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### Key Points:

- Impact of fluids on wave velocity and attenuation/dispersion
- Fluids, fractures, and seismicity
- Dynamic fluid injection and substitution

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## Seismic and Microseismic Signatures of Fluids in Rocks: Bridging the Scale Gap

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**Abstract** The aim of this collection is to record a snapshot of our current state of understanding of the impact of fluids on the evolution and monitorability of subsurface rock formations during anthropogenic fluid injection/withdrawal operations, accounting for scale and frequency effects. In this introduction we provide a summary of the key challenges and findings reported in these 23 articles. This suite of articles addresses a variety of issues related to the impact of fluids on subsurface rocks, which can be grouped in three themes: (i) impact of fluids on wave velocity and attenuation/dispersion (five articles); (ii) fluids, fractures, and seismicity (nine articles); and (iii) dynamic fluid injection and substitution (nine articles).

### 1. Introduction

Rock physics, geophysics, and seismology are disciplines aimed at understanding the structure and dynamics of the subsurface using seismic and microseismic monitoring techniques. Typical applications requiring this knowledge include exploration for and production of hydrocarbon resources, monitoring the injection and sequestration of carbon dioxide, and recovery of geothermal energy, to cite a few. A common denominator in these applications is the need to characterize fluid migration, substitution, and diffusion, as well as their impact on the deformation, fracturing and faulting of underground rock formations during fluid injection and withdrawal operations, for example, reservoir depletion, subsidence, fault reactivation, and so forth. The scales of observation and the probing frequency involved cover a broad range: from millimeters (rock physics experimentation) to kilometers (seismology) or from subhertz frequencies to megahertz. Contrasting observations or interpretations are often made at these scales/frequencies, and discrepancies need to be explained in physical terms in order to predict effectively the evolution of the rock formation of interest and hopefully the occurrence of damaging earthquakes.

Bridging this scale gap motivated the organization of an international research workshop held 13 June 2016 at the University of Cergy-Pontoise (France) and jointly sponsored by the University's Institute for Advanced Studies and the Department of Geosciences and Environment. The workshop attracted experts in the fields of seismology, geophysics, geomechanics and rock physics to share information on the state-of-the-art laboratory experimentation and field monitoring techniques employed for subsurface characterization and modeling, with particular focus on the behavior of rock formations subjected to anthropogenic perturbations by fluid injection or withdrawal. The practical aim of the workshop was twofold: (i) report the commons and differences between the various scales of observation and (ii) identify the knowledge gaps and explore the strategies to overcome them in order to reconcile laboratory experimentation and field data interpretation.

This 1-day workshop attracted 55 experts from 10 countries, across three continents (Europe, the Americas, and Australia). Following the success of this workshop, the American Geophysical Union offered the opportunity to gather contributions relevant to this workshop into a dedicated Special Collection in the *Journal of Geophysical Research-Solid Earth*. In total, 23 articles were eventually published as part of this Special Collection, the aim of which is to record a snapshot of our current state of understanding of the impact of fluids on the evolution and monitorability of subsurface rock formations during anthropogenic fluid injection/withdrawal operations, accounting for scale and frequency effects. In this introduction we provide a summary of the key challenges and findings reported in these 23 articles. This suite of articles addresses a variety of issues related to the impact of fluids on subsurface rocks, which can be grouped in three

themes: (i) impact of fluids on wave velocity and attenuation/dispersion (five articles); (ii) fluids, fractures, and seismicity (nine articles); and (iii) dynamic fluid injection and substitution (nine articles).

