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Interpretation of Field Seismic Tomography at The Geysers Geothermal Field, California

G. N. BOITNOTT
New England Research, Inc.

ANN KIRKPATRICK
Lawrence Berkeley National Laboratory

ABSTRACT

Tomographic inversions of compressional and shear velocities from field seismic observations at The Geysers have been performed by a number of investigators in an attempt to image important reservoir properties. Anomalies in compressional velocities (V_P), shear velocities (V_S), and the ratio V_P/V_S, have been interpreted to reflect variations in lithology, fracture density, and pore fluid compressibility within the reservoir. Here we critically review those interpretations in the context of physical insight gained from laboratory measurements of velocities on core samples from The Geysers. Systematics between V_P and V_S values within the reservoir are found to be incompatible with a simple interpretation based solely on pore fluid compressibility. With constraints from the laboratory velocity data, a scaling model which incorporates the effects of field-scale compliant features is evaluated. and used to extract information concerning fracture properties independently from other effects such as matrix properties. Model fits to field data are used to test hypotheses concerning possible interpretations of field anomalies. Two potential physical models are proposed.

I. INTRODUCTION

1. Background:

From a detailed 1-d velocity inversion at the central Geysers, *O'Connell and Johnson* [1991] noted anomalously low V_P/V_S at a depth range thought to correlate with the steam dominated portion of the reservoir. As steam production at The Geysers has declined unexpectedly over the last 10 years, there is growing interest in developing methods to characterize the distribution of water within the reservoir. To address this issue, three dimensional tomographic inversions of velocities within The Geysers reservoir have been performed by a number of investigators, including *Zucca et al.* [1993], *Romero et al.* [1995], *Julian et al.* [1996], *Foulger et al.*, [1997], and *Kirkpatrick et al.* [this issue]. Each of these studies has identified velocity anomalies, and interpreted them in the context of various models which reflect, in part, the distribution of fluid phases within the reservoir.

2. Traditional Interpretations:

For a low porosity reservoir such as The Geysers, traditional poroelastic theory would suggest that the presence of a relatively incompressible pore fluid phase (i.e. liquid water as opposed to steam) will increase the effective bulk modulus of the reservoir, resulting in an increase in the compressional wave velocity. In contrast, at field seismic frequencies, pore fluid compressibility is typically thought to have no effect on the shear modulus and thus the shear velocities should be insensitive to variations in fluid properties (other than a slight sensitivity resulting from associated changes in bulk density). Based on this argument, it is commonly assumed that both V_P and V_P/V_S should be sensitive to pore fluid compressibility (and thus water content). For the simple case where V_P variations are primarily controlled by pore fluid compressibility (e.g. possibly V_P anomalies at a particular depth), one should expect that anomalies in V_P will correlate with anomalies in V_P/V_S.

II. FIELD OBSERVATIONS

Observations at The Geysers repeatedly indicate that there is little systematic change in V_P/V_S with depth, indicating that the effects of field scale compliant features (which are controlling the depth dependence of both the compressional and shear velocities) do not appear to systematically change V_P/V_S at the reservoir scale. For this reason, V_P/V_S is a more useful indicator of pore fluid compressibility than V_P, owing to its insensitivity to fracture density and compliance, as well as changes in stress.

Low V_P/V_S anomalies at The Geysers are found to correlate reasonably well with regions in the reservoir known or thought to be vapor dominated, consistent with the fluid compressibility mechanism. However, detailed examination of three dimensional inversions of compressional and shear velocities at The Geysers do not seem to support a simple interpretation based solely on variations in fluid compressibility. The inversions commonly exhibit a negative correlation between V_S and V_P/V_S, along with a notable lack of correlation between V_P and V_P/V_S. These observations are at odds with simple interpretations based on poroelasticity, and suggest that the velocity anomalies reflect processes or phenomena not typically included in interpretations of field seismic data.

A particularly clear example of the observed systematics is found in the inversion results from the Northwest Geysers by *Romero et al.* [1995] (see Figure 1). Here we have plotted the velocities for each node in the inversion as scatter plots in terms of V_P, V_S, and V_P/V_S. There are a number of striking features which are clearly apparent when plotted in this fashion. First, both the compressional and shear velocities increase sharply with depth, asymptotically approaching values consistent with that measured in the laboratory on unfractured matrix material. The depth dependence of the velocities is similar to that found in the 1-d velocity inversion of *O'Connell and Johnson* [1991], and is believed to reflect the increase in stiffness of the field scale joints and faults with increase in pressure. The ratio V_P/V_S does not show a systematic change with depth; however, the variation in V_P/V_S appears to reduce with increasing depth. The negative correlation between V_S and V_P/V_S is apparent at each depth, as is the lack of correlation between V_P and V_P/V_S.

