

## **TITLE PAGE**

### **Title: Seismic and Rockphysics Diagnostics of Multiscale Reservoir Textures**

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## **ABSTRACT**

As part of our study on “Relationships between seismic properties and rock microstructure”, we have continued our work on analyzing shale textures from scanning acoustic microscope images. Our analysis is now extended to over 280 images of shales, giving us better statistics. The shales cover a range of depths and maturity. We estimate different statistical measures 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. We observed quantifiable and consistent patterns linking texture, shale maturity, and elastic P-wave impedance. The textural heterogeneity and P-wave impedance increase with increasing maturity (decreasing kerogen content), while there is a general decrease in textural anisotropy with maturity. We also found a reasonably good match between elastic impedance estimated from SAM images and impedance computed from ultrasonic measurements.

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## **PROJECT STATUS REPORT**

**MILESTONE LOG**

## INTRODUCTION

In this quarter, we submit we a continuation of our work on analyzing shale textures from scanning acoustic microscope images. Our analysis is now extended to over 280 images of shales, giving us better statistics. The shales cover a range of depths and maturity. We estimate different statistical measures 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. We observed quantifiable and consistent patterns linking texture, shale maturity, and elastic P-wave impedance. The textural heterogeneity and P-wave impedance increase with increasing maturity (decreasing kerogen content), while there is a general decrease in textural anisotropy with maturity. We also found a reasonably good match between elastic impedance estimated from SAM images and impedance computed from ultrasonic measurements.



## **PAPER 1**

### *ANALYSIS OF MICROSTRUCTURAL TEXTURES AND WAVE PROPAGATION CHARACTERISTICS IN SHALES*

Paper 1: Total of thirteen figures in paper

# **ANALYSIS OF MICROSTRUCTURAL TEXTURES AND WAVE PROPAGATION CHARACTERISTICS IN SHALES**

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## **ABSTRACT**

This is a continuation of our work on analyzing shale textures from scanning acoustic microscope images. Our analysis is now extended to over 280 images of shales, giving us better statistics. The shales cover a range of depths and maturity. We estimate different statistical measures 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. We observed quantifiable and consistent patterns linking texture, shale maturity, and elastic P-wave impedance. The textural heterogeneity and P-wave impedance increase with increasing maturity (decreasing kerogen content), while there is a general decrease in textural anisotropy with maturity. We also found a reasonably good match between elastic impedance estimated from SAM images and impedance computed 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  $0^\circ$  to  $180^\circ$  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 (Figure 2).

