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► **To cite this version:**

Perveiz Khalid, Daniel Broseta, Dan Nichita, Guillaume Galliero, Nathalie Favretto-Cristini, et al.. Vitesses et impédances sismiques en milieu poreux faiblement saturé en gaz. CFM 2009 - 19ème Congrès Français de Mécanique, Aug 2009, Marseille, France. hal-03378722

**HAL Id: hal-03378722**

**<https://hal.science/hal-03378722>**

Submitted on 14 Oct 2021

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# Vitesses et impédances sismiques en milieu poreux faiblement saturé en gaz

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## Résumé :

*Les vitesses et impédances sismiques dans les milieux poreux saturés de liquide et de gaz sont souvent modélisées par le modèle de Gassmann, dans lequel la compressibilité fluide est égale à la moyenne des compressibilités des phases liquide et gazeuse pondérées par leur fraction volumique. Cette approximation, dite de Wood, n'est pas appropriée aux (basses) fréquences sismiques, car elle néglige les échanges de matière et de chaleur entre phases. L'effet de ces derniers est toutefois significatif aux faibles saturations en gaz, ce qui sera illustré par quelques exemples rencontrés en exploration et monitoring sismiques.*

## Abstract :

*The seismic wave velocities and impedances in porous media saturated with liquid and gas are usually estimated using the Gassmann model, in which the bulk modulus of the fluid is the harmonic average of the adiabatic bulk moduli of the liquid and the gas phases. This approximation, referred to as the Wood approximation, is not valid for (low) seismic frequencies because it neglects mass conversion and heat transfer effects between phases. These effects are however significant for low gas-saturated media, which is illustrated by some applications in seismic exploration and monitoring.*

**Mots clefs :** milieu poreux, effet de la saturation en gaz, vitesse sismique, impédance sismique, modèle de Gassmann-Wood.

## 1 Introduction

While the presence of gas is easily detected, it is difficult to infer gas saturation from conventional seismic reflectivity measurements. Indeed, significant gas saturations which correspond to economic gas reservoirs give rise to reflections as strong as those generated by low gas saturations which correspond to non-commercial gas reservoirs. Both reservoirs cannot be therefore distinguished from each other.

This poor sensitivity is to some extent captured by the Gassmann model, in which the bulk modulus of the saturating two-phase fluid is usually approximated by the harmonic average of the liquid and gas bulk moduli. This approximation, referred to as the Wood model, holds when the liquid and gas phases are homogeneously distributed within the porous space down to scales much smaller than the seismic wavelength. Within this approach, the P-wave velocity varies with gas saturation in a very characteristic manner. For reasonable rock parameters and contrasted liquid and gas phases (e.g., such as water and gas in shallow reservoirs), the P-wave velocity first decreases sharply but continuously with increasing gas saturation, reaching a minimum value for gas saturation equal to 5-10%. The P-wave velocity then increases slowly with gas saturation [1].

The Gassmann-Wood approach assumes that there is negligible conversion of one phase to the other during the propagation of the seismic wave. The phases are "frozen". For low enough frequencies and/or for small enough phase domains, phase conversion effects can however no longer be neglected. In this case, the two-phase fluid is more compressible compared to Wood's approximation due to the condensation of gas into liquid upon a pressure increase. Hence, the effective bulk modulus and the P-wave velocity are lower than

their Wood's counterparts. In the thermodynamic limit (i.e., in the zero-frequency limit), Landau and Lifshitz [2] have evaluated these parameters in the case of pure (i.e., one-component) fluids. They turn out to vary discontinuously at the crossing of phase boundaries, in contrast to the continuous variation predicted by Wood's approach. This feature persists in the extensions of the Landau-Lifshitz model to real (i.e., multi-component) fluids such as reservoir fluids [3,4]. Sharp discontinuities occur at the crossing of bubble point conditions, corresponding to the (dis)appearance of a 'free' gas phase in the liquid.

For low gas saturations, the bulk moduli of the two-phase fluid predicted by the Wood model and the thermodynamic model (hereafter referred to as the Landau-Lifshitz model) differ significantly. In the following, we examine and discuss this difference and its impact upon the seismic properties in typical reservoir (fluid/rock) systems.

