

The role of gravity in normal and reverse faulting earthquakes

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Abstract

Gravity is a force contributing to the strain energy and the tectonic stress driving faulting and generating earthquakes. This paper discusses the role of gravity in earthquake mechanics for different tectonic settings. Considering the stress state in normal and reverse tectonic settings, including gravity as a direct contribution to lithostatic load, it is possible to show that earthquakes on normal faults do not have a different energy source than elastic rebound and that this explains differences with reverse faulting earthquakes. The paper discusses the implications from dismissing the elastic rebound theory or limiting its validity to reverse or strike-slip faulting, as suggested to support the graviquakes model, and the consequences on the mechanics of dip-slip earthquakes. A simple model of tectonic stress relying on Anderson theory of faulting can describe the different stress state of normal and reverse faulting earthquakes, showing higher values of tectonic stress acting on reverse faults than normal faults, for different values of the static friction coefficient. The model shows that the difference between tectonic stress before and after a dip-slip earthquake increases with the static friction coefficient, emphasizing the effect of the drained conditions on compressional tectonic stress, and the negligible effect for extensional tectonic settings. Slip can occur on normal faults creating horizontal extensional deformation when the minimum stress is compressional, since extension is caused by the deviatoric stress acting on the fault plane. The different stress state can explain numerous seismological observations, likely accounting for non-Byerlee friction, stress and strength heterogeneity and geometrical complexity. The adoption of elastic rebound does not imply that the energetics of normal and reverse faulting earthquakes is the same. Considering crustal faults as passive subjects accommodating slip caused by volume collapse contradicts geological observations of fault zone structure, laboratory experiments and the spectrum of fault slip behavior. Faults are active geological subjects characterizing the strain localization and the energy release.

Keywords: Dip-Slip Faulting; Elastic Rebound; Gravitational Potential Energy; Dislocation Theory; Elastic Strain Energy

1. Introduction

The role of gravity in earthquake mechanics has been widely discussed in the literature, from its role on continental deformation (Artyushkov, 1973; England and McKenzie, 1982) to earthquake-induced variations

in the Earth's gravity field (Harms et al., 2015 and references therein). This paper addresses a more specific topic, namely the role of gravity in explaining differences between normal faulting and thrust or strike-slip faulting earthquakes. This distinction has been recently used to support a conceptual model for normal faulting earthquakes. This model is based on a series of assumptions and conceptual argumentations proposed to overcome alleged paradoxes whose solution should corroborate the new paradigm of graviquakes (Doglioni et al., 2011, 2015; Doglioni, 2024, and references therein). The graviquakes model relies on proposing a different relation with the gravitational force in extensional and compressional tectonic settings. The goal of this paper is discussing the role of gravity in faulting and earthquake mechanics for different tectonic settings relying on theoretical models, geological observations, and laboratory experiments.

Gravity is included in the earthquake energy budget since the available strain energy for initiating a coseismic rupture and dynamic slip instability contains both elastic and gravitational strain energy. A key issue to address for proposing a distinction between the graviquakes and other tectonic earthquakes is the role of gravitational potential energy as a source of earthquake driving energy. To this task, it could first be considered a gravitational tectonic stress field in which the load acting upon a volume and the fault is solely due to gravity. In this case, the vertical stress is a principal stress axis represented by the lithostatic load. This might be the case in which the tectonic stress within the Earth crust originates from gravity acting upon density structures due to lateral density variations (Artyushkov, 1973; Barrows and Langer, 1981) causing, for instance, the complete or partial collapse along a fault of a gravitationally unstable density structure. This gravitational force-driven mechanism, alternative to the elastic rebound, implies that the forces acting in the volume and creating the stress on the fault supply the energy to the faulting process. The energy released during faulting comes directly from a net decrease in gravitational potential energy. However, this force-driven stress would imply the existence of volumetric body-force displacements (Barrows and Langer, 1981), which must exist if gravity force determines the energetics of the faulting process, and they are in addition to displacements generated by slip on the fault (Barrows and Barrows, 2010). This would yield non-double-couple moment tensors, which cannot explain the mechanics of normal faulting earthquakes. Moreover, the gravitational force-driven mechanism has a specific energetics according to which the released gravitational potential energy is split between the energy released in normal faulting (including radiated energy) and an increase in stored elastic strain energy. The stress associated with this elastic strain field should oppose further fault slip (Barrows and Langer, 1981; Barrows and Barrows, 2010) on the normal fault. This implies that this gravitational stress mechanism cannot explain observations from normal faulting earthquakes (such as moment tensor solutions). For this reason, in the following of this study we refer to the classic tectonic stress tensor with vertical and horizontal principal stresses determining differential stress and use it to discuss the graviquakes model.

Earthquakes have traditionally been assumed to result from an elastic strain field (i.e., elastic rebound theory, Reid, 1910) according to which previously accumulated strain energy through tectonic deformation is released within the fault zone and the resulting stress on the fault drives coseismic slip, unlike gravity collapse which stops slip on the fault (Barrows and Barrows, 2010). The elastic rebound model was developed for strike-slip fault systems, where gravitational forces do not contribute to the energy budget. In both cases (elastic rebound and gravity force-driven faulting), the sudden deformation in extensional settings is accompanied by the release of gravitational potential energy (Simpson, 2024). The implications from the adoption of elastic rebound model go far beyond the concept that the elastic strain field is built up by quite continuous elastic deformation in the period between events, since they involve both the localization of total strain energy causing faulting and its dissipation, thus affecting the energy balance and the dynamics of earthquake ruptures. Moreover, several geological observations and laboratory experiments have shown that dynamic instabilities occur on localized shear zones containing principal slipping planes, where elastic strain is concentrated, and available strain energy is released (Di Toro et al., 2011; Smith et al., 2015; Scholz, 2019; Scuderi et al., 2020; Barras and Brantut, 2025; Salazar et al., 2024, among many others). Theoretical models commonly assume that elastic strain is localized on the selected causative faults, but a few theoretical studies have modeled earthquakes on normal and reverse faults on time scales extending beyond a single event (Duan and Oglesby, 2005; Simpson, 2023, 2024 and references therein), showing that elastic strain is localized and released along the dip-slip fault. Therefore, dismissing the elastic rebound theory or limiting its validity to reverse or strike-slip faulting has profound consequences on the mechanics of dip-slip earthquakes. Discussing this issue is one of the goals of this study.