## 2. Impact of Fluids on Wave Velocity and Attenuation/Dispersion

Seismic monitoring in the field is a powerful tool to understand rock properties at depth and their evolution with stress perturbations or fluid injection. Over the last century, this tool allowed great advances in our understanding of the behavior of Earth's crust and mantle. It is however an inverse problem where the rocks are identified based on their seismic attributes, a proxy for their actual physical properties. Because at depth fluids often saturate porous and/or fractured rocks, it is also vital to understand their impact on rocks' physical properties. In fact, the presence of fluids plays an active role on the effective poro-mechanical properties of fluid-saturated rocks. Because fluids infiltrate the rock microstructure, a coupling occurs between the mechanical properties of the rock and those of the saturating fluids, through the permeability of the rock and the viscosity of the saturating fluids. Therefore, wave velocities measured in rocks reflect not only the intrinsic elastic property of the rock frame but also the impact of the saturating viscous fluids, making the measurements frequency dependent (source of dispersion). At the field scale, the frequency ranges typically between the subhertz to few hundreds of hertz. In the laboratory, because rock samples are smaller, typical wave velocity monitoring is carried out at ultrasonic frequencies (MHz). Relating field data to laboratory measurements is thus not straightforward and involves understanding the interplay between the rock frame and the intrinsic properties of the saturating fluids. While of major importance for field-scale geophysical applications, waves velocity monitoring is also a powerful tool in the laboratory to investigate rocks' physical and mechanical properties under well-constrained conditions (e.g., stress and temperature). Ongoing developments aim at better understanding the evolution of rocks' mechanical properties in the laboratory, how they relate to seismic attributes measured in the field, and how they are impacted by anthropogenic perturbations, for example, stress, pressure, and/or temperature (Ba et al., 2016, 2017; Noh et al., 2016; Tisato et al., 2015).

The impact of fluids on rocks behavior might be of chemical nature (e.g., mineral dissolution/precipitation), hence leading to irreversible changes in elastic wave velocities. Such situations may arise from either natural or anthropogenic causes, when the injected fluid on one hand, and the system porous rock and natural pore fluids on the other, are not in chemical equilibrium. In the context of CO<sub>2</sub> geo-sequestration, Kanakiya et al. (2017) investigate how acidic fluids might interact with basalts. Tracking mineralogical evolutions, they show that fluids might induce dissolution of the rock initially but can lead to precipitation later on. They also estimate the evolution of porosity and permeability induced by these mineralogical alterations. They finally relate the independent measurement of ultrasonic *P* and *S* wave velocities, to the mechanical properties of the rock.

In recent years, new technological developments have allowed scientists to experimentally measure the dependence on frequency of rock properties. Squirt flow is a key mechanism conjectured to induce wave dissipation at the field scale. It is related to time-dependent local fluid pressure equilibration between neighboring microstructures of varying geometry. By measuring the elastic properties of a tight sandstone at varying effective confining pressures and comparing the data to squirt-flow models, Yin et al. (2017) investigate the dependence of the squirt-flow mechanism on the rock's microstructure. They show that existing models for squirt flow from a compliant crack to a stiff pore successfully explain the measured dispersion and attenuation. In doing so, the authors assume that the experimental boundary conditions allow them to disregard global viscous flow occurring at the transition between drained and undrained deformation regimes (Biot-Gardner). This mechanism is not expected to occur at the field scale.

On the other hand, changing the boundary conditions, Pimienta et al. (2017) report the frequency dependence of five sandstone samples with contrasting porosity. The rock's elastic response (Young's modulus and Poisson's ratio) and hydraulic response (fluid flow out of the sample) are measured as a function of frequency in the laboratory. The authors report significant dispersion/attenuation in these rocks when saturated with a viscous fluid. Accounting for local (squirt) flow and global (Biot-Gardner) flow, they identify three regimes of behavior across the frequency range, separated by the two critical cutoff frequencies characterizing these fluid-induced dissipation mechanisms. The Biot-Gardner cutoff frequency is found to correlate with the permeability of each rock sample.

While fluid-induced dissipation mechanisms are expected in isotropic porous and microcracked rocks with heterogeneous microstructures (pores and cracks coexist), the question arises of whether similar mechanisms could be at play in rocks with a uniform microstructure. To this end, Sarout et al. (2017) quantify the impact of a homogeneous distribution of randomly oriented microcracks in the Carrara marble on ultrasonic wave velocity (high frequency  $\sim 1$  MHz) and elastic strain (low frequency  $\sim 0.01$  Hz) measured at varying effective pressures. Using additional permeability measurements and a joint inversion of hydraulic and elastic properties, the authors show that this combination of elastic, dispersion, and permeability measurements in the dry and water-saturated Carrara marble is compatible with the predictions of simple effective medium models in the non-interaction approximation, and that the evolution with pressure of the crack network morphology can be reliably predicted.

While fluid effects are expected in isotropic rocks, many rocks at depth can be anisotropic. Because the degree of anisotropy of rocks' mechanical and hydraulic properties might differ, it is vital to evaluate the impact of rock anisotropy (hydraulic and/or elastic) on the dispersive properties of rocks (Barbosa et al., 2017b). Using numerical models, the authors show that very different degrees of effective (overall) elastic anisotropy and dispersion might be expected from the variable ratio between elastic and hydraulic anisotropy.

