Simulation of Seismic Wave Propagation in Porous Rocks Considering the Exploration and the Monitoring of Geological Reservoirs

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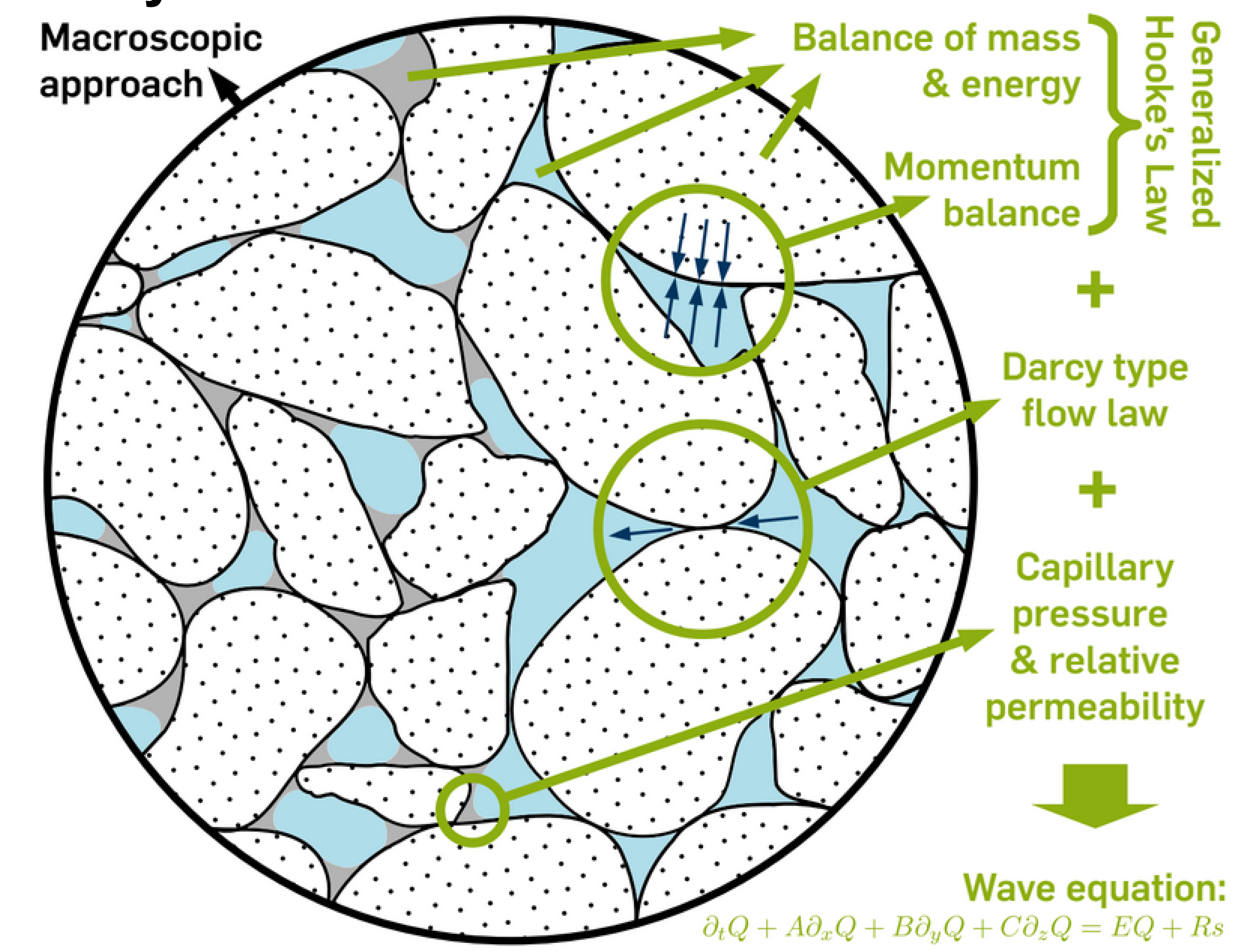
Introduction

Modeling seismic waves in porous media is a challenging task. The additional slow P-wave leads to small elements in the computational domain and, hence, larger computational costs. However, this detail is sometimes necessary as it is demonstrated in the following CCS example. Before, the basis for the theory is described and the verification and validation of the code is demonstrated.

