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A classification of induced seismicity

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ABSTRACT

In order to adopt the best safety procedures, man-made earthquakes should be differentiated as a function of their origin. At least four different types of settings can be recognized in which anthropogenic activities may generate seismicity: (I) fluid removal from a stratigraphic reservoir in the underground can trigger the compaction of the voids and the collapse of the overlying volume, i.e., graviquakes; the deeper the reservoir, the bigger the volume and the earthquake magnitude; (II) wastewater or gas reinjection provides the reduction of friction in volumes and along fault planes, allowing creep or sudden activation of tectonic discontinuities, i.e., reinjection quakes; (III) fluid injection at supra-lithostatic pressure generates hydrofracturing and micro-seismicity, i.e., hydrofracturing quakes; (IV) fluid extraction or fluid injection, filling or unfilling of artificial lakes modifies the lithostatic load, which is the maximum principal stress in extensional tectonic settings, the minimum principal stress in contractional tectonic settings, and the intermediate principal stress in strike-slip settings, i.e., load quakes; over given pressure values, the increase of the lithostatic load may favour the activation of normal faults, whereas its decrease may favour thrust faults. For example, the filling of an artificial lake may generate normal fault-related seismicity. Therefore, each setting has its peculiarities and the knowledge of the different mechanisms may contribute to the adoption of the appropriate precautions in the various industrial activities.

1. Introduction

Induced seismicity has become a relevant scientific and social issue (Suckale, 2009; Grigoli et al., 2017). Even if the discrimination for natural versus anthropogenic seismicity is not always straightforward (Dahm et al., 2015), seismicity induced by fluid injection was definitely proven by Raleigh et al. (1976). Fluid injection into the subsurface is associated with industrial operations, particularly wastewater disposal, gas storage or geothermal exploitation (Healy et al., 1968; Zoback, 2007; National Research Council, 2013). It has also been demonstrated that human activities can determine the magnitude of the events as a function of the volume and rate of fluid injected (McGarr, 2014; Weingarten et al., 2015) and the fluid pressure increase (Hsieh and Bredehoeft, 1981). Particularly in Oklahoma, the rate of seismicity had a drastic increase due to wastewater injection at depth (Ellsworth, 2013; Keranen et al., 2014). Earthquakes were discovered to be also controlled by loading effects on artificial lakes and quarry excavations (Simpson, 1976, 1986). It pointed out that industrial activities do not supply energy to the geological phenomena, but they only accelerate them in lowering the friction on tectonic structures already at a critical state of stress failure when fluids increase the pore pressure (Walsh and Zoback, 2015).

Evidence of seismicity induced by injecting wastewater fluid in depleted oil reservoirs are well established (Valoroso et al., 2009; Shapiro et al., 2011; Stabile et al., 2014; Improta et al., 2015; Buttinelli et al., 2016), but also for gas storage (Ruiz-Barajas et al., 2017 and references therein). Therefore, a scientifically grounded policy on induced seismicity is required (Giardini, 2009; McGarr et al., 2015; Langenbruch and Zoback, 2016). For this reason, the Ministry of Industry of the Italian Government introduced guidelines for future subsurface industrial activities (MISE-CIRM Working Group, 2014). Based on a review of the existing different geological settings, this paper proposes a classification of different types of induced seismicity in order to discriminate among the several tectonic environments and the effects of the anthropogenic perturbations. A number of useful classifications have already been proposed, but this paper addresses rises on the relationship of induced seismicity with respect to the hydrostatic and lithostatic pressures, respectively. The hydrostatic pressure rises on average

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10 MPa/km. The lithostatic pressure is σ_1, σ_3, σ_2 in extensional, contractional and strike-slip tectonic settings respectively. The lithostatic load (ρgz, where ρ is the rock density, g is the gravity acceleration and z is the depth) increases with depth in general between 23 and 27 MPa/km, assuming a density of 2.3 or 2.7 g/cm^3. The ratio between pore pressure and lithostatic load (Hubbert and Rubey, 1959) is on average 0.35 in the shallow upper crust but it tends to increase close to lithostatic (e.g., 0.9) with depth (Sibson, 1992). Static friction (μ) values in the upper crust are on average $<$0.6 (Zoback and Townend, 2001). Tiny variations of these values can modify the deviatoric stress in a given region and induce seismicity. Chemical and temperature variations in rock and fluid composition may significantly affect the average values (e.g., Fossen, 2010).

