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.

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AAPG Latin America & Caribbean Region
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Geosciences Technology Workshop
Co-hosted by the Argentine Association of Petroleum Geologists and Geophysicists

A simplified workflow for estimation of elastic anisotropy in Vaca Muerta

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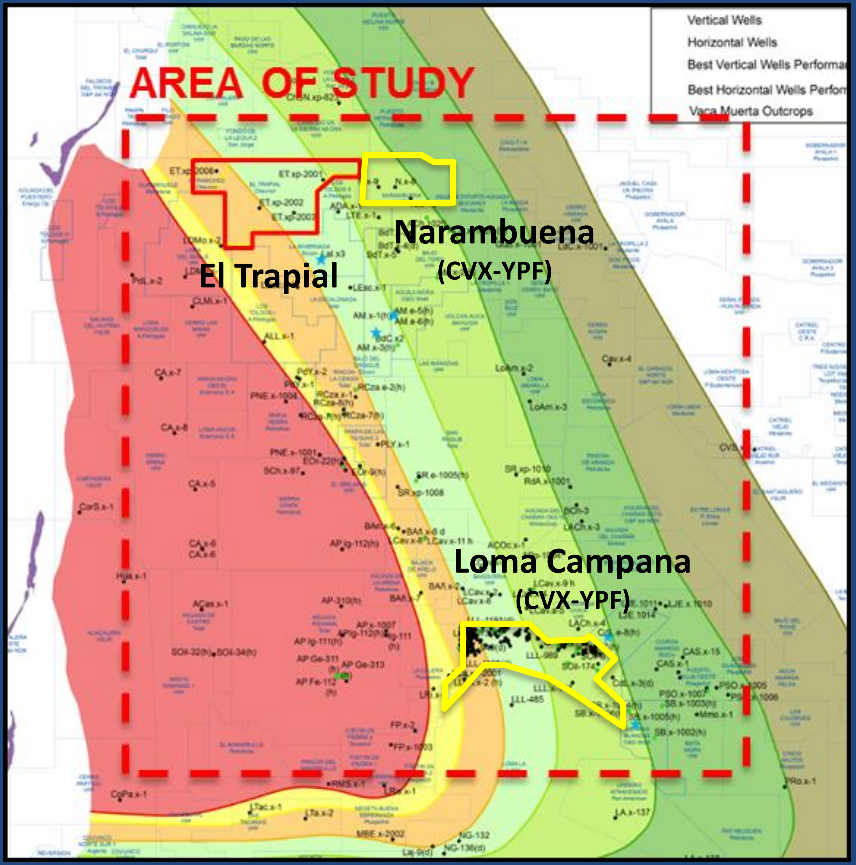
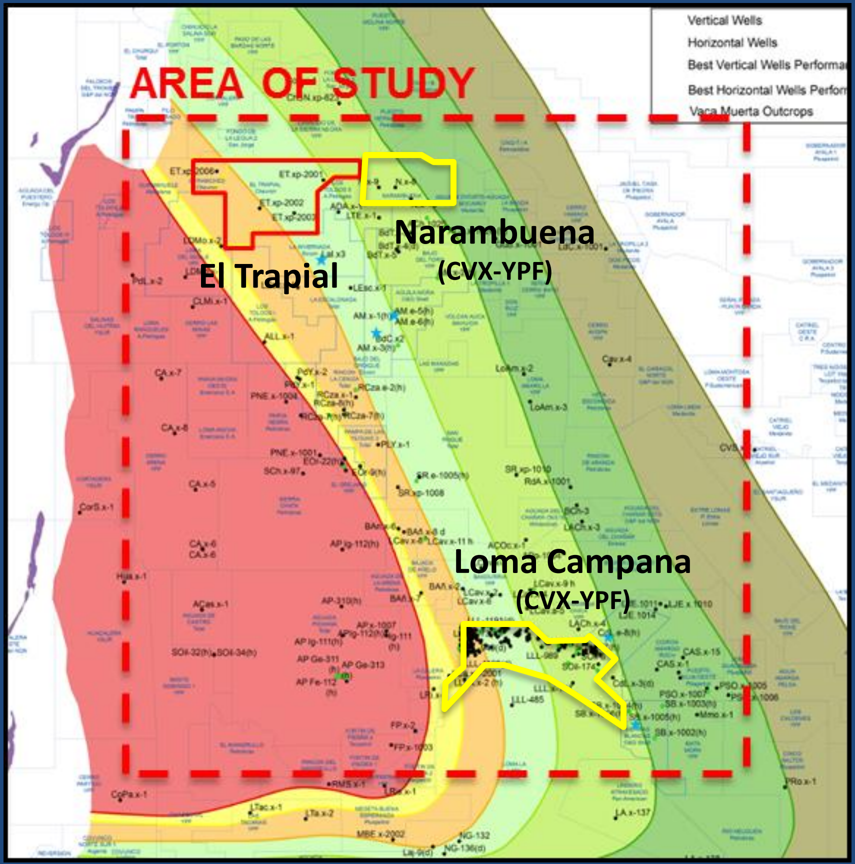
- Cuervo Sergio
  - Chevron Argentina

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. *Cijs 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*

Neuquén Basin & Chevron Assets in Argentina
Introduction & Summary



- ***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*

MAIN CONCEPTS - ELASTICITY
Stress tensor, strain tensor & elastic moduli

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

In order to characterize geomechanically the Vaca Muerta formation is necessary to know the relation between stress and strain, thus, the **elastic parameters.**

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

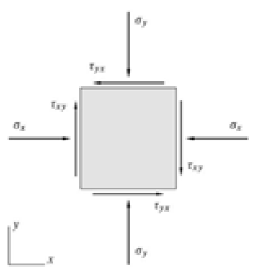
STRESS

Normal

$$\sigma = \frac{F_n}{A''}$$

Shear

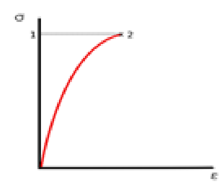
$$\tau = \frac{F_p}{A''}$$



ELASTIC MODULI

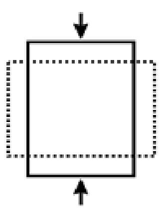
Young

$$E = \frac{\sigma}{\epsilon}$$



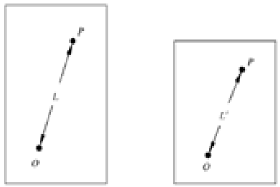
Poisson

$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{long}}$$



STRAIN

Strained
(elongation)



Shear strain
(angular)

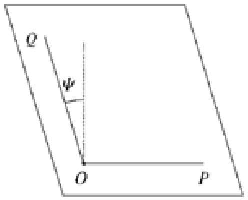


Image from Fjaer "Petroleum related rock mechanics"

ANISOTROPY:
The orthorombic symmery

- *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**.*

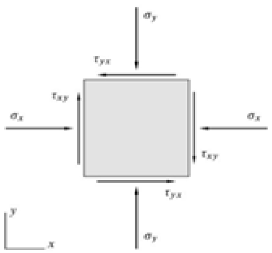


Fig. 1.4. Stress components in two dimensions.

