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CHARACTERIZATION OF ROCK FOR CONSTRAINING RESERVOIR SCALE TOMOGRAPHY AT THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

A suite of laboratory measurements are being conducted on Geysers graywacke recovered from a drilled depth of 2599 meters in NEGU-17. The tests are being conducted to characterize the effect of pressure and fluid saturation on the seismic properties of the graywacke matrix. The measurements indicate that the graywacke is an unusual rock in many respects. Both compressional and shear velocities exhibit relatively little change with pressure. Water saturation causes a slight increase in the compressional velocity, quantitatively consistent with predictions from the Biot-Gassmann equations. Shear velocity decreases with water saturation by an amount greater than that predicted by the Biot-Gassmann equations. This decrease is attributed to chemo-mechanical weakening caused by the presence of water. Measurements of Q_s from torsion experiments on room dry samples at seismic frequencies indicate unusually high Q_s ($\approx$500). Water saturation decreases the shear modulus by 12 percent, again indicative of chemo-mechanical weakening. Q_s is lower for the water saturated condition, but still relatively high for rock at low stress. Results of ultrasonic pulse propagation experiments on partially saturated samples are typical of low porosity rocks, being characterized by a monotonic decrease in compressional and shear velocity with decrease in saturation. An increase in shear velocity and low frequency shear modulus after vacuum drying indicates the presence of chemo-mechanical weakening resulting from the presence of small amounts of water.

I. INTRODUCTION

Field seismic imaging experiments at the Geysers have indicated velocity, V_p/V_s, and attenuation anomalies associated with the dry stream reservoir [*O'Connell and Johnson*, 1991; *Zucca et al.*, 1994]. They observe an increase in compressional velocity and decrease in Q_p with depth below the dry steam reservoir and suggest that they reflect changes in the degree of fluid saturation associated with the water/steam transition. However, this interpretation of the field seismic results has been hampered by a lack of knowledge of the physical properties of the reservoir rocks. Of particular interest is whether the observed variations of the field scale velocity and attenuation can be explained by the intrinsic properties of the matrix and its sensitivity to the degree of fluid saturation.

There are four phenomena typically assumed to be important in controlling the effect of saturation on velocities of rock. These can be summarized briefly as follows:

- **Local-Flow:** unrelaxed fluid in thin pore spaces and/or at grain contacts produces a frequency dependence on the measured velocity (see for discussion *Mavko and Jizba* [1991]). The presence of local-flow causes a visco-elastic like rheology exhibiting both velocity dispersion and attenuation. This effect is strongest at low effective pressures due to the increased compliance of and grain contacts and pores. The frequency band over which local-flow causes dispersion is largely unknown, however it is typically thought to be in the kHz to MHz range for most rocks.
- **Frame Weakening:** The presence of aqueous solutions in the pore space interacts with the rock matrix and alters the mechanical properties of the bulk material. Chemo-mechanical weakening of quartz and other minerals by the presence of water is well known and thus velocities measured under water saturated conditions should be lower than predictions based on the velocities of dry samples.
- **"Biot" effects:** the bulk modulus of the pore fluid acts to stiffen the pores to the deformation of the compressional wave, thus increasing the compressional velocity (see for discussion *Biot,* [1956a,b]). There is no similar effect on the shear modulus.
- **Density effects:** the addition of the pore fluid increases the bulk density of the material, thus decreasing both the compressional and shear velocities for a given set of elastic moduli.

The "Biot" and density effects combined constitute the Biot-Gassmann equations (see *Murphy*, [1982], *Winkler*, [1985]), which are commonly used for predicting the effects of fluid saturation on velocities at seismic frequencies. The experiments presented here are designed to determine which effects are active under various conditions of pressure, saturation, and frequency.