Gravity is also included in the calculation of interseismic strain rate and active deformation. Indeed, regional-scale crustal strain rates are interpreted in terms of a localized balance between remote tectonic load

(i.e., boundary conditions), gradient of gravitational potential energy and other resisting forces internal to the volume (England and McKenzie, 1982; D'Agostino et al., 2014). This affects the stresses acting on the faults and included in the formulation of tectonic loading. At intermediate scales, gravity is also included in the interpretation of topography in extensional basins in terms of coseismic and post-seismic deformation (Ward, 1986; Thompson and Parsons, 2016, 2017) in addition to interseismic strain rate (D'Agostino et al., 2014). These studies have shown that post-seismic relaxation of the ductile (viscoelastic) lower crust contributes to counterbalance the coseismic deformation and to explain the observed uplift and topography. However, this does not represent a deviation from the classic theory of faulting and, more importantly, it does not justify the proposition of a different energy balance (gravitational versus elastic) for normal and thrust faulting earthquakes.

The graviquakes model relies on a peculiar conceptual model in which the normal fault is cross-cutting the brittle upper crust penetrating in the ductile lower crust, and a dilated band (i.e., an antithetic dilated wedge) is formed during the interseismic period at and above the brittle-ductile transition (Doglioni et al., 2011, 2024; Albano et al., 2021). This has strong implications on the nucleation process of normal faulting earthquakes since the brittle fault is expected to move when the weight of the hanging-wall exceeds the strength of the dilated wedge just above the brittle-ductile transition. Moreover, this model assigns a specific role to the hanging-wall volume. Recently, Differential Interferometric Synthetic Aperture Radar (DInSAR) observations have been used to constrain maps of vertical displacement that are integrated to estimate an uplift volume. Bignami et al. (2019) interpreted the negative uplift volume associated with the 2016 Amatrice-Norcia (central Italy) earthquake sequence in terms of this “graviquake” deformation model and argue that it requires a coseismic volume collapse of the hanging wall. However, Segall and Heimisson (2019) have shown that DInSAR observations from the Amatrice-Norcia sequence are consistent with conventional dislocation theory and do not require a volume collapse at depth. Although this controversy might be explained considering the non-uniqueness of modeled surface deformation, the key point to discuss is considering dislocation theory not appropriate to interpret the deformation pattern of normal faulting earthquakes, but suitable for reverse and strike-slip faulting.

Furthermore, it is well known that earthquake sequences in extensional and compressional tectonic settings can be characterized by different features of seismicity patterns, peak ground motion and stress parameters (see Simpson, 2024, and references therein). This evidence has been used to propose that earthquakes on normal faults are actually driven by gravity, rather than by the drop in elastic strain energy accumulated during the interseismic interval, to support the graviquakes model (Doglioni, 2024 and references therein). In this paper, I plan to consider the stress state in normal and reverse tectonic settings to discuss statements asserting that earthquakes on normal faults have a different energy source than elastic rebound and that this is necessary to explain differences with reverse faulting earthquakes.

2. A simple Anderson's model for dip-slip faulting

The role of gravity in the different tectonic settings is considered in the Anderson theory of faulting (Turcotte and Schubert, 1982) for an elastic half-space with brittle rheology through the lithostatic load. Assuming that the vertical stress is equal to the lithostatic load, and the horizontal stresses are obtained from the sum of the lithostatic load and a deviatoric stress (Fig. 1), we can easily represent the tectonic stress (i.e., the principal tectonic stresses) changing the sign of the deviatoric stress: positive for compressional settings ($\Delta\sigma > 0$) and negative for extensional settings ($\Delta\sigma < 0$). Following this representation, we can write the tectonic stress field as:

$$\begin{aligned}\sigma_z &= \rho gz \\ \sigma_x &= \rho gz + \Delta\sigma \\ \sigma_y &= \rho gz + \nu\Delta\sigma\end{aligned}\tag{1}$$

where, ρ is the density, g is the gravitational acceleration, ν is the Poisson coefficient and z is the depth. Compressional stress is positive, and plain strain (no-strain in the y -direction) is assumed in this formulation. The deviatoric stress is $\Delta\sigma$ and its sign for dip-slip faults depends on tectonic setting. Indeed, the horizontal stress components are computed from the lithostatic load and the deviatoric stress $\Delta\sigma$. This simple Anderson's model applies to a compressional setting since the maximum principal stress component (σ_1) is σ_x , and to an extensional setting in which σ_1 is σ_z . The intermediate stress (σ_2) is always σ_y . This conceptual model relies on the assumption that the

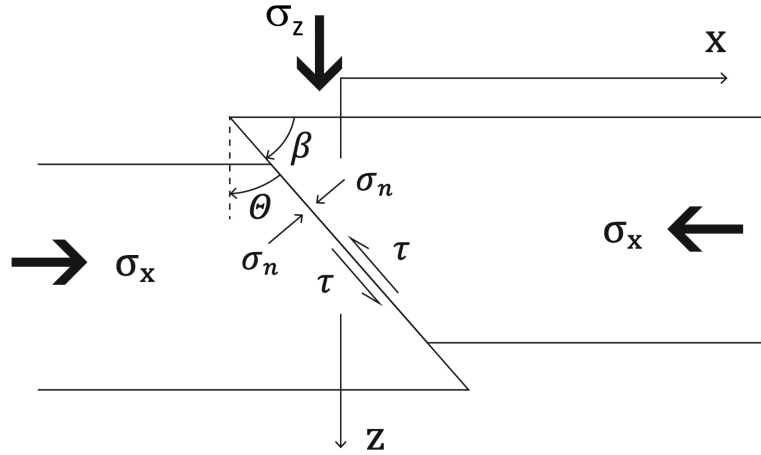


Figure 1. Fault model and tectonic stresses in an elastic half-space ($z = 0$ is the free surface) with brittle rheology. The dip angle is β , τ and σ_n are the shear and normal stress acting on the fault plane, respectively. The vertical stress σ_z is the lithostatic load, ρ is the density, g is the gravitational acceleration and z is the depth. The horizontal stress components are computed from the lithostatic load and a deviatoric stress $\Delta\sigma$, which is positive for compressional and negative for extensional settings, ν is the Poisson coefficient. In a compressional setting the maximum principal stress component (σ_1) is σ_x , while in an extensional setting it is σ_z . The intermediate stress (σ_2) is σ_y . According to this conceptual model, the minimum stress in extensional tectonic setting is positive (i.e., compressional) and smaller than the lithostatic load. Note that, according to Anderson’s theory, all the principal stresses are positive and compressional.