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

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ 2\Gamma_{yz} \\ 2\Gamma_{xz} \\ 2\Gamma_{xy} \end{pmatrix}$$

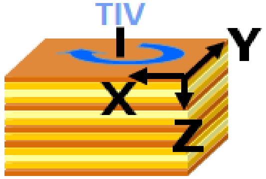
***σij =** Stress tensor*
***εkl =** Strain tensor*
***Cij =** elastic constants*
(Stiffness matrix)

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

ISOTROPIC

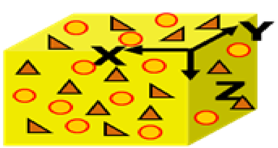
For an **isotropic material**, the linear elastic properties are completely described when any *two* of the elastic moduli.

TIV



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

ORTHOTROPIC



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

$$G = \rho v_s^2$$

$$\lambda = \rho v_p^2 - 2\rho v_s^2$$

Using the relationships between elastic moduli

DYNAMIC ELASTIC MODULI

$$K = \rho v_p^2 - \frac{4}{3}\rho v_s^2$$

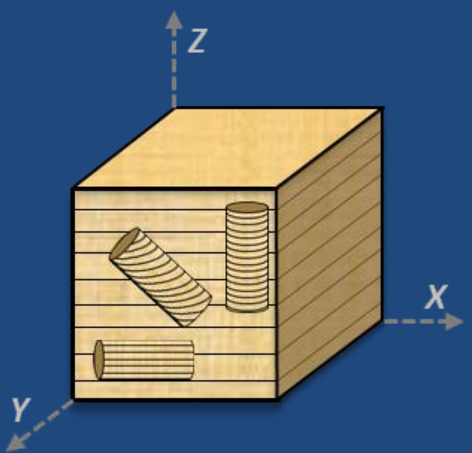
$$E = \rho v_s^2 \frac{3v_p^2 - 4v_s^2}{v_p^2 - v_s^2}$$

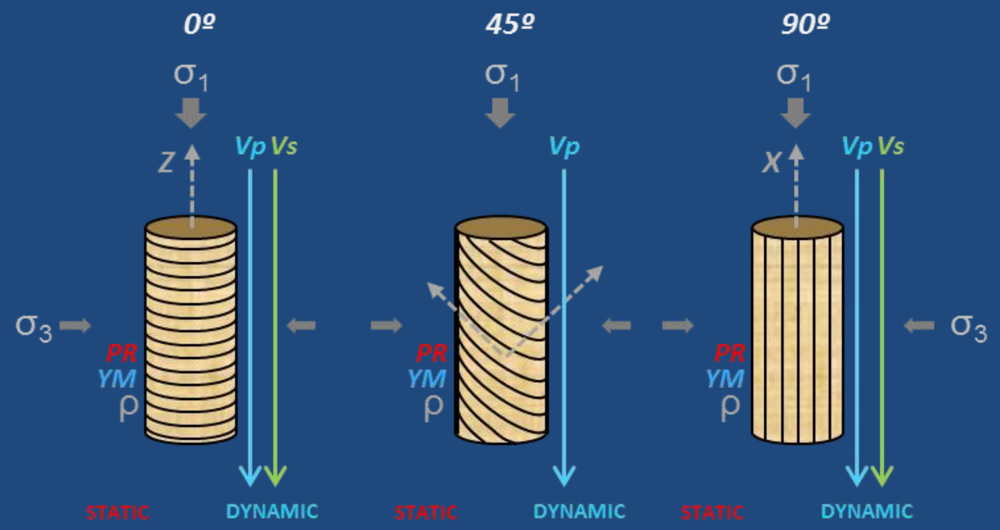
$$\nu = \frac{v_p^2 - 2v_s^2}{2(v_p^2 - v_s^2)}$$

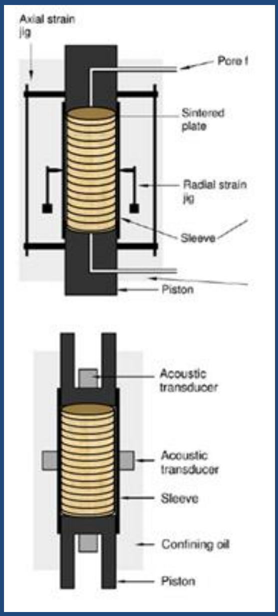
Sound velocities depend explicitly on elastic moduli

Image from Fjaer "Petroleum related rock mechanics"

MECHANICAL LABORATORY ANALYSIS
Elastic moduli measurement: Dynamic & Static





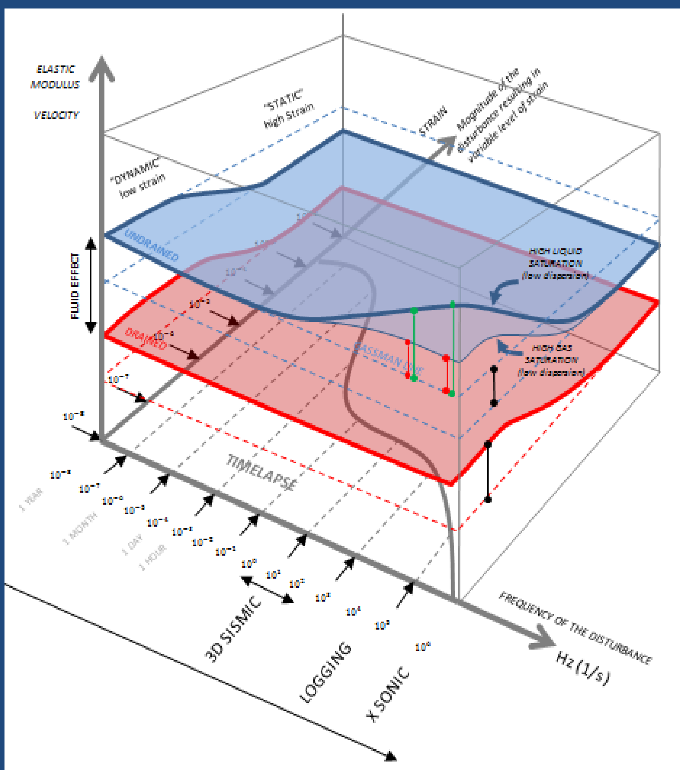


				Static Elastic moduli		Dyn measurements			Cij dyn						Dyn Elastic moduli	
Set #	Sample Name	Plug Depth	Plug Direction	YM_STA	PR_STA	Vp(0)	Vs1(0)	Bulk Density	C11	C33	C66	C44=C55	C12	C13	YM_DYN	PR_DYN
		(m)	(°)	(10^6psi)	-	(ft/sec)	(ft/sec)	(g/cc)	(GPa)	(GPa)	(GPa)	(GPa)	(GPa)	(GPa)	(10^6psi)	-
1	SAMPLE 1	2981.22	0	3.93	0.24	14932.2	8768.9	2.55							6.38	0.23
2	SAMPLE 2	2981.25	45	4.83	0.26	15648.6		2.55	66	53	23	18	20	19	7.20	0.21
3	SAMPLE 3	2981.30	90	6.75	0.27	16727.5	9366.1	2.55							8.19	0.25