2. Types of seismicity associated with human activities

The terms induced and triggered seismicity are used to differentiate seismicity generated by industrial operations and natural seismicity catalysed and anticipated by human activities (Hornbach et al., 2015). The transition among the two types of seismicity is subtle because the crust is widely at a critical state of stress and very often the induced seismicity can be considered as triggered. Here, for sake of simplicity, we consider all anthropogenic seismicity as induced, implying a potential activation of faults ready to move, regardless of their regional tectonic significance. The basic rationale is to analyse the different human activities with respect to deviations from the hydrostatic and lithostatic natural pressures.

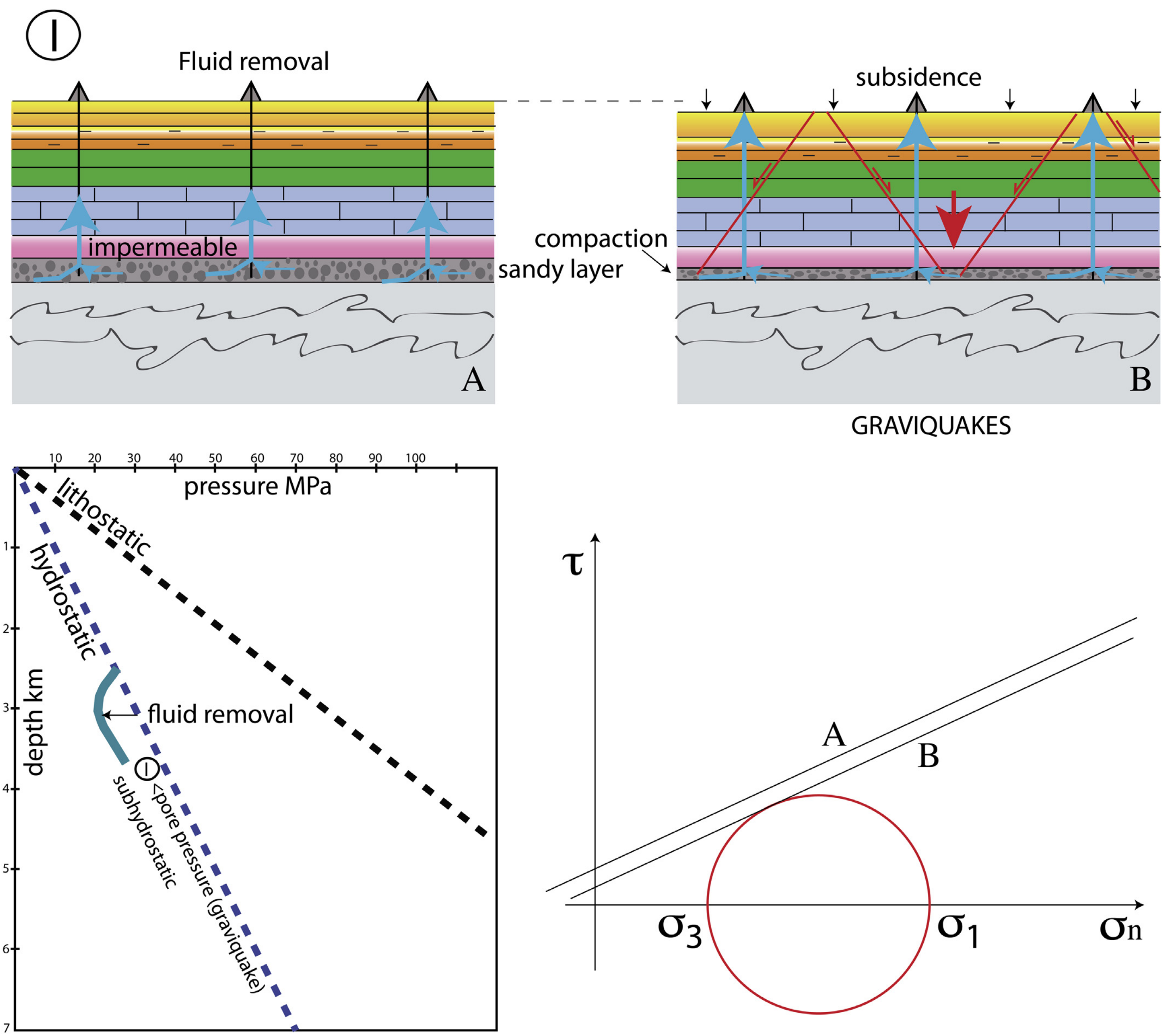

Figure 1. Type I induced seismicity or graviquakes. The fluid removal (either gas, oil or water) from a layer with intergranular primary porosity may generate a sub-hydrostatic condition and the gradual or instantaneous collapse of the overlying rock volume, causing earthquakes and subsidence. The depletion generates a vacuum that may be closed by the weight of the overlying volume, lowering the failure Coulomb criterium. Moreover, it may increase the normal stress since it decreases the pore pressure and it diminishes the ratio between fluid pressure and lithostatic pressure. The deeper the depleted layer, the larger is the volume and the earthquake. Since this seismicity is controlled by the release of gravitational potential, we may consider these events as graviquakes.

