EFFECTS OF TEMPERATURE AND SATURATION ON THE VELOCITY AND ATTENUATION OF SEISMIC WAVES IN ROCKS: APPLICATIONS TO GEOTHERMAL RESERVOIR EVALUATION

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INTRODUCTION

In the evaluation of a geothermal resource it is critical to know the reservoir geometry, temperature, saturation, state of saturants, pore pressure, porosity and permeability. These are the parameters which will determine the production feasibility and cost effectivness of a geothermal prospect. The increasing sophistication of seismic wave data collection and processing and recent exerimental work on factors governing wave propagation in rocks has stimulated increased interest in the use of active seismic techniques to determine the in situ physical state of crustal rocks for engineering applications. In this paper we review experimental work showing how wave velocities in rocks are sensitive to parameters of interest to geothermal exploration; effective pressure, the degree of water saturation of the pores, and the bulk modulus of the pore phase. Seismic attenuation is even more sensitive to the degree of saturation and the microgeometry of the pores. Both velocity and attenuation are strongly temperature dependent and reflect thermal fracturing of the rocks at elevated temperatures. By combining data on attenuation and velocity of compressional and shear waves considerably greater constraints may be placed on the environmental state of the rocks than on the basis of P velocities alone.

WAVE PROPAGATION IN ROCKS

It is now well known that the major factor governing wave propagation in rocks is the presence of small interconnected pores and cracks within the rock. Seismic wave velocities depend on the elastic moduli and the density of the rock, and the presence of pores may alter these parameters. All pores in rock tend to lower the effective moduli and hence lower the velocity, but long narrow pores are much more effective in softening the rock than equidimensional ones. The dissipation factor Q^{-1} of seismic waves, defined as the fractional energy loss per wave cycle, is generally controlled by the interaction of the dynamic strain wave in the rock with fluids and/or gasses contained in the pores which irreversibly dissipate energy from the wave. As the presence of pores is the most important factor controlling wave propagation in rocks, most features of wave propagation are relatively insensitive to lithology but very sensitive to the environmental conditions of the rock.

As an example the dependence of compressional (V_p) and shear (V_s) wave velocites in Berea sandstone (porosity 20%) on effective pressure and saturation is shown in Figure 1. The results indicate that pore pressure is roughly as effective in lowering velocity as confining pressure is in raising it. Both V_p and V_s increase rapidly with effective pressure at low pressure due to the closing of thin microcracks. Above about 200 bars velocities increase more slowly with pressure as most of the small aspect ratio pores have been closed. V_p is greater in fully saturated rocks than dry rocks as the fluid filled pores makes the rock stiffer in bulk compression. The shear wave velocity in contrast does not depend on the bulk modulus, only the shear modulus, and as the shear modulus of fluid is zero, saturating the pores does not increase the effective shear modulus of the sample; rather it increases its effective density and lowers the velocity. Thus when both V_p and V_s are known we may distinguish between fully saturated and dry or partially saturated rocks. This effect is particularly apparent in the velocity ratios, or Poisson's ratio (Figure 2): Dry rocks have lower ratios than saturated rocks, and for the saturated samples the ratio depends on the type of fluid present. Because steam has a much lower bulk modulus than water a steam saturated sample would behave more like a dry rock, even if small amounts of water were present. The saturation effect is present at elevated pressures.

Figures 3 and 4 show in more detail the dependence of extensional waves, a combination of pure shear and bulk compression, and shear waves on water saturation S_w. Over most of the saturation range velocities are insensitive to S_w. At $S_w < 1\%$ velocities increase rapidly with decreasing saturation. Small amounts of water weaken the rock, possibly due to chemical reactions of the water with grain boundaries. There is a small negative slope over the intermediate saturation range due to the increased effective density as the pores fill with fluids. At S_w of 95% the extensional velocities increase rapidly as the pores are becoming completely filled with water which stiffens the rock in bulk compression. There is no effect on shear, which again shows how V_p/V_s may be diagnostic of the change from fully to partially saturated rocks. Figure 4 shows that attenuation is much more sensitive to the degree of saturation than velocities. At low saturations attenuation is very low. Adding small amounts of water to completely dry rock increases attenuation drastically, to a peak at $S_w \sim 1\%$. At S_w from 2% to about 50% attenuation is roughly constant. At $S_w = 60\%$ the extensional attenuation begins to increase with further saturation due to the motion of fluid in pores which dissipate energy from the passing wave. This occurs mostly in bulk compression, hence the higher attenuation of extensional waves. In a fully saturated rock pressure induced flow within pores ceases, whereas shear induced flow between interconnected pores is maximized. At $S_w \approx 85\%$ the extensional attenuation begins to decrease and shear attenuation increases and they cross over at about 98% saturation.

