Recovery of body-wave reflections from ambient seismic noise with application to mineral exploration

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Introduction

Keeping pace with the global demand for metals and minerals requires the ongoing discovery of new ore deposits. The typical procedure for mineral exploration begins with magnetic or gravity surveys followed by a drilling program to investigate potential targets. In some cases, active seismic is used as an intermediary imaging step, but the sources (e.g. vibrating trucks or explosive shots) are expensive and difficult to operate in remote or environmentally sensitive areas.

In recent years, ambient seismic imaging using dense surface arrays has emerged as a low-cost and environmentally sensitive approach for exploring the sub-surface. This technique dispels with active seismic sources by exploiting weak coherencies in the multiply scattered background wavefield through the cross-correlation and stacking of waveforms recorded at spatially separated stations.

Under suitable noise conditions, a sub-surface reflector should create an arrival in a station-pair's cross-correlation function (CCF) at a lag time equal to the traveltime of the reflected ray traveling from one station to the other. These arrivals are expected to be extremely weak, however, and will need to be enhanced via double-beamforming methods. The resulting arrival waveforms will then be migrated into space to localize the sub-surface reflectors.

Dataset

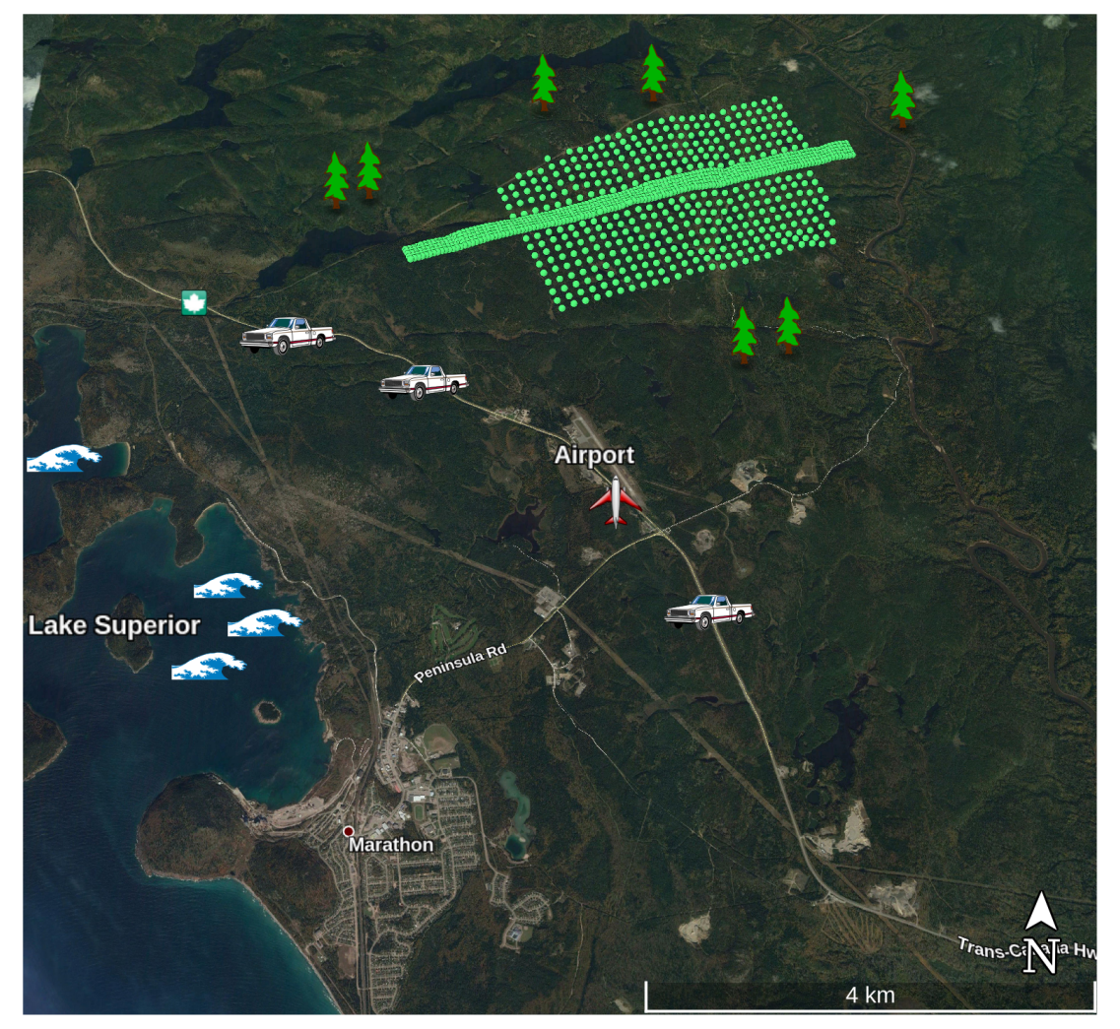

Figure 1: Surface array and noise sources.