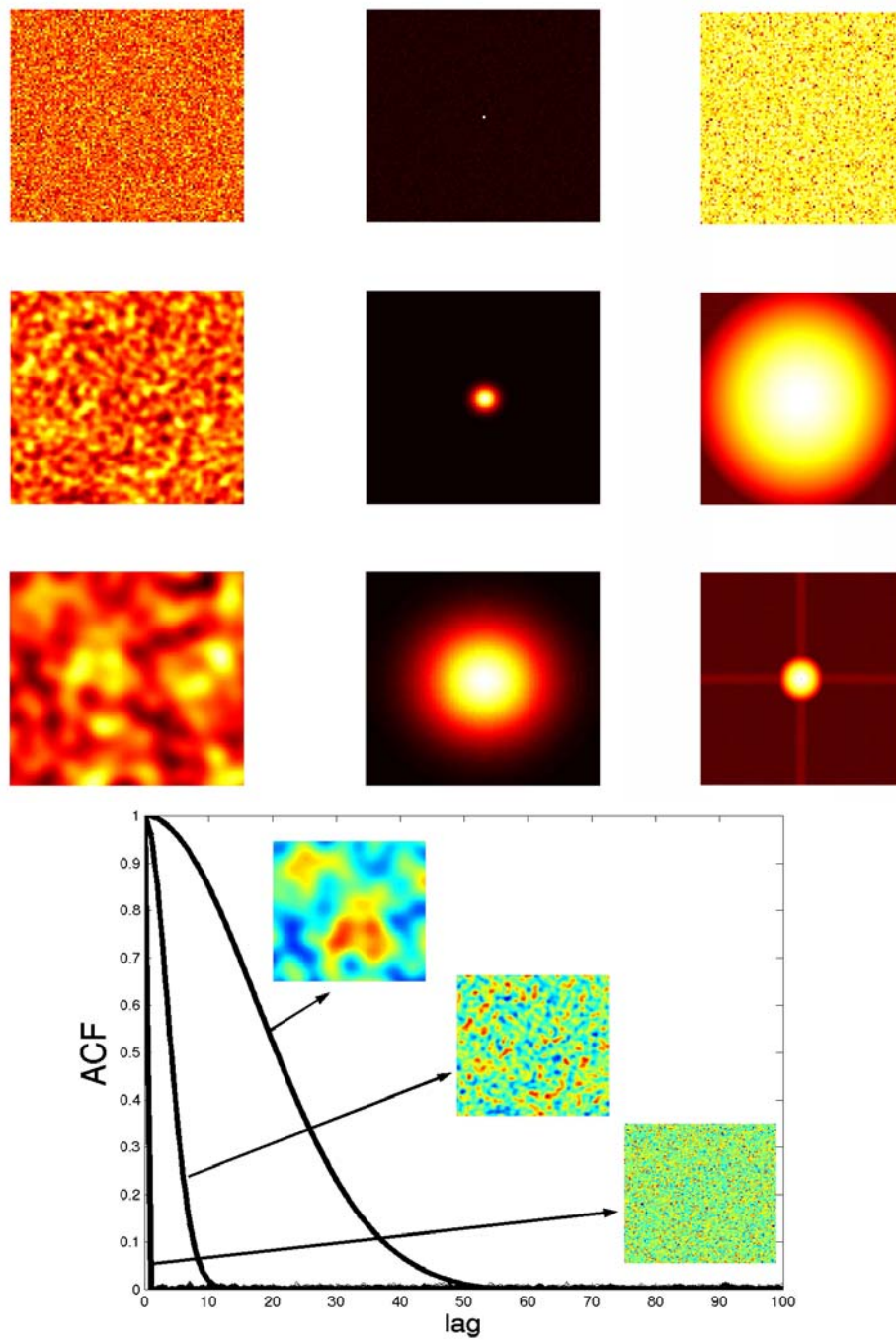


Figure 1: Spatial autocorrelation and spatial spectrum can be used to stochastically describe image textures and scales. Top left: Synthetic images with increasing spatial correlation; center: corresponding 2D autocorrelation function; right: corresponding 2D Fourier power spectra. Bottom: radial profiles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

## 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. 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.

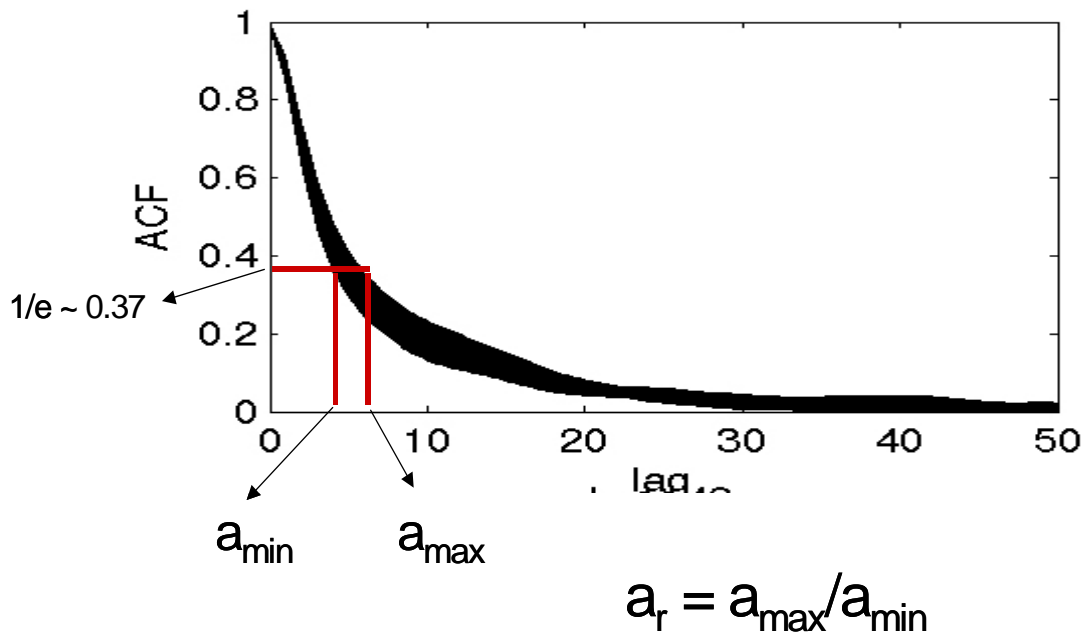


Figure 2: 1D radial profiles (0-180 at 1 degree increments) of a 2D autocorrelation function. The anisotropy ratio is estimated from the ratio of the maximum to minimum correlation length over all radial profiles.