ACOUSTIC VELOCITY
Dynamic to static discrepancy

Dispersion:

"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)	≠	*DYNAMIC ELASTIC MODULI (from log velocity)*	≠	*DYNAMIC ELASTIC MODULI (from lab acoustic velocity)*	>	*STATIC ELASTIC MODULI (from rock mechanical test)*
1 to 100 Hz		*10 to 40 kHz*		*100 kHz to 1MHz*		

DISPERSION

Cause: *Frequency*

The conversion depends on the Strain magnitude

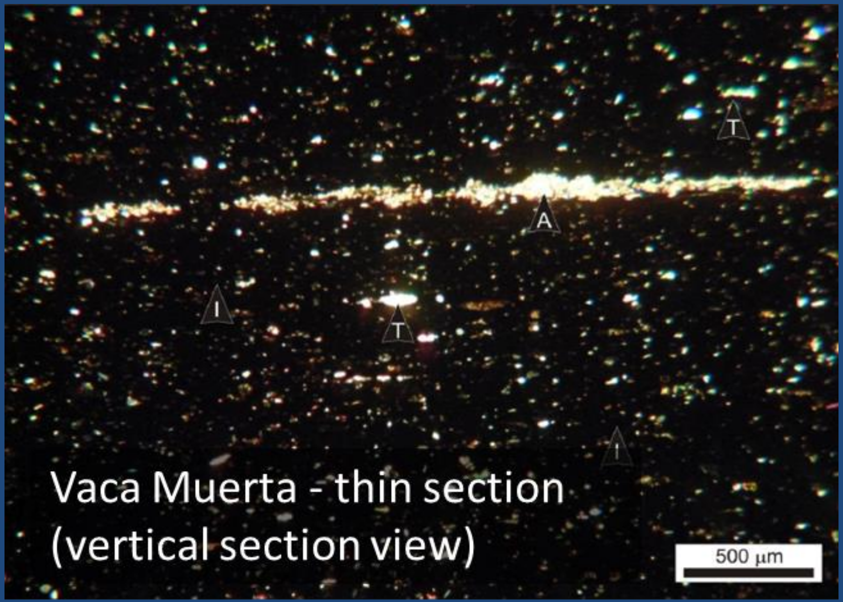
- ***The term DYNAMIC means small strains***
- ***The term STATIC means large strains***

Empirically based correlations are not universally applicable since the correction is not a constant shift

VACA MUERTA
TIV evidence

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 .

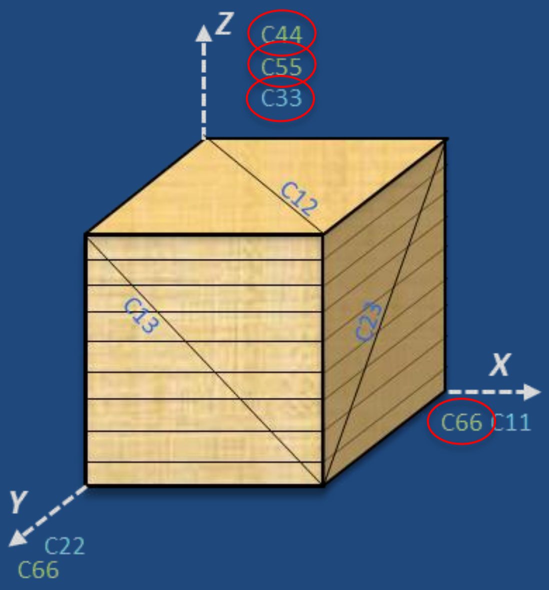
- *Shales are usually strongly anisotropic by nature, due to the sharp lamination they exhibits in all the scales.*



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.



$$C_{33} = \rho V_p^2$$

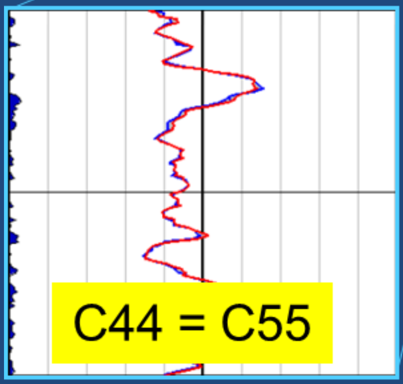
$$C_{44} = \rho V_{slow\_s}^2 = \rho V_{fast\_s}^2$$

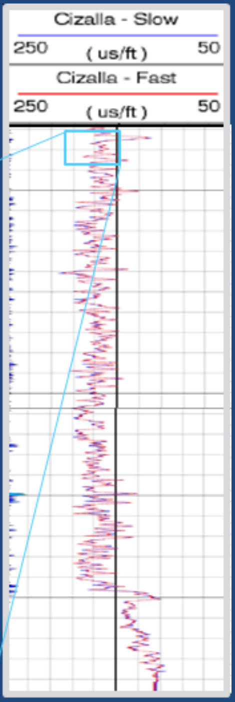
$$C_{66} = \rho V_{shear\_horizontal}^2$$

Besides providing information anisotropy, Sonic Scanner allows to estimate C33, C44 and C66. Needs to the fully definition of the Cij tensor for TIV symmetry.

ISOTROPY evidence in the y-x plane

ET well "B"