II. ULTRASONIC VELOCITIES

A variety of ultrasonic pulse propagation experiments have been conducted on three samples of core from reservoir graywacke in the northeast Geysers (NEGU-17: drilled depth 2599 *m*). One plug was cored parallel (denoted X) and the other two cored perpendicular (Y1 and Y2) to the axis of the borehole. Identical tests were performed on Berea sandstone and Westerly granite for comparison, since measurements on Westerly and Berea have been used to infer seismic properties of geothermal areas [*Ito et al.,* 1979; *DeVilbiss,* 1980].

Each sample was nominally 1 inch in diameter and 1 inch long. Porosity was measured on the intact plugs using an He^2 gas pycnometer after drying in a vacuum at 80 C. The results are summarized in Table 1, illustrating that the graywacke exhibits very little porosity. The variation between the three samples reflects the fact that samples Y1 and Y2 contain veins with associated vugs and pores, while sample X was free of visible veins (see *Gunderson,* [1990] for a discussion of the porosity distribution in similar rocks). Included in Table 1 is the weight gain per unit volume after saturation with distilled water. For the NEGU-17 samples, each sample appears to have adsorbed more water than would be expected based on the pycnometer results (consistently by an amount of 9 mg/cc). This may be indicative of water absorbing minerals, however the pycnometer results should be viewed as preliminary and must be reproduced to make sure that very tight porosity (requiring unusually long pressure equilibration times) was not missed in the pycnometer results reported here.

TABLE 1

Rock Type	Sample	Porosity	Grain Density	Weight Gain
		%	g/cc	g/cc
NEGU-17	X	0.11	2.666	0.010
NEGU-17	Y1	0.93	2.659	0.018
NEGU-17	Y2	0.90	2.668	0.018
Westerly	wd1	1.0*	2.680	0.010
Berea	bd1	20.67	2.690	0.191
Berea	bd2	20.24	2.686	0.202

* assumed based on published data.

Compressional and shear ultrasonic velocities were measured as a function of confining pressure from 2 to 90 MPa. The results are summarized in Figure 1. Along with the dry and saturated ultrasonic velocities, the predicted velocities based on Biot-Gassmann equations are given for reference. Note that NEGU-17 sample exhibits different behavior from both Berea and Westerly in a number of ways.

In Berea, all four mechanisms listed above are thought to contribute to differences in dry and saturated velocities. The Biot-Gassmann effect appears to explain roughly half of the difference between dry and saturated compressional velocities. The rest is typically attributed to local-flow, although we should not ignore the presence of frame weakening. For shear, the saturated velocities are lower than predicted by Biot-Gassmann, implying that the amount of frame weakening is greater than the stiffening due to local-flow for shear. In contrast, for Westerly granite, both the compressional and shear velocities are greater saturated than dry, reflecting the fact that local-flow effects are dominant for both compressional and shear velocities.

For the NEGU-17 samples, compressional velocities are only slightly higher saturated than dry, being quantitatively consistent with the Biot-Gassmann predictions. This is unusual for measurements at ultrasonic frequencies, implying that local-flow is not important for the NEGU-17 matrix. Shear velocities are lower than predicted by Biot-Gassmann, particularly at high stress, suggesting that frame weakening is important. However, the reduction in shear velocity with saturation was not found in sample Y1, which exhibited similar compressional effects but no measurable effect of saturation on the shear velocity (as predicted by Biot-Gassmann). Thus the weakening may be anisotropic or spatially heterogeneous at the centimeter to decimeter scale. More testing is required to have confidence in this interpretation.

III. TORSION AT SEISMIC FREQUENCIES

A sample from the same specimen of NEGU-17 core was also tested in a torsion apparatus at seismic frequencies (see *Bonner and Wanamaker,*, [1991] and *Bonner et al.*, [1992] for a more complete discussion of the apparatus and technique). The apparatus is a driven mechanical oscillator composed of a segmented torsional spring (the segments include the sample and two aluminum torsion bars) and an electromagnetic rotor. The first torsion bar is fixed to the frame of the apparatus. The rotor, which is fixed to the second torsion rod attached to the other end of the sample, is torqued by six electromagnets symmetrically arranged about the rod. Strains are measured by pairs of eddy current proximity detectors mounted on the torsion bars which are connected to the ends of the sample via collets. The strain measurement at the fixed end (which includes only the elastic response of the torsion bar), is used as a measure of the torque, while the other sensor measures the strain of the sample. Both the shear modulus and shear attenuation are computed as a function of frequency and shear strain amplitude while the sample is subjected to a continuous sinusoidal oscillation. The tests reported here where conducted at frequencies ranging from 4 to 40 *Hz* with peak shear strains from 1 to $3 \cdot 10^{-6}$. No end load or confining pressure were applied to the sample during testing.

