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Observation of two longitudinal and two transverse waves in a frozen porous medium

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Experimental results on the transmission of elastic waves in a water-saturated sample of glass powder are presented. Both longitudinal and transverse waves are studied in a temperature range of $[-30, 0\text{ }^{\circ}\text{C}]$. Two longitudinal and two transverse waves are detected. For a temperature of $-28\text{ }^{\circ}\text{C}$ and a frequency of 500 kHz, the measured velocities are of the order of 4000 and 2300 m/s for the two longitudinal waves and of 2400 and 1400 m/s for the two transverse waves. The two supplementary signals detected (one longitudinal and one transverse) are very unlikely the result of spurious reflections or electromagnetic coupling since such phenomena were not observed when replacing the porous sample by water. The values of the experimental velocities are in good agreement with the predictions of the extension of Biot's theory to frozen porous media developed by Leclaire *et al.*

INTRODUCTION

The theory of propagation of elastic waves in fluid-saturated porous solids has been established by Biot in 1956. Several authors have shown the validity of this theory (Beryman, 1980; Johnson and Plona, 1982) and its great interest for the interpretation of geophysical results (Murphy, 1982; Bourbié *et al.*, 1987; Hovem and Ingram, 1979). A particular feature of Biot's theory is the prediction of two longitudinal waves in a consolidated medium as a consequence of the presence of solid and fluid in the porous medium: a fast wave and a second wave with a lower velocity. The viscous dissipations are responsible of a large attenuation of the second wave and make its detection difficult in almost all the experimental situations. In fact, the dispersion of the second wave also called Biot's slow wave can be assimilated to a diffusion process (Biot, 1956). The observation of the slow wave has been successfully performed by Plona and Johnson (1980) in a consolidated water-saturated sample of sintered glass beads.

An extension of Biot's theory to frozen porous media has been proposed recently by Leclaire *et al.* (1994) for applications in civil engineering and geophysics in cold regions. Let us recall that solid substrate, ice and liquid water can coexist in finely dispersed frozen media at negative Celsius temperatures and that water tends to form a film around the solid particles isolating them from ice (Aguirre-Puente and Bernard, 1978). The model of Leclaire *et al.* predicts that three longitudinal and two transverse acoustic waves can propagate in a three-phased material containing a solid substrate, ice, and liquid water. The purpose of this paper is to report investigations on the possible existence of several

waves in frozen porous media and to give the interpretation of the experimental results with the help of the theoretical predictions.

I. EXPERIMENTAL SETUP

Laboratory tests have been performed in a nonconsolidated glass powder sample of porosity 0.3 and composed of mean size particles of about $120\text{ }\mu\text{m}$. The experimental setup is shown in Fig. 1. A cell made of Plexiglas containing the water-saturated sample at ambient temperature is dropped to $-30\text{ }^{\circ}\text{C}$. During a slow reheating over 10 h in an isolating enclosure, temperature is monitored by thermocouples located in the sample while acoustical measurements are made. They consist in the transmission through the sample of short acoustical pulses (-300-V amplitude, $1\text{-}\mu\text{s}$ duration) generated by a pulse generator. The selection of the longitudinal or transverse mode is made by switches in emission and reception. The transducers nominal frequency is 500 kHz. The signals are amplified and displayed on a sampling oscilloscope triggered by the pulse generator. Then the signals are digitized with a 12-bit A/D converter and recorded by a microcomputer for analysis in time or frequency domain.

Our first experiments (Leclaire *et al.*, 1993) were designed to determine the velocity and attenuation for samples at temperatures in the vicinity of $0\text{ }^{\circ}\text{C}$. For these experiments the propagation distance in the sample was around 2 cm to reduce amplitude decay when the medium is almost totally defrosted. In such a configuration, wave reflections occur at sample/cell and transducers/cell interfaces. The reflections appear on the oscilloscope as spurious oscillations at the end of the signals and prevent the detection of possible other waves. A new cell has been made (Fig. 2) with perforated walls at the transducers diameter to eliminate reflections in the cell. Transducers are applied directly on the sample. The propagation distance is increased up to 9.7 cm to isolate

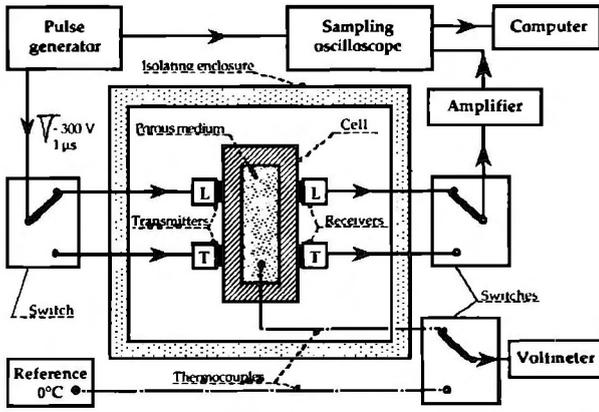


FIG. 1. Experimental setup for the study of acoustic waves in frozen porous media. The cell is rectangularly shaped and the sample thickness is 2 cm.

useful signals from unexpected reflections and to improve the precision of the velocity measurement. Although the propagation distance is increased, signal should be observed at low temperatures where wave attenuation is low. No vacuum was used during the preparation of the sample as we assume that the influence of air bubbles on velocities is small at low temperature.