Theory

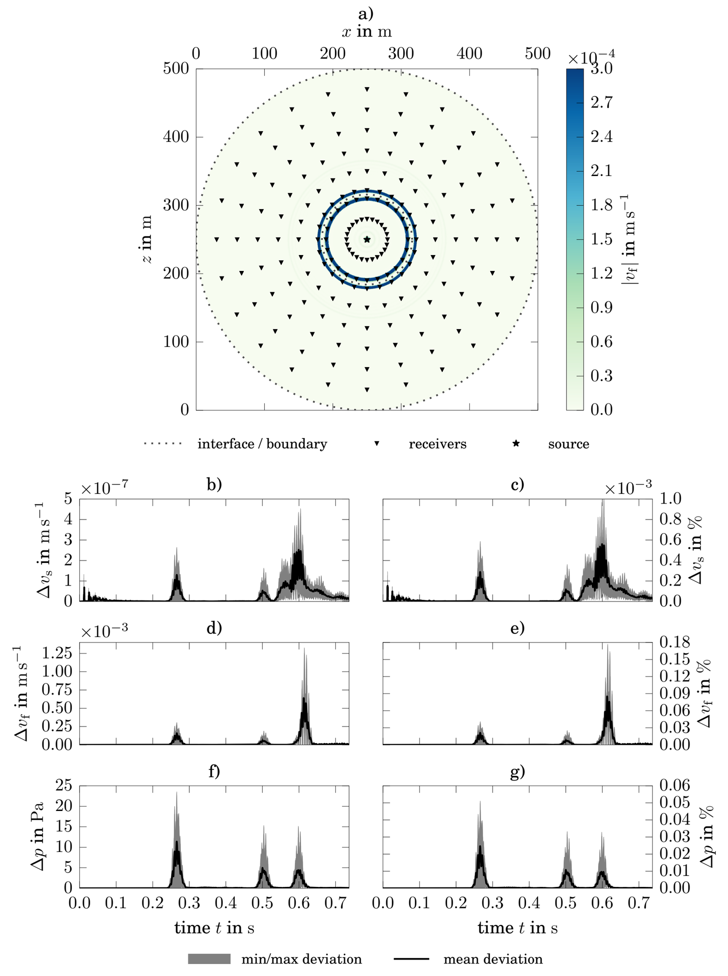


▲ **Fig. 1:** Illustration of the equations and laws used to derive the wave equation that describes wave propagation in porous media. In this work, a macroscopic approach is used. The background image is a schematic close-up of a porous medium that is saturated by two fluids on the left side, where the wetting fluid is denoted by gray areas and the non-wetting fluid is denoted by light blue areas, and saturated by one fluid (light blue) on the right side. The sketch shows the ingredients of the seismic wave equation as well as the final wave equation, where the vector $\boldsymbol{Q}$ contains the state variables, i.e. the particle velocities of the solid and both fluids, the effective stress, and the partial pressures of the fluids. The vector $\boldsymbol{s}$ is a point force. $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{E}$ and $\boldsymbol{R}$ are matrices that consist of material properties (Boxberg, 2019).

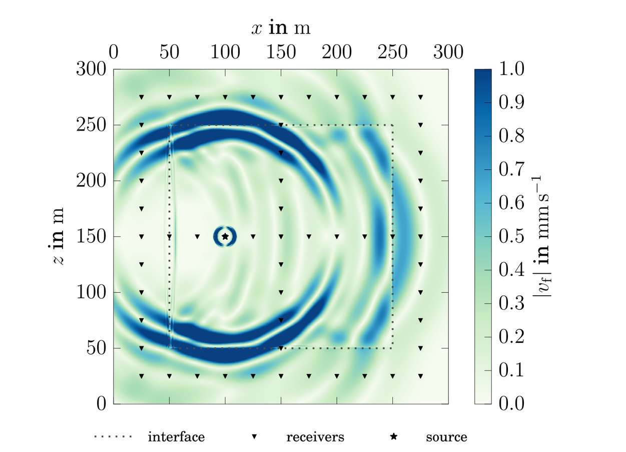
Code Verification

Software verification and validation is a very important step in the software life cycle. Boehm (1979) gives an intuitive informal definition of verification and validation. Verification is answering the question 'Am I building the product right?' and validation is answering to 'Am I building the right product?'. Applying these questions to this work means to ask 'Am I solving the equations right?' and 'Am I solving the right equations?'.

