COMPRESSIONAL AND SHEAR WAVE VELOCITIES IN WATER FILLED ROCKS DURING WATER-STEAM TRANSITION

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ABSTRACT

Both compressional and shear wave velocities were measured in water-filled Berea sandstone as a function of pore pressure under a constant confining pressure of 200 bar. At 145.5°C, compressional velocity increased from steam-saturated (low pore pressure) to water-saturated (high pore pressure) rock, whereas shear wave velocity decreased. Furthermore, a velocity minimum, attenuation and dispersions occur at water-steam transition for compressional wave. Results at 198°C show that both compressional and shear velocities decrease from steam-saturated to water-saturated rock, and a small velocity minimum is observed for compressional waves, but no attenuation nor dispersion occur. At both temperatures, the V_p/V_s ratio and Poisson's ratio increased from steam-saturated to water-saturated rock.

The results are reasonably compatible with the mechanical effects of mixing steam and water in the pore space near the phase transition, and may be applicableto *in situ* geothermal field evaluation.

INTRODUCTION

One of the methods of exploration for geothermal resources is seismic surveying, including microearthquake studies, V_p/V_s ratios, and seismic wave attenuation.

However, few laboratory measurements of velocity of rocks at high temperature with hot water or steam have been made (e.g., Spencer and Nur, 1976). It is important therefore to extend our knowledge of velocities in water-filled rocks at high temperature with an emphasis of difference between the liquid (water) and gas (vapor) phase of pore fluid, which we have done in this study. Specifically, we have measured both compressional V_P and shear V_s velocities and wave amplitudes in porous rock at geothermal temperatures, as the water in the pores is converted to steam and steam to water, with particular attention to the effects of the phase transition itself. From the velocities, we also computed Poisson's ratio.

Experimental Procedure

The basic method used is the measurement of pulse travel time through rock samples with pore water. At fixed temperature, we vary the pore pressure P_P back and forth across the transition from steam (low P_P) to water (high P_P). The transition pressures for the temperatures used, 145.5°C and 189°C, were taken from Keenan et al., 1969.

Ultrasonic compressional and shear wave velocities and amplitudes were measured by the conventional pulse transmission method, with a mercury delay line as a reference. 1 MHz PZT ceramic transducers were used for generating compressional and shear waves.

Results

We measured both compressional and shear wave velocities at a constant confining pressure (300 bar) and temperature (19.5°C, 145.5°C, and 189°C) as a function of pore pressure. The pore pressure was changed from high pore pressure to low pore pressure (decreasing pore pressure cycle) and then increased again (increasing pore pressure cycle). Varying the pore pressure over the range of 7.0 bars in a saturated sample at 19.5°C produced almost no changes in either V_P or V_s.

In contrast, marked changes of velocities, Poisson's ratios, and wave amplitudes with changing pore pressure were observed at the higher temperatures of 145.5°C and 198°C. The results show:

(1) There is a minimum for compressional velocity at pore pressure of 4 bar (Fig. 2) which is very close to the water-vapor transition pressure of 4.212 bar at 145.5°C (Keenan et al., 1969). Below this pore pressure, water is in vapor phase (steam) and above the transition pressure it is in liquid phase. No minimum is observed for shear wave velocity (Fig. 3).

(2) Compressional wave velocity of steam-filled rock is lower than that of water-filled rock. Shear wave velocity in steam-filled rock is higher than that of water-filled rock.

(3) Poisson's ratio and V_p/V_s ratio calculated from compressional and shear wave velocities increase from steam-saturated to water-saturated rock, as shown in Fig. 4.

(4) We observe changes of wave amplitude vs pore pressure (Fig. 5 and Fig. 6). We notice a sharp drop in the compressional wave amplitude at the water-vapor transition, which is reproducible with pore pressure cycling. However, no minimum of shear wave amplitude is observed. In Fig. 5, the time intervals from first arrival to the first, second, and third peaks are plotted vs pore pressure with a large time interval corresponding to lower frequency of the wave. Again the water-steam transition, a peak time interval, was observed for compressional wave but not for shear wave. This suggests that high frequency components of the compressional wave are significantly more attenuated at the water-vapor transition.