### 3. Fluids, Fractures, and Seismicity

Microseismic activity (MS) or acoustic emissions (AE) in rocks have attracted the attention of the geoscience community for the past three decades or so. Monitoring MS (field scale) or AE (laboratory scale) activity has been successfully used to remotely characterize rock fracturing and slip events (e.g., hydraulic fracturing, shear fracturing/faulting, and reactivation), as well as fluid migration through porous and/or fractured rocks when local pore pressure perturbations impact the in situ stress field. Most recently, numerous studies focused on the interplay between fluids, fractures, and seismicity have been published (e.g., Barbosa et al., 2017a; Brown & Ge, 2018; Cueto-Felgueroso et al., 2017; De Barros et al., 2016; Dempsey et al., 2016; Dempsey & Suckale, 2016; Diehl et al., 2017; Fazio et al., 2017; Goodfellow et al., 2015; Improta et al., 2017; Jeanne et al., 2017; Levandowski et al., 2018; Noël et al., 2019; Rivet et al., 2016; Segall & Lu, 2015; Zhang et al., 2016). This highlights the growing interest for such issues in the geoscience community, which is clearly driven by an increased need to better address actual problems encountered during fluid injection/withdrawal operations. In a recent article, Yoshimitsu et al. (2014) argue that earthquakes, MS, and AE are highly similar physical processes down to magnitude  $M_w = -7$  (typical in the laboratory) and that they can all be characterized unambiguously by their magnitude and their focal mechanism. This important finding reconciles the historical lexical distinction between MS and AE, traditionally based on the scale of observation, the frequency of the spontaneously radiated waves, or the apparent magnitude of the events. This new paradigm is corroborated by the increasing use in the literature of terms like microearthquakes, ultramicroearthquakes, or even picoearthquakes in place of acoustic emissions, which emphasize the similarity rather than the contrast between these self-similar physical phenomena. At the source location, one can either analyze individual fracturing or slip events (e.g., modes I, II, III, or mixed) occurring at the grain scale in the laboratory with a relatively small magnitude ( $M_w < 0$ ) or analyze the emergent and statistically “averaged” events recorded in the field with larger magnitudes ( $M_w > 0$ ). Both approaches are in fact necessary and complementary if a better understanding of the mechanisms at play is to be achieved. This suggests that the relationship between the scales of observation can be deciphered based only on common physical and statistical principles, rather than on a hypothetical difference between the physical mechanisms at play at these different scales. An indirect consequence of this finding is that laboratory experiments with AE monitoring, more than ever before, can be confidently used to better understand, and hopefully predict, earthquakes and microseismicity in the field. This opportunity is further promoted by recent advances in experimental laboratory technology for monitoring MS activity. As an additional benefit, laboratory experiments can also be used to improve the design of field monitoring operations. Obviously, the completeness of the recorded catalogs of events at these different scales is critical if reliable conclusions are to be drawn from field or laboratory observations. Unfortunately, the completeness of the catalog is affected by the inherent sensitivity and intrinsic characteristics of the instruments/transducers used for remote monitoring, and by their coupling to the rock formation/sample. This in turn impacts our “vision” of the events, and therefore, our ability to understand them in physical terms and unambiguously interpret them.

This physics-driven lexical simplification, and the similarity between earthquakes, microseismicity, and acoustic emissions introduced by Yoshimitsu et al. (2014), is further supported by the multiscale experiments reported by Colombero et al. (2018). The authors show that the attributes of the MS activity recorded in an unstable granitic cliff (spectral content, source location, and event rate) correlate with meteorological parameters such as air temperature and rainfalls. On the other hand, laboratory experiments with acoustic emissions monitoring are carried out by the authors under controlled fluid and temperature conditions. By comparing the attributes of MS and AE activities in light of additional physical characterization of the rock in the laboratory, the authors conclude that thermal stresses originating from abrupt thermal variations govern the microcracking observed at both field and laboratory scales.

Using strain and ultrasonic monitoring tools in the laboratory, Baud et al. (2017) investigate the compaction behavior of water-saturated samples of the porous Saint-Maximin limestone. The authors show that the presence of quartz as a secondary mineral phase does not impact the mechanical strength of the limestone in both the brittle faulting and cataclastic flow regimes, but that the presence of water induces a significant mechanical weakening. In contrast to previously published results on other limestones, inelastic compaction in Saint-Maximin limestone induces abundant MS activity, which is attributed to the presence of quartz grains, and more specifically to cracking events located at the quartz grain interfaces.

