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Seismicity-Driven Insights into the Extensional Architecture of the Northern Apennines, Italy

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Understanding the spatio-temporal evolution of seismicity is essential for unveiling the seismotectonic architecture of active regions, as it links earthquake occurrence with the geometry, kinematics, and origin of seismogenic processes.

We investigate persistent microseismic and moderate seismic activity in the central-northern Apennines (Italy) using the CLASS (Italian Absolute Seismic Catalogue), which is based on a 3D velocity model, and applying a template matching technique following seismic clustering. From an initial dataset of ~230.000 events, we analyse a subset of 69.875 seismic events ($0.0 < M_L < 4.8$) recorded between 2010 and 2023. Seismicity within the well-known 2016–2017 Amatrice–Visso–Norcia seismic sequence, the 2013–2015 Gubbio seismic activity and events classified as anthropogenic are excluded.

Seismic clusters are identified using the HDBSCAN algorithm, a hierarchical density-based clustering method that extends DBSCAN and is well suited for detecting clusters with variable density and shape in extensive spatial datasets. By introducing the temporal component, it is observed that HDBSCAN may produce clustering artefacts if applied to large datasets spanning long time intervals (14 years). To mitigate this effect, a Kernel Density Estimation is additionally applied to obtain more robust and well-defined spatio-temporal clusters. The analysis is performed by dividing the study area into six equal-area subregions and seven non-overlapping two-year time windows.

The resulting spatio-temporal clustering identifies 78 clusters, primarily classified as seismic swarms, distributed across the study area, with magnitudes up to M_L 4.8. Most clusters exhibit spatial patterns and focal mechanisms consistent with known active faults documented in the QUIN database (QUaternary fault strain INdicator). Conversely, three groups of clusters occur in the upper crust and align along an ~100 km-long arcuate trend between the foothills south of Bologna and the Apennines west of Pesaro. In this sector, lithological conditions may hinder fault outcropping, suggesting the presence of blind faults whose activity is expressed mainly at depth, near fault roots. These clusters refine the complex architecture of the extensional domain and may indicate previously unrecognized southwest-dipping blind normal faults, or structural complexities (e.g., synthetic or antithetic structures) within the basal detachment.

The envelope of the seismic clusters reveals that the front of the Apenninic extensional domain, hosting the most significant historical and instrumental earthquakes, extends eastward beyond the outcropping west-southwest-dipping normal faults. This finding has important implications for seismic hazard assessment in the densely populated foothill areas of the Northern Apennines and contributes to a better understanding of the architecture of low-angle normal fault systems.