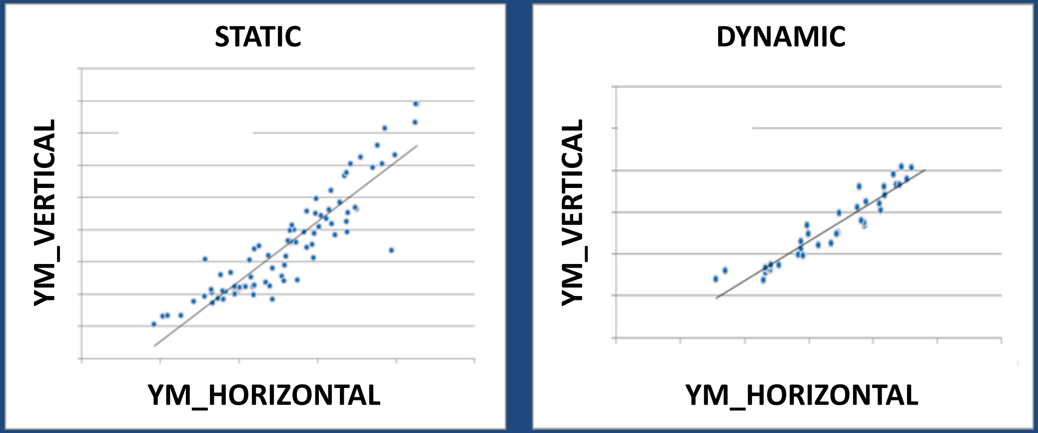


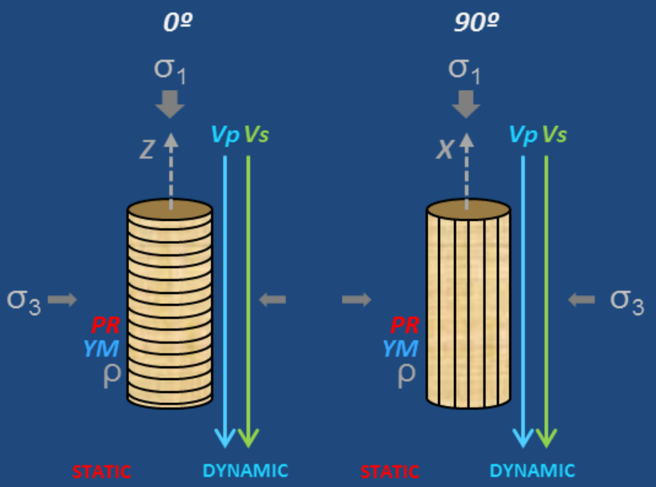
VACA MUERTA
TIV evidence

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.*

YOUNG MODULUS





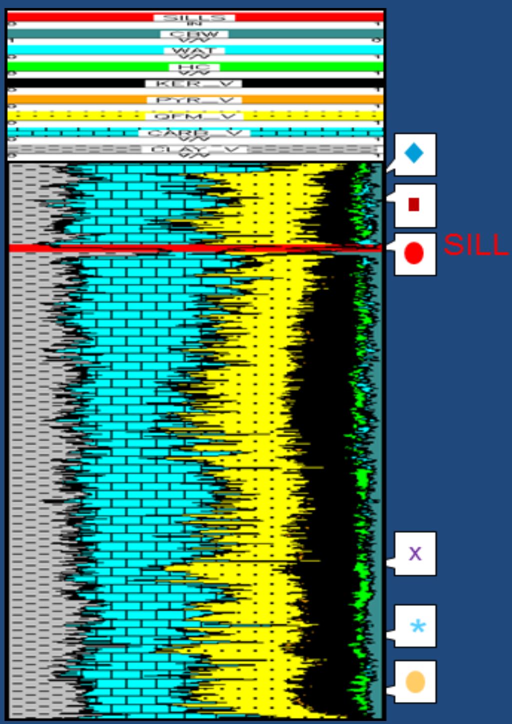
V/H Anisotropy ranges between 30 to 60%

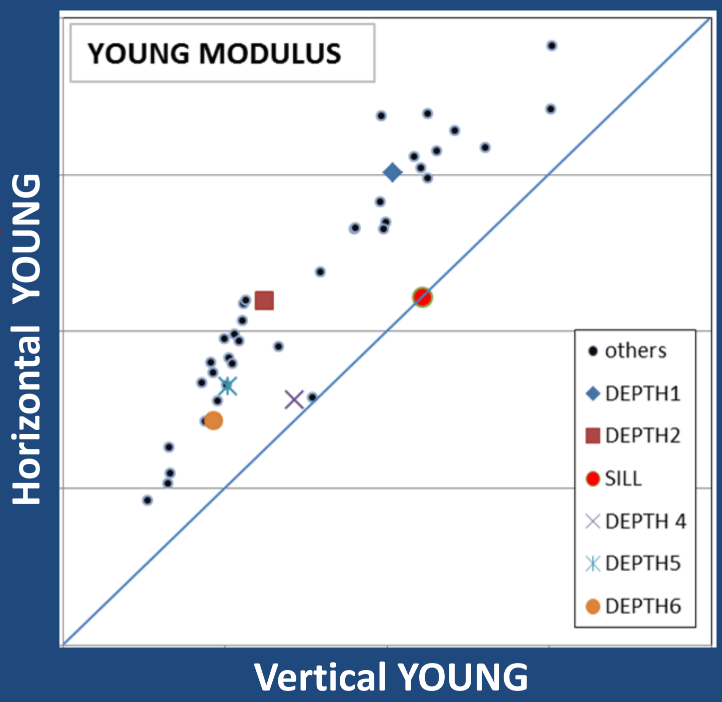
(*)139 Triaxial Test

VACA MUERTA
TIV evidence

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 .

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





ET well "A"

			YM Aniso
Average elastic Moduli	DEPTH1	V	33%
	DEPTH1	H	
	DEPTH2	V	43%
	DEPTH2	H	
	SILL	V	0%
	SILL	H	
	DEPTH4	V	8%
	DEPTH4	H	
	DEPTH5	V	38%
	DEPTH5	H	
	DEPTH6	V	35%
	DEPTH6	H	

STIFFNESS MATRIX
Cij definition

$$\begin{pmatrix} C_{11} & C_{11}-2C_{66} & C_{13} & 0 & 0 & 0 \\ C_{11}-2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

symmetry in TIV:
$C_{23} = C_{13}$
$C_{22} = C_{11}$
$C_{55} = C_{44}$
$C_{12} = C_{11} - 2\,C_{66}$

- Cij estimation workflow summary

Assumption & Simplifications:

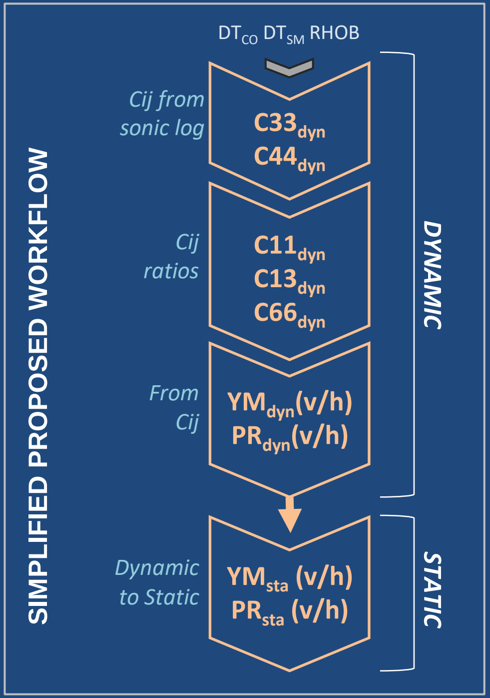
Based on TIV symmetry, acoustic wave, and Cij ratios, rock stiffness tensor could be characterized by:

- 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.