Another example exhibiting similar systematics is found in the results from the Southeast Geysers [*Kirkpatrick et al.*, this issue]. Results are plotted in Figure 2. In their inversions, the negative correlation between V_S and V_P/V_S is apparent at the shallower depths. Variation in V_P/V_S decreases slightly with depth, although less markedly than in *Romero et al.'s* results from the Northwest Geysers.

Interpretation of the Southeast Geysers data is complicated by the transition with depth from metagraywacke dominated to felsite dominated matrix. Notably lower V_P/V_S is inferred at a depth layer of -0.5 *km bsl*, coincident with the top of the producing stream reservoir [see *Kirkpatrick,* this issue]. At deeper depths, which are thought to be primarily in felsite dominated host rock, V_P/V_S exhibits some positive correlation with V_P (and reduced negative correlation with V_S).

These results, combined with the observations from the central Geysers that V_P anomalies do not correlate with V_P/V_S anomalies [see *Julian at al.,* 1996], provide a consistent picture from The Geysers that V_P/V_S anomalies within metagraywacke dominated reservoir correlate (negatively) with V_S anomalies, and exhibit little or no correlation with V_P anomalies. This observation appears in conflict with simple interpretations of V_P/V_S anomalies based solely on the effects of variations in pore fluid compressibility on V_P. Assuming the fluid compressibility effects are indeed present, a second process is thus required which counteracts the otherwise positive correlation between V_P and V_P/V_S anomalies.

III. BEHAVIOR OF THE MATRIX

A possible clue to the physical origin of this second process may be found in laboratory studies of reservoir matrix from The Geysers. In Figure 3, laboratory values of V_P/V_S for dry and saturated samples of metagraywacke and argillite from The Geysers reservoir are plotted against V_P and V_S. Note how saturation tends to produce systematic changes in V_S and V_P/V_S, but not V_P. This apparent V_S domination of the V_P/V_S variation is understood to reflect a chemo-mechanical weakening of the shear modulus due to the presence of water. The weakening has been found to correlate with illite content within the samples (see *Boitnott* [1997]). A modified *Biot* poro-elastic theory [see *Boitnott and Boyd* 1996] predicts the observed effects, including the lack of correlation between V_P/V_S and V_P. This lack of correlation occurs because the shear modulus reduction acts to reduce V_P as well as V_S, counteracting the increase in V_P due to finite pore fluid compressibility.

IV. THE FIELD SCALING MODEL

Although the similar patterns observed in the laboratory and the field might lead one to conclude that shear weakening effects are contributing to the observed velocity anomalies, the inference is clouded by the fact that field values of velocities are considerably lower (particularly at shallow depths) than velocities observed in the laboratory. This "scaling problem" is generally recognized to reflect the effects of field scale compliant features (joints and faults) which act to reduce the velocities, yet it makes it difficult to assess whether variations in matrix properties are visible in the field data.

A field-scaling model has been implemented to provide a means to separate matrix signal from the effects of field-scale features. The scaling model follows that of *Boitnott* [1995], and includes the effects of compliant features such as joints and faults on the field-scale velocities. The model has two parts, a matrix model and a scaling model. In its simplest form (as applied here), the model assumes that, at both the field and core scale, the

