Computational Modeling of Wellbore Acoustics for Early-Kick Detection (EKD) using Logging-While-Drilling (LWD) Tools

NETL Multiphase Flow Workshop

August 13th, 2024

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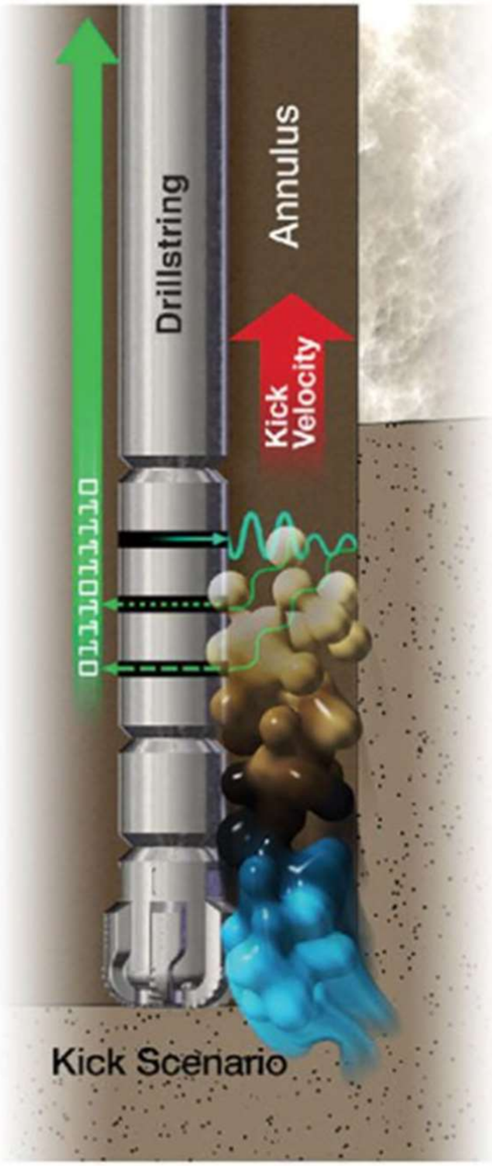


Disclaimer

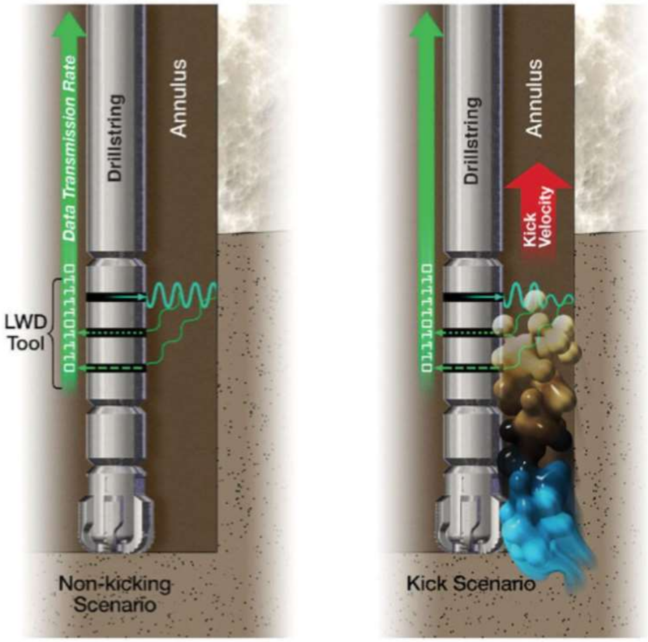
Motivation: Early Kick Detection (EKD)

Unexpected gas invasion (kick) into the borehole is a persistent threat during drilling. Traditional kick detection has a significant time lag and is affected by missed and false detection.

Gas influx can result in a loss of well control and/or blowouts. Accurate Early Kick Detection (**EKD**) is crucial to improvement in well control safety.

Deepwater Horizon explosion in Louisiana's Gulf of Mexico on April 20, 2010 (Photo: US coast guard)

The proposed method for **Early Kick Detection (EKD)** involves utilizing geophysical signals from **Logging-While-Drilling (LWD)** sensors, enabling real-time detection within minutes.[1,2]



- Challenge: field and laboratory data are not readily shared or 'valuable'
- **Goal: Produce synthetic data** to help fill the knowledge gap and to aid in Early Kick Detection (EKD) algorithm development

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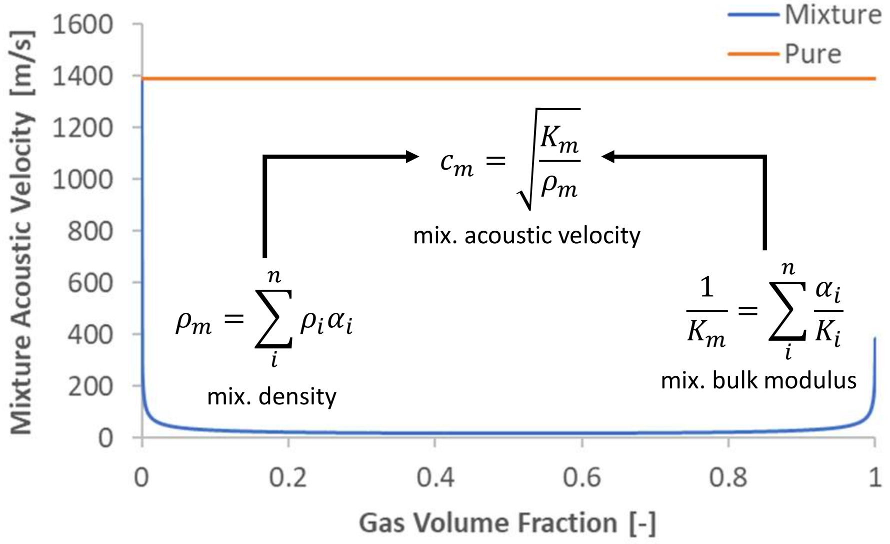
1) Rose, K., et. al., 2019, USPO #10253620;
2) Adapted from Tost, B., et. al., 2016, https://doi.org/10.2172/1327810

Acoustics of Mixtures

Sonic signals are sensitive to variations of in ‘gas’ volume fraction bringing up the potential of using LWD acoustic methods for early kick detection.