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2.1. The removal of gas or oil from a stratigraphic interval can trigger the compaction of the voids and the collapse of the overlying volume, provoking seismicity and subsidence. An example is the Groningen field in Holland (Van Thienen-Visser and Breunese, 2015), in which the gas reservoir is located at about 3 km deep in the porous eolian-fluvial sandstones Permian Rotliegend Formation. Focal mechanisms of the induced seismicity generated by the gas field are indicating normal faulting. It has been shown that normal faults-related earthquakes are the dissipation of stored gravitational energy and the depth of the activated seismic volume is about one third of the length of the collapsing hanging wall (i.e., the graviquakes, Doglioni et al., 2015). It implies that the deeper the reservoir, the bigger the volume and the earthquake magnitude. In the Groningen example, the fluid removal from the voids of the sandstone could allow the collapse of the overlying thickness of the stratigraphic sequence. As the reservoir is at 3 km deep, the maximum volume that could be mobilized is around 40 km^3, which would correspond to an energy dissipation of an earthquake of about *M* 3.5–4, being *M* 3.6 the largest magnitude recorded in the gas field (Van Wees et al., 2014). To support the simple interpretation of compaction and creeping and the coseismic collapse, the gas field exploitation has generated a subsidence of about 20–30 cm (Van Thienen-Visser and Breunese, 2015). According to Zoback and Zinke (2002), poroelastic stress changes may explain fault reactivations by fluid depletion during production. However, the removal of oil from the Valhall and Ekofisk reservoirs in the North Sea has generated normal faulting-related seismicity, which can alternatively be interpreted as the gravitational fall of the overlying rocks. This is type I induced seismicity in Fig. 1, i.e., graviquakes.

