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Fluid substitution for an HTI medium

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Outline

➢Motivation

3D printed models➔ fractured rocks, anisotropy and fluid substitution

4D time lapse seismic

➢Experiments

3D printed model, velocity measurements, fluid substitution experiments

➢Theory

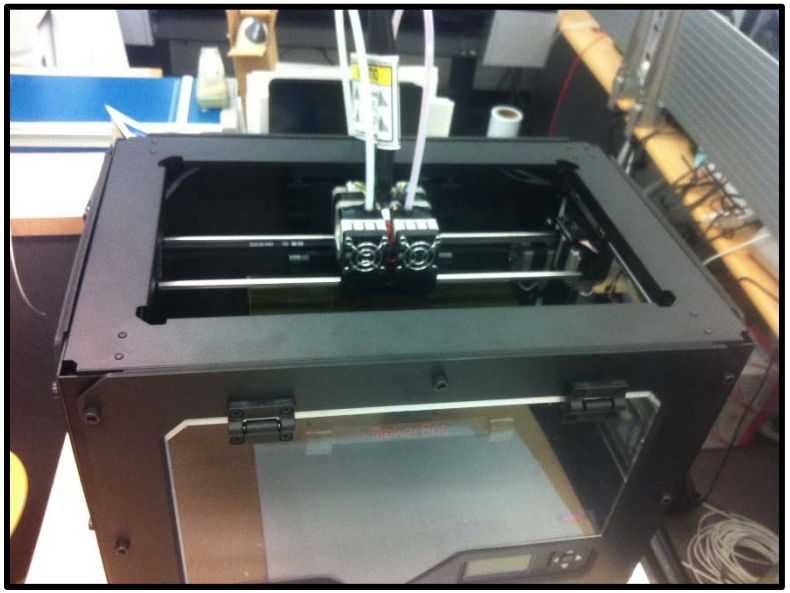
anisotropic Gassmann's equations (recast for an HTI medium)

➢Discussion

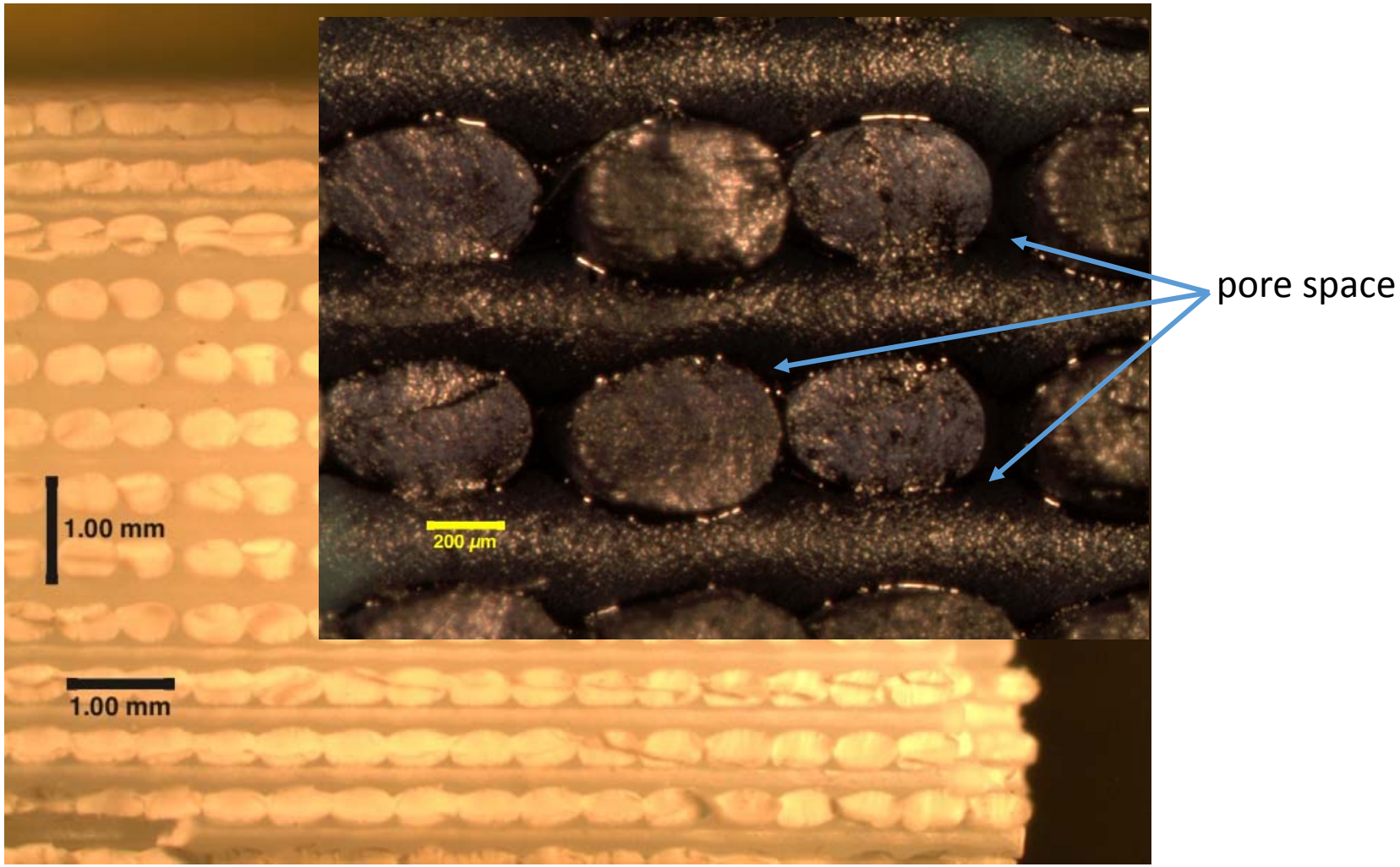
experiment results versus theoretical predictions

➢Conclusions

We are the first generation of geophysicists to use 3D printed models!