Because attenuation depends so sensitively on many factors, and because the sample length is short, we cannot yet calculate exact Q values for these data. Nevertheless, it is obvious that attenuation and dispersion occur at the water-steam transition in our rock sample for compressional waves, but not for shear waves.

CONCLUSION

We have studied experimentally the nature of wave propagation in steam-, water-, and mixture-saturated sandstone. The results show that the P wave velocity is abnormally low in the phase transition region at 145°C and 198°C, whereas the shear velocity has no minimum there. Poisson's ratio undergoes a marked increase upon the transition from the steam-saturated to water-saturated state. The amplitude of the P wave at 145°C also has a strong minimum at the transition region, whereas the S amplitude does not.

All these results can be explained by the effects of a mixture of steam, vapor, and water in the pores at the transition conditions: for a few percent steam, the density of the mixture is relatively high, similar to water, whereas the bulk modulus, $\overline{K}$, is low, similar to steam. The shear velocity, which is insensitive to the bulk modulus of the fluid inclusion, is therefore barely influenced, whereas the compressional velocity is sensitive to $\overline{K}$, and thus undergoes a measurable change. Furthermore, the large relative P attenuation at the transition is probably due to local flow in the partially saturated state.

The results of this study suggest that in situ interfaces between steam and hot water, if they exist, may be recognizable using the seismic method. Furthermore, regions with both steam and hot water should exhibit anomalous low velocity and high attenuation of P waves, but not of S waves. Furthermore, Poisson's ratio is, as expected, a good discriminator between steam and hot water in the pore space and may be a useful tool, as suggested in previous work (e.g., Combs and Rotstein, 1976) on the basis of room temperature measurements. The data presented here demonstrate that the conclusion is valid also at temperatures anticipated in a geothermal area.

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TABLE 1

Physical Properties of Berea Sandstone

grain density	2.66	*
total porosity	18.9%	*
	18.75%	**
crack porosity	0.25%	**
pore porosity	18.50%	**
water permeability	160 md	**

