Converted-Wave Reverse Time Migration Imaging in Subduction Zone Settings

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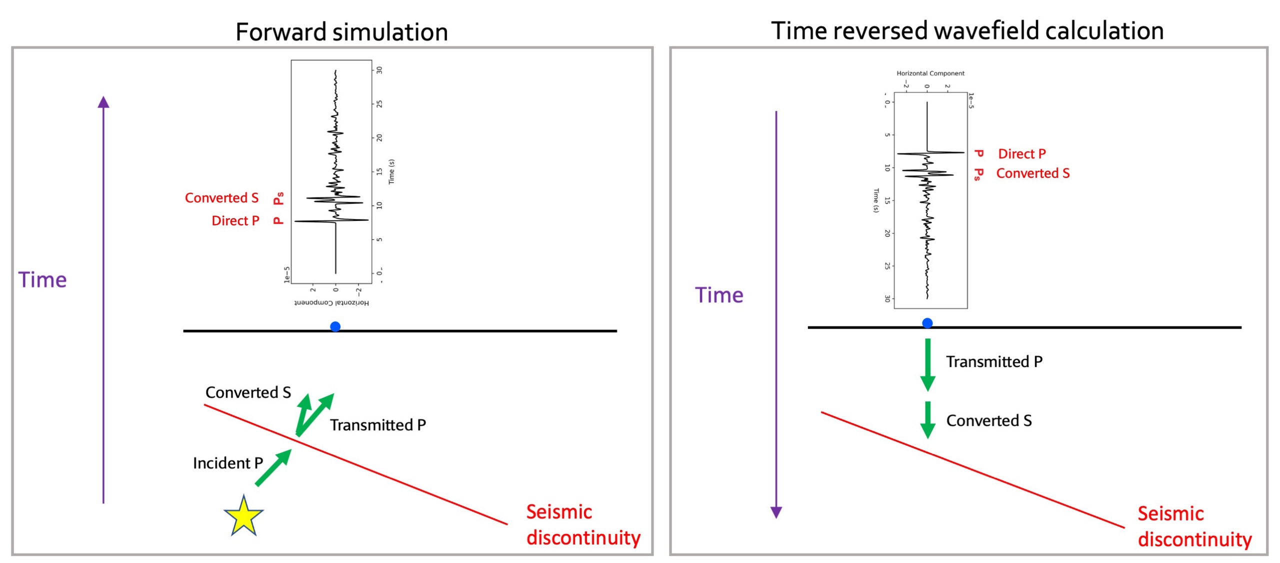
ABSTRACT

We use a newly developed 2D elastic reverse time migration (RTM) imaging algorithm based on the Helmholtz decomposition to test approaches for imaging the descending slab in subduction zone regions using local earthquake sources. Our elastic RTM method is designed to reconstruct incident and scattered wavefields at depth, isolate constituent P and S wave components via Helmholtz decomposition, and evaluate normalized imaging functions that leverage dominant P and S signals. Through tests on synthetic data using either S to P or P to S conversions, we find that our technique can successfully recover the structure of a subducting slab using data from a dense wide-angle array of surface stations. We also demonstrate that our method successfully recovers the topographic shape of the surface of a subducting slab and yields high-resolution information even when the starting model is highly smoothed and does not include topography.

Method: converted wave RTM imaging

How can one obtain a sharp image of a seismic discontinuity? Our technique: Backpropagate seismograms and see where converted S and direct P waves interfere constructively. This is the location of the discontinuity where the conversion occurred.



Prior attempts to formalize converted wave imaging have had issues with SNR. We overcome these issues through (1) increasing signal amplitude by cross correlating only the components of direct P and converted S that are expected to have large amplitudes and (2) decreasing artifacts by windowing seismic data prior to backpropagation to prevent undesired interference from other seismic phases. We also normalize by the ray parameter to remove dependence on the seismic wavefield.

