



Origin of Seismicity in Italy as a Clue for Seismic Hazard

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Abstract. Italian seismicity is generated by the ongoing subduction of the European lithosphere beneath the Alps, and the Adriatic lithosphere beneath the Apennines. The two belts are extremely different due to their opposite polarity relative to the inferred underlying ‘eastward’ mantle flow. Contractual tectonics is concentrated in low topography areas, whereas extensional tectonics and the larger magnitude seismicity due to normal faulting is preferentially located along the Apennines ridge, where the brittle crustal layer is thicker and the lithostatic load is maximum. Seismicity is the result of dissipation of energy along passive faults but stored mostly in crustal volumes located in the hangingwall of the faults. The 2–5 mm/yr deformation in all Italian tectonic settings prevents the occurrence of great earthquakes (Mw 8) that rather occur in other areas of the world where deformation rates are at least one order of magnitude faster. The maximum event so far recorded in Italy is Mw 7.3, 1693 southeast Sicily. InSAR data nowadays provide a precise definition of the epicentral area of an earthquake, which can be several hundred km². The epicentral area is defined as the ‘active’ domain where the hangingwall is moving along the fault and it is contemporaneously crossed by the seismic waves radiated by the fault plane due to the friction in it. Within the active domain occur the strongest coseismic shaking, both vertical and horizontal. The vertical coseismic motion allows the horizontal shaking to be much more effective.

Keywords: Italian geodynamics · Epicentral areas · Active domain · Passive domain · Vertical motion · Gravitational · Elastoquakes

1 Geodynamic Setting

Italian geodynamics is shaped by two subduction zones, i.e., the Alps and the Apennines. Their vitality generates the seismicity repeatedly devastating the nation. The two belts pertain to two very different subduction styles. In the Alps the subduction hinge of the downgoing European plate converges relative to the upper Adriatic plate, whereas in the Apennines the Adriatic plate subducts beneath the European plate and the subduction hinge diverges relative to the upper plate (Carminati and Doglioni 2012). This different kinematics determine mostly contraction in the Alps and widely distributed extension in the Apennines (Fig. 1), where the contracting accretionary prism is confined in the

eastern external areas (Po Basin, Western Adriatic, Ionian Sea and Sicily). Contractual seismicity is mostly confined in the low topography frontal ranges of the Alps and Apennines due to the lower lithostatic load, favoring larger differential stress. Unlike the Alps, the extensional seismicity is rather widespread within the Apennines, and it increases in magnitude in highly elevated areas where the brittle thickness is larger and the lithostatic load is maximum (Carminati et al. 2004). There are in average 15.000–20.000 recorded earthquakes per year in Italy, most of them felt only by the INGV seismic network. Between 1900 and 2000 AD, 248 events occurred with $M_w \geq 5$ and they listed in the INGV Italian Parametric Earthquake Catalogue https://emidius.mi.ingv.it/CPTI15-DBMI15/query_eq/ (Rovida et al. 2022). The extensional area in the hanging wall of the Apennines subduction is where most of the earthquakes occur (Fig. 2). Moving from the Tyrrhenian Sea eastward in the belt, the crustal thickness increases, and the brittle-ductile transition (BDT) deepens. Since the seismogenic layer is controlled by the brittle thickness, and the length of the volume increases with the depth of the BDT (in average 3 times the brittle thickness), the magnitude grows moving from the western side of the Apennines to their main ridge where the brittle crust is thicker (Fig. 3). The volumes adjacent to faults accumulate the energy that will eventually be released by earthquakes, that is elastic energy in strike-slip and contractional settings, whereas is gravitational in extensional tectonic environments. That's why we can distinguish earthquakes into elastoquakes and graviquakes (Doglioni et al. 2015). Based on the involved volumes, we can infer the maximum magnitude that every area in Italy can experience (Fig. 4). Seismic sequence last longer in extensional tectonic settings because the volumes are gravitationally enhanced (Fig. 5). Therefore, also the Gutenberg–Richter b-value differs, as well as the Omori p-value, in the different tectonic settings, as a function of whether the volume moves in favor or against gravity (Fig. 6).