* present measurement

** Zoback

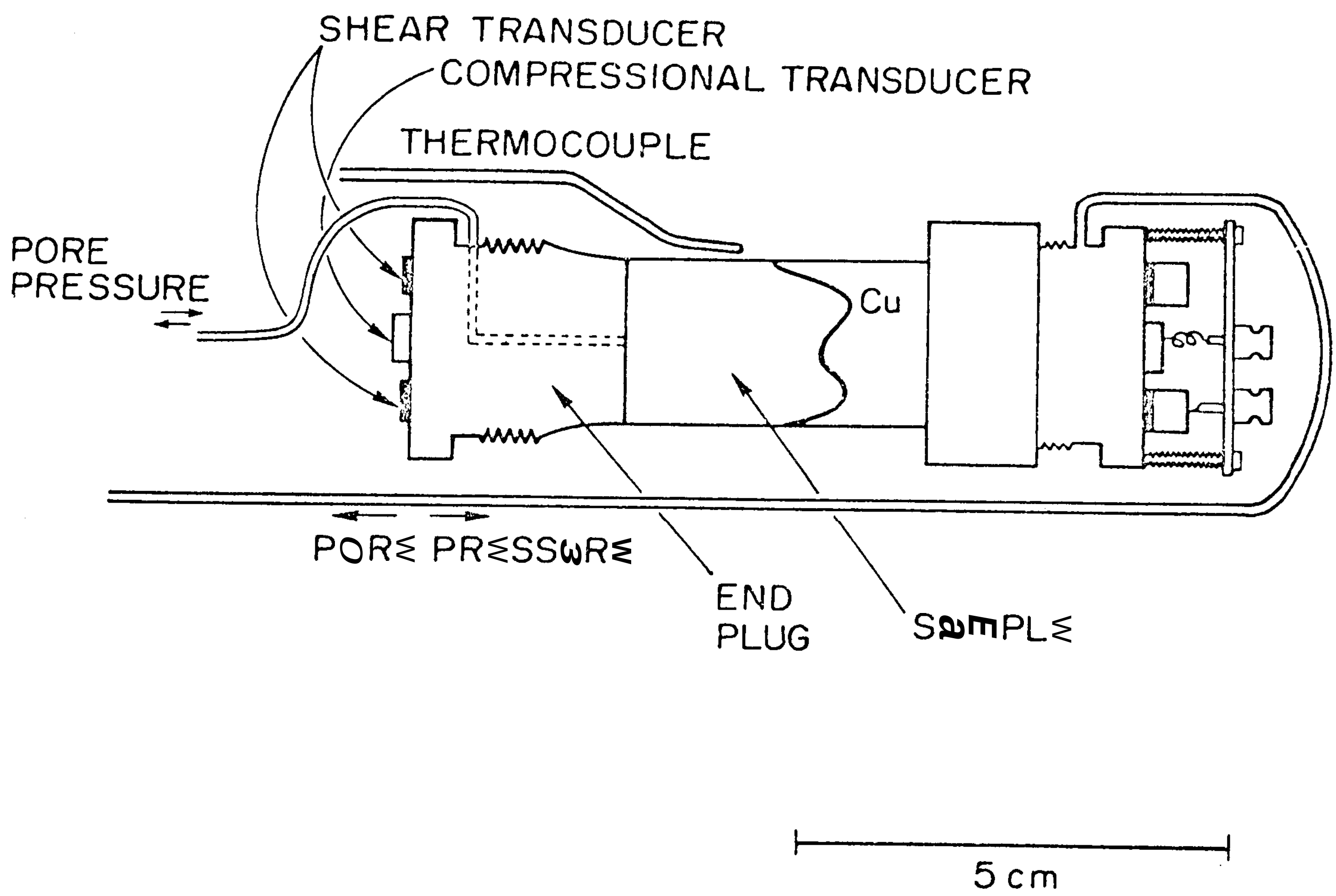

FIGURE 1. SCHEMATIC DIAGRAM AT SAMPLE ASSEMBLY

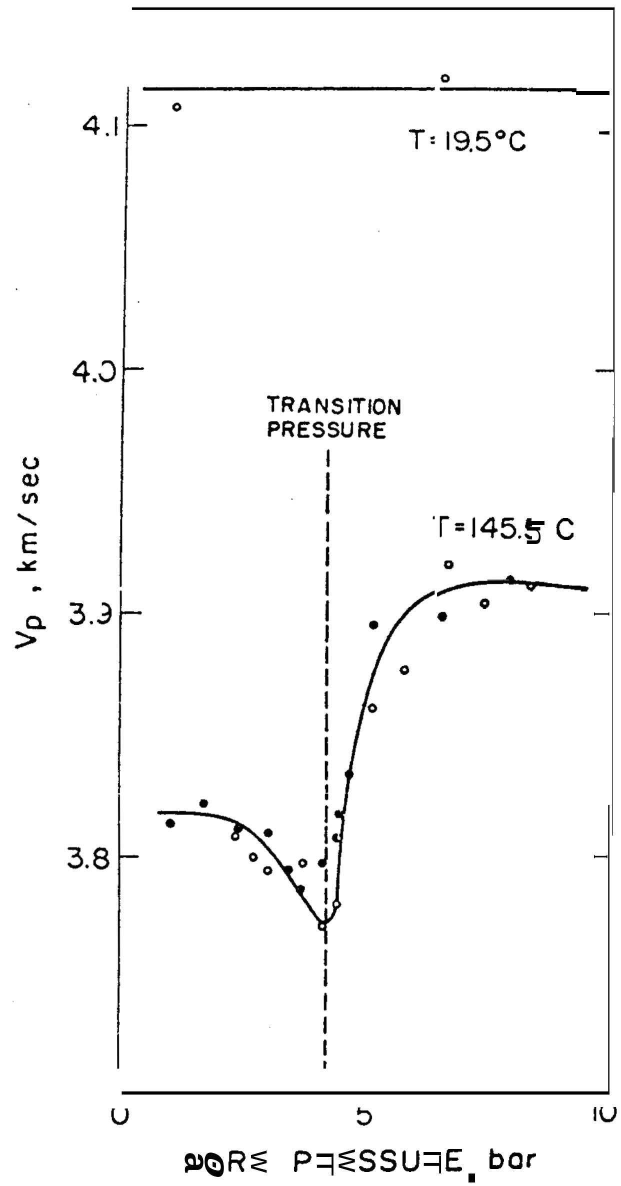

FIG. 2. Compressional wave velocity V_p vs pore pressure at 19.5°C and 145.5°C. Open circles show the data during decreasing pore pressure cycle, closed circles show the velocities during increasing pore pressure cycle. Saturation pressure at 145.5°C is also shown.