Ray parameter normalization   Converted S wavefield   Direct P wave

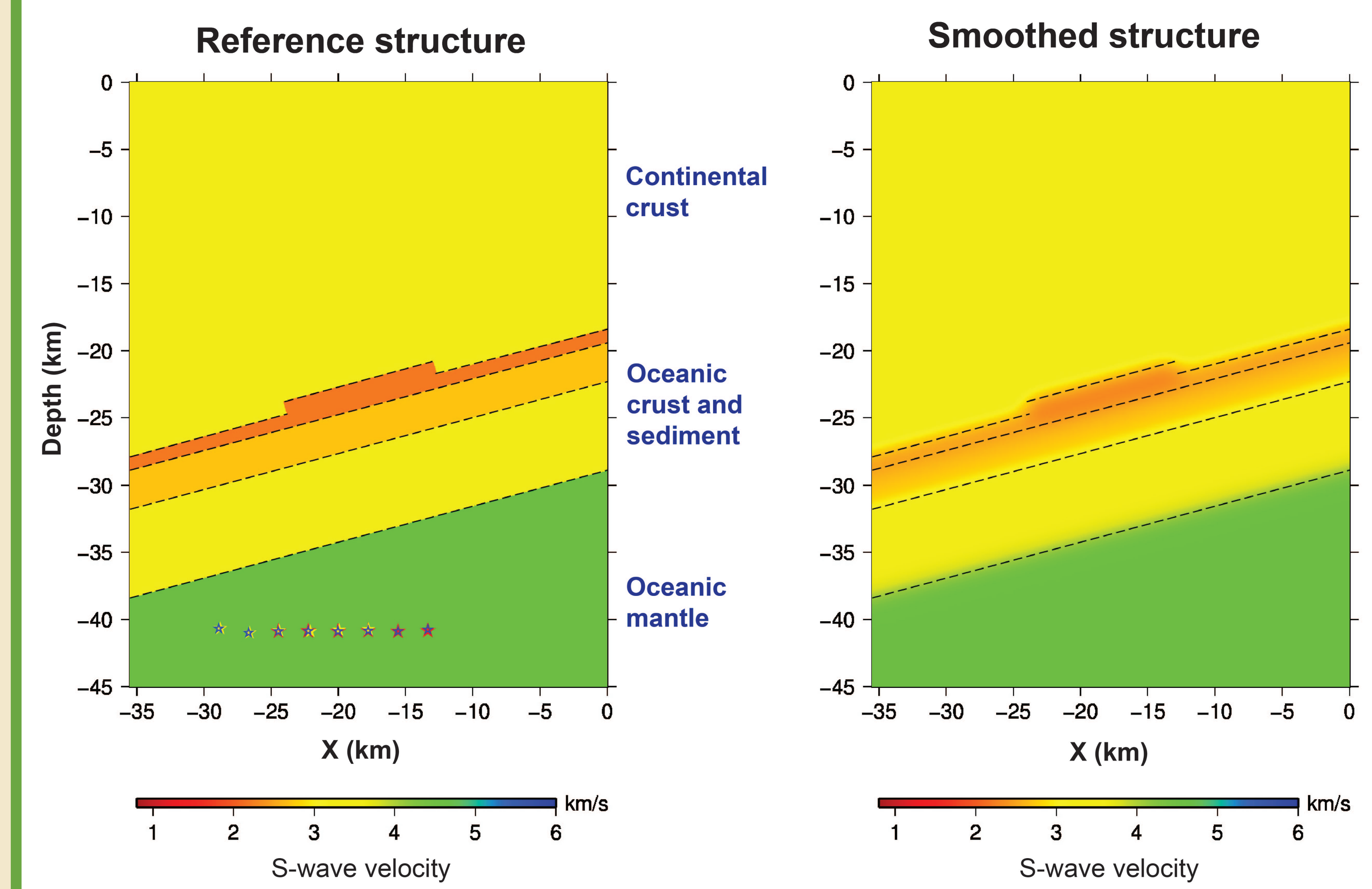
$$I_{P\to S}(\xi) = \frac{1}{\alpha(\xi)\sum_j p(\xi,j)} \sum_j \frac{\int_0^T \left(\partial \mathbf{u}_j^{\dagger}(\xi,t)\cdot \hat{\mathbf{t}}\right)_S \left(\mathbf{u}_j^{\dagger}(\xi,t)\cdot \hat{\mathbf{n}}\right)_P dt}{\int_0^T \left(\mathbf{u}_j^{\dagger}(\xi,t)\cdot \hat{\mathbf{n}}\right)_P^2 dt}$$

