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High-resolution crosshole seismic imaging of glacial sediments by full-waveform inversion

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icdp DOVE

1 ICDP site 5068_1: Tannwald Basin

The glacially overdeepened Tannwald Basin was excavated by the Rhine Glacier below the fluvial base level in several glacial cycles, forming an elongated structure (1 km long, 250 m wide) that is filled with glacial deposits (Buness et al., 2022). In 2021, three boreholes were drilled in an isosceles triangle with 28 m long edges oriented in N-S and W-E. All three drillings reached the molasse at a depth of about 160 m. While boreholes A and B are flush drillings, borehole C was completely cored.

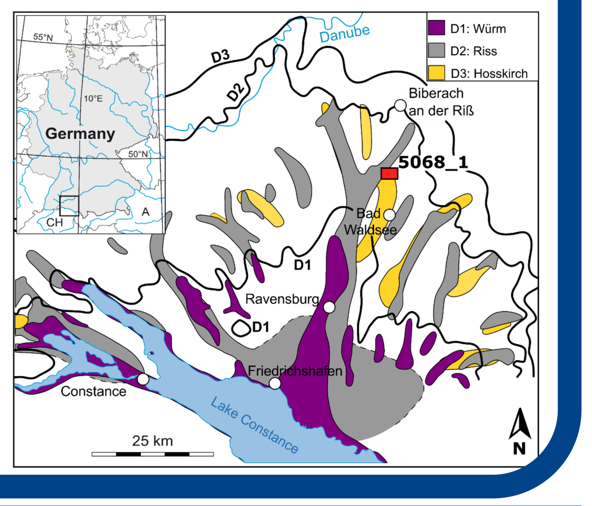
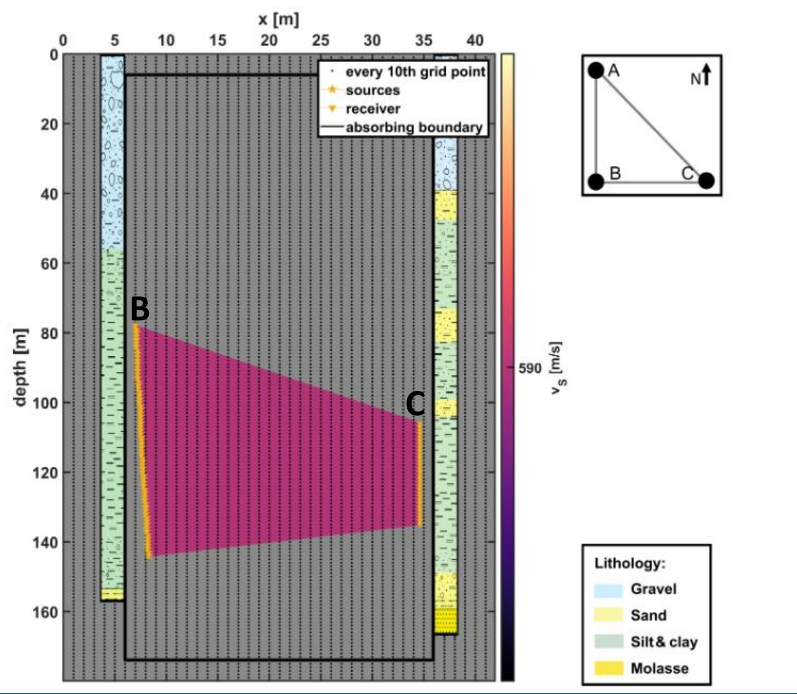


Fig. 1: Location of Tannwald Basin and drill site (red box) about 45 km north of Lake Constance. D1 to D3 depict the discontinuities created by the glacial advances (map modified after Ellwanger et al. (2011) and Beraus et al. (in revision)).