## 2 Breakdown of Wood's approximation for low gas-saturated rocks

We discuss in this section the validity of Wood's assumption (i.e., the assumption of "frozen" phases) in the seismic frequency range (i.e., 1-10<sup>4</sup> Hz).

The saturation state in a low gas-saturated rock is akin to that in a bubbly liquid, in which bubble dimensions do not in practical cases exceed a few microns (i.e., the maximum pore size in most rocks). The acoustic behavior of bubbly liquids has been the subject of a number of theoretical and experimental studies, which provide insights into the range of applicability of Wood's and Landau-Lifshitz' approximations. These studies, summarized in the next paragraph, have been mostly concerned with pure fluid systems, where heat conduction is the rate-limiting process controlling the approach to thermodynamic equilibrium between liquid and vapour.

The phase conversion process at the passage of the seismic wave consists in the condensation of part of the gas phase and the vaporization of part of the liquid phase when pressure, respectively, increases and decreases. In pure fluids, this process occurs only if the heat that accompanies such phase changes is brought to (or evacuated from) the liquid/gas interfaces where these changes occur. For dilute gas bubbles in a liquid, the liquid phase acts as a heat bath. Heat diffusion in the liquid thus fixes the frequency (hereafter, denoted  $f_c$ ) above which the compressive and acoustic properties are those of 'frozen' phases (Wood's regime), and below which these properties are controlled by phase equilibrium effects (Landau-Lifshitz' regime). From a detailed analysis of the heat and mass transfer processes in pure fluids in two-phase (liquid and vapour) conditions, Onuki [5] derived the dispersion relation for the adiabatic compressibility and the P-wave velocity, which tend to the values predicted by the Landau-Lifshitz approach at low enough frequencies and to those predicted by the Wood model at high enough frequencies. The resonance, or maximum attenuation, occurs for a characteristic frequency  $f_c$  such that the thermal diffusion length in the liquid  $(D_l/2\pi f)^{1/2}$  is of the order of the mean distance between bubbles  $l \approx R/S_g^{1/3}$ , where  $D_l$  is the liquid thermal diffusivity,  $S_g$  the gas saturation and  $R$  the radius of the bubbles [6]. The characteristic frequency  $f_c$  is thus given by:

$$f_c \approx D_l / l^2 \approx D_l S_g^{2/3} / R^2. \quad (1)$$

On the experimental side, we are aware of a set of low-frequency acoustic measurements conducted by Coste and his co-workers on a bubbly liquid (diethyl-ether) containing a low fraction ( $S_g < 1\%$ ) of bubbles with radius  $R \sim 1$  mm [6, 7]. These experiments consisted in standing-wave measurements in a Helmholtz resonator filled with the liquid, which allowed resonant curves in a frequency range as low as a few Hz to be investigated. Coste and his co-workers showed clear evidence for the failure of Wood's theory, manifested by strong attenuation effects due to the liquid/vapour transition, even though frequencies were much higher than the value of  $f_c$  (equal to a few milli-Hz for that particular system).

The systems of interest in this paper are however multi-component fluids. In these fluids, the approach to two-phase equilibrium also involves the diffusive transfer of the various components from one phase to the other. This mass transfer is much slower than heat diffusion and, therefore, this is the rate-controlling factor. Mutual diffusion coefficients are 1-2 orders of magnitude below typical thermal diffusivities. For instance,

the diffusion coefficients of methane or CO<sub>2</sub> in water are in the range of 10<sup>-8</sup>-10<sup>-9</sup> m<sup>2</sup>/s, whereas thermal diffusivities of liquids such as water or diethyl-ether are rather in the range of 10<sup>-7</sup> m<sup>2</sup>/s. Nevertheless, in low gas-saturated porous media the gas bubbles trapped in the pore structure are smaller than the bubbles in the experiments performed by Coste (where  $R$  was equal to 1 mm) by, say, three or more orders of magnitude. Therefore, for comparable saturations ( $S_g \sim$  a few parts per thousand), the characteristic frequency  $f_c$  given by Eq. (1), where  $D_l$  is now replaced by the diffusion coefficient of the gas in the liquid phase, is higher by at least four orders of magnitude than that corresponding to Coste's experiments. Hence, for seismic frequencies, Wood's assumption of "frozen" phases is likely to break down in low gas-saturated rocks, where the effects of the phase changes between liquid and gas should affect seismic parameters instead.