2 Seismic Hazard Remarks

Since the development of InSAR technique and the wealth of new data, the pre- and post-earthquake satellite recording precisely depict the fingerprint of the epicentral areas affected by the coseismic deformation. Moreover, it is noteworthy that the stronger shaking and the highest macroseismic intensity coincide with the area depicted by the SAR images, where the vertical component of the PGA and PGV have been manifested (Fig. 7). During the last decades, the earthquake in Italy have shown PGA much stronger than those expected from the national codes for new constructions. In other words, we should focus our efforts in improving seismic hazard evaluation as we were inside the epicentral area, where the vertical coseismic movements are much larger. When the ground coseismically collapses in the epicentral area of a normal fault-related earthquake, the load of a building decreases and the friction between bricks is attenuated, facilitating the shear imposed by the horizontal shaking, hence producing larger damages (Fig. 8). This area/volume can be defined as the 'active domain', where there occur both the main tectonic movement and the volume is contemporaneously crossed by the seismic waves radiated from the fault surfaces (Fig. 9). It is there, in the future epicentral areas where we should concentrate the seismic hazard assessment; in fact, besides site amplification effects that may occur also outside the epicentral area, any region undergoing tectonic

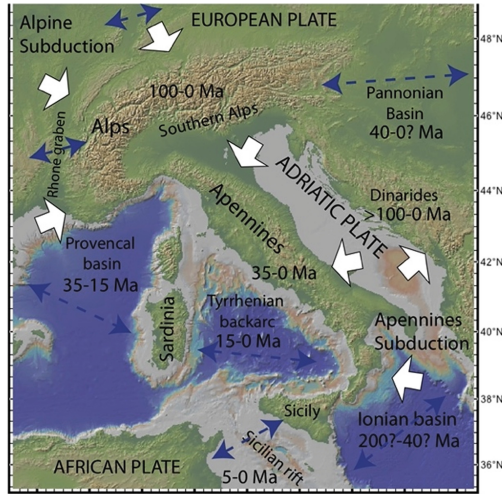


Fig. 1. Italian geodynamics and related seismicity are featured by the subduction of the European plate beneath the Adriatic plate, generating the Alps, and the westward subduction of the Adriatic plate beneath Europe producing the Apennines and the Tyrrhenian backarc basin due to the slab retreat.

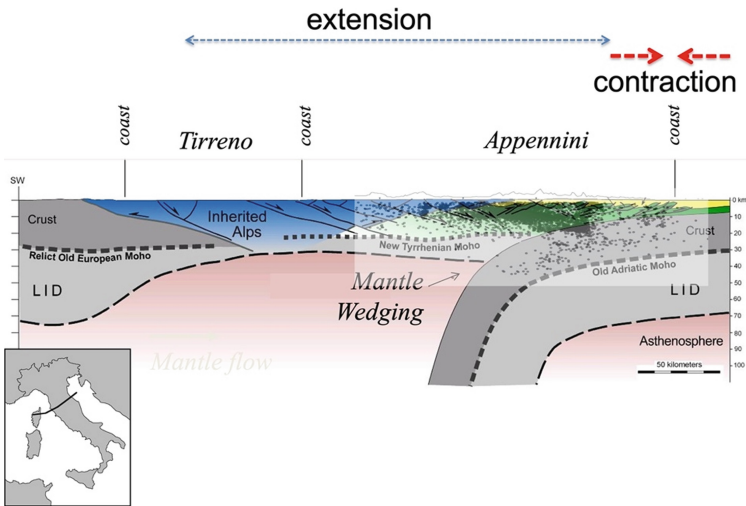


Fig. 2. Cross-section of the central-northern Apennines showing the westward subduction of the Adriatic plate and the distribution of seismicity (thin black dots).

deformation is prone to seismic events. Their magnitude depends on the volume (Fig. 10), whereas their frequency is related to the deformation rate. With a given magnitude, again apart the site effects, the resulting PGA increases as the hypocenter is shallower (Fig. 11).

Seismic hazard maps should be made considering that each area could be an active domain where the shaking will be much higher than the surrounding passive domain.