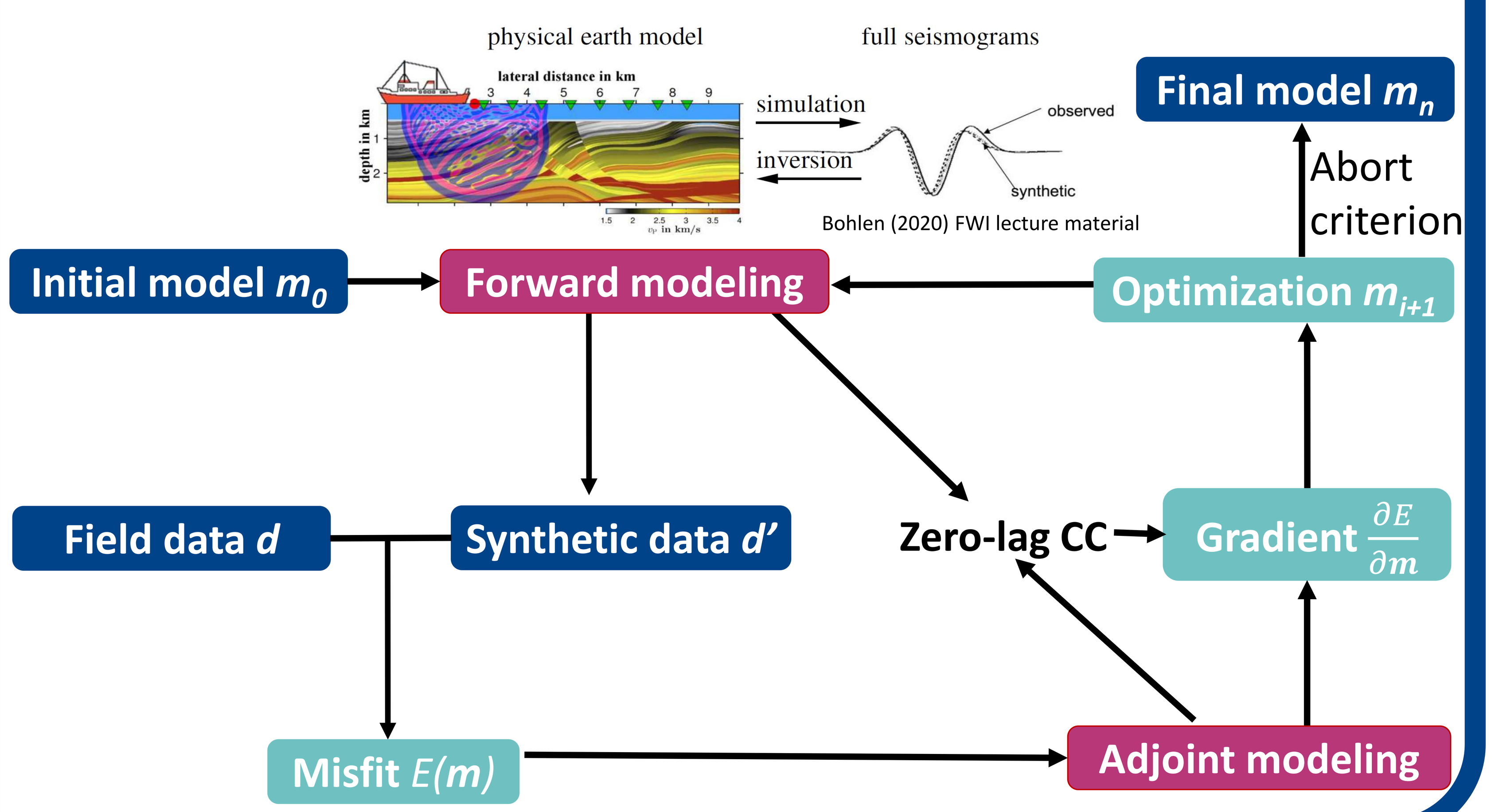
2 Seismic crosshole experiment



- Target: finely layered sediments
- SV-source depth (B): 77 to 143 m
- 3C receiver string depth (C): 105 to 134 m
- Source and receiver spacing: 1 m
- Finite difference (FD) grid:
  - Grid point spacing: DH = 0.1 m
  - Grid point number in horizontal and vertical direction: NX = 420, NY = 1800

Fig. 2: SV-survey coverage (magenta), FD grid (black points), and preliminary lithology (priv. comm. B. Schuster) based on cuttings (B) and core catcher information (C).