### 3 Comparison between the Gassmann-Wood and Gassmann-Landau&Lifshitz approaches

In this section we compute the seismic parameters of two reservoir (fluid/rock) examples by means of Gassmann equation, in which the bulk modulus of the two-phase fluid is obtained by assuming that liquid and gas phases are either "frozen" (Wood's approach) or thermodynamically equilibrated (Landau-Lifshitz' approach). The fluid systems taken as examples are a water/methane mixture representative of "fizz water" [1], and a water/CO<sub>2</sub> mixture such as that resulting from CO<sub>2</sub> injection and storage in a deep aquifer [8]. The chosen temperature,  $T=335$  K, and the bubble point pressure,  $P_b \sim 185$  bar, are typical of reservoir conditions. We consider a situation in which pressure decreases (at constant  $T$ ) from above  $P_b$  (single-phase liquid,  $S_g = 0$ ) to below  $P_b$  (two-phase conditions,  $S_g > 0$ ), thus simulating a reservoir depletion process. In this process, the gas saturation  $S_g$  increases in a very nonlinear fashion and remains very low in a large pressure interval below  $P_b$ . For the two above examples, the value  $S_g = 1\%$  is reached for 73 and 55 bar below  $P_b$ , respectively.

The first step consists in estimating the effective bulk modulus of the two-phase fluid, which is somewhat more complex in the thermodynamic regime than in the Wood regime. Various procedures have been proposed in the literature to estimate the former modulus [3, 4]. We will use the results obtained in the latter reference for the above two water/gas systems, whose "thermodynamic" bulk modulus can also be approximated by a much simpler approach which we briefly outline here.

This approach consists in neglecting the difference between the adiabatic and isothermal bulk moduli of the two-phase fluid and in evaluating the latter modulus in terms of the "black oil" parameters of the fluid system. This neglect is justified for low amounts of gas (i.e., small  $S_g$ ) in the two-phase fluid and for contrasted liquid and gas phases. In the "black oil" model, the gas can either form a "free" phase, or be dissolved in the liquid phase (conventionally referred to as the "oil", but this liquid can be water as well). The "black oil" parameters of a given fluid at fixed temperature  $T$  and pressure  $P$  are the volume ratio of liberated gas to remaining liquid at standard conditions (often denoted  $R_s$ ) and the liquid (or gas) formation volume factor, hereafter denoted  $B_l$  (or  $B_g$ ), equal to the volume of liquid (or gas) at  $T$  and  $P$  relative to the volume at standard conditions. They can be determined directly from PVT measurements, usually conducted under isothermal conditions, or from simple correlations [9]. There exist simple expressions [10] relating the isothermal compressibility to those parameters, both in the single-phase ( $P > P_b$ ) and two-phase ( $P < P_b$ ) regions. For the above water/gas systems, and using the available correlations [10, 11], we have checked that these expressions yield, in the saturation range  $0 < S_g < 0.05$ , reasonable results compared to those obtained by using a more rigorous procedure [4]. In terms of the above "black oil" parameters, the isothermal compressibility of the single-phase liquid ( $P > P_b$ ) is

$$\beta_{\text{BO}} = -\frac{1}{B_l} \left( \frac{\partial B_l}{\partial P} \right)_T \quad (2),$$

and that of the two-phase fluid ( $P < P_b$ ) with gas and liquid saturations  $S_g$  and  $S_l$  is (see, e.g., [10])

$$\beta_{BO} = S_l \left[ -\frac{1}{B_l} \left( \frac{\partial B_l}{\partial P} \right)_T + \frac{B_g}{B_l} \left( \frac{\partial R_s}{\partial P} \right)_T \right] + S_g \left[ -\frac{1}{B_g} \left( \frac{\partial B_g}{\partial P} \right)_T \right] \quad (3).$$

The expression in the r.h.s bracket of equation (3) is the gas phase compressibility and that in the l.h.s. bracket the liquid phase compressibility, in which the second term accounts for the gas phase evolving from the liquid under a pressure variation. The discontinuity in ‘thermodynamic’ isothermal compressibility at the crossing of bubble point pressure is therefore equal to:

$$\left( \frac{B_g}{B_l} \frac{\partial R_s}{\partial P} \right)_{T, P=P_b} \quad (4).$$

