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ABSTRACT

As part of our study on “Relationships between seismic properties and rock microstructure”, we have studied

1. Methods for detection of stress-induced velocity anisotropy in sands.
2. We have initiated efforts for velocity upscaling to quantify long-wavelength and short-wavelength velocity behavior and the scale-dependent dispersion caused by sediment variability in different depositional environments.

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INTRODUCTION

In this quarter, we submit results of our research on: pore textural mapping and its relation to centimeter-scale core measurements of impedance and measurements of seismic properties of unconsolidated sediments at very low effective pressures. The special effect of stress anisotropy on velocity anisotropy is investigated. Two papers have been submitted for publication. This report presents preprints of our research relevant to this project on impedance mapping, soft-sediment measurements, stress anisotropy, and scale effects.

PAPER 1

Vega, S., Prasad, M., Mavko, G., and Nur, A., Detection of stress-induced velocity anisotropy in sands. Submitted to GRL

In this paper, we present a preliminary study on stress-induced velocity anisotropy in two different sands. We describe the method used for sample preparation, and the polyaxial apparatus used for velocity, strain, and stress measurements. Furthermore, we examine the velocity response as a function of stress in different directions of applying uniaxial strain test to the samples. The strains and velocities of the two sands are also compared. We show that stress-induced velocity anisotropy exists and is detectable in sands. A stress anisotropy of 87% corresponds to a velocity anisotropy of 29%-34%, and there is a linear dependency of velocity anisotropy on stress anisotropy in the sands.

Paper 1: Total of five figures in paper

PAPER 2

Mukerj, T., and Prasad, M. Image processing of SAM data to estimate textural scales and anisotropy: abbreviated form submitted for the SEG Annual Conference to be held in Dallas in October 2003.

We apply different statistical methods for characterizing heterogeneity and textures from scanning acoustic microscope (SAM) images of shale microstructures. Characterizing and understanding the microgeometry, their textures, scales, and textural anisotropy is important for better understanding the role of microgeometry on effective elastic properties. We analyzed SAM images from Bakken shale, Bazhenov shale, and Woodford shale. Our analysis, based on spatial autocorrelation functions shows that there is a small positive correlation between the degree of heterogeneity and the mean spatial correlation length of the microstructure. The textural anisotropy ranges from 10% to 80%. There is considerable variability within each image, as well as from one image to another. A singular value decomposition (SVD) spectral analysis showed that the shale microstructures have characteristics in common with fractal stochastic images. We also obtain a correlation between maturity and textural heterogeneity. The textural heterogeneity increases with increasing maturity (decreasing kerogen content), while there is a general decrease in textural anisotropy with maturity. The accompanying paper A4 in this volume relates the textural characteristics obtained from image processing to characteristics obtained from ultrasonic measurements.

Paper 2: Total of nine figures in paper

Detection of stress-induced velocity anisotropy in sands

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Abstract

In this paper, we present a preliminary study on stress-induced velocity anisotropy in two different sands. We describe the method used for sample preparation, and the polyaxial apparatus used for velocity, strain, and stress measurements. Furthermore, we examine the velocity response as a function of stress in different directions of applying uniaxial strain test to the samples. The strains and velocities of the two sands are also compared. We show that stress-induced velocity anisotropy exists and is detectable in sands. A stress anisotropy of 87% corresponds to a velocity anisotropy of 29%-34%, and there is a linear dependency of velocity anisotropy on stress anisotropy in the sands.

1. Introduction

It has been shown that stress changes in rocks can be monitored using stress-induced velocity anisotropy (Nur and Simmons, 1969; Nur, 1971; Mavko et al., 1998; Sinha and Kostek, 1996). However, to our knowledge, very few studies have been conducted on stress-induced velocity anisotropy in sands.

Textural anisotropy in sands can be observed in nature, for example at beaches and in turbidite deposits. The effect of gravity settling on natural stratification in granular materials has been shown through lab tests and theoretical simulations (Makse et al., 1997; Baxter et al., 1998; Cizeau et al, 1999). This textural anisotropy influences the

anisotropy of mechanical properties (Wong and Arthur, 1985; Jiang et al., 1997; Hoque and Tatsuoka, 1998). The directional dependence of mechanical properties becomes more pronounced at higher stresses. Hoque and Tatsuoka (1998) demonstrated that static Young's modulus and strain anisotropy can be induced by stress anisotropy. Nevertheless, the effect of anisotropic stress on the dynamic elastic properties of unconsolidated materials is not well understood. In a comparison between sand and rocks, Yin (1993) found that velocity anisotropy was more sensitive to anisotropic stresses in the sand and soft rock (siltstone). Sinha and Kostek (1996) confirmed this result in a theoretical analysis of stress-induced shear velocity anisotropy in boreholes. However, Wang (2002) found that sands were intrinsically isotropic and shaly sands were more anisotropic at lower pressures.

