



Attenuation and dispersion in porous media – a rock physics perspective

Boris Gurevich (1)

(1) Centre for Exploration Geophysics, School of Earth and Planetary Sciences, Curtin University, Perth, Australia

ABSTRACT

Understanding attenuation and dispersion of elastic waves in fluid-saturated media is important for a range of disciplines that utilise seismic, acoustic or ultrasonic waveforms and amplitudes. A major cause of elastic wave attenuation is viscous dissipation due to the flow of the pore fluid induced by the passing wave. Wave-induced fluid flow (WIFF) occurs as the passing wave creates pressure gradients within the fluid phase and the resulting fluid flow causes internal friction until the pore pressure is equilibrated. The fluid flow can take place on various length scales. Wavelength-scale fluid pressure relaxation between peaks and troughs of a passing wave is known as global or macroscopic flow as described by Biot's theory of poroelasticity. WIFF caused by spatial variations of matrix or fluid properties on a scale much smaller than the wavelength but much larger than individual pore size is known as mesoscopic flow. Local or squirt flow occurs between more compliant and stiffer pores. A similar mechanism causes very substantial seismic attenuation in media saturated with viscoelastic substances such as heavy oil or bitumen.

1 INTRODUCTION

Wave propagation in all fluid and solid matter is always accompanied by attenuation and dispersion in a broad range of frequencies and scales from free oscillations of the entire Earth to ultrasound in small rock samples. Attenuation is the exponential decay of wave amplitude with propagation distance; dispersion is a variation of propagation velocity with frequency. Attenuation and dispersion can be caused by a variety of physical phenomena that can be divided broadly into two main classes: elastic processes, where the total energy of the wavefield is conserved (scattering of the waves by randomly distributed inhomogeneities), and inelastic dissipation (internal friction), where wave energy is converted into heat (see, e.g., Sato et al., 2012). In fluid-saturated porous media, the most common cause of internal friction is wave-induced motion of the fluid relative to the solid frame. Often, this phenomenon is termed wave-induced fluid flow (WIFF) or, perhaps more accurately, wave-induced fluid-pressure relaxation. Understanding of the fluid-related dissipation, combined with improved laboratory and field measurements of attenuation and/or dispersion, can be useful for a number of applications, such as estimation of hydraulic properties of rocks. Dissipation-related attributes already are employed in seismic interpretation and reservoir characterization, but to date their use has been mostly empirical and qualitative (see, e.g., Castagna et al., 2003; Rapoport et al., 2004; Hermana et al., 2014). Theoretical models of frequency-dependent attenuation and dispersion may help develop quantitative attributes, which can be calibrated against well logs and laboratory measurements. Here we summarise some of these mechanisms and models based on a detailed description given in Müller et al (2010) and Gurevich and Carcione (2022).

2 BIOT'S GLOBAL FLOW

The first description of attenuation and dispersion due to WIFF probably should be credited to a Russian physicist Jacob Frenkel (Frenkel, 1944). Subsequently, his theoretical analysis has been expanded in a series of papers by Belgian-American physicist Maurice A. Biot (1956). Biot's theory of dynamic poroelasticity is based on his earlier analysis of quasi-static deformation of fluid-saturated porous media, which in turn is an extension to porous media with an elastic frame of the concepts of soil mechanics developed by Karl von Terzaghi and his followers in 1920s and 1930s. The dispersion/attenuation mechanism described by Biot's theory is caused by pressure relaxation between peaks and troughs of a passing wave, which, in turn, occurs due to the density differences between the solid frame and the pore fluid. When the fluid is inviscid, application of the same pressure to the medium results in different particle velocities in the solid and fluid, and longitudinal waves propagating in the matrix and fluid (known as fast and slow waves, respectively) with no dissipation or dispersion. In the fast wave,

the fluid and solid motion is almost in-phase, and in the slow wave out-of-phase. When the fluid is viscous, attenuation is very high in the slow wave (especially at low frequencies) and relatively low in the fast wave – but nonzero due to some small motion of the fluid relative to the solid.

