# Coherence-based GPR diffraction imaging and inversion

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# Why do diffractions matter?

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# Why do diffractions matter?



- Diffractions are caused by small-scale subsurface heterogeneities, e.g.:
  - [Seismics:] faults, pinch-outs, caves...
  - [GPR:] buried small objects, voids, water intrusions in glaciers...
- Diffracted waves imply superior illumination than reflected waves
- No offsets required for velocity estimation
- Methods from applied seismics can be adapted to GPR data

# From applied seismics to GPR

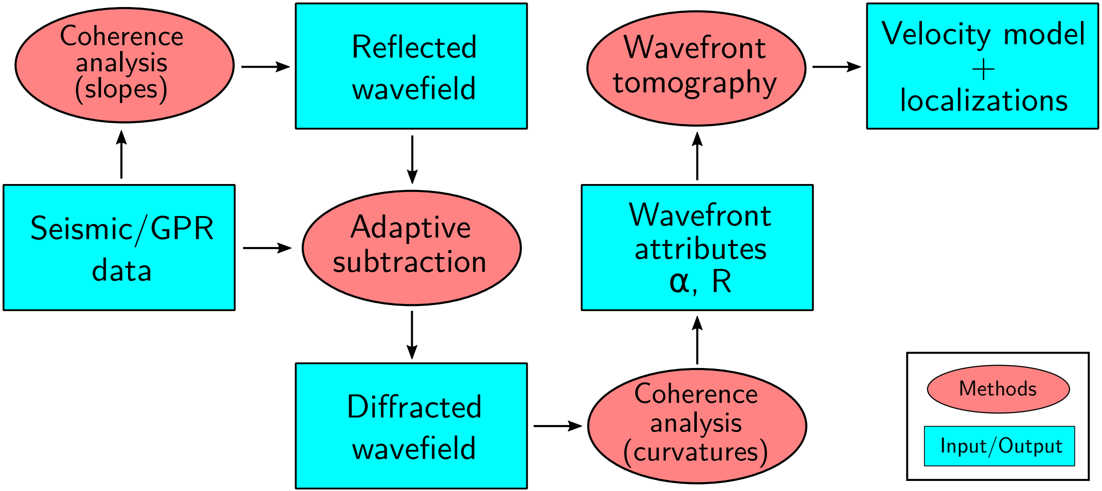
- The different scales have to be accounted for
- Typical magnitudes and units:

| | **Applied seismics** | **GPR** |
|---|---|---|
| **Distances** | $10^3$ m → [km] | $10^1$ m → [m] |
| **Traveltimes** | $10^0$ s → [s] | $10^{-7}$ s → [ns] |
| **Velocities** | $10^3$ m/s → [km/s] | $10^8$ m/s → [m/ns] |
| **Frequencies** | $10^1$ Hz → [Hz] | $10^8$ Hz → [MHz] |
| **Wavelengths** | $10^1$ m → [m] | $10^{-1}$ m → [cm] |

- Seismic velocities typically increase with depth, electromagnetic velocities decrease with depth

# Workflow




Coherence analysis (slopes)
Reflected wavefield
Wavefront tomography
Velocity model + localizations
Seismic/GPR data
Adaptive subtraction
Wavefront attributes α, R
Diffracted wavefield
Coherence analysis (curvatures)
Methods
Input/Output

# Wavefront attributes

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- Diffraction separation by coherent wavefield subtraction yields diffraction-only data [Schwarz, 2019]
- Automatic extraction of wavefront attributes ($\alpha$, $R$) from diffraction-only data via coherence analysis [Jäger et al., 2001]
- Hyperbolic second-order approximation of diffraction traveltime moveout

$$\Delta t^2(x_0, t_0) = \left(t_0 + 2 \underbrace{\frac{\sin\alpha}{v_0}}_{\text{slope}} \Delta x\right)^2 + 2t_0 \left(\underbrace{\frac{\cos^2\alpha}{v_0 R}}_{\text{curvature}} \Delta x^2\right)$$

with $\alpha$: emergence angle of diffracted wavefront, $R$: wavefront radius, $t_0$: zero-offset two-way time, $v_0$: near-surface velocity