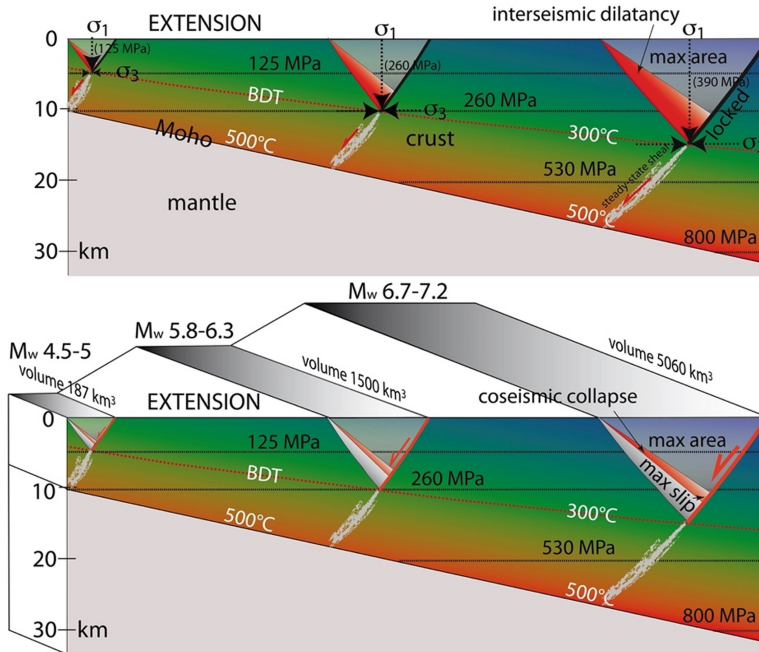


Fig. 3. In extensional tectonic settings, the ratio between the seismogenic layer depth and the hanging wall length appears to be, in average, 3 ± 1 . As the thickness increases, the volume enlarges, the fault is longer, and the hanging wall collapse determines a greater fault slip and a consequent higher earthquake magnitude. Note that doubling the seismogenic layer from 5 to 10 km, the volume increases about 1 order of magnitude, as the maximum earthquake size, from M5 to M6. BDT, brittle-ductile transition. The red wedges in the section above suggest the inferred dilated crustal volume permeated by thousands of millimetric microfractures. Therefore, the deeper the BDT, the bigger the volume and magnitude of the earthquake, and the larger the area affected by coseismic subsidence. This explains why seismicity increases in terms of number of earthquakes and their magnitude moving from the Tyrrhenian Sea to the Apennines main ridge (after Bignami et al. 2020; Petricca et al. 2021).

Moreover, new computations of the seismic hazard should include the time dependence of earthquakes (Akinci et al. 2018), the rheological parameters of the lithosphere (Doglioni et al. 2011; Riguzzi et al. 2012, 2013; Petricca et al. 2015), the deformation rates recorded by space geodesy (e.g., Pezzo et al. 2020), the dimension of areas where the vertical component will be concentrated in the active volume (Bignami et al. 2019; Petricca et al. 2021) and seriously include the incompleteness of the catalogs (Scholz 2019).

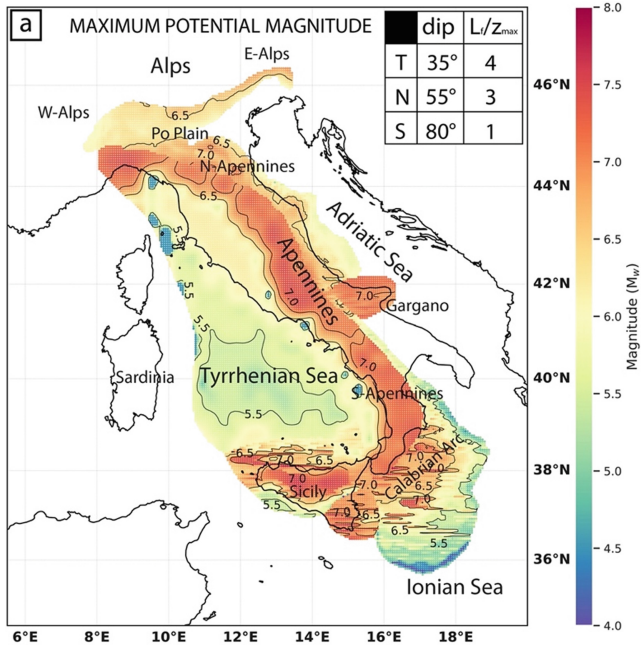


Fig. 4. Map of the maximum potential magnitude (M) predicted for the Italian territory due to normal, thrust and strike-slip faulting (after Petricca et al. 2022). Results assume the following fault dip α and $C = L/z_{max}$ (i.e., fault length—maximum faulting depth ratio): $\alpha = 35^\circ$ and $C = 4$ (thrust faults); $\alpha = 55^\circ$ and $C = 3$ (normal faults); $\alpha = 80^\circ$ and $C = 1$ (strike-slip faults).