Two-phase response



$$c_m = \sqrt{\frac{K_m}{\rho_m}}$$

mix. acoustic velocity

$$\rho_m = \sum_i^n \rho_i \alpha_i$$

mix. density

$$\frac{1}{K_m} = \sum_i^n \frac{\alpha_i}{K_i}$$

mix. bulk modulus

Fig. Estimated change in drilling-fluid (WBM) acoustic velocity as a function of the natural gas volume fraction at 27°C (80°F) and 0.1 MPa (14.5 psi)

Single-phase response

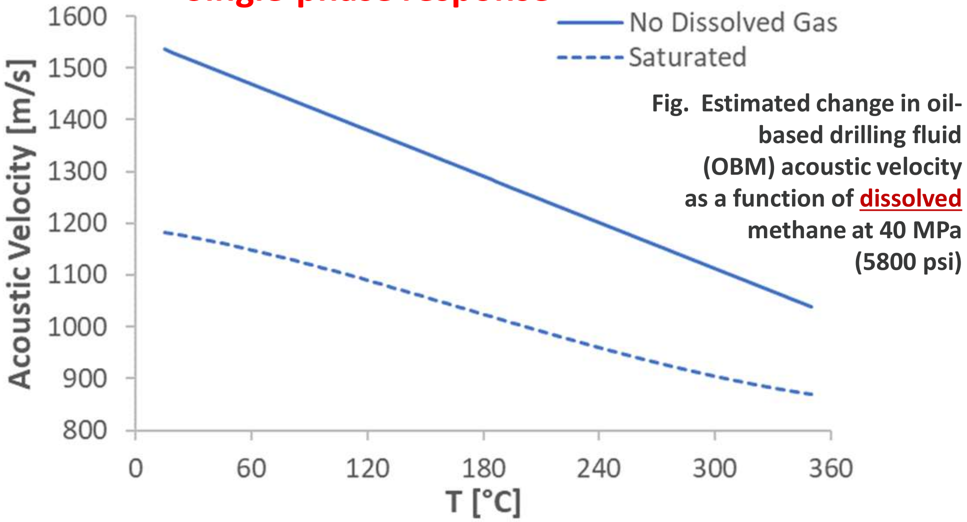
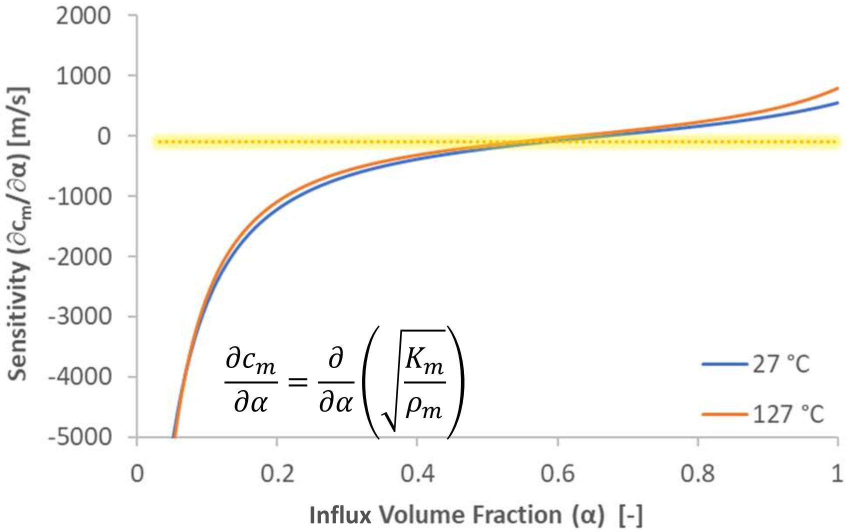


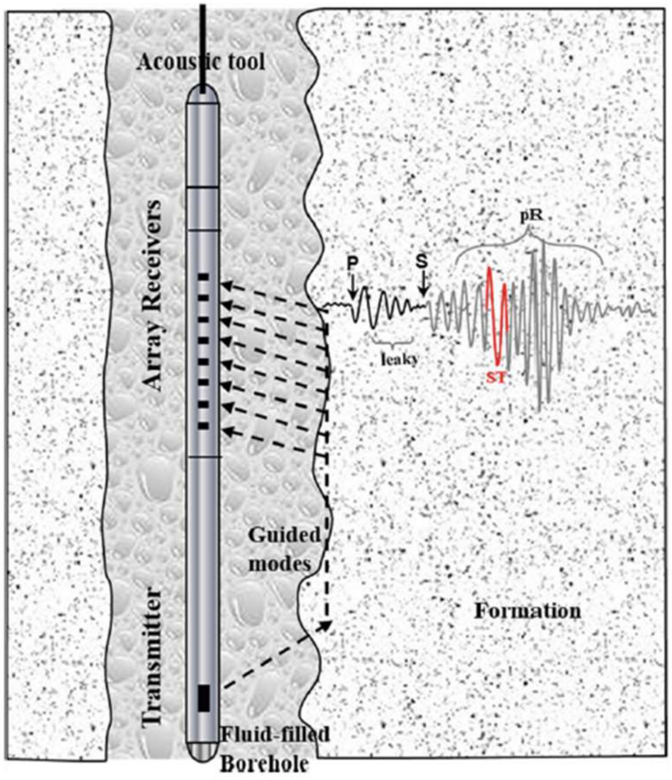
Fig. Estimated change in oil-based drilling fluid (OBM) acoustic velocity as a function of dissolved methane at 40 MPa (5800 psi)



$$\frac{\partial c_m}{\partial \alpha} = \frac{\partial}{\partial \alpha}\left(\sqrt{\frac{K_m}{\rho_m}}\right)$$

Fig. Sensitivity of drilling-fluid (WBM) acoustic velocity to changes in natural gas volume fraction as a function gas volume at 50. MPa (7250 psi)

Sonic-Logging Wellbore Acoustics



Sonic Logging: Illustration of acoustic logging with a source (transmitter) and an array of receivers.[3]

1. The sonic tool produces an acoustic signal
2. Sound travels outward through the fluid

   Directly through the fluid to the receivers, and

   Indirectly through/along the formation via other modes of propagation

3. The sonic log is complex and analyzed to understand formation properties

4* The proposed effort seeks to identify and use the mud acoustic velocity to flag a possible kick

Approach: Create synthetic data for EKD development

3) Wang et al. Bottomhole Acoustic Logging. https://doi.org/10.1007/978-3-030-51423-5

Computational Acoustics: Pressure Acoustics (Fluids)

Fluid wave propagation : pressure acoustics

Fluid Pressure Acoustics via General Scalar Wave Equation (GSWE):

$$\frac{1}{\rho c^2}\frac{\partial^2 p_t}{\partial t^2} + \nabla\cdot\left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q}_d)\right) = Q_m$$

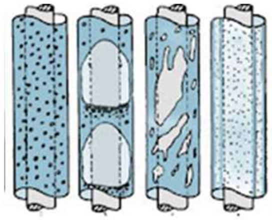
- “Small” acoustic pressure variations, p_t
- Speed of sound, $c = \sqrt{K/\rho}$
- Accommodates monopole, Q_m, and dipole sources, $\mathbf{q}_d$

Current simplifications/challenges:

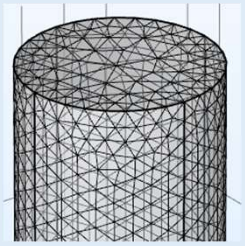
- Resonance effects are neglected
- Interphase (mass/momentum) transfer is neglected

Modeling Two-Phase Fluids:

In the event of a gas kick, two phase gas-liquid mixtures may be expected



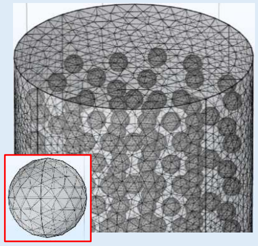
1) Homogenized model



Using a mixture approximation (Wood’s Equation)

$$\frac{1}{c_{mix}^2} = \left(\alpha_g\rho_g + \alpha_l\rho_l\right)\left(\frac{\alpha_l}{\rho_l c_l^2} + \frac{\alpha_g}{\rho_g c_g^2}\right)$$

