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# Biot's Slow Wave in Massillon and Berea Sandstones

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## SUMMARY

Biot's slow wave has been elusive in natural rocks because of strong attenuation and interference from the common compressional and shear waves. We report that unambiguous slow arrivals can be detected for Massillon and Berea sandstones with a technique that uses air coupling and saturation to preferentially impedance match to the slow wave. Velocity and attenuation of the phase can be measured over a wide frequency range, 50-500 kHz. Slow velocities are 0.57 $V_f$ for the Massillon and 0.49 $V_f$ for the Berea, where $V_f$ for air is ~332 M/s. Slow wave properties depend on the morphology of the pore space, which also controls fluid transport. These results suggest that new acoustic methods to determine formation properties such as permeability and tortuosity may be possible.

## INTRODUCTION

In a series of papers beginning in 1956, Biot (1962 and earlier referenced papers) proposed a comprehensive theory that has explained many of the important features of wave propagation in fluid-saturated porous media. One striking feature of the theory is the prediction of a slow compressional wave with a speed lower than that of either component. Since the slow mode involves a coupled motion of fluid and solid, it's speed and attenuation depend on the morphology of the pore space, which also determines fluid transport properties such as formation permeability.

Mode conversion from fast to slow waves at interfaces should contribute a source of strong wave attenuation as the slow wave propagates. The first clear observations of a propagating slow wave were reported in 1980 by Plona for water saturated sintered glass beads.

In spite of the revival of interest in the predicted mode, no unambiguous examples of slow wave propagation in natural rocks for viscous fluids have been reported because of strong attenuation and interference from the ordinary fast compressional and shear waves. By depositing kaolinite from suspension in the pore spaces of cemented glass bead specimens that showed strong slow wave arrivals, Klimentos and McCann (1989) demonstrated that restrictions to local flow caused by clays play a major role in slow wave attenuation. Strong viscous attenuation is also implied by the observation of the slow mode in liquid helium saturated Berea sandstone by Johnson et al (1986) which were successful because superfluid liquid helium has negligible viscosity at cyrogenic temperatures.

We describe here a new experimental technique using air coupled ultrasonic waves and air saturation that overcomes these problems to allow unambiguous observations of slow waves in both synthetic and natural porous materials. This method provides a direct link between fluid transport and wave propagation properties for porous rocks.

## SAMPLE MATERIALS AND PREPARATION

Sintered glass beads, and two sandstones, from the Berea and Massillon formations were used in the experiments. The glass bead sample,with porosity of 30%, and permeability of 6000 mD, enabled us to compare our results to water saturation experiments. Berea sandstone is often used in studies of reservoir rocks, has a porosity of ~20%, and was taken from a block with air permeability of 400-500 mD. Massillon sandstone is slightly more porous (22%), permeable (600 mD), and heterogeneous. Samples were selected for high permeability and low formation factors for these initial measurements.

Since attenuation of the slow wave is known to be severe, we developed a method to prepare thin specimens by surface grinding with water coolant. With care it is possible to produce wafers as thin as 1-2 mm with a nominal diameter of 100 mm.

## EXPERIMENTAL METHODS

The samples are supported to be insonified by airborne pulses at normal incidence with the ultrasonic transducers arranged for pulse transmission. Components used to generate, detect and record the received signals are shown in Figure 1 and are standard for use in nondestructive evaluation. The transducers are designed for contact testing near 1 MHz, and so are very inefficient operating in air. As a result, system response is very broadband, allowing measurements from 30-500 kHz. Diffraction of the beam is unimportant for these conditions. The system is described in greater detail by Nagy et al., in press.

The new experimental technique used here has several advantages, although no particular effort was made to optimize generation efficiency or detection sensitivity. Airborne waves couple to the slow mode preferentially, because the impedance match is much more favorable than for the fast wave. High attenuation is circumvented by extensive signal averaging (up to $10^5$) samples, because the most troublesome correlated noise due to reverberating fast compressional waves has been greatly reduced by unfavorable mode conversion characteristics at the interface.

Air saturation is easy to achieve, avoiding the additional attenuation expected for partial saturation.

## RESULTS

Data are collected by placing the sample in the ultrasonic beam, and making direct comparison with a reference beam obtained for the same transducer positions with the sample removed. Averaged arrivals obtained at 150 kHz for the reference, sintered porous beads, Massillon sandstone and Berea sandstone are shown in Figure 2. Additional delays due to the sample are clearly resolved in the data. Measured slow wave velocities for the three samples are 215 <2.3>, 190 <3.0>, and 164 <4.0> m/s respectively. Values in brackets are acoustic tortuosities calculated from the observed velocities and a fluid velocity of ~332 m/s for the stiff frame limit.

Particular care was taken to insure that these arrivals are propagating slow waves. 1) Slight rotations of the sample delay the arrival. 2) Results obtained by us for the water saturated glass beads with Plona's technique agree with the air saturation results. 3) Water applied to the area of sample in the beam extinguishes the arrival, which reappears as the water evaporates.

After the tortuosity for a sample is known, we can better apply sensitive techniques designed to observe the Lamb mode (Xue et al. this meeting) to search for slow wave propagation in water saturated sandstone. We will present preliminary evidence that suggests the presence of the slow wave in the vicinity of the interface between water and water-saturated Berea sandstone.