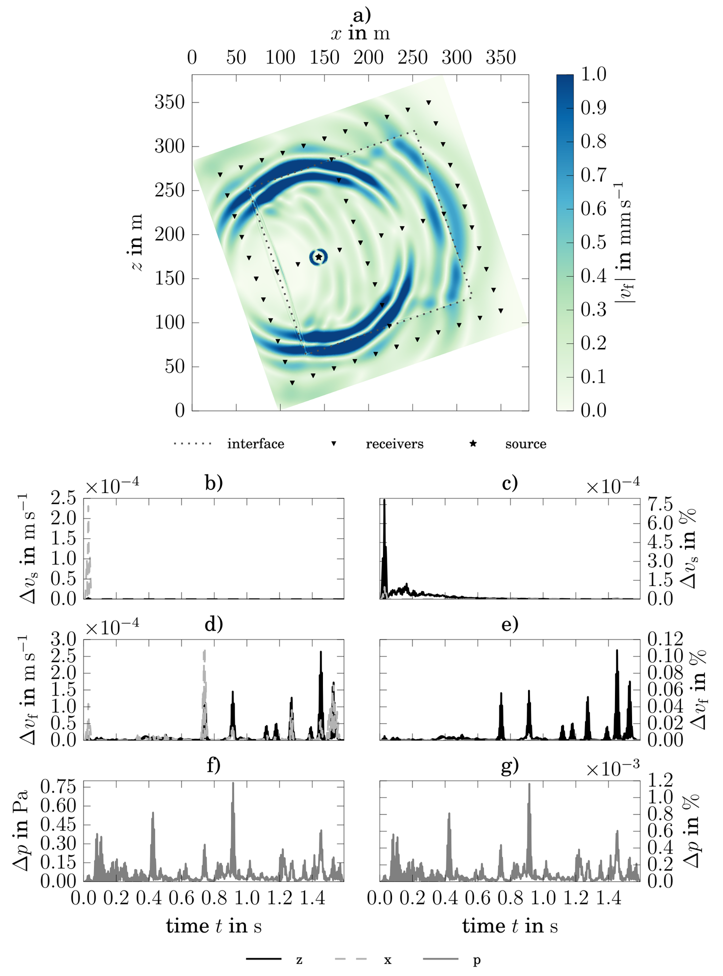
Here, two symmetry tests are shown as part of the verification: an a priori symmetric solution and a rotation test (Boxberg, 2019).



◄ **Fig. 2:** Results for a symmetry test with an a priori symmetric solution and absorbing boundary conditions. The material in the inner circle has smaller P1- and S-wave velocities, but a larger P2-velocity as the material in the outer ring. a) Wavefield in the fluid particle velocity at t = 0.604 s; b), d) and f) show the root-mean-square deviation and c), e), and g) show the normalized root-mean-square deviation of the solid particle velocity v_S, the fluid particle velocity v_F and the fluid pressure p (Boxberg, 2019).