The purpose of this paper is to show that stress-induced velocity anisotropy exists and is measurable in sands. We present experimental results of uniaxial strain tests of ultrasonic velocity and strain in sands with two different grain sizes and packings.

2. Procedure

We used a uniaxial strain apparatus (Yin, 1993) to make compressional velocity and strain measurements in unconsolidated materials. For our study, we modified the apparatus to facilitate velocity and strain measurements in these materials.

We measured velocity, stress, and strain in three perpendicular directions (Z, X, and Y) under uniaxial strain conditions. In these tests, a compressive stress was applied in the vertical (Z) direction while the platens in the X and Y directions stayed constrained. All sand samples were measured during loading and unloading. We loaded the samples

with the initial compressive stress, σ_z , and waited eight to ten hours before starting the measurements. At each loading step, we allowed stresses to stabilize, i.e. until the force read-out did not change, (1.5 hours in loading, and 0.5 hour in unloading) before making the measurements. Grain-size analyses were made by sieving; grain density was measured using a pycnometer; and porosity (ϕ) was calculated from the volume and grain density of the sands.

2.1. Experimental setup

Figure 1 shows a plan view of the setup, which consists of a square welded steel frame for polyaxial loading in three orthogonal directions. The frame has four steel pistons for loading the sample in the horizontal (X, Y) directions, and one in the vertical (Z) direction. The samples are loaded manually using a torque wrench, and a cubic aluminum cell of 12.1 cm on each side is used for holding them. On the six faces of the cell, there are six platens (5cm x 5cm x 4cm) that contain piezoelectric transducers to measure the acoustic P waves. The side of each piston in contact with the platens has ball bearing caps to allow for slight unevenness in the sample. We made a base to place the cubic sample cell in the square frame and to align the sample platens with the pistons. The Z direction displacement gauge was positioned on the wall of the cell. For measuring the stresses, we positioned load cells between the piston and plates, one in each direction. The load cells are connected to digital read-outs (Sensotec) that display the force in pounds. The force (F) was converted to pressure (P) by $P=F/A$, where A is the area of the loading pistons that transfer stress to the sediments. We measured the

deformation in the sample using dial gauges in the X, Y, and Z directions (displacement uncertainty: $\Delta l = 0.03$ mm).

Each of the six platens carries one piezoelectric P mode transducer with a central frequency of 1 MHz. There are two platens in each direction, one functions as the transmitter and the other as the receiver. We use a pulse generator (Panametrics 505 5PR) and an oscilloscope (Tektronix 2430) to excite the transmitter and receive the signals, respectively. We used “Spectrum Division” software to acquire and process the acoustic data. The apparatus was tested by measuring velocity in aluminum (Becker, 1982), granite and shale (Yin, 1993). The velocities lay within 1% of the expected values.

2.2. Samples and sample preparation

We used two dry sands for our tests: A beach sand with an average grain size of 0.25 mm and grain density 2.060 g/cc, and a construction sand with an average grain size of 0.91 mm and grain density 2.613 g/cc. We repeated the velocity measurements on two samples to check for consistency in the sample preparation. The sample-to-sample range of initial porosity was 38-41% for the coarse-grained construction sand, and 45-47% for the fine-grained beach sand. The coarse-grained sand was well-sorted and had a higher sorting coefficient (see Table 1) than the fine-grained sand.

In the sample preparation, we poured the grains vertically into the cell and tamped the sand pile. In this process we were as consistent as possible to insure reproducible results. We found that the fine-grained samples showed natural stratification, with roughly horizontal layers. This natural stratification has been seen in mixtures of (a) large rounded grains and small rough grains (Makse et al., 1997; Cizeau et al, 1999), and (b)

various grain sizes with similar grain shapes (Baxter et al., 1998). Our coarse-grained samples did not show natural stratification.