To visualize this phenomenon, consider a solid pipe filled with a viscous fluid being shaken back and forth in the axial direction. If the fluid is inviscid, it should have remained stationary. But if the fluid is very viscous, it will be dragged along by viscous forces, but it will lag behind the solid pipe, creating relative motion and hence energy dissipation. The same phenomenon occurs in a porous medium, although the tortuous pore space results in additional inertial coupling between the solid and fluid motion.

This dissipation mechanism often is called global or macroscopic flow because it occurs on the scale of a wavelength, which, at frequencies below 1 MHz, is much larger than an individual pore size. The slow compressional wave predicted by the Biot theory is observed experimentally by Plona (1980) but most relevant for many applications is attenuation and dispersion of the fast compressional wave.

The development of the Biot theory of poroelasticity in the 1950s and 1960s provided a solid understanding as to how the presence of fluids in the pore space of a rock can cause attenuation and dispersion. This was exciting for many applications, such as petroleum geophysics, as attenuation and dispersion potentially could become useful attributes for seismic exploration (it is worth noting that Biot developed the poroelasticity theory while working for the oil giant Shell). Biot's theory can indeed describe attenuation and dispersion in shallow marine sediments (see, e.g. Figure 1). However, it soon became apparent that the attenuation and dispersion predicted by the poroelasticity theory was prominent only at frequencies of 100 kHz or higher, and negligibly small at seismic (10–100 Hz) and sonic (100–10,000 Hz) frequencies. Furthermore, progress in laboratory measurements and field observations in the 1970s, both in ocean acoustics and borehole seismic methods, showed that measured attenuation of seismic and acoustic waves at frequencies between 10 Hz and 10 kHz was one to two orders of magnitude higher than the poroelasticity predictions.

This discrepancy has prompted a quest to find other mechanisms of dissipation. One approach is to include these mechanisms as an additional attenuation in the rock frame, making it viscoelastic (e.g. Stoll and Bryan, 1970; Carcione, 2022). While this approach cannot shed light on the physics of attenuation and dispersion, sometimes it is useful in modelling the observations. Furthermore, also realized in the 1970s is the idea that the global flow alone does not account for all of the WIFF effects in porous rocks. In particular, if a rock has heterogeneities smaller than the wavelength, a passing wave will create pressure gradients on a length scale of these heterogeneities. This, in turn, will cause fluid flow relative to the solid, and hence attenuation and dispersion. Depending on the scale of the heterogeneities, we can distinguish between mesoscopic flow and local flow.

