Anisotropic static and dynamic moduli measured on shale plugs cut parallel and perpendicular to bedding
or
Serendipity in the quest for C13

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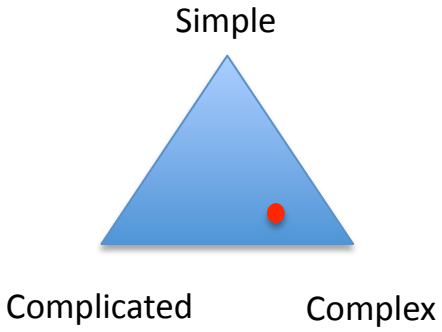
Serendipity

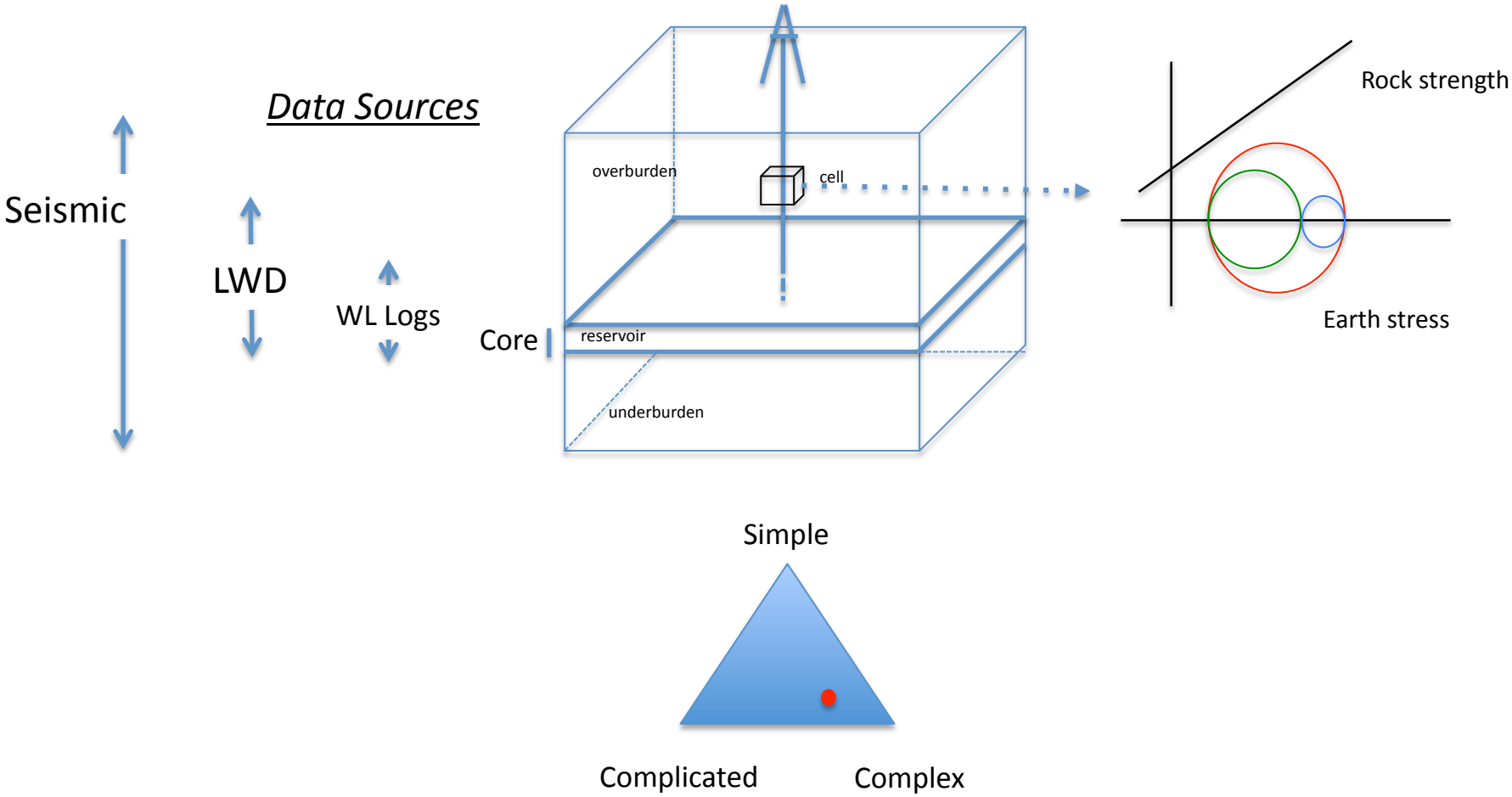
The faculty of finding valuable or agreeable things not sought for