Table 1. Sample characteristics.

	fine-grained sample		coarse-grained sample	
ρ (g/cc)	2.606		2.613	
grain size average (mm)	0.25		0.91	
S^*	0.66		0.82	
σ^{**}	0.15		0.11	
Packing	natural stratification		non stratification	
ϕ^1	45%	47%	38%	41%
$\Delta\phi^2$	4%		7%	
velocity-repeatability ³	94%		97%	

* S : sorting coefficient, S = grain size @ 75% wt/ grain size @ 25% wt

** σ : grain size standard deviation

¹ ϕ : initial porosity. The two ϕ for each sand are for the repeated measurements.

² $\Delta\phi = (\phi_{\text{highest}} - \phi_{\text{lowest}}) / \phi_{\text{highest}}$ at all stresses

³ velocity repeatability = $1 - (Vp_{(\phi \text{ highest})} - Vp_{(\phi \text{ lowest})}) / Vp_{(\phi \text{ highest})}$ for all the stresses

The velocity measurements were repeatable from sample to sample within 94% and 97% for the fine-grained sand and coarse-grained sand, respectively; the corresponding sample-to-sample porosity difference ($\Delta\phi$) was 4% and 7%, respectively (Table 1). The uncertainty of individual measurements was 1%. In this paper, we present velocity and strain results for the two samples with the most similar porosity: the coarse-grained sample with $\phi = 41\%$ and the fine-grained sample with $\phi = 45\%$.

3. Results and discussion

3.1. Grain size effect

Vp seems to be affected by grain size and porosity (Figure 2b shows Vp in Z direction, Vpz): velocities in the coarse-grained sample (with lower porosity) are slightly higher than in the fine-grained sample, which agrees with Prasad and Meissner (1992).

On the other hand, our measured strain showed ductile behavior during the loading and unloading for both sands. Figure 2a shows that strain is larger in the coarse-grained sand than in the fine-grained sand. The strain hysteresis is slightly larger in the coarse-grained sand, particularly at low stresses. It is possible that the grain packing in the fine-grained sand is more efficient due to its poured sorting. Finer grains fill in the space between coarser grains and limit their movement.

3.2. Anisotropic stress effects

3.2.1. Induced stress

As the applied stress increased in the Z direction, it induced compressive stresses in the orthogonal (X-Y) directions. Figure 3 shows that the induced compressive stresses, σ_x and σ_y , were lower in the loading process than in the unloading process. This stress hysteresis corresponds to the strain hysteresis shown in Figure 2a. We suggest that grain rearrangements and a tighter packing lead to an induced stress accumulation in the X and Y directions that remains during unloading. For the coarse-grained, non-stratified samples, σ_x and σ_y were the same. For the fine samples with natural stratification, σ_x and σ_y were the same in one of the samples ($\phi = 47\%$), and slightly different in the other sample ($\phi = 45\%$). The difference in induced stresses between the two samples of fine-grained sand probably shows effects of sample preparation variations also reflected in the lower velocity-repeatability of 94% (Table 1).

3.2.3. Velocity

Figure 4 shows the velocities in the Z, X, and Y directions as functions of applied stress for (a) the fine-grained sample, and (b) the coarse-grained sample. There is

considerable velocity anisotropy in both sands, as for the sand reported by Yin (1993). The highest velocity, V_{pz} , is in the direction of applied stress. The other two lower perpendicular velocities, V_{px} and V_{py} , are roughly the same. This observation is in contrast to results of velocity anisotropy measured in layered media under hydrostatic stress (Prasad et al., 1994). Such measurements have found that velocity is lower in propagation directions perpendicular to the layers. Our results indicate that stress anisotropy has a more significant effect on the velocity than the textural anisotropy. Velocities during unloading were higher than during loading. This velocity hysteresis was more notable in the directions of the induced stresses (X and Y) than in the applied stress direction (Z). This coincides with the stress hysteresis pattern found in Figure 3.

We define relative stress anisotropy ($\Delta\sigma$) and relative velocity anisotropy (ΔV_p) as

$$\Delta\sigma = \frac{\sigma_z - \text{average}(\sigma_x, \sigma_y)}{\sigma_z} * 100, \quad (1)$$

$$\Delta V_p = \frac{V_{pz} - \text{average}(V_{px}, V_{py})}{V_{pz}} * 100. \quad (2)$$

Figure 5a shows the change in relative velocity anisotropy ΔV_p as a function of applied stress, σ_z . ΔV_p was almost constant during loading. During unloading, it decreased significantly, from 34% to 9% for the fine-grained sand and from 29% to 6% for the coarse-grained sand. The relative stress anisotropy $\Delta\sigma$ shows a similar behavior. $\Delta\sigma$ was roughly constant during loading and decreased from 87% to around 61% during unloading. In order to investigate the relationship between velocity anisotropy and stress anisotropy, we plot ΔV_p versus $\Delta\sigma$ in Figure 5b. In both sands, ΔV_p varies linearly with $\Delta\sigma$, with coefficient of determination R^2 of 0.96-0.99 for the fits. The fine-grained sand

sample, with natural stratification, has higher ΔV_p , which is also evident in Figure 4. The coarse-grained, non-stratified sand also showed considerable ΔV_p , indicating preferential alignment of grains.

