Robust determination of rock anisotropy in the laboratory using laser ultrasonics

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Abstract

Robust characterization of rock anisotropy is the preferred laboratory method to support seismic data interpretation in the field. Especially in shale formations, accurate elastic anisotropy helps delineate subsurface stress distribution, improve seismic imaging, and enhance hydraulic fracturing design. The conventional technique for evaluating rock elastic anisotropy involves ultrasonic pulse transmission between source and receiver transducers attached to the rock surface. The size, position and orientation of the source and receiver in relation to the propagation distance and direction, and their coupling to the rock surface introduce undesired uncertainties in Thomsen's anisotropy parameters and rock attenuation: effective propagation distance; group or phase velocity; impact of the contact interface on measured wave attenuation; impact of heterogeneity on wave velocity measurements. We apply here the contactless laser ultrasonic method, involving a source laser (short-pulse high-peak power), a probing laser (vibrometer), and a cylindrical rock sample set on a rotating stage. The footprint of the source laser beam is 2 mm, and that of the receiver beam is 0.1 mm, which can conveniently be approximated by a point on a centimetric rock sample. The propagation distance is hence unambiguously known, implying that a group velocity is effectively estimated, and the observed attenuation is solely due to the rock, not to the rock-transducer interface (extrinsic). The technique also allows for a denser ultrasonic probing. Four samples are probed, where the P-wave velocity along up to 630 independent ray paths is evaluated. Three samples are made of a known, homogeneous, and layered synthetic material phenolic grade, approximately transversely isotropic. These samples were cored along, across and at 45° to the layers. The fourth sample is a heterogeneous shale from the Goldwyer formation (Canning basin, Western Australia). The measurements on the three known phenolic samples are used to validate the method, and optimise the measurement protocol. Application of the method to the unknown heterogeneous shale suggests that (i) anisotropy can be reliably estimated in the homogeneous sub-volume of the sample and that (ii) the mineralogical heterogeneity can be detected and identified in other sub-volume.

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ROBUST DETERMINATION OF ROCK ANISOTROPY IN THE LABORATORY USING LASER ULTRASONICS

Partha Pratim Mandal*, Jonathan Simpson, Joel Sarout, Yevhen Kovalyshen, Ludmila Adam, Kasper van Wijk, & Reza Rezaee

Session Title: MR43A - Physical Properties of Earth Materials (PPEM): The Long and the Short of It I Oral

Date: 17-December-2021

AGU FALL MEETING

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2 – CSIRO Energy: Rock Properties Team, Perth, Australia

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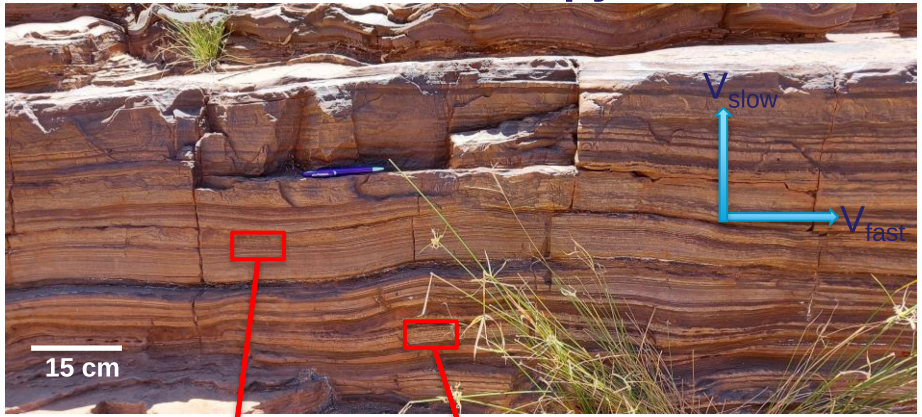
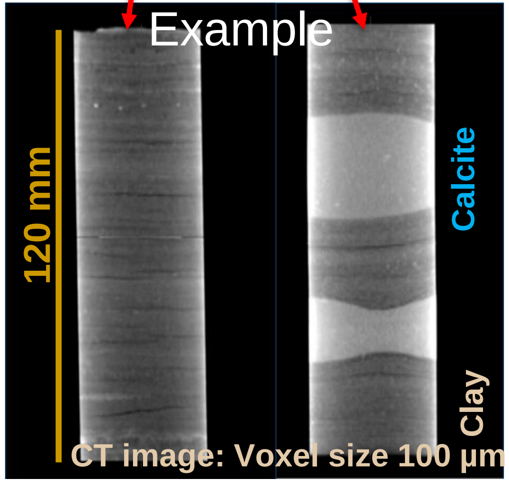
AGENDA

- Background – shale anisotropy
- Rationale – laboratory technique
- Laser Ultrasonic Survey (LUS) & sample characterization
- LUS waveform Inversion (Thomsen's anisotropy parameters & Symmetry axis orientation)
- Advantages & limitations of LUS
- Conclusions