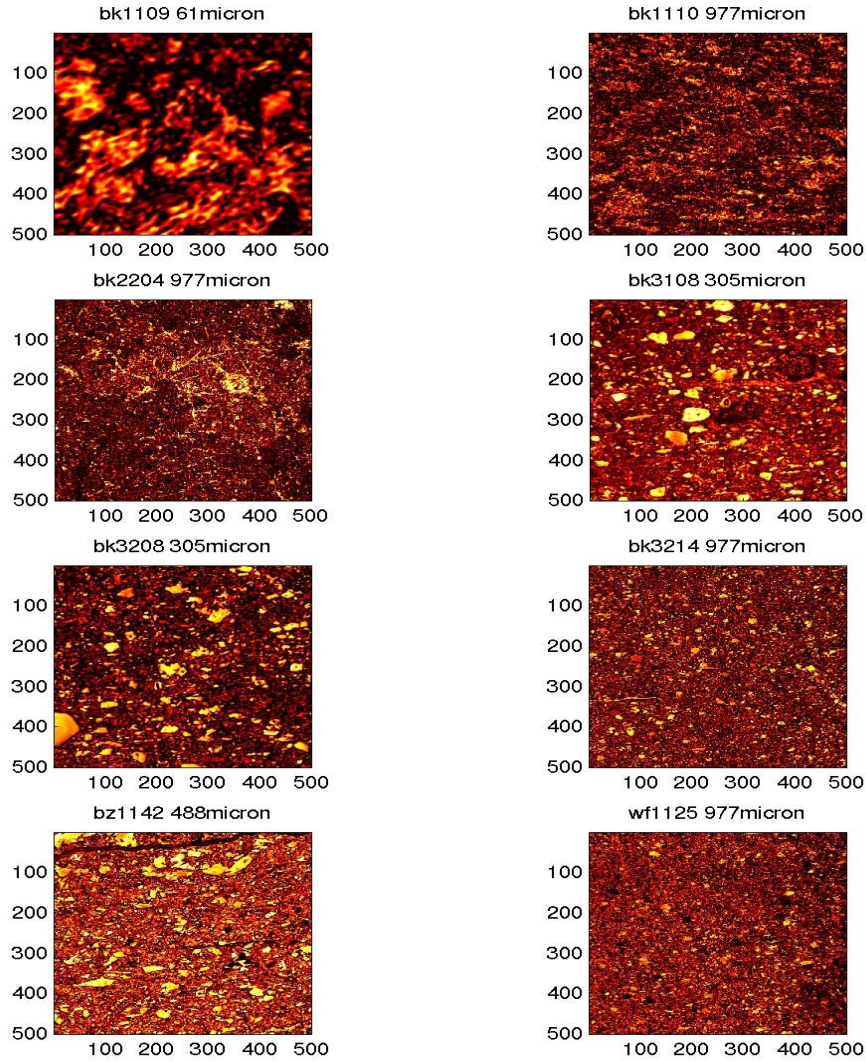


Figure 3: SAM images of Bakken shales (bk), Bazhenov shale (bz, lower left), and Woodford shale (wf), lower right. The images have differing resolutions. The image size in microns is indicated. The top left image has an order of magnitude higher resolution

## RESULTS

The results of texture analyses are discussed below and shown in the following figures. The data points plotted in the figures are averages over multiple samples, with one standard deviation bars around the estimated average. The coefficient of variation (CV) of the impedance heterogeneities ranged from about 7% to 12%. The mean correlation length ranged from 2 to 10 microns while the textural anisotropy ratio ranged from 1.1 to 1.7 (10% to 70%). We will examine the patterns between textural anisotropy and mean correlation length, and between textural heterogeneity and correlation length. We will also see how these patterns change with depth and maturity. In general, when

considered over the whole collection of images, the textural anisotropy (AR) increased with increasing mean correlation length, as seen in Figure 4. This trend can be subdivided further for the Bakken samples based on depth. Figure 5 presents AR vs. mean correlation length estimated from shallow (< 10,000 ft) and deep (> 10,000 ft) Bakken SAM images. The trend steepens with depth, and the textural anisotropy decreases while the mean correlation length increases as we go from shallow (less mature) to deeper (more mature) shales.

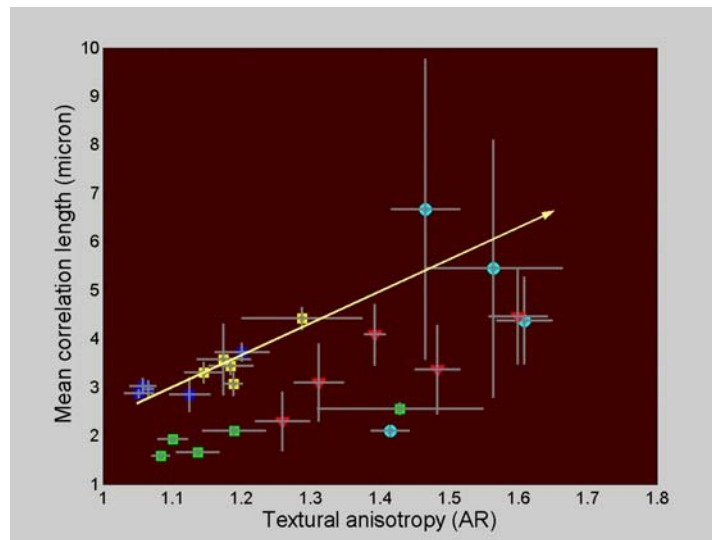


Figure 4: Mean correlation length increases with anisotropy ratio. Woodford shale – cyan circles; Bazhenov shale – triangles; Bakken shale – squares.