One thin rod, 0.89 *cm* in diameter and 5.08 *cm* in length was cored parallel to the core axis. The sample was saturated with distilled water and tested. The specimen was then vacuum dried at 35 degrees C for 24 hours and retested while in a dry argon atmosphere. The results, along with a comparison of shear moduli with those computed from ultrasonic velocities are shown in Figure 2.

Water saturation has a dramatic effect on both the shear modulus and the attenuation. Shear modulus decreases with saturation by about 12 percent. This reduction, which is a clear indication of frame weakening due to the presence of water, is consistent with but much larger than the weakening observed in the ultrasonic data (most likely due to the different pressure conditions of the two types of tests). In both the dry and saturated results, there is a slight increase in shear modulus with frequency, with the saturated sample exhibiting a greater sensitivity to frequency than in the dry case. The shear moduli are relatively high for rock, but less than those determined from the ultrasonic velocities. This could reflect the difference in load on the samples and/or that there is moderate dispersion between seismic and ultrasonic frequencies (particularly for the saturated case). Shear attenuation increases with saturation and exhibits a significant increase with frequency, consistent with velocity/modulus dispersion at higher frequencies (i.e. between seismic and ultrasonic). Again, the frequency effect is largest for the saturated case, possibly indicating that the frame weakening is influencing (activating) anelastic/inelastic mechanisms of deformation.

