is widespread with clusters in all the structural domains of the region. Some of the faults may be currently locked as inferred by surface velocities and strain rates changes.

5. THE 1920 Mw 6,5 FIVIZZANO EARTHQUAKE

On 7 September 1920 at 05:55, the area between southern Lunigiana and Garfagnana (SD 2 and SD3) was struck by a devastating earthquake with an estimated Mw of 6.4–6.5 [6,7]. The mainshock was preceded by some foreshocks on the previous day, and was followed by aftershocks that lasted until August 1921 [38]. The earthquake induced a vast area over about 160 km² of severe damages (which in some zones reached I 10 MCS). From the interpretations of the macroseismic field [6,7,8], different causative faults were proposed and are under discussion as the source of the 1920 Fivizzano earthquake.



(a) Macroseismic field of the 1920 Fivizzano earthquake. MCS intensities are those of the database in [7], while epicentral positions are derived from different works (see legend); **(b)** Area of maximum intensity of the 1920 Fivizzano earthquake [7,8,9]; **(c)** Recognized seismogenic source according to DISS 3 [1]; **(d)** North Apuane Fault System architecture in surface and subsurface, with location of historical and recent earthquakes. Light yellow represents the North Apuane seismogenic source.

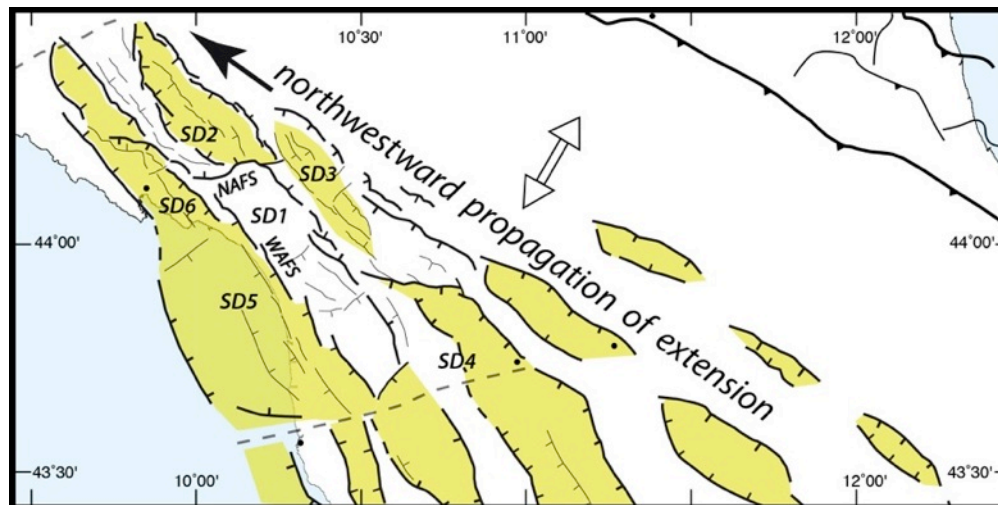
5: Key points. As the North Apuane Fault forms the northern termination of the NNW-trending, east-dipping westernmost faults of Garfagnana/D3 (Casciana-Sillicano and Gorgigliano Faults) and the southernmost tip for west-dipping easternmost fault of Lunigiana/SD2 (Compione-Comano Fault) we hypothesize that the earthquake ruptured both one of the NNW trending faults and the North Apuane fault.

6. CONCLUSIONS

Fault Distribution and Evolution

Our work shows that the region of study is densely dissected by large faults of 10 to 40 km lengths. The dominant faulting trends NW–NNW, and has normal slip, with an additional component of left-lateral slip. The faults are steep and commonly combine in conjugate pairs of antithetic faults bounding grabens. These grabens are disconnected from each other or nested within one another, and their width is narrowing northwestward. Collectively, they form an overall area that tapers northwestward. This architecture might thus suggest the northwestward propagation of extensional faulting [14,15] in this part of the Apennines in addition to the eastward migration of extensional strain over time from west to east [3,5].

The map shows in yellow a simplified view of the principal grabens with their sedimentary Plio-Quaternary filling.



Our study provided a review of most available knowledge on Cenozoic geology, stratigraphy, faulting, seismicity, and current surface strain in the inner northwest Apennines.

The architecture of the faults depicted in our study markedly differs from the seismotectonic model proposed so far, in which faulting would be mainly related to a major low-angle, east-dipping active detachment [16,17]. Rather, we show that faults are steep, paired in conjugate sets bounding grabens, and disconnected, although forming a kinematically coherent overall fault system.

Our study calls for a new evaluation of the recent activity and the earthquake potential of the many faults we identified as potentially seismogenic source. Further studies are therefore needed to better assess the seismic hazard of the investigated area.

Evidence for Recent Fault Activity and Implications for Seismic Hazard

One of the most important results of our work was to document that the majority of faults described in the study have been active over the Quaternary. Most show displacements post-800 ka, and in some cases clear slips across Late Pleistocene and Holocene deposits. In addition, some of these faults show evidence of recent to current activity. Yet, most of these seismogenic faults are not considered in the national and local hazard evaluations. While most of the faults we identified are shorter than 35–40 km, they may have the potential to produce strong earthquakes as already occurred in the past. The properties of the faults are such that these earthquakes are expected to be potentially large ($M_w \geq 6.0$), to produce up to several meters of slip at the ground surface, and to possibly occur in temporal cascades as in other part of Apennines [15].

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