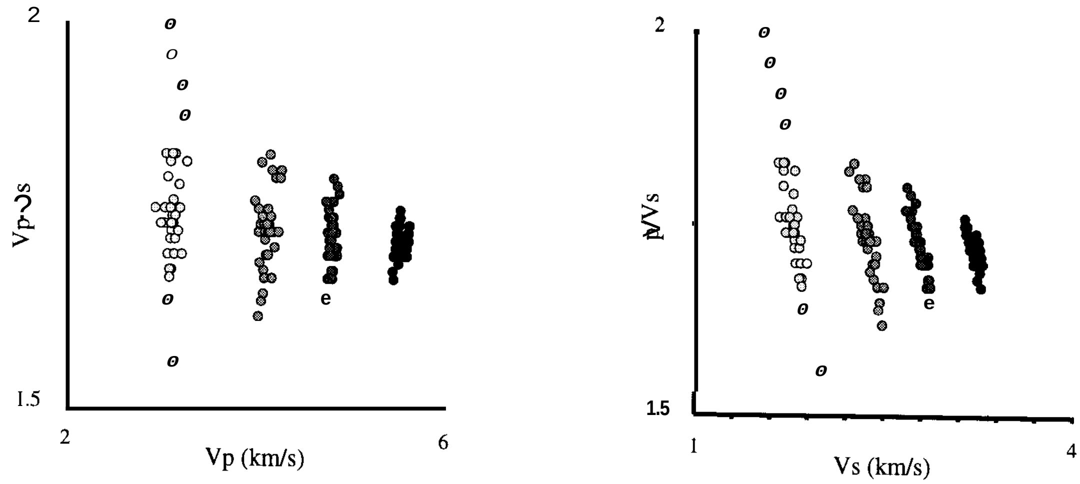


Figure 1: V_P and V_S versus V_P/V_S from a three dimensional velocity inversion at the Northwest Geysers [data from *Romero et al.* 19951. Shading of symbols indicates depth, with darker shades reflecting increasing depth.

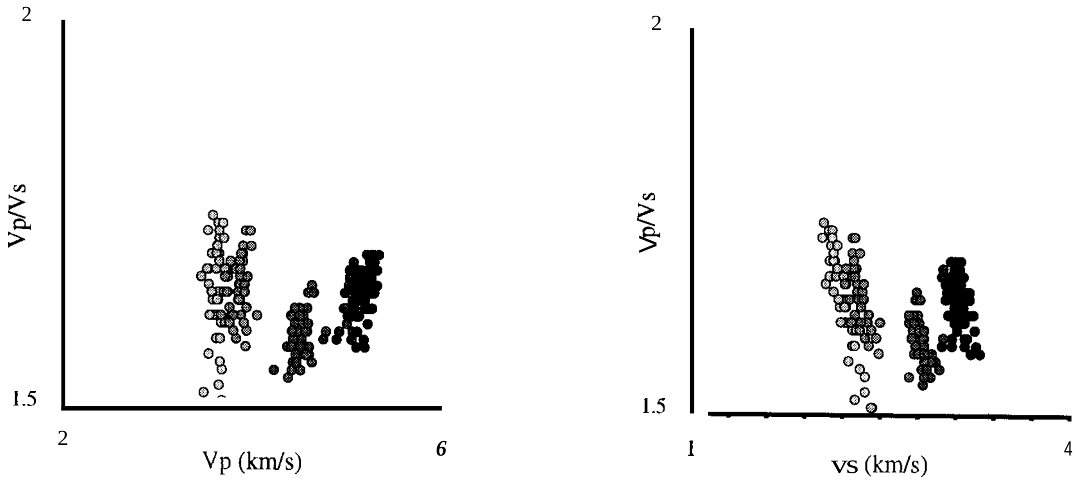


Figure **2:** V_P and V_S versus V_P/V_S from a preliminary three dimensional velocity inversion at the Southeast Geysers [see *Kirkpatrick **et** al.* this issue]. Shading of symbols indicates depth, with darker shades reflecting increasing depth.