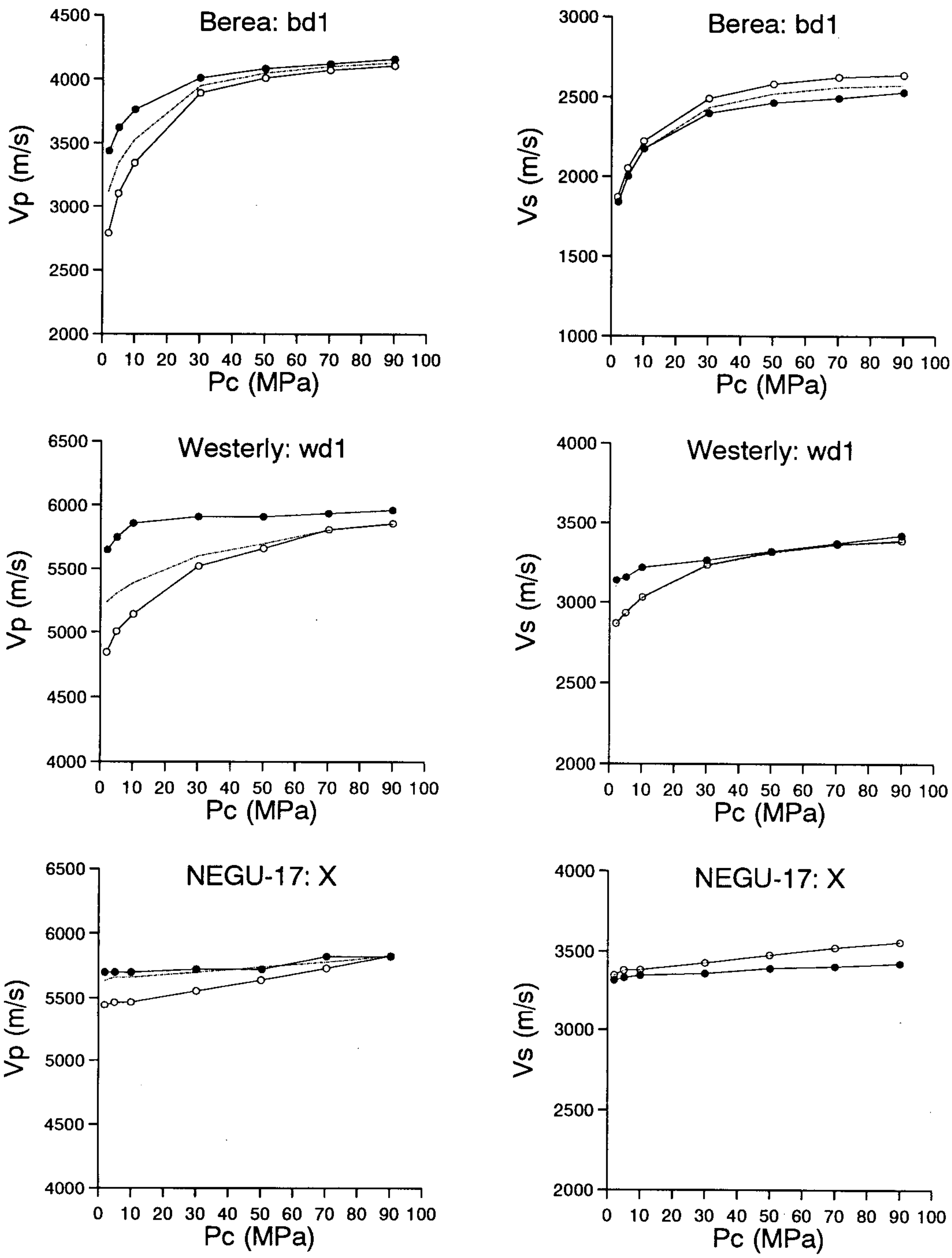
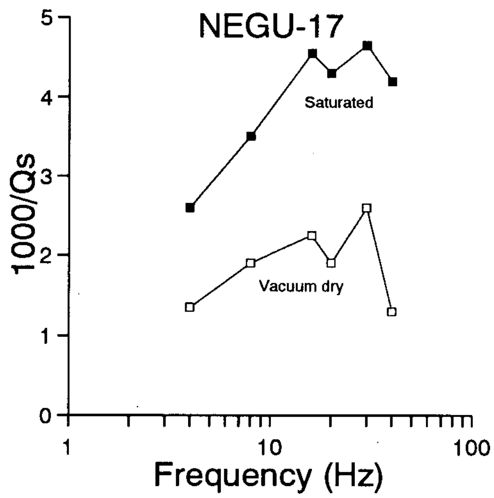


Figure 1: Ultrasonic velocities as a function of confining pressure for dry and saturated samples of Berea sandstone, Westerly granite, and NEGU-17 graywacke. Results on dry samples are shown with open circles and saturated with closed circles. The predicted saturated velocities using the dry velocities and the Biot-Gassmann equations are shown for reference (dot-dashed line).



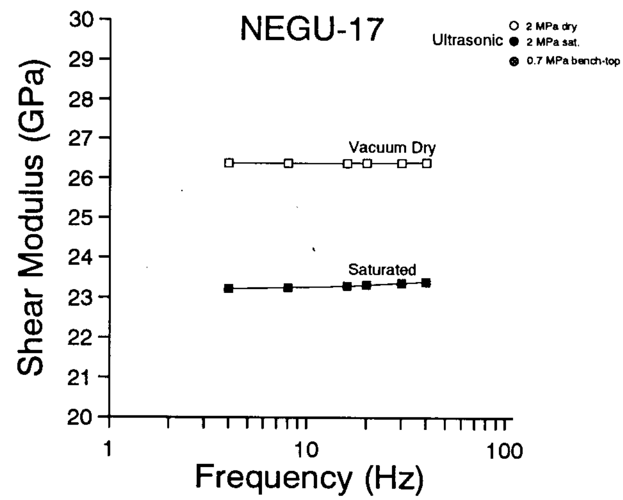


Figure 2: Shear attenuation and shear modulus as a function of frequency for NEGU-17 graywacke. The results for the dry case are shown with open boxes and the results for the saturated case are shown with closed boxes. Shear moduli computed from ultrasonic shear velocities are shown to the right (circles) for reference.