horizontal stress in extensional tectonic settings is smaller ($\Delta\sigma < 0$) than the lithostatic load and the opposite in compressional tectonic settings ($\Delta\sigma > 0$) (Turcotte and Schubert, 1982; Bonafede et al., 1988).

This implies that, for the same depth, the stress state for reverse faults is larger than that for normal faults assuming that the vertical stress is constant (see Fig. 2): following simple calculations using Eq. (A2) in the Appendix we can measure an absolute value of the tectonic deviatoric stress of 300 MPa for a reverse fault at 5 km depth dipping 25° and 65 Mpa for a normal fault at the same depth and dipping at 65° (for a friction coefficient equal to 0.85, see Appendix for details and Turcotte and Schubert, 1982, pp. 639-640). Note that the horizontal stresses are compressional (as expected in the crust) also in extensional tectonic settings (Fig. 1), where only the deviatoric stress is extensional. Figure 2 shows the tectonic stress $\Delta\sigma^1$ acting on a dip-slip fault before faulting (i.e., pre-stress) as a function of the static friction coefficient for reverse (dashed blue curve) and normal (solid blue curve) faults according to Eq. (A2) in the Appendix. This figure clearly shows the higher values of tectonic stress acting on reverse faults than normal faults, for different values of the static friction coefficient determining peak stress (Bonafede et al., 1988). Figure 2 also shows the tectonic stress ($\Delta\sigma^2$) acting on the dip-slip fault after coseismic slip (i.e., the final or residual tectonic stress at the end of the coseismic stage) as a function of the static friction coefficient for different values of the Skempton parameter B (see Eq. A5). The solution for $B = 0$ corresponds to neglect the presence of fluids, while $B = 0.85$ corresponds to the value proposed by Rice and Cleary (1976) for Westerly granite. Usually, for incompressible solids the Skempton parameter is assumed to be $B = 1$. This figure emphasizes that the difference between the tectonic stress before and after a dip-slip earthquake increases with the static friction coefficient. It also shows the evident effect of the drained conditions on compressional tectonic stress, and the negligible effect for extensional tectonic stresses.

Following Bonafede et al. (1988), the static stress drops of normal and thrust earthquakes in a saturated poro-elastic medium (see the Appendix) can be computed from the tectonic stress values before and after the earthquake. As expected, it results that the change in pore pressure is opposite in sign for extensional ($\Delta p < 0$) and compressive settings ($\Delta p > 0$), and it depends on the values adopted for the Skempton parameter B (see Appendix for details). The equation for the static stress drop is presented in the Appendix (Eq. A6).

Simple calculations reveal that the stress drop of thrust earthquakes is larger than that of normal faulting earthquakes. Figure 3 shows the comparison between the stress drop of compressional (orange curves) and normal (blue curves) faulting earthquakes as a function of the static friction coefficient at two depths 5 km (a) and 10 km (b).

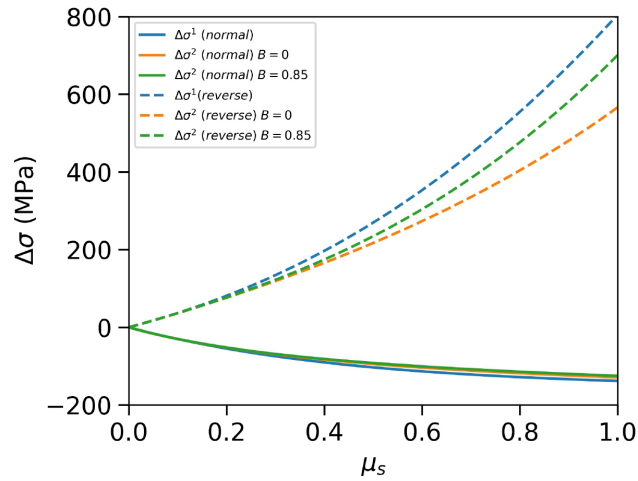


Figure 2. Tectonic deviatoric stress acting on reverse (dashed curves) and normal (solid curves) before faulting ($\Delta\sigma^1$) and after faulting ($\Delta\sigma^2$) as a function of the static friction coefficient (see Appendix for details) computed at 10 km depth. The final tectonic stress after faulting ($\Delta\sigma^2$) is plotted for two different values of the Skempton parameter B ($B = 0$, and $0,85$) according to Eq. (A5) in the Appendix.

The stress drop values of thrust earthquakes might be associated to small values of the ratio between dynamic and static friction coefficients, as expected for an asperity model (small μ_d and relatively large μ_s). This figure explains the difference in the stress drop between thrust and normal faulting earthquake consistently with the observations by Cocco and Rovelli (1989). It is important to emphasize that the interpretation of the difference in stress drop does not involve the work done by gravitational forces, since it is well explained by a simple Anderson's model in which gravity accounts for lithostatic load. Moreover, the difference in stress drop observed by Cocco and Rovelli (1989) lies within the dispersion of stress drop estimates around the moment-independent scaling (Cocco et al., 2016). In other words, stress drop variations due to the tectonic setting are smaller than the dispersion of stress drop estimates observed over a broad range of seismic moment values (Baltay et al., 2024). Furthermore, this stress drop variation reflects different high frequency contents of seismic radiation likely due to the different gradient of slip along the fault plane between shallow thrust and normal faulting earthquakes (Cocco and Rovelli, 1989).