WAVE ATTENUATION

Figures 5 and 6 show the dependence of compressional and shear wave attenuation on pressure and saturation in Massilon sandstone. Increasing pressure closes pores and decreases attenuation. Again attenuation is very low in dry rocks whereas in partially saturated rocks ($S_w \approx 95\%$) attenuation is significant probably due to intra-crack fluid flow, with P attenuation about twice as large as S. In fully saturated rock, intercrack flow is eliminated, Q_p^{-1} is sharply lowered and again shear attenuation due to intercrack fluid flow is maximized. Figure 7 illustrates schematically how the change from partial to full saturation changes the types of pore fluid flow induced by passing strain waves which may occur within rocks and hence changes the relative amounts of attenuation in compression and shear.

In fully saturated rocks first order intercrack flow may occur only in shear, not in compression. Since the P wave is strongly affected by bulk compression it is less attenuated than an S wave. In partially saturated rock flow will occur within all pores, induced by bulk compression; whereas shear induces flow only in properly oriented pores. Consequently S attenuation is less than P. In rocks containing no liquid phase, no flow occurs and attenuation is low for all waves. Hence, the ratio of P to S attenuation may allow us to distinguish between a partially saturated and dry or fully satruated rocks.

These results suggest that we may estimate parital saturation solely from seismic data as illustrated in Figure 8, showing P and S attenuation ratios vs. P to S velocity ratios for sandstone and granite. Data for rocks separate readily into 3 fields depending on saturation: Fully saturated rocks are distinguished from dry and partially saturated rocks due to their higher V_p/V_s. Partially saturated rocks have higher P attenuation/S attenuation.

Another parameter of great ineterst in geothermal applications is temperature. Figure 9 shows extensional and shear velocities in a room dry Berea sandstone. Velocities increase rapidly with temperature intially due to drying. At about 160°C thermal fracturing becomes dominant causing the velocities to decrease rapidly at higher temperatures. After cooling, the sample's velocities were lower than the initial values due to the permanent thermal fracturing. Also Q first increases with temperature again due to drying (Figure 10), with a peak again at about 160°C, and with marked decrease at higher temperature due to thermal fracturing. The Q_s/Q_e ratio increases with temperature.

TWO PHASE SATURATION

Figures 11 and 12 show velocity and attenuation data at elevated temperatures and two phase saturation in Berea sandstone, Massilon sandstone, and a thermally fractured Westerly granite all taken at 150°C and 100 bars confining pressure. The velocities were measured as the pore pressure was varied to transform water to steam and back. V_p is lower in a steam saturated rock than in water saturared rock due to the lower bulk modulus of steam. In shear the behavior is more complicated. For the Berea sandstone

V_s is greater in steam saturated rock than water saturated rock due to the density effect. In granite V_s is lower in steam saturated rock than water saturated rock, caused by the stiffening of cracks with water at the high frequences used in this experiment (1MHz). At the phase transition V_p goes through a minimum: A small amount of steam lowers the bulk modulus and sufficient water is present to raise the effective density and further lower the velocities.

Amplitudes plotted in Figure 12 provides a relative measure of attenuation. In both shear and compression, attenuation is much lower in steam saturated rock than water saturated rock. A maximum occurs in P attenuation but not in S attenuation at the phase transition where the rock is partially saturated. This is due again to intercrack flow of water which occurs mainly in bulk compression.

The examples show how velocity and attenuation may be diagnostic of whether a geothermal system contains water, steam or both. An example of field data (from McEvilly, et al., 1978) which may be interpreted on the basis of our experimental work is shown in Figure 13. Several seismic records are shown from a distant earthquake recorded over the La Primavera geothermal system in Mexico. Stations on the bottom were located outside the Caldera and show typical well developed P and S arrivals. Stations on top were located inside the caldera and they show marked changes obvious even on this unprocessed data. This is particularly evident on the third trace down. P waves are severely attenuated relative to S waves as can be seen from the smaller amplitudes and the depletion of high frequencies. As demonstrated from previously discussed experimental work, high P attenuation relative to S attenuation is diagnostic of a partially saturated rock. This may be confirmed in the field in this case as this station is located immediately adjacent to a steam vent, indicating a mixture of water and steam are present at depth.

