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LABORATORY MEASUREMENTS ON RESERVOIR ROCKS FROM THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

A suite of laboratory measurements have been conducted on Geysers metagraywacke and metashale recovered from a drilled depth of 2599 to 2602 meters in NEGU-17. The tests have been designed to constrain the mechanical and water-storage properties of the matrix material. Various measurements have been made at a variety of pressures and at varying degrees of saturation.

Both compressional and shear velocities exhibit relatively little change with effective confining pressure. In all of the samples, water saturation causes an increase in the compressional velocity. In some samples, saturation results in a moderate decrease in shear velocity greater in magnitude than would be expected based on the slight increase in bulk density. It is found that the effect of saturation on the velocities can be quantitatively modeled through a modification of Biot-Gassmann theory to include weakening of the shear modulus with saturation. The decrease is attributed to chemo-mechanical weakening caused by the presence of water. The degree of frame weakening of the shear modulus is variable between samples, and appears correlated with petrographic features of the cores.

Two related models are presented through which we can study the importance of saturation effects on field-scale velocity variations. The model results indicate that the saturation effects within the matrix are significant and may contribute to previously observed field anomalies. The results help to define ways in which we may be able to separate the effects of variations in rock properties, caused by phenomena such as degree of fracturing, from similar effects caused by variations in matrix saturation. The need for both compressional and shear velocity data in order to interpret field anomalies is illustrated through comparisons of model results with the field observations.

I. INTRODUCTION

Results of field seismic experiments by *O'Connell and Johnson,* [1991] and *Zucca et al.,* [1994] have identified anomalies which have been interpreted to reflect variations in the degree of fluid saturation associated with the water/steam transition. However, these interpretations have been based on laboratory data on other rock-types and field data from other geologic settings. The purpose of this project is to provide direct measurements on reservoir material from The Geysers to assess and constrain these interpretations.

Over the last 18 months, a suite of measurements have been conducted on Geysers rocks recovered from reservoir depths in NEGU-17. The tests have focused on studying the physical properties of the matrix and their relationship to the degree of saturation. Ultrasonic velocity data has demonstrated that the V_p/V_s signature of saturation is quantitatively similar to anomalies observed in field data. However the interpretation is complicated by a number of factors concerning the extrapolation of laboratory scale velocity measurements to field scales, since velocities at the field scale are considerably lower than the matrix velocities measured in the laboratory.

In this work, we are emphasizing measurements required to enable the extrapolation of laboratory data to field scales. Models are being developed to better understand the importance of matrix properties in influencing field scale observations. In order to have confidence in extrapolating from laboratory measurements to field observations, a physical understanding of the influence of saturation on matrix properties is required.

II. SAMPLE SELECTION AND DESCRIPTION

The results of tests performed on 8 plugs from 4 core samples of NEGU-17 material are reported here. The samples were selected to obtain representative and uniform pieces of the intact matrix material, as well as to represent the range of lithologies prevalent in the reservoir. Table I provides a summary of the hand samples from which the plugs were taken and a brief description of the individual plugs which were tested. A detailed discussion of the petrography of the NEGU-17 core and its geologic context has been given by *Hulen et al.* [1992].

Table I				
Sample Description				
Sample	Depth (m)	Sample Description	Plug	Plug Description
2	2598.82-2598.91	Massive metagraywacke, moderately veined with quartz, locally ferroaxinite and epidote. Abundant flakes and grain-sized inclusions of meta-shale. A highly altered portion with associated veining and enhanced porosity dominates in one corner of the sample.	2x	Massive metagraywacke, relatively unaltered, oriented parallel axis of NEGU-17 core.
			2y1	Massive metagraywacke, moderate to little alteration with some enhanced porosity in the form of macro-pores, oriented perpendicular to axis of NEGU-17 core.
			2y2	Massive metagraywacke, moderate to little alteration with some enhanced porosity in the form of macro-pores, oriented perpendicular to axis of NEGU-17 core.
			2u	Massive metagraywacke, highly altered with significantly enhanced porosity in the form of macro-pores, oriented parallel to axis of NEGU-17 core.
12	2599.64-2599.73	Metagraywacke with stringers of argillaceous graywacke metasiltstone; prominent quartz-ferroaxinite-epidote veinlets concentrated in the metagraywacke.	12u	Metagraywacke, darker and finer grained than samples 2 and 39, and with numerous fine stringers and grain-sized flakes of metashale.
21	2600.49-2600.55	Tectonically and chaotically admixed graywacke metasiltstone and argillite (metashale) with abundant, contorted quartz veinlets (most inherented from franciscan-vintage regional metamorphism.	21u	Dominantly argillite (metashale) with abundant, contorted quartz veinlets.
39	2602.08-2602.17	Massive metagraywacke, moderately veined with quartz, locally ferroaxinite and epidote. Less abundant grain-sized inclusions if metashale than as in sample 2.	39u	Massive metagraywacke with prominent quartz vein cutting through one corner of the plug.
			39u2	Massive metagraywacke.

