Effect of microporous fabric and stromatolitic stratigraphy on seismic properties of limestones. I. Concepts

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Abstract

Fabric controls the seismic behavior of limestones. Microstratigraphy requires new methods to estimate properties at all length scales. Without the benefit of sample from Brazil, we have begun to examine the conceptual challenges posed by microporous fabric and stromatolitic stratigraphy.

Introduction

Fabric dominates the behavior of limestones (Archie, 1948, Lucia, 2007, Ward and Barnaby, 2007). Composition dominates the behavior of sandstones. Sandstones are granular complicated often by colloidal clays. Limestones can be granular, moldic, microporous, honeycombed, brecciated, vuggy, ... Limestone fabric begins at 10^{-7} meters and ends at stratigraphic boundaries. Limestone fabric controls variations in porosity, porosimetry, resistivity, moduli, saturation, and permeability and the relationships among these properties. Of course, compositional impurities such as quartz and dolomite perturb the fabric controls.

Limestones are highly stratified (Lucia, 2007). That is, fabric and properties vary strongly with age and superposition, primarily affecting the vertical axis. The stratification can begin at roughly 10^{-3} meters and be as thick as 10^{3} meters. These variations cause anisotropy and scaling in seismic properties that cannot currently be deduced from sparsely spaced well logs (Murphy et al, 1984; Grouchau, 2010).

Our emphasis at this point is to begin a program to understand microporous fabric, stromatolitic stratigraphy, and their effects on seismic properties. Both causes are primary and strong. Seismic properties are particularly important when there are few wells in large fields.

Moduli

Modulus space clarifies the effects of fabric; that is, we break all data down into frame stiffness and pore-space stiffness. We translate all fabrics into geometric representations for constitutive modeling of the frame. Particular care is taken with definitions as we hope to relate geometric forms to richer descriptive bio-geological terminology. Our objective is to begin to determine what intrinsic physical properties and stratigraphic packaging the seismic waves sense and discriminate. Our examples are from the Middle East, North America, and Australia. We do not have access to Brazilian examples at this time.

We begin by defining a simple limestone as

$$K = \rho_c V_p^2 - 1.33G$$
$$G = \rho_c V_s^2$$

The composite moduli are

$$K = K_p + K_{fr}$$
$$G = G_p + G_{fr}$$

The pore space moduli are

$$K_p = [\alpha_K^2 K_o K_f]/[(\alpha_K - \phi)K_f + \phi K_o]$$
$$G_p = [\alpha_K^2 G_o G_f]/[(\alpha_K - \phi)G_f + \phi G_o]$$

If $G_f=0$, then the $G_p=0$. For saturation, $S_w=1.0$, with brine, and ignoring the effects of varying temperature, pore pressure, and salinity:

$$K_f(S_w=1) = 2.2\text{GPa}$$
$$G_f(S_w=0) = 0.0\text{GPa}$$

For saturation, $S_w=0.0$, with 38°-API oil with 1500 GR and ignoring the effects of varying temperature and pore pressure:

$$K_f(S_w=1) = 1.0\text{GPa}$$
$$G_f(S_w=0) = 0.0\text{GPa}$$

The frame moduli for limestones are

$$K_{fr} = K_o(1-\phi)^n$$
$$G_{fr} = G_o(1-\phi)^m$$

where for calcite,

$$K_o = 70\text{GPa}$$
$$G_o = 30\text{GPa}$$

Figure 1 plots the simple limestone hypothesis against porosity with rocks from Cretaceous North America and Cretaceous Middle East. The effect of fabric, Φ, is controlled by n,

$$n = \mathscr{A}(\Phi, P_e)$$
$$m = \mathscr{B}(\Phi, P_e)$$

Ramamurthy and Murphy, 1998, used sandstone relations for the frame moduli. We prefer treating limestones explicitly. An open wormtube or open coral fabrics are described by:

$$n=1$$
$$K_{fr}/G_{fr}(\phi=\phi_c)=1.0$$
$$K_{fr}/G_{fr}(\phi=0)=K_o/G_o=2.3$$

For moldic limestones with oomolds or vugs. the exponent n is

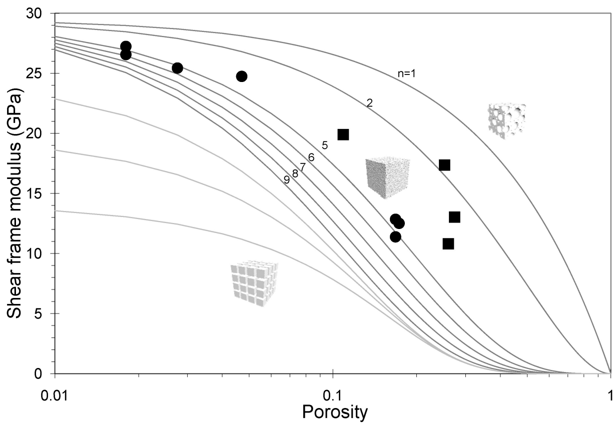

Figure 1. Shear frame modulus versus porosity as a function of fabric. Squares and circles are moldic and granular samples, respectively.

