A Simplified Workflow for Estimation of Elastic Anisotropy in Vaca Muerta*

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Abstract

Lab studies and acoustic logs have shown that Vaca Muerta elastic properties indicate strong differences measured parallel and perpendicular to bedding. Shear velocities and microscopic analysis indicate that the anisotropy on the bedding planes is negligible. This specific case of anisotropy, common in shale plays, is known as TIV (transverse isotropic vertical), which is a fairly accurate assumption since most of the Vaca Muerta bedding planes in the area of study are near to horizontal. The important differences observed in elastic moduli suggest that the assumption of isotropy for stress computations may lead to significant errors. The estimation of the TIV strain tensor from well logs acquired in vertical wells is challenging due to the limitation of the logging tools to measure compressional and shear velocities in directions different than the direction of the well. Service companies have proposed procedures based on the estimation of horizontal shear from Stoneley waves and the implementation of correlations to overcome this problem. Here we are proposing a simplified and innovative methodology based on ultrasonic velocities and stress-strain relationship measured in triaxial tests on core plugs to derive a pseudo-anisotropic model from compressional and shear well log measurements.

References Cited


A simplified workflow for estimation of elastic anisotropy in Vaca Muerta

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• Cuervo Sergio
  – Chevron Argentina
Agenda

1. Study Area, Scope of Work, Scope of Presentation
2. Rock Elasticity General Concepts
3. Elasticity Estimation from Sonic Waves Concepts
4. Dynamic and Static Measurement / Triaxial Tests
5. Dynamic to Static Conversions / Analysis
6. TIV evidence in Vaca Muerta
7. Stiffness Tensor Definition in TIV
8. Cij estimation from sonic Velocities
9. Vendor Models (MANNIE)
10. Pseudo Anisotropic Model Proposal
11. Estimation of Common Elastic Moduli
12. Proposed Dynamic to Static conversion for Vaca Muerta
13. Conclusions
14. References
Objective: calibrate a TIV geomechanical model to compare variations of elastic parameters of the rocks and stresses along the basin. It was developed a complete workflow using a basic set of logs which can be applied in any well in the basin with a good level of confidence.

Application: model the stresses variation from a well scale to help defining the fracture intervals and improve fracture design, to the block scale to optimize appraisal and development campaign and regional scale to be able to compare results from competitors and potentially assess different areas.

Key challenges
- TIV model construction
- Dynamic to static conversion
In order to characterize geomechanically the Vaca Muerta formation is necessary to know the relation between stress and strain, thus, the **elastic parameters**.

*Stress tensor, strain tensor & elastic moduli*

**Stress**
- Normal: \( \sigma = \frac{F_n}{A''} \)
- Shear: \( \tau = \frac{F_p}{A''} \)

**Elastic moduli**
- Young: \( E = \frac{\sigma}{\epsilon} \)
- Poisson: \( \nu = -\frac{\epsilon_{\text{trans}}}{\epsilon_{\text{long}}} \)

**Strain**
- Strained (elongation)
- Shear strain (angular)

*Linear elasticity assumption:*
The rock behavior is considered perfect elastic (constant relationship between the applied stress and the resulting strain (\( \sigma_x, \epsilon_z \)) - Hooke Law.

Image from Fjaer “Petroleum related rock mechanics”
ANISOTROPY: The orthorombic symmetry

To give a complete description of the stress state at a point within a sample, it is necessary to identify the stresses related to surfaces oriented in three orthogonal directions.

\[ \sigma_{ij} = \sum_{k,l} C_{ijkl} \varepsilon_{kl} \]

- \( \sigma_{ij} = \text{Stress tensor} \)
- \( \varepsilon_{kl} = \text{Strain tensor} \)
- \( C_{ijkl} = \text{elastic constants} \) (Stiffness matrix)

Not all the elastic moduli are independent. Depending on the symmetry, some of them may be cancelled or expressed as function of the others.

For an isotropic material, the linear elastic properties are completely described when any two of the elastic moduli.

For transverse isotropic, just 5 of the 9 constants must be known.

To give a complete description of an anisotropic rock, all the nine constants.

Image from Fjaer “Petroleum related rock mechanics”
ROCK ACOUSTIC: ELASTIC WAVE
Sonic logs to estimating dynamic elastic modulus

- Waves moves perturbing the medium in a wavelike motion. This disturbance of the medium is understood as a movement of particles that can be expressed in terms of stress / strain

WAVE EQUATION in terms of elastic MODULI

\[ v_p = \frac{\omega}{q} = \sqrt{\frac{\lambda + 2G}{\rho}} \]
\[ v_s = \frac{\omega}{q} = \sqrt{\frac{G}{\rho}} \]

we can express the elastic coefficients in terms of the phase velocities

\[ G = \rho v_s^2 \]
\[ \lambda = \rho v_p^2 - 2\rho v_s^2 \]