Normalization by squared magnitude of direct P wave

To calculate our imaging function, we must separate the backpropagated seismic wavefield into its constituent P and S components via the Helmholtz decomposition.

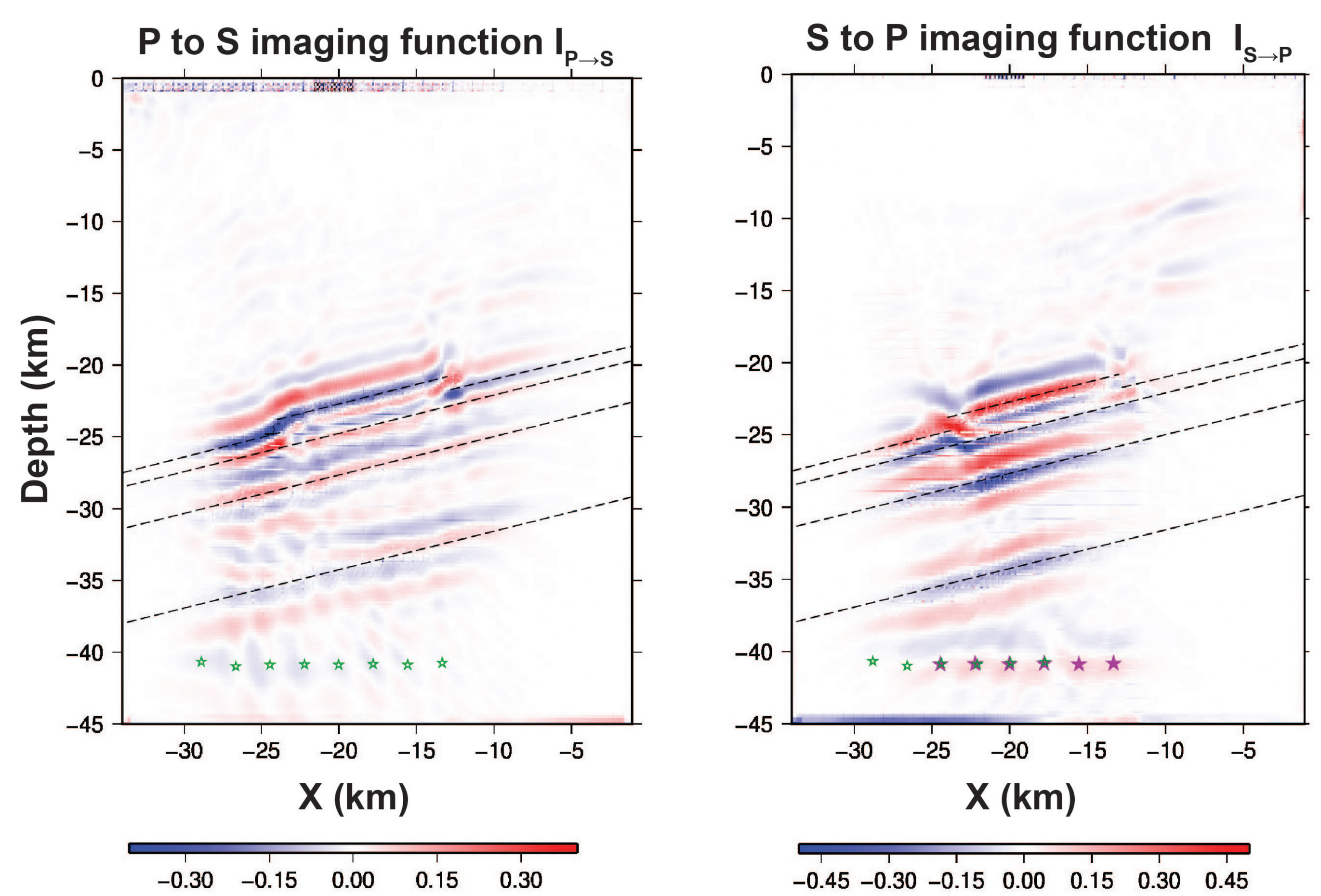
$$(\mathbf{u})_P = \alpha^2 \nabla(\nabla\cdot\mathbf{u})$$
$$(\mathbf{u})_S = -\beta^2 \nabla\times(\nabla\times\mathbf{u})$$

