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Quantification of rock stress heterogeneity: Application to hydraulic fracturing of hydrocarbon reservoirs

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Fluid injection-induced earthquakes occur due to opening of new and re-activation of pre-existing fractures contained in the rock volume stress-perturbed by the fluid injection. We compare elastic rock heterogeneity measured by borehole logging to the occurrence of seismic events caused by hydraulic fracturing of the corresponding rock sections. Our observations made from two hydraulic fracturing case studies suggest that elastic rock heterogeneity controls the occurrence of fluid injection-induced earthquakes. The seismic events occur preferentially in rock sections characterized by low Poisson's ratio and high Young's modulus. Fracture opening and re-activation probability and the occurrence of associated seismic events should be strongly related to the initial state of stress in the unperturbed reservoir rock. We describe the sedimentary reservoir rock by a perfectly layered linear elastic medium in equilibrium to an externally applied homogeneous far field stress and quantify the relation between stress changes leading to fracture opening and re-activation and elastic rock heterogeneity. We extend existing analytic solutions of stress fluctuations in heterogeneous linear elastic media consisting of elastically isotropic layers to the case of vertical transverse isotropic layers. This allows application to unconventional shale gas reservoirs, which are usually characterized by a high intrinsic anisotropy. We find that magnitudes of rock stress fluctuations originating from elastic rock heterogeneity are significant. Moreover, we show that stress changes leading to fracture opening and re-activation in rocks undergo scale invariance spatial fluctuations. The scale invariant nature of rock stress fluctuations is caused by scale invariant fluctuations of elastic rock properties measured along the borehole. This gives a physical explanation for scale invariance of seismogenic processes. Based on our model, we analyze the physical meaning of a heterogeneity index of rocks, which indicates rocks sections of high Young's modulus and low Poisson's ratio. This index is an indicator of occurrence probability of brittle rock failure during hydraulic reservoir stimulations in the analyzed cases. However, our quantitative study demonstrates that rock failure indicator, which are based solely on elastic properties of rocks cannot have a universal physical meaning. In addition, our results suggest that even though the intermediate principal stress magnitude is not directly involved in the Mohr Coulomb failure criterion, it has a significant influence on the stress changes leading to re-activation and opening of fractures. This finding coincides with observations made during fracturing tests of rock samples in laboratory. In summary, our study demonstrates that stress fluctuations resulting from elastic rock heterogeneity are of significant importance for the seismogenesis of fluid injection-induced earthquakes. The physics of seismogenic processes can be understood by analyzing the physical origin of rock stress fluctuations and their relation to brittle rock failure processes.