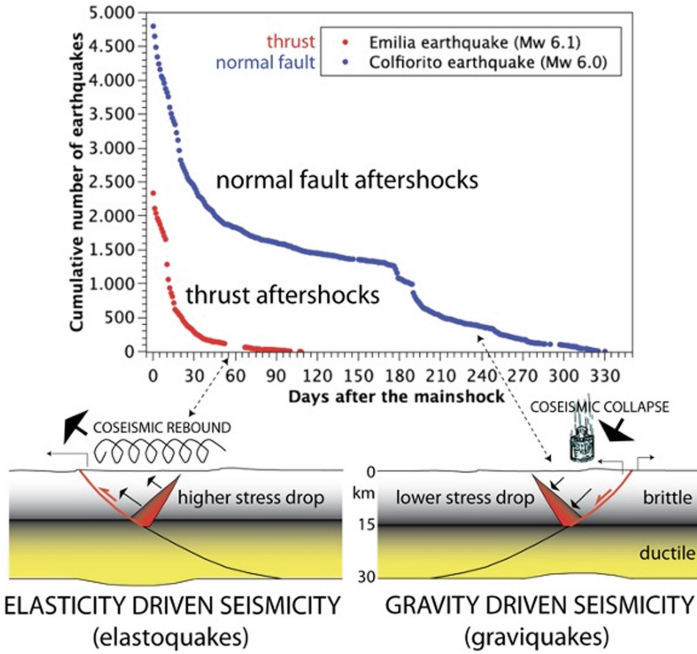


Fig. 5. Aftershocks are more numerous and last longer in extensional tectonic settings because the volumes move in favor of gravity. The contrary occurs in contractional settings because the volume must win gravity (modified after Valerio et al. 2017).

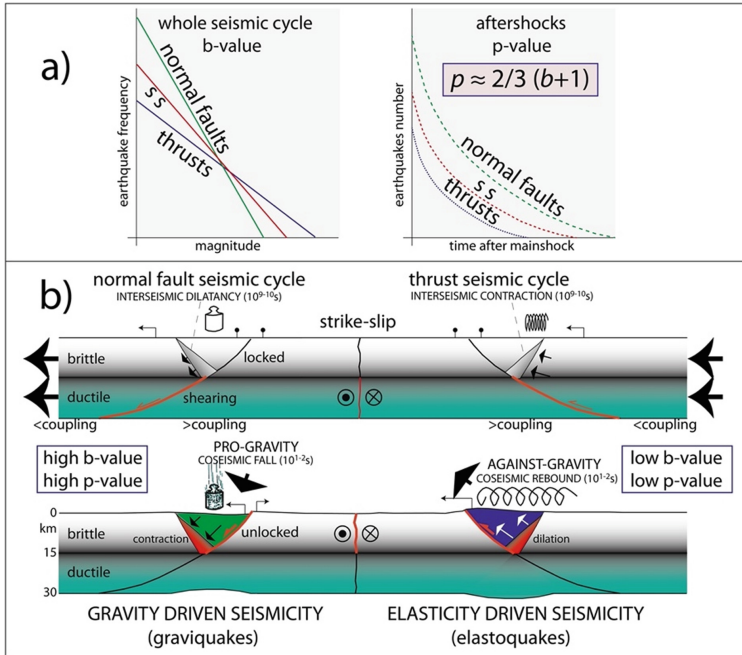


Fig. 6. (a) Left panel, the b -value of the Gutenberg–Richter law differs as a function of the tectonic setting, being higher in extensional tectonic settings. Therefore, normal faults have a steeper alignment, which means more low magnitude events and lower maximum magnitude earthquakes with respect to strike-slip (SS) and thrust faults; right panel, being the p -value of the Omori law correlated to the b -value, it shows different aftershocks evolution in time depending on the tectonic settings. On the base of theoretical considerations and statistical analysis of one hundred seismic sequences, the most reliable relationship between them reads $p \approx 2/3 (b + 1)$. Larger p -values mean that seismic dynamics moves more rapidly towards stability, which also implies relatively higher probability of secondary ruptures and more numerous aftershocks than the average reference. (b) A geological interpretation of different scaling behaviors can be given in the light of different contributions to energy balance in the long-term rock volumes mobilization. In extensional tectonic settings the seismogenic volumes are smaller, producing lower maximum magnitudes with respect to the other tectonic settings. Contractional settings require more energy to move against gravity and they may involve much larger volumes before reaching the threshold to slip, i.e., producing much larger magnitude events and a lower b -value and p -value (after Zaccagnino et al. 2022).