II. RESULTS

Figure 3 shows the signal received by longitudinal [Fig. 3(a)] and transverse [Fig. 3(b)] transducer for a temperature of -28°C . We observe two signals for each mode which have been marked Λ_1 , Λ_2 for longitudinal modes and θ_1 , θ_2 for transverse modes. As seen in Fig. 4 for a temperature of -11.5°C , the arrival time of the signals increases with temperature as the medium defreezes, their amplitude decreases and they lose their high-frequency content. These remarks apply noticeably more for transverse waves. The evolution of the amplitude and of the delay of the signals between -5 and -2°C is shown in Fig. 5. One may observe a large increase of the delay of θ_1 between these temperatures while the variation of the delay of Λ_2 is smaller. The Λ_1 and θ_1 waves have been studied in previous works (Leclaire *et al.*, 1993). The previous results on velocity given by the ratio of the propagation distance to the delay of the received signal are comparable to those obtained in the present study but these last results may be considered as better since the measurements are more accurate in the configuration of the cell of

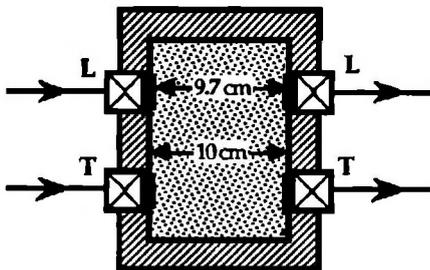


FIG. 2. New configuration of the rectangular cell containing the sample for the detection of possible secondary waves in frozen porous media. The propagation distance is now of 9.7 cm and the transducers are in direct contact with the sample.

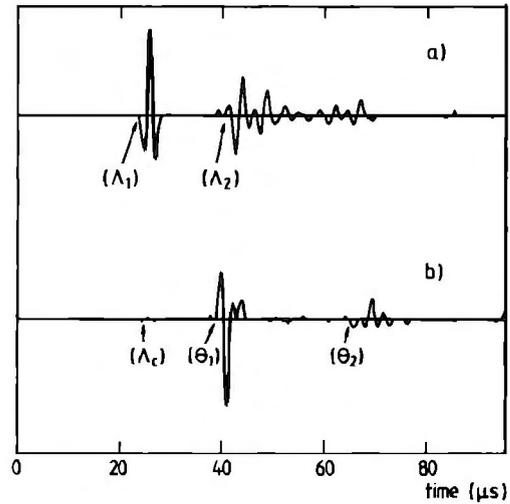


FIG. 3. Signals received by (a) longitudinal receiver and (b) transverse receiver at -28°C in glass powder.

Fig. 2, where the propagation distance is increased. On the other hand, wave attenuation is higher near 0°C in this configuration. The time delay of the detected supplementary signals Λ_2 and θ_2 is approximately twice as long as the delay of Λ_1 and θ_1 , respectively. Experiments have been made replacing the porous sample by water at room temperature to determine if these extra signals could be the result of spurious reflections on the cell walls or on the transducers surface. No signal was detected by the receiver at a time delay double of that of the first received signal. Thus Λ_2 and θ_2 cannot be the consequence of wave reflections or electromagnetic coupling between the emission and the reception of the electronic apparatus. Considering transverse signals [Figs. 3(b) and 4(b)], one may observe a very small signal located by the marker Λ_c which correspond to a longitudinal component. Consequently, it is unlikely that θ_2 can be a longitudinal component resulting from a mode conversion at the surface of the transverse transmitter since the amplitude of θ_2 is much greater than the amplitude of Λ_c . Elsewhere, Fig. 5 shows that Λ_2 cannot be a longitudinal component resulting

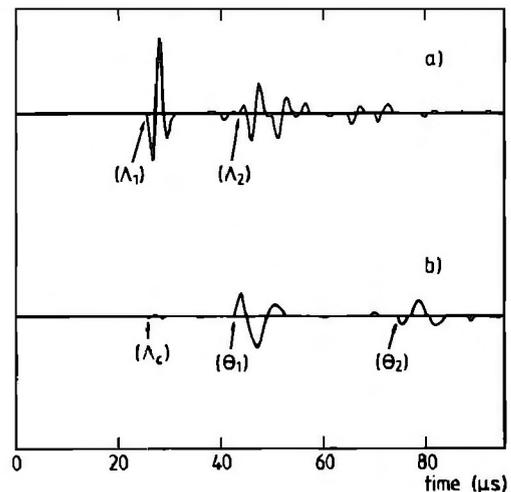


FIG. 4. Signals received by (a) longitudinal receiver and (b) transverse receiver at -11.5°C in glass powder.