2) Discrete bubble approach



\+ Does not require a mixture model

\+ Allows for scattering: reflection, refraction, diffraction

– Computationally expensive

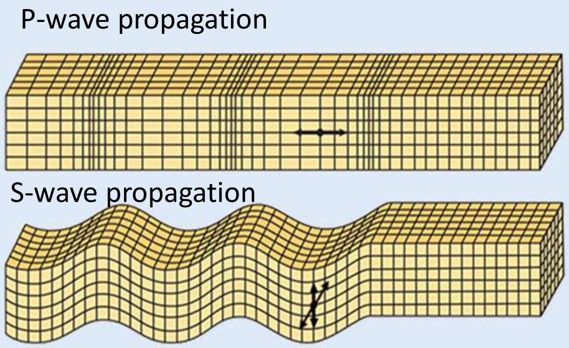
Computational Acoustics: Solids Mechanics

Elastic wave propagation

Equation of motion in a linearly elastic medium

$$\rho \frac{\partial \mathbf{v}}{\partial t} = \mathbf{F}_V + \nabla \cdot \mathbf{S}$$

- velocity, $\mathbf{v} = \frac{d\mathbf{u}}{dt}$; ($\mathbf{u}$ = displacement)
- possible body force, $\mathbf{F}_V$
- stress relation, $\mathbf{S}$, given by Cauchy stress tensor w/ assumption of isotropic material: $\sigma = \left(K - \frac{2}{3}G\right)\mathrm{tr}(\boldsymbol{\varepsilon})\mathbf{I} + 2G\boldsymbol{\varepsilon}$; $\boldsymbol{\varepsilon} = 0.5\left(\nabla \cdot \mathbf{u} + (\nabla \cdot \mathbf{u})^{\mathrm{T}}\right)$



Fig[4]

$$c_p = \sqrt{\left(K + \frac{4G}{3}\right)/\rho}$$

$$c_s = \sqrt{G/\rho}$$

G – Shear Modulus
K – Bulk Modulus
ρ – Density

Solid Acoustics Interaction couples the pressure field in the fluid to the elastic wave (structure deformation) in the solids :

$$-\mathbf{n} \cdot \left(-\frac{1}{\rho_c}(\nabla p_t - q_d)\right) = -\mathbf{n} \cdot \frac{\partial^2 \mathbf{u}}{\partial t^2}$$

$$\mathbf{F}_A = p_t \mathbf{n}$$

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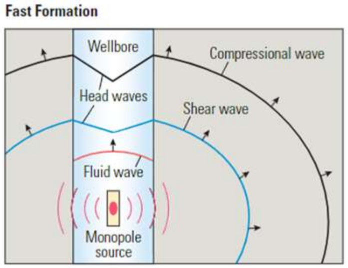
[4] Peterie, Shelby L., Richard D. Miller, and Julian Ivanov. "Seismology and its applications in Kansas." *Kansas: Kansas Geological Survey* (2014).

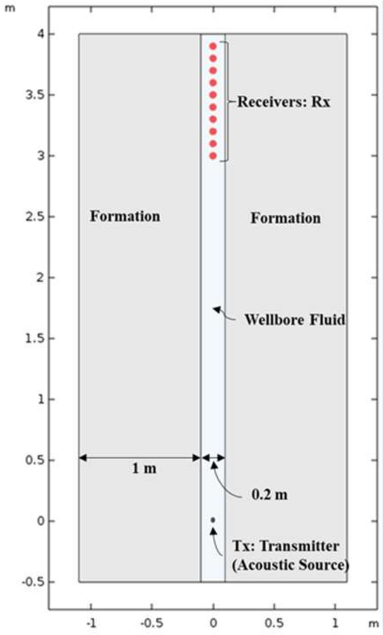
Computational Acoustics: Wellbore

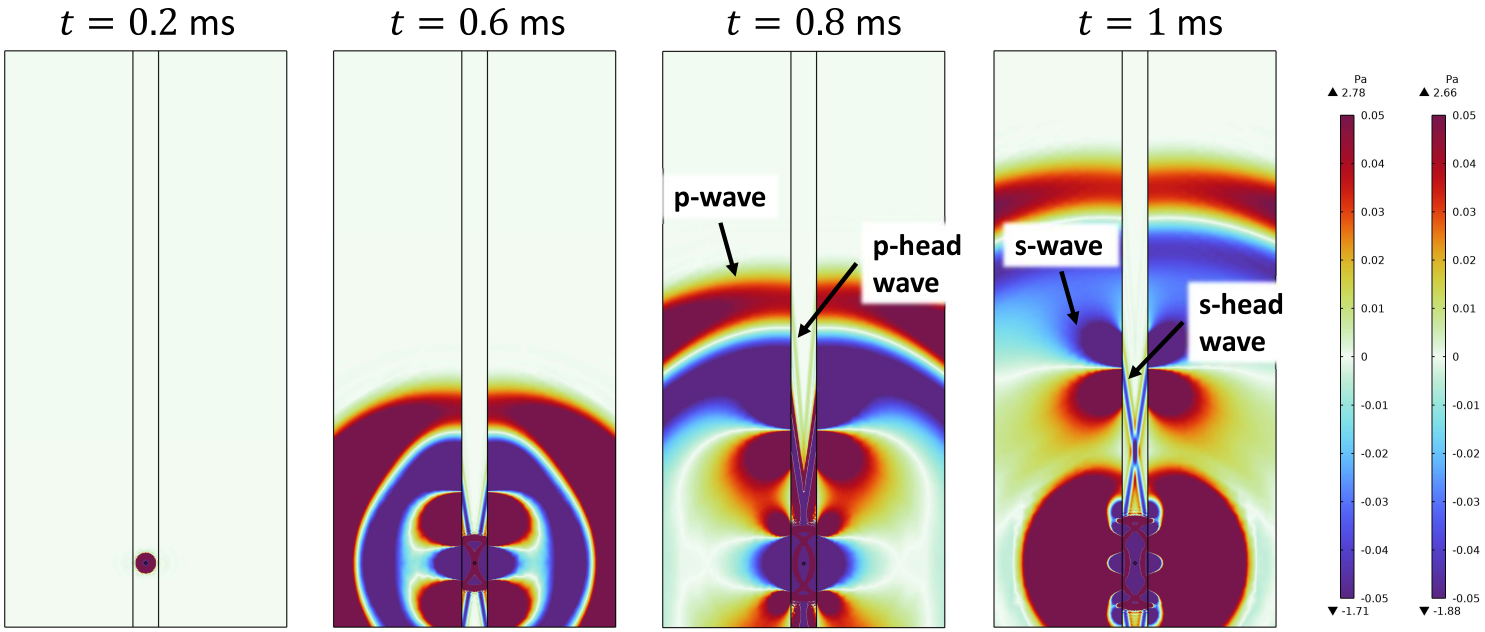
Acoustic Properties		
	Formation	**Wellbore Fluid**
$\rho\ [kg/m^3]$	2400	990-1000
$c_s\ [kg/m^3]$	2000-3000	-
c_p or c_f $[kg/m^3]$	4500	119.3-1500