3 Full-waveform inversion (FWI)



5 Seismic crosshole SV-FWI resolves lithology to less than 1 m

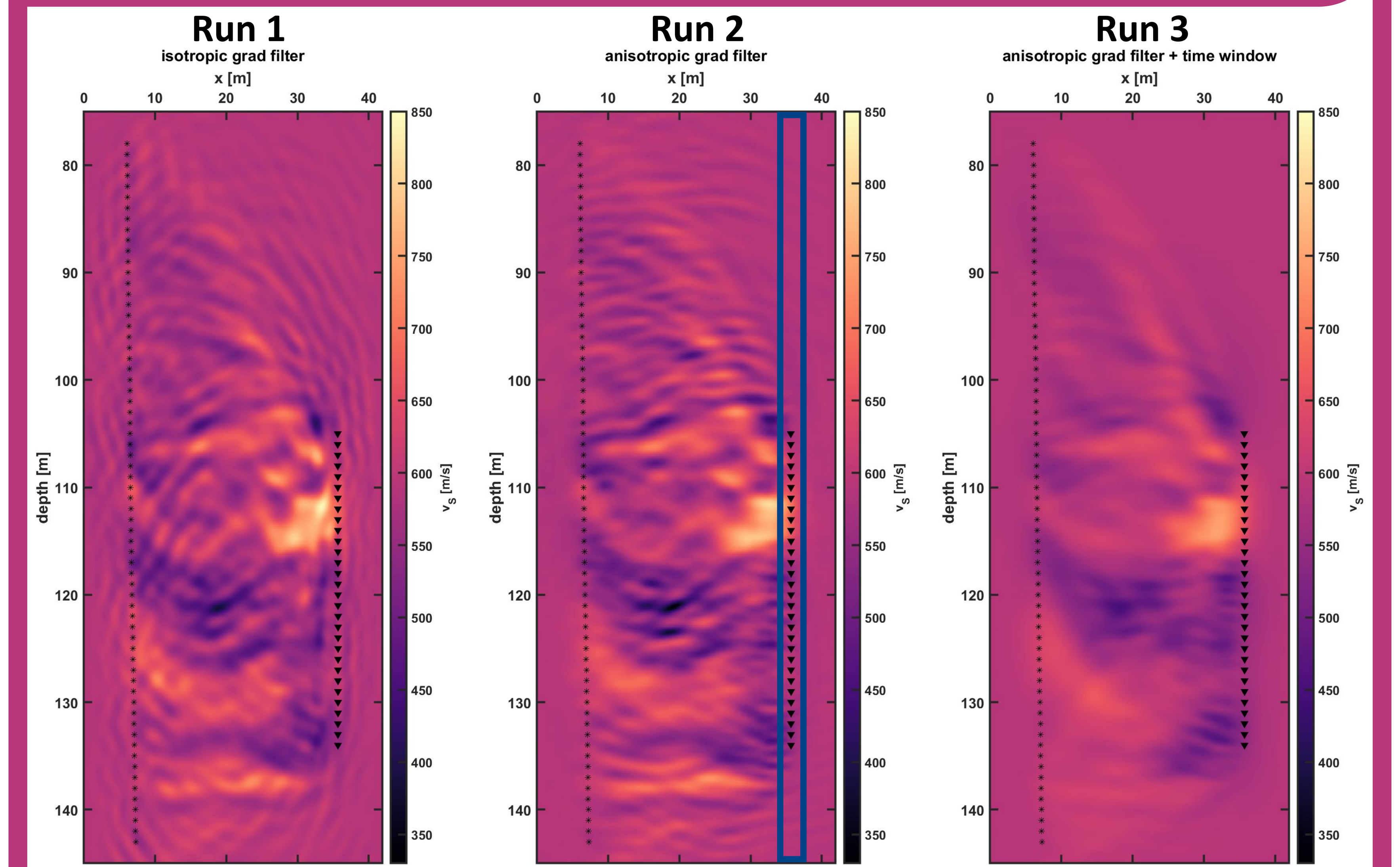


Fig. 3: FWI results using the three FWI workflows described in section 4. Source positions are marked by stars (*) and receiver positions by triangles (▼). The blue box refers to the velocity profile presented in Fig. 4. The result of run 1 contains many artifacts, while the result of run 3 shows a very smooth model lacking in resolution and with a larger misfit than that of run 2.

