Department of Geology and Geophysics

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ROLES OF POROELASTICITY IN OIL AND GAS EXPLORATION AND EXPLOITATION

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Two Main Areas of Research

- Understanding how liquids and gases interact with waves such as seismic, ultrasound, electromagnetic
  - Exploration and exploitation in oil and gas industry
  - Ocean acoustics, coastline defense, etc.
  - Spinoffs in medical imaging through bone, etc.
- Underground imaging using seismic, acoustic, and electrical methods (EM)
  - Seismic exploration, both on land & off-shore
  - Imaging polluting conductors underground (EM)
  - Spinoffs in ultrasound for diagnosis and treatment of kidney stones, etc.

Recent Work

In fluid saturated and partially saturated rocks:

- Compressional wave velocities
- Shear wave velocities
- Attenuation of both types of waves
- AVO: Amplitude Versus Offset
  (how these waves reflect off interfaces underground)
- Permeability
  (controlling factor for injecting or removing fluids
  from the ground)

Methods We Use

- Effective medium theory (EMT)
- Biot-Gassmann theory/Poroelasticity
- Generalizations of Poroelasticity:
  - EMT – for inhomogeneous rocks (and virtually all rocks are inhomogeneous)
  - for cracked or fractured rocks – double-porosity method
  - modelling: both analytical and computational
- Image processing methods developed especially for permeability analysis

Collaborations

- Rock physics research was done at some level of effort by major oil companies until about the mid-1980's
- Almost without exception, the major oil companies cut these efforts back, and actually gave away both equipment and personnel to university, private and government labs
- This type of work is now mostly restricted to:
  - Well-logging firms (such as Schlumberger-Doll)
  - A handful of universities: Stanford, Wisconsin, Colorado School of Mines, MIT, Oklahoma, and abroad
  - DOE National Labs: LLNL, LBNL, Sandia

Main Question to Be Answered:

What can be said about porosity and partial saturation when the only data available are the seismic velocities V_p and V_s?

OUTLINE

- Introduction to the Physical Problem
- Role of Gassmann's Equations
  - Amplitude Versus Offset (AVO)
  - Gassmann triangle for patchy saturation
- Low Frequency Examples
- Higher Frequency Examples
  - Well logs
  - Laboratory tests and breakdown
- Conclusions

Seismic Velocities Related to Elastic Parameters

$$V_p = \sqrt{(K + \tfrac{4}{3}\mu)/\rho} \qquad \text{and} \qquad V_s = \sqrt{\mu/\rho}$$

where ρ is the density, μ is the shear modulus,

and K is the bulk modulus of the elastic medium.

$K = \lambda + 2\mu/3$ also relates K to the

Lamé elastic coefficients λ and μ.

Thus, $V_p = \sqrt{(\lambda + 2\mu)/\rho}$ is also true.

Shear Modulus Notation

The shear modulus is often denoted by μ and probably just as often by G. The μ notation is fairly universal in the seismology community, while the G notation is fairly universal in the engineering mechanics and civil engineering communities.

In order to offend everyone equally, I usually am not careful about which notation I use in talks, so I will just note here that $\mu = G$ and hope you are not confused.

What Information Is Contained in V_p and V_s?

At low frequencies, Gassmann and Biot tell us that:

First, the shear modulus μ contains no information about fluid presence or saturation levels.

Second, the bulk modulus K *does* contain information about liquids when present and their saturation levels.

Third, the density ρ contains information about total quantity of fluid mass present.