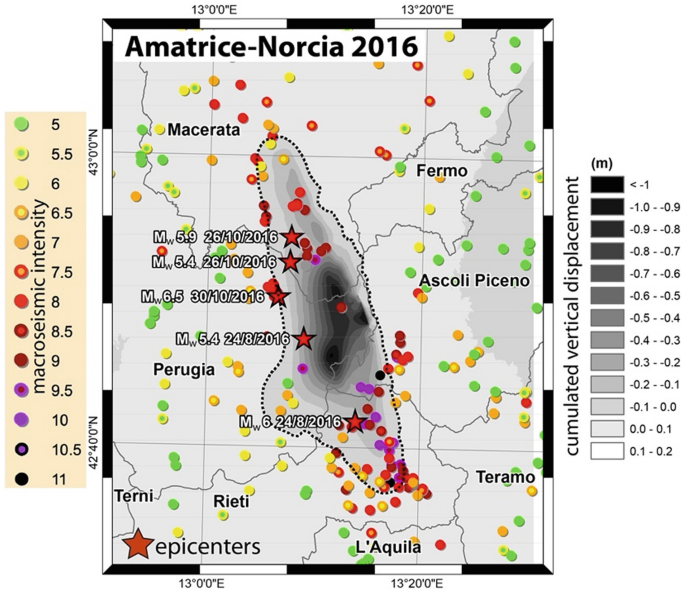


Fig. 7. Coseismic subsidence computed through DInSAR data compared to the macroseismic intensity of the Mw 6 and 6.5 Amatrice-Norcia August 24th and October 30th 2016 Central Italy seismic sequence. Most of the damage occurred in the area that underwent vertical deformation, apart from rare scattered local amplification sites outside the elliptical area (after Al Shawa et al. 2021).

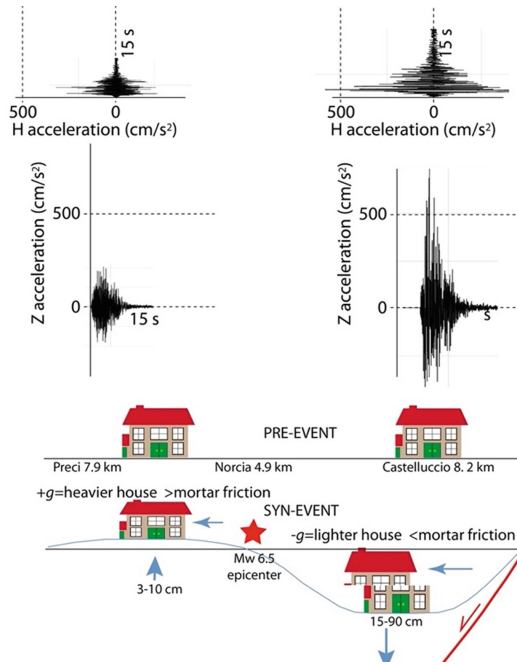


Fig. 8. Higher panels: Ground motion components occurring during the Mw 6.5 October 30th 2016 Norcia mainshock outside (coseismic uplift) and inside the epicentral area (coseismic subsidence). Lower panel: two cases in which the coseismic motion is upward (left) or downward (right) during the increase of horizontal components (after Liberatore et al. 2019). Within the coseismically subsiding area there have been the strongest shaking and the horizontal components acted while the volume and the house were falling down, hence with decreased load acting on the building.