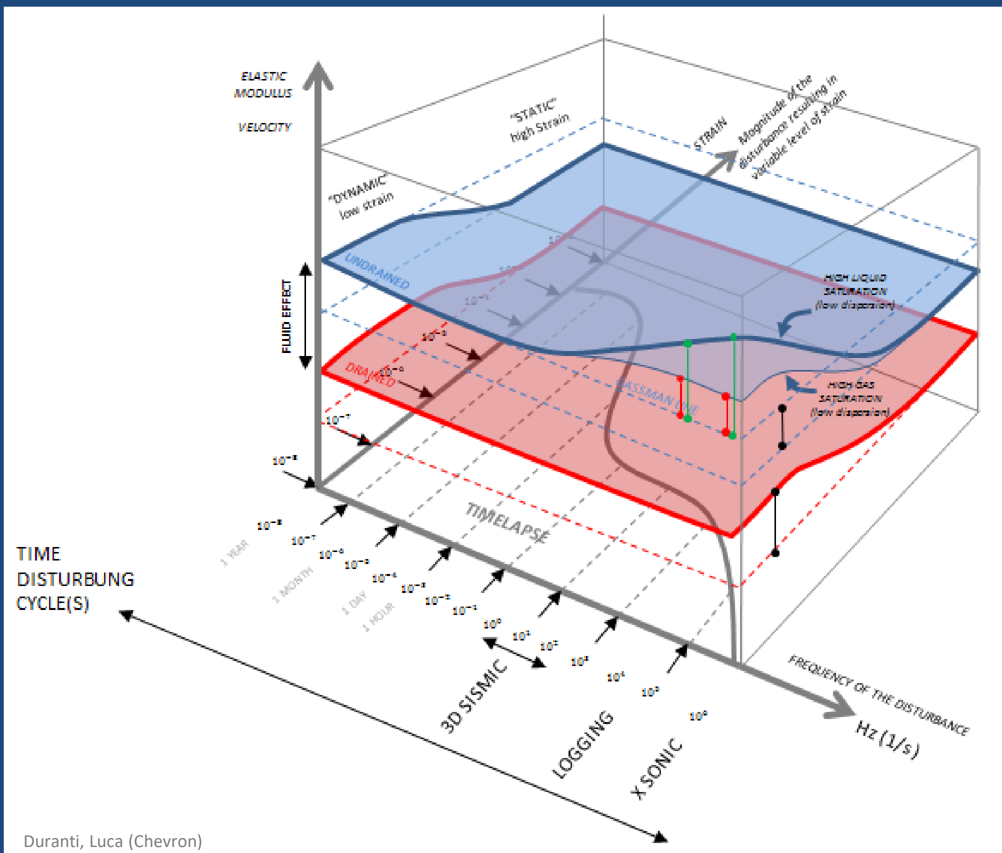
TIV Symmetry
$C_{23} = C_{13}$
$C_{22} = C_{11}$
$C_{55} = C_{44}$
$C_{12} = C_{11} - 2\,C_{66}$

Acoustic measurements
$C_{33} = f(C_{33})$
$C_{44} = f(C_{33})$

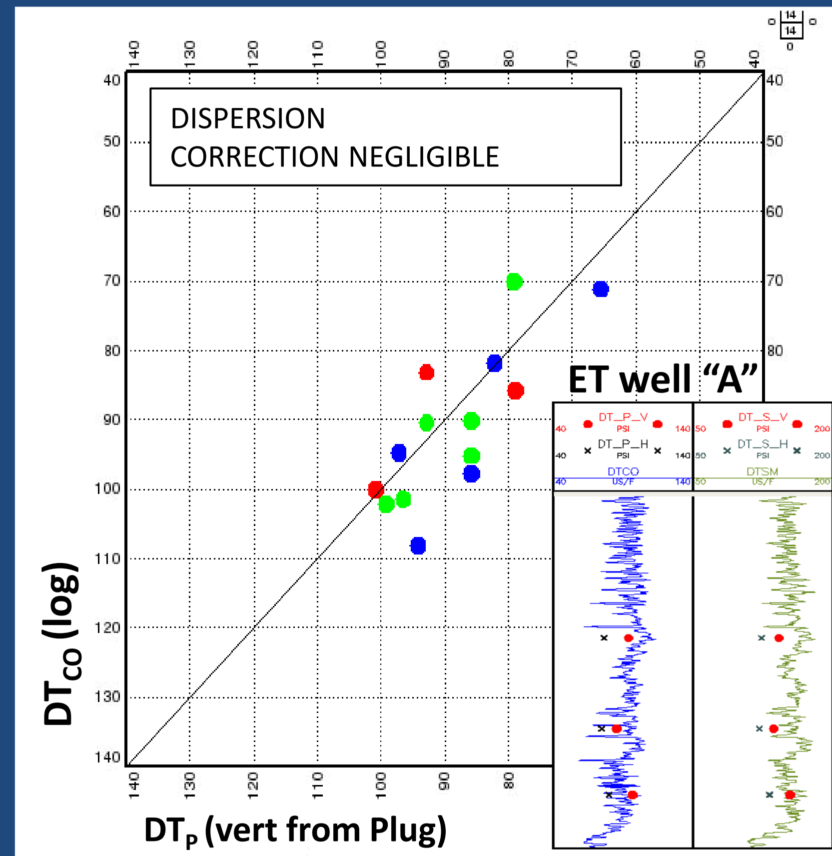
Proposed correlations
$C_{11} = f(C_{33})$
$C_{13} = f(C_{33})$
$C_{66} = f(C_{44})$



STIFFNESS MATRIX
Cij definition



Duranti, Luca (Chevron)



STIFFNESS MATRIX
Cij definition

$$\begin{pmatrix} C_{11} & C_{11}-2C_{66} & C_{13} & 0 & 0 & 0 \\ C_{11}-2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

symmetry in TIV:

$C_{23} = C_{13}$

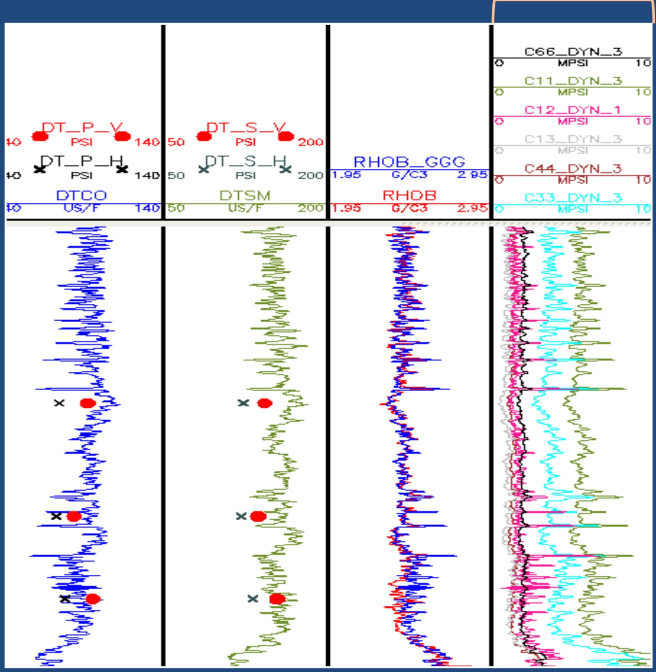
$C_{22} = C_{11}$

$C_{55} = C_{44}$

$C_{12} = C_{11} - 2\,C_{66}$

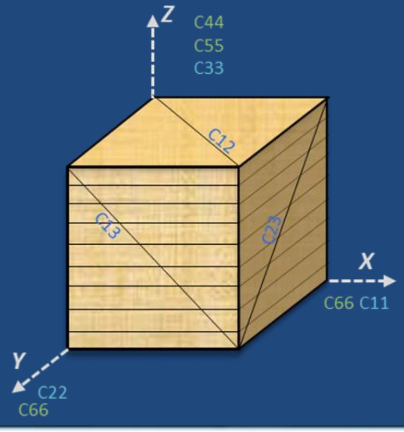
- C33 & C44 calculation by compressional and shear sonic and Density logs