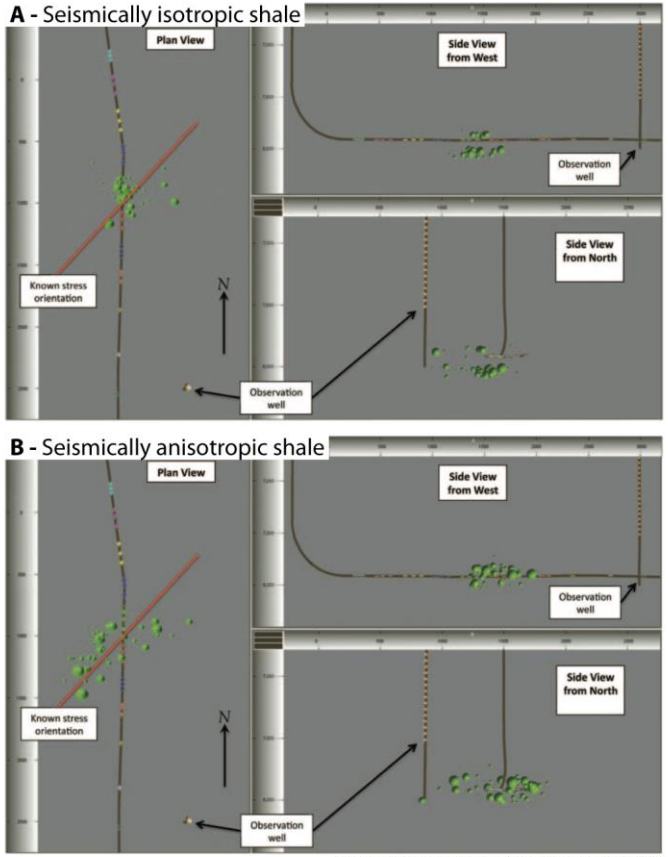
BACKGROUND – SHALE ANISOTROPY

Rock anisotropy





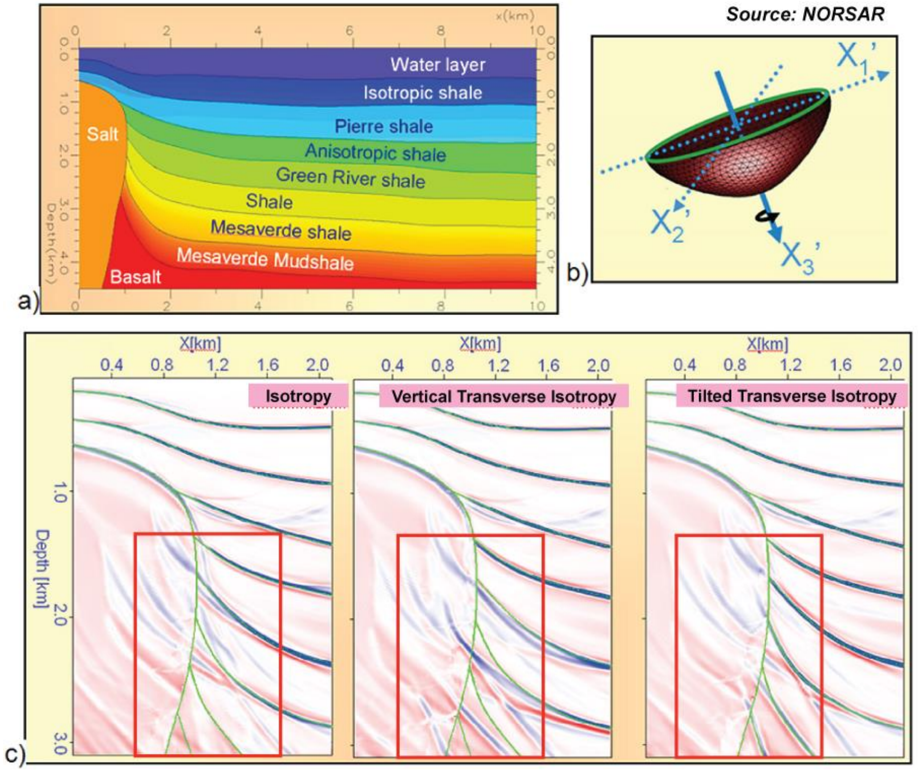
Subsurface stress distribution & hydraulic fracturing – shale



Bakken shale, North Dakota, from Van Dok et al. (2011)