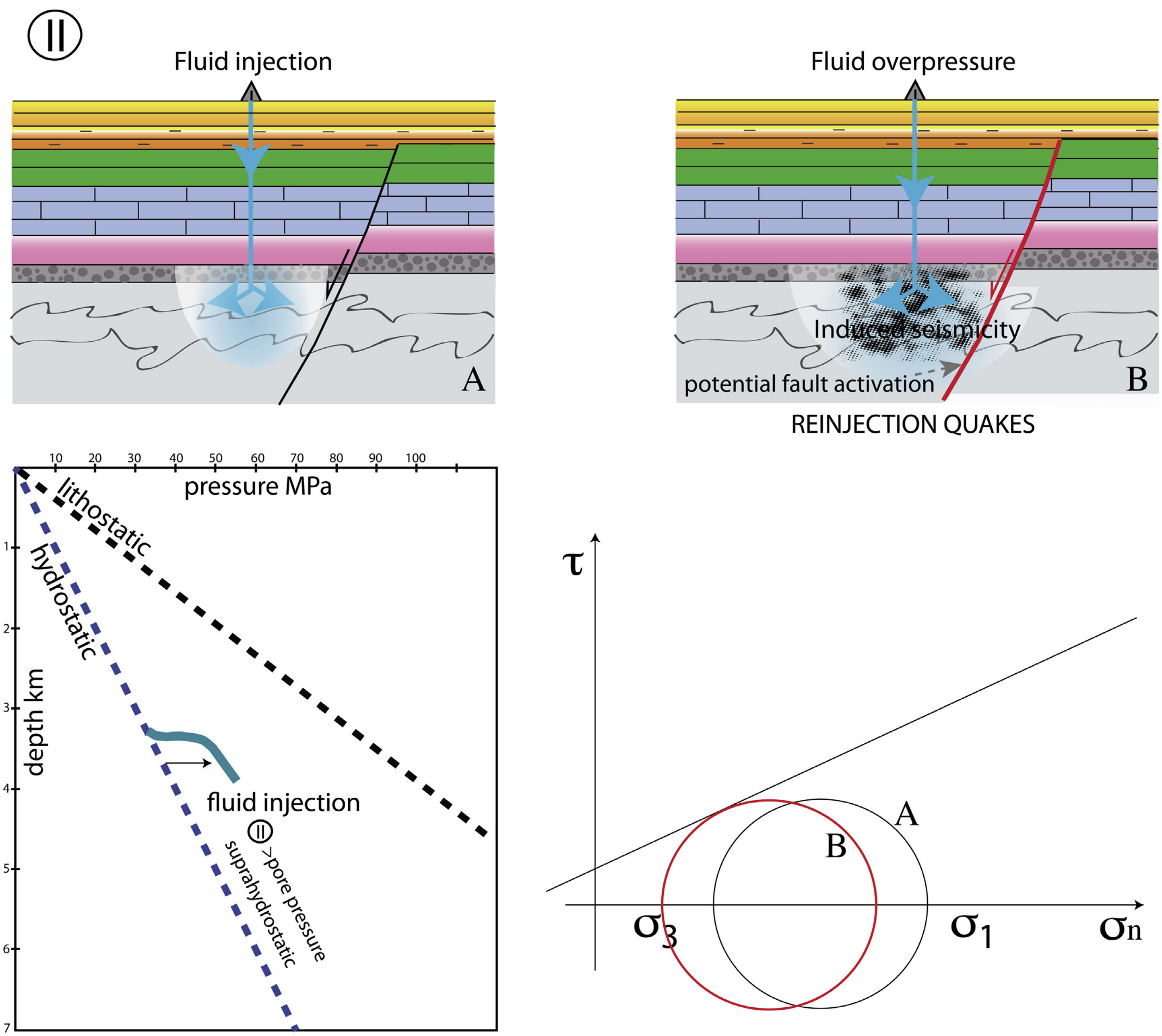

Figure 2. Type II induced seismicity or reinjection quakes. Fluid injection is possibly the most common mechanism of induced seismicity. If fluid injection overtakes the natural pore pressure, moving into the supra-hydrostatic condition, the system may become instable approaching the envelope of the critical failure. The increase of pore pressure decreases the normal stresses and it increases the ratio between fluid pressure and lithostatic pressure. The fluids permeate a volume at the well bottom, migrating into the more permeable rocks and usually generating microseismicity within a sort of half-moon, apart when natural discontinuities occur, hence focussing the seismicity along fault surfaces.

