Apr 2nd-4th – 2024 Resource Sustainability Project Review Meeting

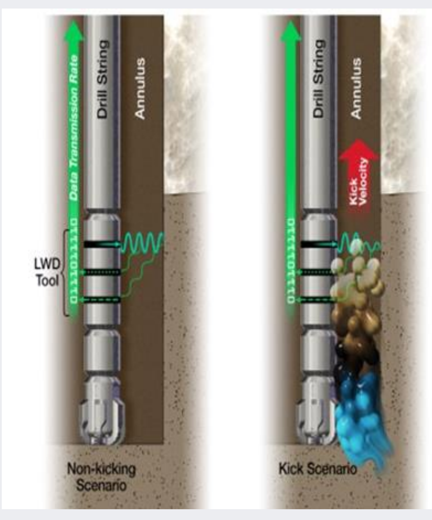
KICK SIGNATURES THROUGH ADVANCED MULTI-PHASE DATA

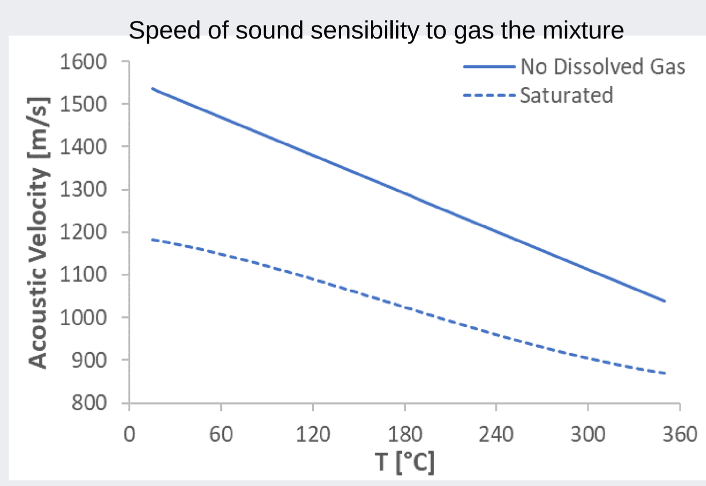
Project Number: EPS FWP 1025020

INTRODUCTION / OBJECTIVES

Unexpected gas invasion (kick) into the borehole is still a persistent threat during the drilling. Traditional kick detection has a significant time lag (hours) and is affected by missed and false detection. The development of accurate Early Kick Detection (EKD) is crucial to improvement in well control safety.

This project focus on creating a numerical platform for simulating the acoustic response from an LWD sonic tool in the wellbore using CFD modeling to generate synthetic data and assist in EKD algorithm development.