Subsurface seismic imaging

Source: NORSAR



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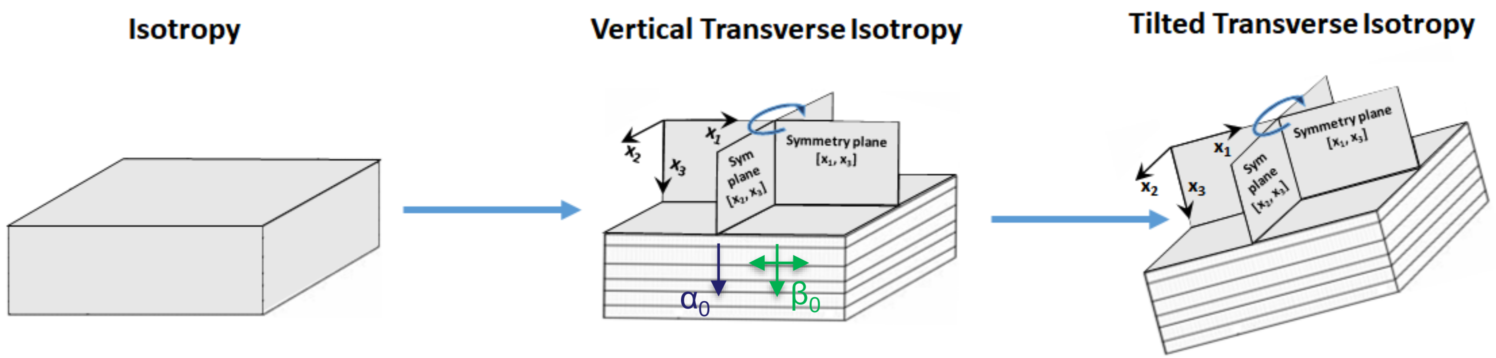
RATIONALE – DESCRIBING TRANSVERSE ISOTROPY (TI)

Five independent parameters $\alpha_0, \beta_0, \varepsilon, \gamma, \delta$ (Thomsen, 1986) to describe TI media (in a known symmetry frame, azimuth angle *p* and dip angle *q* of the symmetry axis):



He et al., 2013

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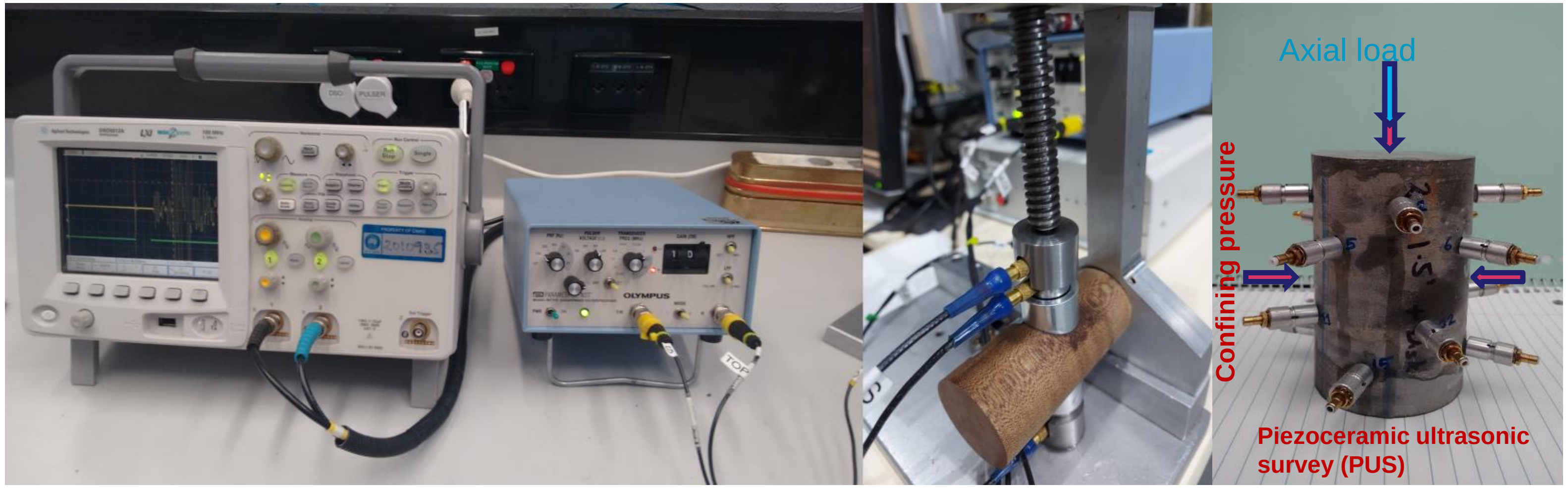
RATIONALE – PIEZOCERAMIC ULTRASONIC SURVEY (PUS)

- Which conventional technique is used to define Thomsen's anisotropy parameters?
- <u>Thomsen's anisotropy parameters</u> (α_0, ε, δ) and orientation of symmetry axis from inversion of P-wave velocities with PUS
- Challenges of PUS setup?