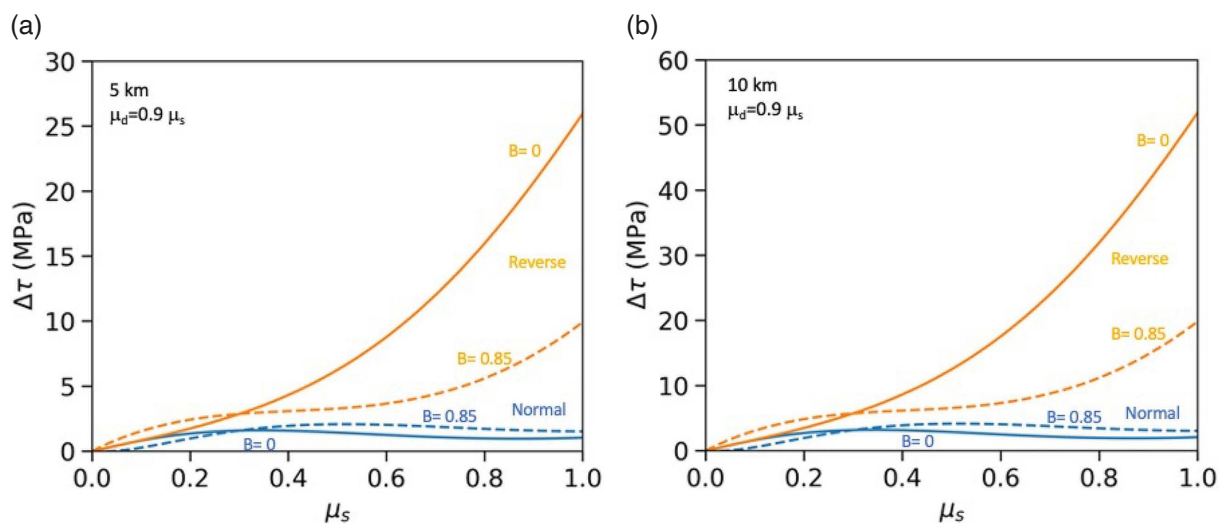


Figure 3. Stress drop as a function of the static friction coefficient for reverse (orange) and normal (blue) faulting earthquakes computed from Eq. A6 (Appendix). Solid lines correspond to $B = 0$, no fluids, while dashed lines correspond to $B = 0.85$ (Rice and Clearly, 1976). (a) The stress drop behaviors computed at 5 km depth, (b) behaviors at 10 km depth.

The simple model presented in Eq. (1) and Fig. 1 relies on the Anderson theory of faulting for an elastic half-space with brittle rheology in which gravity is considered in the lithostatic load (the vertical principal axis). The model explains the higher values of shear stress and differential stresses characterizing compressional settings with respect to normal tectonic settings (Sibson, 1974; Kohlstedt et al., 1995). These conditions can explain several seismological observations such as the difference in stress drop values (Cocco and Rovelli, 1989), the higher values of peak ground motions also determined by the shallow depths and low dip angles of thrust earthquakes (McGarr, 1984; Oglesby et al., 1998, 2000), the difference in b-values (Gulia and Weimer, 2010), the maximum earthquake magnitude (Neely and Stein, 2021), among several other features. This implies that there is no need to use these differences to corroborate the alleged distinction between graviquakes and the so-called elastoquakes. The latter term is quite misleading as discussed in the following of this paper. The abovementioned seismological observations can be explained using a simple Anderson's model of faulting, likely implemented to account for non-Byerlee friction, stress and strength heterogeneity (Simpson, 2024), and geometrical complexity.

3. Elastic rebound and earthquake energy budget

The observation that integrated surface displacement associated with earthquakes on normal faults is oriented downward in the same direction as gravity has been used to suggest that normal faulting earthquakes are driven by gravity (Albano et al., 2021; Bignami et al., 2019, 2020; Doglioni et al., 2011, 2015, 2024) and not by the drop in elastic strain energy within the fault zone and along the fault plane. According to this interpretation, these authors proposed that normal faulting earthquakes in extensional tectonic settings should not follow the elastic rebound, unlike strike-slip and thrust earthquakes that should do (Doglioni, 2024 and references therein). This implies that the decrease of gravitational potential energy in the volume governs the dynamic failure along the normal fault and not the release of elastic strain energy on the fault as expected by elastic rebound. It is therefore legitimate to ask whether this distinction is necessary and justified by the observations.

The elastic rebound theory (Reid, 1910) interprets an earthquake as the result of the instantaneous release along the causative fault of the elastic strain energy stored in the rocks (i.e., in the volume) around the fault. This continuous buildup of strain energy in the period between events (that is, in the interseismic period) supplies the energy to the faulting process and determines the stress state of the fault enabling earthquake nucleation and the subsequent dynamic propagation. During the coseismic stage, the elastic strain energy release determines the energy balance at the crack tip between the energy flow (i.e., the crack driving load) and the dissipated energy, enabling earthquake rupture propagation responsible of the radiated seismic waves (Cocco et al., 2023; Kammer et al., 2024). The elastic rebound assumes that the coseismic slip on the fault relieves in a few seconds most of interseismic deformation of the surrounding volume: the more the crustal rocks are strained the more elastic energy is stored and the greater potential for a large earthquake magnitude and slip. The adoption of brittle rheology for the upper crust and the ubiquitous observation of strain localization in rocks deforming both in elastic and plastic regimes (both on natural and laboratory faults) explain why the elastic rebound is widely adopted in earthquake mechanics, even if there is a limited amount of accurate experimental observations to predict or constrain predictions of dynamic failure. The large seismic slip velocities during dynamic rupture propagation (\sim m/s) are a further evidence of strain localization (Barras and Brantut, 2025). The strain energy released during the earthquake is composed of both elastic strain energy generated by the active tectonic stress field and the gravitational potential energy stored in the volume because of lateral variations of crustal thickness (D'Agostino et al., 2014) and/or because of coseismic and post-seismic deformation during the seismic cycle (Simpson, 2024). The total strain energy is called "elastic" because of the adoption of brittle rheology with linear elasticity in the upper crust and because the gravitational potential energy is a stored energy, which determines the ability of gravitational forces existing in the volume to do work. There are no constraints on the partitioning between these two energy sources in the elastic rebound theory. Therefore, adopting the elastic rebound does not exclude the work of gravitational forces that is included in the energetics of dip-slip earthquakes.