Assuming that wave attenuation ( $Q_S$  or  $Q_P$ ) in a heterogeneous rock formation is a random variable, Vera Rodriguez and Stanchits (2017) show that the parameters of its probability distribution function can be retrieved through a mapping workflow using the  $Q_S/Q_P$  ratio. This allows for the estimation of  $Q$  from microseismic events induced by the hydraulic fracturing of a decimetric block of porous Colton sandstone in a true triaxial stress vessel in the laboratory, while accounting for uncertainties in source location and velocity model. Temporal variations of  $Q$  are tracked during the hydraulic fracturing, and wave attenuation is then related quantitatively to the stress conditions around the hydraulic fracture.

As a transition from laboratory experimentation to field-scale monitoring, Meller and Ledésert (2017) offer a reinterpretation of the MS activity recorded during the hydraulic stimulation of a deep granitic geothermal reservoir at Soultz-sous-Forêts. A review of the various hydraulic tests conducted in four deep wells and the analysis of additional petro-hydromechanical data acquired along these wells show a clear correlation between mineralogy and the petrophysical, mechanical, and hydraulic behavior of this granite formation. In particular, high calcite contents are correlated with abundance of clay minerals, low Young's modulus, low magnetic susceptibility, and spectral gamma ray variations. MS activity is generated in the fresh granite zones, whereas clay and calcite-rich zones might deform aseismically during stimulation.

Duboeuf et al. (2017) present a comprehensive investigation of the seismogenic and hydromechanical behavior of a fractured limestone formation in response to fluid injection at the decameter scale. The strain and MS monitoring of fracture reactivations show that fluid injection essentially induces aseismic motions that drive a sparse seismicity away from the injection well. The field-scale experimental data are used to assess the role of fluid pressure diffusion and stress perturbation through failure as key driving mechanisms for MS activity.

In a first of a set of two companion articles on the microseismic monitoring of hydraulic stimulation operations in a shale gas reservoir in SW China, Meng et al. (2018) report a matching and locating technique (iMLT) to robustly detect and accurately locate weak microseismic events ( $-4 < M_L < 0$ ). This new method not only improves the detectability of weak events compared to the conventional matched filter analysis, but it also enhances the accuracy of the source location and especially its depth.

In a companion paper, Chen et al. (2018) apply the iMLT to field MS data recorded in November 2014 and show that the resulting expanded microseismic catalog allows for a more robust interpretation of the spatio-temporal evolution of the MS activity. In particular, they identify two distinct clusters in this catalog that are closely related to the injection activity both spatially and temporarily. They attribute the first cluster of triggered events to the reactivation of a preexisting fault and the second one to the shear failure of natural fractures.

Staněk and Eisner (2017) report the analysis and interpretation of a catalog of microseismic events recorded during the hydraulic fracturing of a shale gas reservoir in the Arkoma basin (USA). The epicenters of these

events appear to be aligned along the direction of the maximum principal stress. Their focal mechanism is dominated by shear failure with opposite directions of slip on nearly identical fault planes. The authors explain the observed mechanisms with a geomechanical model involving slippage along bedding planes activated by the aseismic opening of vertical hydraulic fractures. This model is typically suitable for shales with mechanically weak bedding planes.

In contrast with previous laboratory studies, Petley-Ragan et al. (2018) focus on past lower crustal earthquakes (Bergen Arcs, Western Norway), where coseismic damage was accompanied by postseismic annealing and fluid-mediated metamorphism. Based on electron microscopy, electron microprobe analysis, and electron backscatter diffraction applied to outcrop (surface) rock samples, the authors argue that coseismic damage governs the evolution of the physical and chemical properties of the lower crust at the regional scale and infer a transition from brittle deformation to crystal-plastic recrystallization. The presence of feather features suggests that fractures propagated at a velocity close to that of shear wave into the wall rock of earthquake slip planes. The observed grain size reduction and crystallization associated with the microfractures create rheologically weak areas, making way for potential strain localization to occur within the plagioclase-rich lower crust.