Background/Motivation

- Exploration well-significant NPT due to wellbore instability in a thick shale formation
- No knowledge of the state of stress or rock mechanical properties



Nature of the problem



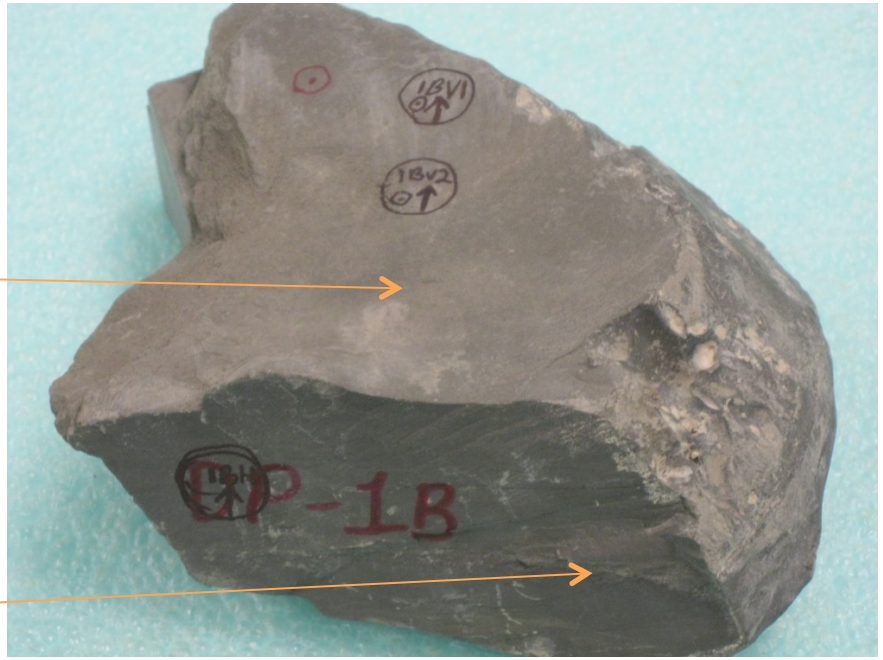
Serendipity Event#1

Found sample of the problem rock

Shale Sample of Opportunity

Bedding enhanced by erosion by water

Conchoidal-like fracture surface



1”