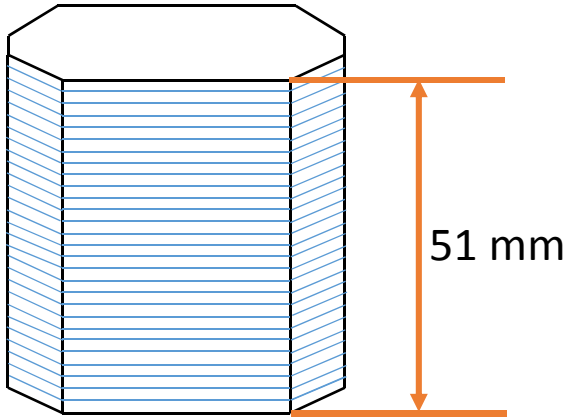


How it prints and where are the pores?

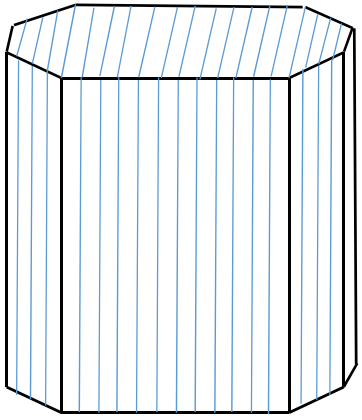


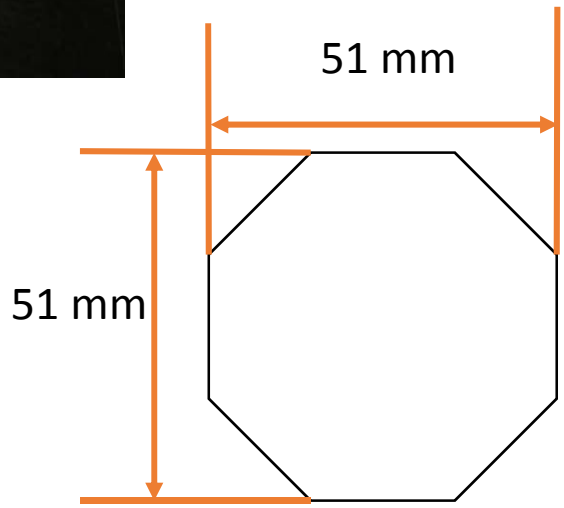
3D printed models

VTI model

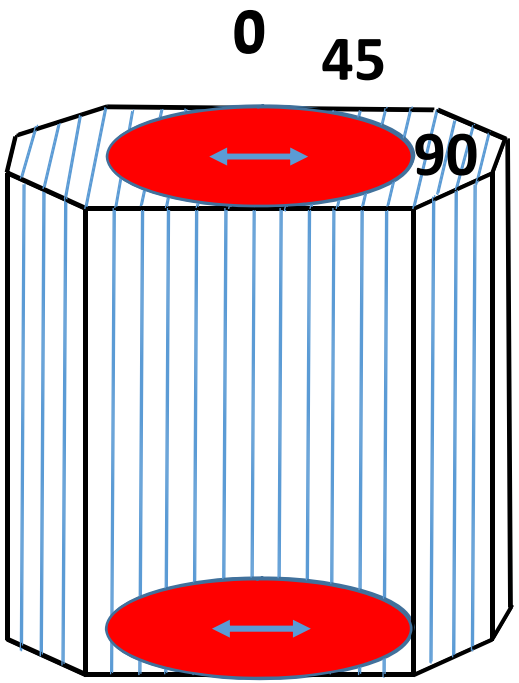


HTI model



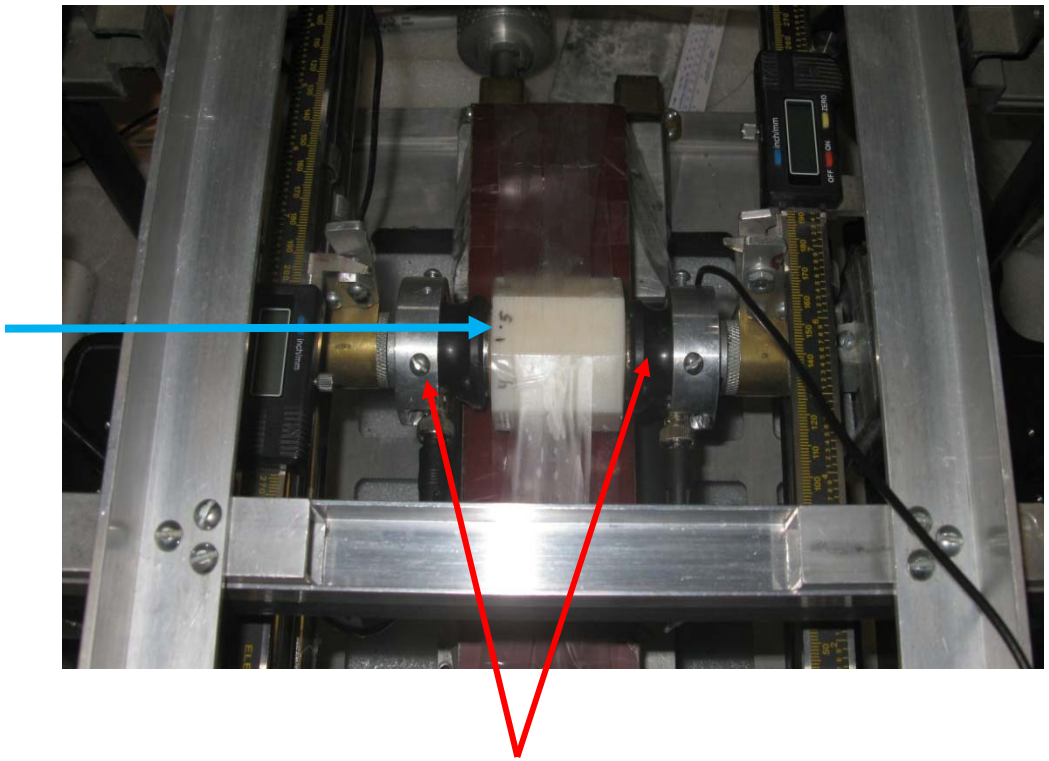


Rotation experiments



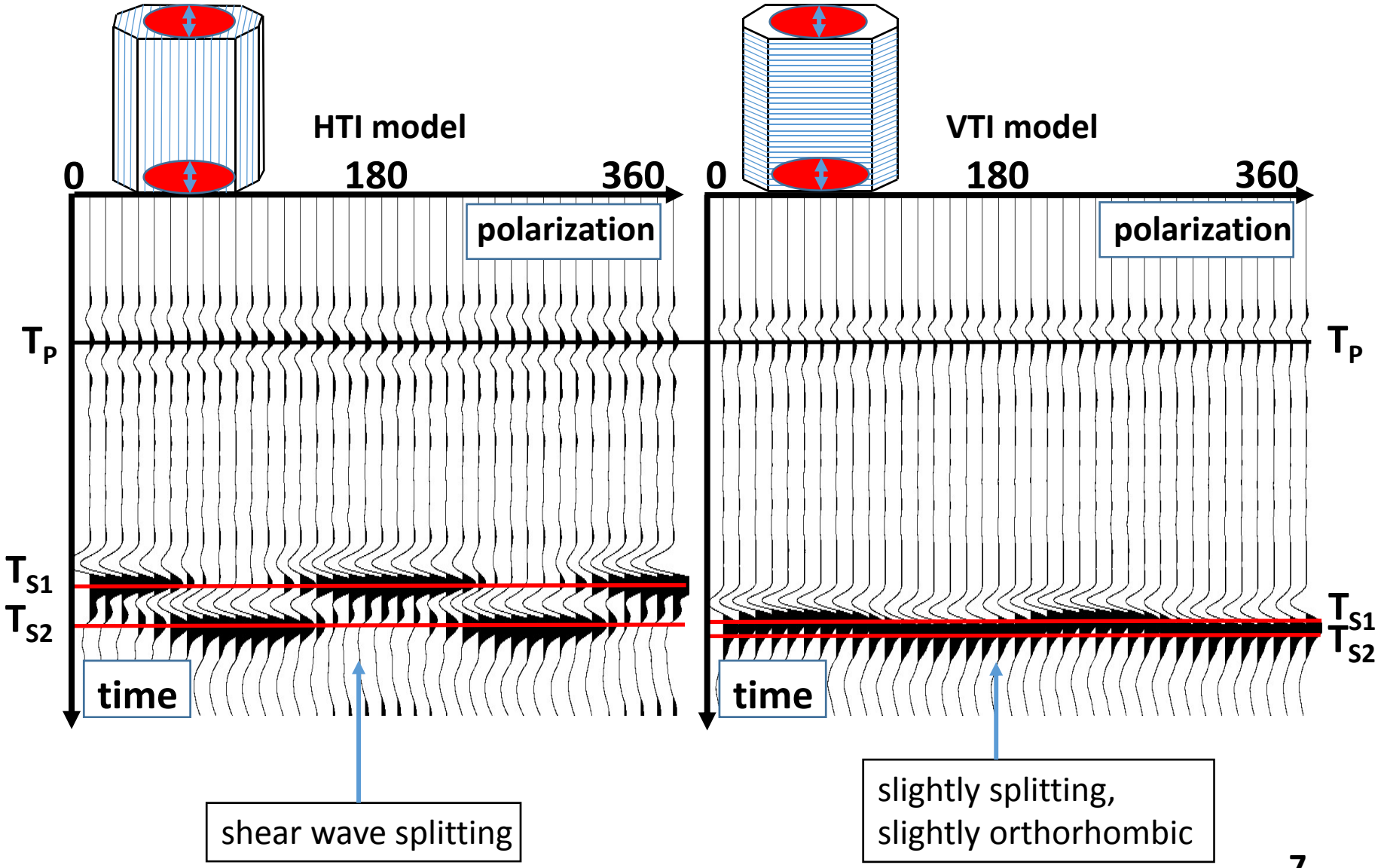
HTI model

polarization vector



Transducer: 500 kHz horizontal component

Velocity variation with polarization



What if we saturate the models?

- How velocity will change after saturation?
  (P-wave, S-wave?)
- How can we theoretically predict the changes?
  (Gassmann's equations?
  isotropic or anisotropic? VTI, HTI, orthorhombic?
  Hudson's model? Linear slip model? GSA?)
- Why do we care?
  (simulating 4D time lapse seismic!)

Recast Gassmann's equations

$$C_{ijkl}^{sat} = C_{ijkl}^{dry} + \frac{\left(K_m\delta_{ij} - C_{ij\alpha\alpha}^{dry}/3\right)\left(K_m\delta_{ij} - C_{\beta\beta kl}^{dry}/3\right)}{\left(K_m/K_{fl}\right)\phi\left(K_m - K_{fl}\right) + \left(K_m - C_{ppqq}^{dry}/9\right)}$$

(Gassmann, 1951)

linear slip model

(Schoenberg and Sayers, 1995)

New!