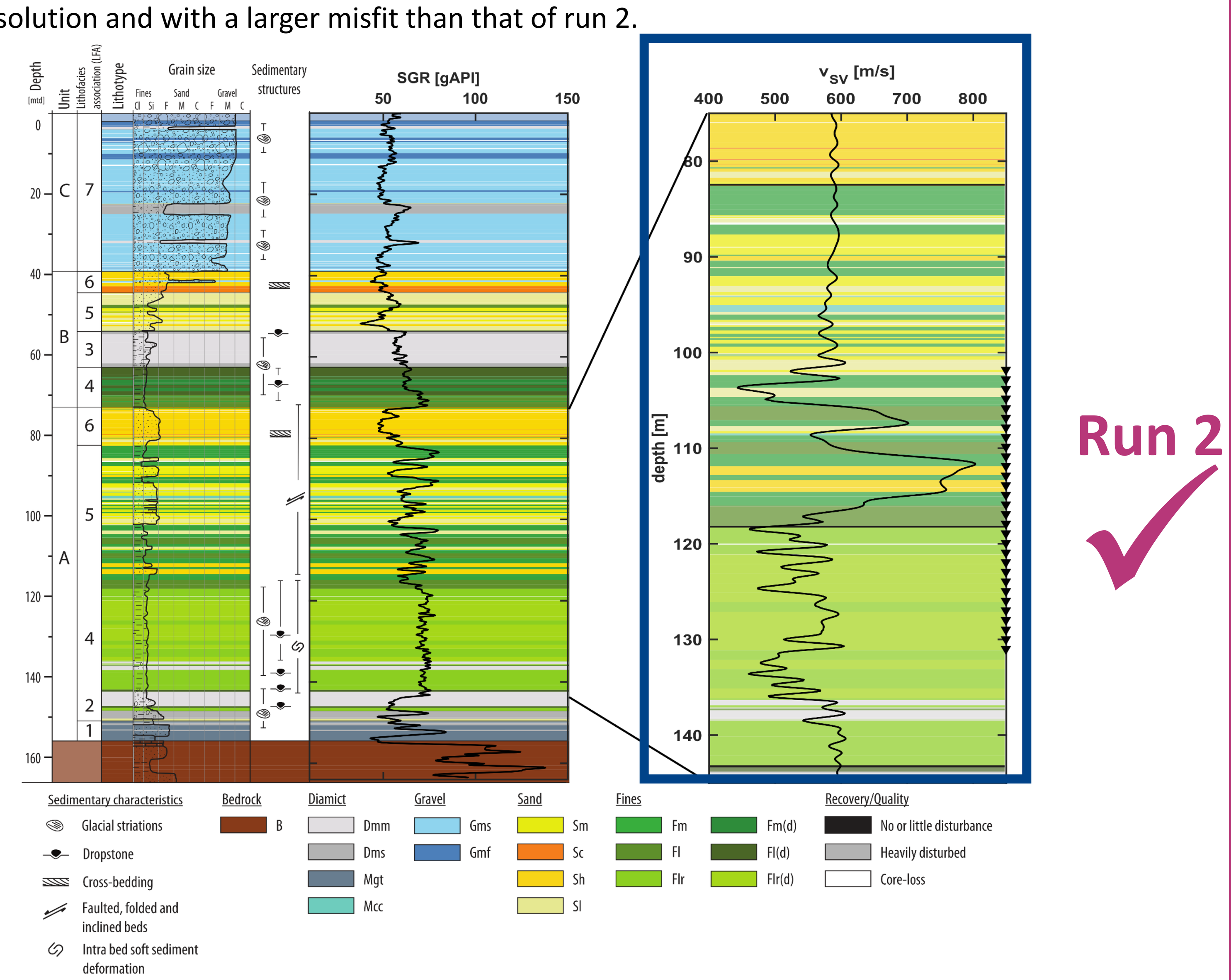


Fig. 4: The lithology obtained from the core of borehole C (Schuster et al., 2024; submitted), spectral gamma ray (SGR) from wireline logging, and v_{SV}-profile extracted along borehole C from run 2 FWI model (s. blue box Fig. 3) show an impressive correlation at the decimeter scale. Sandy layers, especially the horizontally bedded ones (Sh), appear as high-velocity zones in the inverted SV-wave velocity model. Outside the region of maximum coverage, i.e., above 105 m and below 134 m depth, the velocity variations are less well recovered.

4 FWI strategy

- Vertical component, mono-parameter v_{SV} FWI
- Homogeneous starting model using median apparent velocity
- Global correlation norm to mitigate source and receiver coupling effects
- Preconditioned quasi-Newton l-BFGS optimization with Hessian approximation according to Zhang et al. (2012) to accelerate convergence and save memory
- Source-time-function inversion: stabilized Wiener deconvolution performed in the frequency domain using the Newton method together with the Marquardt-Levenberg regularization (Jeong et al., 2012)
- Workflows:

Stage	f_{min} in Hz	f_{max} in Hz	Spatial gradient filter	Hori. corr. length	Vert. corr. length
1	80	100	Gaussian	2.5 λ	2.5 λ
2	80	150	Gaussian	2 λ	2 λ
3	80	200	Gaussian	1.5 λ	1.5 λ
4	80	250	Gaussian	**Run1:** 1.0 λ **Run 2+3:** 2.5 λ	**Run1:** 1.0 λ **Run 2+3:** 0.5 λ

- Run 3 additionally uses a 0.1 s time-window around the first S-wave arrival.