C_{ij}

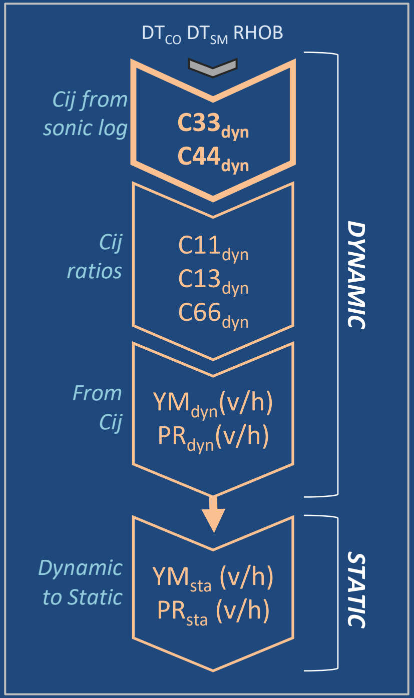


$$C_{33} = \rho V_p^{\,2}$$

$$C_{44} = \rho V_{slow\_s}^{\;\;2} = \rho V_{fast\_s}^{\;\;2}$$



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

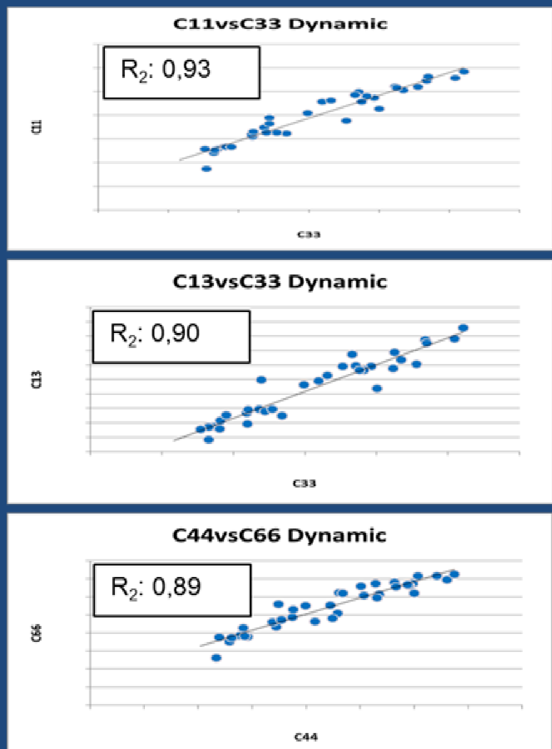


STIFFNESS MATRIX
Cij definition

$$\begin{pmatrix} C_{11} & C_{11}-2C_{66} & C_{13} & 0 & 0 & 0 \\ C_{11}-2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

symmetry in TIV:
$C_{23} = C_{13}$
$C_{22} = C_{11}$
$C_{55} = C_{44}$
$C_{12} = C_{11} - 2\,C_{66}$

CORRELATIONS 2



Cij useful ratios

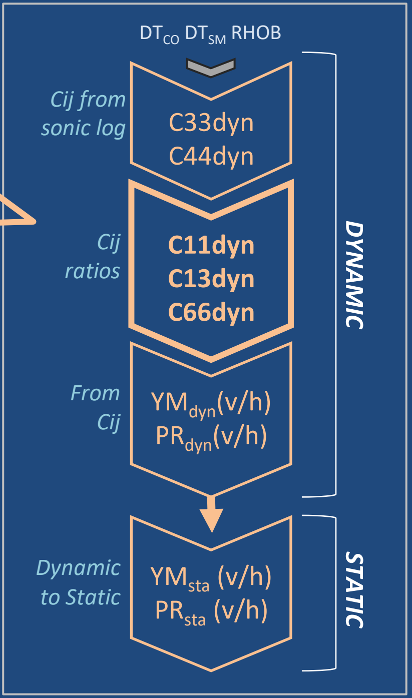
- Based on Cij ratios & TIV symmetry: just C11, C13, C66 remain to be calculated to the full Cij description.

$$C11_{dyn} = A + B * C33_{dyn}$$
$$C13_{dyn} = -C + D * C33_{dyn}$$
$$C66_{dyn} = E + F * C44_{dyn}$$

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*

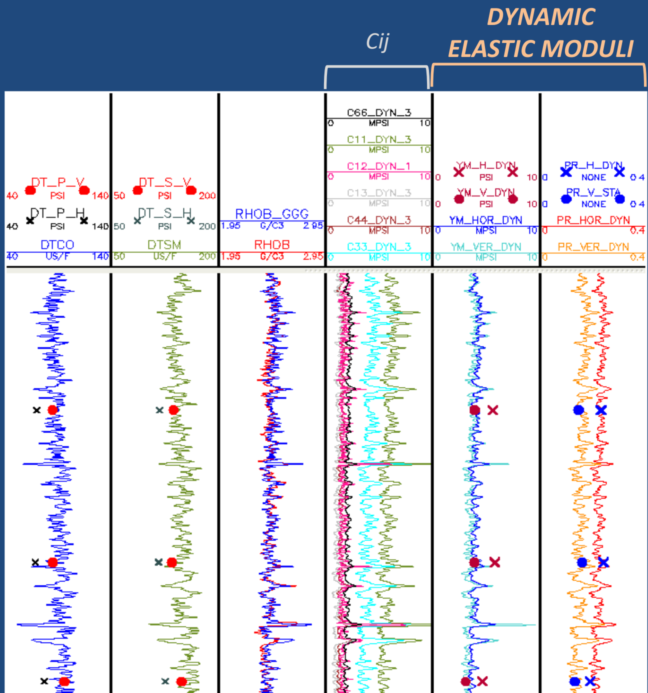
From Mannie Model (assumptions)

$$C_{11} = \xi(\zeta C_{33} - 2C_{44}) + 2C_{66}$$
$$C_{13} = \zeta C_{33} - 2C_{44}$$



STIFFNESS MATRIX
Cij definition

- **Dynamic elastic moduli**: Elastic moduli expressed as Cij



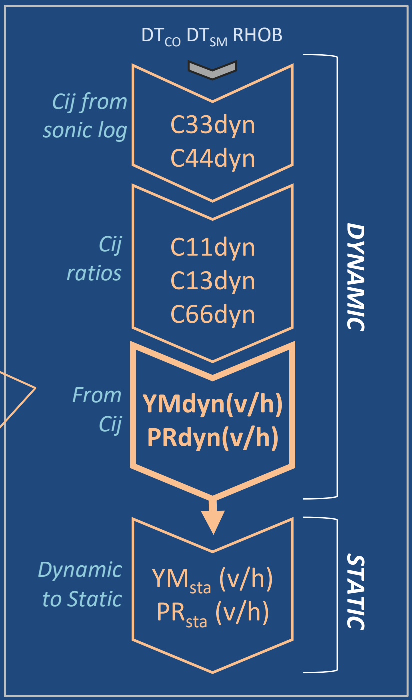
Dynamic elastic constants (stiffness matrix) may rewritten as elastic modulus (Young & Poisson expression)

$$YM_{dyn}(v) = \left(\frac{2 * C_{13} * C_{13}}{C_{11} + C_{12}}\right)$$

$$YM_{dyn}(h) = \frac{(C_{11} - C_{12}) * (C_{11}C_{33} - 2C_{13}C_{13}) + C_{12}C_{33}}{C_{11}C33 - C_{13} * C_{13}}$$