$$C_{11}^{sat} = \left(\lambda+2\mu\right)\left(1-\delta_N\right) + \frac{\left(K_m - K_{iso}^{dry} + \delta_N K_{iso}^{dry}\right)^2}{\left(K_m/K_{fl}\right)\phi\left(K_m - K_{fl}\right) + K_m - K_{iso}^{dry}\left(1-\delta_N K_{iso}^{dry}/\left(\lambda+2\mu\right)\right)}$$

$$C_{33}^{sat} = \left(\lambda+2\mu\right)\left(1-\frac{\lambda^2\delta_N}{\left(\lambda+2\mu\right)^2}\right) + \frac{\left(K_m - K_{iso}^{dry} + \lambda\delta_N K_{iso}^{dry}/\left(\lambda+2\mu\right)\right)^2}{\left(K_m/K_{fl}\right)\phi\left(K_m - K_{fl}\right) + K_m - K_{iso}^{dry}\left(1-\delta_N K_{iso}^{dry}/\left(\lambda+2\mu\right)\right)}$$

$$C_{44}^{sat} = \mu$$

$$C_{55}^{sat} = \mu\left(1-\delta_T\right)$$

Dry term

Fluid term

Parameter estimation

Well logs: $\rho, V_P, V_{S1}, V_{S2}, \phi$

(Hsu and Schoenberg, 1993)

$$Z_T = 1/C_{55} - 1/C_{44}$$

$$Z_N = (1 - \nu/2) Z_T$$

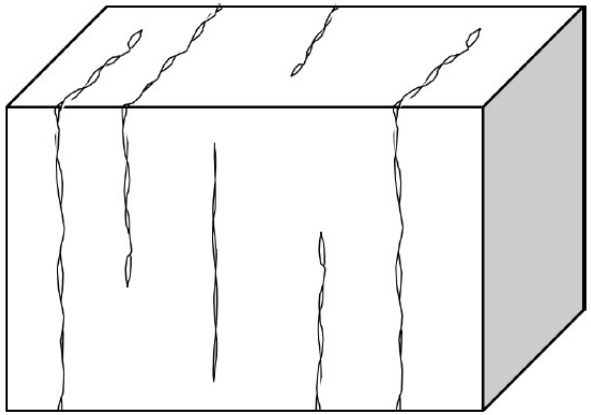
(Sil et al., 2013)

$$\lambda, \quad \mu, \quad \mathrm{K_{iso}}$$

$$M = \lambda + 2\mu$$

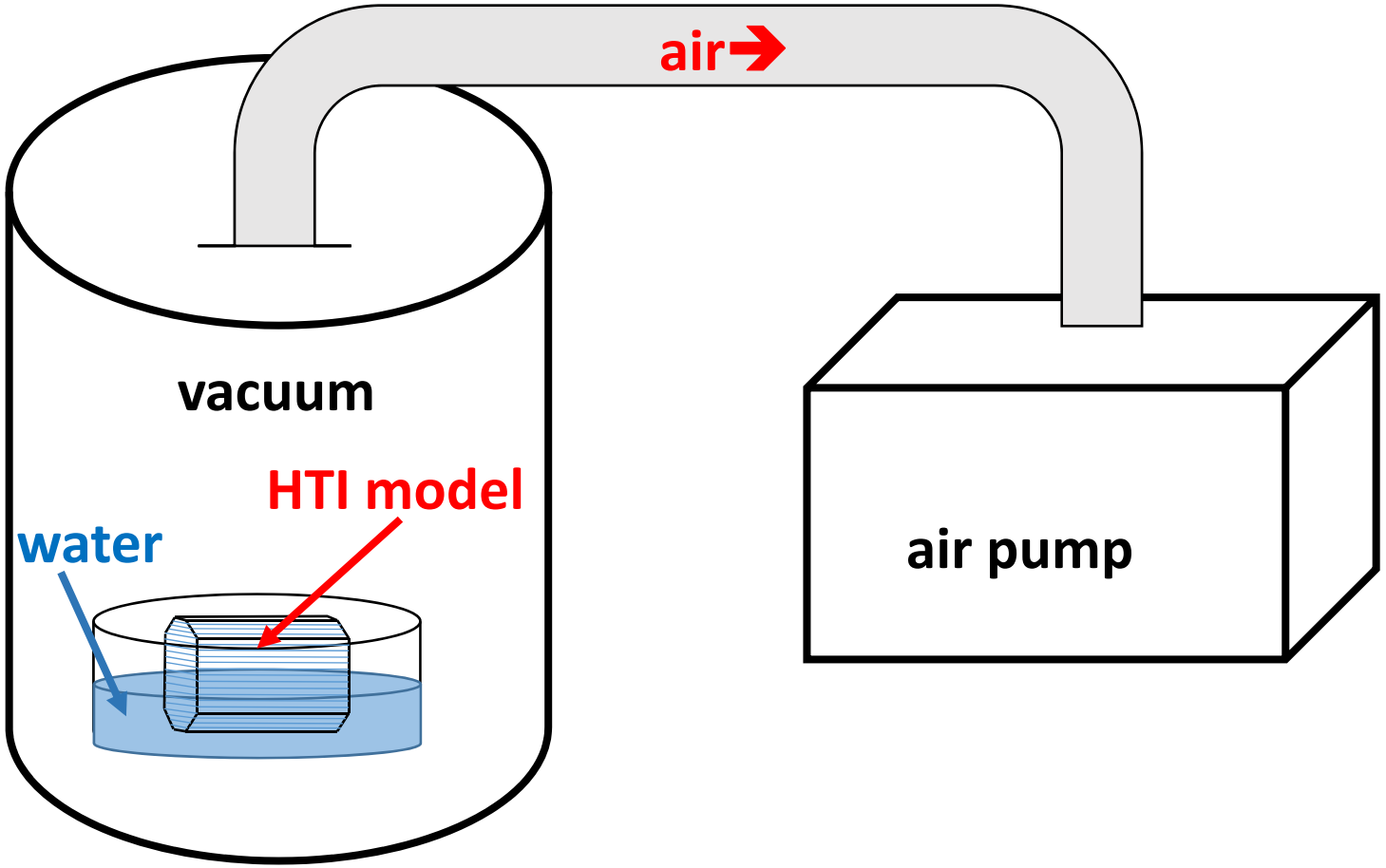
(Sayers and Kachanov, 1995)