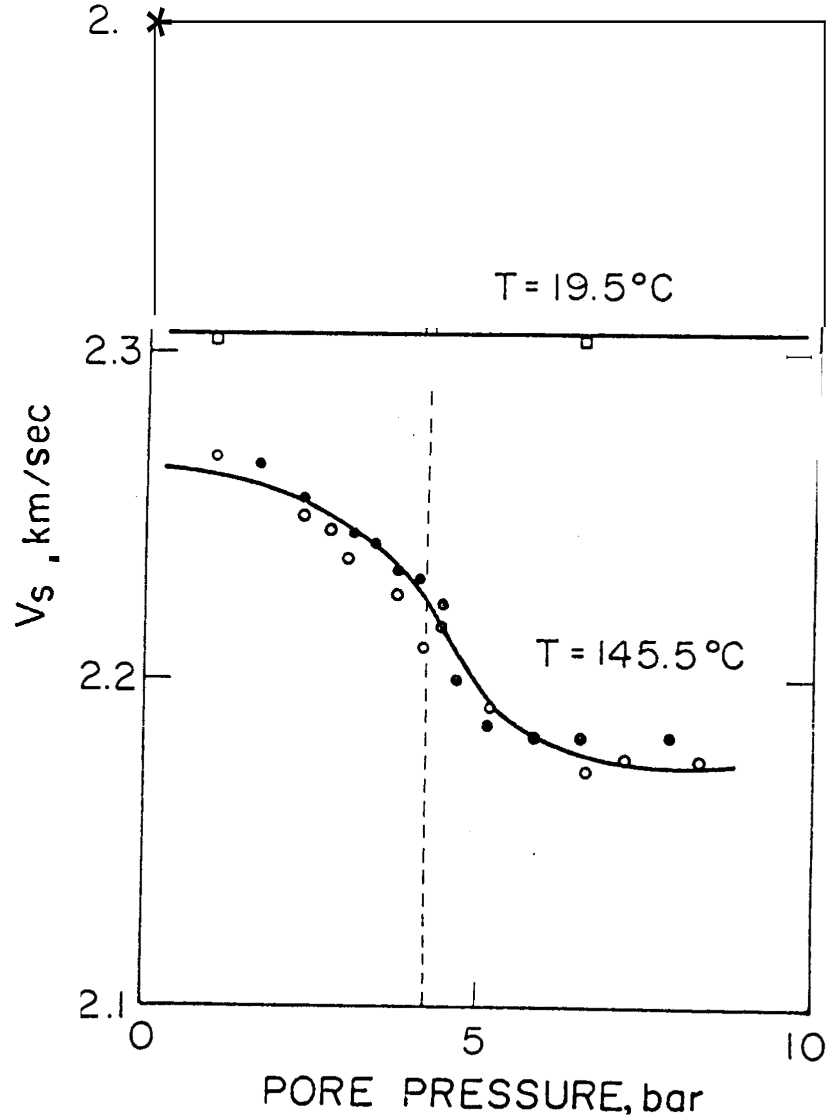

FIGURE 3. Shear wave velocity V_s vs pore pressure at 19.5°C and 145.5°C.