Imaging a 2D synthetic subduction zone



Procedure for constructing imaging functions:

1. Seismograms from each earthquake source (locations at stars) are calculated at 132 stations that cover the surface of the domain with the reference velocity model
2. Seismograms from each earthquake are backpropagated in a domain with the smoothed velocity model
3. Compute the Helmholtz decomposition of the backpropagated wavefield
4. The decomposed P and S wavefields are used to calculate the imaging function
5. Imaging functions from all earthquakes are stacked and normalized



Our method successfully recovers all of the important boundaries in the subduction zone structure using either Ps or Sp converted waves.

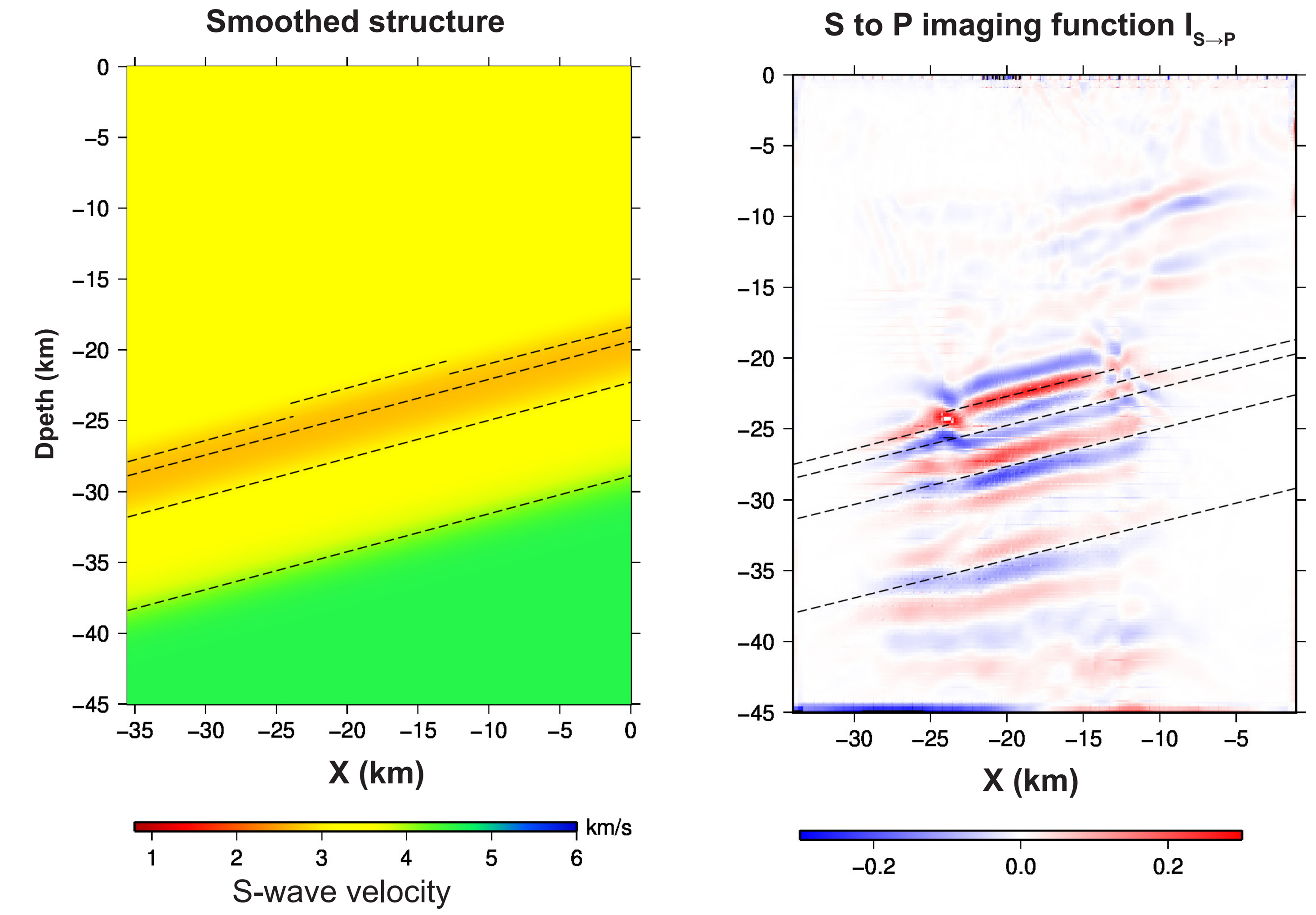
We can interpret these images using the equation below, which shows that the imagign function depends on the change in shear velocity and density across a boundary.