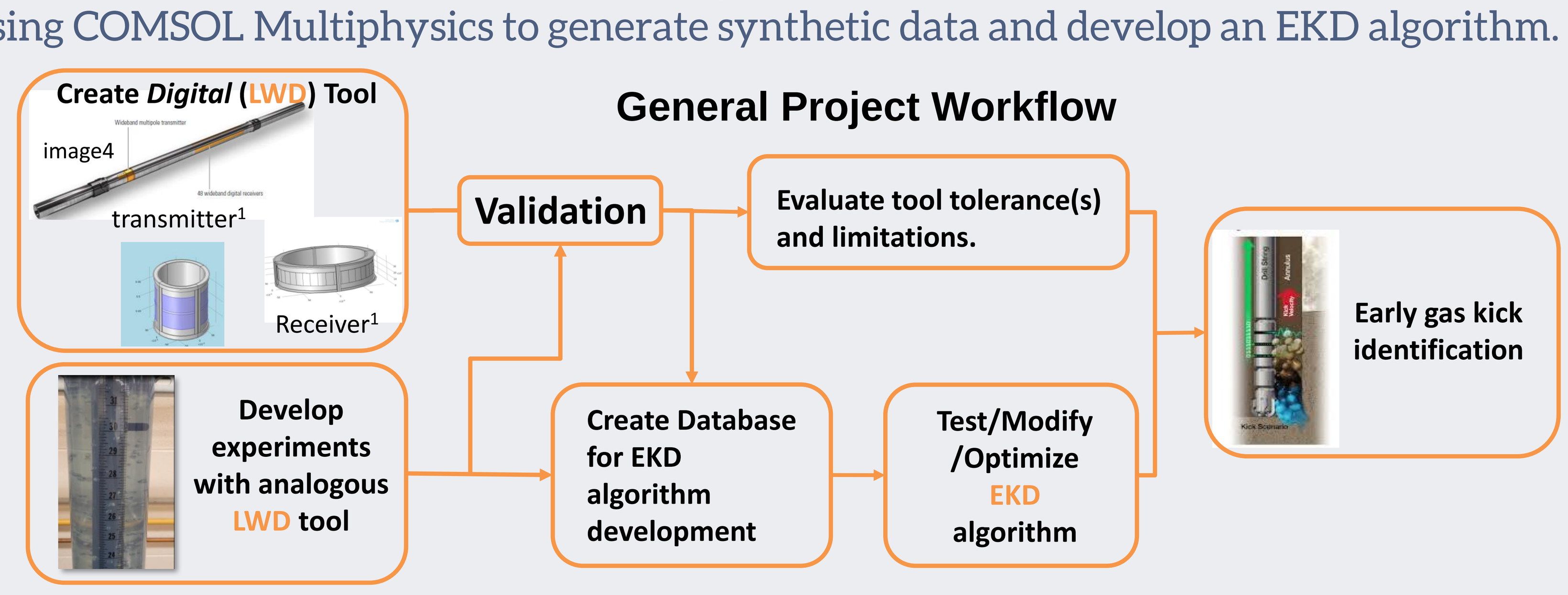


Schematics of a LWD tool and a gas influx event (image[3])

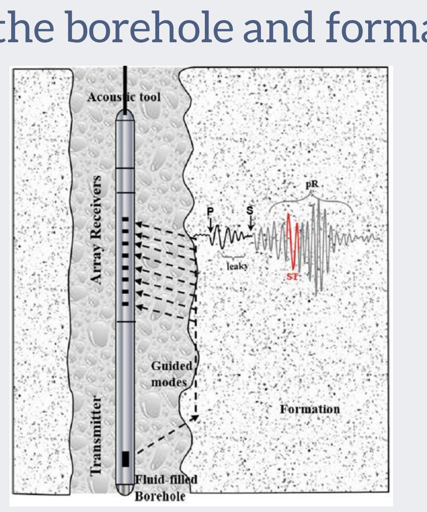
Sonic signals are sensitive to gas fraction variations, enabling early kick detection with LWD and acoustic methods.

BACKGROUND / METHOD

The main approach is based on combining experimental and numerical acoustic simulation using COMSOL Multiphysics to generate synthetic data and develop an EKD algorithm.



SIGNIFICANT WELLBORE PHYSICS: The sonic tool is based on the principles of wave propagation in elastic media. The source emits an acoustic wave that propagates through the borehole and formation, which returns to the receivers.



Schematic of acoustic logging from Wang et al. (2020)

Wave propagation (linear elastic)

- Fluids – compressional wave
- Solids – shear waves
- Fluid-solid interaction

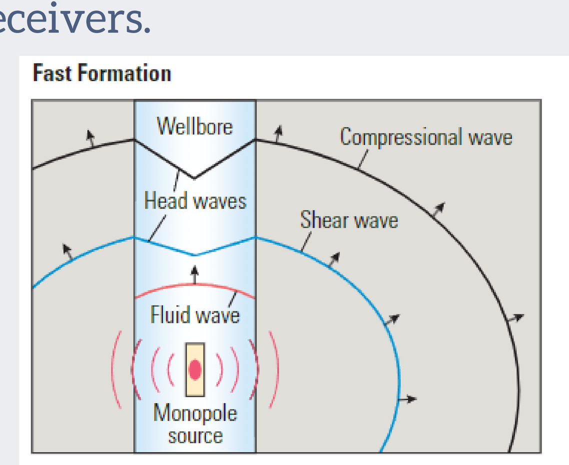
Compressional speed of sound (p-wave)

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

Shear speed of sound (s-wave)

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

K: bulk modulus
G: shear modulus
ρ: density



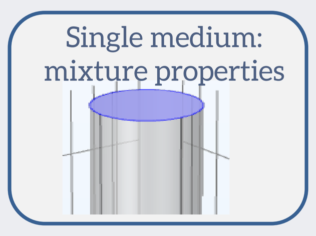
1) WELLBORE MODEL: Sound behavior in different materials is described by different governing equations. COMSOL is used for this Multiphysics problem.