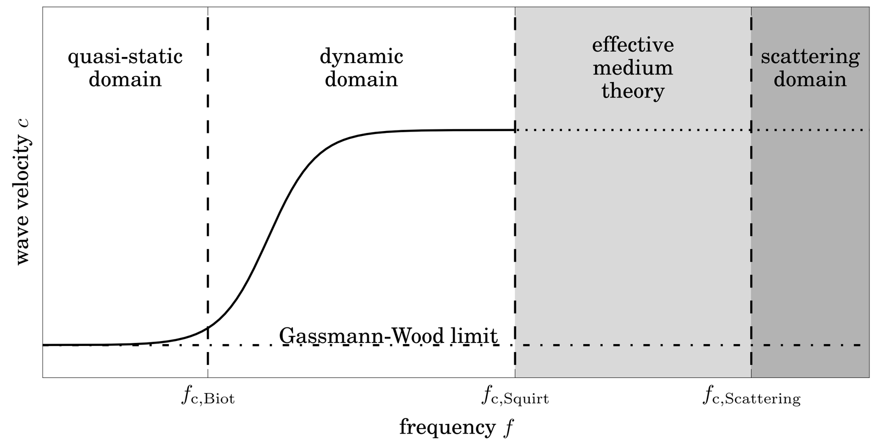


▲ **Fig. 3:** Reference simulation

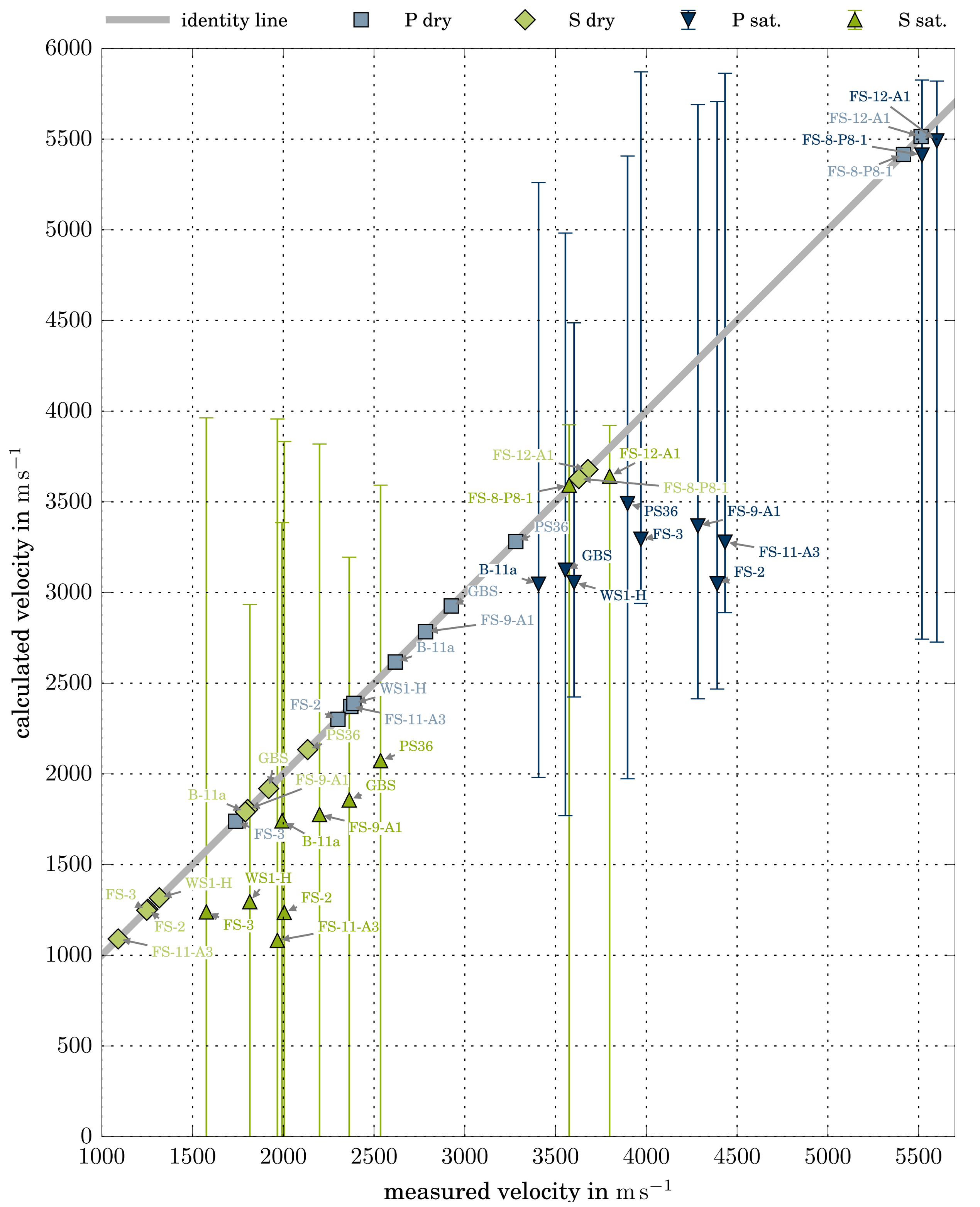


► **Fig. 4:** Results for 19.09° rotation. a) wavefield in the fluid particle velocity at t = 0.029 s; b), d) and f) show the RMS deviation and c), e), and g) show the normalized RMS deviation of the solid particle