Table II				
Bulk Properties				
Plug -	Dry Density g/cc	Saturated Density g/cc	Porosity %	Grain Density g/cc
2x	2.664	2.674	1.0	2.691
2y1	2.634	2.651	1.7	2.680
2y2	2.644	2.662	1.8	2.692
2u	2.506	2.584	7.8	2.718
12u	2.654	2.669	1.5	2.694
21u	2.736	2.752	1.6	2.780
39u	2.654	2.674	2.0	2.708
39u2	2.642	2.660	1.8	2.690
Westerly	2.646	2.652	0.6	2.662
Berea#1	2.134	2.319	18.8	2.628
Berea#2	2.141	2.329	18.9	2.640

In addition to the Geysers material, identical tests were performed on samples of Berea sandstone and Westerly granite. Berea and Westerly were chosen because they have been heavily studied, they have microstructures and petrographic characteristics which are different from the Geysers material, and they have been used in the past as material for studies of rock properties under hydrothermal conditions (see *Ito et al.* [1979], *DeVilbiss* [1980], and *Zucca et al.* [1994]).

Sample dimensions, bulk densities (dry and saturated), and inferred porosities and grain densities (based on dry and saturated densities) are given in Table II. For the NEGU-17 samples, porosities range from 1.0 to 2.0 percent with the exception of sample 2u, which was recovered from a highly altered piece of metagraywacke containing significantly enhanced porosity. Grain densities are confined to a limited range of 2.68 to 2.72 g/cc, with the exception of the metashale (21u) which exhibited a moderately higher density.

III. ULTRASONIC VELOCITIES

A variety of ultrasonic pulse propagation experiments have been conducted. The results of measured velocities versus pressure for the NEGU-17 samples and comparisons with field values are shown in Figure 1. The results illustrate that all samples exhibit relatively little pressure effect on velocities, even in the case of dry samples. This indicates that the matrix is very tight, an observation further supported by the high velocities and low acoustic attenuation characteristic of the samples. The comparisons with the field values illustrate that matrix values are consistent with the highest field velocities and asymptotically approached by the field velocities at depth, consistent with the notion that the field velocities are influenced (reduced) by field-scale features such as rock joints which are not sampled at the laboratory scale.

All samples exhibit some increase in compressional velocity with saturation, the effect being most notable at low pressures. Shear velocities are either not effected by saturation (i.e. samples 2u and 2y1), or more commonly exhibit some reduction with saturation. This behavior, which is uncommon in low porosity rocks, is thought to reflect the presence of chemo-mechanical weakening of the matrix material. The metashale sample (21u) exhibits a persistent shear velocity reduction with saturation, while some of the metagraywackes commonly exhibit a slight decrease in shear velocity with saturation which appears to increase with increasing effective confining pressure.

