Coupled seismic and electromagnetic wave propagation

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Coupled seismic and electromagnetic wave propagation is studied theoretically and experimentally. This coupling arises because of the electrochemical double layer, which exists along the solid-grain/fluid-electrolyte boundaries of porous media. Within the double layer, charge is redistributed, creating an excess electrical charge in the fluid along the boundary. Electrokinetic theory describes coupled seismic and electromagnetic wave propagation. It predicts that seismic waves disturb the fluid excess charge, thereby creating an electric streaming current (seismoelectric effect). Inversely, the theory predicts that electromagnetic waves generate mechanical/seismic signals (electroseismic effect). Electrokinetic conversions can potentially be used as an effective means of detecting hydrocarbon reservoirs: it inherently combines seismic resolution with electromagnetic hydrocarbon sensitivity.

Electrokinetic theory predicts the existence of two seismoelectric effects: (1) a coseismic (electric) field that is coupled to seismic waves, and therefore propagates with seismic wave velocity, and (2) a seismic wave that traverses an interface with a contrast in electrical or mechanical properties produces electromagnetic (EM) signals that propagate outside the support of the seismic waves with much higher EM-wave speeds. These are called the coseismic and interface response fields, respectively. Electroseismic counterparts of these fields exist as well.

In this thesis, electrokinetic theory is reformulated along the lines sketched by Biot. The reformulation employs effective frequency-dependent densities, in which both viscous and electrokinetic coupling are comprised. The reformulated theory predicts the existence of four wave modes within a fluid-saturated porous medium: fast and slow P-waves, a shear wave and an EM-wave. The electrokinetic dispersion relations, which predict wave speed and intrinsic attenuation of each wave, are expressed in terms of generalized elastic coefficients and the effective densities. Each of the wave modes has a specific fluid-solid amplitude displacement ratio. These are derived and expressed in terms of generalized elastic coefficients and effective densities too. Each wave mode also has a specific ratio of electric potential to solid displacement potential. These are expressed in terms of the conventional fluid-solid ratios and the so-called (frequency-dependent) electrokinetic coupling coefficient. This coefficient describes the coupling between electric and mechanical fields. When the coupling coefficient is zero, the electrokinetic equations decouple in the familiar Biot's poroelastic equations and Maxwell's EM relations.

Subsequently, the wave coupling at a fluid/porous-medium interface is theoretically solved, where the modified theoretical formulation is applied. First a straightforward scattering problem of an incident fluid P-wave into fluid electromagnetic and pressure waves, and porous medium waves is considered. Secondly, the electrokinetic scattering matrix for a fluid/porous-medium interface is derived. This matrix summarizes all electrokinetic reflection and transmission coefficients applicable to this boundary. These coefficients describe how incident P-waves are converted at electrical/mechanical interfaces to electromagnetic signals, and, inversely, how electromagnetic signals are converted into acoustic signals. They are contained in the full-waveform seismoelectric and electroseismic interface response field models. The seismoelectric model employs the Sommerfeld approach, while the electroseismic model uses wavefield (de)composition techniques. These models provide the electrokinetic theoretical predictions.

Laboratory seismoelectric fluid/porous-medium interface response field measurements are performed as a function of time, space and fluid salinity. These measurements are compared against the seismoelectric model predictions. It is found that the seismoelectric model predictions excellently describe the measured interface response fields in terms of waveform, spatial amplitude pattern, and travel times. One scalar amplitude scaling factor only is needed to bring the amplitudes of the theoretical predictions and the measurements in agreement with each other. The factor is shown to depend on electric conductivity, i.e., predicted amplitudes significantly deviate at low pore fluid conductivity (~10^{-3} S/m), while they are close to the actual measurements for higher conductivities (~10^{-2} S/m). The poroelastic, electromagnetic and specific electrokinetic parameters that enter the seismoelectric model are independently measured or known from literature. The seismoelectric Sommerfeld integral model incorporates a so-called directivity function that closely resembles the independently measured spatial distribution pattern of the incident acoustic field. As a check, the seismoelectric origin of the measured electric signals is confirmed as well. Finally, also an electroseismic laboratory setup that measures the inverse effects, is described and corresponding electroseismic measurements are presented and discussed.