Numerical simulation of ultrasonic waves in reservoir rocks with patchy saturation and fractal petrophysical properties

J.E. Santos a,b,c, C.L. Ravazzoli a,b, P.M. Gauzellino a and J.M. Carcione d

a Departamento de Geofísica Aplicada, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, La Plata 1900 Argentina
E-mail: santos@fcaglp.fcaglp.unlp.edu.ar

b CONICET, Argentina

c Department of Mathematics, Purdue University, 150 N. University Street, West Lafayette, IN 47907-2067, USA

d Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42c, 34010 Sgonico, Trieste, Italy

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We simulate the propagation of ultrasonic waves in heterogeneous poroviscoelastic media saturated by immiscible fluids. Our model takes into account capillary forces and viscous and mass coupling effects between the fluid phases under variable saturation and pore fluid pressure. The numerical problem is solved in the space–frequency domain using a finite element procedure and the time–domain solution is obtained by a numerical Fourier transform. Heterogeneities due to fluid distribution and rock porosity–permeability are modeled as stochastic fractals, whose spectral densities reproduce saturation and petrophysical variations similar to those observed in reservoir rocks. The numerical experiments are performed at a central frequency of 500 kHz, and show clearly the effects of the different heterogeneities on the amplitudes of shear and compressional waves and the importance of wave mode conversions at the different interfaces.

Keywords: finite elements, porous media, fractals, reservoir geophysics

1. Introduction

During the past few years an important number of theoretical and experimental studies have demonstrated the significant influence that spatial heterogeneities within porous rocks have on elastic moduli, seismic wave velocities and other related quantities. In the context of hydrocarbon exploration, understanding the relation between the seismic response, the distribution pore fluids and the petrophysical properties may provide useful information about the reservoir.

As pointed out in [22], the heterogeneous nature of porous rocks often results in the heterogeneity of fluid distribution on scales greater than pore or grain size. In a rock saturated by immiscible fluids (such as water and gas) at macroscopic scales two
simplified models of fluid distribution are generally considered in most published works in the subject:

(i) the proportion of both fluids within the pores is the same everywhere, i.e., homogeneous saturation, and

(ii) the fluids are arranged in patches, i.e., macroscopic regions (which may include thousands of grains), fully saturated with one of the two fluids.

However, these must be considered as limiting cases since saturation usually exhibits irregularities of different scale and in most cases there exists a residual saturation [21] as well as capillary forces. In many cases the existence of patchy saturation in reservoir sandstones is closely related with variations in lithology and clay content, which may cause small effects on elastic properties but have a very important influence on permeability and capillary pressure curves [22,47].

The computation of bulk elastic moduli and compressional wave velocities for this situation was studied by different authors by means of empirical relations [8] and effective medium theories. This latter approach is generally based in the validity of Gassmann’s equations [24] within each patch under the assumption that their characteristic length is significantly smaller than a wavelength [22,31]. It is also assumed that the fluids are distributed in patches of 100% saturation of either gas or water.

Using a different approach, White [45] analyzed the physics of wave propagation through patchy partially-saturated porous media using Biot’s theory [5]. This model considers spherical gas pockets embedded in a water-saturated porous medium. White found that one of the main attenuation/dispersion mechanisms is the conversion of fast P wave to slow modes, diffusive or wave-like, depending on the frequency range. Two other important mechanisms are the Biot loss, generally occurring beyond the sonic frequency range, and scattering attenuation, whose relaxation frequency depends on the size of the patches and frequency content of the source. The simulation of acoustic wave fields in this kind of media was recently treated in [11,27].

While the analysis of the acoustic response of reservoir rocks for heterogeneous saturation has been studied by different authors, to our knowledge, the influence of spatially variable petrophysical properties on the wave fields has not received much attention yet. This encouraged us to develop a numerical model to investigate the influence of all these type of heterogeneities on wave propagation in porous saturated reservoir rocks.

The use of stochastic fractals for the statistical description of variable scale heterogeneities arising in porous media has become widely accepted for flow studies and reservoir simulations [12,46]. This approach will be adopted to model the spatial variability in saturation and porosity–permeability.

Our model is based on a generalization of Biot’s theory [5–7] for porous rocks saturated by two immiscible fluids [36,39,40]. It takes into account the existence of capillary forces at the pore scale, assuming that each fluid phase has a continuous distribution within the tortuous pore space and that both fluids can flow (funicular saturation regime). The formulation includes viscous and mass coupling interaction coefficients.