6 Evaluation of FWI results

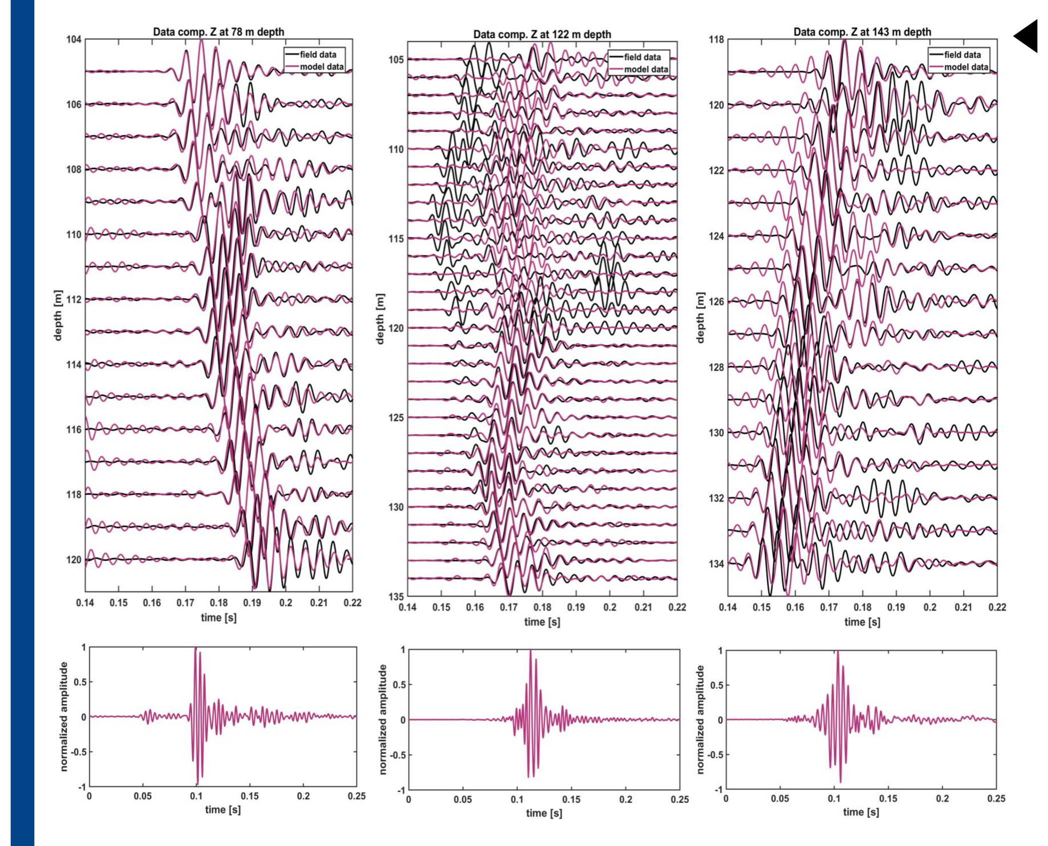


Fig. 5: Waveform fit after FWI run 2 in shot gathers (top) and the inverted source wavelets (bottom). The first SV-wave arrivals are fitted for the shallowest and deepest shot, while a later phase is fitted for shots at intermediate depths. This may indicate the presence of 3D effects that cause early arrivals in the field data and cannot be modeled by the 2D code.

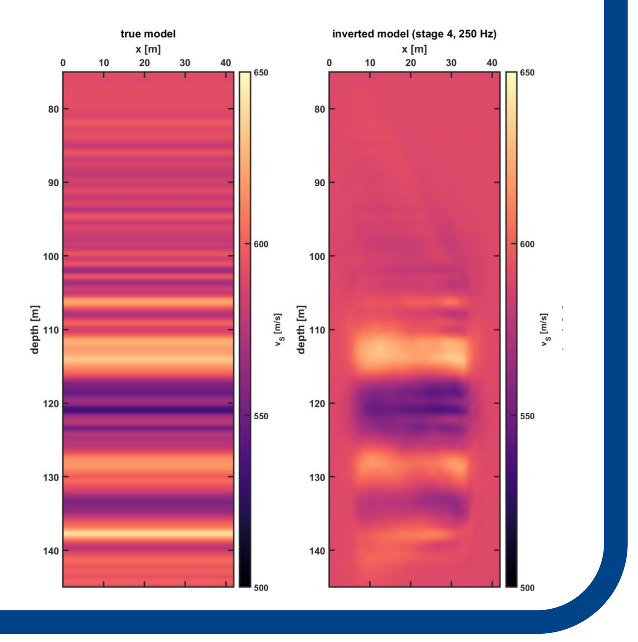


Fig. 6: Resolution test result (right) using the horizontally smoothed stage 4 SV-wave velocity model of FWI run 2 (left) shows that layers of less than 1 m thickness are resolved by the workflow in the region of maximum coverage between 105 and 134 m depth.

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