1a) Pressure Acoustic Module for predicting pressure (sound) wave behavior in single and multiphase fluid flows based on the General Scalar Wave Equation (GSWE) with custom acoustic properties:

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

p_t – total acoustic pressure
c – speed of sound
ρ – density

In a gas kick event, two-phase mixtures are expected. The speed of sound of the multiphase mixture is sensible to the gas fraction (Wood's 1930 equation). In COMSOL two approaches can be used to model acoustics through a mixture:



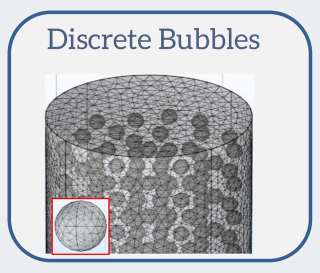
Single medium: mixture properties

Homogeneous Model:

- c_{mix} and ρ_{mix} (Wood's 1989 Equation)

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

(l and g denotes liquid and gas respectively)

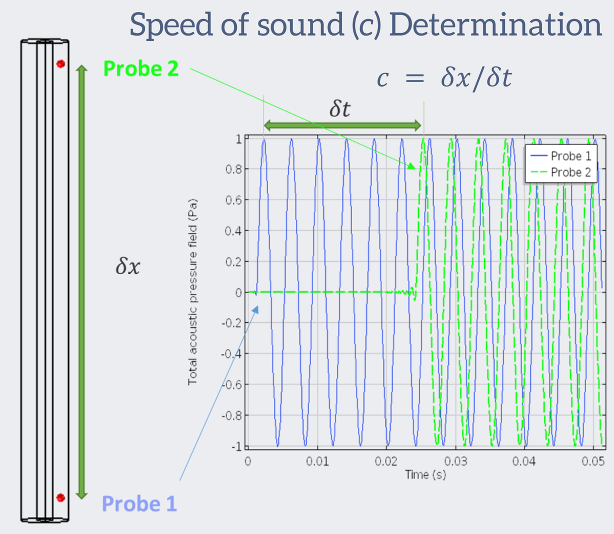


Discrete Bubbles

Discrete Bubbles Approach:

- Separate domains with $\varepsilon_g = \frac{V_{bubble}}{V_{total}}$
- More complex: successive reflections
- Computationally more expensive

Speed of sound (c) Determination



1b) Solid Mechanics Module for predicting elastic wave behavior in solids based on the continuum equation of motion and a linear elastic material with specified properties:

$$\rho\frac{\partial^2\mathbf{u}}{\partial t^2} = \mathbf{F}_V + \nabla\cdot S$$

$\mathbf{u}$ – displacement vector
$\mathbf{F}_V$ – body force
S – second Piola-Kirchhoff stress

1c) Solid Acoustics Interaction couples the pressure field in the fluid to the elastic wave (structure deformation) in the solids :