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2.2. Saltwater or gas reinjection in the subsurface above the natural threshold provides the increase of pore pressure and the reduction of friction in volumes and along fault planes, allowing creep or sudden activation of tectonic discontinuities. This phenomenon has been demonstrated with any type of fluid injected in geothermal fields (e.g., the Geysers geothermal field in Northern California, Eberhart Phillips and Oppenheimer, 1984, or the Basel power plant in Switzerland, Kraft et al., 2009), in wastewater injection such as the Arbuckle Formation in the Oklahoma oil field (Keranen et al., 2013) or the Zigong reservoir in the southwest Sichuan Basin in China (Lei et al., 2013), and in methane or CO_2 gas storage as for the Castor field offshore eastern Spain (Zoback and Gorelick, 2012; Del Potro and Diez, 2015; White and Foxall, 2016). The crust has been demonstrated to be at a critical state of stress, close to failure, and small perturbations of the pore pressure may determine the activation of rock rupture of sliding along well-oriented fault planes with respect to the regional stress field (e.g., Alt and Zoback, 2017). Therefore, the increase of the pore pressure to values larger than those naturally occurring in a crustal volume may determine the activation of faults, regardless the tectonic setting. However, it is important to distinguish between fluid injection disposal and stimulation that generates large perturbation of pore pressure. The maximum magnitude reported for this type of induced/triggered seismicity in Oklahoma is the Pawnee *M* 5.8 at 2016 event (Langenbruch and Zoback, 2016). Far-field pressurization may occur to generate seismicity even at several km distance with respect to the injection wells (Yeck et al., 2016). The time dependence of the associated seismicity depends on the distance, pressure gradient introduced and permeability (e.g., Juanes et al., 2016; Albano et al., 2017 and references therein). Lithologies and their