Seismic Velocities for Partial Saturation

$$V_p = \sqrt{(K + \frac{4}{3}\mu)/\rho}$$

$$V_s = \sqrt{\mu/\rho}$$

where

$$\rho = (1 - \phi)\rho_s + \phi\rho_f$$

and for partial saturation

$$\rho_f = S_l\rho_l + (1 - S_l)\rho_g.$$

Gassmann/Domenico Relations

$$K = K_{dr} + \frac{constant}{constant' + \phi / K_f}$$

$$\mu = \mu_{dr}$$

where, for partial saturation,

$$1/K_f = S_l/K_l + (1 - S_l)/K_g.$$

Recall that the Lamé parameter

$$\lambda = K - \frac{2}{3}\mu$$

Lamé Parameters from Seismic Velocities

$$\mu/\rho = V_s^2 \text{ and } \lambda/\mu = (V_p/V_s)^2 - 2$$

When Gassmann/Domenico applies, we expect:

$$1/V_s^2 = \frac{1}{\mu}[(1-\phi)\rho_s + \phi(S_l(\rho_l - \rho_g) + \rho_g)].$$

$$\lambda/\mu = \frac{1}{\mu}[\lambda_{dr} + \frac{constant}{constant' + \phi/K_f}]$$

So, $1/V_s^2$ should be a linear function of S_l, and

$(V_p/V_s)^2 - 2$ should be independent of S_l except for $S_l \simeq 1$.

Saturation Proxy

$$S_{proxy} = \frac{(1/V_s^2)|_S - (1/V_s^2)|_{S=0}}{(1/V_s^2)|_{S=1} - (1/V_s^2)|_{S=0}}$$

$$= \frac{(\rho|_S/\mu) - (\rho|_{S=0}/\mu)}{(\rho|_{S=1}/\mu) - (\rho|_{S=0}/\mu)}$$

$$= \frac{\rho|_S - \rho|_{S=0}}{\rho|_{S=1} - \rho|_{S=0}}$$

$$= S,$$

if the assumptions hold.

Analysis of Amplitude Versus Offset (AVO)

AVO analysis in isotropic layered systems uses the reflectivity moveout for compressional wave scattering (Aki and Richards, 1980)

$$R(\theta) = A + B\, sin^2\,\theta,$$

where θ is the angle of incidence measured from the vertical. Coefficients A and B depend on the elastic properties of the system through $v_p^2 = (\lambda + 2\mu)/\rho$ and $v_s^2 = \mu/\rho$, which are the squares of the compressional and shear wave speeds, respectively. The Lamé elastic parameters are λ and μ, while ρ is the density.

Analysis of Amplitude Versus Offset (AVO)

According to the standard results:

$$A = \frac{\Delta v_p}{2v_p} + \frac{\Delta\rho}{2\rho},$$

and

$$B = \frac{\Delta v_p}{2v_p} - 4\frac{v_s^2}{v_p^2}\left(\frac{\Delta v_s}{v_s} + \frac{\Delta\rho}{2\rho}\right).$$

The coefficients A and B can then be rewritten in terms of the three parameters ρ, λ, and μ, and when this is done we have

$$A = \frac{\Delta(\lambda+2\mu)}{4(\lambda+2\mu)} + \frac{\Delta\rho}{4\rho},$$

and

$$B = \frac{\Delta(\lambda-6\mu)}{4(\lambda+2\mu)} - \frac{\Delta\rho}{4\rho}.$$

Analysis of Amplitude Versus Offset (AVO)

Since Gassmann's fluid substitution equations show that $\Delta\mu = 0$ when any fluid is introduced into a porous medium, we therefore find the particularly simple results at gas/liquid interfaces that

$$A + B = \frac{\Delta(\lambda)}{2(\lambda+2\mu)},$$

and that

$$A - B = \frac{\Delta\rho}{2\rho}.$$

Thus, a very clean decoupling of the changes in the reflectivity coefficients *due to fluid effects* has been obtained in terms of physical parameters λ and ρ.

CONCLUSIONS

• For Gassmann materials, the $(\rho/\mu,\lambda/\mu)$-plane is a useful means of analyzing v_p and v_s data:

- ◦ Partial saturation level discrimination is possible.
- ◦ The presence of patchy saturation effects can also be deduced from these data displays.

• The same physical ideas can be used with AVO data, well-log data, vertical seismic profiling data, or cross-well seismic data — most easily in those cases were direct measurements of v_p and v_s are both available.