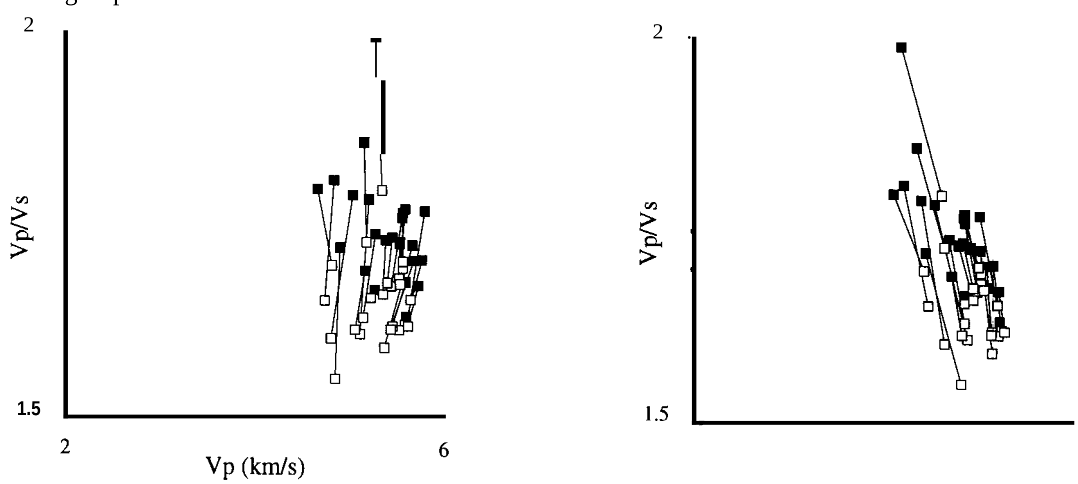


Figure **3:** V_P and V_S versus V_P/V_S from laboratory measurements on matrix material from The Geysers. Open symbols indicate dry matrix and filled symbols indicate saturated matrix.

reservoir acts as an isotropic, linear elastic solid, which is heterogeneous at scales larger than the scale of the seismic inversions (but effectively homogeneous at smaller scales). The field scale velocities are determined uniquely from the bulk and shear moduli appropriate at the field scale (denoted K_{eff} and G_{eff} respectively), along with the field scale density which will be assumed to be constant and uniform. These moduli are in turn determined from the bulk and shear moduli of the matrix (K_m and G_m) and the volumetric and shear compliances due to the presence of fractures and other field scale compliant features ($1/K_f$ and $1/G_f$). The respective field scale compliances (volumetric and shear) are assumed to reflect the sum of the compliances due to the matrix and fracture deformation respectively.

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

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

Thus, the matrix model consists of any set of parameters sufficient to specify K_m and G_m of the matrix. The matrix model can simply be a direct use of empirical velocity data or it can be a physical model such as the modified Biot model discussed in *Boitnott and Boyd* [1996]. The matrix can be assumed to be either homogeneous or heterogeneous at the scale of the field observations. The scaling model involves a set of parameters sufficient to specify the two independent variables (K_f and G_f) which determine the added compliances resulting from field scale features. K_f and G_f are treated as the model variables, as the others are constrained by observations of the field and core scale velocities.

V. APPLYING THE MODEL

1. Overview

In a previous application of the model, *Boitnott* [1995] showed that the 1-d velocity inversion of *O'Connell and Johnson* [1991] could be modeled rather simply by assuming that the ratio K_f/G_f is constant. The model was implemented by using *O'Connell and Johnson's* results for V_S to predict their V_P. Constrained by laboratory measurements of velocities on core samples from The Geysers reservoir, the model illustrated that the effects of saturation on the matrix could contribute to (if not cause) the observed V_P/V_S anomaly.

Here we will begin by applying this same model to the 3-D data of *Romero et al.* [1995]. We show that the assumption of constant K_f/G_f is not consistent with observation in this case, and proceed to develop the model further in the context of variable K_f/G_f.