IV. EFFECTS OF PARTIAL SATURATION

An important issue to be addressed is the effect of partial saturation on the acoustic velocities and attenuation. A number of studies have indicated that compressional wave attenuation and V_p/V_s are quite sensitive to partial saturation. In addition, experiments on acoustic velocities through the steam-water transition (*Ito et al.* [1979], *DeVilbiss-Munoz* [1980]) have illustrated a variety of phenomena which may be explainable (at least in part) by a simple partial saturation model. As a starting point, ultrasonic velocities have been measured as samples dried from fully saturated to room dry conditions. The results indicate a variety of responses, dependent on the dominant mechanisms of velocity dispersion for each rock type. Results of compressional and shear velocities as a function of time are shown in Figure 3.

For Berea, we see a complex response to drying which seems to reflect the separation of the various dispersion mechanisms from one another. The compressional velocity exhibits a sharp decrease with decreasing saturation from 100% to approximately 90%, reflecting the drainage of the larger pores and thus the loss of the Biot effect. The slight increase in compressional velocity for saturations from 90% to 10% reflects the decrease in bulk density due to the loss of pore fluid. Below 10% saturation, a relatively strong minimum in the compressional velocity is thought to reflect the loss of the local-flow stiffening (as the small compliant pores and grain contacts dry) followed by a recovery of the frame weakening effect during the final stages of drying. The shear velocity history is consistent with this interpretation, were we see a gradual increase in shear velocity from 100% to 10% (decrease in bulk density due to the loss of fluid). At about 10% saturation and below, a strong minimum in the shear velocity appears, reflecting the loss of the local-flow effect followed by recovery of the frame weakening. Note that in the shear response, the local-flow effect is of the same order as the frame weakening effect, consistent with our interpretation from the results in section II.

The response of the NEGU-17 graywacke and Westerly granite are quite different from that of Berea. In these samples, we see a monotonic decrease in both the compressional and shear velocities with drying. This may result from the fact that the drying of low porosity rocks is such that the water distribution is less uniform, not being able to selectively drain larger pores first. Thus the change in velocities are more gradual and monotonic with drying, reflecting loss of both local-flow and Biot effects.

For the case of the NEGU-17 graywacke (X), the degree of drying after 17 hours was only near 50%, and thus longer term tests are required to fully characterize the drying history. After the test, the sample was vacuum dried at 80 C and remeasured, the results being shown in Figure (3c). Here we see that further drying caused a decrease in compressional velocity and a slight increase in shear velocity, consistent with our observations of frame weakening for shear discussed in sections II and III.