# Wavefront tomography: image space

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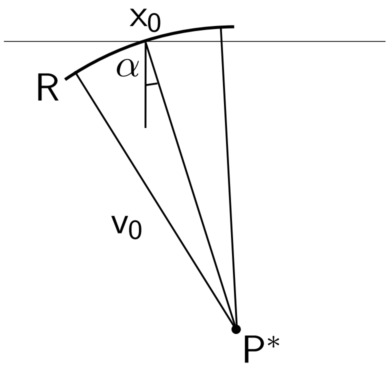
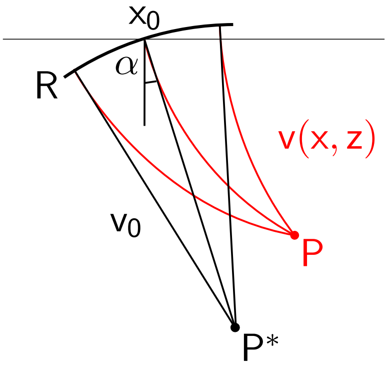



- Efficient and stable inversion scheme for smooth depth-velocity models [Duveneck, 2004, Bauer et al., 2017]
- Initial localizations $P^*$ of data points obtained by downward kinematic ray tracing starting from $(x_0, \alpha)$ into constant initial model $v(x, z) = v_0$ (image space) until $t_0/2 = T_0 = 0$
- Initial localizations are quite stable because they do not depend on second-order curvature attribute $R$

# Wavefront tomography: model space






- Upward dynamic ray tracing starting from $P^*$ yields modeled attributes $(x_0, T_0, \alpha, R)$
- Goal: Find velocity model $v(x,z)$ such that $P^* = P$, i.e. the true scatterer locations

# Wavefront tomography: inverse problem



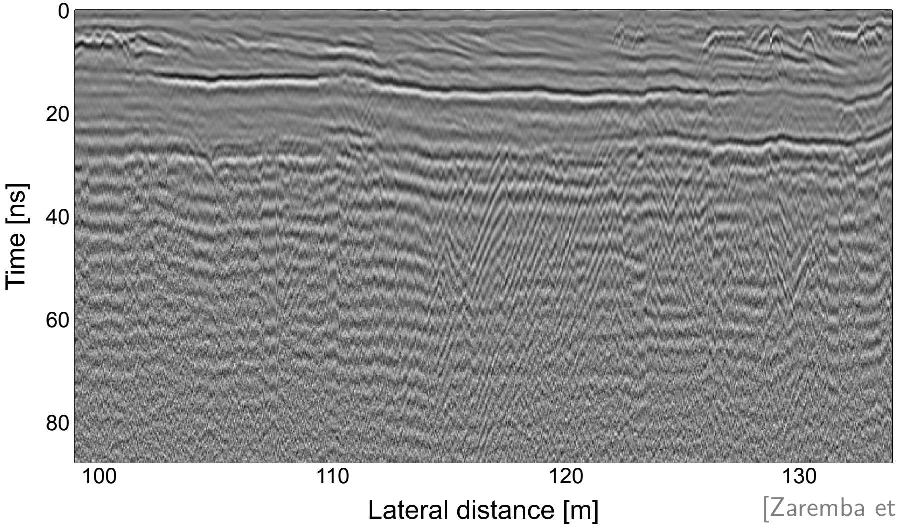
- Data parameters $\mathbf{d}$: $n$ automatically picked data points $(x_0, T_0, \alpha, R)_i$
- Velocity model is defined by B-spline functions on given grid of $n_x \times n_z$ knots
- Model parameters $\mathbf{m}$: B-spline velocity coefficients and ray start points $(x, z)$
- Minimize misfit between measured data $\mathbf{d}$ and modeled data $\mathbf{d}_{mod} = \mathbf{f}(\mathbf{m})$ by damped weighted least-squares

$$\Psi(\mathbf{m}) = \frac{1}{2}\left\|(\mathbf{d} - \mathbf{d}_{mod})\,\mathbf{W}\right\|_2^2 + \Lambda\left[\partial_{xx}v(x,z), \partial_{zz}v(x,z)\right]$$

- Output: smooth velocity model $v(x, z)$ and localizations of data points
- The method is equally applicable in 3D

# GPR data from Long Beach Island, New Jersey






[Zaremba et al., 2016]