velocity v_S, the fluid particle velocity v_F and the fluid pressure p (Boxberg, 2019).

Code Validation

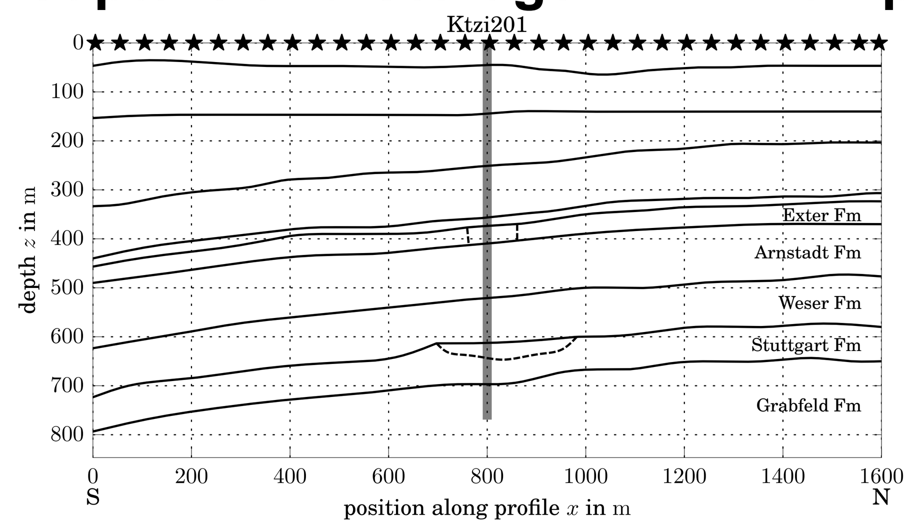


◄ **Fig. 5:** Frequency domains for poroelastic media: Domains with a white background are covered by the presented theory whereas those with grey background are not (Boxberg, 2019).

