# Microstructural characterization of Green River shale from GSA inversion

*Malleswar Yenugu* and Tao Jiang, University of Houston*

**Summary**

A detailed knowledge of microstructure properties help us to understand the pore connectivity, fluid mobility, which is critical in successful characterization of unconventional shale reservoirs. We used GSA (Generalized Singular Approximation) method to determine the microstructure such as pore/crack shape, and their connectivity for the Green River shale outcrop samples. The optimized anisotropic microstructure properties can be obtained from solving an inverse problem of GSA modeling, by minimizing the objective function, which is defined as the difference of anisotropic P and S velocities between ultrasonic measurements and the GSA calculation.

**Introduction**

One of the major challenges to characterize the shale reservoirs is to get the microstructure information i.e. the clay platelet orientation, the type, density, shape and connectivity of the inclusions. These are directly linked to three physical parameters: porosity, aspect ratio and friability with the assumption that the pore/cracks are gas-filled and have ellipsoidal shape.

The problem of calculating the effective stiffness tensor is a many body problem, which can be solved, in general case, only approximately (Chesnokov et al. 1995). The majority of the methods of effective medium theory is based on the Eshelby (1957) solution, which finds the strain field in an individual ellipsoidal inclusion embedded in a homogeneous matrix with other elastic properties, caused by a stress (or strain) field applied at infinity. In the effective medium theory, it is assumed that the inclusions (mineral grains, pores and cracks) have an ellipsoidal shape. Hornby et al. (1994) used biconnected clay matrix cracks in isotropic clay matrix and rotated them in accordance with the distribution function of the clay platelet orientation. Then, silt-sized minerals were inserted resulting the anisotropic 'clay-cracks' material.

We used GSA method to compute the effective elastic constants of cracked anisotropic media for arbitrary crack concentration and aspect ratio. We consider that clay forms a matrix containing grains of different minerals, pores and cracks with different shape and orientation as inclusions. This consideration is in line with the microstructure seen in SEM (Scanning Electron Microscope) image shown in Figure 1.

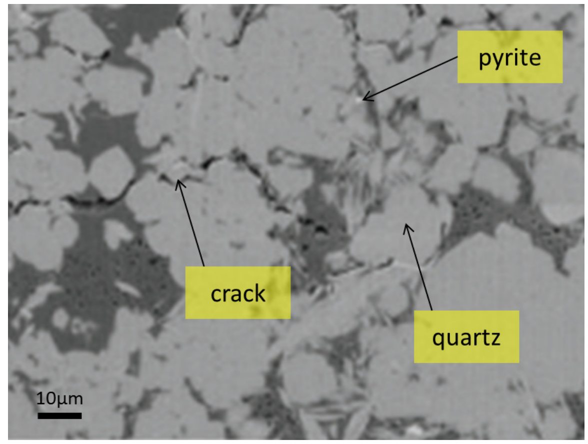


Figure 1: SEM image of a shale microstructure

**GSA Method**

GSA (Shermergor, 1977) uses the singular part of Green's function to get the analytic solution. GSA is a powerful effective medium modeling method for porous media. It gives the effective properties of the whole medium provided the components of the rock (i.e. matrix and inclusions). The advantages of GSA over other EMT (Effective Medium Theory) models are: GSA can handle large volume of inclusions, it takes into account the effect of the connection of pores, it works for arbitrary ellipsoidal inclusion with any aspect ratios, it assumes that the elastic properties are anisotropic for both matrix and inclusions.

According to Hooke's law, the effective stiffness tensor is related via strain (ε) and stress (σ) fields averaged over a representative volume:

$$\langle\sigma\rangle = C^* \langle\varepsilon\rangle \quad (1)$$

The derivation is based on a comparison of the displacement fields arising in the heterogeneous body whose effective properties have to be found in a homogeneous reference body. The stiffness tensors of heterogeneous body and homogeneous reference body are represented by C and $C^c$ respectively.

In the GSA method, the choice of reference body is arbitrary. If a two-component body is considered (as porous cracked medium), the choice of reference body as mineral matrix, gives the upper Hashin-Shtrikman bound (isolated fluid inclusion and continuous mineral matrix), the choice



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of reference body as fluid inclusions gives the lower Hashin-Shtrikman lower bound (continuous fluid phase and isolated solid inclusions).

Figure 2 shows the workflow for the GSA modeling and inversion for microstructural characterization.