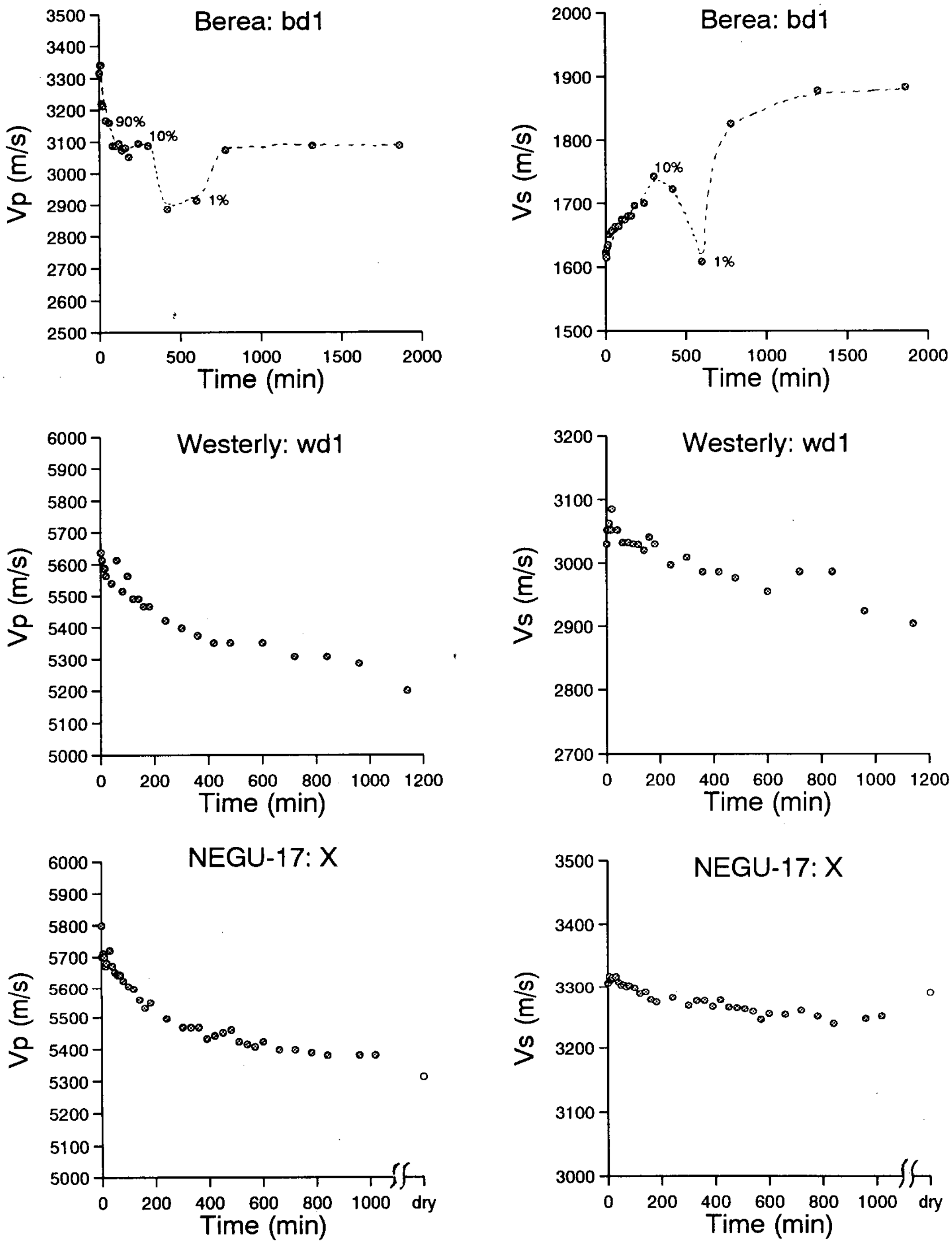


Figure 3: Compressional and shear ultrasonic velocities as a function of time during air-drying from a fully saturated state. The samples were subjected to a 0.7 MPa unconfined axial load during the tests. For the case of Berea sandstone, a complex relationship between velocity and saturation is observed (percentage saturation is shown at key points). In contrast, Westerly granite and NEGU-17 graywacke exhibit monotonic decreases in both compressional and shear velocities with decreasing saturation. For Westerly and NEGU-17, drying was not complete at the end of the test. For the NEGU-17 graywacke, velocities after vacuum drying are shown to the right of each plot.

V. DISCUSSION AND CONCLUSIONS

Laboratory measurements on reservoir graywacke recovered from NEGU-17 indicate that the matrix is very tight, yielding high velocities and very low acoustic attenuation. The lack of a strong pressure effect on the velocities even at low confining stresses indicates that the porosity is confined to relatively stiff pores and/or mineralized grain contacts and micro-fractures (in contrast to other tight rocks such as Westerly granite where the presence of compliant micro-cracks are easily recognized in velocity vs. pressure data). Similarly, the effects of fluid saturation on ultrasonic velocities shows no evidence of a strong local-flow stiffening, again suggesting that the porosity is primarily in the form of stiff pores supported by welded grain contacts. Frame weakening due to the presence of water in the pore structure is a relatively large effect and is worthy of further investigation.