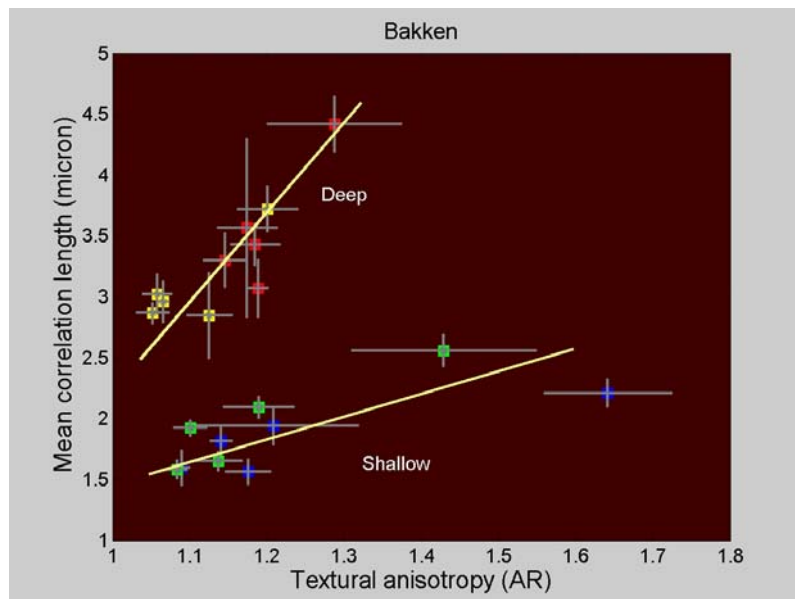


Figure 5: Mean correlation length versus anisotropy ratio for Bakken shales, separated by depth.

The textural heterogeneity and mean correlation length show a general negative correlation (Figure 6). An interesting en-echelon pattern emerges when we plot the Bakken samples separated by depths. This is shown in Figure 7. For each depth we see a negative trend between heterogeneity and correlation length, but overall there is a trend of increasing heterogeneity and correlation length with increasing depth and maturity. This is consistent with the observed trend of increasing heterogeneity (CV) with decreasing kerogen content and total organic content (TOC), as seen in Figure 8.

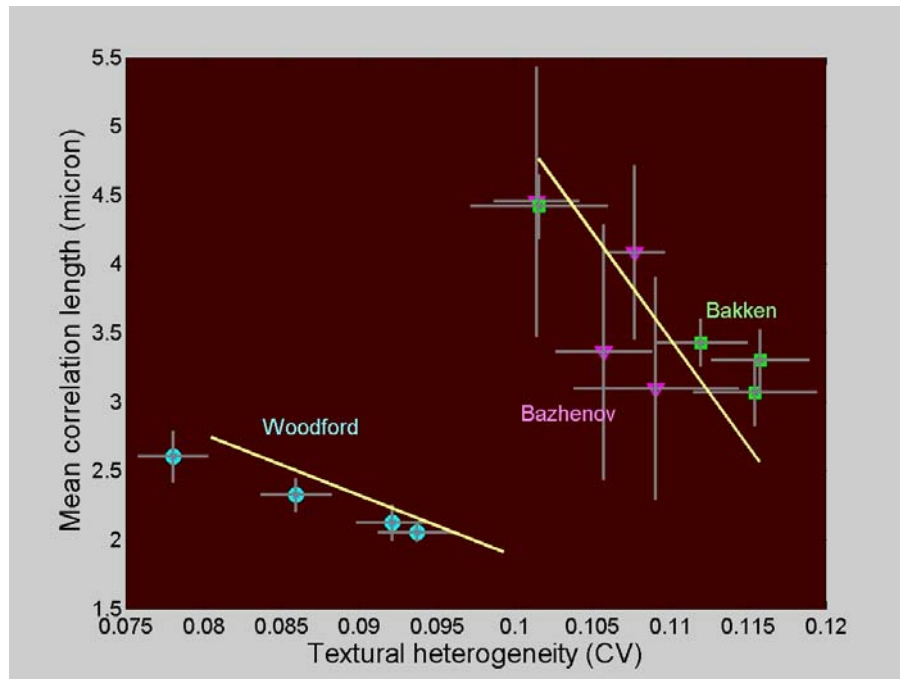


Figure 6: Textural heterogeneity versus mean correlation length showing a general negative correlation.