REFERENCES

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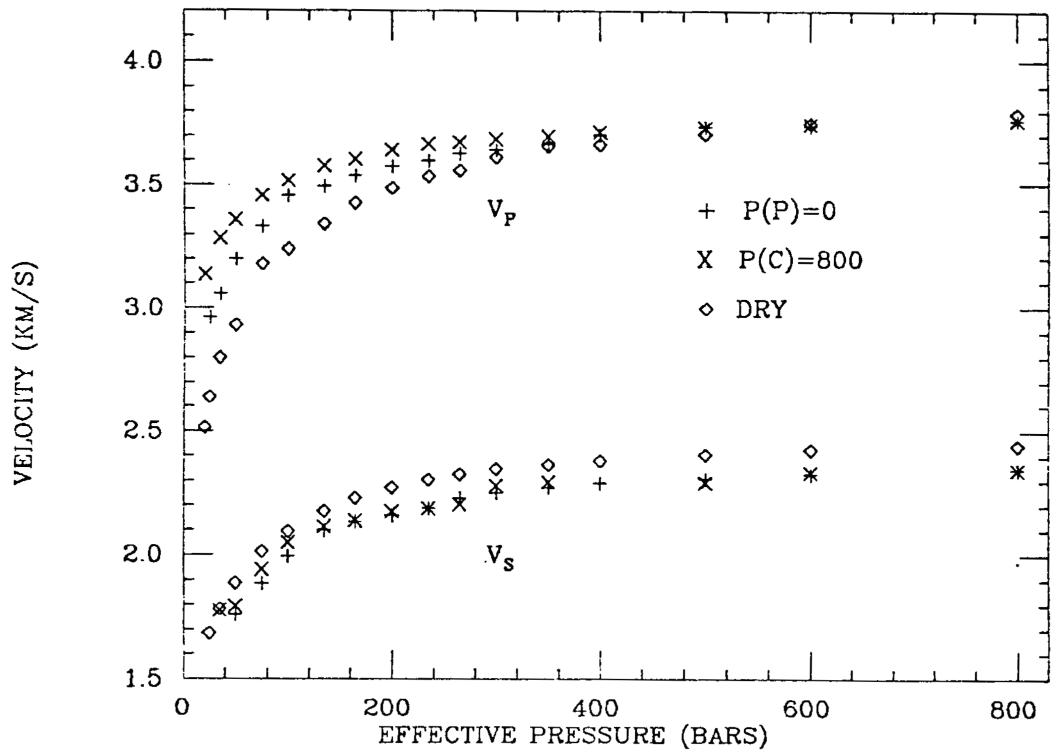