$$n=2$$
$$K_{fr}/G_{fr}(\phi=\phi_c)=1.0$$
$$K_{fr}/G_{fr}(\phi=0)=2.3$$

For granular limestones,

$$n=5$$
$$K_{fr}/G_{fr}(\phi=\phi_x)=1.0$$
$$K_{fr}/G_{fr}(\phi=0)=2.3$$

For limestones with microporosity of varying concentration and compliance,

$$5<n<10$$
$$K_{fr}/G_{fr}(\phi=\phi_x)=1.0$$
$$K_{fr}/G_{fr}(\phi=0)=2.3$$

The presence of quartz (toward travertine) changes the behavior as

$$K_o=70GPa$$
$$G_o=30GPa$$
$$K_{fr}/G_{fr}(\phi=\phi_x)=0.9$$
$$K_{fr}/G_{fr}(\phi)=0.9$$
$$K_{fr}/G_{fr}(\phi=0)=0.9$$

For fractures and fragmented limestones, we use a completely different approach (D'Agosto et al., 2008). For the purposes of this discussion, we may think of the effect as

$$n=10$$
$$K_{fr}/G_{fr}(\phi=\phi_c)=1.0$$
$$K_{fr}/G_{fr}(\phi=0)=1.0$$

Microstratigraphic hypothesis and Ward number

The continuum hypothesis in the mechanics of materials has been a primary scaling law for materials since Euler. The idea applied to rocks is that as the scale of our measurements increases from molecules to pores to grains the values observed fluctuate dramatically until a scale large enough is reached such that the properties achieve the asymptotic value for a uniform, homogeneous, smoothly varying, continuous material. In fluid mechanics, one estimates the Knudsen number to determine whether or not to use continuum mechanics or another method such as statistical mechanics. The Knudsen number is defined as the ratio of the molecular mean free path length to the characteristic length scale of the problem. This length scale could be, for example, the radius of the body in a fluid. The Knudsen number is then many times its own diameter a particle will travel on average before hitting another particle. Problems with Knudsen numbers at or above unity are best evaluated using statistical mechanics for reliable solutions.

The relevant observation is that in many limestones, the asymptote is never reached. The stratigraphic hypothesis is that the oscillations in the envelope of the microstratigraphic variations constitute the variations measured in cores or logs or seismic waves.

The Ward number, W, is defined as the ratio of the scale of observation to the characteristic length of limestone heterogeneities whose fluctuations are within an order of magnitude of the measured value:

$$W=l/h$$

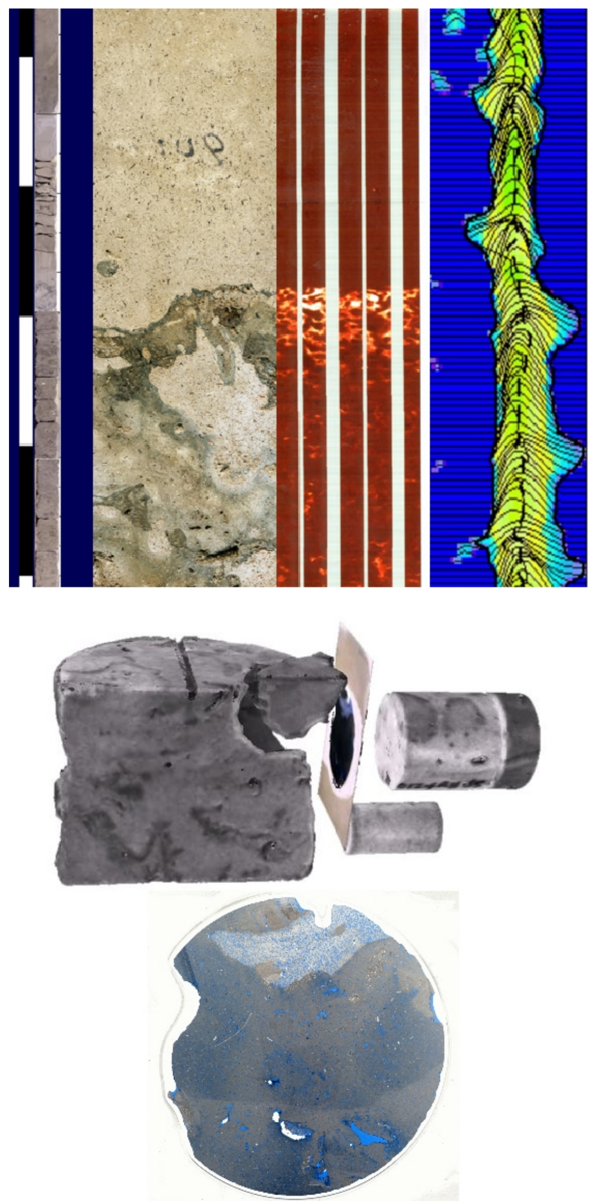

Figure 2. Core sample dominated by microstratigraphy and heterogeneities.

If W<<1, then the continuum hypothesis and rock physics holds. If W≈1, then an accurate interpretation requires more advanced analyses. In a W≈1 material, the measurements fall within an envelope around the fluctuations in the behavior. Borehole logging measurements would track within the envelope of the behavior. We need to apply a spectral decomposition of the stratigraphic variation. Seismic waves sense a package of strata. We must convolve the seismic properties of the strata into a composite response.

Equipresence

The principle of equipresence states that if a parameter is included in any constitutive description of material behavior if must be considered in all constitutive relations for that material. Why is that relevant? Traditionally, geophysicists have focused ad hoc on one parameter or another to the exclusion of others. We begin with porosity, porosimetry, fabric, temperature, pressure, GOR, and frequency and carry these through the investigation.

The moduli are:

$$K=\mathcal{C}(T, P_e, P_p, S_w, \phi, \Phi, K_o)$$
$$G=\mathcal{D}(T, P_e, P_p, S_w, \phi, \Phi, G_o)$$
$$K_p=\mathcal{E}(T, P_e, P_p, S_w, \phi, \Phi, K_o)$$
$$G_p=\mathcal{F}(T, P_e, P_p, S_w, \phi, \Phi, G_o)$$
$$K_f=\mathcal{G}(T, P_e, P_p, S_w, \phi, \Phi, K_o)$$
$$G_f=\mathcal{H}(T, P_e, P_p, S_w, \phi, \Phi, G_o)$$
$$K_{fr}=\mathcal{I}(T, P_e, P_p, S_w, \phi, \Phi, K_o)$$
$$G_{fr}=\mathcal{J}(T, P_e, P_p, S_w, \phi, \Phi, G_o)$$
$$K_{fr}/G_{fr}=\mathcal{K}(T, P_e, P_p, S_w, \phi, \Phi, K_o, G_o)$$
$$K_p/G_{fr}=\mathcal{L}(T, P_e, P_p, S_w, \phi, \Phi, K_o, G_o)$$

Of course, we may determine later that, say, the frame moduli are independent of water saturation, but from the beginning one must include all parameters within constitutive relationships for all moduli until proven otherwise.

Limestone fabric and stratification

Limestone fabric can varies even when the porosity is uniform (Ward et al., 2006). Figure 3 shows an example of a limestone with ϕ=0.30 through with textures varying from granular and moldic to microporous muds. Figure 4 shows an outcrop with a uniform ϕ=0.30.

Table 1. Fabrics from limestone platform.

Deposit	Dip	Rock type	Fossils	Ext (m)	Ht (m)	Fabric	Porosity
Lagoon	<1	Mudstone, wackestone	Forams, molluscs	10^4	10	Moldic	0.10
Buildups	10	Grainstone, packstone	Rudists, molluscs, coral	10^3	10^1	Moldic, intergranular	0.35
Slope	10	Grainstone, packstone	Rudists, molluscs, coral	10^3	10^1	Moldic, intergranular	0.40
Open shelf	<1	Fine packstone	Forams	10^3	10^1	Vuggy, intraskeletal	0.40