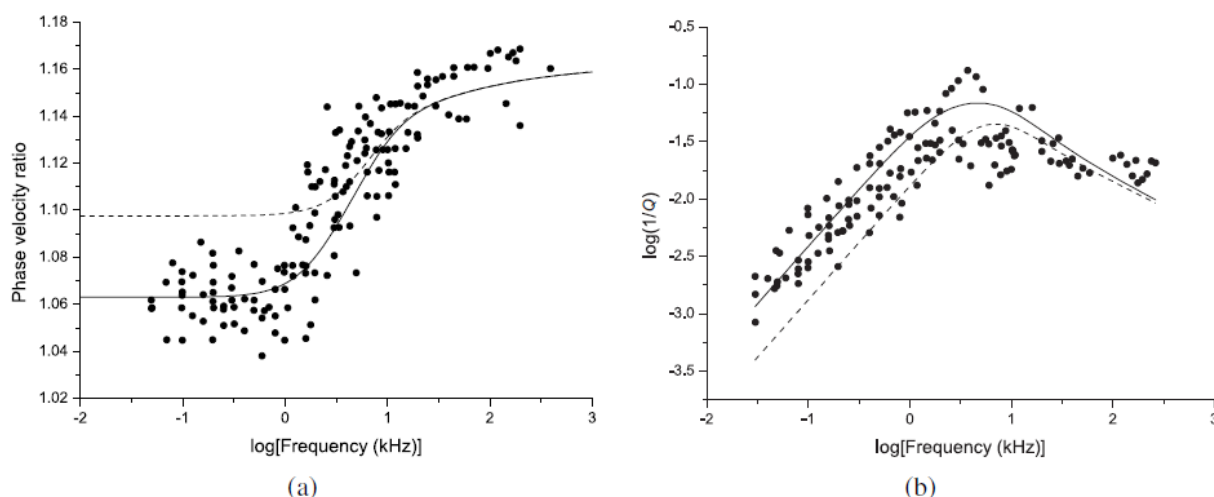


Figure 1. (a) Phase velocity ratio and (b) attenuation factor from the Biot theory (lines) compared to the experimental data (symbols) from ocean-bottom acoustic experiments (Zhou et al., 2009)

3 MESOSCOPIC FLOW

Mesoscopic flow is caused by heterogeneities having a length scale is much smaller than the wavelength but much larger than the typical pore size. When a porous medium with mesoscopic heterogeneities is compressed

by a passing wave, the fluid will tend to flow (squeeze out) from more compliant into stiffer regions, and the flow will cause dissipation due to viscous friction (see Figure 2).

The concept of mesoscopic pressure relaxation was developed in two papers by J. E. White and co-workers (White et al., 1975; White, 1975). In many natural and artificial porous media, mesoscopic flow can occur on a wide range of scales from the largest pore size to the smallest wavelength, and thus can cause attenuation in a broad range of frequencies. Therefore, mesoscopic flow is increasingly believed to be a key mechanism of fluid-related attenuation in the seismic exploration frequency band. To cause significant attenuation and dispersion, the degree of heterogeneity, that is, the contrast between elastic properties of different portions of the rock, must be relatively large. There are a number of scenarios where this is manifestly the case. The two most obvious scenarios, which have received substantial attention in recent years, are partially saturated media and fractured porous media.

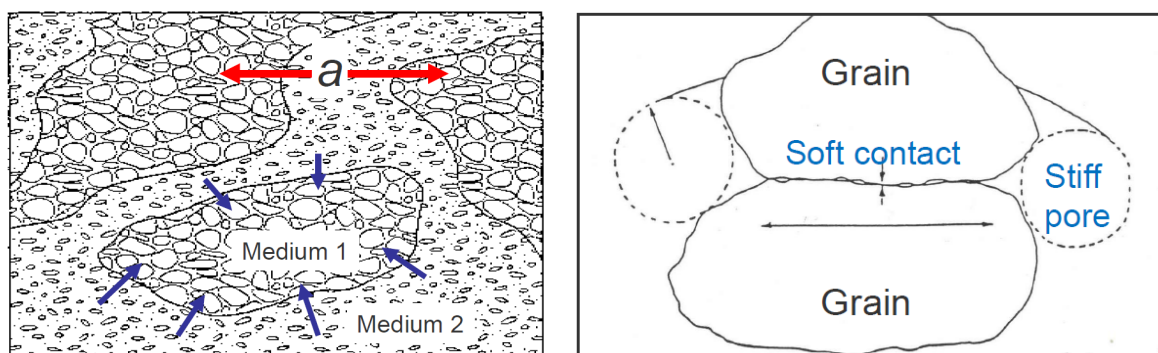


Figure 2. Schematic representation of mesoscopic (left) and local (right) flow dissipation mechanisms