The adoption of the elastic rebound is not limited to prescribe the driving source of energy of repeated earthquakes during the seismic cycle, rather it also accounts for the dissipated energy during coseismic failure (i.e., the earthquake). The available strain energy is dissipated during an earthquake through radiated energy (elastic waves), on-fault (i.e., within the fault core) and off-fault (i.e., within the damage zone) frictional and fracture processes (Cocco et al., 2023, and references therein). On-fault energy dissipation is further partitioned in the

mechanical work sustaining dynamic rupture propagation (i.e., fracture energy or breakdown work; Tinti et al., 2005; Cocco et al., 2006; Kammer et al., 2024) and other forms of frictional dissipation in the fault core including heat. The former is associated with the flow of elastic strain energy at the rupture front. This conceptual interpretation is coherent with numerous seismological, laboratory and geological studies (see Cocco et al., 2023, and references therein), as well as with the theoretical description of earthquake dynamics (Kammer et al., 2024). The scaling of dissipated energy density with seismic moment does not show any dependence with tectonic setting (Cocco et al., 2023), corroborating the evidence that the coseismic energy release is associated with breakdown and frictional processes within fault zones. The dynamic breakdown process associated with the earthquake rupture propagation is dissipative and irreversible. Therefore, the introduction of the concept of elastoquakes (Doglioni et al., 2015; Doglioni, 2024), as opposite to graviquakes, is speculative and not supported/required by observations.

Adopting the elastic rebound does not imply that the energetics of normal and reverse faulting earthquakes is the same. Recent simulations by Simpson (2024) clearly show that normal faulting is clearly favored by gravity and that earthquakes on normal faults result in a large drop in gravitational potential energy, larger than the changes in elastic strain energy. This differs from thrust faulting earthquakes in which both the elastic strain and the gravitational potential energy increase, as expected for the uplift of the hanging wall, the compression, and for the work done against gravity. However, Simpson (2024) concludes that his modeling results do not support the idea that earthquakes on normal faults are actually driven by gravity as opposed to elastic rebound. In particular, the onset of the rupture on a normal fault is associated with an initial drop in elastic strain energy that anticipates the significant change in gravitational potential energy. Thus, the rupture is induced by a drop in elastic strain energy and not in gravitational potential energy. The former enables the latter to occur. The initial drop in elastic strain energy is not observed in models in which inertia is neglected (Barrows and Barrows, 2010; Dempsey et al., 2012), where only an increase in strain energy is witnessed. The subsequent increase of elastic strain energy (see Fig. 7 in Simpson, 2024) is caused by the work done by gravity resulting in the change of gravitational potential energy due to the coseismic gravitational subsidence of the hanging wall compressing the elastic crust and creating elastic energy (Dempsey, 2012; Simpson, 2024).

The main implication of the adoption of the elastic rebound is the localized release of elastic strain energy within the fault zone. This is the main difference with the gravitational force-driven mechanism, which assumes that the gravitational volume collapse is creating the stress on the fault supplying energy to the faulting process. Therefore, in addition to excluding the force-driven gravitational stress as the tectonic loading because it yields volumetric body-force displacements and non-double-couple mechanisms, the observed strain localization along geological faults supports the adoption of the elastic rebound. It is important to further highlight that the elastic rebound includes a reduction of gravitational potential energy for normal faulting earthquakes, which can be larger than the drop in elastic strain energy during the coseismic stage. This explains geodetic observations of normal earthquakes on dip-slip faults showing a significant subsidence of the hanging wall, involving gravitational potential energy as a contributor to coseismic deformation in extensional tectonic settings. Strain localization and its implications on dynamic instabilities and failures is corroborated by numerous laboratory experiments (Di Toro et al., 2011; Smith et al., 2015; Scuderi et al., 2021; Salazar et al., 2024), geological observations (Scholz, 2019), and numerical modeling (Barras and Brantut, 2025).

The strain energy localized within the fault zone supplies the energy to faulting and earthquake ruptures. The elastic rebound foresees that the earthquake rupture is driven by a sudden transfer of strain energy (elastic and gravitational) into the fault zone, but the drop in elastic strain energy drives failure sustaining work against friction. This is the crack driving force, that is the energy flow within the propagating rupture front zone (Kammer et al., 2024, and references therein). For all these reasons, it is difficult to believe that elastic rebound can be ruled out, because the distinction between elastic strain energy and gravitational potential energy to define the energetics of dip-slip faults is neither necessary nor justified by observations.

4. Discussion

In this paper, I have presented and discussed a theoretical framework, a few conceptual argumentations, and several observations from the literature (from natural and experimental faults) to propose that normal faults do not have a different mechanism for energy accumulation and dissipation with respect to other tectonic settings. Although there exist differences between normal and reverse tectonic settings in terms of high frequency radiation,

maximum slip, magnitude and stress drop, fault plane dimensions and related coseismic stress changes, they can be explained in terms of the different stress state of the seismogenic volume as well as the geometry and depth of activated fault planes without invoking different driving and dissipation mechanisms. This implies that there are no conceptual and observational reasons to dismiss elastic rebound and dislocation theory to model both the deformation pattern and the radiated waveforms generated by normal faulting earthquakes (see also Malagnini et al., 2025). In particular, it should be noted that a 3D extended source model for normal faults does not imply horizontal tensional stresses (negative σ_3) as claimed by Bignami et al. (2020) (see Fig. 1 and Appendix) and, more importantly, gravity is considered because shear dislocation and stress drop are associated with the tectonic stress causing dip-slip earthquakes (see Eq. 1). The assertion by Bignami et al. (2020) that the development of a normal fault can be activated only by the vertical maximum stress component (i.e., the lithostatic load) is incorrect since activation is caused by the deviatoric stress, which does not require a negative (i.e., extension) minimum horizontal stress.