$$\delta_N = Z_N M / (1 + Z_N M)$$

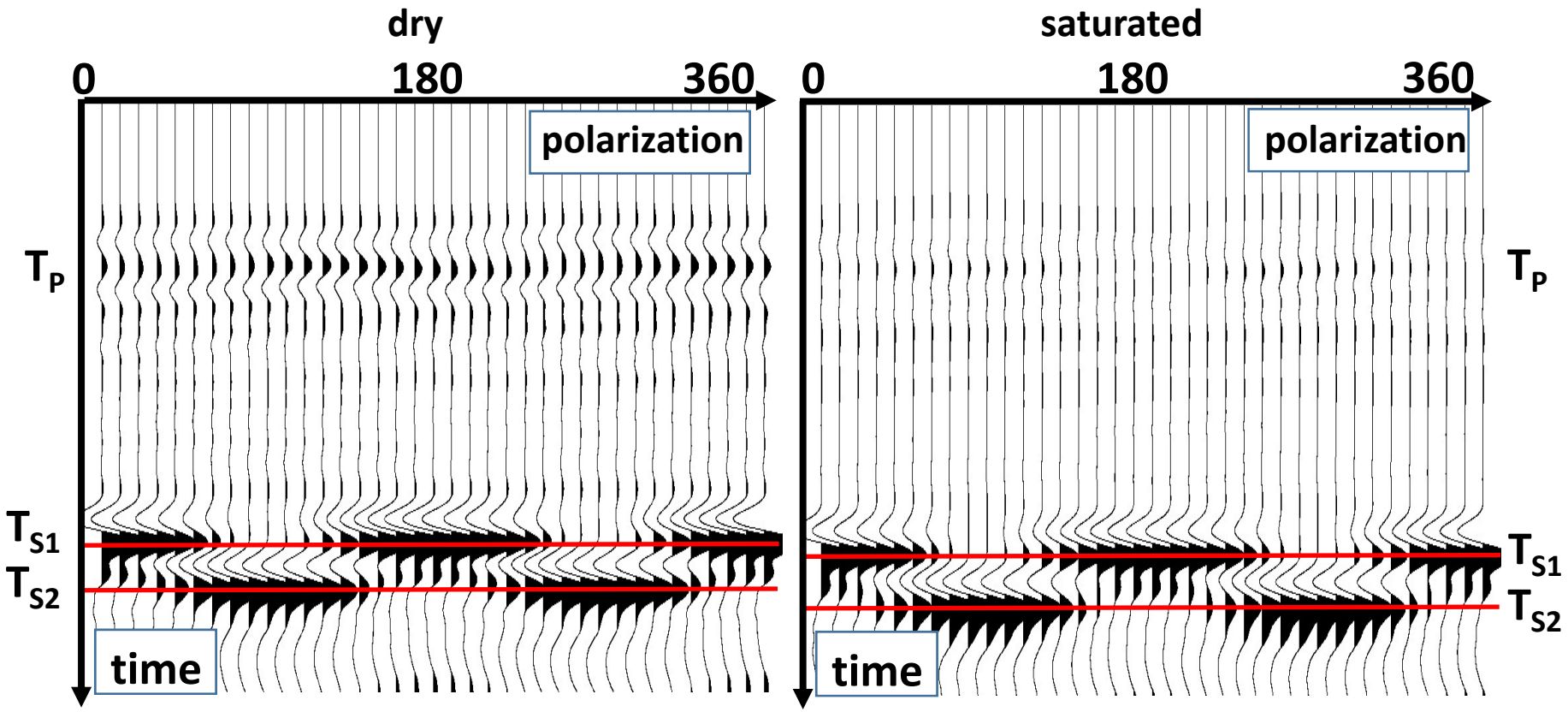


$$C_{11}^{sat} = (\lambda + 2\mu)(1 - \delta_N) + \frac{(K_m - K_{iso} + \delta_N K_{iso})^2}{(K_m / K_{fl})\phi(\mathrm{K_m} - \mathrm{K_{fl}}) + \mathrm{K_m} - K_{iso}(1 - \delta_N K_{iso}/(\lambda + 2\mu))}$$

Fluid substitution experiment (HTI model)