Table III summarizes the variations in velocities among samples at 30 MPa effective confining pressure. Despite the general lack of pressure effect on the velocities of the NEGU-17 matrix, the saturation effects are of similar relative magnitude as other rocks of diverse micro-structure (i.e. Berea sandstone and Westerly granite). Note that there is between 4 to 9% variation among the NEGU-17 samples in compressional velocities, shear velocities, and V_p/V_s ratios for both the dry and saturated results. Also of interest is the fact that sample 2u exhibited the highest velocities and the smallest effect of saturation of all the samples tested, despite its exceptionally high porosity and degree of alteration. In addition, the slowest velocities and one of the largest shear velocity reductions with saturation were recorded for sample 12u, which exhibited one of the lowest porosities. These observations serve to illustrate some of the odd behavior of the NEGU-17 material.

IV. MODELING THE DATA

The effects of saturation on acoustic velocities have been well studied, and are qualitatively understood to result from four basic mechanisms: "Biot-Gassmann stiffening" of the bulk modulus, "local flow stiffening of both the bulk and shear moduli; change in bulk density with saturation; and chemo-mechanical effects (usually weakening) (see *Murphy*, [1982], *Mavko and Jizba* [1991]).

In contrast to most other rocks, we have found that for the NEGU-17 matrix samples the dominant effect of saturation on the compressional velocities is quantitatively consistent with Biot-Gassmann poroelastic theory. The classically used Biot-Gassmann theory provides as simple relationship between the dry and saturated dynamic elastic moduli, resulting from changes in density with saturation as well as the increase in bulk modulus due to the finite bulk modulus of the saturating fluid. According to the low frequency version of the theory, the saturated bulk modulus (K_{sat}) is given by

$$K_{sat} = K_{dry} + \Delta K \qquad (1a)$$

where ΔK represents the increase in bulk modulus due to saturation and is given by

$$\Delta K = \frac{(K_{solid} - K_{dry})^2}{K_{solid}\left[1-\phi-(K_{dry}/K_{solid})+\phi(K_{solid}/K_f)\right]} \qquad (1b)$$

ΔK is a function of the porosity (ϕ), the bulk moduli of the fluid (K_f) and the solid (K_{solid}) comprising the matrix, and the bulk modulus of the dry matrix itself (K_{dry}) (see *Biot*, [1956]; *Winkler*, [1985]). The shear modulus G is assumed to be independent of saturation (i.e. $G_{dry} \equiv G_{sat}$).

While the low frequency Biot-Gassmann theory does a reasonable job of being able to model the increase in compressional velocity with saturation

Table III									
Velocities @ 30 MPa Effective Pressure									
	Dry			Saturated			Effect of Saturation		
Plug	V_p m/s	V_s m/s	V_p/V_s	V_p m/s	V_s m/s	V_p/V_s	$\Delta V_p/V_p\|_{dry}$	$\Delta V_s/V_s\|_{dry}$	$\frac{\Delta(V_p/V_s)}{(V_p/V_s)_{\_dry}}$
2x	5593	3446	1.623	5770	3378	1.708	0.032	-0.020	0.052
2y1	5529	3421	1.616	5605	3431	1.634	0.014	0.002	0.011
2y2	5622	3467	1.621	5732	3424	1.674	0.020	-0.012	0.033
2u	5917	3573	1.656	6008	3586	1.675	0.015	0.004	0.011
12u	5370	3370	1.593	5668	3277	1.727	0.055	-0.028	0.084
21u	5650	3412	1.656	5799	3272	1.772	0.026	-0.041	0.070
39u	5458	3367	1.621	5598	3334	1.679	0.026	-0.010	0.034
39u2	5437	3362	1.617	5683	3329	1.707	0.045	-0.010	0.056
NEGU-17†	5574†	3427†	1.626‡	5733†	3379†	1.697‡	0.028‡	-0.014‡	0.044‡
Westerly	5577	3252	1.715	5908	3312	1.784	0.059	0.018	0.040
Berea#1	3908	2510	1.557	3989	2399	1.663	0.021	-0.044	0.068

† Average values of velocities of all NEGU-17 samples.
‡ Computed from average values of velocities of all NEGU-17 samples.