Bayuk and Chesnokov (1998) used the stiffness tensor of the reference body for a porous cracked medium in the form of a combination of matrix and fluid stiffness tensors as

$$C^c = (1-f)\, C^m + f\, C^{fl} \qquad (2)$$

Here the indices m and fl are matrix and fluid respectively. The coefficient f is called the friability, which is an empirical coefficient that to some degree reflects pore/crack connectivity.

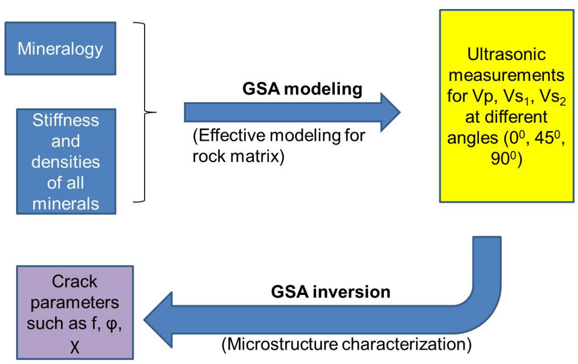


Figure 2: The workflow for GSA method

### Ultrasonic measurements on Green River shale

An outcrop rock of Green River shale is collected from Wyoming, USA. The rock is cored into three different plugs at $0^0$, $45^0$, and $90^0$ and the petrophysical properties such as mineralogy, grain density and porosity of each plug is measured in the laboratory. The average mineralogy of the samples is measured using FTIR (Fourier Transform Infrared Spectroscopy). The images and average mineralogy of the plugs is shown in the Figure 3. The porosity of each plug is around 30%.

Ultrasonic measurements are made using pulse transmission method. The measurements were made initially on the dry samples and the same samples are saturated with brine (specific gravity is about 1 gr/cc) for couple of days and again measured the velocities. The pore pressure is kept at atmospheric pressure so that the confining pressure equals to effective pressure.

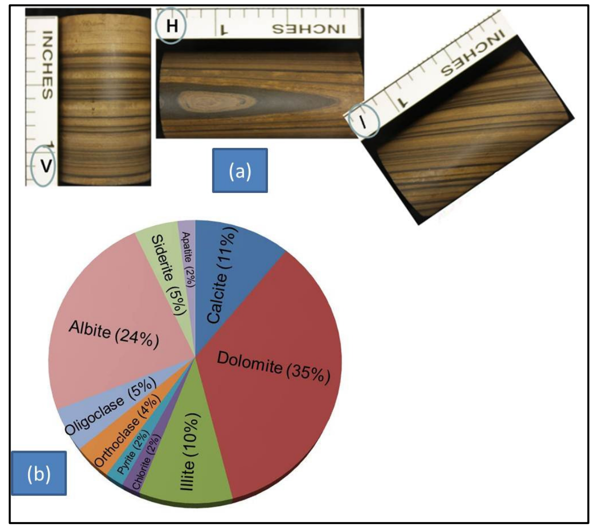


Figure 3: (a) images of the three Green River shale plugs (b) average mineralogical composition

### GSA modeling and inversion for microstructure

GSA method is used for microstructure characterization of Green River shale samples. It involves two steps. In the first step, modeling is carried out only for minerals. It treats clay minerals as matrix and other minerals such as quartz, calcite, dolomite, feldspar as inclusion. It uses the matrix property as comparison body, because friability of the inclusion of granular minerals is zero i.e. isolated. The velocities at different angles ($0^0$, $45^0$, and $90^0$) are calculated using Green-Christoffel equation. These velocities are then compared with the ultrasonic velocities for the same angles.

In the second step, inversion is carried out which includes pores/cracks. It uses the GSA result from pure minerals as matrix and adds gas-filled pore/cracks as inclusions. Finally, we get the following microstructural properties from the inversion: 1. porosity ($\phi$) 2. aspect ratio of cracks ($\chi$) and 3. friability (f). A global search algorithm is applied for the range of above parameters to minimize the objective function. Figure 4 shows the schematic for the microstructure properties from GSA modeling and inversion.