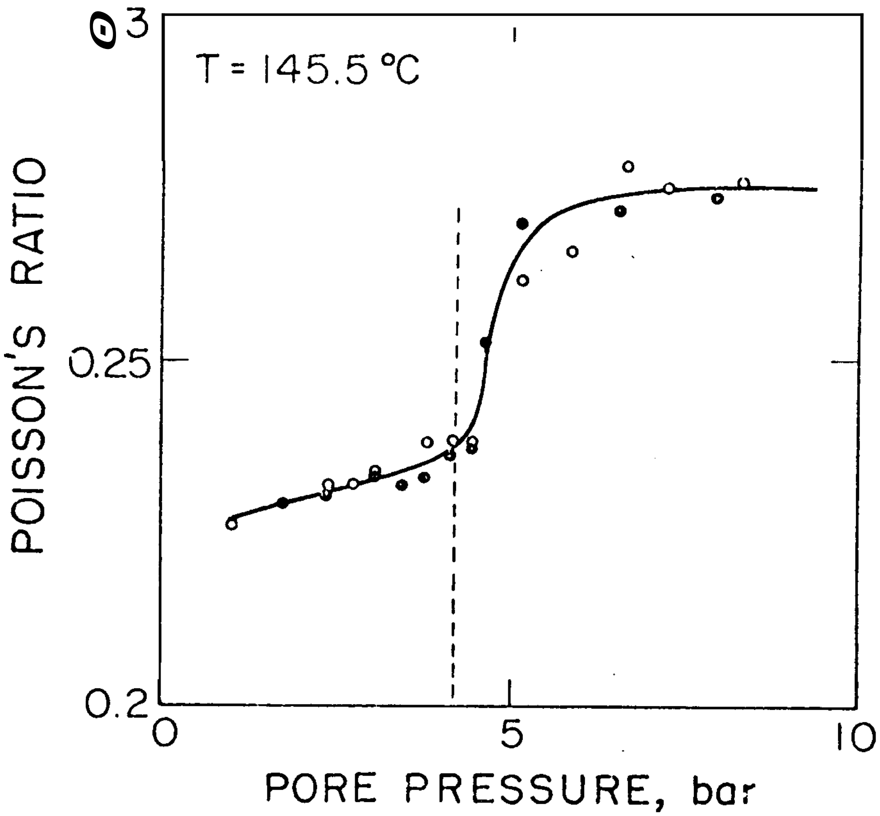

FIGURE 4. Poisson's ratio vs pore pressure calculated from compressional and shear wave velocities at 145.5°C.