# Long Beach: separation and attributes

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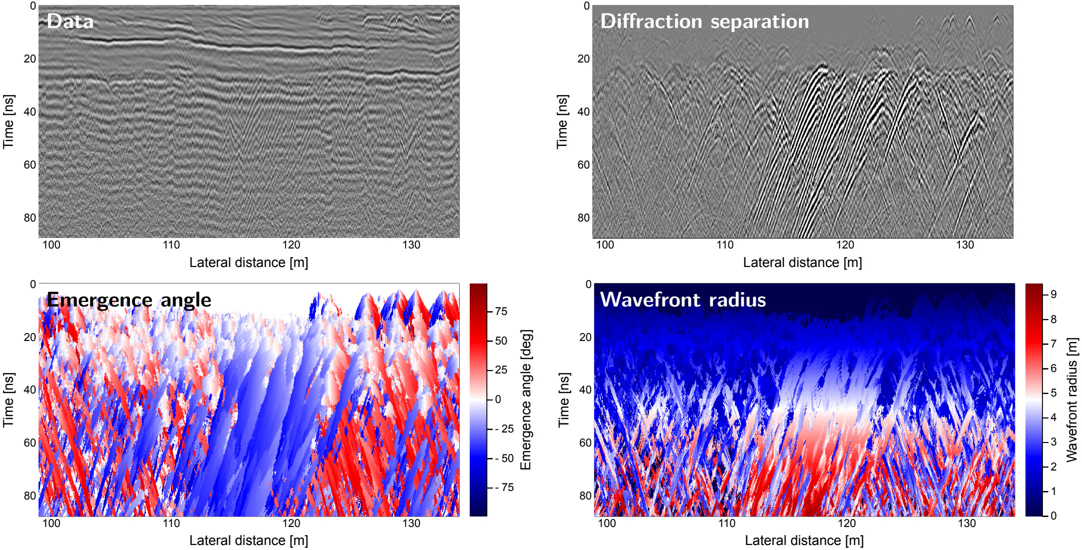
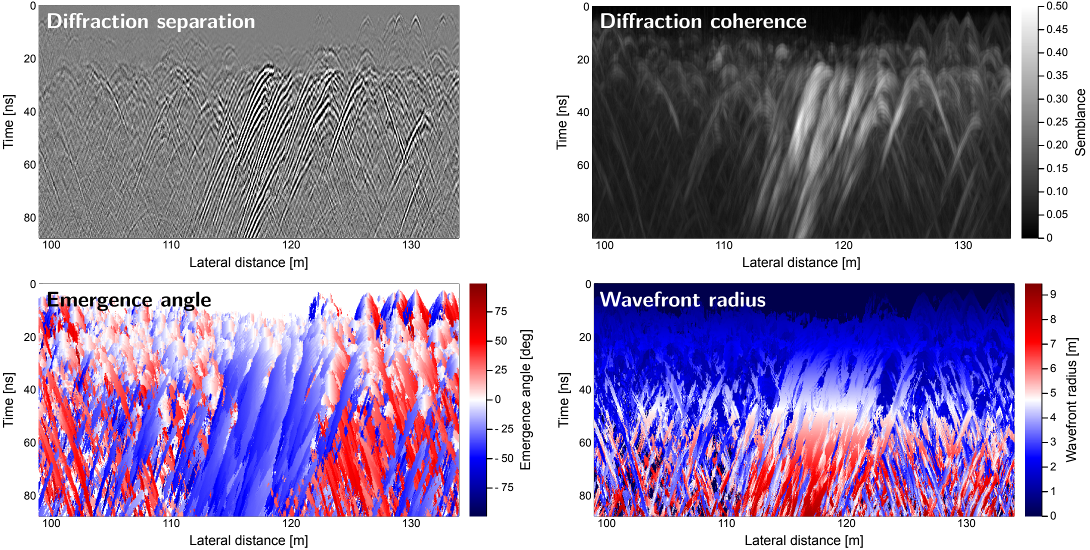
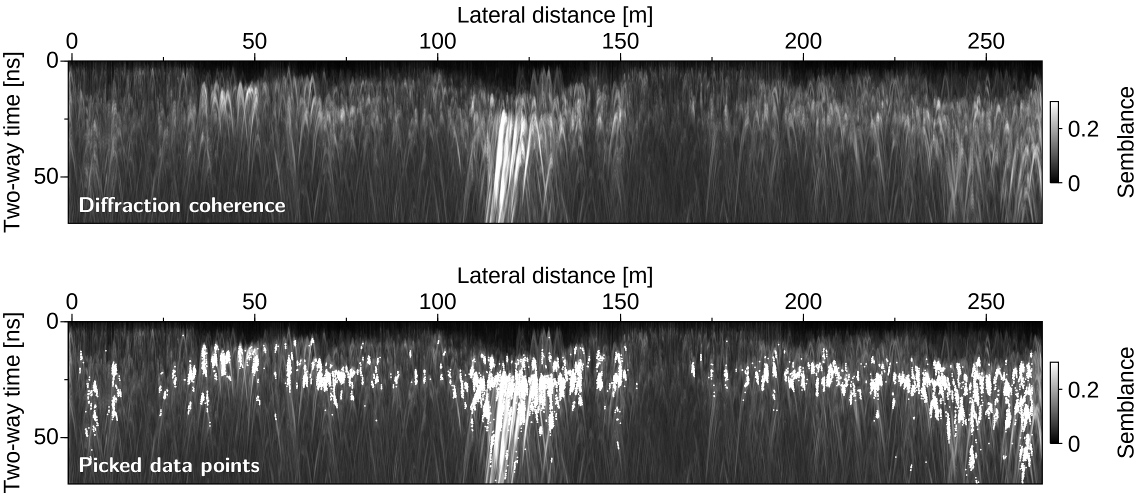