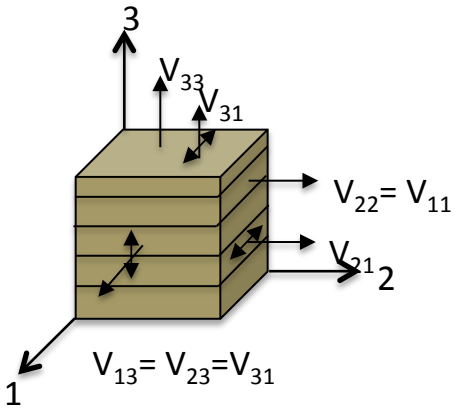
scale

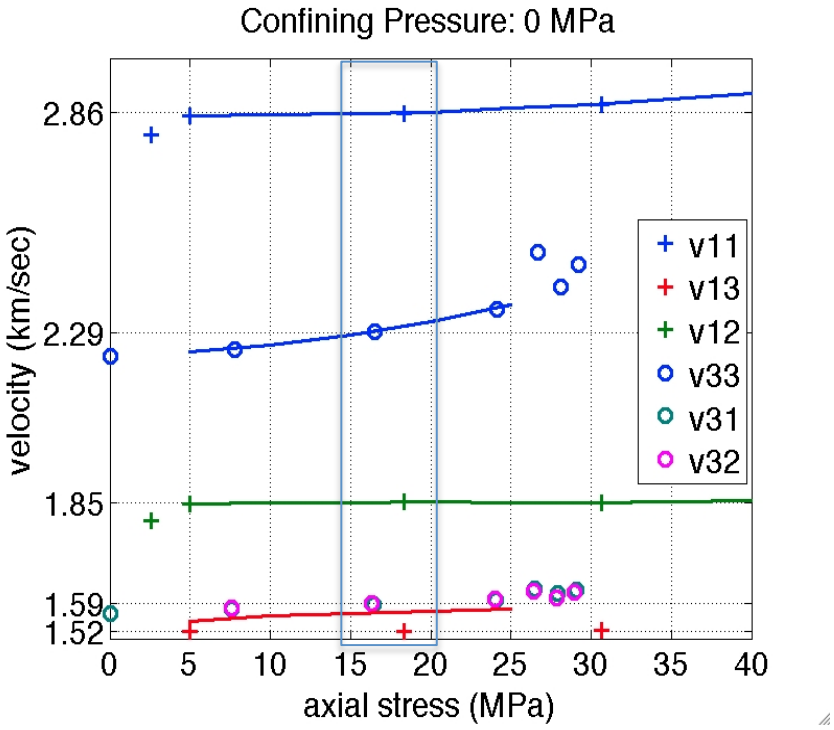
Weak compositional layering

Serendipity Event#2

I shared the experimental data with Doug Miller

TI parameters from ultrasonics





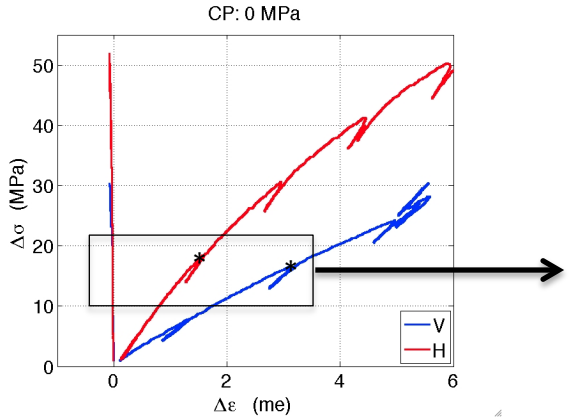
Theory and Measurement

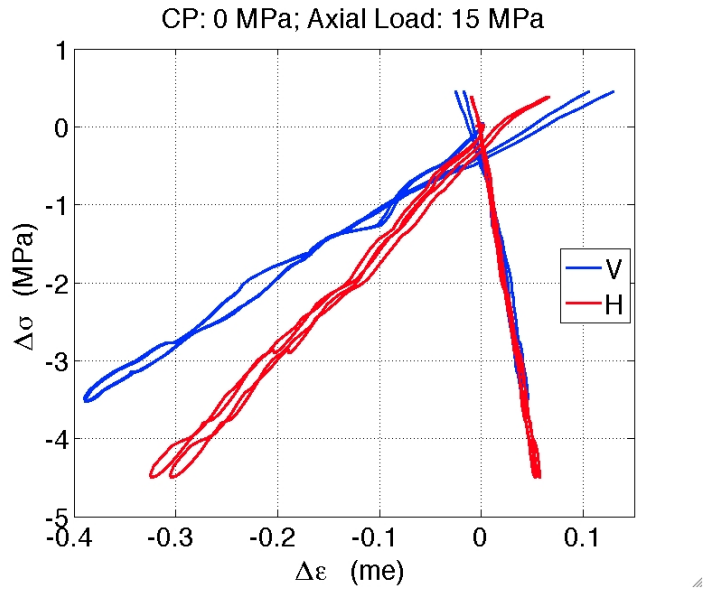
1. $V11^2 = C11/\rho$
2. $V33^2 = C33/\rho$
3. $V12^2 = C66/\rho$
4. $V13^2 = V31^2 = V32^2 = C55/\rho$

For TI symmetry: C12 + 2 C66 = C11.

