SUMMARY

Understanding the complex physical processes that define the seismic response of heterogeneous rock formations is a prerequisite for reaping the full benefits offered by modern seismic exploration techniques. In particular, understanding the impact of fractures is of interest, as they commonly govern both the mechanical and hydraulic properties of geological formations. When a seismic wave propagates through a fractured and fluid-saturated formation, pressure gradients develop between the softer fractures and the embedding porous background, as well as between connected fractures with different orientations. This in turn causes fluid to flow between the different regions, dissipating energy through viscous friction, and, thus, resulting in seismic attenuation and dispersion. The underlying process is known as wave-induced fluid pressure diffusion (FPD). In contrast to standard elastic modelling approaches, the theory of poroelasticity allows to model the seismic response of fluid-saturated porous rocks formations containing fractures in the mesoscopic scale range, that is, larger than the pore size but smaller than the prevailing seismic wavelength, while naturally accounting for FPD effects. However, poroelasticity is not widely employed as a seismic characterization tool, mainly due to the inherent complexity of this theory. In this Thesis, I explore practically relevant and pertinent scenarios related to enhanced geothermal reservoirs based on the theory of poroelasticity in order to showcase its potential to aid seismic characterization efforts. To do so, I

implement a poroelastic upscaling technique, in combination with a methodology based on the generation of stochastic distributions of fractures with realistic length distributions, which permits to obtain representative seismic signatures accounting for FPD effects.

The first project investigates the impact of wave-induced FPD effects in Rayleigh wave monitoring of reservoirs in fractured crystalline rocks. It is shown that, for the range of seismic frequencies, there is no dispersion or attenuation due to FPD effects, as these frequencies fall in the so-called non-dispersive plateau. This frequency regime prevails when, as a seismic wave passes, there is enough time for fluid pressure equilibration between connected fractures, but not enough time for fluid flow between fractures and background. Consequently, the connectivity of fractures can cause a significant reduction of the stiffening effect of the fluid located within them. This, in turn, has a strong impact on seismic velocity, which can only be appropriately modelled by taking FPD effects into account. The analysis also shows that body wave velocity and Rayleigh wave dispersion are sensitive to the degree of connectivity of fracture networks, as well as to fracture density variations. On the other hand, standard elastic modelling is shown to be insensitive to changes in fracture connectivity. This comparison illustrates the importance of FPD effects, as the degree of connectivity of fractures is a parameter that is of critical importance in the context of geothermal reservoir productivity, and ignoring its impact on seismic data can result in overestimating fracture density changes.

The second project explores the potential of poroelastic modelling to identify partial steam saturation in an otherwise water-saturated fractured geothermal reservoir. A sensitivity analysis shows that partial steam saturation manifests itself primarily as changes in P-wave velocity while the S-wave velocity is practically unchanged. In addition, the results show that while both steam saturation changes and fracture density variations might cause similar changes on the P-wave velocity, their differing effects on the S-wave velocity allow for discrimination between the two scenarios. The impact of partial steam saturation on Rayleigh wave velocities, on the other hand, is shown to be negligible when considering a poroelastic approach, while elastic approaches overestimates this effect. Finally, inversion methods based on seismic reflection amplitude with angle are shown to be sensitive to steam saturation changes and to have the potential to discern between changes due to steam saturation or fracture density variations.

For the third and last project, the detailed characteristics of the poroelastic representation of fractures are explored in order to improve the realism of the modelled seismic response of fractured formations. To do so, existing datasets from the literature are employed to determine relationships between fracture aperture, permeability, and compliance with fracture length. These relationships are then utilized to obtain the seismic response of formations containing fractures at different scales. The fracture density is kept constant to facilitate the analysis. The results show that shorter fractures tend to control the seismic response of fractured formations, and are associated with lower velocities and higher dispersion and attenuation levels, mainly due to their lower dry frame elastic moduli. It is also shown that the transition frequency associated with FPD effects between connected fractures shifts to lower frequencies for shorter fractures, which causes a significant reduction of the range of frequencies corresponding to the non-dispersive plateau. These characteristics are not appreciated when considering length-independent fracture properties, which can lead to erroneous predictions of the seismic response of fractured formations. The study considers dynamic and static estimations of compliance to derive fracture properties, and it is demonstrated that considering the former results in negligible attenuation and dispersion even for elevated values of fracture density, while the latter is associated with a significant impact on the seismic response of the fractured formation.