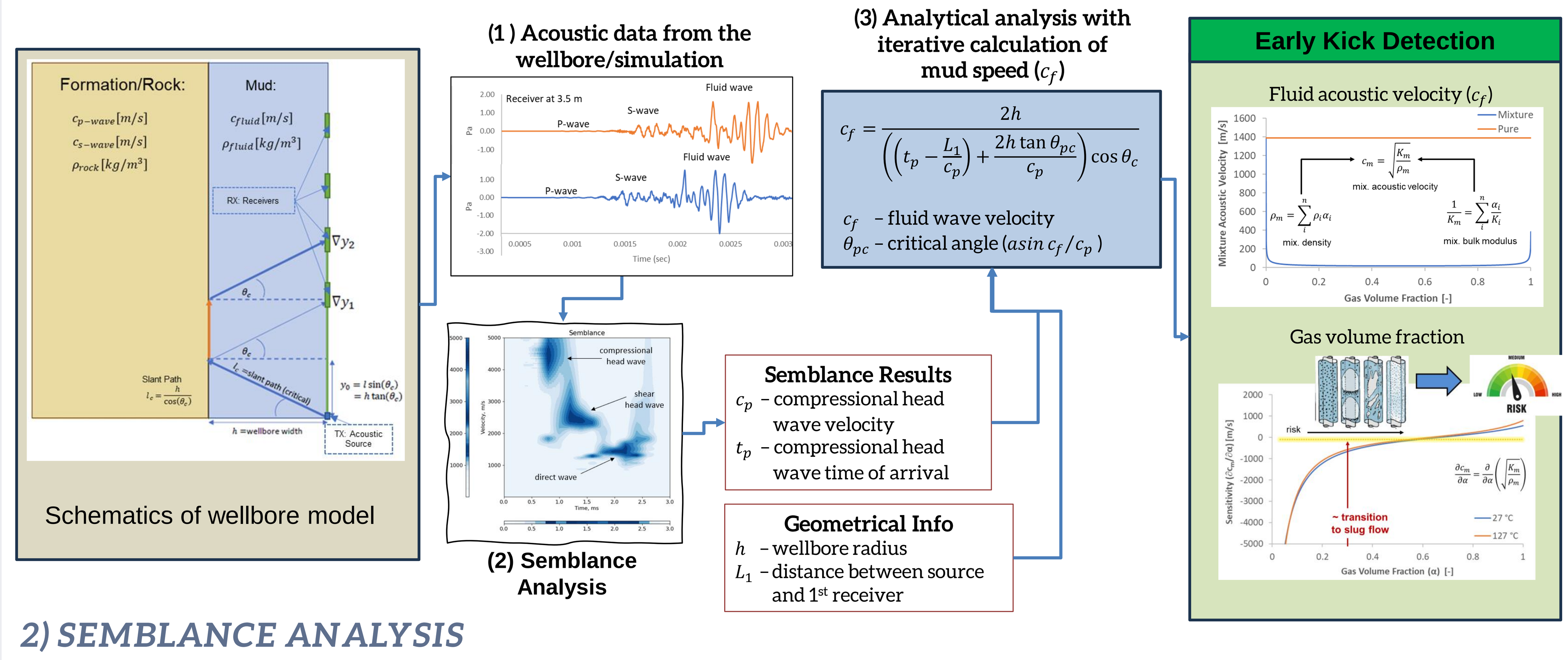
$$-\mathbf{n}\cdot\left(-\frac{1}{\rho_c}\left(\nabla p_t - q_d\right)\right) = -\mathbf{n}\cdot\frac{\partial^2\mathbf{u}}{\partial t^2}$$

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

$\mathbf{n}$ – surface normal
p_t – total acoustic pressure
F_A – load experienced by the structure

PROPOSED EKD METHOD: FLUID WAVE SPEED OF SOUND DETERMINATION

Mud acoustic velocity reflects gas content, but direct measurement/identification can be challenging and obscured by interference. The compressional wave, which is the first arrival at the probes, provides crucial data and an indirect measure of the mud velocity. Namely, from the arrival time (t_{Hp}) and speed of the compressional wave (c_p) we can also calculate the mud velocity, and thus aid gas fraction assessment and influx detection.