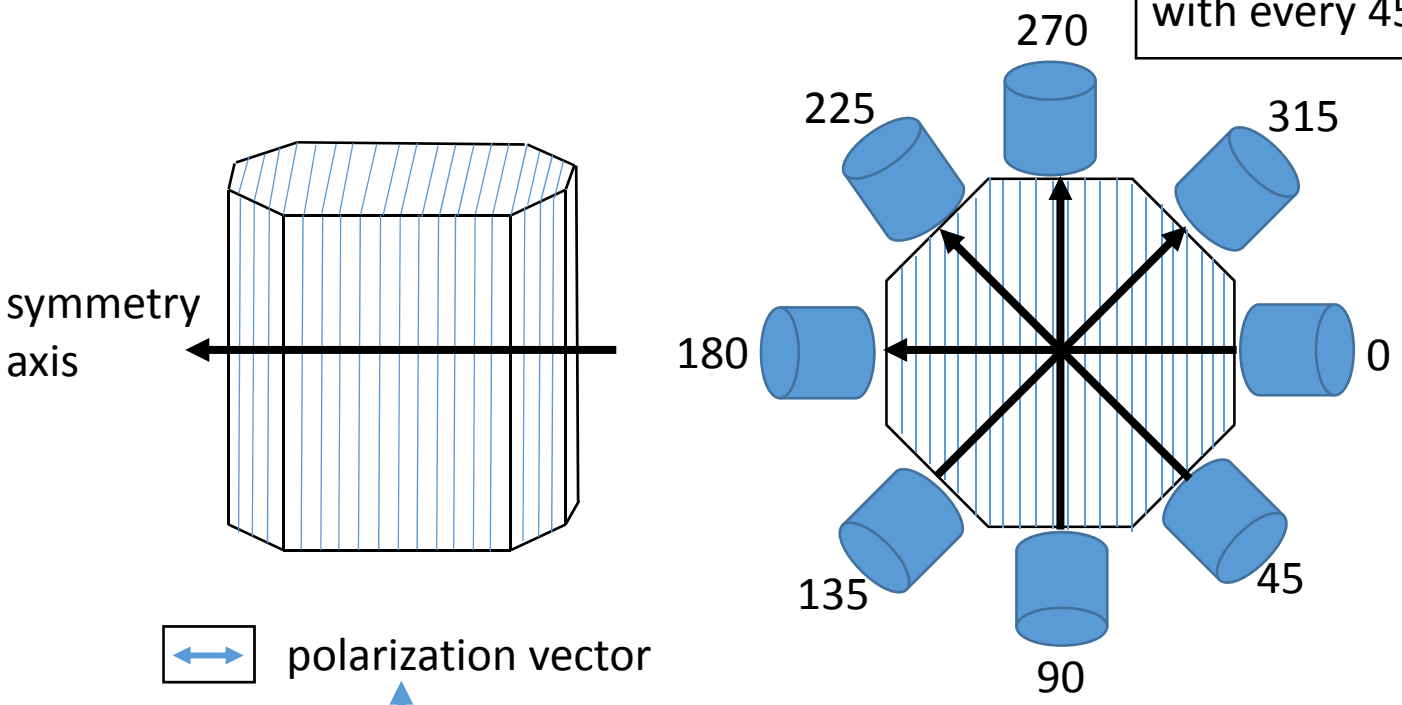


Fluid substitution



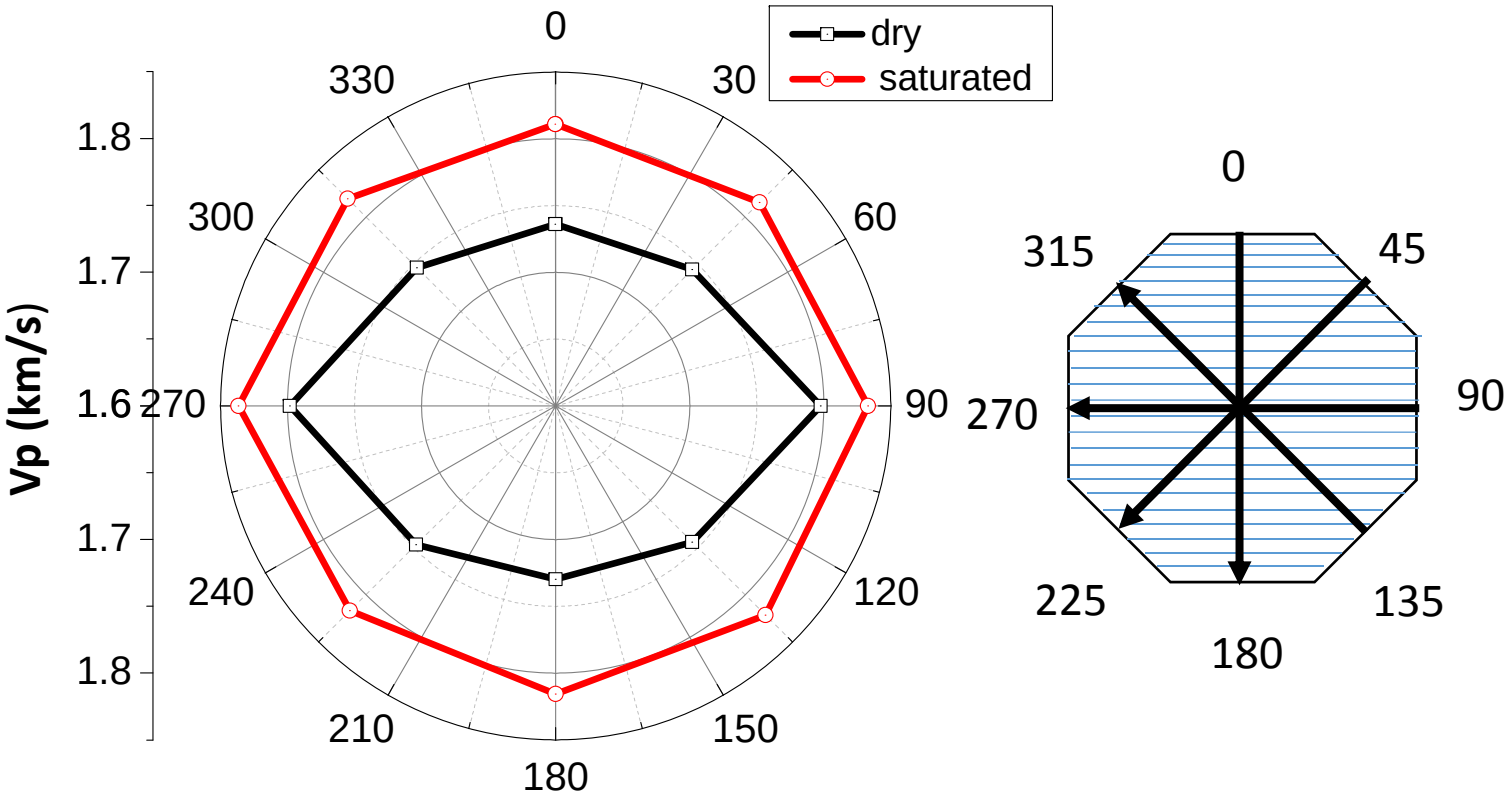
Velocity measurement from sides

transmission measurements with every 45-degree azimuth



P-wave velocity measurement:
500 kHz vertical component transducer
S-wave velocity measurement:
500 kHz horizontal component, **polarized in two orthogonal directions**