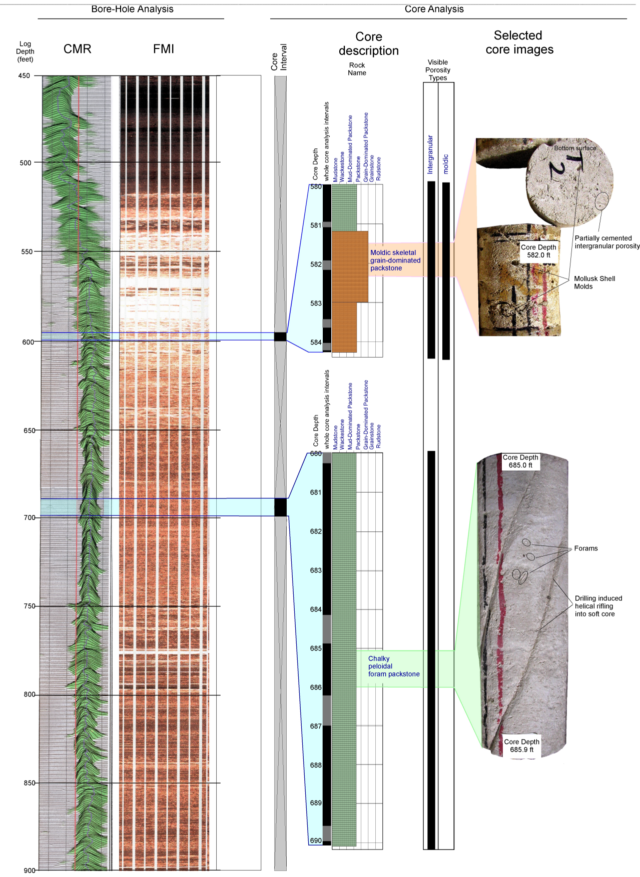

Figure 3. Microporous Eocene limestones from Avon Park formation, Florida.

(a)

(b)

(c)

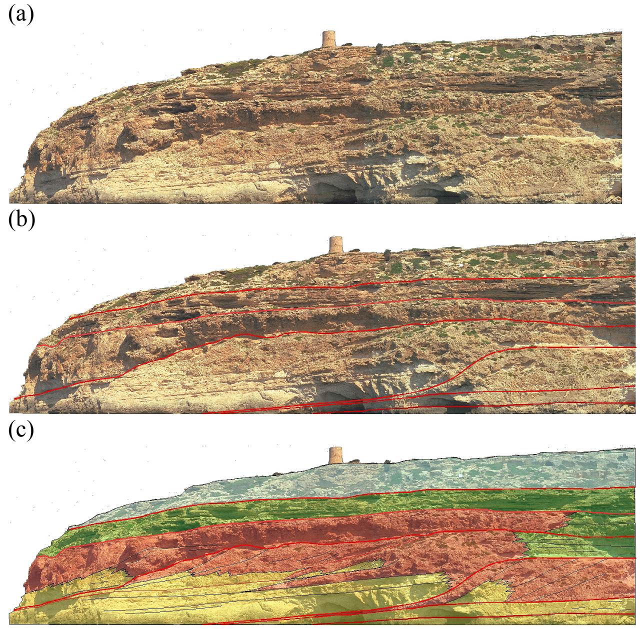

Figure 4. Interpretation of Miocene reef facies for the Cap Blanc cliff wall in Mallorca (adapted from Pomar). (a) Uninterpreted photograph. (b) Bounded surfaces between 6th order depositional packages. (c) Facies and time lines within these depositional packages. The facies consist of the inner and outer lagoon (green), reef front (red), and reef slope (yellow). Pleistocene eolianites (light blue) overly the Miocene.