Image[5]

2D Wave Propagation in Wellbore (full domain)
Acoustic propagation in wellbore and formation domains considering mud as air/water with c_{fluid} =365 m/s: gas fraction of 0.1% (@0.1MPa, 20°C) or 3.2% (@2.98MPa, 30.2 ° C)





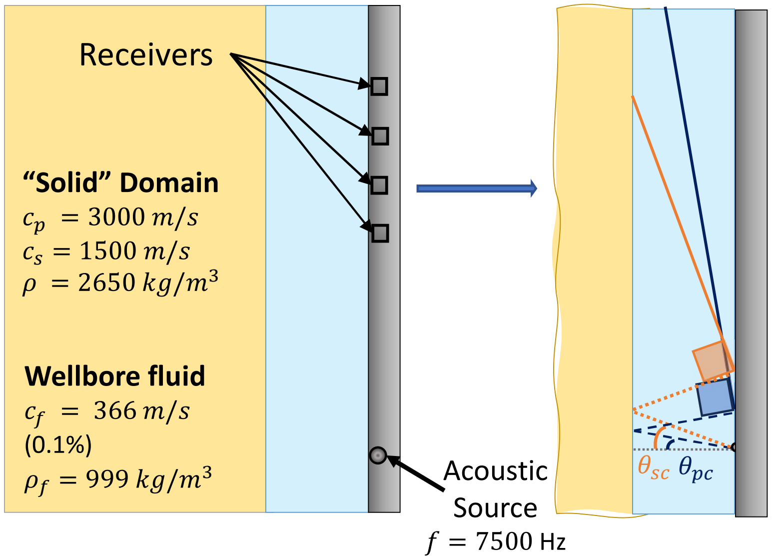
magnify color range x 10

☑ Model captures significant modes

5) Alford, et al., Oilfield Review Spring 2012: 24, no. 1;

Verification: Critical Angle

Critical angles (θ_{ic}) where $i{=}p$ is the compressional and $i{=}s$ the shear



Receivers

"Solid" Domain

$c_p = 3000\ m/s$

$c_s = 1500\ m/s$

$\rho = 2650\ kg/m^3$

Wellbore fluid

$c_f = 366\ m/s$

(0.1%)

$\rho_f = 999\ kg/m^3$

Acoustic Source

f = 7500 Hz

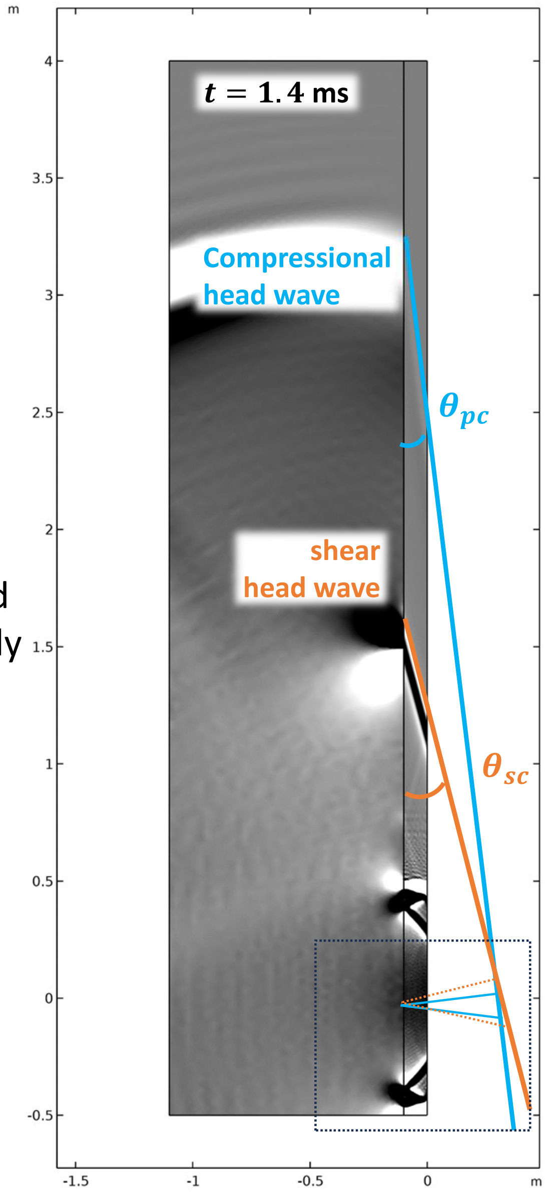
For angles of incidence larger than θ_c the sound wave is completely reflected

Compressional Wave

- $\boldsymbol{\theta_{pc} = asin(c_f/c_p)}$
- $\theta_{pc} = \mathrm{asin}(366/3000)$
- $\theta_{pc} = 7.0°$

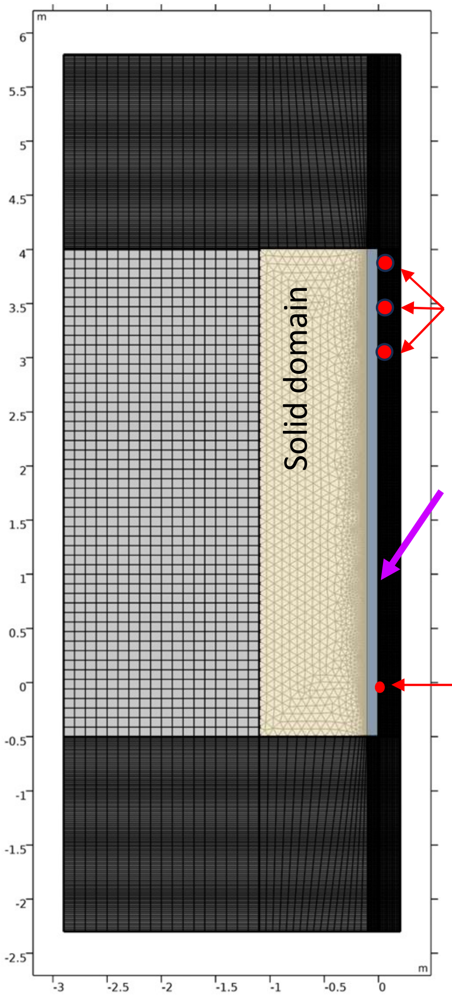
Shear Wave

- $\boldsymbol{\theta_{sc} = asin(c_f/c_s)}$
- $\theta_{sc} = \arcsin(366/1500)$
- $\theta_{sc} = 13.8°$



☑ Model captures the critical angles for both p-wave and s-wave

Sensor Measure: Wave train



receivers

Fluid domain

acoustic source

$f = 5000$ Hz

Mesh showing PML layers 'absorbing' layers

2D Wave Propagation in Wellbore (half domain)
Transient evolution considering mud as air/water with gas fraction of 0.05% (@0.1MPa, 20°C) or 1.6% (@2.98MPa, 30.2°C)