Oscilloscope Pulser Transducers

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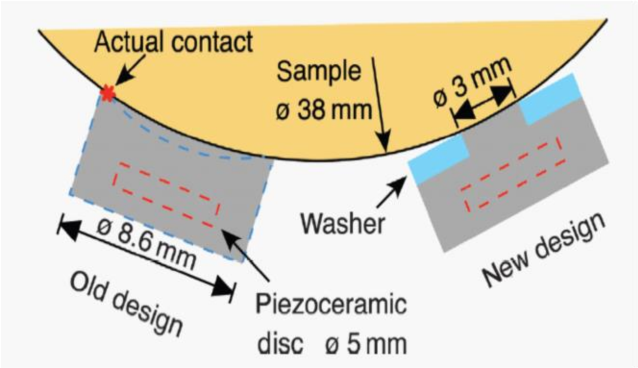
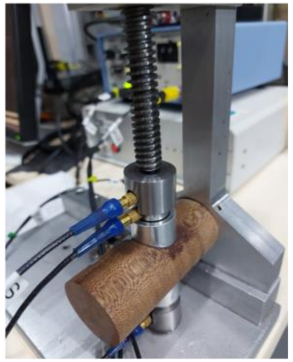
CHALLENGES OF PUS

- Phase or group velocity measurement?
- Coupling ?
- Sampling density?
- Identification of fast and slow P-wave direction in TI media?

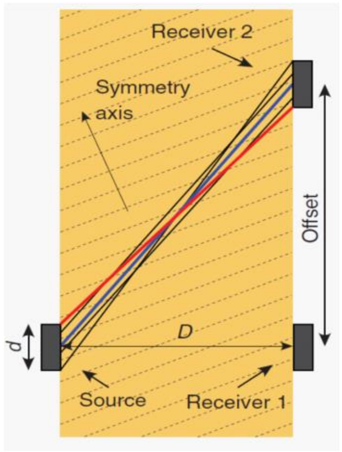
Transducer size



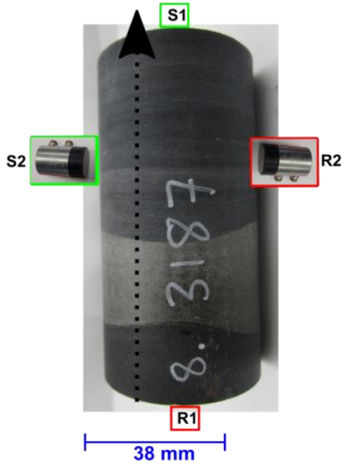
Coupling



Propogation path



known axis of symmetry



(Kovalyshen et al., 2020 ; Kovalyshen et al., 2017)

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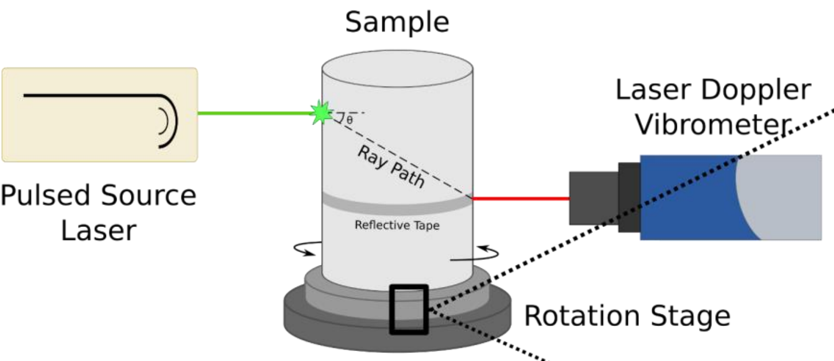
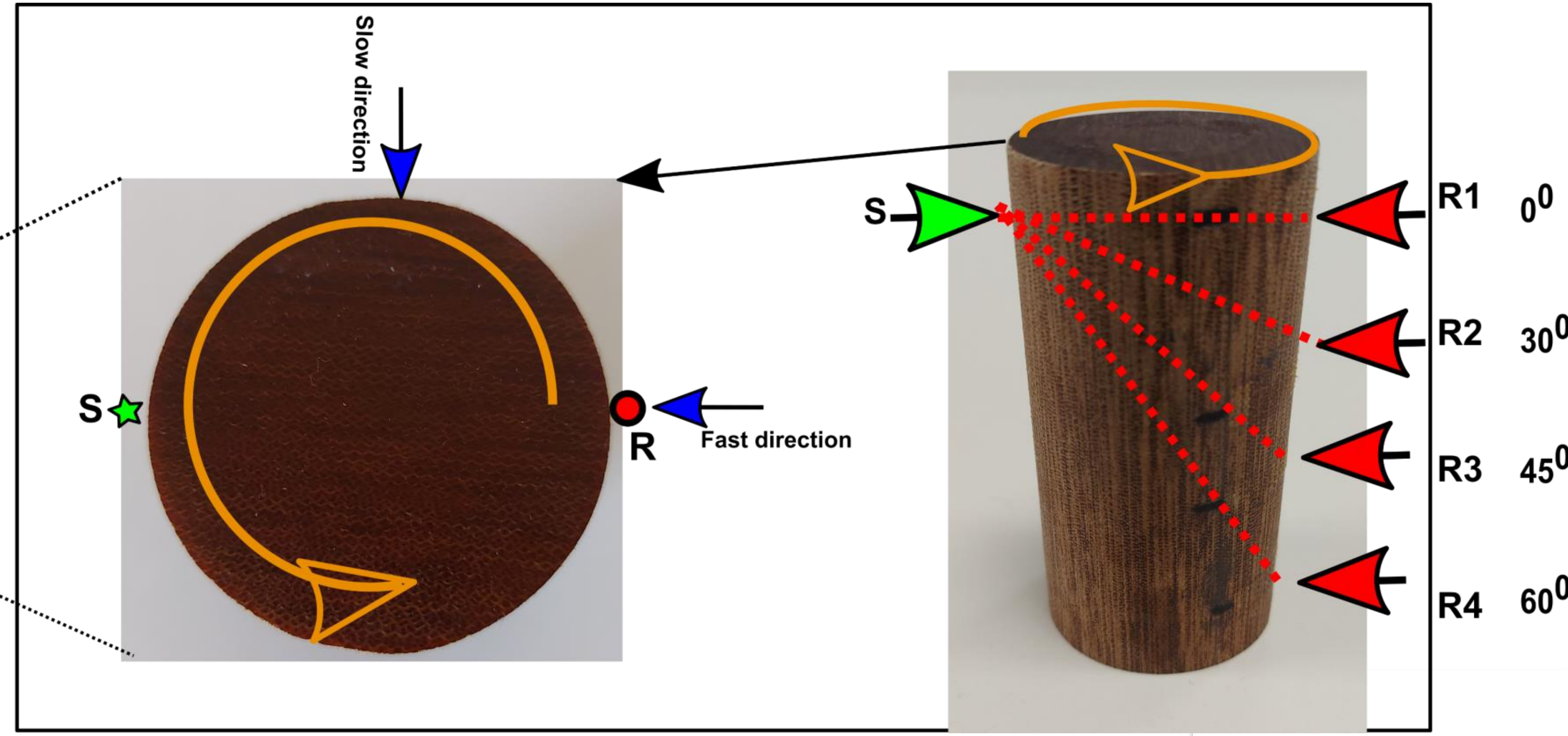
LUS EXPERIMENT PROTOCOL