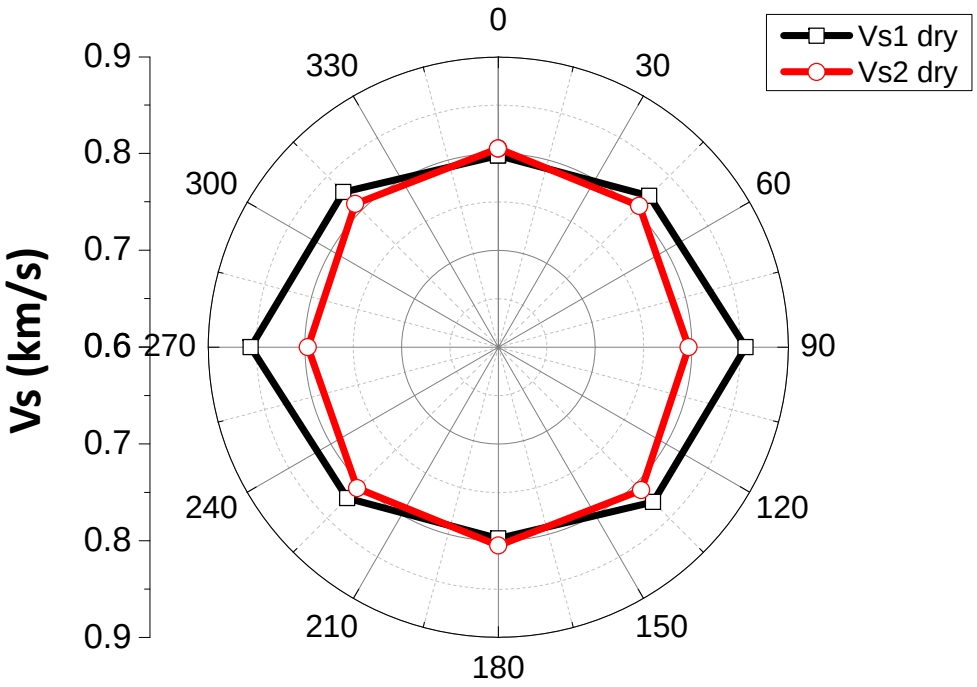
P-wave velocity change after saturation



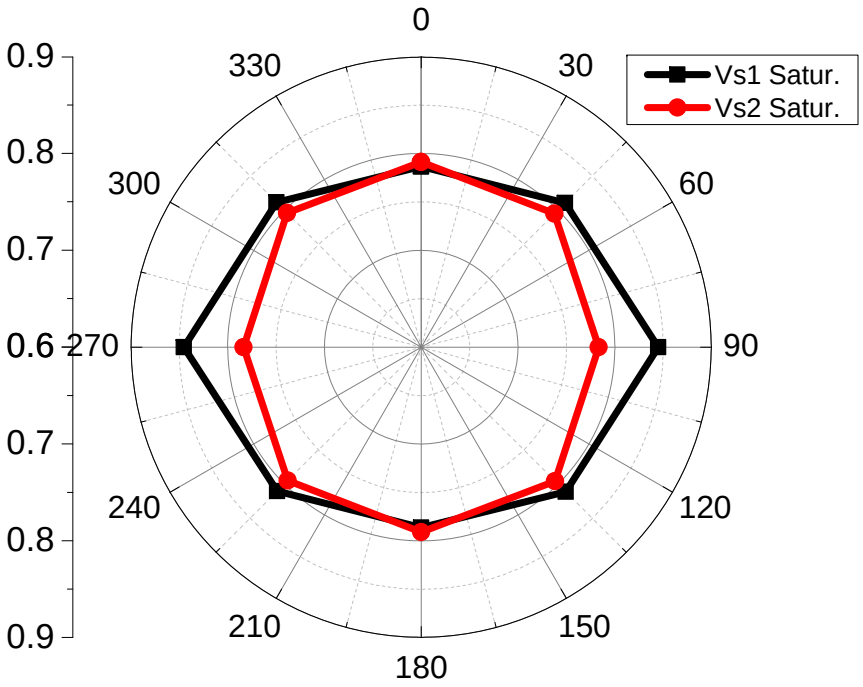
We see 2% - 4.6% increase in P-wave velocity