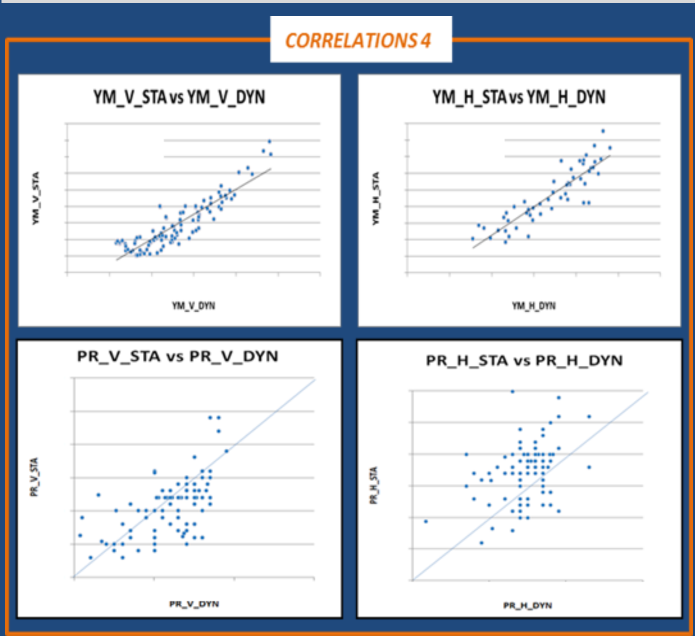
$$PR_{dyn}(v) = \frac{C_{13}}{C_{11} + c_{12}}$$

$$PR_{dyn}(h) = \frac{C_{33}C_{12} - C_{13}C_{13}}{C_{11}C_{33} - C_{13}C_{13}}$$



STIFFNESS MATRIX
Cij definition

- Dynamic to pseudo-static conversion



Elastic moduli dyn to sta

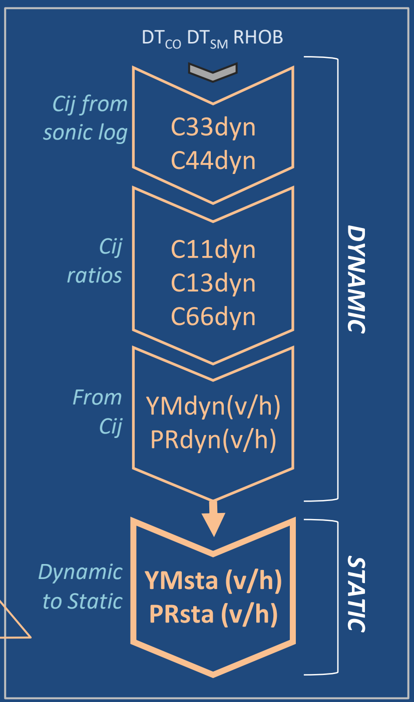
Triaxial compression test on core samples provide the static values to calibrate the dynamic properties (Franquet, J.A. 2012)