$$(\alpha p)^{-1}\frac{\acute{P}\acute{S}}{\grave{P}\grave{P}} = \frac{1}{2}\left[-\left(1-2\frac{\beta}{\alpha}\right)\frac{\Delta\rho}{\rho} + 4\frac{\beta}{\alpha}\frac{\Delta\beta}{\beta}\right]$$

Imaging example with a poor starting model

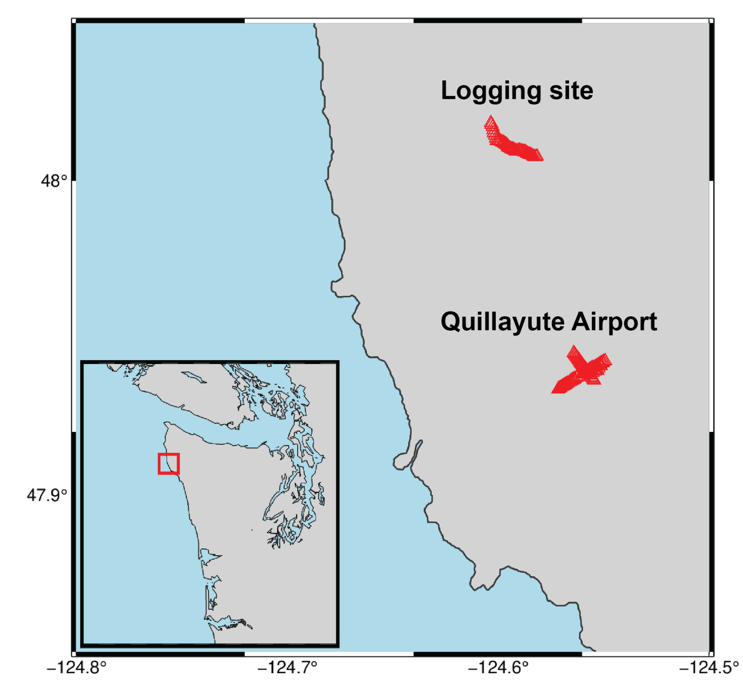
We investigate the ability of our method to recover high-resolution structure given a very low-resolution starting model. The velocity model shown here has been highly smoothed, and the topography on the surface of the subducting slab has been removed. The recovered S to P image is quite similar to the one shown in the previous panel for the upper seismic discontinuity; it is able to recover a high-resolution image of the topographic shape of the slab without any prior knowledge of this structure.