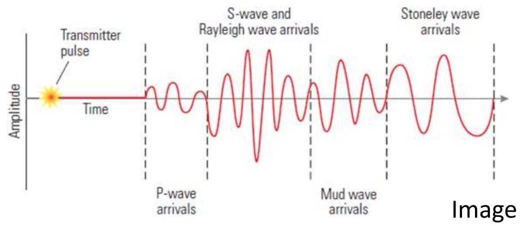


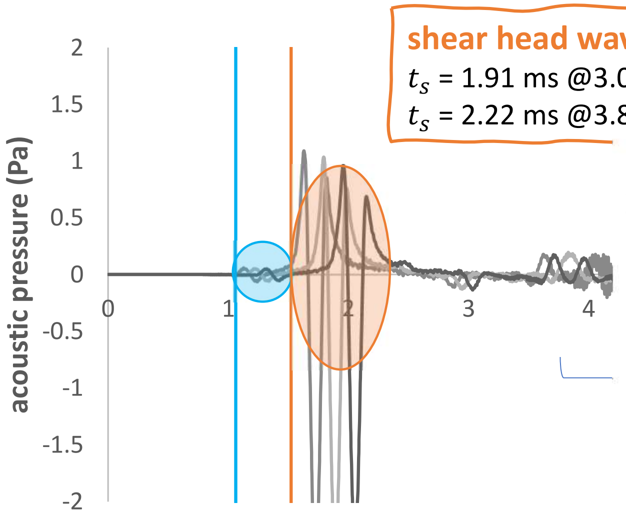
Image from[4]

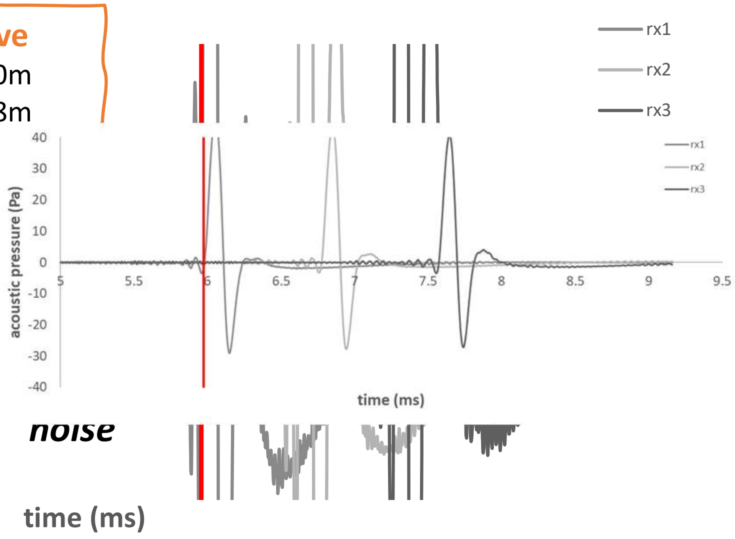
4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.

compressional head wave
t_p = 1.46 ms @ 3.0m
t_p = 1.64 ms @ 3.8m

Mud (fluid) arrivals
t_f = 5.97 ms @3.0m
t_f = 7.57 ms @3.8m

shear head wave
t_s = 1.91 ms @3.0m
t_s = 2.22 ms @3.8m

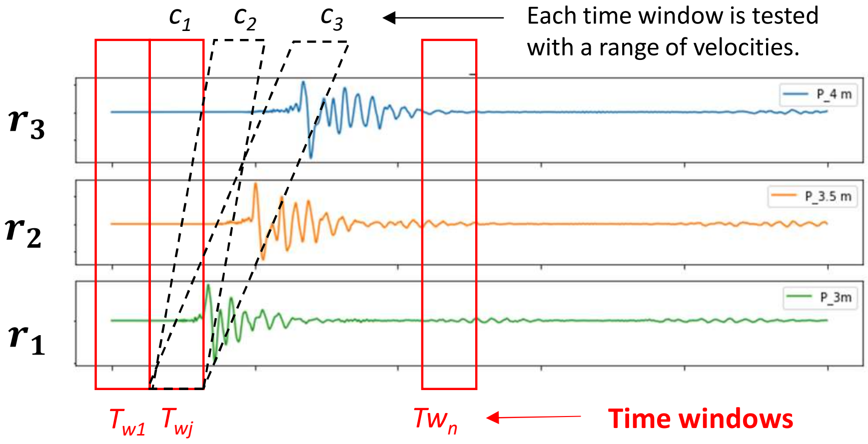




☑ Model captures expected arrival times

Signal Analysis/Algorithm Development

Waveforms recovered by receivers (wellbore/simulation acoustic data)



Wave velocities

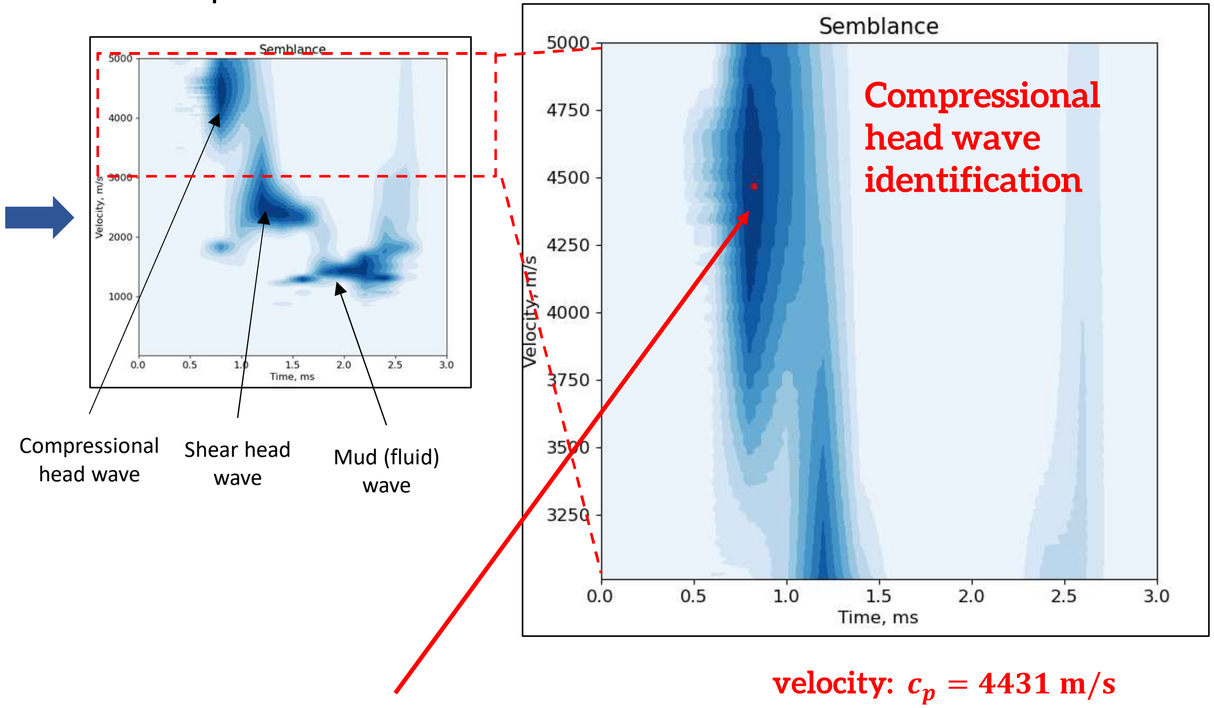
Each time window is tested with a range of velocities.