# Long Beach: separation and attributes

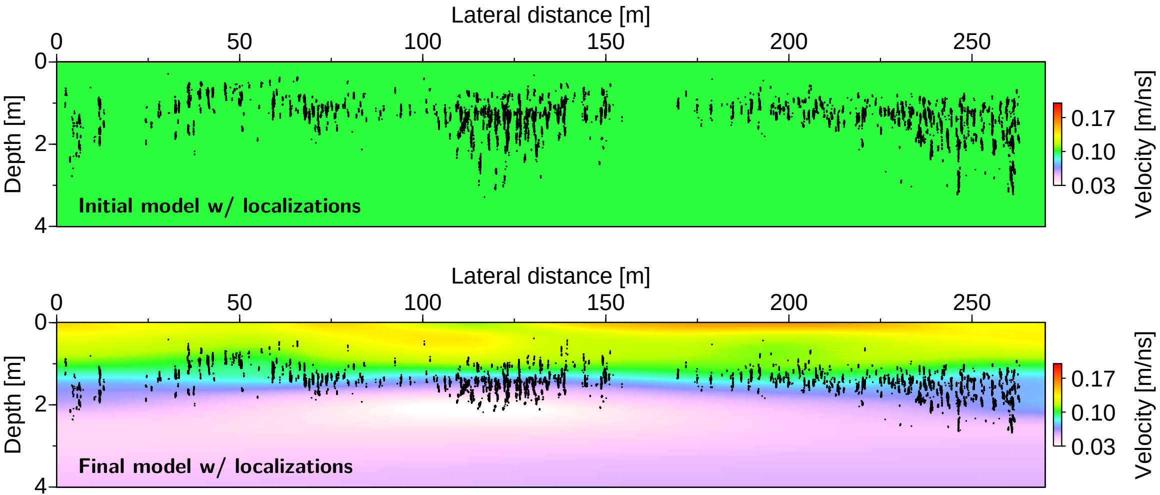




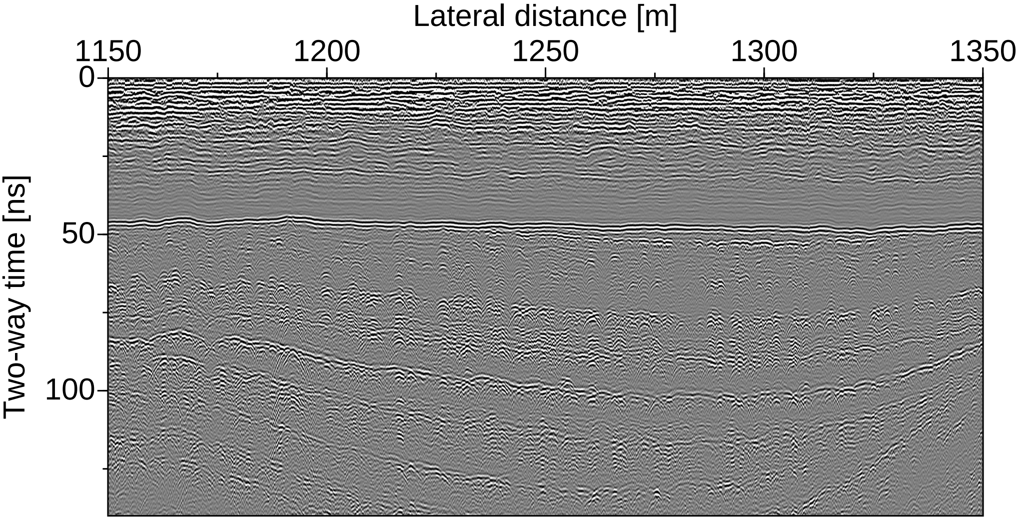
# Long Beach: inversion



# Long Beach: inversion

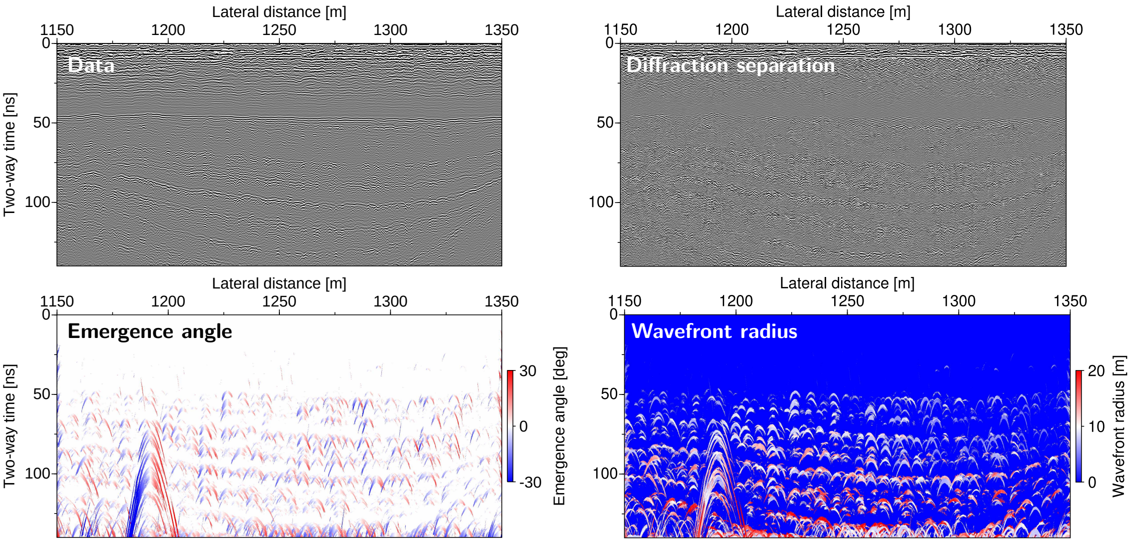


# GPR data from Wolverine glacier, Alaska

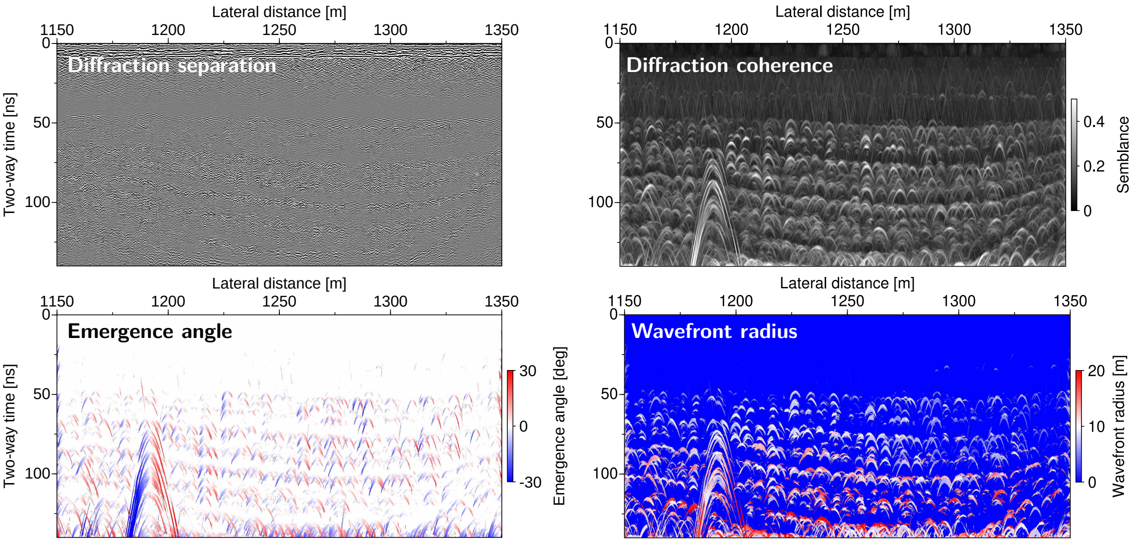



[O'Neel et al., 2018]

# Wolverine glacier: separation and attributes



# Wolverine glacier: separation and attributes



# Wolverine glacier: inversion

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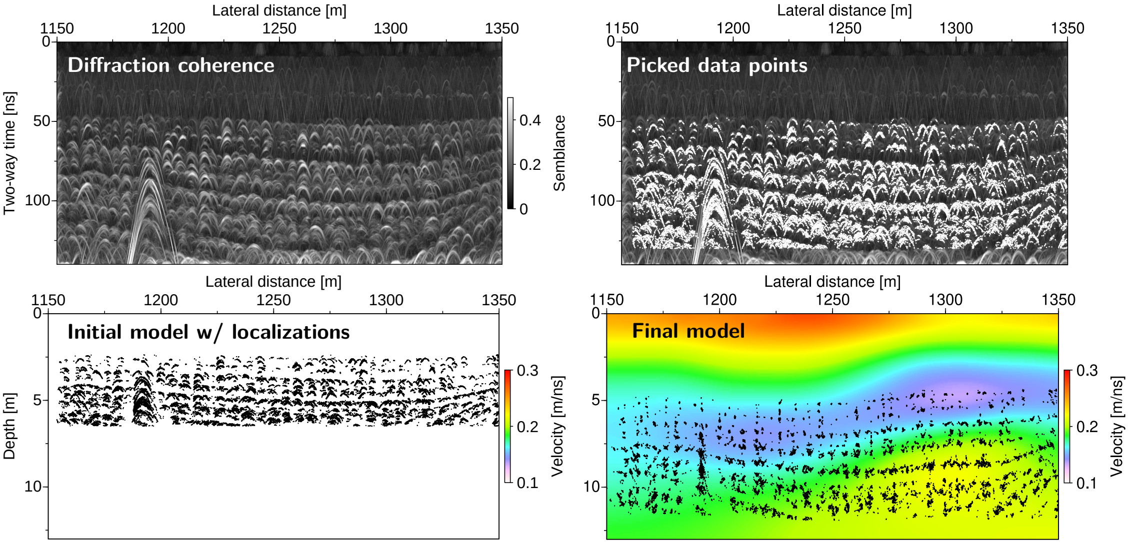

# Conclusions



- Diffraction separation and imaging and automatized depth-velocity model building for GPR data
- Joint localization of scatterers
- Applicable to all seismic and GPR data with rich diffracted wavefield
- No offsets required
- Workflow equally applicable in 3D
- Estimation of second-order wavefront attributes can be challenging
- 2D applications may be affected by out-of-plane scatterers

# Outlook

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- Applications to different GPR datasets [Bauer et al., 2020a, Klahold et al., 2022]
- Applications to zero-offset/low-fold seismic data (P-Cable data, vintage academic data) [Bauer et al., 2020b, Preine et al., 2020]
- Passive-seismic applications [Diekmann et al., 2019]
- Improved diffraction separation [Schwarz, 2019]
- Unsupervised identification and tagging of diffractions [Bauer et al., 2019b]
- Enforced focusing of diffractions during the inversion [Bauer et al., 2019a]
- Applications in 3D [Bauer et al., 2020b]
- Diffraction separation with convolutional neural networks [Bauer et al., 2021]

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  [O'Neel et al., 2018, Zaremba et al., 2016]
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