2. Homogeneous K_f/G_f, Heterogeneous Matrix

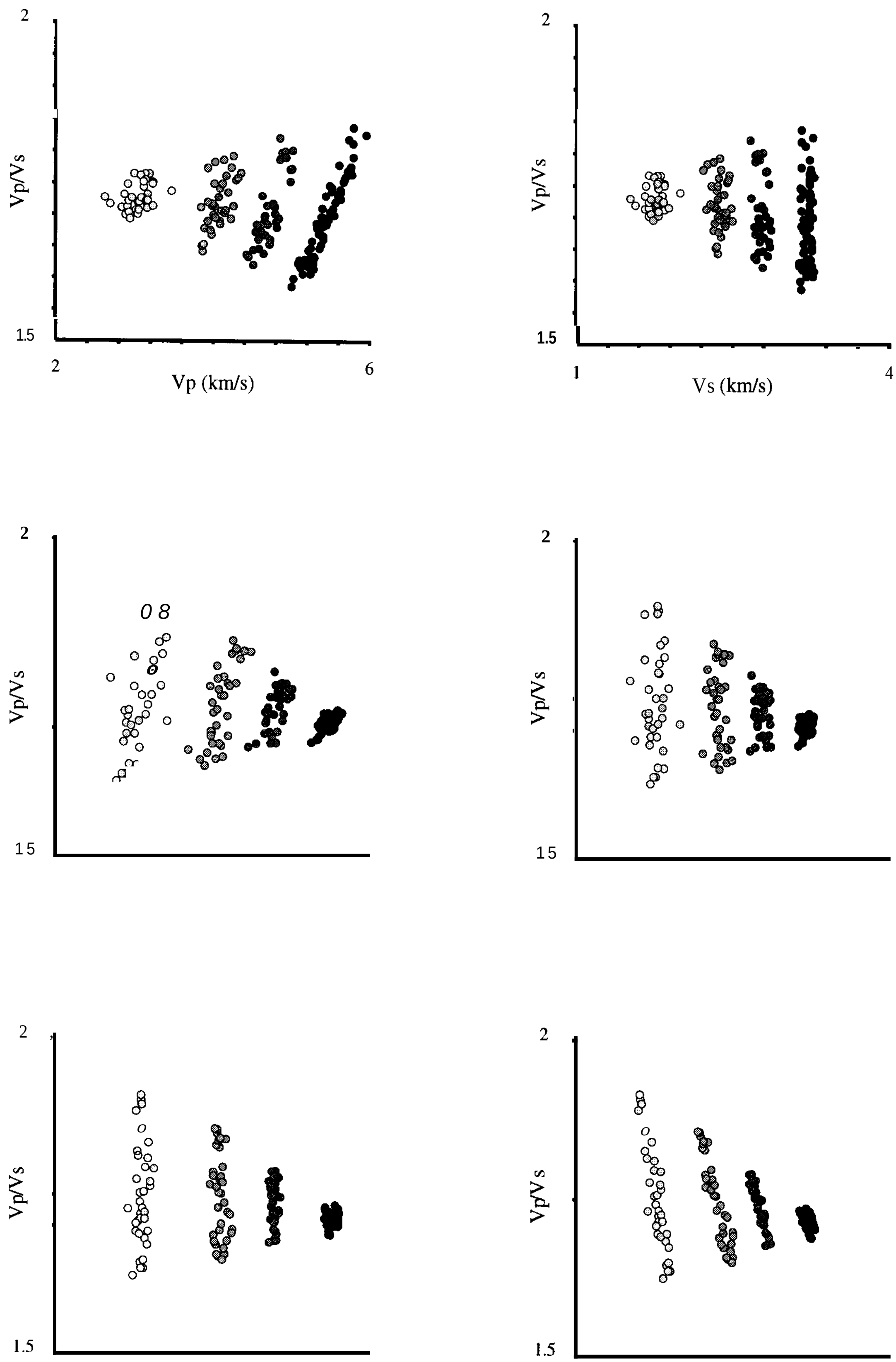
Following the procedure outlined in *Boitnott* [1995], we take the field scale V_S from *Romero et al.* [1995] and a matrix model based on laboratory measurements. K_f/G_f is assumed constant and the matrix K_m and G_m are allowed to vary randomly throughout the reservoir. Variation in matrix properties are constrained to reflect the variation observed in the laboratory at the core scale, and thus should greatly exceed the expected variation when averaging on the scale of the field data (i.e. kilometers).

The predicted field-scale velocities are presented in Figure 4. Note that the systematics in the predictions between V_P, V_S, and V_P/V_S are quite different from those in the inversion (Figure 1). Most notably, despite the extreme variability in the matrix heterogeneity, the model exhibits little variation in V_P/V_S at shallow depths. In addition, relative variation in V_P/V_S increases gradually with increasing depth. The patterns in the model result from the fact that at shallow depths, the field scale velocities are controlled by K_f and G_f. It follows that, under these conditions, V_P/V_S is dominated by the ratio K_f/G_f, which was assumed constant. As the pressure increases with depth, the relative effect of the field scale compliant features decreases, and the variations in matrix properties become increasingly important in controlling V_P/V_S. From this model simulation, it is clear that variations in V_P/V_S at shallow depths are not dominated by matrix properties, and thus must have their origins in the spatial distribution of compliant field scale features such as joints and faults.

3. Homogeneous Matrix, Heterogeneous K_f/G_f

In an attempt to reproduce the observed depth dependence of the variation in V_P/V_S, a second model simulation was performed assuming a homogeneous matrix and a heterogeneous (random) distribution of K_f/G_f. Again basing the model on the observed V_S, the predicted velocities are shown in Figure 5. Here we see that the decrease in variation in V_P/V_S with depth is reproduced fairly well.