The SAM images had different sampled area and resolution ranging from image size of 1000 $\mu$  to 100 $\mu$  with pixel resolution ranging from about 2 $\mu$  to 0.2 $\mu$  respectively. The different sizes and resolution gave rise to a scale-dependence of the estimated textural parameters. As shown in Figure 9 the 1000 $\mu$  images showed larger textural anisotropy and smaller textural heterogeneity. The textural anisotropy seen in the 1000 $\mu$  images showed a depth and maturity dependence. The textural anisotropy decreased with increasing depth and decreasing kerogen content (Figure 10). However the textural anisotropy at the fine scale (100 $\mu$  images) did not show any trend with depth or kerogen content.



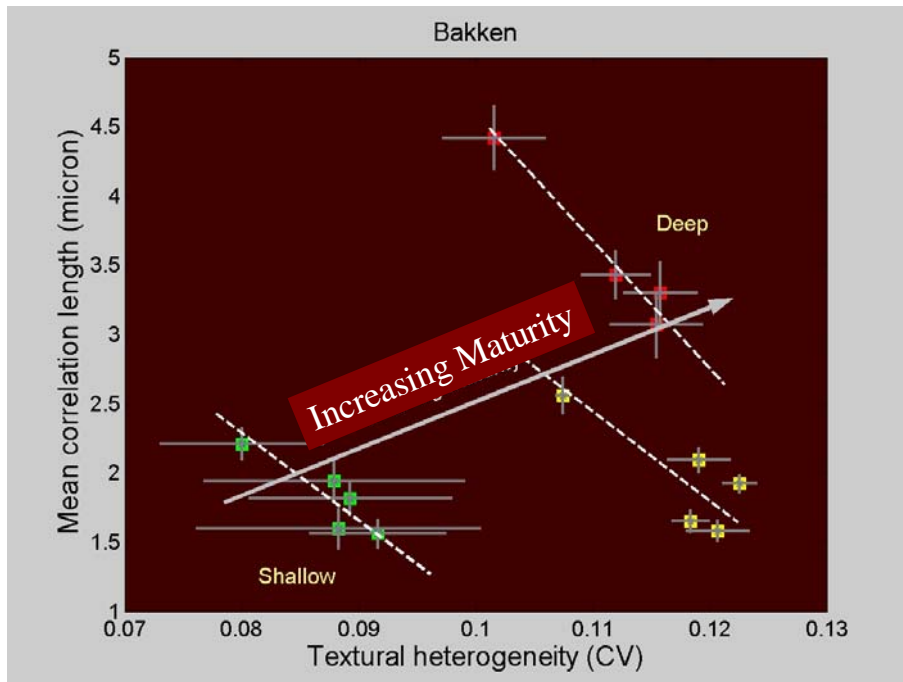


Figure 7: En echelon pattern of textural heterogeneity and correlation length with increasing depth and maturity.

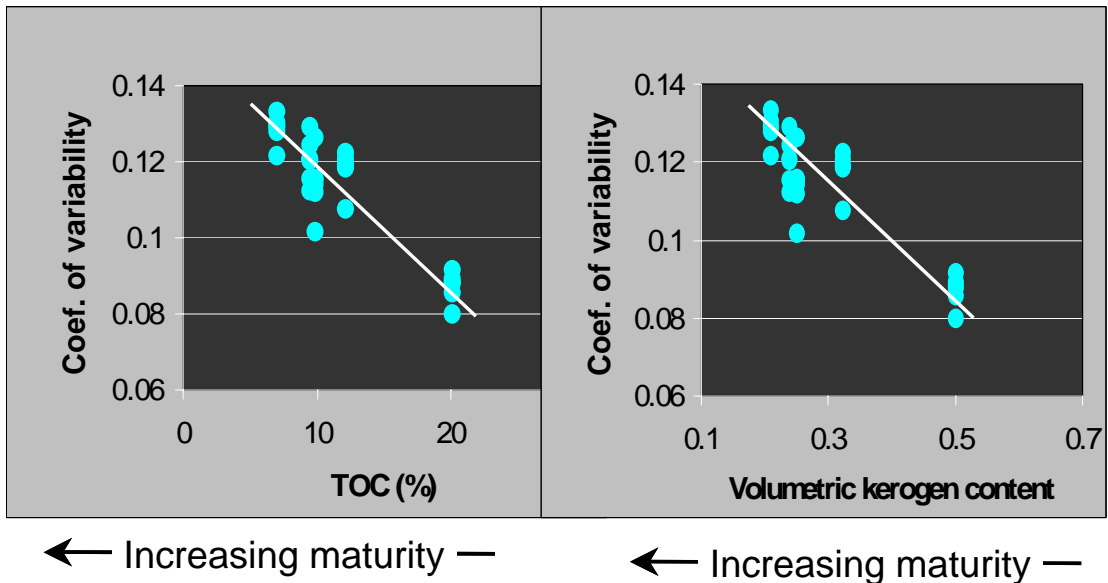


Figure 8: Coefficient of variability (textural heterogeneity) increases with decreasing kerogen content and total organic content.