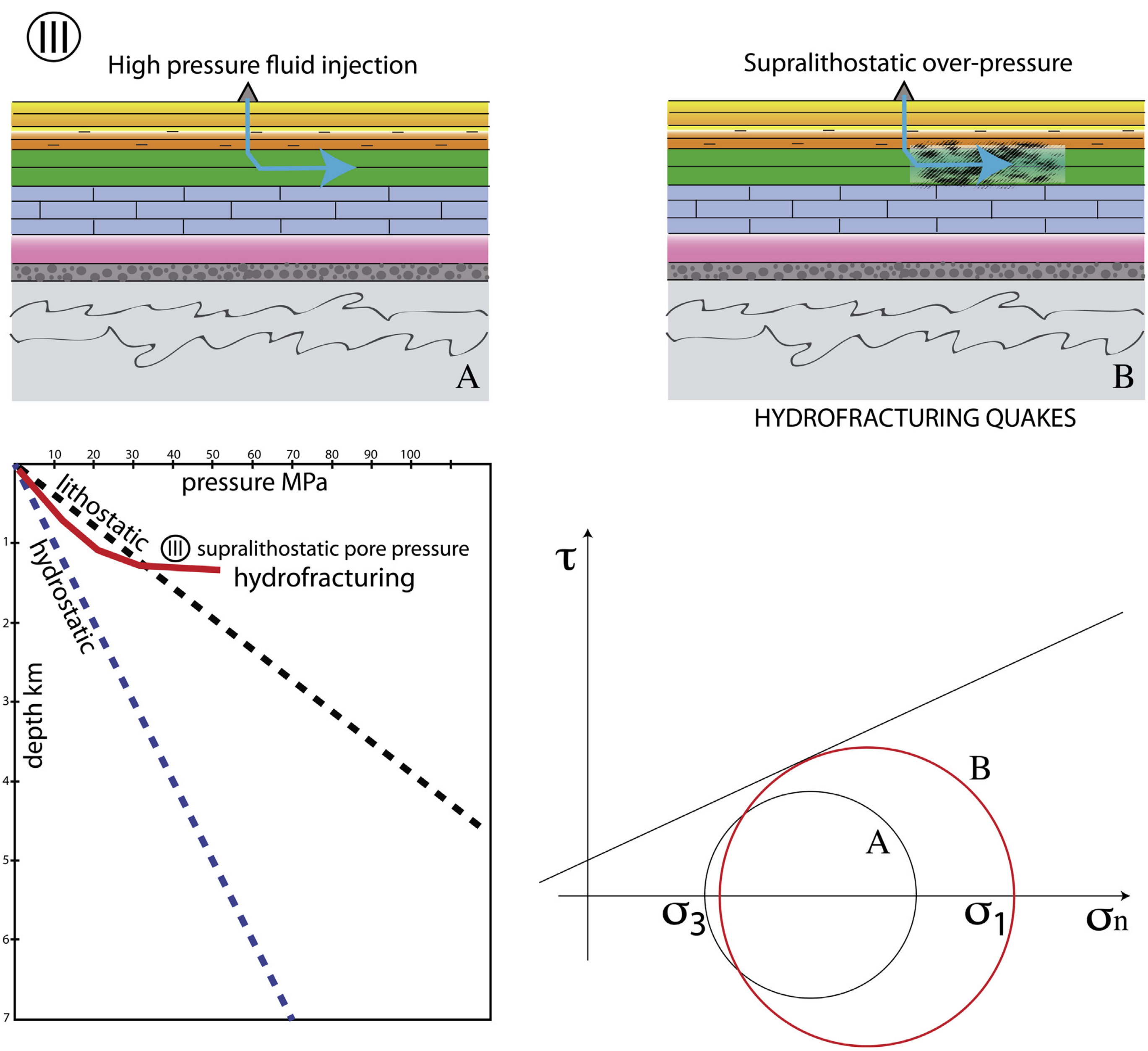

Figure 3. Type III induced seismicity or hydrofracturing quakes. The fluid injection at supra-lithostatic pressure may induce hydro-fracturing, commonly called fracking. This phenomenon occurs also naturally during the coseismic stage. The increase of pore pressure above the normal stresses determines a ratio between fluid pressure and lithostatic pressure larger than 1.

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related porosity can highly focus induced seismicity; e.g., diffused porosity may buffer higher pore pressure than concentrated porosity (Shah and Keller, 2017). In the Zigong reservoir, between early 2009 and mid-2011, more than 120,000 m^3 of wastewater was pumped under a wellhead pressure of up to 6.2 MPa into carbonates at 2.5 km deep. This generated 7000 earthquakes, being two of ML 4–4.4. Seismicity was mostly concentrated between 2.5 and 4 km, beneath the well bottom, showing a half-moon distribution, but locally concentrated along pre-existing fractures and faults (Lei et al., 2013). Induced seismicity has been detected within a radius of 4–12 km from the injection point, as a function of the fluid volume (McGarr, 2014). Hydraulic diffusivity of the fluid in the rock volume around the well bottom has been computed up to 0.1 m^2/s (e.g., Lei et al., 2013). This is type II induced seismicity in Fig. 2, i.e., reinjection quakes.

2.3. The fluid injection at supra-lithostatic pressure determines hydro-fracturing and micro-seismicity; this is known as fracking (King and Willis, 1972; Schultz, 2013), but this type of operational techniques are more frequently used at shallow depth and therefore are usually associated only with superficial microseismicity, which may be felt due to low depth. Fracking has been shown to generate earthquakes at least up to *M* 3.9. Larger magnitude can be expected only if pre-existing faults are reactivated. Hydro-fracturing is also a well known natural phenomenon (e.g., Sibson, 1981), since the rock record shows the effects of deformation by