$$YM_{sta}(v) = -G + H * YM_{dyn}(v)$$

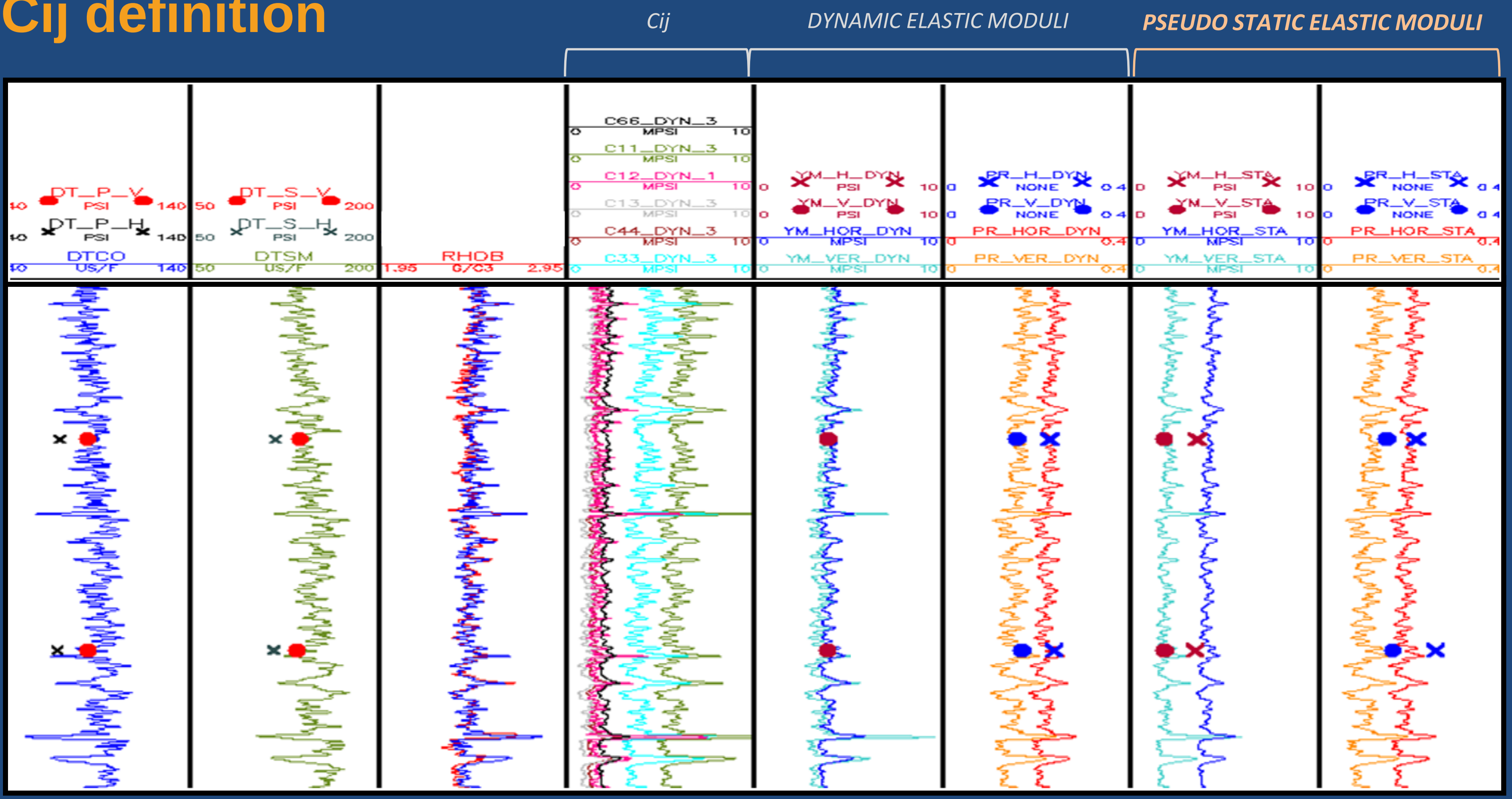
$$YM_{sta}(h) = I + J * YM_{dyn}(h)$$

$$PR_{sta}(v) = -K + PR_{dyn}(v)$$

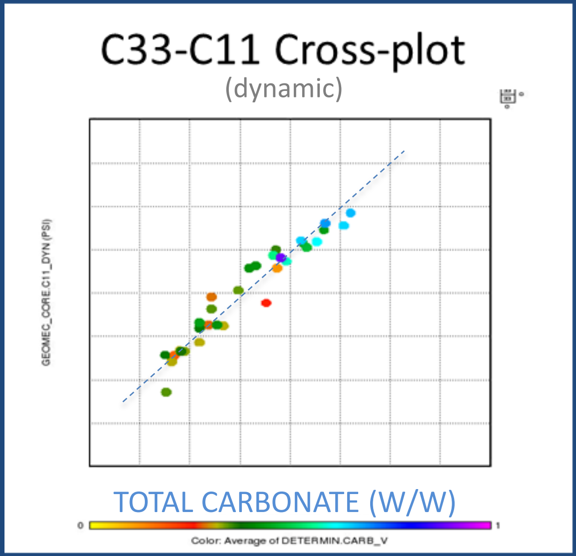
$$PR_{sta}(h) = -L + PR_{dyn}(h)$$

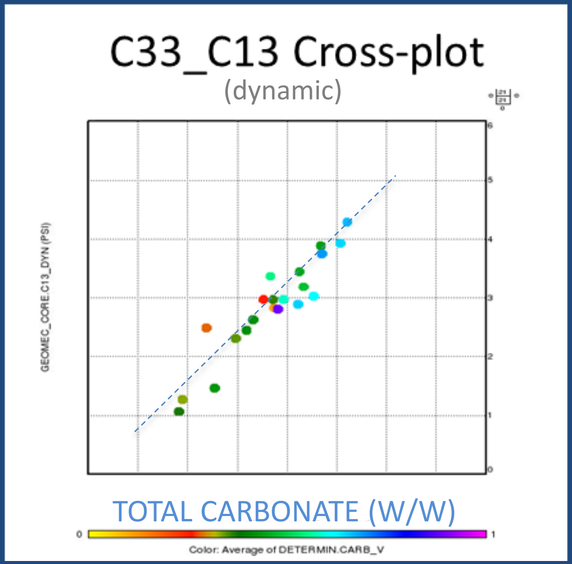


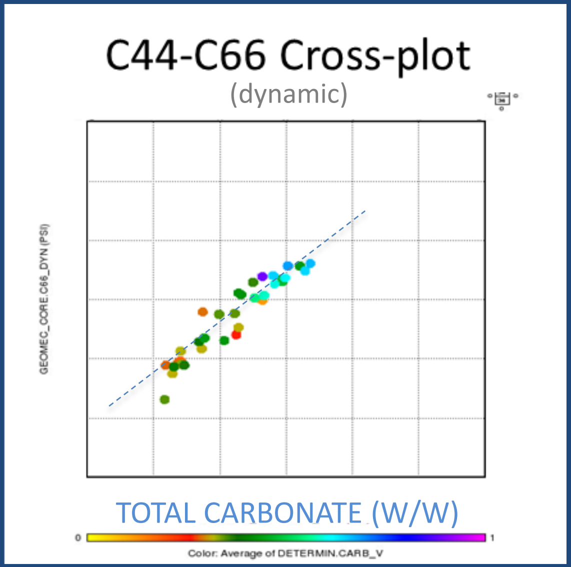
STIFFNESS MATRIX
Cij definition



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 Cij (C33, C44)** 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 !

References

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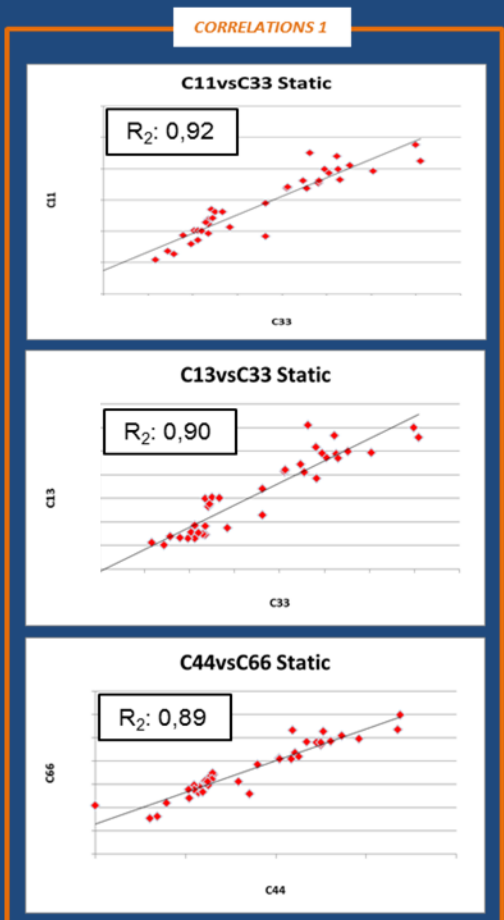
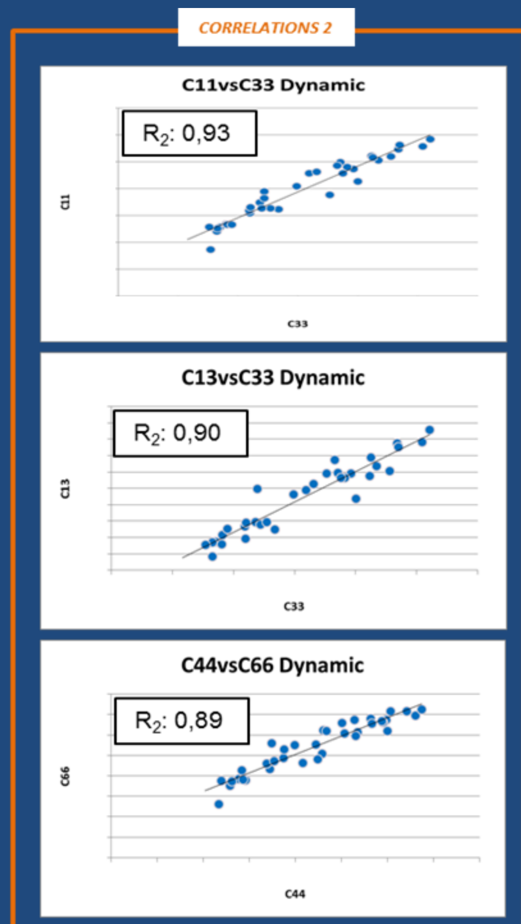
- *Sonic Scanner: Acoustic Scanner Platform - Brochure – Schlumberger 2005*
- *Petroleum Related Rock Mechanics , 2nd edition. E. FJÆR, R.M. HOLT, P. HORSRUD, A.M. RAAEN & R. RISNES - 2008*

Cij ratios consistency





- Dynamic & Static Cij ratios shows the same trend