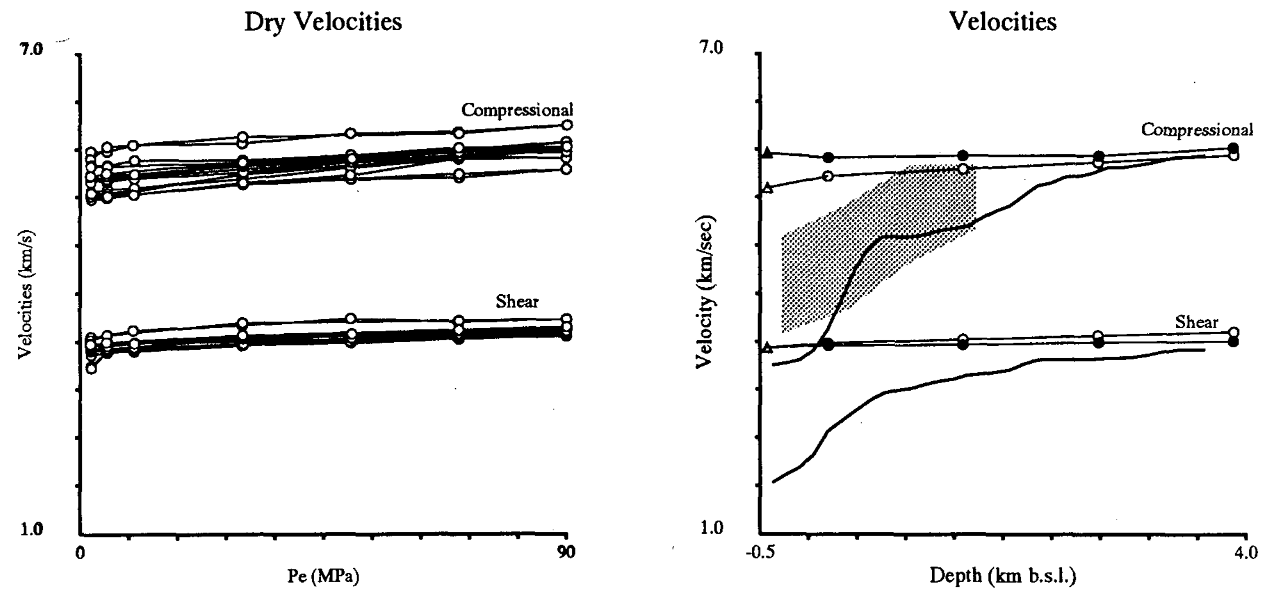

Figure 1:
a) Dry compressional and shear velocities as a function of confining pressure for the eight NEGU-17 plugs. Note the lack of a significant pressure effect, indicating the tight nature of the matrix material.
b) Comparison of laboratory velocity measurements on sample 2x with the results of field seismic inversions from the central Geysers. Ultrasonic velocity measurements were conducted on dry (open circles) and saturated (closed circles), and exhibit small but measurable saturation effects on both compressional and shear velocities. Solid lines are from *O'Connell and Johnson,* [1991] and the gray shaded region represents the variation in compressional velocities from the 3-D work of *Zucca et al.,* [1994].

exhibited by the NEGU-17 samples, many samples exhibit a shear velocity reduction with saturation which is far in excess of what can be explained by the theory. In the simplest case, the weakening effect can be modeled by assuming that the weakening effects the shear modulus but has little influence on the bulk modulus. Thus we replace the assumption that $G_{dry} = G_{sat}$ with a weakened shear modulus, where the weakening is a function of effective pressure.

$$G_{sat} = G_{dry} - \Delta G \tag{1c}$$

Note that this weakening effects both the saturated shear and compressional velocities.

Applying the modified theory to the data at hand, we find that we have two free parameters, namely the bulk modulus of the solid material comprising the matrix (K_{solid}) and the shear weakening term ΔG. The value of K_{solid} is determined from equations 1a and 1b by first computing K_{dry} and K_{sat} from the high pressure dry and saturated compressional and shear velocities and using the bulk properties from Table II. Likewise, the values of ΔG are determined through use of the dry and saturated shear velocities as a function of effective pressure.

An example of comparisons of data and model are given in Figure 2. Note that both the reduction in shear velocity as well as second order effects of the shear weakening on compressional velocities are modeled by the theory. All of the NEGU-17 samples are modelable with this approach, with values of K_{solid} near 59 GPa, reasonable values for rocks of these compositions.