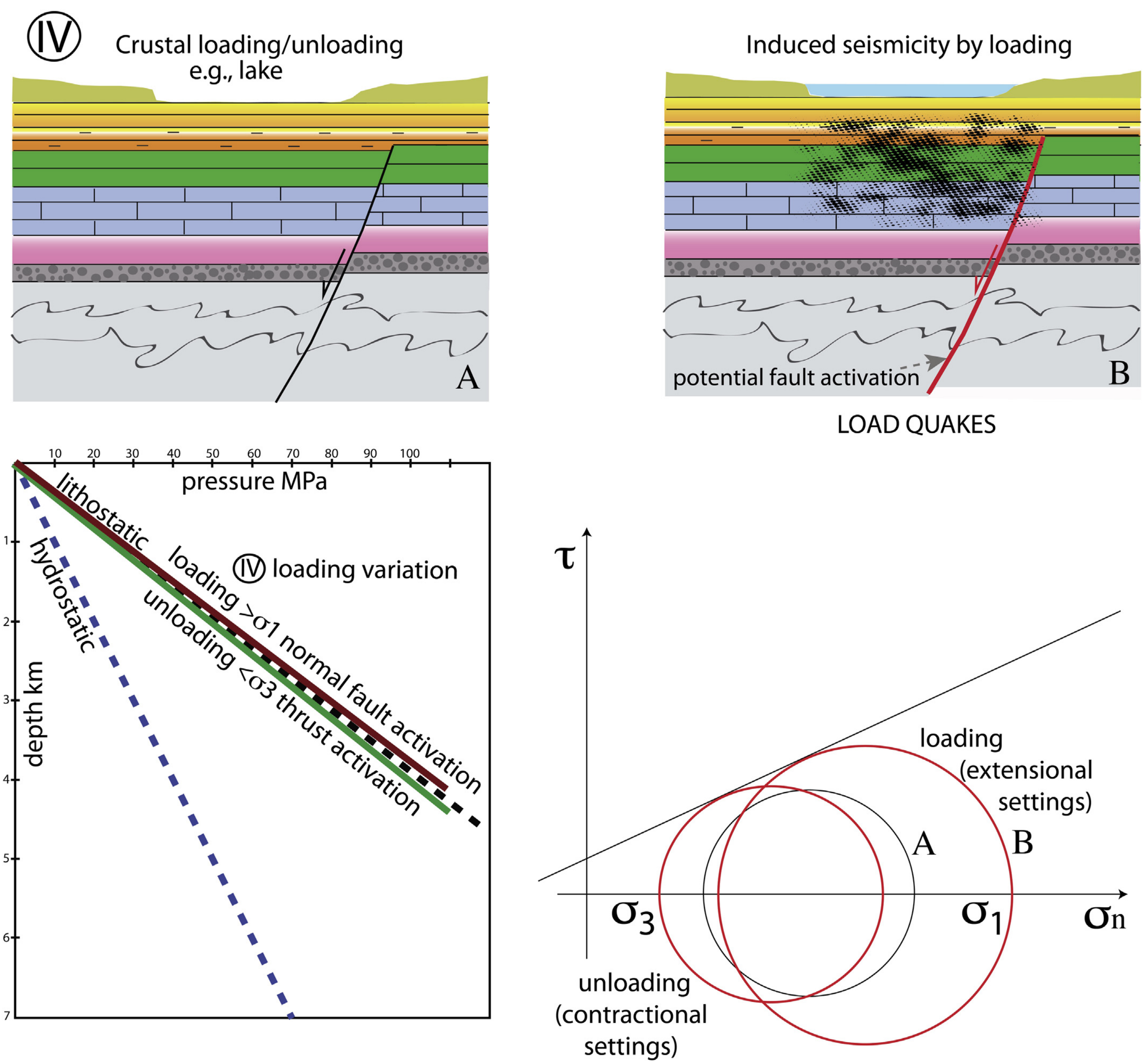

Figure 4. Type IV induced seismicity or load quakes. The loading or unloading of the crust can be generated by the filling or depletion of a hydroelectric lake or by the removal or refilling of deep geological reservoirs. The modification generates increase or decrease of the total weight, i.e., the lithostatic load, hence providing potential seismicity. The increase of load favours the activation of normal faults (rising σ_1), whereas the decrease of load vice-versa may trigger the activation of thrusts (decreasing σ_3).