- Laser source size – 2 mm
- Receiver (LVD) size – 0.1 mm
- Automated rotating stage
- Automated data acquisition with PLACE
- Double LVD configuration

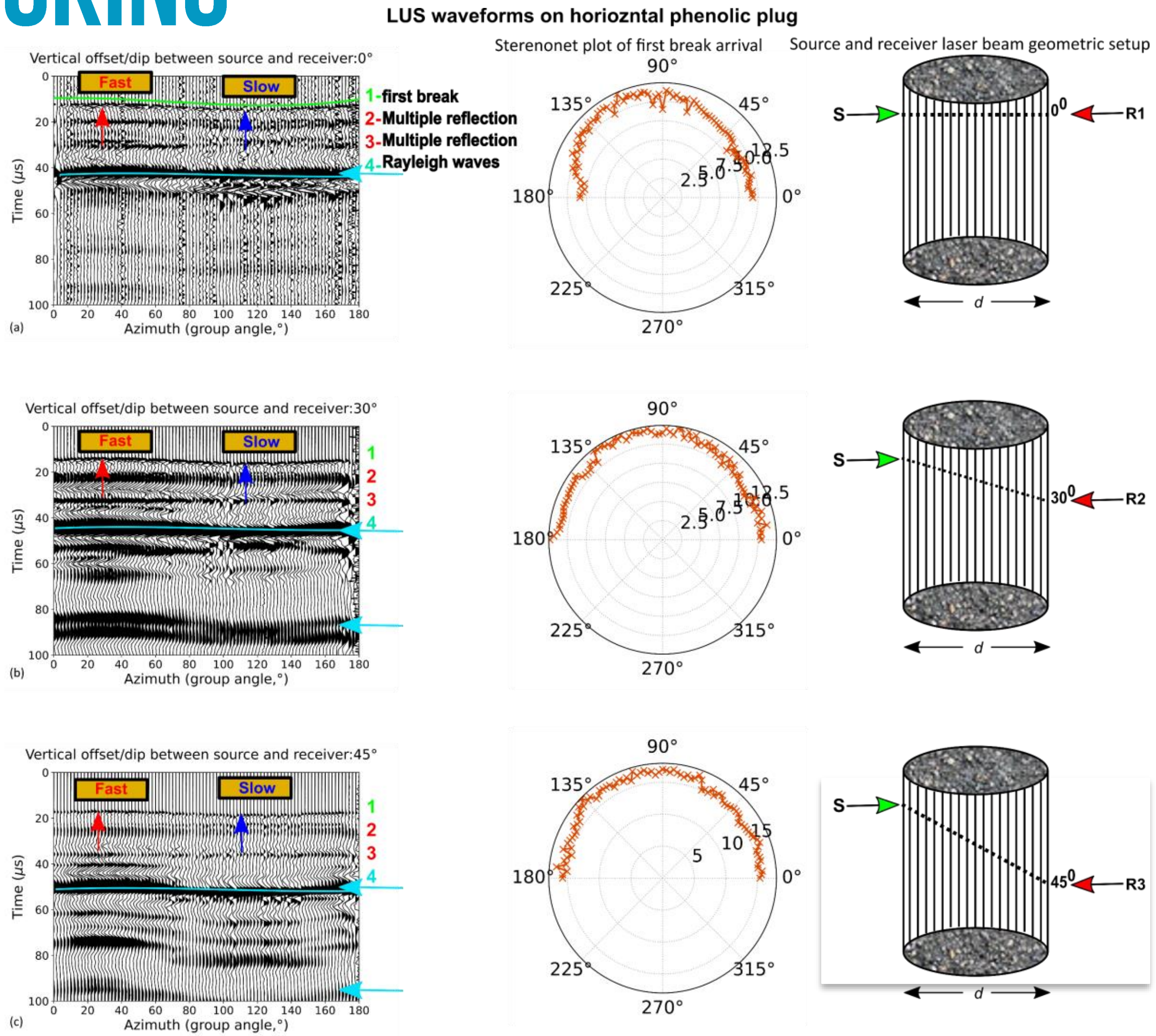
Simpson et al., 2019; Simpson, 2019; PAL, The University of Auckland