The modified Biot-Gassmann theory provides us with a theoretical foundation upon which to interpret field observations, develop models of wave propagation in partially saturated rock, and identify physical processes and phenomena which may be important to reservoir performance.

V. EXTRAPOLATING TO FIELD SCALES

Field seismic imaging experiments at The Geysers have indicated V_p, V_p/V_s, and attenuation anomalies associated with the dry steam reservoir [*O'Connell and Johnson*, 1991; *Zucca et al.*, 1994]. The observed anomalies have been interpreted as reflecting changes in the degree of saturation associated with the water/steam transition. It has been observed that the measured difference between V_p/V_s for dry and saturated matrix is quantitatively consistent with the observed anomaly reported by *O'Connell and Johnson* [1991], however the correlation is not straightforward since the average field scale velocities are significantly lower than the velocities measured in the laboratory on the reservoir matrix material (see Fig. 1).

The discrepancy between field and laboratory velocities is certainly not surprising, and is commonly attributed to the presence of joints and other large scale features not sampled in the laboratory specimens. In order to assess whether the matrix effects measured in the laboratory may be the cause of the field scale anomalies, two related models have been developed to incorporate the measured matrix properties with the expected properties of joints in order to predict the field scale properties. As a starting point, we would like to see if by adding sufficient number of joints to lower the lab velocities to field values, we can still preserve the V_p/V_s signature of saturation exhibited by the matrix.

For The Geysers rocks, there is little evidence of significant rate dependent phenomena (i.e. local flow), with the lab results being fairly easily modeled with the modified low-frequency Biot-Gassmann theory. Thus, we are left with dealing with field scale features such as joints and fractures, features which are well known to be ubiquitous within The Geysers reservoir. Because rock joints are compliant features, their presence within a matrix can significantly reduce the field-scale velocities. Here we present two simple models to include the effect of rock joints and use the models to test if the matrix properties are potentially important in controlling and/or influencing the observed field scale anomalies.

At the scale of the passing elastic wave, we assume that the stresses within the medium are continuous, while the displacements are discontinuous across the joints. We assume that the scale of deformation (i.e. the wavelength) is large enough that we can treat the deformation of the matrix as independent from that the joints. This is to say that the compliance of the jointed medium subject to a given stress is the sum of the compliances resulting from the elastic deformation of the matrix and that attributed to the compliance of the joints. For convenience, we parameterize field-scale (effective) bulk and shear moduli in terms of the moduli of the matrix (denoted by the subscript m) and the moduli associated with the presence of joints and fractures (denoted by the subscript f) :

$$\frac{1}{K_{eff}} = \frac{1}{K_m} + \frac{1}{K_f} \tag{2a}$$

$$\frac{1}{G_{eff}} = \frac{1}{G_m} + \frac{1}{G_f} \tag{2b}$$

From laboratory and theoretical studies of joints, we know that both the compressional (k_n) and shear (k_s) stiffnesses increase with normal load across the joint, and that for each the relationship is approximately linear with effective stress for a wide variety of joints. It follows that the ratio k_n/k_s is roughly independent of stress. As a result we might postulate