During dip-slip faulting the volume does matter because of the Volterra equations (Segall, 2010, pp. 52-58) relating the displacement to an arbitrary distribution of forces (volume integral) or, more specifically, to the slip on the fault plane and the Green's tensors (surface integral on the fault surface). Moreover, during faulting and 3D dislocations the strain energy is modified depending on the coseismic shear traction changes and slip. However, the change in strain energy depends on total stress, not simply the stress change associated with slip (Segall, 2010, p. 86). The key point here is that according to dislocation theory, normal faulting ruptures release gravitational potential energy, whereas earthquakes on reverse faults expend work in uplifting crustal rocks, but the source of energy driving coseismic ruptures is the same on reverse and normal faults. Simpson (2024) demonstrated that earthquakes on both fault types result from abrupt release of elastic strain energy, which generate and essentially drive variations in gravitational potential energy. This further corroborates that vertical displacements and uplift volumes (positive or negative) can be modeled with elastic dislocation theory without invoking a volume collapse at depth for normal faulting. Moreover, the temporary unbalance is partially rebalanced by the viscoelastic relaxation of the lower crust during the post-seismic phase (Ward, 1986; Thomson and Parsons, 2016). As pointed out by Simpson (2024), for a compressible solid, the integrated surface displacements do not vanish and the observation of unbalanced integrated surface coseismic displacements is not inconsistent with elastic rebound theory. Extensional deformation is caused by elastic strain energy and stored gravitational potential energy.

As discussed in this paper, gravity plays a role in the tectonic stress tensor, contributing to the lithostatic load and influencing the mechanical behavior of normal faults. Gravity acts as a modulating factor within the broader framework of elastic strain accumulation and release (Malagnini et al., 2025). Therefore, any reference to the role of gravity should be done by precisely explaining the conceptual framework being used. Gravity alone cannot be the primary driving force for faulting and earthquakes. A gravitational single force model would generate moment tensors with non-double-couple solutions, in contrast to seismological observations of dip-slip earthquakes. Furthermore, most of the seismological and geodetic observations cited to justify the new graviquakes paradigm can be explained with a simple Anderson faulting model considering the different values of tectonic stress present in compressional and extensional tectonic environments. According to this model, the horizontal stress is considered compressional in extensional tectonic settings. Elastic energy is the source of energy for coseismic ruptures during normal faulting earthquakes (Simpson, 2024) which involves a drop in stored gravitational potential energy. All this leads us to conclude that the graviquakes model is not supported by observations and it is essentially based on proposing the existence of the dilational wedge at the brittle-ductile transition. In other words, it relies on a conceptual model not corroborated by seismological and geodetic observations.

Discussing the existence of the dilational wedge is beyond the goals of this paper, also because this would imply discussing the rheology adopted to model a ductile lower crust. To my knowledge, viscoelastic relaxation is not taken into account in numerical modeling of graviquakes (Albano, 2021; Doglioni, 2015). Therefore, the post-seismic relaxation of the lower crust (Ward, 1986; Thompson and Parsons, 2016) is not considered to explain the total volume unbalance during the seismic cycle. Thompson and Parsons (2016) also mention several examples of post normal faulting earthquake uplift in the Basin and Range, measured with a variety of geodetic observations that persist for decades providing observational evidence of post-seismic relaxation. Moreover, the graviquakes model relies on a very specific conceptual framework which foresees the penetration of the normal fault in the ductile lower crust and a steady slip behavior of the deep extension of the normal fault. Malagnini et al. (2025) have demonstrated that a gravitational collapse would yield a moment tensor with relevant isotropic components and that observed ground motion and stress-drop levels remain fully consistent with elastic dislocation theory. These authors

also highlight that finite-element modeling of normal faulting replicates observed surface deformation without invoking a collapsing wedge. Malagnini et al. (2025) have shown that the sudden closure of the wedge would cause significant energy radiation resulting in a further event of magnitude 6.4 for the 2016 Norcia 6.5 main shock characterized by a cumulative isotropic source (first-motion dilatations across most of the entire focal sphere), and a massive expulsion of fluids from the fault zone. These authors raised concerns about the hypothesized rapid expulsion of overpressurized fluids because it lacks supporting seismological evidence and it seems inconsistent with observed diffusion rates. If on the contrary the wedge slowly closes (diffusion time of several hundred seconds), it would result in a slow-quake with no or modest high-frequency radiation which contradicts the observed ground motions. Therefore, Malagnini et al. (2025) conclude that no independent evidence supports the occurrence of large-scale volumetric collapse and the existence of the dilational wedge, as proposed by the graviquakes hypothesis, and that seismological, geodetic, and hydrological evidence supports the classical interpretation of normal faulting earthquakes as elastic dislocation events governed by tectonic loading and elastic rebound.

In this discussion about the role of gravity in dip-slip faulting, I have implicitly referred to planar faults with homogeneous slip distributions and constant stress drops. Furthermore, I referred to Anderson's theory, which holds under specific assumptions about the orientation of the principal stresses (one of the principal stresses must be perpendicular to the Earth's surface), the adoption of brittle rheology for the crust, and the validity of linear elasticity. All of this results in a relationship between the fault's dip angle and the coefficient of static friction (see Appendix). Anderson-Byerlee frictional fault mechanics (Turcotte and Schubert, 1982; Sibson, 1985) predict no slip on normal faults dipping less than 30° in an extensional tectonic setting characterized by a vertical σ_1 if faults have a friction coefficient (μ_s) ranging between 0.6 and 0.85 (Byerlee, 1978). Anderson's conditions result in specific ranges of values for the dip angle, namely 22° - 32° for reverse faults and 58° - 68° for normal faults (Anderson, 1905; Turcotte and Schubert, 1982; Basili and Tiberti, 2025). However, geological faults are complex and heterogeneous and governed by non-linear processes acting together for governing strain localization, stress accumulation and dynamic weakening during earthquakes (Cocco et al., 2023 and references therein). Therefore, we should expect both deviations from Byerlee friction and, consequently, different dip angles for both normal and reverse faults, as suggested for example by the existence of low-angle normal faults (Sibson, 1985; Collettini et al., 2011; Chiaraluce et al., 2009). Basili and Tiberti (2025) report significant differences between the average empirical fault dip-angle distributions and the values predicted by the Anderson's theory. They found that dip-slip crustal faults show the same mode at 40° - 50° for both normal and reverse faulting, whereas transcurrent faults have a large spread of dip angle values around 80° - 90° . This implies that fault zone architecture, rheological properties of fault core, complex geometries of principal slipping planes depending on the orientation of the local stress field and heterogeneous frictional behaviors control faulting and dynamic weakening during earthquakes. In this context, it is important to highlight that the graviquakes model predicts that the steeper the normal fault, the larger the vertical displacement, and the larger the seismic energy released (Doglioni et al., 2015; Petricca et al., 2015). Therefore, the model is in contrast with the existence of low-angle normal faults (LANF) or less effective for normal faults dipping at angles less than 50° . This, together with neglecting the role of strain localization during faulting, leads to the conclusion that the graviquakes model is not constrained by observations.

