Evaluation of the representativeness of shale samples on basis of analysis of elastic wave velocities

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Unconventional oil and gas reservoirs are playing a significantly increasing role in offsetting production losses due to declining conventional oil and gas production for the past decade. For this reason, one of the great challenges and opportunities facing the oil and gas industry today is identifying, quantifying and properly exploiting gas and oil resources in unconventional reservoirs, particularly shale.
Shale comprises clay and silt-sized particles that have been consolidated into rock layers of extremely low permeability. This low permeability claims the use of intense fracturing in order to allow hydrocarbon production, and appropriate fracturing claims adequate advanced modeling. Unfortunately, the heterogeneities and high level of anisotropy contained in unconventional gas plays make it impossible to use the existing conventional techniques for many applications due to the need for higher precision information.
While laboratory testing plays a fundamental role for geomechanical characterization, representativeness of laboratory samples is often questionable. For one, core-plug measurements are highly variable and they are unlikely to provide representative information at the scale of a reservoir model. For another, when delivered to the laboratories cores proceeding from shale formations are normally affected by a high number of fractures, mostly aligned along the sedimentation planes, which also represent preferential weakness planes. Spacing among fractures can be low that sometimes it is almost impossible preparing specimens of the size used in normal triaxial testing. . One of the main questions of fundamental importance for the set up of fracturing models is then whether these fractures are due to coring (stress relief effects) or are already present in the insitu formation – and to what extent samples have been damaged by coring.
Wireline log data can provide information on the state of the material at in situ condition, although they do not allow a full geomechanical characterization. This work introduces preliminary results concerning a methodology aimed at merging information from both laboratory characterization and in situ logging to ascertain the rapresentativeness of shale samples tested in the laboratory. It relies on the conjugate analysis of the results of ultrasonic measurements performed in the laboratory, at increasing level of confinements, and on sonic measurements performed at the geostatic stress through wireline logging – together with concurring data from porosity logs and gamma ray logs.
Representativeness of samples is evaluated on basis of the different wavelenth and travel distance of ultrasonic and sonic measurements. Ultrasonic measurements, performed in the laboratory, are taken at frequencies f of the order of the MegaHertz and on travel distances of the scale of a few tens of mm, while sonic logging measurements are taken at frequencies of the order of the kiloHertz along distances of the order of meters. Wavelength λ can be evaluated through the expression:

$$\lambda = \frac{V}{f}$$

where V is the elastic wave velovity, whose range is on the order of km/s. Since the answer recorded by the elastic wave depends on the scale of investigation, related to the wavelength, it follows that two different scales are investigated by the two different devices (order of the mm for the ultrasonic, order of the m for the sonic logs).
Elastic wave velocities are known to depend on the elastic properties of the rock material constituents, on porosity, on the geometrical arrangement and bonds between the grains (structure effects, see e.g. Mavko et al., 2009), together with on stress conditions.
The effect of structure and porosity on the elastic velocity at a reference stress, in the following denoted by α, can be expressed by the following relationship:

$$\alpha(\phi) = AF(\phi)$$

where α is the velocity at reference stress p'_0, A is the elastic velocity in the rock material constituents and ϕ is porosity. The function $F(\phi)$ introduces both the effects of porosity and of structure on the wave propagation.
The effect of stress can be described by Hertz – Mindlin type laws, which foresee an exponential increase of velocity with stress p':

$$V(p') = \alpha\left(\frac{p'}{p'_0}\right)^{\beta}$$

where the exponent β depends on the material and on the type of contacts between particles (according to the Hertz Mindlin original formulation - spherical grains with no bonding - it is equal to 1/6). It is also recognised (Santamarina et al., 2001, Cha et al., 2009) that for a given meterial β can be related to α by a linear decay relationship:
Ultrasonic measurements taken at increasing stress on mineralogically homogeneous shale samples, with different porosoties, are used to calibrate parameters of the function $F(\phi)$ and of the β – α relationship: a specific expression for $F(\phi)$ is then obtained, which is representative of the structural state of the dataset of samples in the laboratory. Thus, the expression

$$\alpha^{pseudo}(z) = AF(\phi_{log}(z))$$

where ϕ_{log} is porosity recorded in logs, provides along the formation values of elastic wave velocities at reference stress for the structural state of the specimen dataset $\alpha^{pseudo}(z)$.
Supposing known the in situ stress *p'(z)*, the actual value of α for the formation, $\alpha^{well}(z)$, can be determined. This is achieved through optimization methods, minimizing at each depth the objective function *g*:

$$g(\alpha,\beta,z) = \left(\alpha\left(\frac{p'(z)}{p'_0}\right)^{\beta} - V_{log}(z)\right)^2$$

where $V_{log}(z)$ is the elastic wave velocity measured by logs. The ratio SI

$$SI(z) = \frac{\alpha^{well}(z)}{\alpha^{pseudo}(z)}$$

is thus a ratio of the effects of structure on wave velocity in the rock formation compared to the effects of structure on the specimen dataset. If SI > 1, the structure of the formation is such that the

elastic wave velocity is higher than in the specimen dataset at the same porosity – therefore we can infer that coring induced damage of the samples. On the other hand, if SI<1, the structure of the formation is such that the elastic wave velocity is lower than in the specimen dataset at the same porosity – possibly due to the effect of natural fractures: these are not investigated at the laboratory scale, but are relevant for the in situ measurements because of the higher wavelength.
The method briefly described was used to evaluate the representativeness of some shale samples (location, depth and every other specific data are omitted because of industrial interest). In the following figure (on the left) strucutural index evaluated by P and S wave velocities are shown. SI values are above 1 highliting a coring induced damage of the samples. Coring effects are visible in the following figure (on the right) where X-ray computed tomographies of the cores for the depth indicated (shlightly shadow zone) are shown. It is possible to observe persistent horizontal fractures along the core.

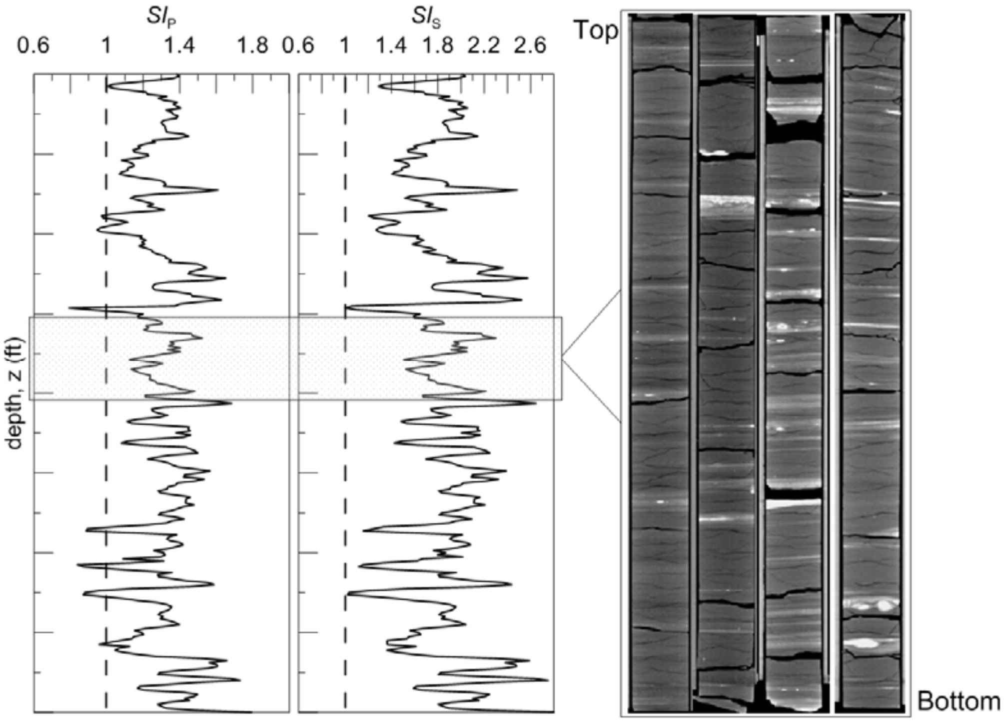

Figure 1: SI = $\alpha^{well}/\alpha^{pseudo}$ versus depth for P-wave and S-wave (on the left), X-ray computed tomographies of the cores (on the right).

These preliminary results indicate that the proposed method is able to ascertain the representativeness of shale samples tested in the laboratory. The advantage of the method relies on basing the evaluation on the mechanical response at small strains. This allows the introduction of a new “structural index”, through which quantify the representativeness of the laboratory samples, and that can contribute in converting the parameters obtained in the laboratory (e.g. from triaxial tests) into a reliable geomechanical model.

References

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