FIGURE 1

Velocity vs. Pressure and Saturation in Berea Sandstone

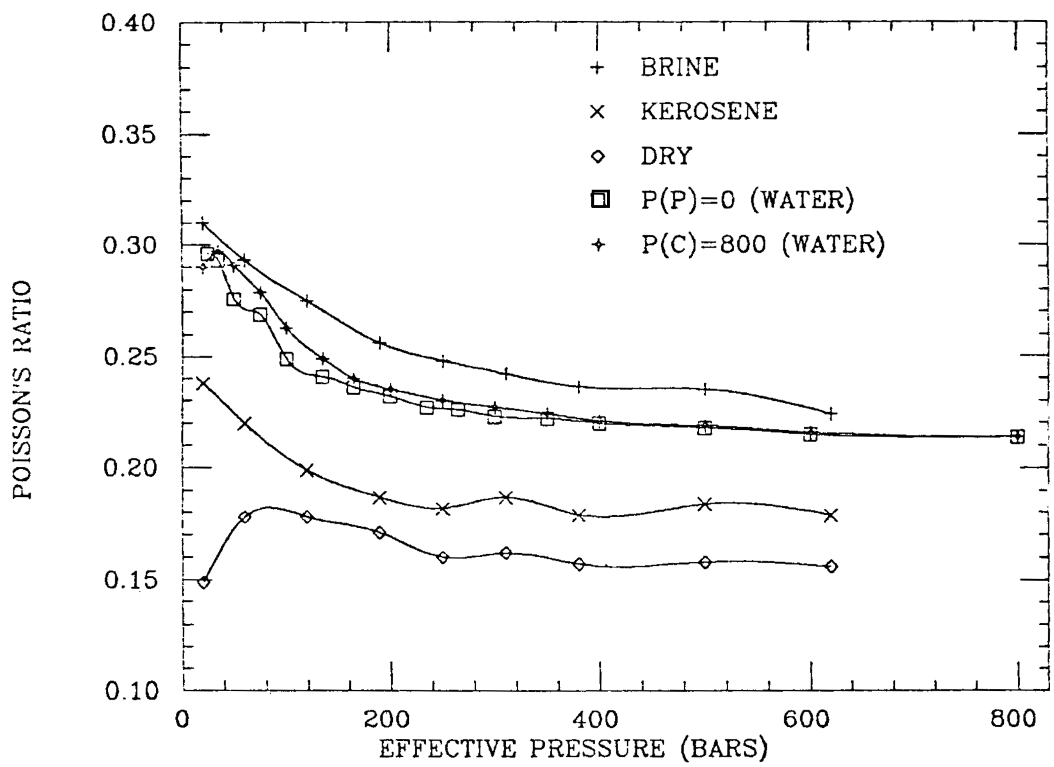


FIGURE 2

Poisson's Ratio vs. Pressure and Saturation in Berea Sandstone