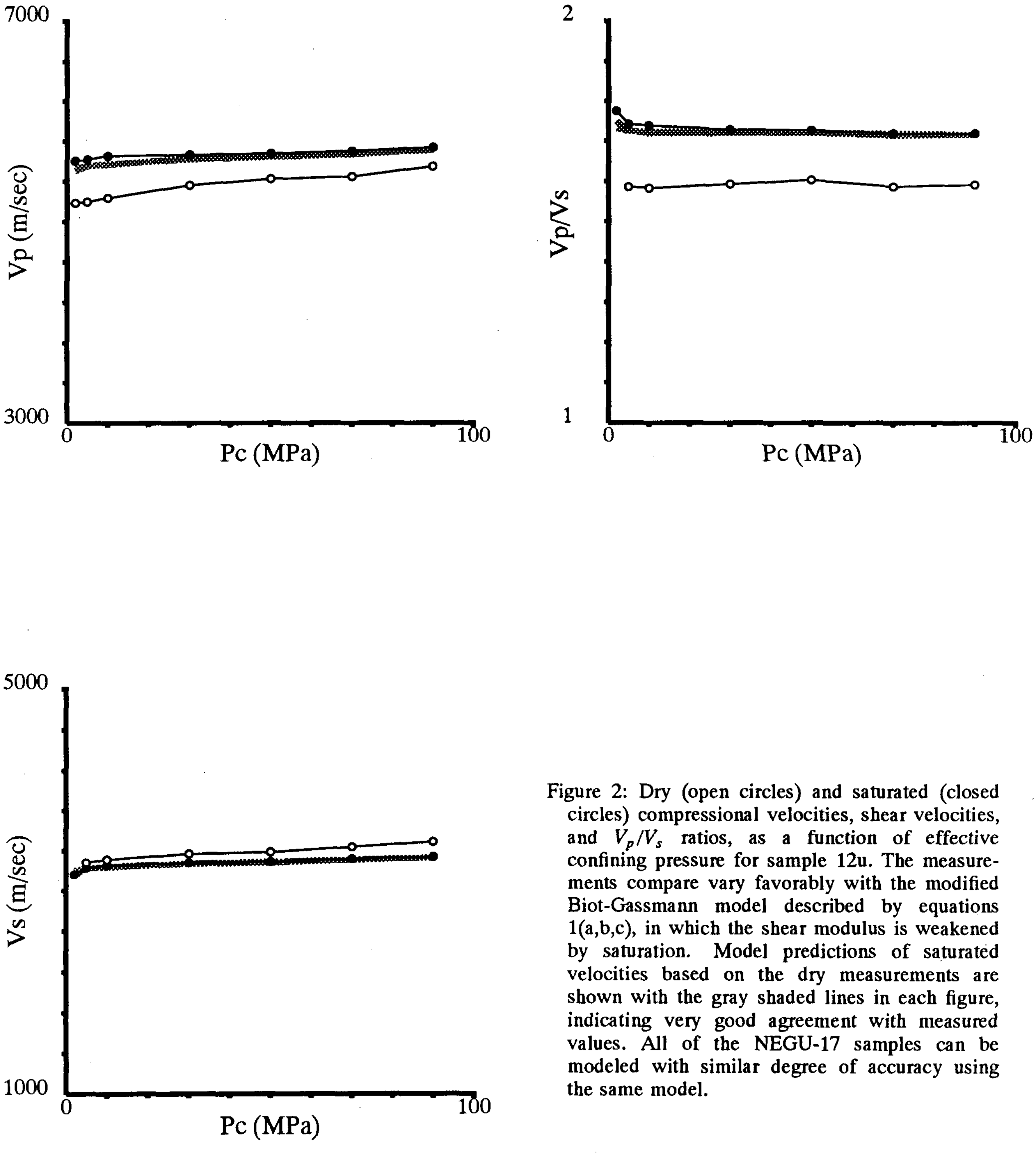

Figure 2: Dry (open circles) and saturated (closed circles) compressional velocities, shear velocities, and V_p/V_s ratios, as a function of effective confining pressure for sample 12u. The measurements compare vary favorably with the modified Biot-Gassmann model described by equations 1(a,b,c), in which the shear modulus is weakened by saturation. Model predictions of saturated velocities based on the dry measurements are shown with the gray shaded lines in each figure, indicating very good agreement with measured values. All of the NEGU-17 samples can be modeled with similar degree of accuracy using the same model.

that K_f/G_f will be insensitive to effective stress as well as fracture density, and thus treat it as a physical constant of the fractured rock mass.