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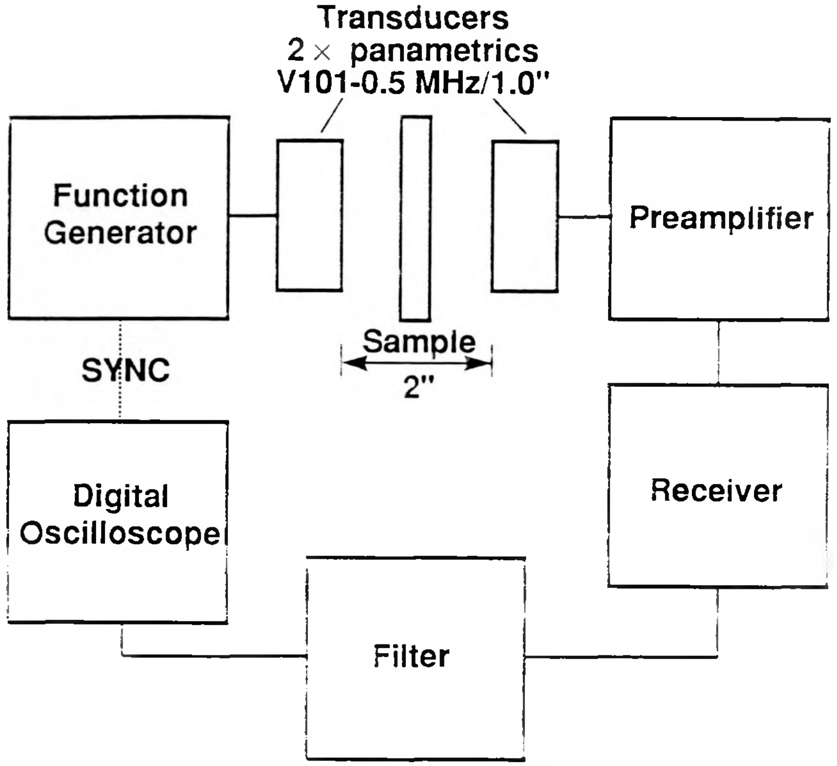
## Fig captions

Fig. 1. Block diagram of components for generating and detecting slow waves in air-saturated media.

Fig. 2. Reference beam (a) and transmitted signals through glass bead (b), Massillon (c), and Berea (d) samples.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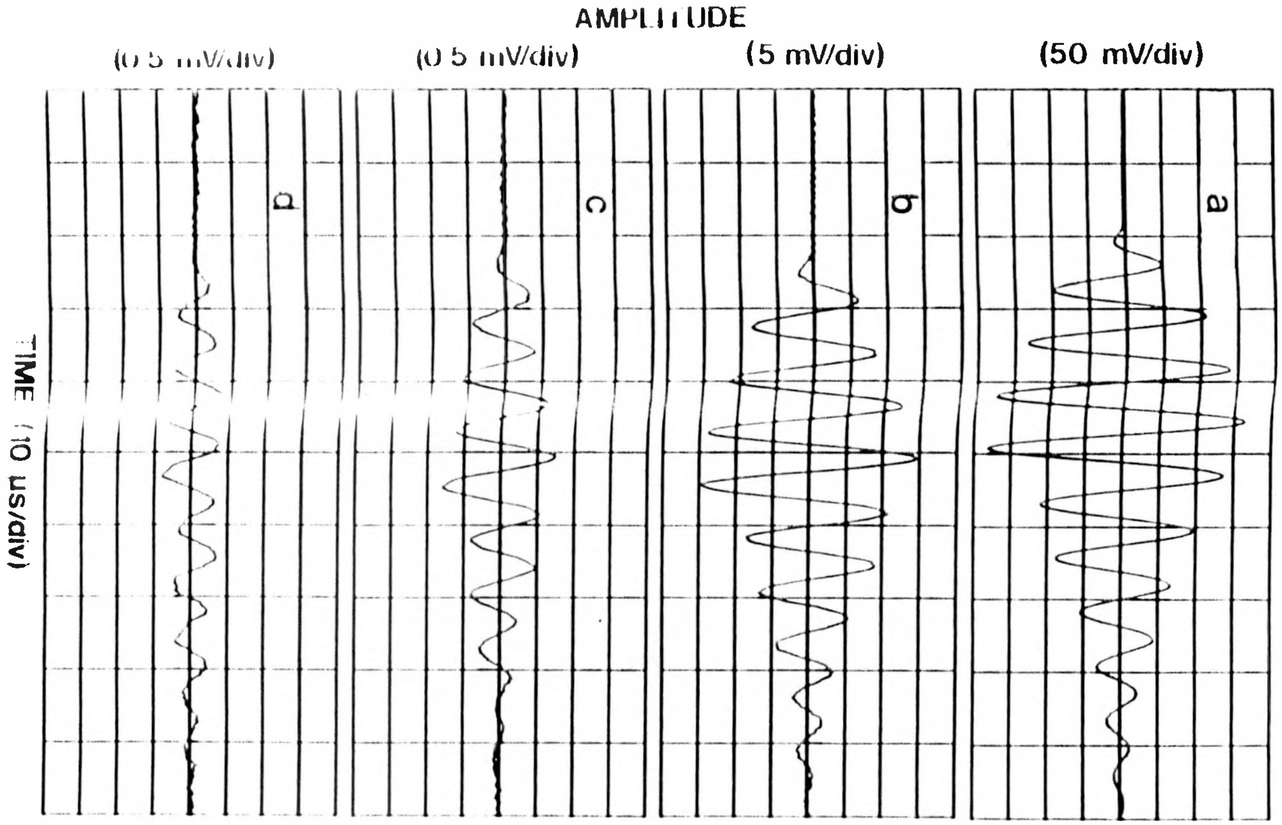
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