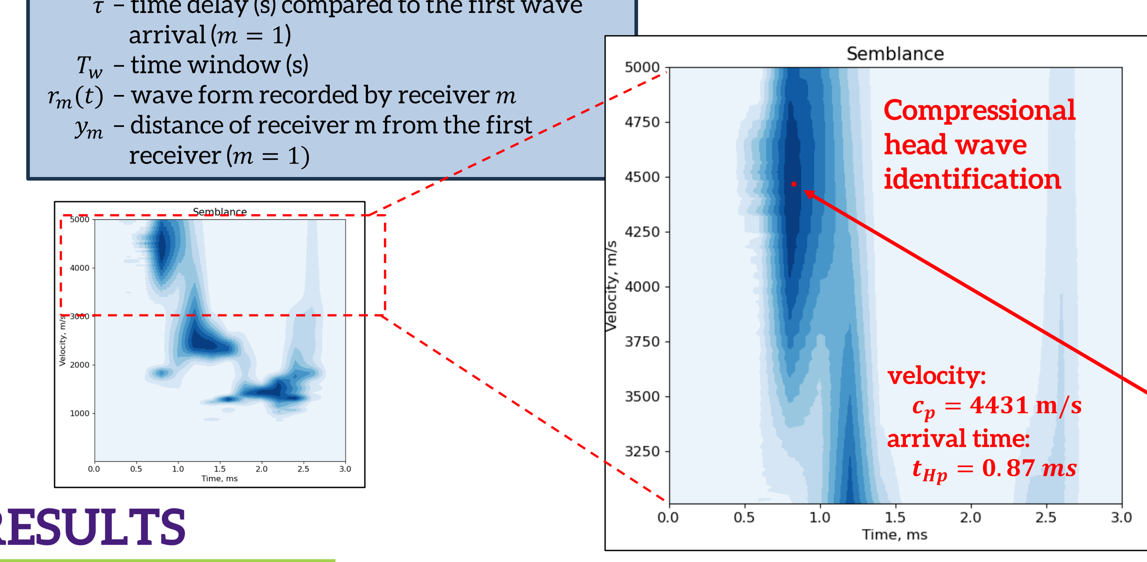


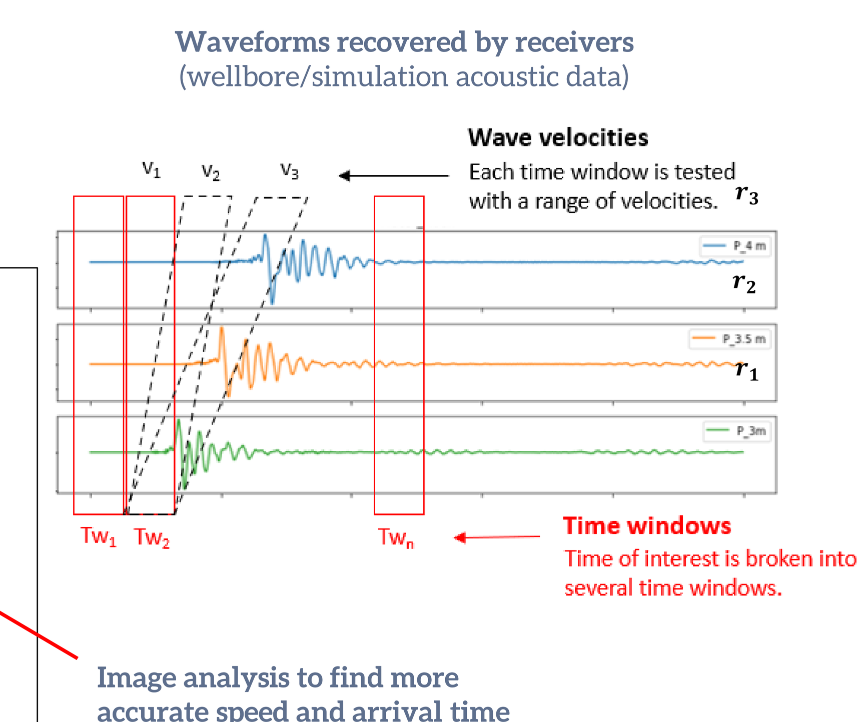
2) SEMBLANCE ANALYSIS

Based on slowness-time coherence method (Kimball and Marzetta, 1984) used commonly for array sonic waveforms to detect wave speed and arrival time:

$$\rho^2(c,\tau) = \frac{\frac{1}{M}\int_{t=0}^{T_w}\left[\sum_{m=1}^{M} r_m\left[t + \left(\frac{z_m}{c}\right) + \tau\right]\right]^2 dt}{\sum_{m=1}^{M}\int_{t=0}^{T_w}\left\{r_m\left[t + \left(\frac{z_m}{c}\right) + \tau\right]\right\}^2 dt}$$