DYNAMIC ELASTIC MODULI

\[ K = \rho v_p^2 - \frac{4}{3} \rho v_s^2 \]
\[ E = \rho v_s^2 \frac{3v_p^2 - 4v_s^2}{v_p^2 - v_s^2} \]
\[ \nu = \frac{v_p^2 - 2v_s^2}{2(v_p^2 - v_s^2)} \]

Sound velocities depend explicitly on elastic moduli

Image from Fjaer “Petroleum related rock mechanics”
# MECHANICAL LABORATORY ANALYSIS

Elastic moduli measurement: Dynamic & Static

<table>
<thead>
<tr>
<th>Set #</th>
<th>Sample Name</th>
<th>Plug Depth (m)</th>
<th>Plug Direction (°)</th>
<th>YM_STA</th>
<th>PR_STA</th>
<th>Vp(0) (ft/sec)</th>
<th>Vs1(0) (ft/sec)</th>
<th>Bulk Density (g/cc)</th>
<th>C11 (GPa)</th>
<th>C13 (GPa)</th>
<th>C66 (GPa)</th>
<th>C44=C55 (GPa)</th>
<th>C12 (GPa)</th>
<th>C13 (GPa)</th>
<th>YM_DYN</th>
<th>PR_DYN</th>
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<tr>
<td>1</td>
<td>SAMPLE 1</td>
<td>2981.22</td>
<td>0</td>
<td>3.93</td>
<td>0.24</td>
<td>14932.2</td>
<td>8768.9</td>
<td>2.55</td>
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<td></td>
<td></td>
<td>6.38</td>
<td>0.23</td>
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<tr>
<td>2</td>
<td>SAMPLE 2</td>
<td>2981.25</td>
<td>45</td>
<td>4.83</td>
<td>0.26</td>
<td>15648.6</td>
<td>9366.1</td>
<td>2.55</td>
<td>66</td>
<td>53</td>
<td>23</td>
<td>18</td>
<td>20</td>
<td>19</td>
<td>7.20</td>
<td>0.21</td>
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<tr>
<td>3</td>
<td>SAMPLE 3</td>
<td>2981.30</td>
<td>90</td>
<td>6.75</td>
<td>0.27</td>
<td>16727.5</td>
<td>9366.1</td>
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<td></td>
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<td>8.19</td>
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</tbody>
</table>
ACOUSTIC VELOCITY
Dynamic to static discrepancy

Displacement:
“Elastic moduli obtained from stress and strain measurements in a rock mechanical test ("static moduli") differ significantly from those obtained from acoustic velocities and density (dynamic moduli)"

---

DYNAMIC ELASTIC MODULI (from seismic inversion)

1 to 100 Hz

DYNAMIC ELASTIC MODULI (from log velocity)

10 to 40 kHz

DYNAMIC ELASTIC MODULI (from lab acoustic velocity)

100 kHz to 1 MHz

STATIC ELASTIC MODULI (from rock mechanical test)

---

DISPERSION
Cause: Frequency

The conversion depends on the Strain magnitude

- The term DYNAMIC means small strains
- The term STATIC means large strains

Empirically based correlations are not universally applicable since the correction is not a constant shift
VACA MUERTA
TIV evidence

- Shales are usually strongly anisotropic by nature, due to the sharp lamination they exhibit in all the scales.

Building TIV model is complicated and time consuming. Comparing the triaxial test parallel and perpendicular to bedding could justify building a TIV model or not.
VACA MUERTA
TIV evidence

Acoustic tools (cross-dipole shear anisotropy and Stoneley-derived horizontal shear anisotropy) can be used to derive stress profile from anisotropy rock characterization.

- A 3D anisotropy algorithm transforms the **Sonic Scanner** measurements to anisotropic moduli.

\[
C_{33} = \rho V_p^2 \\
C_{44} = \rho V_{\text{slow}\_s}^2 = \rho V_{\text{fast}\_s}^2 \\
C_{66} = \rho V_{\text{shear\_horizontal}}^2
\]

Besides providing information anisotropy, **Sonic Scanner** allows to estimate \( C_{33}, C_{44} \) and \( C_{66} \). Needs to the fully definition of the \( C_{ij} \) tensor for TIV symmetry.

**ET well “B”**

**C44 = C55**

**ISOTROPY evidence in the y-x plane**
Building TIV model is complicated and time consuming. Comparing the triaxial test parallel and perpendicular to bedding could justify building a TIV model or not.

- The first step is defining the rock model based on the anisotropy evidence.

V/H Anisotropy ranges between 30 to 60%

(*)139 Triaxial Test
VACA MUERTA
TIV evidence

- Sill sample shows a **ISOTRIPIC** behavior, while the average anisotropy in the rest of the samples is 32%

Building TIV model is complicated and time consuming. Comparing the triaxial test parallel and perpendicular to bedding could justify building a TIV model or not.
STIFFNESS MATRIX
Cij definition

- Cij estimation workflow summary

Assumption & Simplifications:

Based on TIV symmetry, acoustic wave, and Cij ratios, rock stiffness tensor could be characterized by:

- Definition of 5 of the 9 Cij
- Calculation of C33, C44 using sonic and density logs.
- Estimation of C11, C13 and C66 through Cij ratios.