SAMPLE CHARACTERIZATION

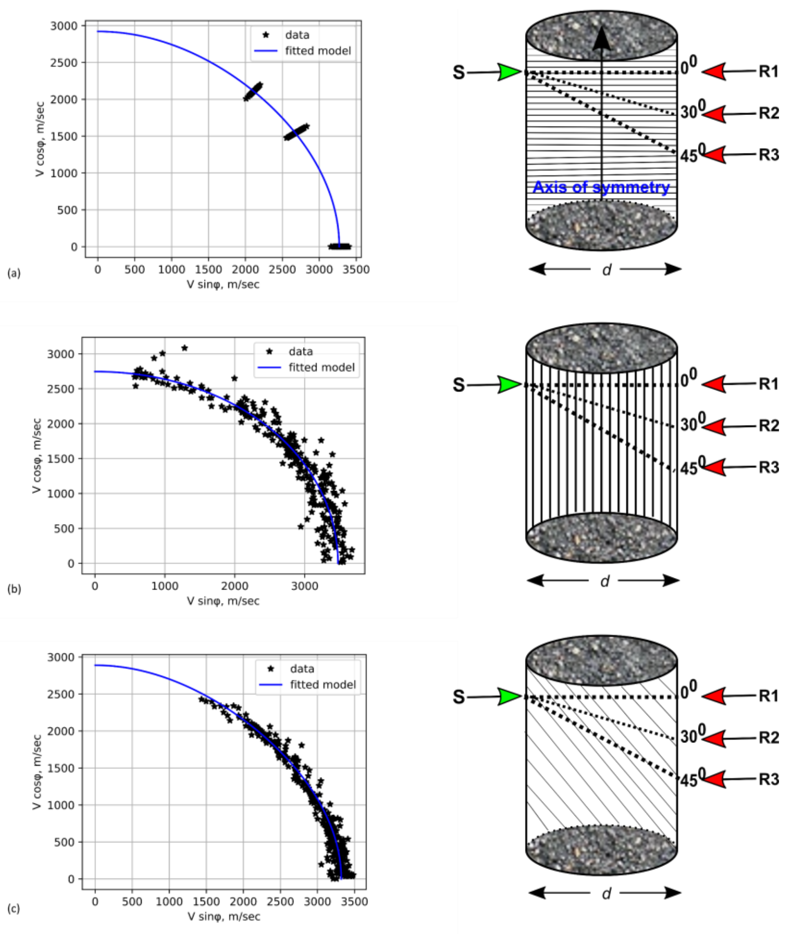
- Length to diameter ratio (l/d)- 2:1
- Heterogenous vertical shale Th8 sample – Goldwyer shale formation
- Porosity and bulk density of Th8 are 8.6% and 2.6 g/cc

LUS WAVEFORM & FIRST BREAK PICKING

- AIC algorithm to pick first break arrival
- Repeated reflections (Multiple) of the body waves
- Fast and slow P-wave direction – from waveform and polar diagram
- Surface Rayleigh wave



INVERSION & ASSUMPTIONS



$$F(\alpha_0, \varepsilon, \delta, p, q) = \sum_i \left[1 - V^i_{model}(\alpha_0, \varepsilon, \delta, p, q)/V^i_{measured}\right]^2$$

- TI media & β_0/α_0 ratio from PUS
- Inversion algorithm (least-square regression) from Kovalyshen et al., 2020
- Output parameters are p, q, α_0, ε, δ