FIGURE 3

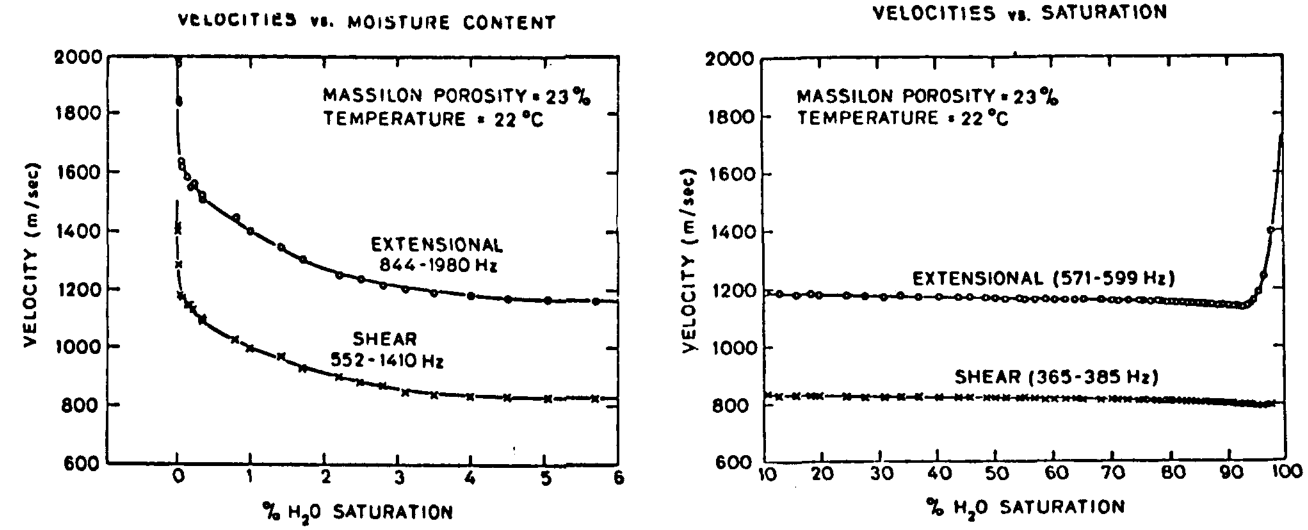


FIGURE 4

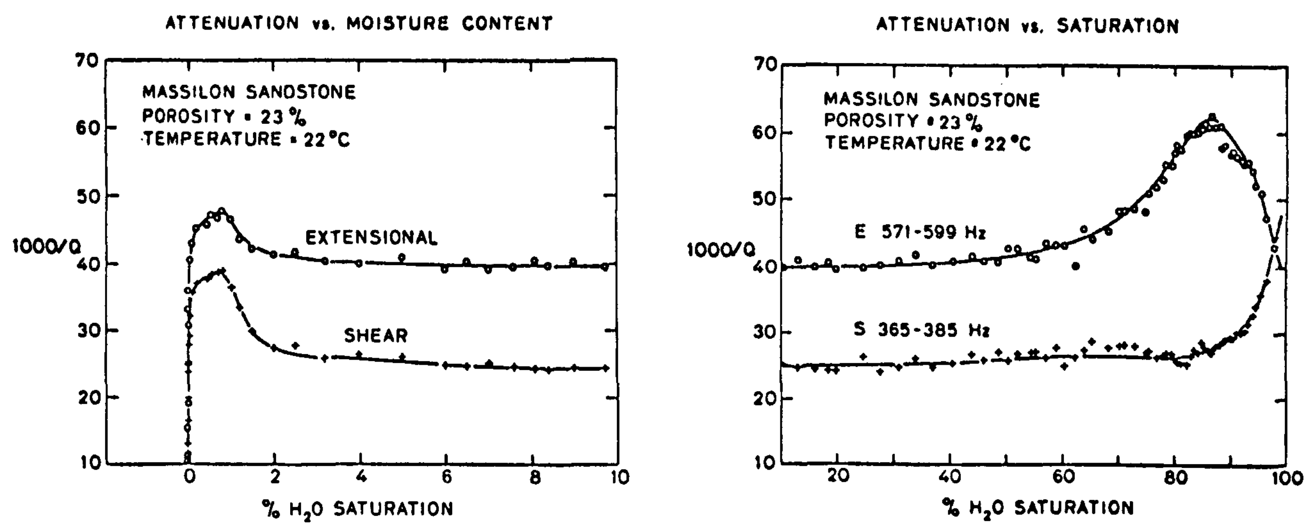
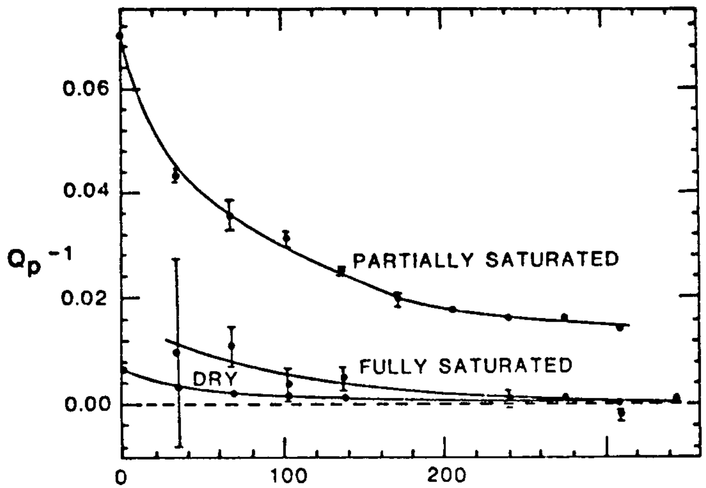