Time windows

$$\rho^2(c,T) = \frac{\frac{1}{M}\int_T^{Tw}\left[\sum_{m=1}^{M} r_m\left[t+\left(\frac{\delta_m}{c}\right)\right]\right]^2 dt}{\sum_{m=1}^{M}\int_T^{Tw}\left\{r_m\left[t+\left(\frac{\delta_m}{c}\right)\right]\right\}^2 dt}$$

M – number of receivers
$r_m(t)$ – wave form recorded by receiver m
c – wave velocity (m/s)
T, T_w – time, time window (s)
δ_m – distance between receiver m and the first receiver ($m = 1$)

Semblance Analysis: based on slowness-time coherence method[6] used commonly for array sonic waveforms to identify wave speed and arrival time



Compressional head wave

Shear head wave

Mud (fluid) wave

Compressional head wave identification

***Peak finding routine**

velocity: $c_p = 4431$ m/s
arrival time: $t_{Hp} = 0.87\ ms$

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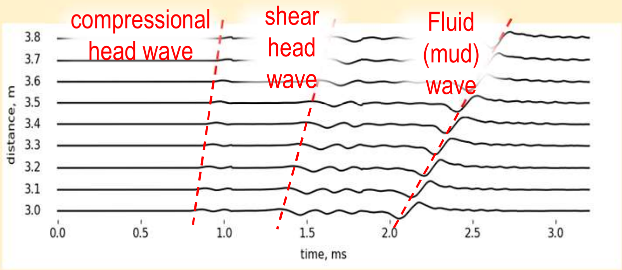
6) Kimball, C.V. & Marzetta, T.L., Geophysics, 1984: 49, no. 3.

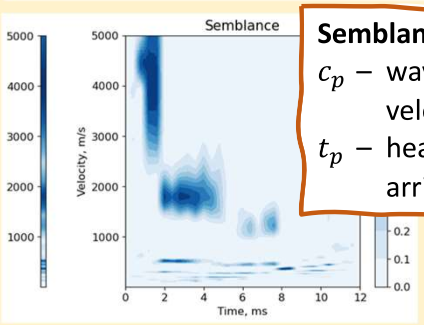
Proposed EKD Method

Mud (fluid) acoustic velocity reflects gas content, but direct measurement/identification can be challenging

Inputs from LWD data

Sonic wave trains





Semblance Results

c_p – wave/head-wave velocity(ies)

t_p – head wave arrival time(s)

Geometrical Info

h – wellbore radius

L_1 – distance between source and 1st receiver

Extract fluid speed (c_f)

Directly

Or

Indirectly

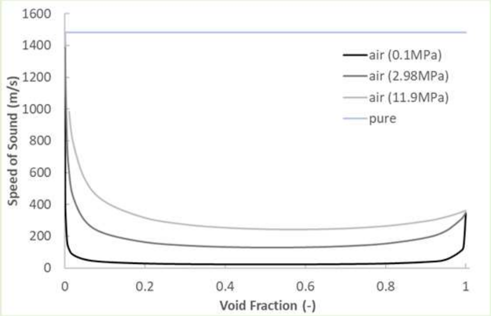
$$c_f = \frac{2h}{\left(\left(t_p - \frac{L_1}{c_p}\right) + \frac{2h\tan\theta_{pc}}{c_p}\right)\cos\theta_{pc}}$$

c_f – fluid wave velocity

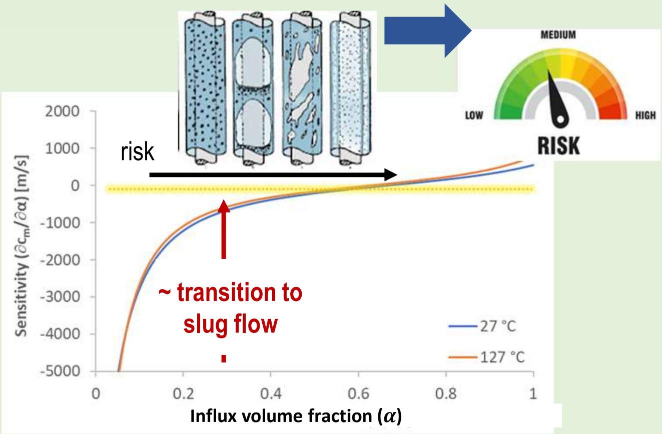
θ_{pc} – critical angle ($\operatorname{asin}(c_f/c_p)$)

Early Kick Detection

Wellbore fluid acoustic velocity (c_f)



Influx volume fraction (α)



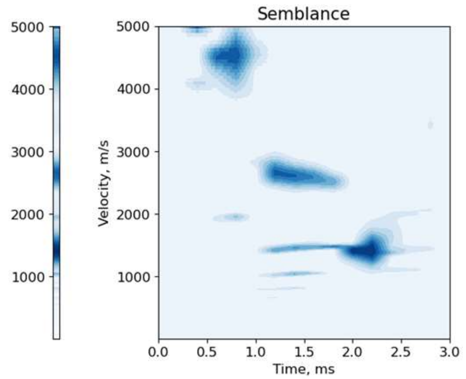
Processing Fluid Speed

Assuming p-wave speed is correct and varying arrival time

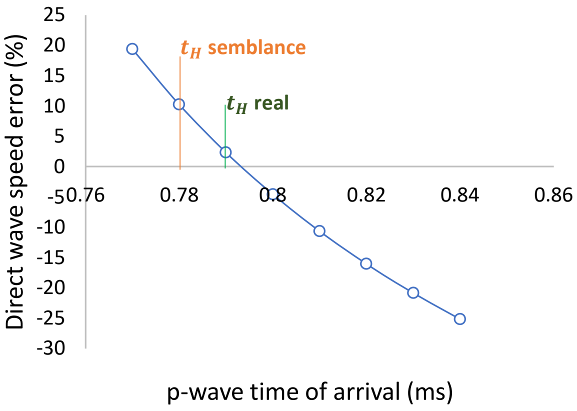
Assuming semblance arrival time is correct and varying p-wave speed

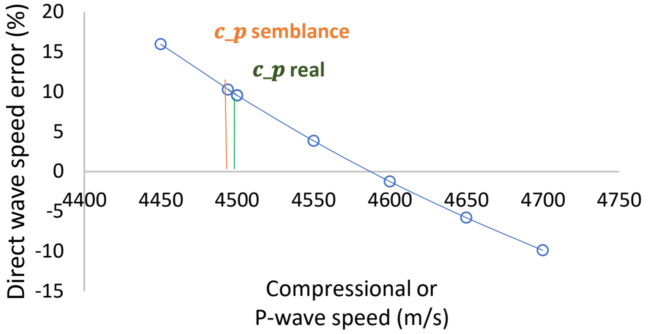
Error (%) Calc. Vs Set COMSOL

$\varepsilon_g = 0.0$ (no gas)