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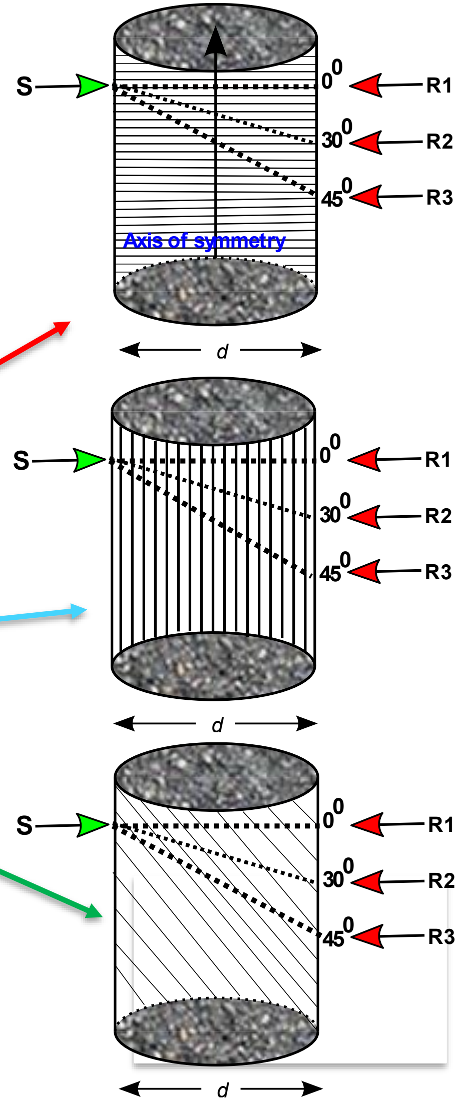
RESULTS

	Sample orientation	p (º)	q (º)	α_0 (km/s)	ε (-)	δ (-)
Literature data	Vertical	0	0	2.8	0.22	0.26
Inversion results	Vertical*	0*	0*	2.92	0.13	n/a*
Literature data	Horizontal	90	90	2.8	0.22	0.26
Inversion results	Horizontal	109	78	2.75	0.30	0.35
Literature data	Inclined (45^0)	45	45	2.8	0.22	0.26
Inversion results	Inclined (45^0)	44	44	2.88	0.16	0.04

** For the vertical sample, no inversion is possible due to the limited number of independent ray paths*



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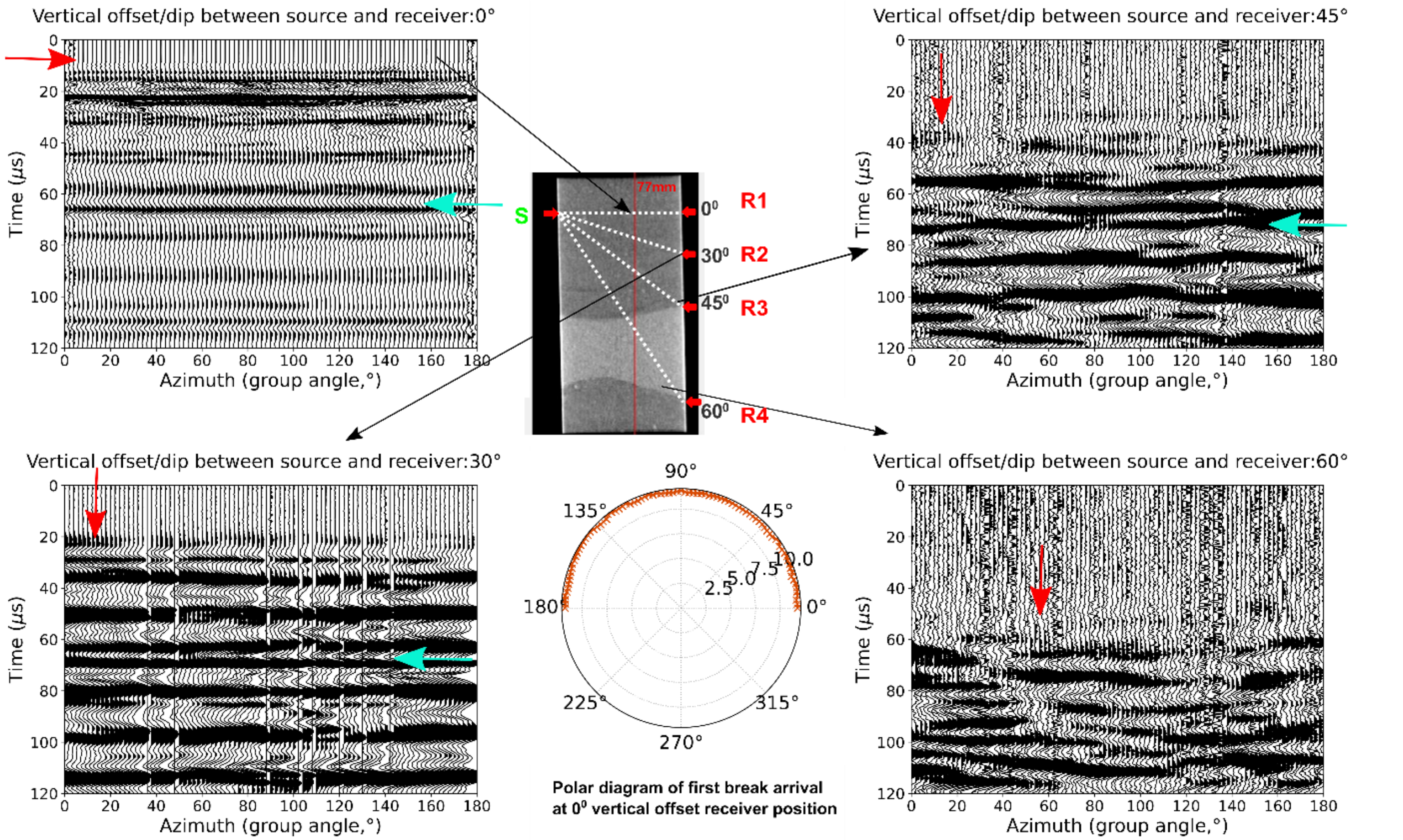
LUS APPLICATION ON VERTICAL SHALE SAMPLE