Thus, ultrasonics determine C33, C55, C11, C12, C66 (but not C13)

TI parameters from load-unload cycles





Theory:

Perpendicular core:

- axial stress/axial strain = σ33/ε33 = 1/S33 = E33
- axial stress/radial strain = σ33/ε11 = 1/S13 = E33/ν33

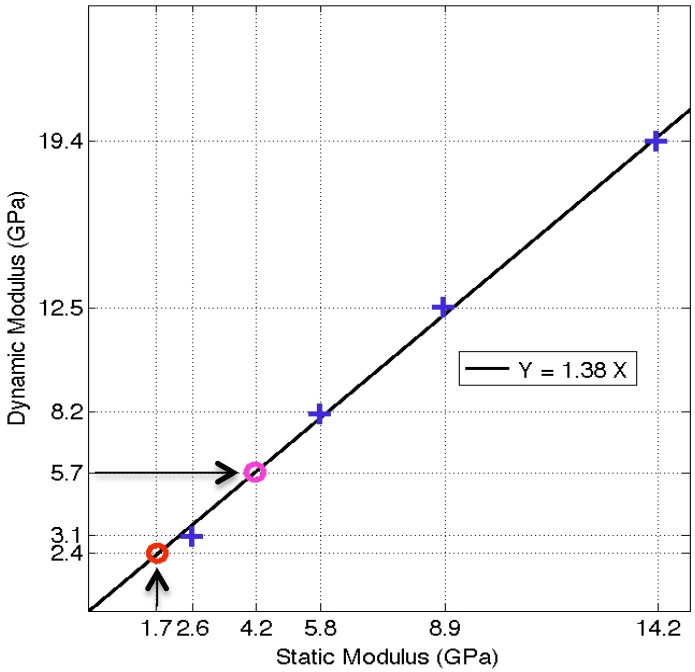
Parallel core

- axial stress/axial strain = σ11/ε11 = 1/S11 = E11
- axial stress/radial strain@45° = 2 σ11/(ε33+ε11) = 2/(S13+S12)

Observe in this case: 1/S12 = 2/(S13+S12), hence S12 = S13.

Statics determine S33, S13, S11, S12, & thence C33, C13, C11, C12, C66 (but not C55)

Combined Methods



C11

C33

C66

C55

C12

C13

- Elastostatics determine: C33, C13,C11,C12,C66 (but not C55)
- Ultrasonics determine: C33,C12,C55,C66 (but not C13)
- Doubly determined parameters are proportional: Dynamic=1.38 x Static
- *Singly determined moduli can be predicted by rescaling.*

Moduli	C11	C13	C33	C55	C66	C12
Ultrasonics	19.4	**2.4**	12.5	5.7	8.2	3.1
Elastostatics	14.2	1.7	8.9	**4.2**	5.8	2.4
Dynamic Stat x 1.38	19.5	2.4	12.2	5.7	8.0	3.3
Static	14.1	1.7	9.1	4.1	5.9	2.3

Conclusions

- The shale is anisotropic w.r.t. elastic moduli and compressive strength-consistent with TI symmetry
- Dynamic elastic moduli are systematically greater than the static moduli determined from small stress unloading cycles.
- There was a remarkably strong correlation between the static and dynamic moduli on this shale
- Consequently the two plug method enabled determination of *static* and *dynamic* values of all 5 TI parameters
- A fruitful research topic is understanding the physics governing the difference between the static/dynamic modulus of shale.

Acknowledgements

- Hunt Oil Dallas for permission to present this rock mechanics data
- New England research for conducting the laboratory measurements and preliminary rock characterization