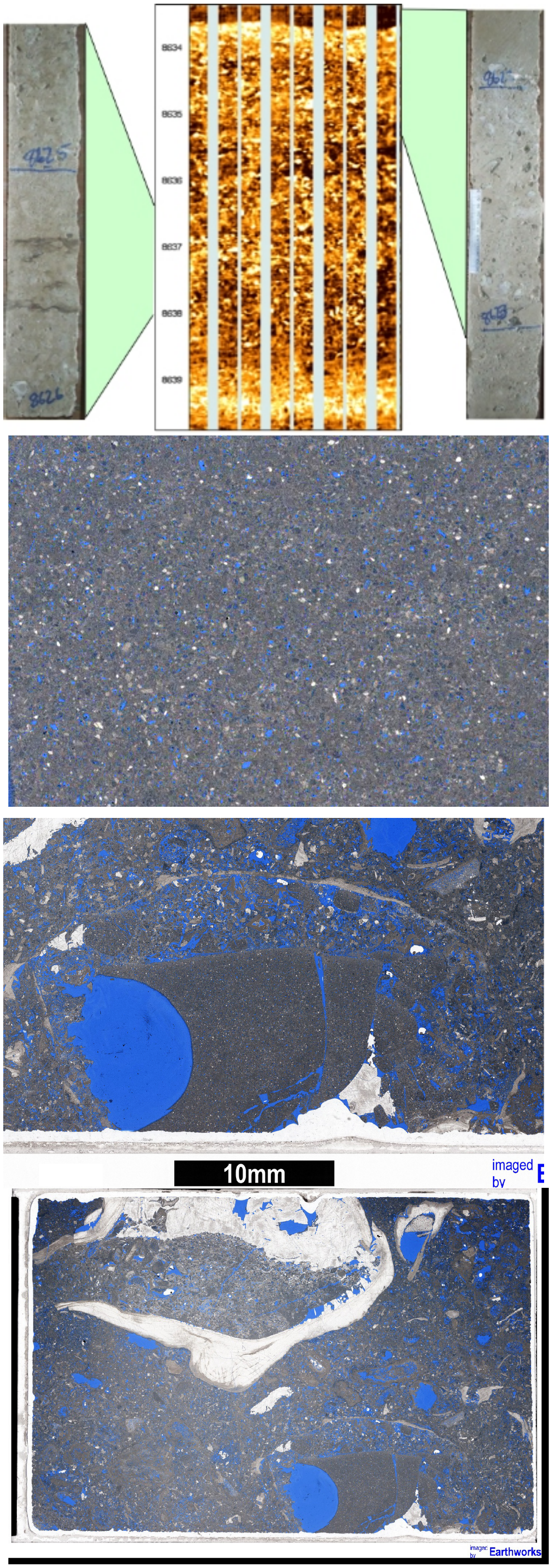

Figure 5. Limestone rudist fabric with microporosity from the Middle East.

Seismic properties and modeling

Figure 6 shows the effect of fabric changes in a limestone body with a uniform porosity. We performed time-domain, finite-difference acoustic modeling on a limestone model with constant porosity but different fabrics. The fabrics were moldic, fractured, and granular. The rock properties were estimated as discussed above. We used a Ricker wavelet with three frequencies: a) 100 Hz, b) 500 Hz, and c) 1000 Hz. This exercise shows that higher frequency content could be helpful to observe changes in fabric from seismic data.

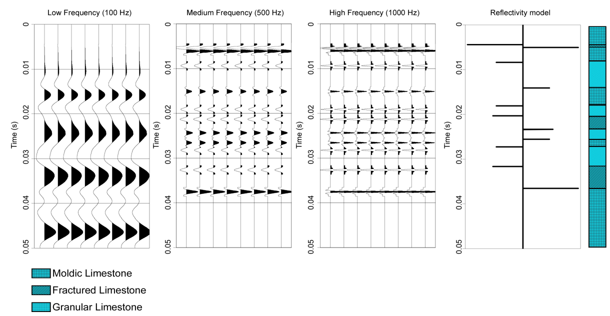

Figure 6. High frequency seismic properties on limestones.

A test of the effect of microstratigraphy is to perform high-frequency measurements on modern lacustrine deposits. We routinely make measurements in Quaternary varved sediments and Mesozoic varved rocks (Murphy et al., 2011). Figure 7 show an example from a river in North America.

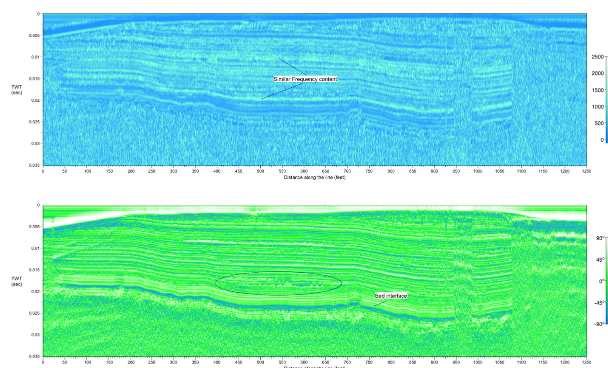

Figure 7. Seismic attributes from the high-frequency zero-offset seismic profile. The seismic source is a 1-10 kHz chirp. The top panel is the instantaneous frequency, that is, a time-dependent mean frequency independent of phase and amplitude. Note how events with similar frequency pattern are identified along the profile. The bottom panel is the instantaneous phase. Note how the top of rock is marked as a very strong bed interface.

Conclusions

1. Fabric controls the seismic properties of limestones.
2. Microstratigraphy affects the packaging of fabrics and filters what seismic waves sense travel through limestones.
3. We have begun to model microporous and microstratigraphic limestones.

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