3.1 Partial saturation

Partial saturation refers to a particular case of mesoscopic relaxation where only the pore- fluid properties vary on the mesoscale while the solid frame properties are all spatially uniform. If two immiscible pore fluids with substantially different fluid bulk moduli (such as liquid and gas) occupy mesoscopic-scale clusters of pores, significant wave attenuation and dispersion may occur due to the build-up of pressure gradients between these clusters. The complete pressure equilibration between the two fluids requires the frequency to be sufficiently low so that the characteristic length of fluid-pressure diffusion in the pore space is large compared to the largest spatial scale of fluid mixing. If the frequency is higher, the pressure in the two fluids will not have sufficient time to equilibrate within a half-period of the wave, resulting in a higher bulk modulus and wave velocity. Hence, the presence of two fluids in the pores causes significant dispersion and attenuation of elastic waves, which is related to the relaxation of pore-fluid pressures. The frequency dependence of wave velocity and attenuation in a partially saturated medium is controlled by the size, shape, and spatial distribution of fluid pockets, and the permeability and elastic moduli of the solid frame, as well as the properties of the two fluids. Compared to general inhomogeneous porous media, partially saturated media with a uniform frame allow for more tractable theoretical analysis and, no less importantly, for controlled experiment (i.e., it is easier to control the fluid saturation in a porous medium than to control its porosity). Partially saturated media are also of significant practical importance, particularly for geophysical exploration and monitoring of hydrocarbon reservoirs, or for monitoring CO₂ injection into porous rocks.

3.2 Fractured porous media

A strong degree of heterogeneity is also typical of fractured reservoirs such as tight sands and carbonates, where compliant mesoscopic fractures embedded in a porous rock mass play a crucial role as flow conduits (Nelson, 2001). During the compression wave cycle, there is WIFF from compliant fractures into the porous background medium and vice versa during the dilatational wave cycle. If the fractures are aligned in space, then fluid-pressure relaxation between pores and fractures will cause frequency-dependent anisotropy. Seismic characterization of fracture sets is an important aspect of reservoir characterization, and therefore attenuation due to wave-induced flow and associated frequency-dependent anisotropy have attracted considerable research interest.

4 LOCAL FLOW

Local flow, also known as squirt flow, is similar in nature but occurs on the pore scale. If pores have irregular shapes and orientations (which is almost always the case), they have different compliances. Under compression, the more compliant pores will deform to a greater extent and will squeeze the fluid into stiffer pores. The physical natures of mesoscopic and squirt flow are quite similar, but the geometry and mathematical formulations often are very different. The concept of local (or squirt) flow, corresponding to pore-scale relaxation of fluid pressure between various pores and cracks of different shapes and orientations, was developed by Mavko and Nur (1975)

and O'Connell and Budiansky (1977). This mechanism corresponds to pore-scale relaxation of pore-fluid pressure between more compliant voids (cracks, grain-to-grain contacts) and relatively stiff pores. When the rock is compressed, much greater pressure builds up in compliant than stiff pores, resulting in a fluid-pressure gradient, local fluid flow, and dissipation. Similarly to the case in mesoscopic relaxation, when the frequency is low, the fluid pressure has sufficient time to equalize within one half-period of the wave, and hence the compliant pores remain compliant. Conversely, at high frequencies, there is insufficient time for the pressure to equalize, and hence the pores that are compliant in the dry state become much stiffer. Therefore, materials with a binary pore structure exhibit significant moduli and velocity dispersion. At the same time, the presence of compliant pores is responsible for the dependence of elastic wave velocities on static pressure. Thus, substantial reduction of the pore compliance at high (e.g., ultrasonic) frequencies results in much weaker pressure dependence. This effect can be demonstrated by a much stronger dependence of the bulk modulus on the static pressure at seismic than ultrasonic frequencies.

5 VISCOELASTIC EFFECTS

Attenuation may be even stronger in porous media whose pores are filled with viscoelastic substances such as heavy oil/bitumen. At low frequencies (and/or high temperatures), the pore fill is in a liquid state, the fluid pressure is equalized between compliant and stiff pores, and the rock is relatively soft. But at high frequencies (or low temperatures), the pore fill is near-solid, and obviously cannot flow, making previously compliant pores very stiff and causing strong dispersion. Although a porous medium whose pores contain an elastic substance is itself elastic and does not exhibit any dissipation, its effective moduli can be described with the same approach as employed to describe the squirt-flow relaxation. Moreover, using the general elastic/viscoelastic correspondence principle, the result for a solid-filled medium can be extended to porous media saturated with viscoelastic substances, which can exhibit very large attenuation and dispersion.

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