Figure 5



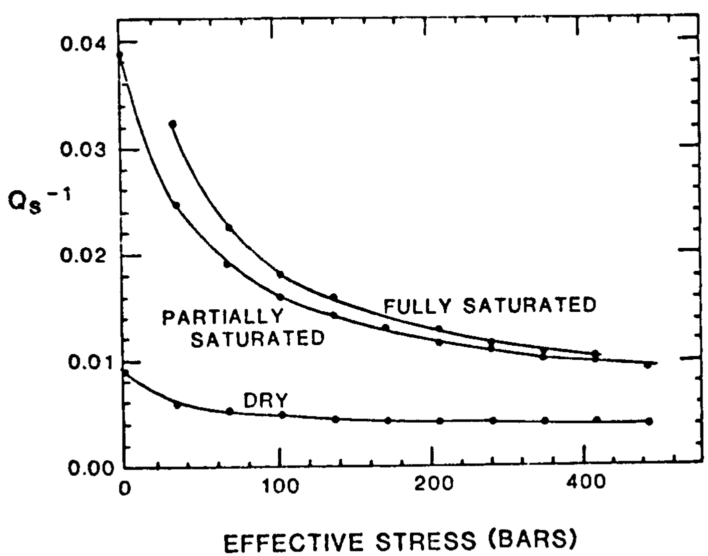


Figure 6
Attenuation vs Pressure and Saturation in Massilon Sandstone

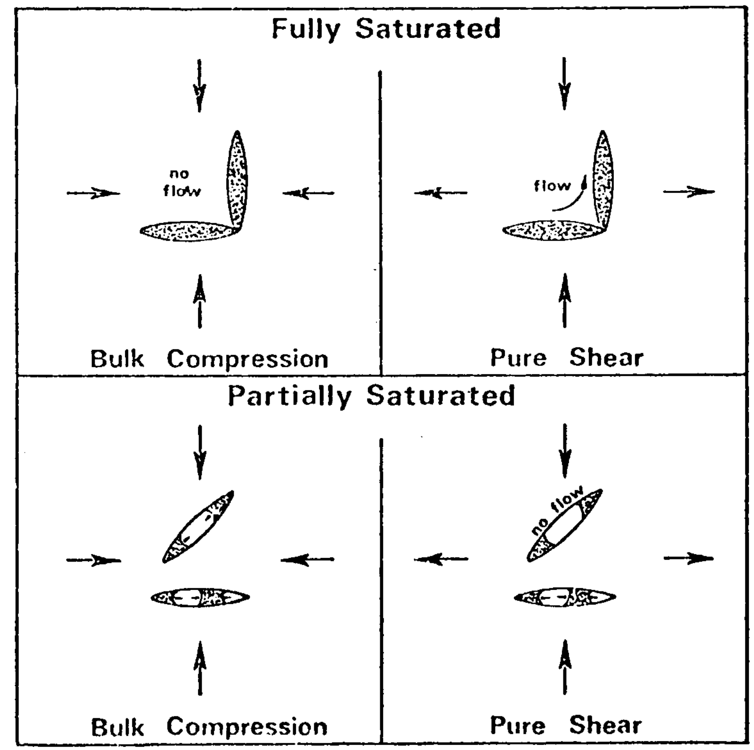


Figure 7 Fluid Flow Mechanisms in Porous Rocks

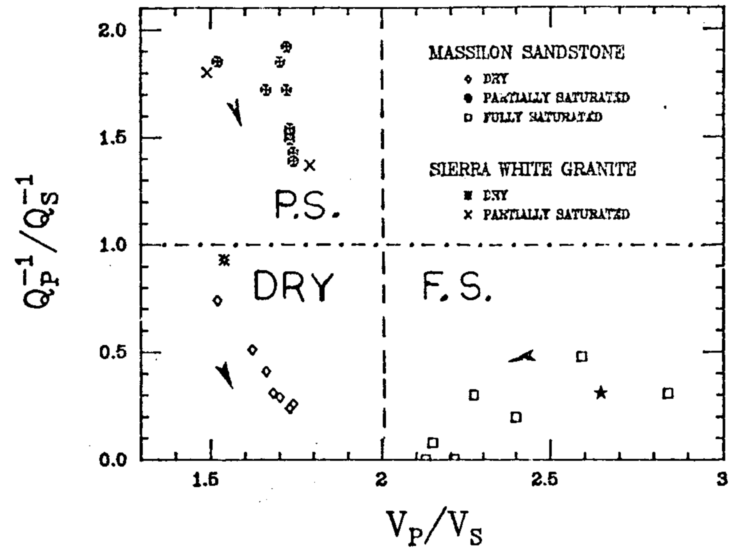


Figure 8.

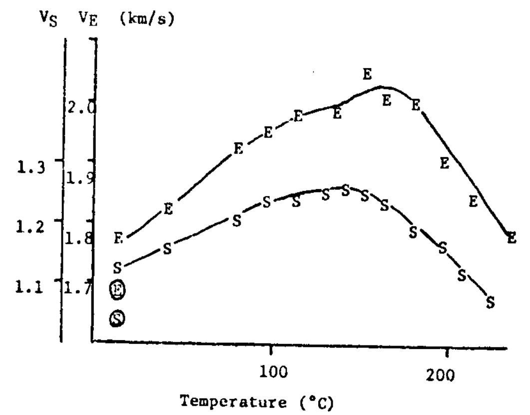


Figure 9 Velocity of E and S waves vs. temperature.

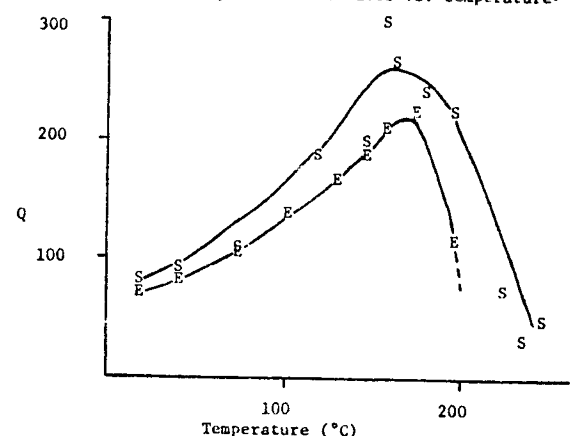


Figure 10 Attenuation of E and S waves vs. temperature.