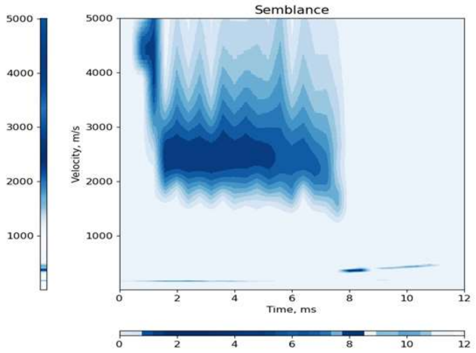


Semblance Results
P-wave: 4494 m/s at 0.78 ms

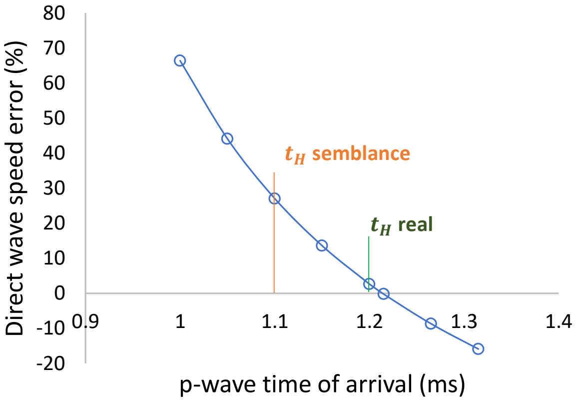


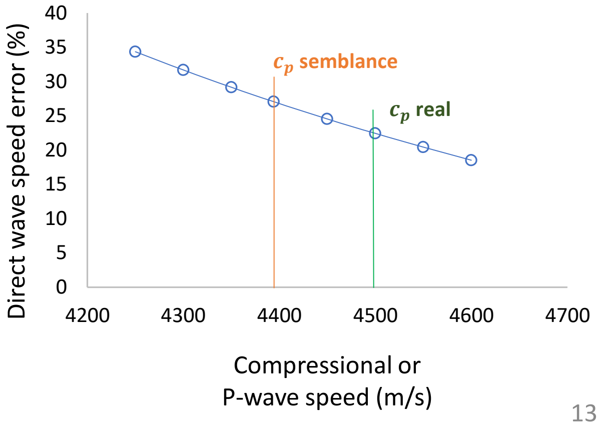


$\varepsilon_g = 0.001$

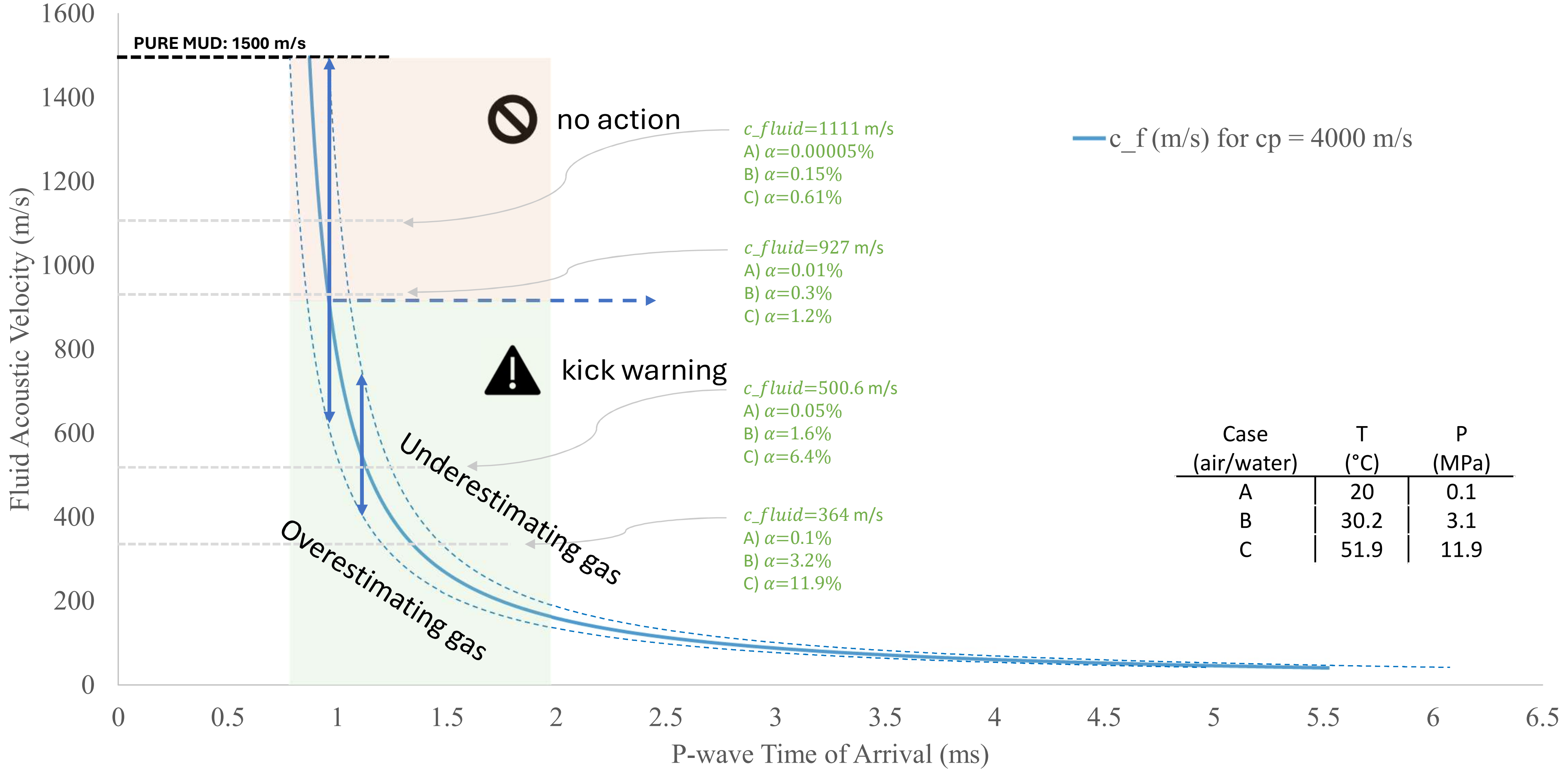


Semblance Results:
P-wave: 4394 m/s at 1.1 ms





Fluid speeds for different c_p arrival times



c_fluid=1111 m/s
A) α=0.00005%
B) α=0.15%
C) α=0.61%

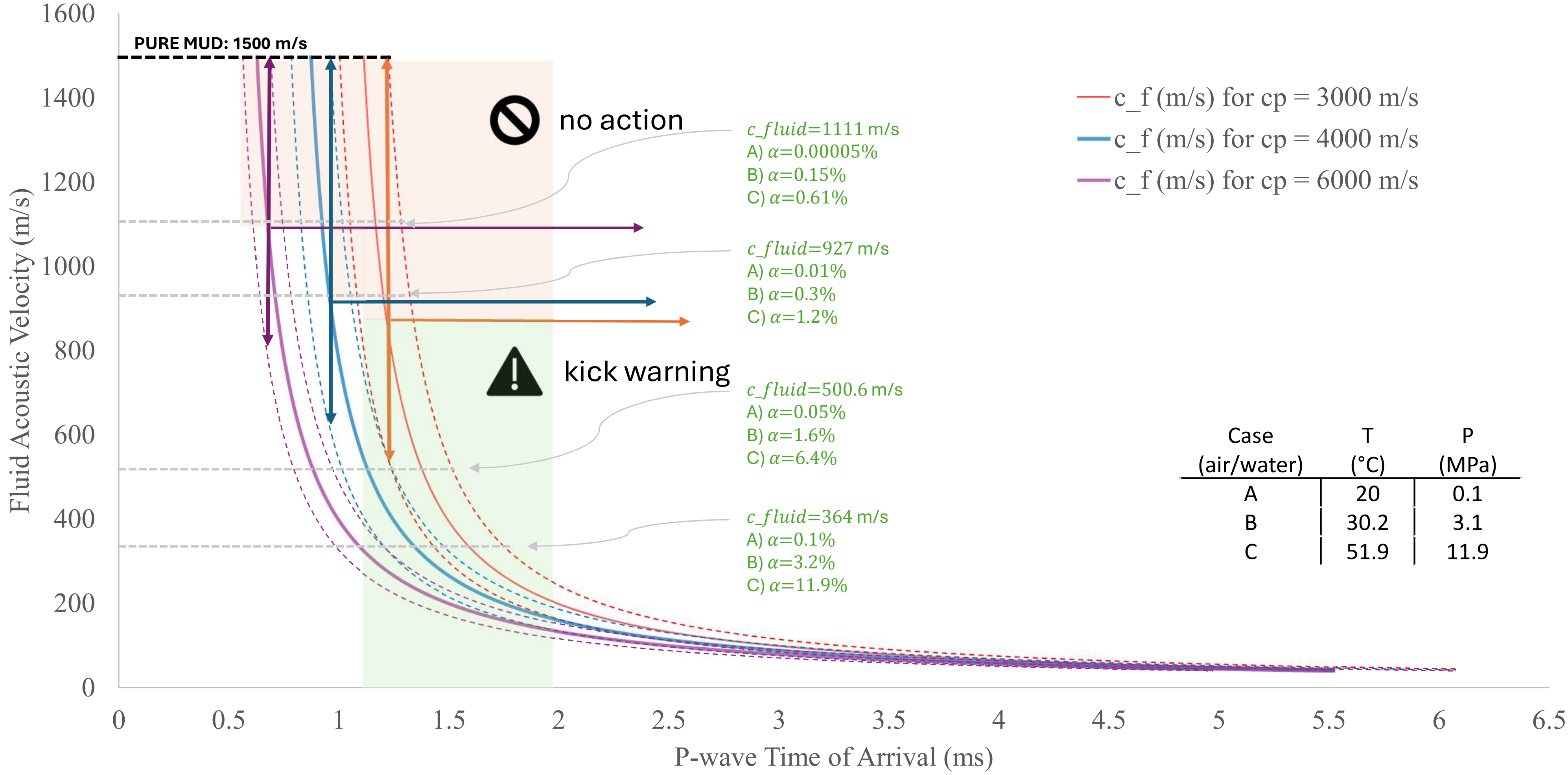
c_fluid=927 m/s
A) α=0.01%
B) α=0.3%
C) α=1.2%

c_fluid=500.6 m/s
A) α=0.05%
B) α=1.6%
C) α=6.4%

c_fluid=364 m/s
A) α=0.1%
B) α=3.2%
C) α=11.9%

Case (air/water)	T (°C)	P (MPa)
A	20	0.1
B	30.2	3.1
C	51.9	11.9

Fluid speeds for different c_p



c_fluid=1111 m/s
A) α=0.00005%
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C) α=0.61%

c_fluid=927 m/s
A) α=0.01%
B) α=0.3%
C) α=1.2%

c_fluid=500.6 m/s
A) α=0.05%
B) α=1.6%
C) α=6.4%

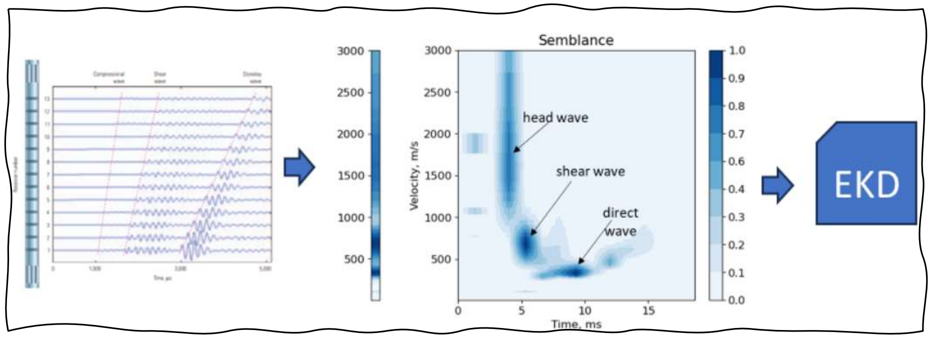
c_fluid=364 m/s
A) α=0.1%
B) α=3.2%
C) α=11.9%

Case (air/water)	T (°C)	P (MPa)
A	20	0.1
B	30.2	3.1
C	51.9	11.9

Final Remarks

Summary

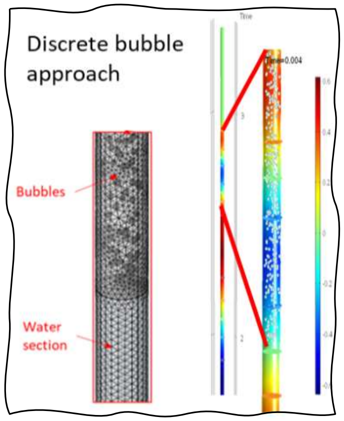
- Model predicts acoustic propagation in wellbore environment (e.g., critical angles & significant wave modes: p-wave and s-wave)
- Proposed an alternative means of assessing the mud speed and therefore gas influx using compressional head wave (and/or shear head wave) arrival and speed