5. Conclusions

In this work, I discuss several theoretical argumentations and observations to demonstrate that normal faults do not have a different mechanism for energy accumulation and dissipation with respect to other tectonic settings. The role of gravity must be contextualized in a conceptual model that clearly specifies the role of the forces and the stress tensor in determining the energetics of dip-slip faulting. In particular, the assertion that the development of a normal fault can be activated only by the vertical maximum stress component (Bignami et al., 2020; Albano et al., 2021) is misleading because it is the deviatoric stress on the fault determining faulting and dynamic rupture. Gravity affects the amplitude of the principal stresses, therefore contributing to the effective normal stress acting on fault planes and plays a role in controlling the dip angles and structural evolution of fault systems. According to the literature, a gravity force-driven loading would yield volumetric body forces and non-double couple moment tensors. For this reason, faulting and earthquake ruptures are modeled and interpreted in terms of a tectonic stress field in which gravity determines lithostatic loading.

I have discussed a simple model of the tectonic stress field based on the Anderson theory of faulting for an elastic medium with brittle rheology (Turcotte and Schubert, 1982; Bonafede et al., 1988). This model assumes that the vertical stress is equal to the lithostatic load and assigns a specific role to the deviatoric stress determining the amplitudes of horizontal principal stress components, which are obtained from the sum of lithostatic load and deviatoric stress. This simple Anderson's model can explain the differences between normal and thrust faulting earthquakes in terms of different stress state and it can explain differences in earthquake stress drop and other seismological features of seismic sequences in extensional and compressional tectonic settings.

The elastic rebound theory is discussed to interpret interseismic strain energy accumulation and localization as well as energy dissipation emphasizing that dynamic processes associated with earthquake ruptures are dissipative and irreversible. This implies that the term elastoquakes is misleading and its use speculative. The observation that the scaling of dissipated energy density with seismic moment does not show any dependence on tectonic setting (Cocco et al., 2023) is a further evidence that the coseismic energy release is associated with breakdown and frictional processes within fault zones. There is no need to dismiss the elastic rebound to explain the relevant role of the gravitational potential energy in normal faulting earthquakes. Numerical simulations performed by Simpson (2024) clearly show that the change in gravitational potential energy is larger in normal faulting than in reverse faulting earthquakes, but it is preceded by a drop in elastic strain energy. Therefore, the adoption of the elastic rebound does not imply that the energetics of normal and reverse faulting earthquakes is the same. Differently from ruptures on reverse faults, the elastic energy released during earthquakes on normal faults is only partially accumulated during the interseismic period; a significant portion of the available strain energy is always there but is only made available to do work once the rocks fail plastically in response to relaxation of horizontal compressive stresses (Simpson, 2024). The main implication of elastic rebound is the localized release of elastic strain energy within the fault zone, which drives the release of gravitational potential energy.

The assumption that coseismic deformation in normal faulting earthquakes is caused by a volume collapse of the hanging wall is not corroborated by observations (Segall and Heimisson, 2019; Malagnini et al., 2025). Moreover, assuming that the volume collapse is creating the stress on the fault supplying energy to the faulting process does not account for widely observed strain localization within fault zones and the role of deviatoric stress on the fault. Geodetic observations for normal faulting earthquakes can be modeled with conventional dislocation theory without invoking a volume collapse at depth (Segall and Heimisson, 2019) and without implying horizontal tensional stresses (negative σ_3). Normal faulting ruptures release gravitational potential energy, whereas earthquakes on reverse faults expend work in uplifting crustal rocks, but the source of energy driving coseismic ruptures is the same on reverse and normal faults. This does not represent a deviation from the classic theory of faulting and, more importantly, it does not justify the proposition of a different energy balance (gravitational versus elastic) for normal and thrust faulting earthquakes. The elastic dislocation theory currently remains the most robust and comprehensive approach for understanding seismicity on dip-slip faults and for seismic hazard assessment.

Interpreting normal faults in terms of the coseismic gravitational collapse of the hanging wall, as done in the graviquakes model, implies that they are passive frictional structures. The foundation of graviquakes model is the coseismic collapse and closure of a subvertical dilated wedge: the brittle normal fault is expected to move when the weight of the hanging-wall exceeds the strength of the dilated wedge just above the brittle-ductile transition. Therefore, the graviquakes model is reduced and based on the existence of the dilated wedge at depth. Malagnini et al. (2025) have shown that the existence of this dilational wedge is not supported by seismological and geodetic observations, since it would produce a relevant seismic moment release associated with non-double couple mechanisms. Discussing the existence of the dilational wedge is beyond the goal of this study. However, it is important to highlight the implications of the graviquakes model for earthquake geology, laboratory experiments and earthquake mechanics: considering faults as passive subjects is against current interpretations of the mechanics of earthquakes and it is not supported by observations.