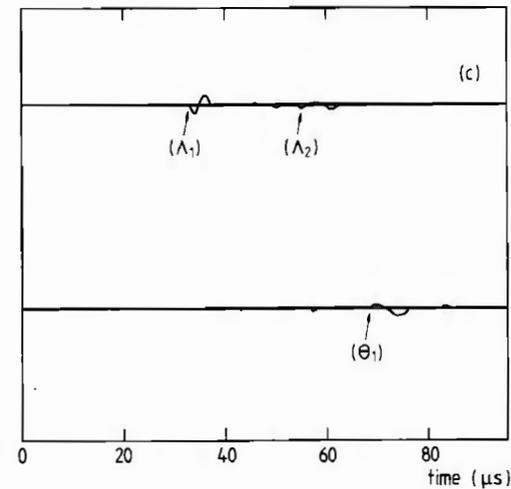
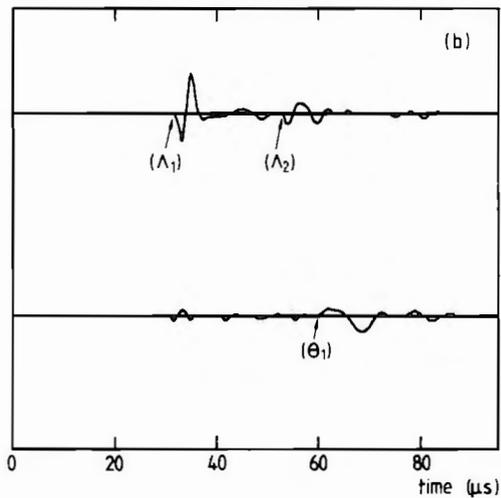
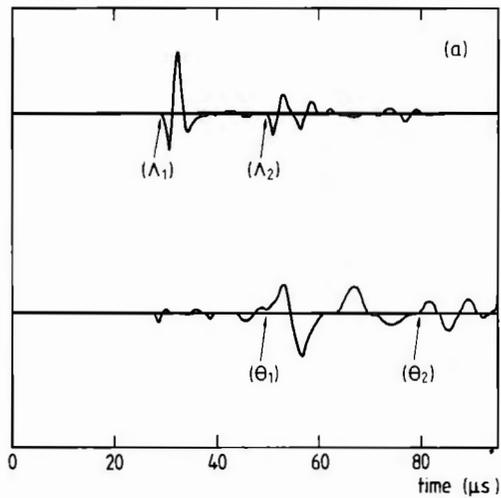


FIG. 5. Evolution of the signals between -5 and -2 °C. (a) signals at -5 °C, (b) signals at -2.5 °C, and (c) signals at -2 °C.

from θ_1 since a separation of the two signals occurs between -5 and -2 °C. In fact, Λ_2 and θ_2 might be considered as secondary waves in frozen porous media. The relative shifts of signals Λ_1 , Λ_2 , θ_1 , and θ_2 caused by temperature variations during the reheating have been followed by plotting their velocities as shown in Fig. 6.

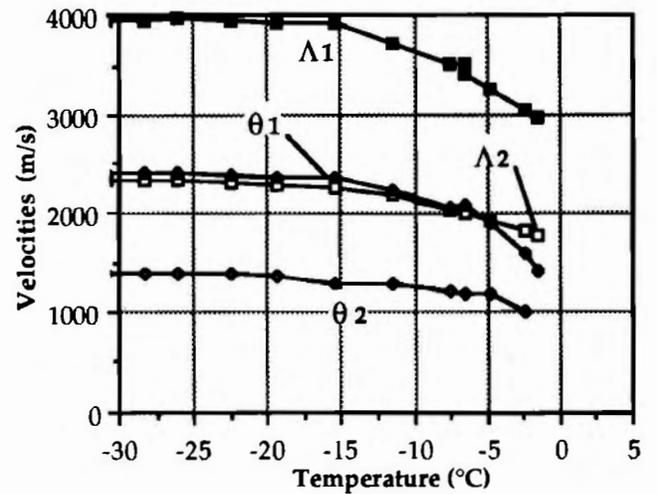


FIG. 6. Experimental velocities of Λ_1 , Λ_2 , θ_1 , and θ_2 waves as functions of temperature (in glass powder).