- First break attenuated at 45^0 and 60^0 LVD receiver location
- Polar diagram confirms TI media assumption
- Poor S/N ratio for far offset receiver

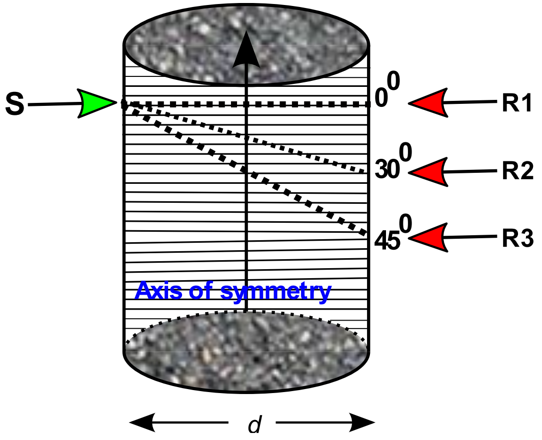


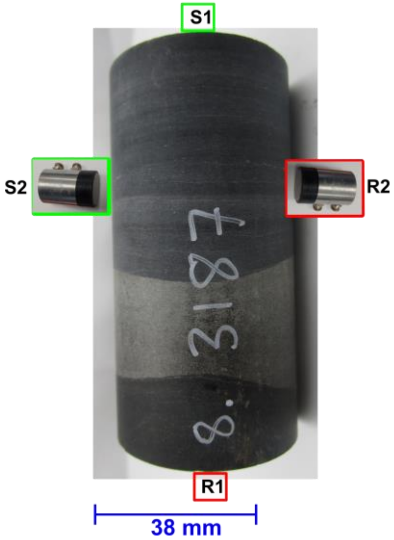
Polar diagram of first break arrival at 0^0 vertical offset receiver position

LUS VS PUS – INVERTED PARAMETERS

	Sample orientation	p (º)	q (º)	α_0 (km/s)	ε (-)	δ (-)
PUS measurements	Vertical*	0*	0*	1.73	1.58	n/a*
LUS inversion results	Vertical*	0*	0*	1.59 ± 0.11	1.57 ± 0.29	n/a*

**The orientation of symmetry axis assumed to be vertical based on visual inspection of the top part of the shale sample (homogeneous and layered)*





ADVANTAGES/LIMITATIONS: LUS VS PUS

Criteria	PUS	LUS
Transducer size	Finite size	Point source-receiver
Velocity type	Group/phase ambiguity	Group velocity
Data recording	Sparsely sampled	Densely sampled in space and time
Signal quality	Stronger P-wave arrival	Weaker P-wave arrival
Symmetry orientation and elastic anisotropy	Bedding parallel/inclined plugs	Bedding parallel

CONCLUSIONS

- LUS technique removes ambiguity of coupling, transducers size and phase/group velocity
- Dense LUS data on a single plug parallel to the visible bedding plane allows accurate estimation of symmetry axis orientation (p, q) and Thomsen's anisotropy parameters (α_0, ε, δ)
- Beyond first break arrival, remaining waveforms can provide insight of rock heterogeneity
- Scope to improve S/N ratio with higher source energy and acquisition with single source-receiver pair

MORE AGU TALKS ON LUS APPLICATION

- MR35B-15 - The Effects of Pressure, Temperature, and Microstructure on the Nonlinear Softening and Recovery of Fault Rocks - Jonathan Simpson*, Kasper van Wijk and Ludmila Adam
- U53A-07 - Probing the Nonlinear Behavior of Rocks to Understand Dynamic Triggering of Earthquakes and Volcanoes (Invited) - Jonathan Simpson*, Kasper van Wijk and Ludmila Adam

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THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Australian Society of Exploration Geophysicists

CSIRO

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THANK YOU

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