It should be noted that in the model, the variation in the ratio K_f/G_f does not vary systematically with depth. The reduction in variation in V_P/V_S with depth reflects the decreasing influence of the compliant field scale features with depth, with V_P/V_S approaching that assumed for the matrix with increasing depth. However, the model predictions deviate from the field inversions in that the model results exhibit a clear positive correlation between V_P and V_P/V_S which is not seen in the field data. The positive correlation between V_P and V_P/V_S in the model reflects the fact the G_f was constrained to reproduce observed V_S, and thus the variation in V_P/V_S was restricted to perturbations in K_f (which only influences V_P). Thus, this model realization


2
Vp/Vs
1.5
2
6
Vp (km/s)
2
Vp/Vs
1.5
1
4
Vs (km/s)
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1.5
2
Vp/Vs
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2
Vp/Vs
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e

indicates that V_P/V_S systematics with depth appear explainable by a random variation in K_f/G_f (independent of depth), while V_P/V_S systematics with V_P and V_S appear to require a control by something other than variations in K_f alone.

A slight modification in the way in which the model is applied can easily produce the observed systematics between V_P/V_S and V_S (and lack thereof between V_P/V_S and V_P). In Figure 6, we use identical input parameters as in Figure 5, with the exception that we take observed V_P to predict V_S. This in essence assures that there will be no correlation between V_P/V_S and V_P, which in turn requires a negative correlation between V_P/V_S and V_S.

Note the general agreement between the model realization (Figure 6) and the field data (Figure 1). The model realization appears to have the necessary systematics to match the inversion data relatively well. We have thus found a minimal set of model assumptions which contains the necessary constraints to fit the data. We will return to discuss the physical implications of the these assumptions in section VII.

4. The Effect of ***Matrix*** *Saturation*

To assess whether matrix saturation effects are visible in the field seismic data, we performed another model simulation with heterogeneous K_f/G_f and heterogeneous matrix properties. Matrix heterogeneity was assumed to be bi-modal (i.e. either saturated or dry), and is identical to that used to model the 1-d velocity inversions of *O'Connell and Johnson* [1991]. As in the last simulation in section V.3, the model was constrained by field V_P and used to predict V_S. The results are presented in Figure 7.

As should be expected, we find that at depth, the V_P/V_S variation is largely controlled by matrix properties (i.e. saturated matrix is clearly separated from dry), but that this clear separation only exists at the deepest depths. At progressively shallower depths, the predictions using dry and saturated matrix show considerable overlap, indicating that matrix saturation effects cannot be reliably resolved at these depths and scale.

It should be noted that the relative shift between the dry and saturated matrix values presented in Figure 7 does not reflect the expected signal due to drying of the matrix. This is because the values of K_f (and hence G_f) are dependent on the saturation state of the matrix. Thus the values of K_f and G_f used in Figure 7 are systematically different for saturated and dry matrix. The more appropriate measure of sensitivity to changes in matrix properties is represented in a simulation such as that in (section V.2), which shows the effect of matrix variations for a single representation of the field scaling model. While that simulation does not represent the observations well (due to the assumption of homogeneous K_f/G_f and the constraint to fit field scale V_S rather than V_P), it illustrates how the ratio K_f/G_f dominates the value of V_P/V_S at shallow depths. Thus it should be expected that changes in V_P/V_S due to temporal changes in matrix saturation will be muted by the effects of field scale compliant features by an amount which reflects the degree to which K_f/G_f dominates V_P/V_S **at** the field scale. Conversely, temporal changes in K_f/G_f will dominate changes in V_P/V_S at shallow depths, but become decreasingly important with increasing depth.

VI. SOME WORDS OF CAUTION

The systematics between V_S and V_P/V_S appear in at least three independent studies of field seismic velocities. However, it should be noted that each of these studies followed similar procedures and used similar inversion algorithms. Thus the potential exists that the observed systematics are artifacts of the inversion process.

Of particular concern is that a simple null hypothesis also reproduces the systematics seen in the data. If the observed variations in compressional and shear velocities are random and uncorrelated and have relative variations of the order observed in the inversions, it follows that one would see a clear negative correlation between V_S and V_P/V_S. Thus noise in the inversion can produce and/or contribute to the same systematics.

This observation serves both as a warning and also as an indication of the broad family of viable models which are consistent with the data. Any combination of processes (either physical or numerical artifact) which act to destroy correlations between V_P and V_S while preserving the observed variability in V_S, will produce the observed systematics.