**TIV Symmetry**

C_{23} = C_{13}
C_{22} = C_{11}
C_{55} = C_{44}
C_{12} = C_{11} - 2C_{66}

**Acoustic measurements**

C_{33} = f(C_{33})
C_{44} = f(C_{33})

**Proposed correlations**

C_{11} = f(C_{33})
C_{13} = f(C_{33})
C_{66} = f(C_{44})

**Symmetry in TIV:**

\[
\begin{pmatrix}
C_{11} & C_{11} - 2C_{66} & C_{13} & 0 & 0 & 0 \\
C_{11} - 2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{44} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{66} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{pmatrix}
\]
STIFFNESS MATRIX
Cij definition

DISPERSION CORRECTION NEGLIGIBLE

ET well “A”

DT (log)

DTp (vert from Plug)
STIFFNESS MATRIX

Cij definition

- C33 & C44 calculation by compressional and shear sonic and Density logs

\[
C_{33} = \rho V_p^2
\]
\[
C_{44} = \rho V_{\text{slow}_s}^2 = \rho V_{\text{fast}_s}^2
\]

Using borehole acoustic measurements, a continuous profile of static rock stiffness could be obtained (C33 and C44)
STIFFNESS MATRIX
Cij definition

- Based on Cij ratios & TIV symmetry: just C11, C13, C66 remain to be calculated to the full Cij description.

\[ C_{11}^{\text{dyn}} = A + B \times C_{33}^{\text{dyn}} \]
\[ C_{13}^{\text{dyn}} = -C + D \times C_{33}^{\text{dyn}} \]
\[ C_{66}^{\text{dyn}} = E + F \times C_{44}^{\text{dyn}} \]

C11, C13, C66 were obtained as C33 and C44 ratios: This approximation is based on the assumption that these 3 independent elastic parameters, actually present some relationship with C33 and C44.
• **Dynamic elastic moduli**: Elastic moduli expressed as Cij

Dynamic elastic constants (stiffness matrix) may rewritten as elastic modulus (Young & Poisson expression)

\[
YM_{dyn}(v) = \left(\frac{2 \times C_{13} \times C_{13}}{C_{11} + C_{12}}\right)
\]

\[
YM_{dyn}(h) = \left(\frac{C_{11} - C_{12}}{C_{11} C_{33}} - C_{13} \times C_{13}\right)
\]

\[
PR_{dyn}(v) = \frac{C_{13}}{C_{11} + C_{12}}
\]

\[
PR_{dyn}(h) = \frac{C_{33} C_{12} - C_{13} C_{13}}{C_{11} C_{33} - C_{13} C_{13}}
\]
STIFFNESS MATRIX
Cij definition

- Dynamic to pseudo-static conversion

Triaxial compression test on core samples provide the static values to calibrate the dynamic properties (Franquet, J.A. 2012)

\[
YM_{sta}(v) = -G + H \times YM_{dyn}(v)
\]

\[
YM_{sta}(h) = I + J \times YM_{dyn}(h)
\]

\[
PR_{sta}(v) = -K + PR_{dyn}(v)
\]

\[
PR_{sta}(h) = -L + PR_{dyn}(h)
\]
STIFFNESS MATRIX

Cij definition

<table>
<thead>
<tr>
<th>Cij</th>
<th>DYNAMIC ELASTIC MODULI</th>
<th>PSEUDO STATIC ELASTIC MODULI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</table>

[Graph and data representation]
Rock typing

- Cij ratios for different rock typing are aligned in the same trend.
- Further information can help to visualize some trend that is not yet clear.
Conclusions

- Vaca Muerta can be correctly characterized as a TIV elastic medium. There is evidence on strong anisotropy across bedding planes and reasonable isotropy along bedding planes to support this hypothesis.

- We haven´t see a clear dependency between composition and moduli relationships neither static to dynamic ratios in Vaca Muerta. Is still unclear how rock typing can help to improve these correlations and how much statistic is need to accomplish that.

- TIV Stiffness tensor can be estimated from commonly available sonic and density logs.

- The high correlation coefficient between measured $C_{ij}$ ($C_{33}$, $C_{44}$) and the rest of the TIV coefficient allow to build a pseudo TIV model from isotropic measurements with good confidence.

- A new dynamic to static correlations for Vaca Muerta are proposed in this contribution.

- A solid elastic characterization is a critical pre requisite for the estimation of stresses, selection of navigation intervals and hydraulic fracture planning.
THANKS FOR YOUR ATTENTION!
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• Estimating Horizontal Stress from Three-Dimensional Anisotropy. Suarez-Rivera et al. 2009

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Cij ratios consistency

- Dynamic & Static Cij ratios shows the same trend