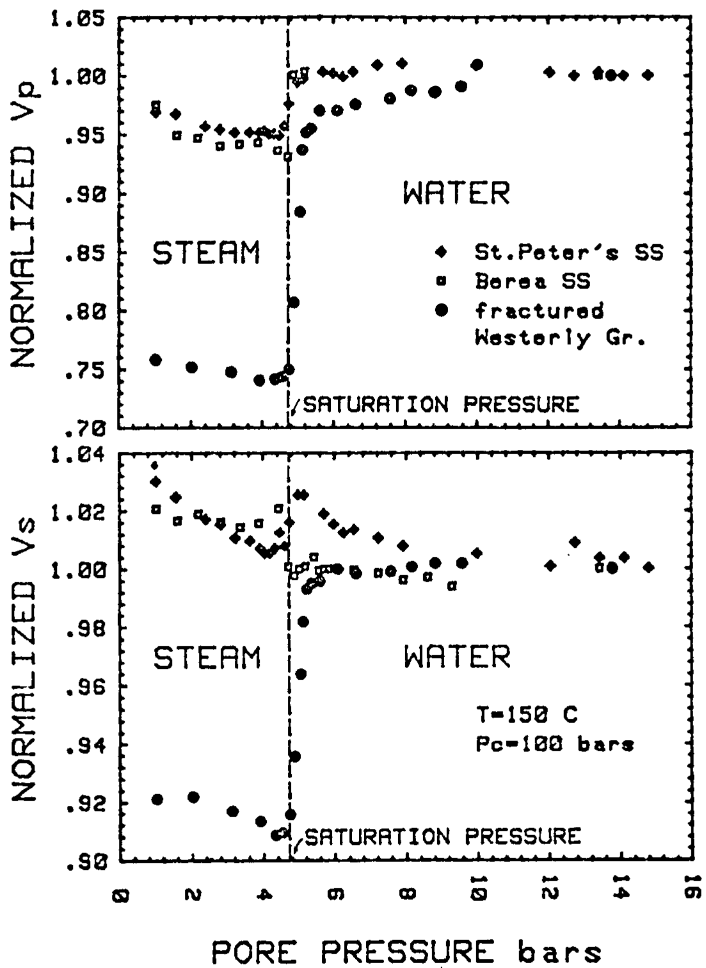


Figure 11

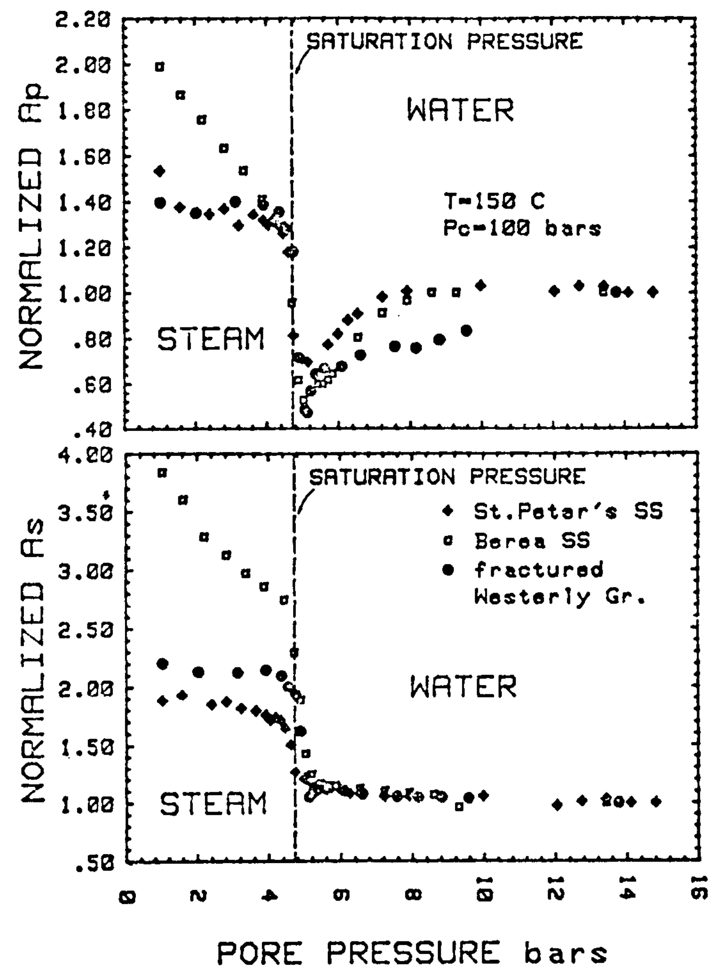


Figure 12

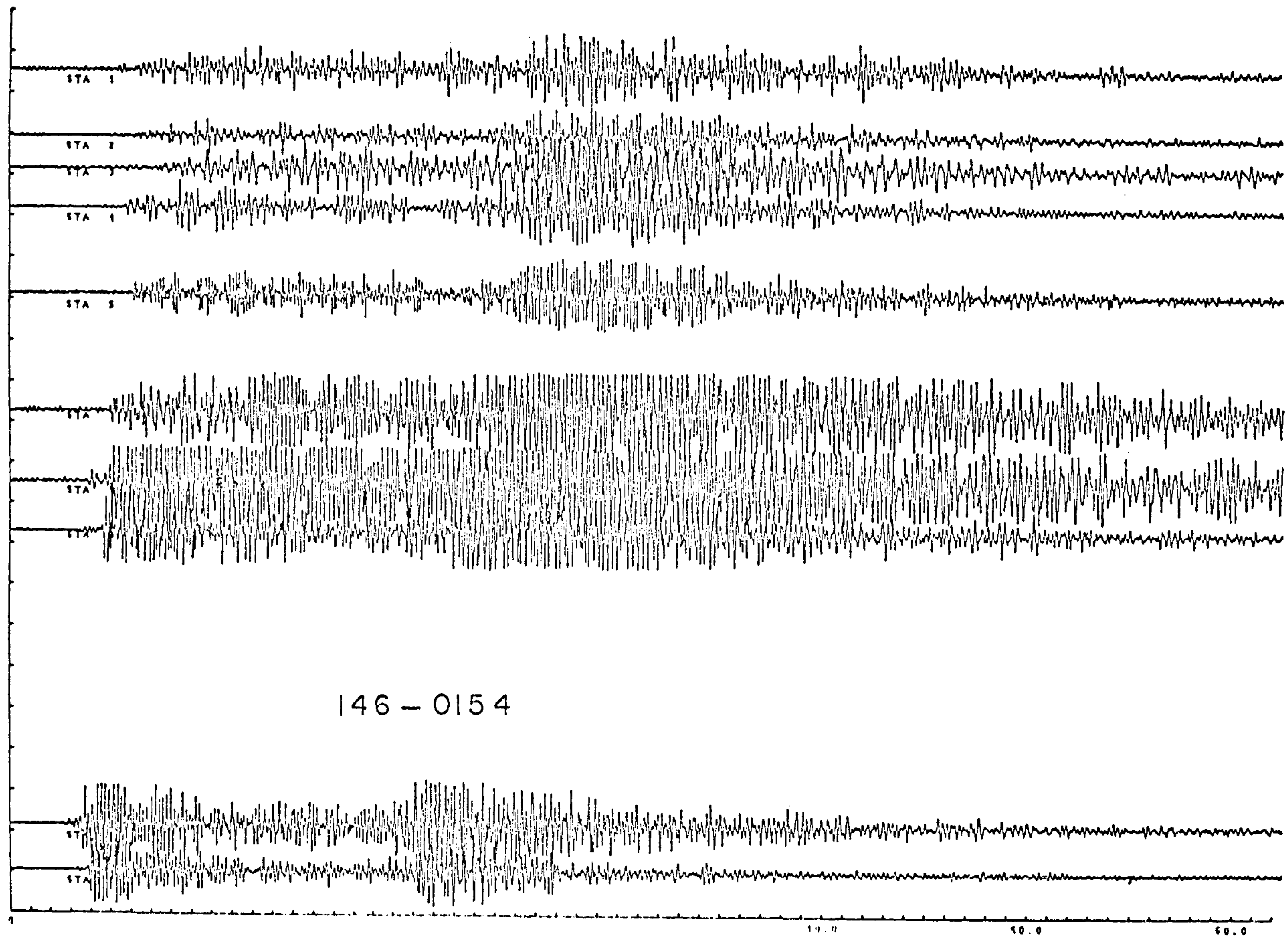


Figure 13. Seismic Records from Distant Earthquake Recorded over the La Primavera Caldera in Mexico. From McEvilly et al (1978).