VII. DISCUSSION

A simple field scaling model is shown to be capable of reproducing field observations with a minimal set of assumptions. Here we discuss the physical implications of these assumptions, and present two contrasting physical models which are consistent with the field inversions.

Field scale velocities at shallow reservoir depths within The Geysers are found to be significantly lower than values measured in the laboratory on reservoir matrix. To the extent that the laboratory data is representative of the reservoir as a whole, it is clear that field scale velocities are largely controlled by field-scale compliant features. Thus, variability in field-scale V_P/V_S at shallow depths requires variability in properties of the field scale features themselves. In the context of the proposed nodel, this variability in V_P/V_S is largely controlled by the ratio K_f/G_f, with minor contributions from expected matrix variations. The importance of K_f/G_f decreases with depth, as variations resulting from matrix heterogeneity become more important. We emphasize that model fits to the field data do not require any systematic changes in the relative variations in K_f/G_f with depth, which should be expected if pressure is the dominant control on fracture compliance [see *Boitnott*, 19951.

The observed systematics between V_P, V_S, and V_P/V_S indicate that, within metagraywacke dominated reservoir, V_P is largely uncorrelated with V_P/V_S at any given depth. Additionally, relative variations in V_S are found to be larger than relative variations in V_P. Attempts to appeal to variations in fluid compressibility alone to explain the observed V_P/V_S anomalies are complicated by the observed lack of correlation between V_P and V_P/V_S anomalies. In order for traditional poroelastic models to apply, some other process (or combination of processes) which influences V_P (but not V_P/V_S) must be active, and it must be correlated with anomalies in V_P/V_S (see Figure 8).

Based on qualitatively similar behavior exhibited by the matrix, we suggest that the same physical mechanism which leads to the observed systematics in the matrix (i.e. shear weakening) may influence the properties of field-scale features. The shear weakening in the matrix is known to correlate with illite content. With illite being a pervasive mineral phase throughout The Geysers reservoir, it is not unreasonable to expect that shear weakening of the field-scale features due to the presence of illite also contributes to observed anomalies. Following this argument, high V_P/V_S and low V_S would be indicative of water-wet (weakened) reservoir. The lack of correlation between V_P and V_P/V_S would be explained by the interplay between fluid compressibility effects and the shear weakening. Increases in V_P due to the relative incompressibility of liquid water would be counteracted by decreases in V_P due to weakening of the shear modulus (see again Figure 8).

Another alternative interpretation which does not require shear weakening at the field scale would be that dry reservoir (low pore fluid compressibility) correlates with regions of low pore pressure (depleted reservoir). In such a scenario, low pore pressure (high effective stress) would cause elevated V_P and V_S anomalies without significantly perturbing V_P/V_S. The V_P/V_S (as well as V_P) would be depressed in these same regions as a result of low pore fluid compressibility. The net effect of these two processes would be to destroy the positive correlation between V_P and V_P/V_S expected from variable fluid compressibility, and produce the negative correlation between V_S and V_P/V_S (see again Figure 8).

Distinguishing between these and other interpretations will likely require additional observations, such as from drilling and production data. More quantitative assessments of each scenario should prove enlightening, as each requires the apparently coincidental balancing of the pore fluid compressibility effect with the secondary mechanism (either shear weakening or pore fluid pressure variations). Quantitative constraints could possibly rule out one of these hypotheses or indicate that both mechanisms could work in concert. It should be noted that both of these interpretations lead to the same qualitative interpretation of V_P/V_S anomalies, namely high V_P/V_S reflects wet reservoir and low V_P/V_S reflects dry reservoir. They also indicate why V_P anomalies may not represent variability in saturation.

Other explanations should also be explored, as the effects of variability in preferred orientation of fractures may also play a role in producing field scale V_P/V_S anomalies. Throughout this paper we have explicitly assumed isotropy both at the matrix and field scale. Introduction of anisotropy into the model will add an additional set of variables controlling V_P/V_S.

It should also be emphasized that these observations and interpretations are sensitive to the relative magnitude of the variations in V_P and V_S. Issues concerning the accuracy of the inversions themselves should be scrutinized, as dependencies on damping parameters, starting models, and input data-sets are known to influence the inversion results in ways which are not always intuitive.