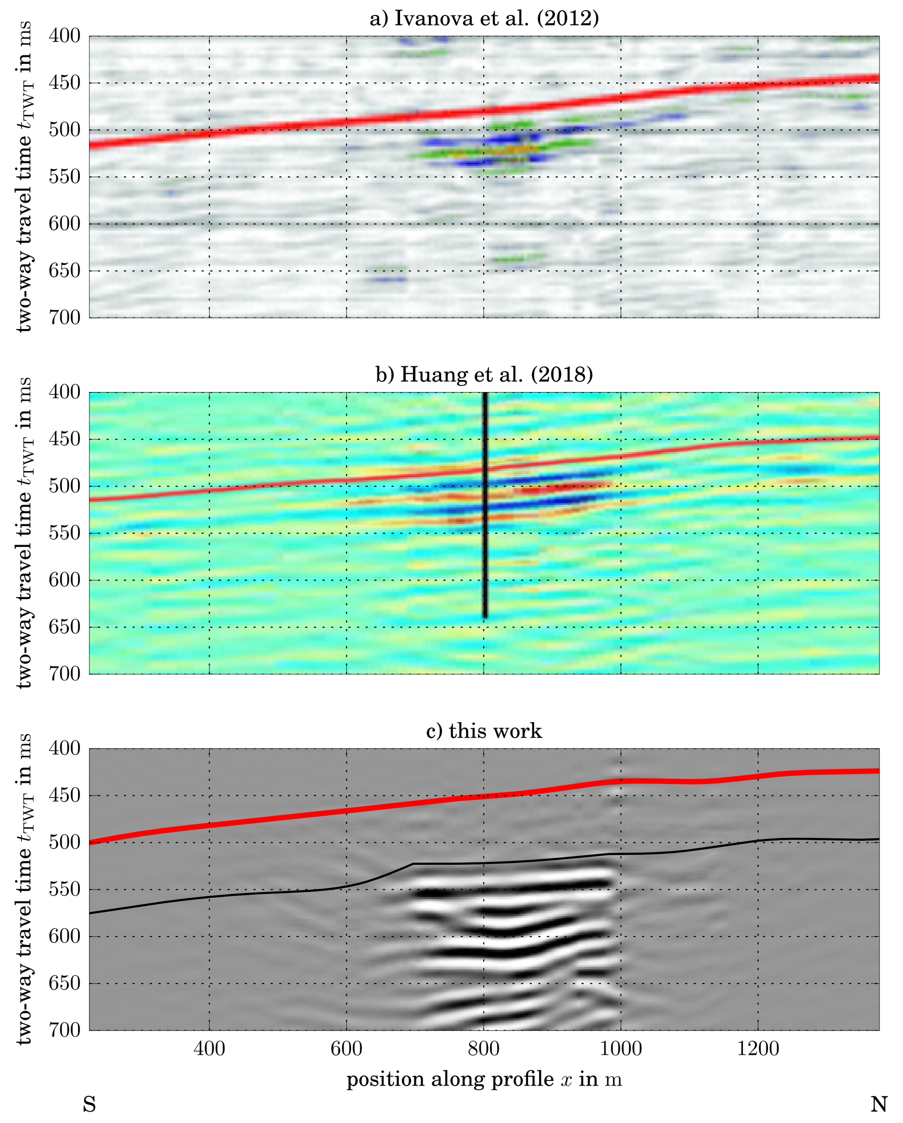


▲ **Fig. 6:** Comparison of measured and calculated velocity for ten different sandstone samples: Bentheim (GBS), Berea (BS-11a), Fonteinbleau (FS), Pfälzer (PS) and Wilkeson (WS) sandstone. The bars do not denote errors but show the upper and lower Hashin-Shtrikman-Walpole limits for all saturated samples. Measurement errors are not shown since they are small compared to the scale of the figure (Boxberg, 2019).

Carbon Capture and Storage – An Example



▲ **Fig. 7:** 2D model of the Ketzin anticline that was used in the Ketzin CCS pilot project (Bergmann et al., 2015). The gray vertical line marks the injection well and the black stars indicate the positions of the shot positions of the synthetic seismic survey. The dashed lines indicate hypothetical contact lines mimicking the distribution of carbon dioxide in the Stuttgart Fm at about 630 m depth and of a hypothetical leakage in the Exter Fm (Boxberg, 2019).



▲ **Fig. 8:** Comparison of a) Ivanova et al. (2012) and b) Huang et al. (2018) with c) this work. The difference between a repeated survey after injection and a baseline survey is plotted. The post-injection survey in c) was simulated with 50% saturation of carbon dioxide. The red line marks the top of the Weser Fm that is characterized by a ca. 20 m thick anhydrite layer (not modeled explicitly here). The black vertical line in b) denotes the position of the injection well. The black line in c) marks the top of the Stuttgart Fm (Boxberg, 2019).

References:

Bergmann, P. et al., 2015, J Petrol Sci Eng, 139:112-136, 10.1016/j.petrol.2015.12.007; **Boehm**, B. W., 1979, Guidelines for verifying and validating software requirements and design specications, In Samet, P. A., editor, Euro IFIP 79, p. 711-719; **Boxberg**, M. S., 2019, PhD thesis, 10.13154/294-6843; **Huang**, F. et al., 2018, Geophys Prospect, 66(1):6284, 10.1111/1365-2478.12497; **Ivanova**, A. et al., 2012, Geophys Prospect, 60(5):957973, 10.1111/j.1365-2478.2012.01045.x