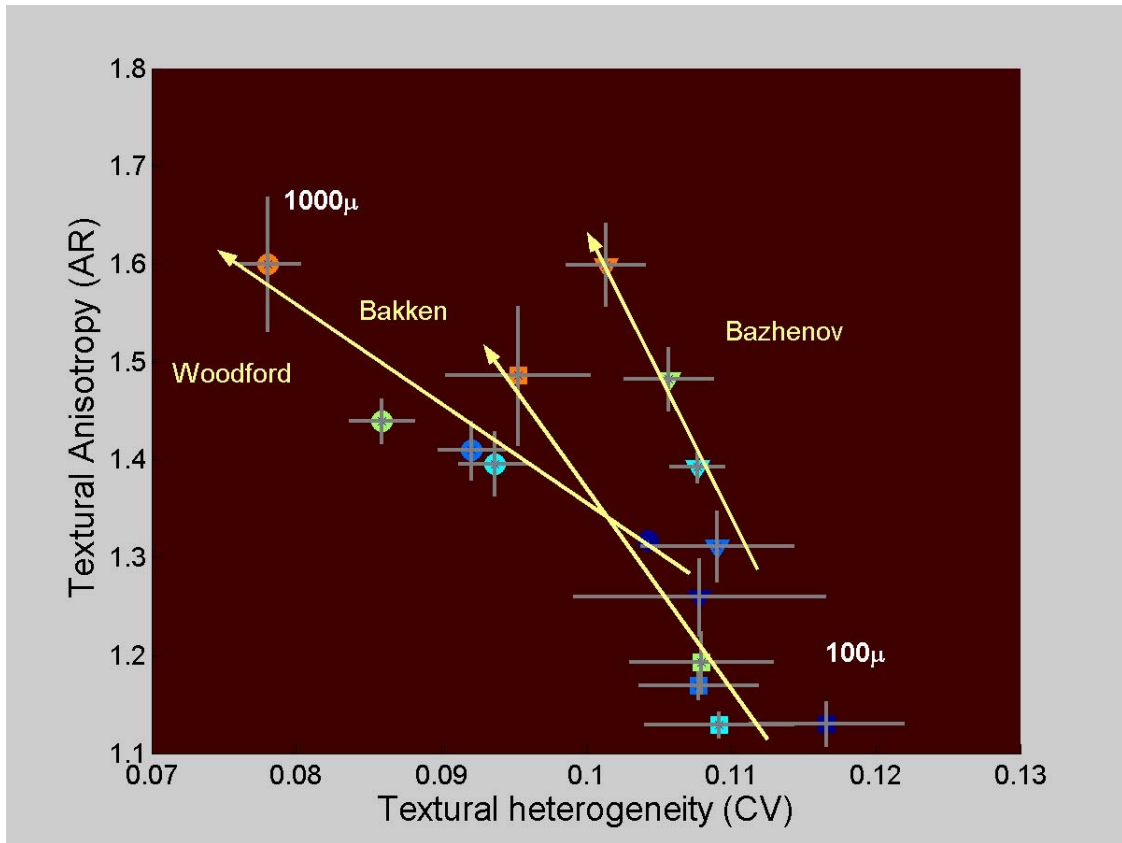
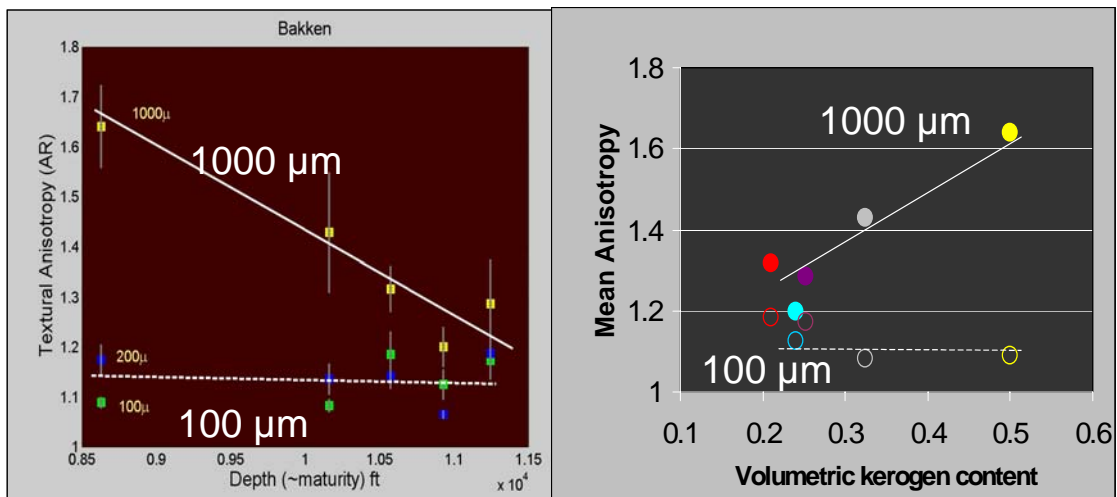