VIII. ACKNOWLEDGMENTS

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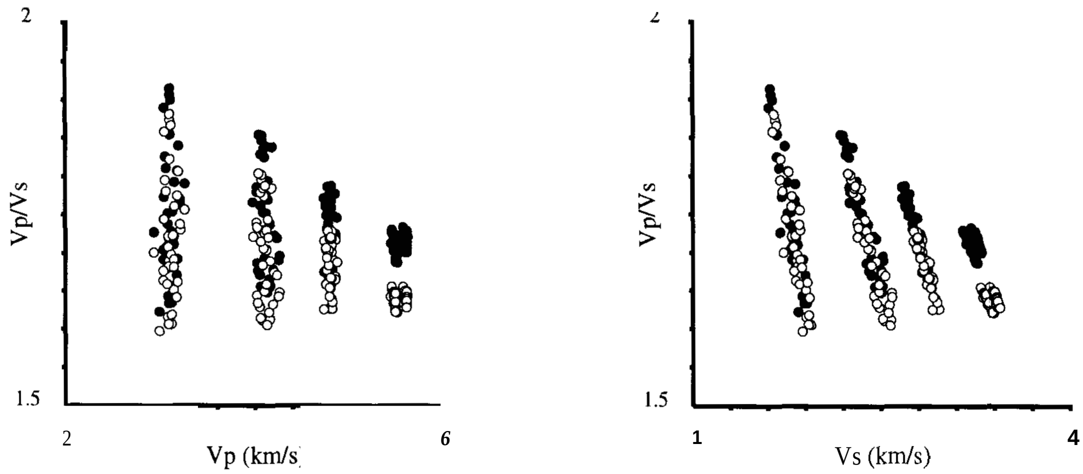

Figure 7: Stochastic model simulation similar to that in Figure 6, but assuming a matrix model with variable saturation. Open symbols indicate dry matrix and filled symbols indicate saturated matrix. Saturation effects in the matrix are clearly distinguishable at depth. but are hidden at the shallower levels by the considerable variation in V_P/V_S due to heterogeneity in K_f/G_f

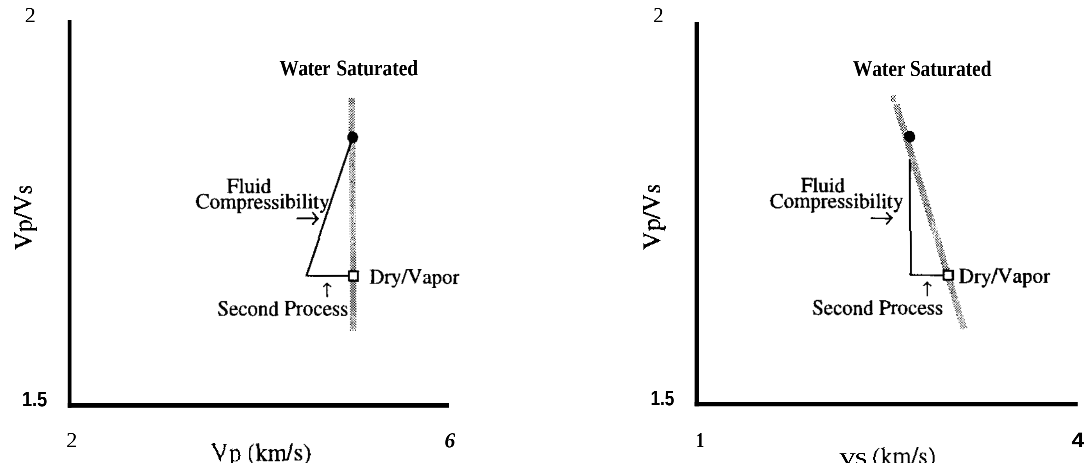

Figure 8: Schematic illustration of the general physical interpretation of the field seismic observations. The solid dot indicates the velocity properties of water saturated reservoir. Upon drying, two effects **are** super-imposed. First, the increase in fluid compressibility decreases the effective bulk modulus, thus decreasing V_P. It is assumed that changes in effective density are negligible and that fluid compressibility does not effect the shear modulus (and thus shear velocity). Second, upon drying a second process occurs, which acts to increase both V_P and V_S, without influencing V_P/V_S. In the context of the shear weakening hypothesis, the second process is the hardening of the shear modulus upon drying, while in the context of the pore pressure reduction hypothesis, this process is the effect of increasing effective stress with depletion.