Alternatively, we might adopt the parameterization of *Fossum* [1985] in which the effective elastic moduli are parameterized directly in terms of the normal and shear stiffnesses of the joints and the joint spacing (s). The model, which assumes a isotropic distribution of fractures, provides alternative estimates of K_{eff} and G_{eff} denoted schematically through functions $\kappa(\ )$ and $\gamma(\ )$ as follows:

$$K_{eff} = \kappa(K_m, G_m, k_n, k_s, s) \qquad (3a)$$

$$G_{eff} = \gamma(K_m, G_m, k_n, k_s, s) \qquad (3b)$$

Either model can be used to test to see if field data and laboratory data are internally consistent with such a simple fractured rock model. Working with the model as parameterized in equations 2(a,b), if we have estimates from field and laboratory shear velocities of G_{eff} and G_m, we can use equation 2b to compute G_f. Assuming K_f/G_f is constant, we then use equation 2a and laboratory measurements of K_m to estimate K_{eff}. Hence, we have a prediction of the field scale V_p.

A similar argument can be used in the context of equations 3(a,b). Again noting that k_n/k_s is roughly independent of stress, as well as the fact that functions $\kappa(\ )$ and $\gamma(\ )$ are such that the joint spacing (s) always appears as a product with k_n or k_s, we can use laboratory measurements of G_m, assume a value of k_n/k_s, and find $s \cdot k_s$ consistent with field measurements of G_{eff} through equation 3b. We then use laboratory measurements of K_m and G_m and equation 3a to predict K_{eff} and thus the field V_p.

These models are well suited for predicting the degree to which matrix saturation will effect field-scale velocities. It should be noted that both models outlined above contain only one free parameter which is assumed independent of depth and fracture density (i.e. the ratio K_f/G_f in equations 2a,b and the ratio k_n/k_s in equations 3a,b). Through use of matrix properties representative of dry and saturated conditions, we can use the models to test to see if field-scale V_p and V_s are compatible, thus indicating both the fracture properties and the state of saturation of the matrix.

VI. DISCUSSION

An example of such an exercise using the field data of *O'Connell and Johnson* [1991] is shown in Figure 3. The velocities at depth are assumed to represent the matrix values, being consistent with the laboratory values. The modified Biot-Gassmann theory is used, along with the laboratory values of velocities versus pressure, to constrain realistic dry and saturated matrix velocities. The shear velocity versus depth from *O'Connell and Johnson* [1991] is then combined with matrix values, and the contribution to the rock mass compliance attributed to the presence of joints is determined.

Using such a procedure, these models can be used to predict the sensitivity of the V_p/V_s signature in the fractured rock mass to the V_p/V_s signature of the matrix. Preliminary calculations as in Figure 3 illustrate that it is conceivable that the observed field scale anomalies may result in part from matrix effects. They also suggest that the overall velocity versus depth (as well as the spatial variations in velocity observed by *Zucca et al.* [1994]) are most likely controlled by fracture properties and/or fracture density.

Importantly, the model results illustrate that both saturation effects and the effects of joints can influence the compressional and shear velocities as well as V_p/V_s (see Fig. 3b). It appears dangerous to assume (as was done by *O'Connell and Johnson* [1991]) that some of the V_p/V_s variations with depth are not the result of joint density and/or the effects of pressure on joints. Thus V_p/V_s ratios alone should not be used to indicate saturation.

Similarly, assumptions that V_p variations reflect saturation effects, as postulated by *Zucca et al.* [1994], also appear dangerous in that the dominant cause of velocity variations appears associated with joints (i.e field scale features). While *Zucca et al.* [1994] noted that low compressional velocities corresponded to regions of the reservoir thought from other evidence to be the driest, this association may result from a correspondence between fracture density and reservoir depletion rather than being direct evidence of dry/depleted matrix. Without high resolution shear velocity information to compare with the compressional velocity variations, it is difficult to assess to what extent low compressional velocities are related to the saturation state of the matrix.

Through use of models as described above, one can begin to separate the two effects if both compressional and shear velocities are well constrained in the field. Using dry matrix values along with the models given by equations 2 and/or 3, correspondence between predicted and measured field-scale compressional velocities may be used to indicate dry reservoir. Likewise, using saturated matrix values, correspondence between predicted and measured compressional velocities can be used to indicate saturated reservoir. In so doing, the effect of fractures on the velocities, and hence V_p/V_s is removed and the fracture properties are constrained. With this accomplished, the effects of saturation within the matrix can then be assessed.

VII. ACKNOWLEDGMENTS

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VIII. 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.