Figure 9: Scale dependence of textural heterogeneity and textural anisotropy. Colors indicate image size from 100 $\mu$  (blue) to 1000 $\mu$  (red).



← Increasing maturity

Figure10: Small scale (100 $\mu$ ) textural anisotropy shows no dependence on depth or kerogen content (equivalently maturity). Textural anisotropy from 1000 $\mu$  images show a clear decreasing trend with increasing depth and maturity.

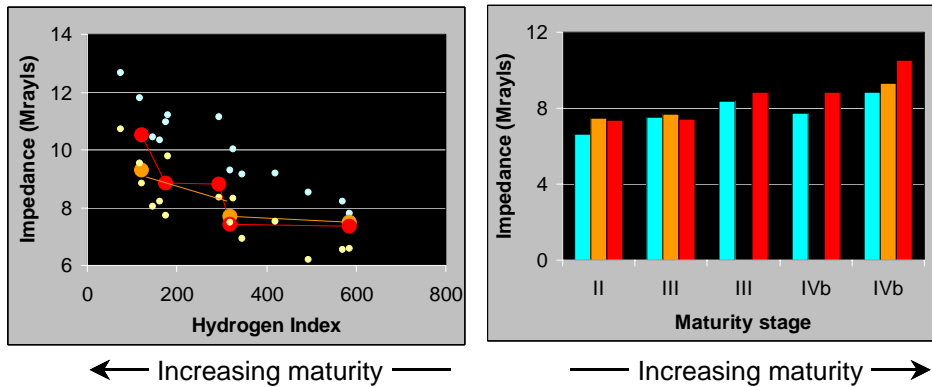


Figure 11: Consistency between P-wave impedance from SAM images (large red and orange spots, and red and orange bars) and impedance estimated from ultrasonic data (small dots, cyan bar). Ultrasonic data from Vernik and Nur, 1994). Impedance shows a general increase with increasing shale maturity.

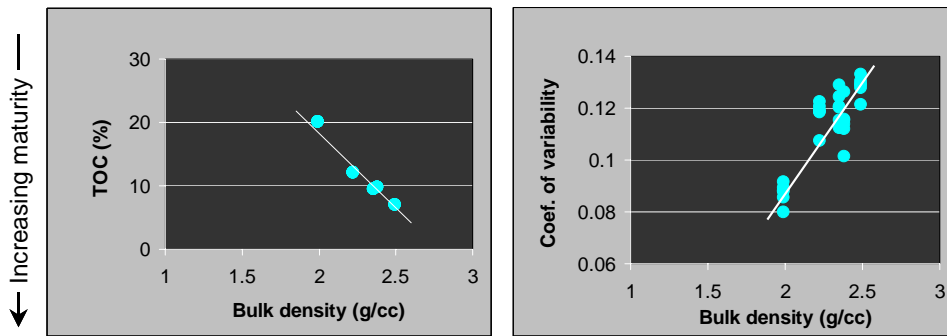


Figure 12: Density increases with decreasing TOC (left). Density and textural heterogeneity show a positive correlation, both increasing with increasing maturity and decreasing organic content.

A satisfying match was obtained between P-wave impedance derived from the SAM images and the corresponding impedance from ultrasonic data on core samples (Figure 11). Figure 11 (left) shows the ultrasonic impedance derived from measured  $V_P$  along both the fast and the slow directions (small dots), along with the SAM impedance (large red and orange dots) for Bakken shales. Elastic impedance, density and textural heterogeneity all increase with increasing maturity (Figures 11 and 12).