The lower discontinuities are also well resolved, but directly beneath the topographic 'bump' in the slab, they are imaged slightly too deep. This is expected because the backpropagated wavefields are traveling too quickly due to the thinner low-velocity layer in that location.

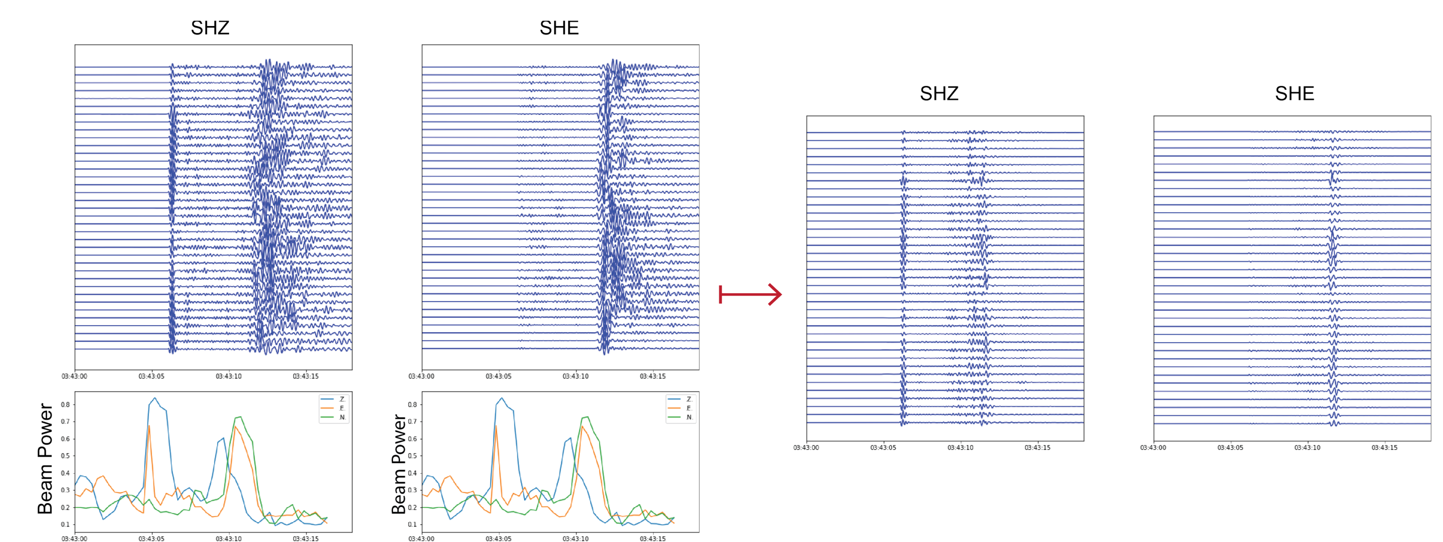


Imaging the Cascadia SZ: Field work in Forks, WA

We wish to provide a constraint on the downdip extent of locking in the Cascadia SZ by recovering high-resolution images of the subducting slab along dip. In the ETS zone, there already exists a seismic dataset which is appropriate for our technique: the Array of Arrays dataset, collected via an Earthscope array that was installed in 2009 (Ghosh et al. 2009). We collected a complementary dataset in the locked zone.



98 seismic nodes were deployed near Forks, WA from August 2021 - December 2021. This location was chosen because the locked zone comes onshore here and there is local seismicity at depths below the overriding plate. The seismometers were deployed at a logging site and at the Quillayute Airport.



These record sections show data collected by our arrays during a M2.2 earthquake that occurred at 29km depth in Oregon on August 31, 2021. The upper panel on the left shows the original data. The panels on the right show seismograms that have been windowed using the beam power to isolate the phases of interest so that we can produce clean backpropagated wavefields.

Acknowledgements

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