I conclude emphasizing the evidence that faults are active geological subjects characterizing the strain localization within the fault zone and the strain energy release during the seismic cycle (Chester and Logan, 1986; Chester and Chester, 1998; Collettini and Sibson, 2001; Sibson, 2003; Faulkner et al., 2010; Simpson, 2024; among many others). Considering crustal faults as passive subjects accommodating slip caused by volume collapse is misleading and contradicts geological observations of fault zone structure, laboratory experiments and the spectrum of fault slip behavior.

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Appendix.

Let's consider an elastic homogeneous half-space with free surface at $z = 0$, density is ρ , g is the gravitational acceleration, ν is the Poisson coefficient and z is the depth. The vertical stress is the lithostatic load, while the horizontal stress components are computed from the lithostatic load and a deviatoric stress $\Delta\sigma$, which is positive for compressional ($\Delta\sigma > 0$) and negative ($\Delta\sigma < 0$) for extensional settings, as in Eq. 1. The fault has a dip angle β (Fig. 1). According to the Coulomb criterion, the fault will slip when shear stress is larger than Coulomb failure stress obtained by the static friction coefficient (μ_s) and the effective normal stress

$$|\tau^1| = \mu_s(\sigma_n^1 - p_f^1)$$

where τ is the shear stress, σ_n is the normal stress and p_f is the fluid pressure. The superscript 1 means values before faulting or earthquake slip. Following Bonafede et al. (1988), the tectonic stress acting on the fault (Turcotte and Schubert, 1982) is

$$\pm\Delta\sigma^1 \frac{\sin 2\theta}{2} = \mu_s \left[\rho g z - p_f^1 + \Delta\sigma^1 \frac{(1 + \cos 2\theta)}{2} \right] \quad (\text{A1})$$

where the sign + apply to compressional settings and - to extensional settings (Eq. 8.31 in Turcotte and Schubert, 1982). The angle θ is the complementary angle to the dip angle β (see Fig. 1). Anderson theory (Jaeger and Cook, 1976) foresees that the following relation between the angle θ and the static friction holds

$$\tan(2\theta) = \mp \frac{1}{\mu_s}$$

where the upper sign (-) holds for compressional settings and bottom sign (+) for extensional. This relation and Eq. (A1) allow the derivation of the following expression for the tectonic stress before faulting and coseismic slip

$$\Delta\sigma^1 = \frac{\pm 2\mu_s(\rho g z - p_f^1)}{(1 + \mu_s^2)^{1/2} \mp \mu_s} \quad (\text{A2})$$

where the upper signs apply to compressional settings and the bottom sign to extensional (Eq. 8.32 in Turcotte and Schubert, 1982). Eq. (A2) can be used to compare the stress state in compressional and extensional tectonic settings (Fig. 2). Assuming that the static friction coefficient is $\mu_s = 0.85$, as confirmed by numerous laboratory experiments, and $p_f^1 = \rho_w g z$ (ρ_w being the water density, i.e., hydrostatic conditions), the optimally oriented fault for failure has a dip angle of $\beta \cong 25^\circ$ and $|\Delta\sigma| = 300$ MPa at a depth of 5 km for reverse faults. Conversely, for a normal fault at the same depth of 5 km the dip angle is $\beta \cong 65^\circ$ and $|\Delta\sigma| = 65$ MPa.

In order to compute the static stress drop of a dip-slip earthquake, it is necessary the calculation of the residual stress after coseismic slip, which is given by the shear stress at the dynamic friction according to the following relation (Bonafede et al., 1988)

$$|\tau^2| = \mu_d(\sigma_n^2 - p_f^2)$$

where superscript 2 means values after faulting (i.e., when coseismic slip is ceased) and μ_d is the dynamic friction coefficient. Implementing this relation using the principal stress components, an equation equivalent to (A1) can be obtained for the stress state after coseismic slip

$$\pm \Delta\sigma^2 \frac{\sin 2\theta}{2} = \mu_d \left[\rho g z - p_f^2 + \Delta\sigma^2 \frac{(1 + \cos 2\theta)}{2} \right] \quad (\text{A3})$$

where the upper sign is for compressional settings. The change in pore pressure caused by coseismic slip can be computed as (Rice and Cleary, 1976)

$$\Delta P = p_f^2 - p_f^1 = \frac{B(1 + \nu_u)}{3} [\Delta\sigma^2 - \Delta\sigma^1] \quad (\text{A4})$$

where ν_u is the Poisson coefficient for undrained conditions. Setting $B = 0$ means neglecting the presence of fluids, while for incompressible solids the Skempton parameter is often assumed to be $B = 1$. In this work I use the parameters proposed by Rice and Cleary (1976) for Westerly granite, namely $B = 0.85$ and $\nu_u = 0.34$. In an extensional setting $\Delta\sigma^1 < \Delta\sigma^2 < 0$, implying that $\Delta P > 0$, while in compressional setting the opposite is true yielding $\Delta P < 0$. Using Eq. (A3) in (A4), the following relation is obtained

$$\Delta\sigma^2 = \frac{2\mu_d \left[(\rho - \rho_w)gz + \frac{B}{3}(1 - 2\nu_u)\Delta\sigma^1 \right]}{\pm \sin 2\theta - \mu_d \left[(1 + \cos 2\theta) - \frac{2}{3}B(1 + \nu_u) \right]}. \quad (\text{A5})$$

Using Eq. (A1) and (A5) Bonafede et al. (1988) computed the stress drop caused by dip-slip earthquakes as follows:

$$\Delta\tau = \tau^1 - \tau^2 = (\mu_s - \mu_d)(\rho - \rho_w)gz + \left[\mu_s \frac{\Delta\sigma^1}{2} - \mu_d \frac{\Delta\sigma^2}{2} \right] (1 + \cos 2\theta) - \frac{B}{3}(1 + \nu_u)[\Delta\sigma^1 - \Delta\sigma^2]. \quad (\text{A6})$$

The depth dependence in Eq. (A2) shows that compressional tectonic pre-stress is larger than normal tectonic pre-stress at any depth (Turcotte and Schubert, 1982). Eq. (A6) corroborates the finding that reverse faulting earthquakes have larger stress drop than normal faulting events (Bonafede et al., 1988; Cocco and Rovelli, 1989).

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