Our results suggest that the change in velocity anisotropy is a consequence of stress anisotropy variation. During loading, the induced stress, in the X and Y directions, increased proportionately with the applied stress and the stress anisotropy remained constant. Consequently, velocity anisotropy also remained constant. During unloading, the induced stresses in the XY plane did not relax proportional to the decreasing applied stress, resulting in a decrease in stress anisotropy. This stress accumulation in the XY plane led to higher velocities in that plane and lower velocity anisotropy during unloading.

4. Summary

We found velocity anisotropy due to stress anisotropy in two different sands. The highest velocity, V_{pz} , was in the direction of applied stress. The other two lower perpendicular velocities, V_{px} and V_{py} , which were in the direction of the induced stresses, were roughly the same. The sand with natural stratification showed higher velocity anisotropy than the non-stratified sand. Furthermore, each separate sample displayed a linear dependence of velocity anisotropy with stress anisotropy. On the other hand, V_{pz} was slightly higher in the coarse-grained sample (with lower porosity) than in the fine-grained sample as a result of grain size and porosity. The results also suggested that the change in velocity anisotropy is a consequence of stress anisotropy variation.

The strain showed ductile behavior during the loading and unloading for both sands, with larger strain for the coarse-grained sand than for the fine-grained sand. Nevertheless, we were unable to discriminate whether the difference in strain was due to grain size, packing, and sorting or some combination of those factors. Future research will study the effect of these factors in the strain as in the velocity anisotropy behavior.

5. Acknowledgements

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Figure 1. Plan view in the X-Y plane of the setup.

Figure 2. (a) Strain in Z-direction, ϵ_z , versus applied stress, σ_z . (b) Compressional velocity in Z direction, V_{p_z} , versus σ_z during loading. (The coarse-grained sample, $\phi = 41\%$, and the fine-grained sample, $\phi = 45\%$ are indicated with black and gray circles, respectively; filled symbols: loading path, and open symbols: unloading path).

Figure 3. Applied stress (σ_z) and induced stress response (σ_x and σ_y) for (a) the fine-grained sample, $\phi = 45\%$, and (b) the coarse-grained sample, $\phi = 41\%$. (The X and Y directions are indicated with circles and squares, respectively; filled symbols: loading path, and open symbols: unloading path).

Figure 4. V_p versus applied stress, σ_z , for (a) the fine-grained sample, and (b) the coarse-grained sample. (The X and Y directions are indicated with circles and squares, respectively; filled symbols: loading path, and open symbols: unloading path).

Figure 5. (a) ΔV_p as a function of applied stress, σ_z , and stress anisotropy $\Delta\sigma$ for the coarse-grained sand sample with $\phi = 41\%$ and the fine-grained sand sample with $\phi = 45\%$. (a) ΔV_p versus σ_z : arrows indicate loading path; (b) ΔV_p versus $\Delta\sigma$: solid lines are linear regression fits through the data of the form $\Delta V_p = C_1 + C_2\Delta\sigma$, with $C_1 = (-70.7, -45.5)$, $C_2 = (1.1, 0.9)$, and $R^2 = (0.96, 0.99)$ for the coarse-grained sand and fine-grained sand, respectively. (Black symbols: coarse-grained sand sample, and gray symbols: fine-grained sand sample).