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

Fossum, A. F., Effective elastic properties for a randomly jointed rock mass, *Int. J. Rock Mech. Mining Sci.*, v. 22, p. 467-470, 1985.

Hulen, J. B., D. L. Nielson, and W. Martin, Early calcite dissolution as a major control on porosity development in The Geysers steam field, California - Additional evidence in core from UNOCAL well NEGU-17, *Geothermal Resources Council, Trans.*, v. 16, p. 167-174, 1992.

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*, 1994.

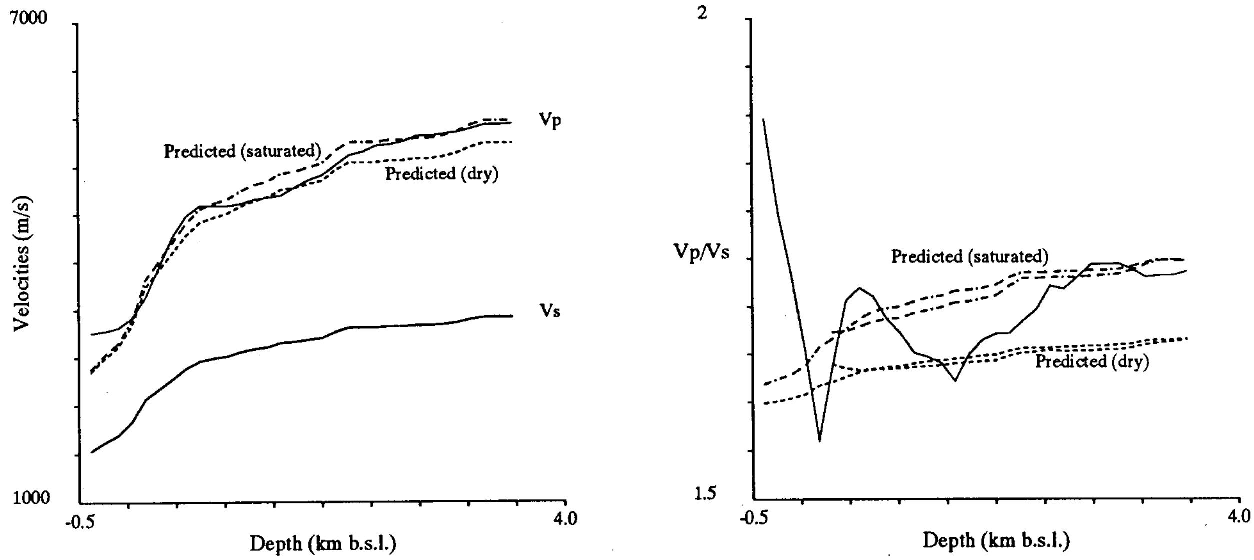

Figure 3: a) Comparison of predicted dry (dashed) and saturated (dot-dashed) compressional velocities with values from an field-seismic inversion of *O'Connell and Johnson* [1991] (solid lines). The model uses the difference between matrix shear velocities (measured in the laboratory) and field measurements of V_s from *O'Connell and Johnson* [1991] to infer shear modulus reduction due to the presence of joints and other field-scale features. Equations 2a,b were used, with a value of K_f/G_f = 2.5, for the predictions in Fig 3a. Similar results can be obtained using equations 3a,b and k_n/k_s = 2.0. Note the remarkable agreement over the entire depth range, indicating the appropriateness of assuming K_f/G_f is constant. The predictions are consistent with (and illustrate) an anomaly thought to reflect and understated region within the reservoir at a depth of approximately 1.8 km.

b) Comparison of predicted V_p/V_s ratios using equations 2a,b (K_f/G_f = 2.5) and equations 3a,b (k_n/k_s = 2.0) with values from a field-seismic inversion of *O'Connell and Johnson* [1991] (solid line). Dashed lines are the model results using dry matrix values while dot-dashed lines are for saturated matrix values. Note that both models produce nearly identical results. The anomaly between 1 and 2 km b.s.l. appears to be explainable by the matrix saturation effects, being consistent with a dry matrix.