III. DISCUSSION

The extension of Biot's theory to frozen porous media proposed by Leclaire *et al.* (1994) predicts the existence of three longitudinal waves labeled L1, L2, L3 and of two transverse waves labeled T1, T2 whose velocity and attenuation can be expressed as functions of unfrozen water content. The velocity and attenuation can also be expressed as functions of temperature with the help of a thermodynamical relationship developed independently from the acoustic model, where physical parameters and porosimetric distribution play a role. Figure 7 shows the velocity of L1, L2, T1, and T2 waves calculated for glass powder with the theoretical model as functions of temperature and for a frequency of 500 kHz. For the calculation, porosimetric distribution has been assumed to be Gaussian with an average pore radius r_{av} of $10 \mu\text{m}$ and a standard deviation Δr of $4 \mu\text{m}$. The large values of r_{av} and Δr imply that large velocity variations exist between -1 and 0 °C.

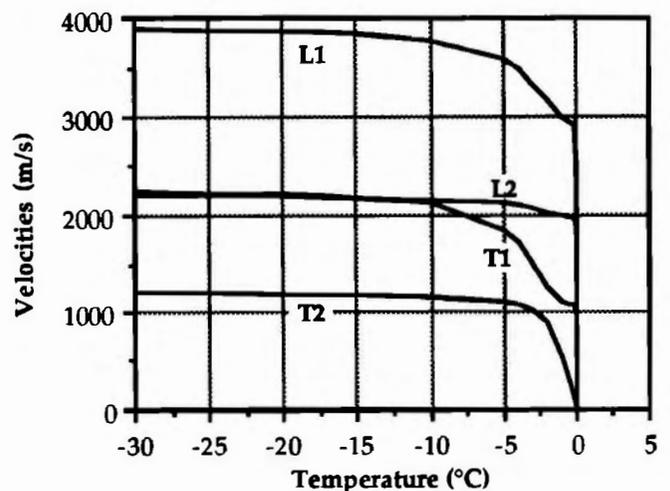


FIG. 7. Calculated velocities of Λ_1 , Λ_2 , θ_1 , and θ_2 waves as functions of temperature at 500 kHz (glass powder).

The experimental velocities of Λ_1 and θ_1 waves (Fig. 6) are in good agreement with the theoretical velocities of L1 and T1 waves (Fig. 7) in the range of temperature explored. In fact, one may identify the experimental longitudinal Λ_1 wave as the theoretical L1 wave, and the experimental transverse θ_1 wave as the theoretical T1 wave. In the same way, the Λ_2 and θ_2 waves might be identified as the L2 and as the T2 wave, respectively. This seems to be confirmed considering the good agreement obtained from the comparison of the experimental results (Fig. 6) to the theoretical predictions (Fig. 7).

The existence of two longitudinal waves in a water-saturated porous medium (without ice) is a consequence of the presence of two continuous phases in the medium but the two waves do not propagate independently, one wave in each phase. In fact, elastic and inertial coupling between water and solid imply exchanges of potential and kinetic energy (respectively) between the two waves. When dealing with frozen porous media, one could admit the possible existence of several waves if the phases are continuous as it can occur for porous media with ice. Elastic and inertial coupling can also occur between solid and liquid water and between ice and liquid water and could therefore influence the propagation. The theoretical model of Leclaire *et al.* (1994) predicts one longitudinal and one transverse wave in addition of those predicted by Biot's original theory. This is a consequence of the presence of one supplementary continuous solid (ice) in the medium. In a mathematical view, the prediction of several waves is a consequence of the use of Biot's formulation.

Although elastic and inertial coupling exist, we think that the main part of the energy of Λ_1 and θ_1 propagates in the solid while symmetrically, the energy of Λ_2 and θ_2 propagates mainly in the ice. The properties of Λ_2 and θ_2 can therefore be considered as similar to those of Λ_1 and θ_1 . Biot's slow wave detected by Plona and Johnson (1980) is highly attenuated and behave as a diffusion process in the low-frequency range (Biot, 1956). Thus the Λ_2 and θ_2 waves detected here are not assimilated as waves of this kind since they propagate with a low attenuation (with respect to Biot's slow wave) at low temperatures when the medium is almost totally frozen.

IV. CONCLUSION

The extension of Biot's theory of wave propagation to frozen media has led to the prediction of three longitudinal and two transverse waves. Experiments have been made to detect possible supplementary waves in a nonconsolidated sample of glass powder. Supplementary signals other than those expected have been observed and might be associated to the existence of secondary waves. A good agreement has been found for the velocities between the experimental results and the theoretical predictions.

The results presented here seems to show that several longitudinal and transverse waves may propagate in porous media composed of continuous solids. The experimental and theoretical investigations in this direction should be of interest for applications in physics of heterogeneous materials.

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