Based on the work of *Zucca et al.* [1994], compressional velocities in the reservoir range from 4400 to 5600 m/s. Their work suggests that the dry steam reservoir is correlated with low compressional velocities, exhibiting a velocity deficit on the order of 10 percent. Compressional wave attenuation appears low in these same regions, with $1/Q_p$ on the order of 0.008 as compared with higher values both above and below the dry steam reservoir (near 0.017). Comparing these observations with the laboratory data reported here, we see the following:

- Compressional velocities in the field are lower (on average) than the laboratory measured values, however the laboratory values are within the variation observed in the field. The laboratory measurements reported here, being made on intact matrix, should (and do) provide an estimate of the upper limit on field scale velocities at depth, and are quantitatively consistent with results of tomographic inversions [*O'Connell and Johnson*, 1991; *Zucca et al.*, 1994].
- Compressional velocities in the steam reservoir as low as 4400 m/s reported by *Zucca et al.,* [1994] are hard to explain based on the laboratory data, suggesting that the core studied here is not representative of the reservoir as a whole. This may be indicative of the presence of joints and fractures in the reservoir and their influence on the bulk (field scale) seismic properties. Alternatively, the effect of temperature and/or the presence of steam may be important and is currently under investigation. In particular, we expect that temperature should influence the frame weakening.
- The variation in $1/Q_p$ inferred from the field tomography (about a factor of 2) is consistent with what we find for the effects of saturation on $1/Q_s$. Quantitative comparison of field and laboratory measurements of $1/Q$ are made difficult by the fact that field measurements are values averaged over large volumes and based on relative measures of dispersion. In addition, estimating $1/Q_p$ from $1/Q_s$ is difficult for conditions of partial saturation without additional measurements.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

Biot, M. A., Theory of propagation of elastic waves in a fluid-saturated porous solid: I. Low-frequency range, *J. Acous. Soc. Amer.*, 28, 168-178, 1956.

Biot, M. A., Theory of propagation of elastic waves in a fluid-saturated porous solid: II. Higher frequency range, *J. Acous. Soc. Amer.*, 28, 179-191, 1956.

Bonner, B. P., and B. J. Wanamaker, Nonlinear attenuation effects outside the zone of macroscopic failure, *in* Explosion Source Phenomenology, Geophysical Monograph 65, AGU, 1991.

Bonner, B. P., D. R. Lesuer, C. K. Syn, and A. E. Brown, Damping measurements for ultra-high carbon steel/brass laminates, *in* Proceedings of the Damping of Multiphase Inorganic Materials Symposium, ASM International, Chicago, IL, 2-5 Nov., 1992.

DeVilbiss-Munoz, J. W., Wave dispersion and Absorption in partially saturated rocks, Ph. D. Thesis, Stanford U. 1980.

Gunderson, R. P., Reservoir matrix porosity at the Geysers from core measurements, *Geothermal Resources Council Transactions,* 14, 1661-1665, 1990.

Ito, H., J. DeVilbiss, and A. Nur, Compressional and shear waves in saturated rock during water-steam transition, *J. Geophys. Res.*, 84, 4731-4735, 1979.

Mavko, G. and D. Jizba, Estimating grain-scale fluid effects on velocity dispersion in rocks, *Geophysics*, 56, 1940-1949, 1991.

Murphy, W. F. III, Effects of microstructure and pore fluids on the acoustic properties of granular sedimentary materials, Ph. D. Thesis, Stanford U., 1982.

O'Connell, D. R. H., and L. R. Johnson, Progressive inversion for hypocenters and P wave and S wave velocity structure: Application to the Geysers, California, geothermal field, *J. Geophys. Res.*, 96, 6223-6236, 1991.

Winkler, K. W., Dispersion analysis of velocity and attenuation in Berea sandstone, *J. Geophys. Res.,* 90, 6793-6800, 1985.

Zucca, J. J., L. J. Hutchings, and P. W. Kasameyer, Seismic velocity and attenuation structure of the Geysers geothermal field, California, *Geothermics*, in press, 1994.