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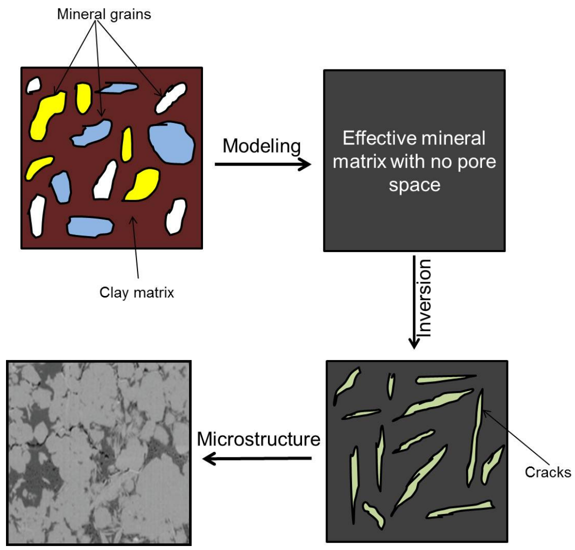


Figure 4: Schematic of the GSA method for microstructure characterization

GSA modeling for the Green River shale is carried out using the mineral composition measured by FTIR, the elastic constants and densities taken from published literature. The velocities calculated and measured from ultrasonic are plotted for the three plugs and shown in the Figure 5. The difference between the velocities is due to only the mineral matrix is considered.

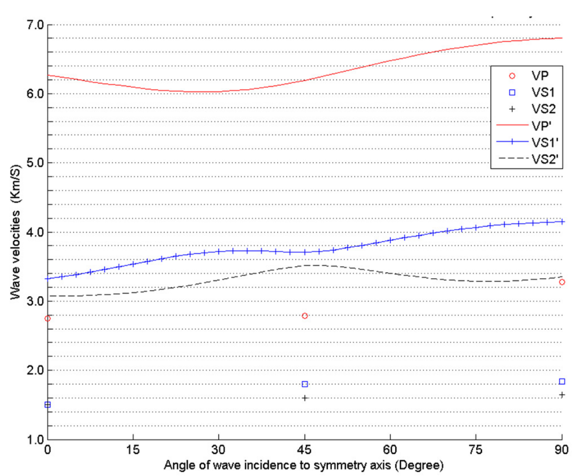


Figure 5: P, S1 and S2 velocities with different incident angles calculated from GSA modeling of pure mineral composite.

In the above figure, circle, square and plus points denote the ultrasonic velocity measurements of 0, 45 and 90 degree samples in laboratory, and line curves denote the GSA modeling result for the pure solid mineral composite without any porosity. The density of mineral composite is 2.69 g/cc.

P, S1 and S2 velocities with different incident angles calculated from GSA modeling of the whole shale sample with full consideration of mineralogy, porosity, pore/crack aspect ratio and friability, where the aspect ratio and friability are obtained from GSA inversion in order to make best agreement between velocities from laboratory measurement and from the GSA modeling results (Figure 6). Circle, square and plus points denote the ultrasonic velocity measurements of 0, 45 and 90 degree samples in laboratory, and line curves denote the GSA modeling result for the whole shale sample with optimal aspect ratio and connectivity of pore/cracks. The average density of the shale samples is 1.883 g/cc.

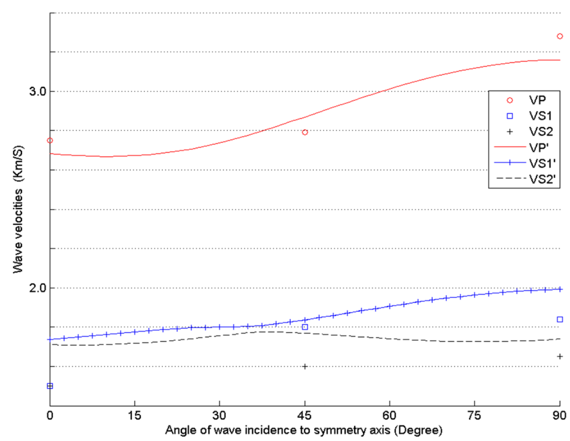


Figure 6: Comparison of calculated and experimental velocities after inversion.

From the inversion result, the aspect ratio ($\chi$) is estimated around 0.9046, which infers that the shape of the fluid inclusions is almost spherical. The friability (f), which indicates the connectivity between inclusions, is estimated around 0.9057. The range of friability is between 0 and 1, where 0 is considered as no connection and 1 is considered as well connected among the inclusions. So, the calculated friability from the inversion indicates that there is a good connection between the inclusions.


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**Conclusions**

GSA method is used for microstructural characterization of Green River shale samples. One of the major advantages of GSA over other methods is that we can estimate the connectivity between pores/cracks (friability). The inversion results show that the pores have spherical shape and are well connected.

The reason for the difference in the velocities between calculated and measured in the lab is due to changes in the pressure and temperature conditions while measuring the elastic moduli of the minerals. The elastic moduli of each mineral are considered from the published literature, so the conditions may not be the same for the each mineral, which contributes to the mis-match between the inversion and ultrasonic results.

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**EDITED REFERENCES**

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