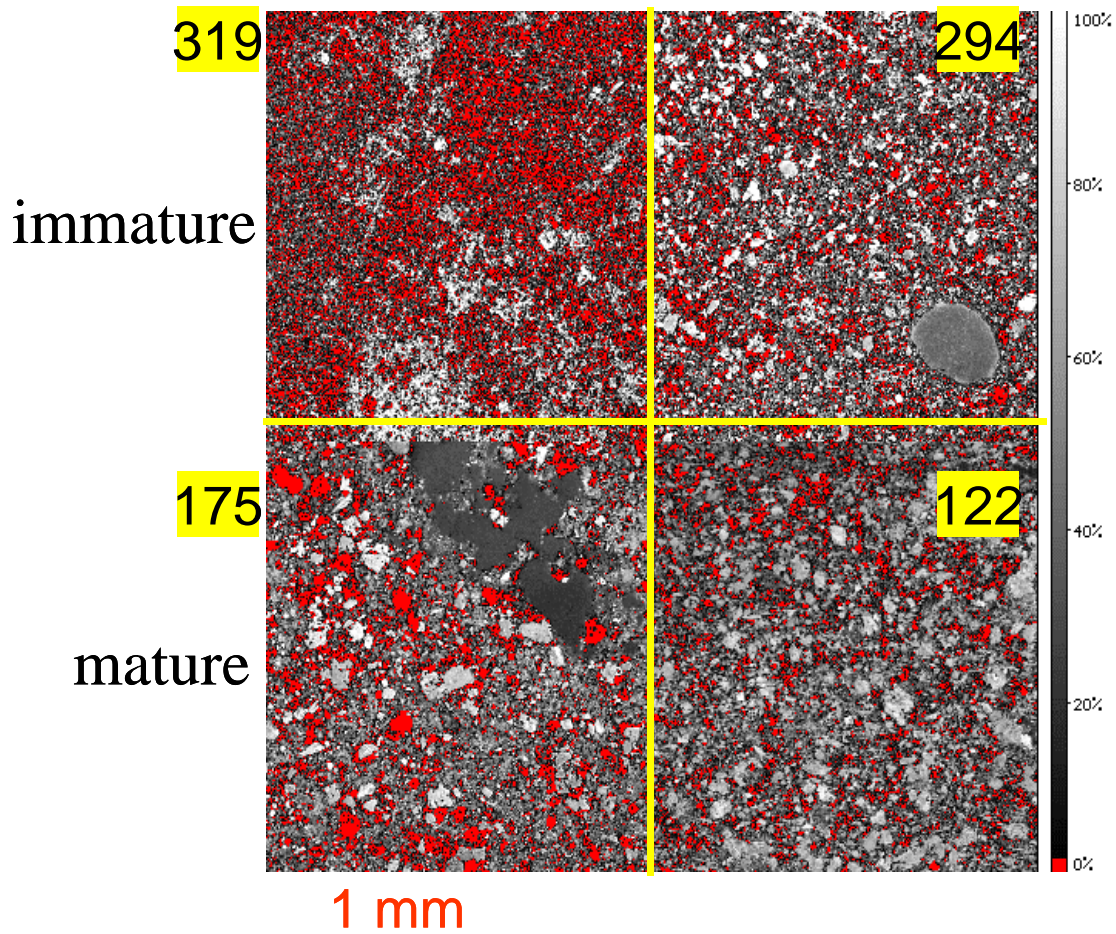


Figure 13: SAM images of immature (top left) and mature shale (bottom right) with red indicating kerogen. Immature shales have less textural heterogeneity compared to the mature shales.

As a result of all of the above analyses the following interrelations between textures and maturation process emerges. Initially when shales are immature, they have high kerogen content. There is not much variability in the impedance heterogeneities (Figure 13), and the coefficient of variation is low. However the high kerogen content gives rise to high textural anisotropy, possibly due to partial alignment of elongated kerogen patches filling bedding parallel cracks. As the shale is buried deeper, the kerogen matures. There is an increase in the heterogeneity as indicated by the increasing coefficient of variation with depth. Elastic impedance and density both increase with increasing maturity but textural anisotropy seems to go down as the kerogen matures and connects to form larger connected globules (Figure 13). Figure 13 shows larger red blobs for the mature shales, which is consistent with the observed increase in mean correlation length with depth.

## CONCLUSIONS

About 300 SAM images from Bakken, Bazhenov, and Woodford shale were analyzed to quantify textural parameters. We observed quantifiable and consistent patterns linking texture, shale maturity process, and elastic P-wave impedance. Image derived impedances matched reasonably well with impedances estimated from ultrasonic data.

The coefficient of variation, CV, (textural heterogeneity) ranges from 7% to about 12% for these samples. Textural heterogeneity, elastic impedance, P-wave velocity, and density all tend to increase with increasing shale maturity. The mean spatial correlation length generally tends to increase with increasing heterogeneity.

The textural anisotropy (AR) ranges from 10% to about 70% and tends to decrease with increasing depth and maturity.

## ACKNOWLEDGEMENTS

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