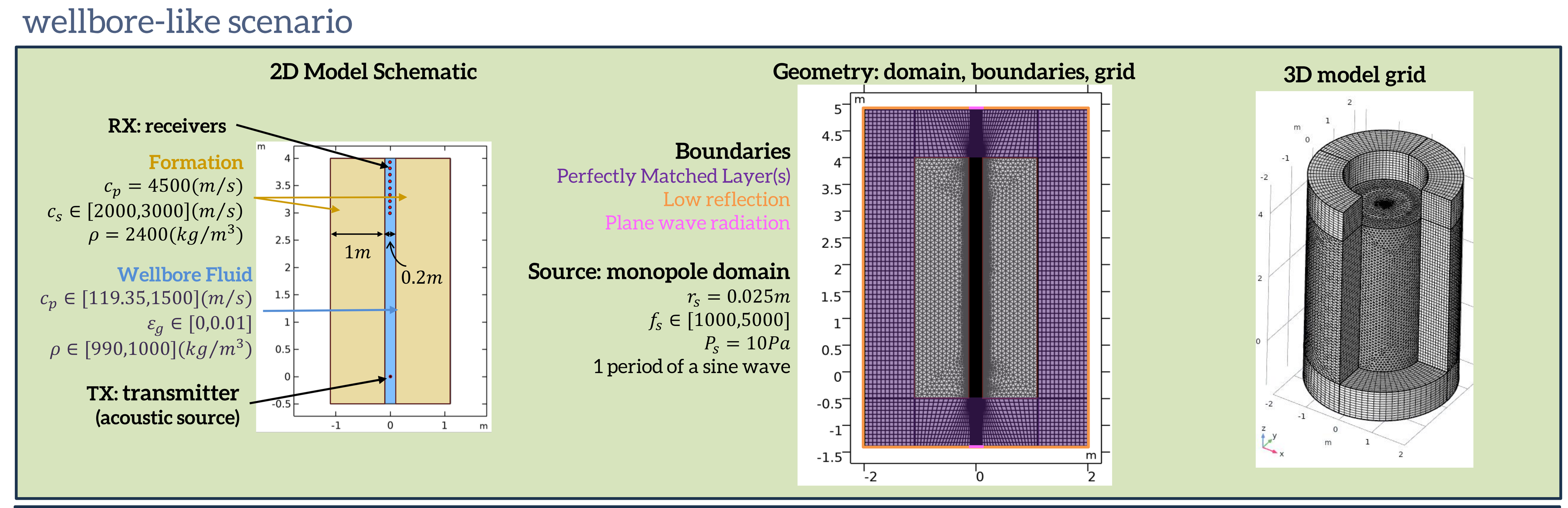
M – number of receivers
c – wave velocity (m/s)
τ – time delay (s) compared to the first wave arrival ($m = 1$)
T_w – time window (s)
$r_m(t)$ – wave form recorded by receiver m
y_m – distance of receiver m from the first receiver ($m = 1$)