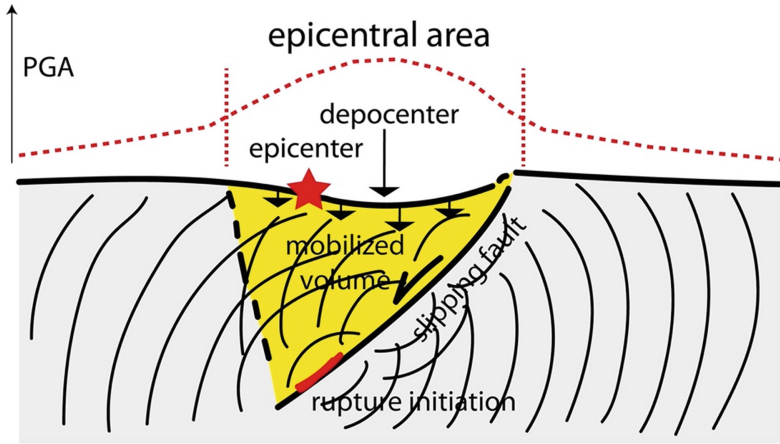


Fig. 9. Cartoon illustrating the overlap of the hanging wall volume undergoing coseismic subsidence and contemporaneously crossed by the seismic waves sourced by the normal fault slip. In the ‘active’ (yellow) volume where the two phenomena overlap, the peak ground acceleration (PGA) is maximum, and it may be referred to as the epicentral area. Outside the mobilized volume, seismic waves propagate into a ‘passive’, i.e., static volume. This may explain the higher macroseismic intensity at the surface of the active volume (after Al Shawa et al. 2021).

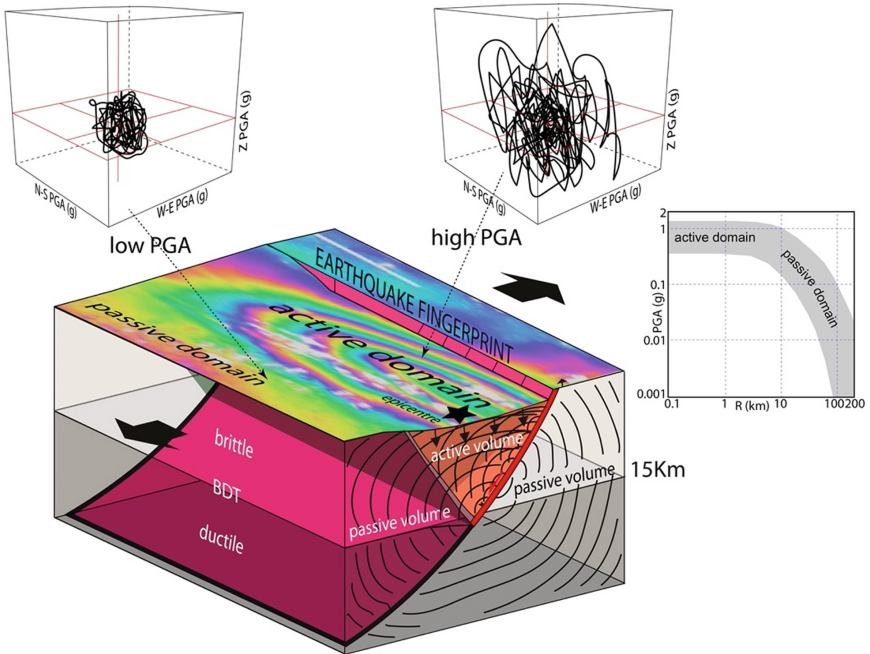


Fig. 10. Sketch illustrating the model. The coseismic ground deformation detected by InSAR data represents the fingerprint of the epicentral area and is located above the volume mobilized in the fault hanging wall in case of extensional setting. The area increases with magnitude. The earthquake epicenter is misplaced relative to the depocenter of the maximum coseismic subsidence where the strongest shaking is recorded. Outside the elongated epicentral area, even if relatively close to the epicenter, the vertical coseismic deformation is drastically reduced as well as the shaking; see the hypothetical trajectory of the acceleration vector inside and outside the epicentral area. Right: diagram of the PGA (g) average data in the gray area from the literature versus distance (R) inferring the active and passive domains (after Petricca et al. 2021).

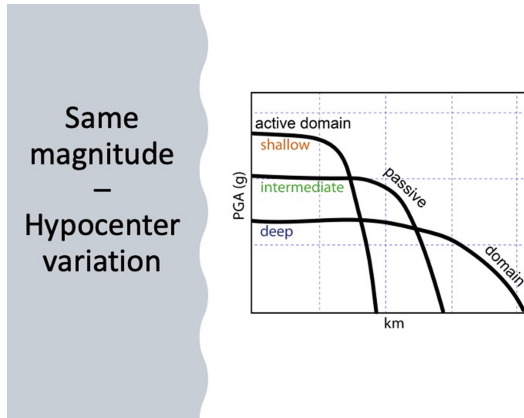


Fig. 11. The highest PGA occur in the epicentral area or active domain, decreasing outside the epicentral area or passive domain. However, assuming the same magnitude, the PGA increases as the rupture occurs at shallower crustal level. Moving deeper, the same energy is partly dissipated by the rocks anelasticity, and the shaking decreases. Although weaker, the active domain becomes wider due to the larger cone of influence.

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