For low enough pressures, this term varies roughly linearly with the reciprocal of (bubble point) pressure, because  $B_g$  is then inversely proportional to  $P$ , whereas  $B_l$  and  $\partial R_s / \partial P$  are almost constant.  $\partial R_s / \partial P$  is proportional to Henry’s law constant (at low pressure, gas solubility in the liquid increases linearly with  $P$ ). The discontinuity in compressibility at bubble point pressure (equation 3) thus follows the following trend: it decreases with increasing bubble point pressure and decreasing gas solubility in the liquid.

For the two above water/gas systems and, more generally, for reservoir fluids obeying the so-called ‘black oil’ description, the above approximations (equations 2 to 4) turn out to be not very different from the more exact adiabatic compressibilities, at least when the two-phase fluid contains a small gas volumetric fraction  $S_g$  [4]. Discontinuities in isothermal compressibility are familiar to reservoir engineers. For instance, bubble point conditions are determined from the angular point of the pressure *vs.* volume curve at constant  $T$ . Once the bulk modulus of the fluid is calculated, its value is injected in Gassmann’s formula for the bulk modulus of the saturated rock, and the corresponding P-wave velocity  $V_P$  is then calculated by Newton-Laplace equation.

The reservoir rock chosen has properties close to those of the Utsira aquifer [8]. The results for  $V_P$  as a function of saturation, calculated using for the fluid modulus either the above ‘thermodynamic’ method, or the Wood method, are plotted in Figure 1, together with the corresponding velocity, impedance and reflectivity profiles for a 100 m-thick low gas-saturated ( $S_g = 1\%$ ) aquifer sandwiched between shales (with density  $2.27 \text{ g/cm}^3$  and  $V_P = 2.4 \text{ km/s}$ ). The results obtained with the two methods are significantly different. For low  $S_g$ , the ‘thermodynamic’ seismic velocity  $V_P$  and impedance are significantly lower than their Wood’s counterparts. This effect is more pronounced in the case of  $\text{CO}_2$ . In particular, when gas starts forming a ‘free’ phase in water (i.e., at bubble point conditions), the ‘thermodynamic’ velocity  $V_P$  drops by  $0.28 \text{ km/s}$  in the case of  $\text{CH}_4$ , and  $0.31 \text{ km/s}$  in the case of  $\text{CO}_2$ . The differences between the results obtained with the two approaches are smaller when gas saturation increases and unnoticeable for  $S_g > 0.1$  in the case of  $\text{CH}_4$ , and  $S_g > 0.15$  in the case of  $\text{CO}_2$ .

## 4 Conclusions

The drops in seismic velocity and impedance caused by small gas saturations are likely to be underestimated by the conventional Gassmann-Wood approach. A proper account of the effects of phase changes on seismic parameters shows that even minute amounts of ‘free’ gas, corresponding to bubble point conditions in the reservoir, should give rise to strong reflections (‘bright spots’). Some practical consequences of these results are illustrated by explicit calculations with two binary water/gas fluid systems and typical rock and geological settings. One fluid system, water and  $\text{CH}_4$ , is representative of ‘fizz water’. For low gas saturation (e.g., lower than 5-10%), the P-wave velocity is much lower than the values predicted by the Gassmann-Wood approach. This feature is more pronounced for lower gas saturation. The results obtained with the other fluid system (water and  $\text{CO}_2$ ) show that seismic reflectivity measurements of a  $\text{CO}_2$  plume stored in an aquifer will detect the *top* of the plume, where the gas saturation is close to zero. If  $\text{CO}_2$  leaks and contaminates a neighboring overlying aquifer, a reflector will appear and will be detectable as soon as the solubility limit is reached in this aquifer. Other reservoir applications, to be addressed in a

forthcoming publication, include the monitoring of secondary gas caps and oil/gas contacts in producing oil fields.

## Acknowledgments

We are grateful to F. Montel (Total) for pointing to our attention the “fizz water” concept. This research has been partially supported by Agence Nationale de la Recherche (project EMSAPCO2, with CGG-Veritas, BRGM, ESPCI, IFP and Magnitude).