Identification of the mud wave in the total acoustic signal may be challenging due to multiple modes of propagation, simultaneous arrivals at the receiver, and attenuation of the mud wave.

Future possible directions

- 2D vs 3D (limited no.) for geometric spreading
- Assess discrete bubble treatment as opposed to homogenous mixture on wave train in wellbore environment (scattering as means for attenuation in fluid)



- Different data analysis methods (e.g., signal analysis & machine learning techniques) for improved EKD

Caveats

- No absorptive (dissipation mechanisms to heat) or scattering losses are considered
- Assume a homogenous formation over the tx/rx spacing

Carney, J.E., Maciel, F.S., Waltrich, P.W., Evaluation of a CFD Commercial Package to the Modeling of Acoustic Wave Propagation in Bubbly-Liquid Column. United States. Technical Report, 2023. https://doi.org/10.2172/2221796

References

1) Rose, K., et. al., 2019, USPO #10253620
2) Adapted from Tost, B., et. al., 2016, ttps://doi.org/10.2172/1327810

3) Wang et al. Bottomhole Acoustic Logging. https://doi.org/10.1007/978-3-030-51423-5

4) Peterie, Shelby L., Richard D. Miller, and Julian Ivanov. "Seismology and its applications in kansas." *Kansas: Kansas Geological Survey* (2014).

5) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.

6) Kimball, C.V. & Marzetta, T.L., Geophysics, 1984: 49, no. 3.