S-wave velocity change after saturation

V_{S1} and V_{S2} before saturation



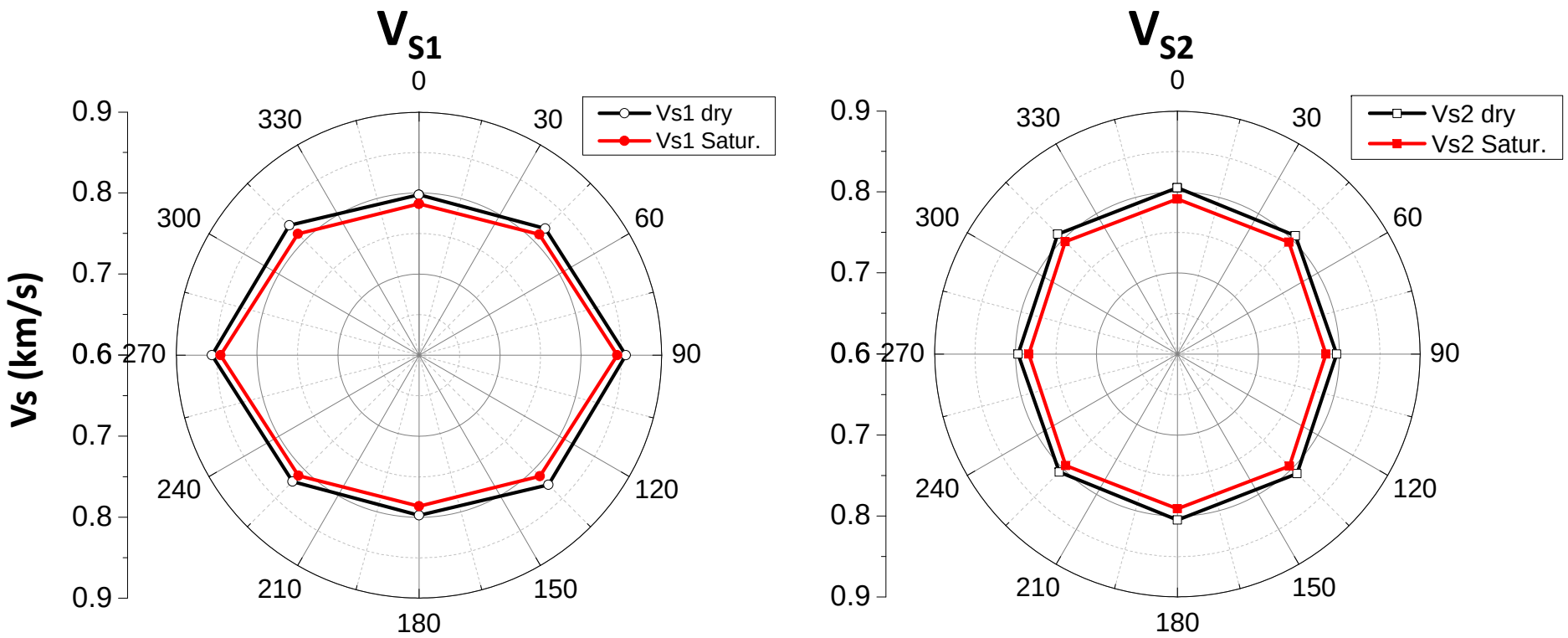
V_{S1} and V_{S2} after saturation



Black denotes fast shear-wave (V_{S1})

Red denotes slow shear-wave (V_{S2})

S-wave velocity change after saturation



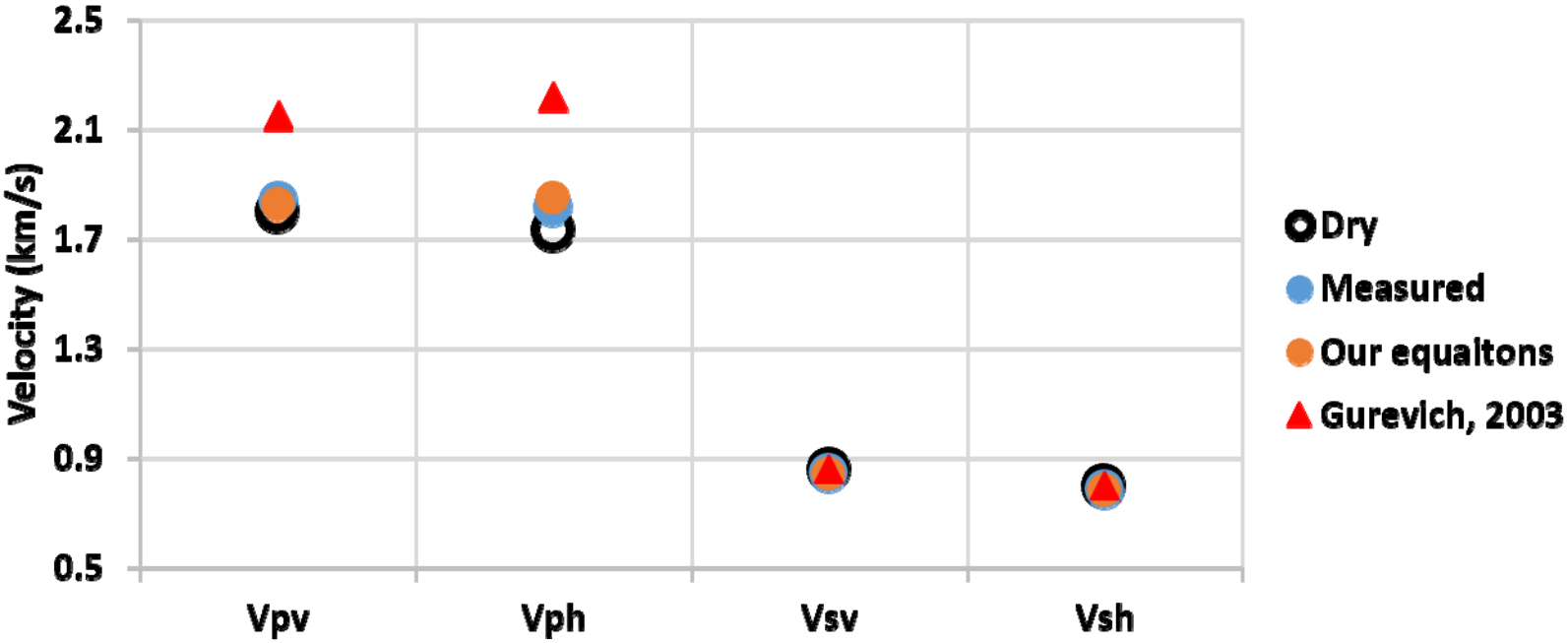
about 1.2% decrease

about 1.6% decrease

Black denotes dry

Red denotes saturated

Theoretical predictions for the HTI model



Density increases about 4% after water saturation, which contributes about 2% decrease in velocity

Conclusions

✓Innovative physical models

- print any structure with 3D printing
- cheap and fast.

✓Rich anisotropic response

- transverse isotropic symmetry
- clear shear wave splitting

✓New equations

- Gassmann's equations for an HTI medium
- predict better results for fluid substitution.

Acknowledgement

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