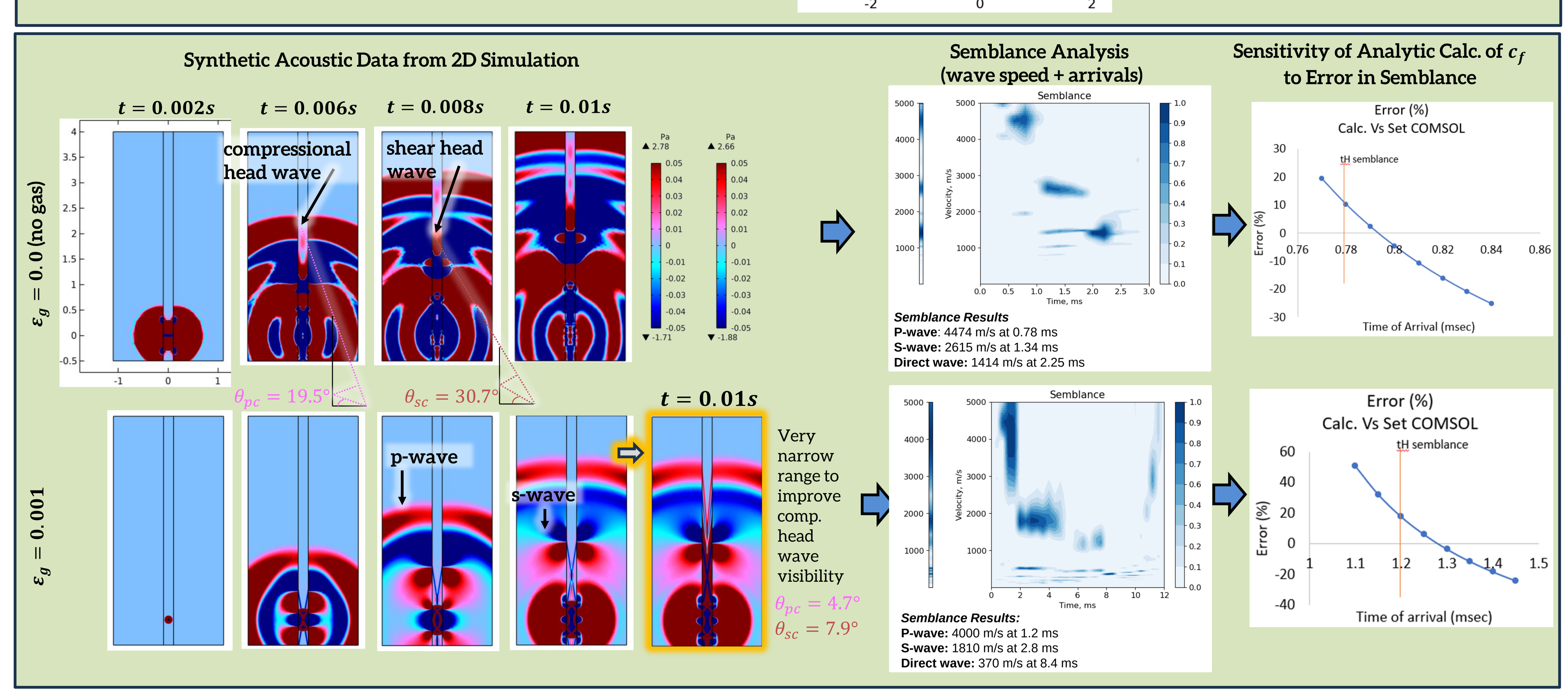




RESULTS

2D and 3D simulations using COMSOL were conducted to produce synthetic acoustic data in a wellbore-like scenario





FINAL REMARKS

- The numerical model can accurately predict acoustic propagation in complicated environments (e.g., predict critical angles, speeds of sounds p-wave and s-wave).
- Identification of the mud wave in the total acoustic signal may be challenging due to multiple modes of propagation, simultaneous arrivals at the receive, and attenuation of the mud wave.
- Knowing the geometrical path and using the arrival time and velocity of the compressional head wave (and/or shear head wave), this effort shows how we can calculate the speed of sound of the mud wave. This provides an alternative means of assessing the mud speed and therefore gas influx.
- FUTURE WORK: Explore how the bubble mixture treatment as opposed to homogenous mixture impacts wave train.
- FUTURE WORK: Explore additional data analysis method (identifying a kick) for improved EKD: Signal analysis/machine learning techniques.

REFERENCES

1) Jiang, et al., Proceedings of the 2014 COMSOL Conference in Boston, Understanding Logging-While-Drilling Transducers with COMSOL Multiphysics® Software; 2) Rose, K., et. al., 2019, USPO #10253620; 3) Adapted from Tost, B., et. al., 2016, https://doi.org/10.2172/1327810; 4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.; 253, https://doi.org/10.1016/j.nucengdes.2011.09.068; 5) Wang, Hua, M. Nafi Toksöz, and Michael C. Fehler. Borehole acoustic logging-theory and methods. Springer International Publishing, 2020.

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