#### 4. Dynamic Fluid Injection and Substitution

Fluid substitution can be conveniently studied in capillary rise experiments in which water invades spontaneously dry rock samples. Coupled with X-ray Computed Tomography (CT) imaging and active ultrasonic monitoring (ultrasonic wave velocity surveys), such simple imbibition experiments provide valuable information on the interplay between fluid substitution processes and variations in seismic wave attributes (velocity, amplitude, spectral content, and energy). Using a method based on a wavelet decomposition of the  $P$  wave traces recorded during spontaneous imbibition, David, Barnes, et al. (2017) showed that the variation of the coda energy can be used as a precursor for the onset of local fluid substitution. They also found that during fluid migration, the amplitude of  $P$  waves decreases well before the velocity does, when the moving capillary front is still far away from the ultrasonic sensors.

One explanation for the delay between amplitude and velocity variations is the diffusion and adsorption of water vapor ahead of the liquid water front driven by capillary forces, which impacts the  $P$  wave amplitude without a significant change in saturation nor a noticeable change in velocity (David, Sarout, et al., 2017). An alternative explanation of this phenomenon was provided as a comment by Kovalyshen (2018), who argues that this time lag is due to the interaction between the direct  $P$  wave and the  $P$  wave reflected by the upward moving liquid water front, that is, destructive summation of the direct and reflected  $P$  waves due to a phase shift of the reflected wave. This would decrease the apparent amplitude of the first arrival, with no noticeable impact on its flight time. In light of this second possible mechanism, David et al. (2018) simulated composite waveforms by combining direct and reflected  $P$  waves using realistic values for the reflection coefficients and the recorded position of the moving water front. They showed that, in most cases, the wave interaction mechanism suggested by Kovalyshen (2018) cannot explain the observed time lag and that the water vapor diffusion mechanism remains the most plausible cause. Most recently, competing physical processes were put forward to explain the time lag between velocity and amplitude variations, namely, surface energy of the constitutive minerals and fluid saturation of the pore space (Pimienta et al., 2019).

Obviously,  $P$  wave amplitude reduction is a manifestation of attenuation. Solazzi et al. (2017) studied the attenuation of seismic waves during imbibition processes using two-phase flow numerical simulations in heterogeneous rock samples. They showed that two peaks of attenuation can arise in imbibition experiments, both linked to water-induced fluid flow: The first one, dominant at high injection rate, is linked to the contrast of compressibility near the saturation front, and the second one, more important at low injection rate, is due to the presence of patches with high saturation behind the moving imbibition front.

Fluid substitution can also be conveniently studied in 2-D analog experiments like the Hele-Shaw cell, a transparent 2-D experimental model. Using a high speed camera and accelerometers, Turquet et al. (2018) follow the pressure-driven compaction of initially loose sphere packings when injecting air into the cell. They show that solid-fluid interactions lead to the generation of acoustic events similar to microseismicity. Numerical simulations were used to understand the solid-fluid coupling leading to the observed temporal

variations of amplitude and frequency of the microseismicity-like events induced by pressure fluctuations or solid stress relaxation.

Fluid injection in fractured media results in a complex interplay between slip, dilation, and permeability variations. Ye and Ghassemi (2018) studied the hydromechanical coupling in shear tests conducted on granite samples with saw-cut or tensile fractures. Stepwise fluid injection resulted in different slip regimes from quasi-static ( $\sim 10^{-8}$  to  $10^{-6}$  m/s) to dynamic ( $\sim 10^{-5}$  m/s) with significant shear-induced asperity degradation and variation in surface roughness. Significant permeability was maintained through shear-induced normal dilation. Such a self-propping mechanism is a key factor for successful stimulation of fractured rock formations.

In partially saturated rocks, the deformation resulting from seismic waves can cause pore fluid pressure relaxation and possible variations in reflectivity (Zhao et al., 2017). A numerical analysis showed that the dependence of seismic reflectivity on hydraulic mobility is affected by the contrasts in fluid compressibility, and the changes in fluid saturation and rock stiffness. Such fluid-induced variations in reflectivity can be used in time-lapse monitoring of partially saturated rock formations to detect changes in hydraulic mobility, for example, in a heavy oil reservoir.

CO<sub>2</sub> injection in deep reservoirs can be monitored through the spatiotemporal variations of *P* wave's first arrival. However, additional constraint on the location, extent, and saturation of CO<sub>2</sub> plumes can be obtained through the estimation of seismic attenuation changes derived from the frequency shift computed by local time-frequency analysis (Zhu et al., 2017). It is shown that a crossplot method combining seismic attenuation and velocity changes applied to continuous seismic recordings during CO<sub>2</sub> injection at the Frio-II brine pilot (Texas) is able to characterize the patch size and the saturation distribution within the CO<sub>2</sub> plume.

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