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fluid over-pressure possibly associated with coseismic phenomena (Doglioni et al., 2014). This is type III induced seismicity in Fig. 3, i.e., hydrofracturing quakes.

2.4. The fluid extraction or fluid injection in the underground, or the filling or unfilling of artificial lakes modifies the lithostatic load, which is the maximum principal stress in extensional tectonic settings, the minimum principal stress in contractional tectonic settings, and the intermediate principal stress in strike-slip settings. In fact, natural normal fault-related seismicity occurs in areas of larger lithostatic load and higher topography, whereas thrust-related seismicity is more frequent in geological settings of low topography (Carminati et al., 2004). Over given pressure values, the increase of the lithostatic load may favour the activation of normal faults, whereas its decrease may favour thrust faults. For example, the filling of an artificial lake may generate normal fault-related seismicity. The maximum magnitude inferred for this type of induced/triggered seismicity is *M* 6.5 at Koyna Reservoir in India in 1967 (Gupta and Rastogi, 1976; Gupta, 2002). Fluids may also penetrate the underground contributing to decrease friction. This is type IV induced seismicity in Fig. 4, i.e., load quakes.

3. Concluding remarks

Each geological setting is characterized by peculiar stratigraphy, porosity, permeability, lithostatic pressure, pore pressure, temperature, friction, etc. Therefore each area has its own peculiar parameters that may determine the amount and rate of induced seismicity in case of anthropogenic perturbation. From the aforementioned discussion, there are at least four different types of induced or triggered seismicity that can be classified as a function of the tectonic setting, the fluids volume and pressure variations relative to the hydrostatic and lithostatic trends (Fig. 5). Each type is characterized by its values of maximum magnitude, but it depends on the pressure gradient introduced with respect to the original natural parameters. Modelling is required for each geological setting in order to adopt the safety pressures in each reservoir preventing induced seismicity with damaging magnitude by industrial activities (e.g., Majer and Peterson, 2007; Juanes et al., 2016; Albano et al., 2017; Mukuhira et al., 2017 and references therein).

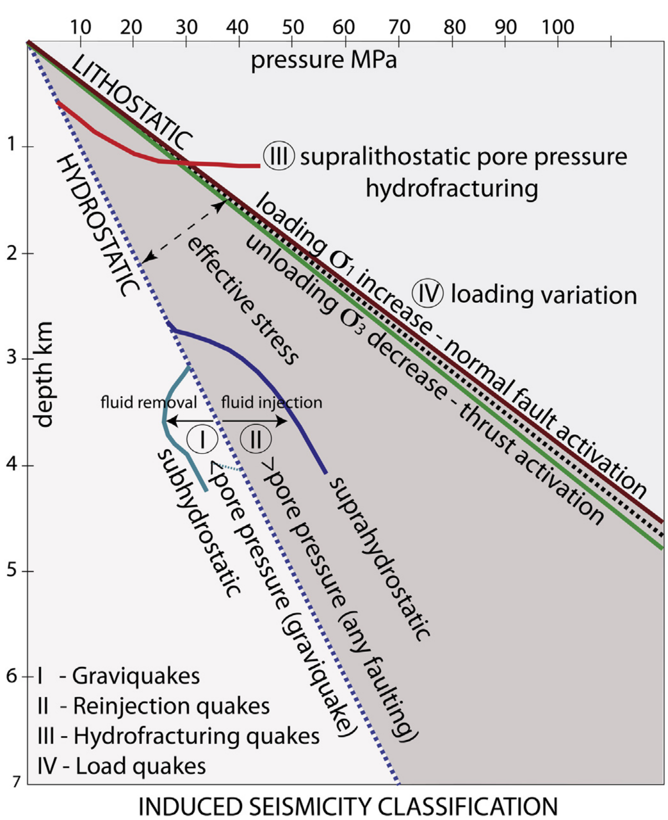

Figure 5. Illustration of the four main types of anthropogenic seismicity described in the text. MPa, Mega Pascal.

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