PAPER A3**IMAGE PROCESSING OF SAM DATA TO ESTIMATE TEXTURAL SCALES AND ANISOTROPY****Tapan Mukerji***Stanford Rock Physics Laboratory***Manika Prasad***Stanford Rock Physics Laboratory***ABSTRACT**

We apply different statistical methods for characterizing heterogeneity and textures from scanning acoustic microscope (SAM) images of shale microstructures. Characterizing and understanding the microgeometry, their textures, scales, and textural anisotropy is important for better understanding the role of microgeometry on effective elastic properties. We analyzed SAM images from Bakken shale, Bazhenov shale, and Woodford shale. Our analysis, based on spatial autocorrelation functions shows that there is a small positive correlation between the degree of heterogeneity and the mean spatial correlation length of the microstructure. The textural anisotropy ranges from 10% to 80%. There is considerable variability within each image, as well as from one image to another. A singular value decomposition (SVD) spectral analysis showed that the shale microstructures have characteristics in common with fractal stochastic images. We also obtain a correlation between maturity and textural heterogeneity. The textural heterogeneity increases with increasing maturity (decreasing kerogen content), while there is a general decrease in textural anisotropy with maturity. The accompanying paper A4 in this volume relates the textural characteristics obtained from image processing to characteristics obtained from ultrasonic measurements.

INTRODUCTION

Microstructural characteristics of organic rich shales can give important insights on the maturation processes and on oil generation from such formations. Since changes in shale texture and in hydrogen content are closely linked with kerogen maturity, a correlation between them would enhance methods for detecting and prospecting of kerogen rich shales. The problem is

complicated by the fact that the intrinsic anisotropic texture of the shales is enhanced by kerogen distribution in the shales. Attempts have been made to relate acoustic velocity and velocity anisotropy to the degree of kerogen maturity of the shales (Vernik and Nur, 1994; Vernik and Liu, 1997). These studies have been instrumental in improving our understanding of the ultrasonic properties in kerogen rich shales. We have revisited the ultrasonic data collected by Vernik and co-authors and interpreted them using recent acoustic microscopy analyses of the impedance microstructure of the shales (Prasad and Nur, 2001)

Optical and scanning electron microscopy methods to analyze kerogen shale microstructure have been utilized in the past. However, due to the opaque nature of the kerogen and the associated pyrite, such methods are rather difficult to implement. In addition to optical and scanning electron microscopy, we used a non-destructive technique to map the impedance microstructure of kerogen-rich shales with a scanning acoustic microscope. With this technique we were able to map changes in elastic properties as the shales undergo maturation. This paper reports results of texture characterization in samples belonging to various maturity grades and with different kerogen contents. Image analyses techniques (described below) are used to detect changes in texture and heterogeneity in the acoustic microscopy images.

STATISTICAL DESCRIPTION OF IMAGE TEXTURES AND HETEROGENEITY

We used statistical descriptors to quantify the heterogeneity and textures observed in the images. The heterogeneity was quantified by the coefficient of variation (CV) given by the ratio of the standard deviation to the mean of the image pixel values. Gray scale image intensity values were converted to elastic impedances using a calibration function before computing their statistics. Textures can be quantified using spatial autocorrelation functions (Figure 1). We used Fourier transform based autocorrelation estimation. Radial profiles of the autocorrelation function along azimuths ranging from 0° to 180° were computed, and the correlation length estimated at each azimuth. The correlation length is taken to be the lag value where the correlation function falls to $1/e$ of its maximum value at zero lag. The texture anisotropy was quantified by the anisotropy ratio (AR) defined as the ratio between the maximum and minimum correlation lengths obtained over all azimuths. Textures were also analyzed using a singular value decomposition (SVD) of the images (Jain, 1989). The SVD spectra are computed by first taking a singular value decomposition of the image matrix. The singular values are normalized by the maximum singular value, and they are plotted in descending order. The spectrum of singular values shows different decay behavior for different textures (Figure 2).

Figure 1: Spatial autocorrelation and spatial spectrum can be used to stochastically describe image textures and scales. Top left: Synthetic images with increasing spatial correlation; center: corresponding 2D autocorrelation function; right: corresponding 2D Fourier power spectra. Bottom: radial profiles of isotropic Gaussian autocorrelation functions showing the relation between textures and correlation length.

Figure 2: Singular value spectrum shows distinctive behavior for images with Gaussian spatial correlation (top left) versus fractal images (top right). In the bottom figure the black lines with a rapid fall off in singular value corresponds to images with Gaussian autocorrelation, while the dotted red lines correspond to SVD spectra of fractal images.

SAM IMAGES

Despite similar chemical compositions, microstructure of the samples differed considerably. Acoustic micrographs of the Bakken shale series samples, a Bazhenov shale and a Woodford shale are shown in Figure 3. The C-scan surface images were made at 1 GHz with a calibrated color scale. The calibrations were made using standard materials with known impedance (Prasad

et al., 2002). From the different maturity shale samples examined in this study, we find following major differences in the impedance microstructural images:

- Increase in impedance as maturity progresses
- Increase in grain size and in the number of coarse grains in mature shales
- Kerogen and grain distribution undergo major change as the maturity progresses. In immature shale, kerogen forms a more or less connected matrix and the higher impedance grains are dispersed in this matrix. In more mature shale, there is a significant increase in number of coarse grains. The grains appear to form a framework with kerogen globules distributed within this frame.
- Bedding parallel kerogen filled cracks appear to be more common in immature shale.