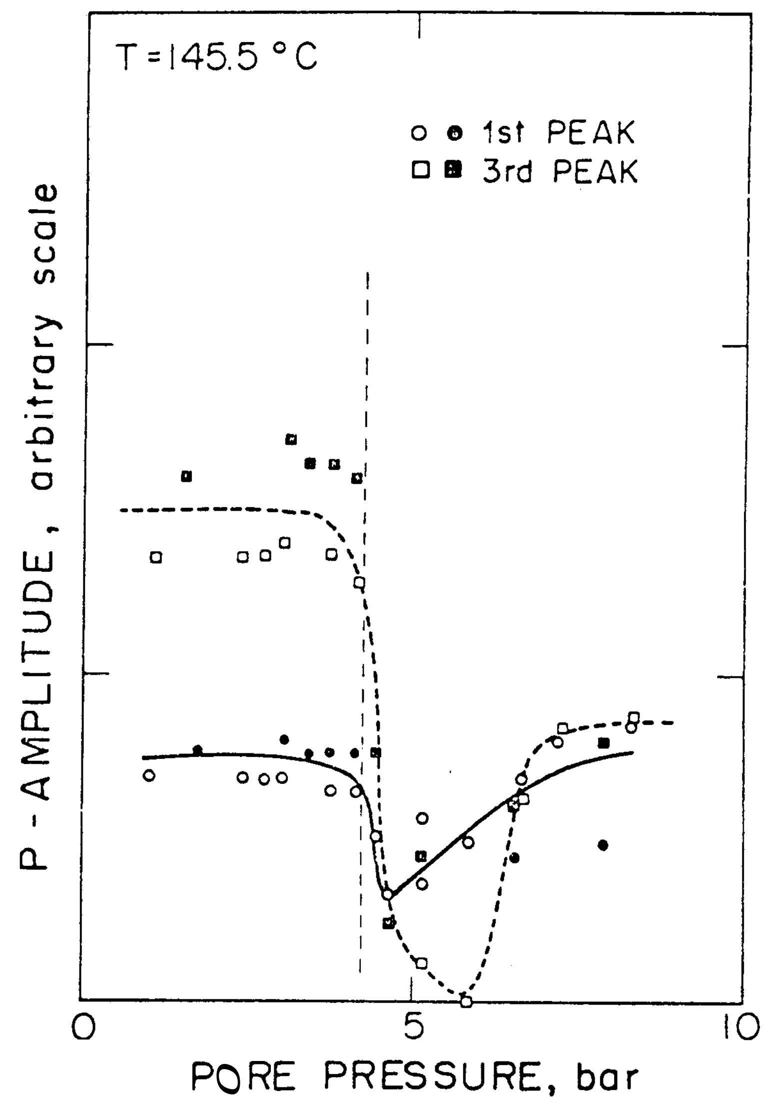

FIGURE 5 V_p/V_s ratio vs pore pressure at 1 5°C

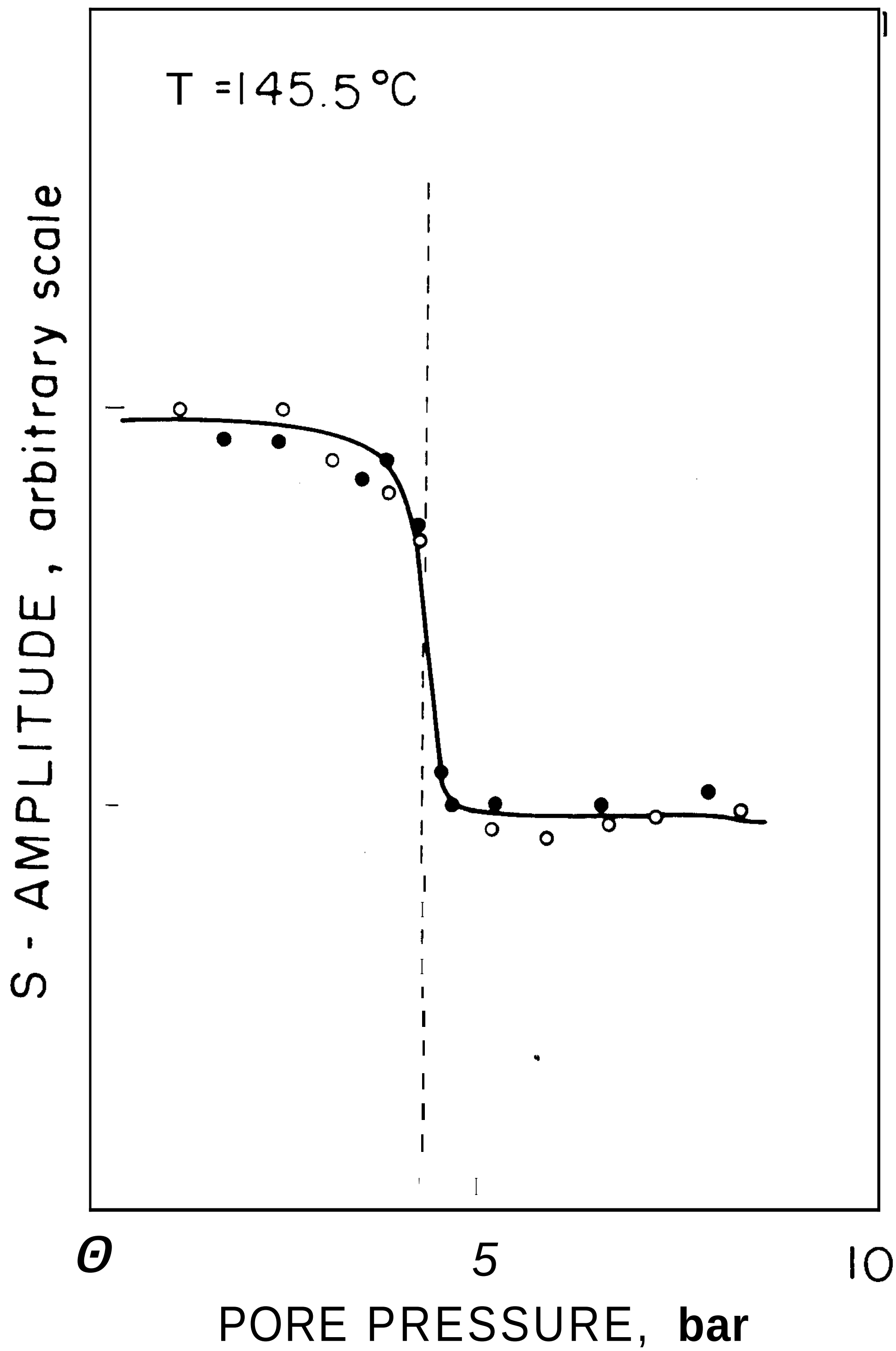

FIGURE 6. **Peak amplitude (first and third) of compressional wave vs pore pressure at 145.5°C.**