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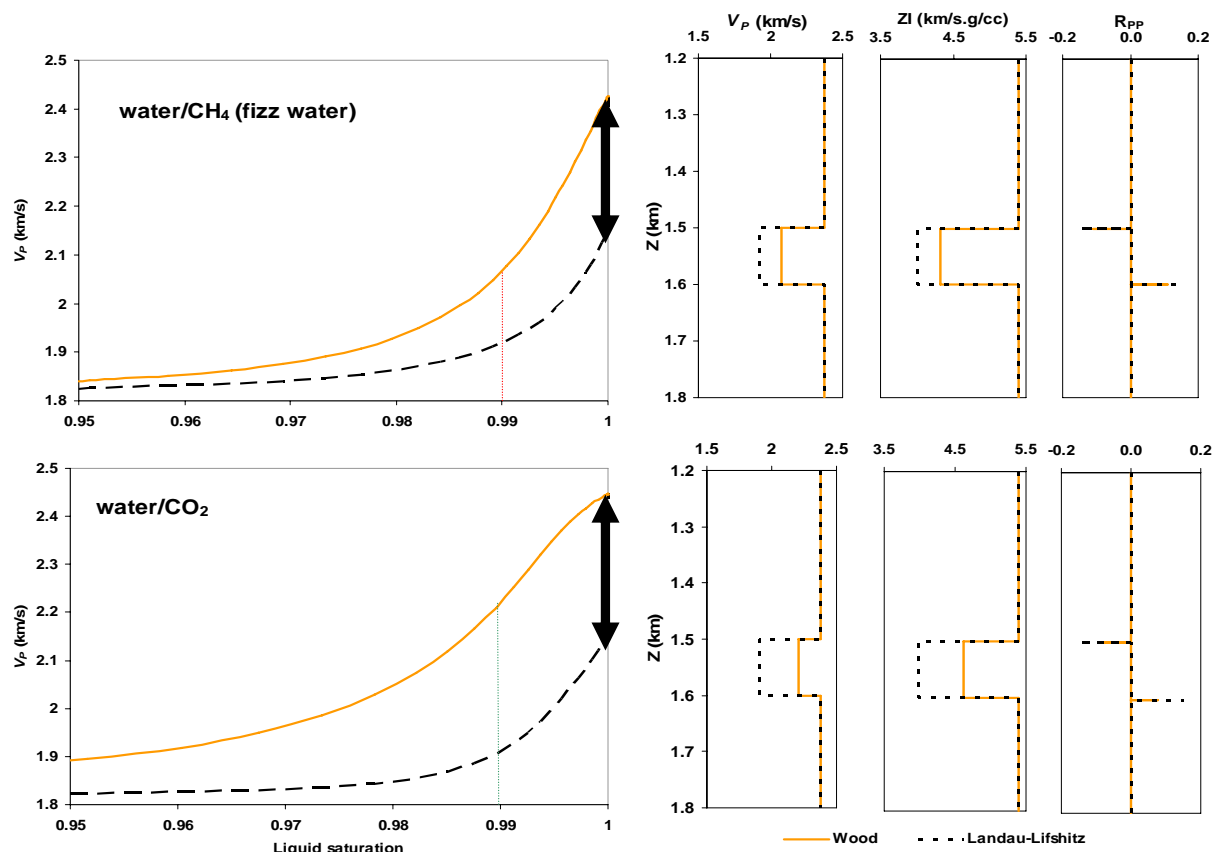


FIG. 1 – Left plots: P-wave velocities as a function of saturation for a porous rock (porosity=34%, Biot coefficient=0.92) saturated with fizz water (top) and a water/CO<sub>2</sub> mixture (bottom) at T=335 K and  $P_b \sim 185$  bar. Full curves are obtained by using the conventional Gassmann-Wood method, and dashed curves by the Gassmann-Landau&Lifshitz method. The arrow marks the strong discontinuity in thermodynamic  $V_p$  at the crossing of bubble point conditions. Right plots: vertical profiles for P-wave velocity ( $V_p$ ), impedance (ZI) and normal reflectivity coefficient ( $R_{PP}$ ) of a 100 m-thick low gas-saturated ( $S_g = 1\%$ ) reservoir sandwiched between shales, calculated according to the two methods.