Figure 3: SAM images of Bakken shales (bk), Bazhenov shale (bz, lower left), and Woodford shale (wf), lower right. The images have differing resolutions. The image size in microns is indicated. The top left image has an order of magnitude higher resolution

RESULTS

The results of texture analyses are shown in Figures 4, 5, 6, and 7. Figure 4 shows the estimated power spectra and the corresponding autocorrelation functions while Figure 5 shows the azimuthal profiles of the autocorrelation functions. The autocorrelation functions were computed from the inverse Fourier transform of the 2-D power spectrum of each image. The azimuthal profiles were computed by two different methods. In one we used the radon transform principle. First radial projections of the 2-D power spectrum were estimated. Then a 1-D Fourier transform was applied to each radial projection to give the corresponding azimuthal profile of the autocorrelation function. In the second method a 2-D Fourier transform was first applied to the 2-D power spectrum. Then bi-linear interpolation was carried out in the autocorrelation domain to estimate the azimuthal profiles. Both methods gave comparable results, with the second method having somewhat smoother interpolation characteristics. We will discuss the results obtained from the second method. The coefficient of variation of the impedance heterogeneities ranged from about 7% to 12%, while the mean correlation length ranged from 2 to 4.5 microns (Figure 6). In general the textural anisotropy (AR) increased with increasing heterogeneity (CV), as seen in Figure 7.

We analyzed variability within images by processing different subsections of the same image, making sure to sample subsections much larger than the mean correlation length to obtain valid statistics. The variability is displayed in Figure 8.

SVD spectra of the images are distinctly different from SVD spectra of synthetic images with Gaussian autocorrelation. They show more resemblance to SVD spectra of fractal images (Figure 9).

Figure 4: Fourier power spectra (left) and corresponding autocorrelation functions (right) estimated from SAM images of Bakken shales (bk), Bazhenov shale (bz, lower left), and Woodford shale (wf), lower right.

Figure 5: Azimuthal profiles of the autocorrelation function (Figure 4) from 0 to 180 degrees.

Figure 6: CV (heterogeneity) versus mean textural correlation length.

Figure 7: CV versus textural anisotropy. Textural anisotropy is measured by the ratio of maximum correlation length to the minimum correlation length

Figure 8: Variability with images. For each image bars indicate range (5 to 95 percentile) of values obtained by sampling different subsections of the same image. Blue symbols indicate values obtained from the whole image. Top: CV versus mean correlation length. Bottom: CV versus anisotropy ratio

Figure 9: SVD spectra of SAM images are similar to SVD spectra of fractal images showing a slower decay than SVD spectra of Gaussian images. Top compares SVD spectra of Gaussian images (black solid curves), fractal images (red dashed curves), and one of the SAM images (WF1125, blue solid curve). The dotted magenta curve corresponds to a random image with no correlation. Bottom figure shows the SVD spectra of all the SAM images. The grey curves outline the Gaussian and fractal trends from top. The curve with two humps, indicating two spatial scales comes from an image with an order of magnitude higher resolution. The dotted line is the SVD spectrum of a random image with no correlation

CONCLUSIONS

Our analysis of SAM images shows the following: the coefficient of variation (CV), which is a measure of heterogeneity, ranges from 7% to about 12% for these shales. The spatial correlation length varies with direction, and the mean correlation length ranges from about 2 to 4.5 microns. There is a small positive dependence between the CV and the mean spatial correlation length. The mean correlation length generally tends to increase with increasing CV. The textural anisotropy (AR), defined as the ratio of the maximum to minimum correlation length within an image, ranges from 20% to about 80% and in general tends to increase with increasing heterogeneity (CV). Singular value analysis of the images indicates that the SVD spectra of the shale microstructure tend to be similar to (but not exactly the same as) SVD spectra of fractal images. The textural heterogeneity (CV) increases with increasing maturity (decreasing kerogen content), while there is a general decrease in and textural anisotropy (AR) with maturity. The accompanying paper in this volume relates the textural characteristics obtained from image processing to characteristics obtained from ultrasonic measurements.

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