Our dataset consists of 30 days of continuous recordings on a 1019 node surface array deployed over an exploration block near Marathon, Ontario. The potential targets of interest are high concentrations of Cu-PGM (platinum group metals) hosted in a gabbro intrusion. We expect these to occur as lenses and irregular bodies up to 200m in strike length and 25m thick.

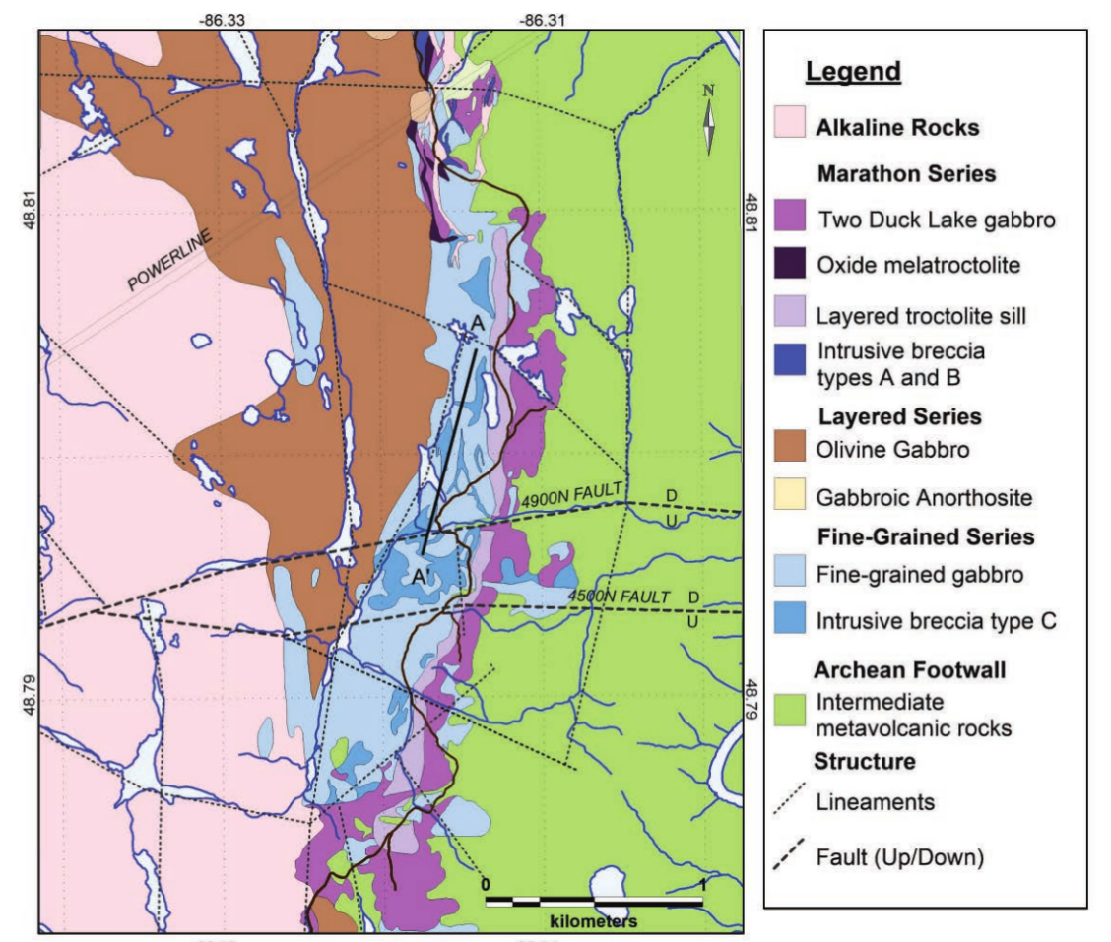

Figure 2: Local geology - reproduced from Good et al. (2015).

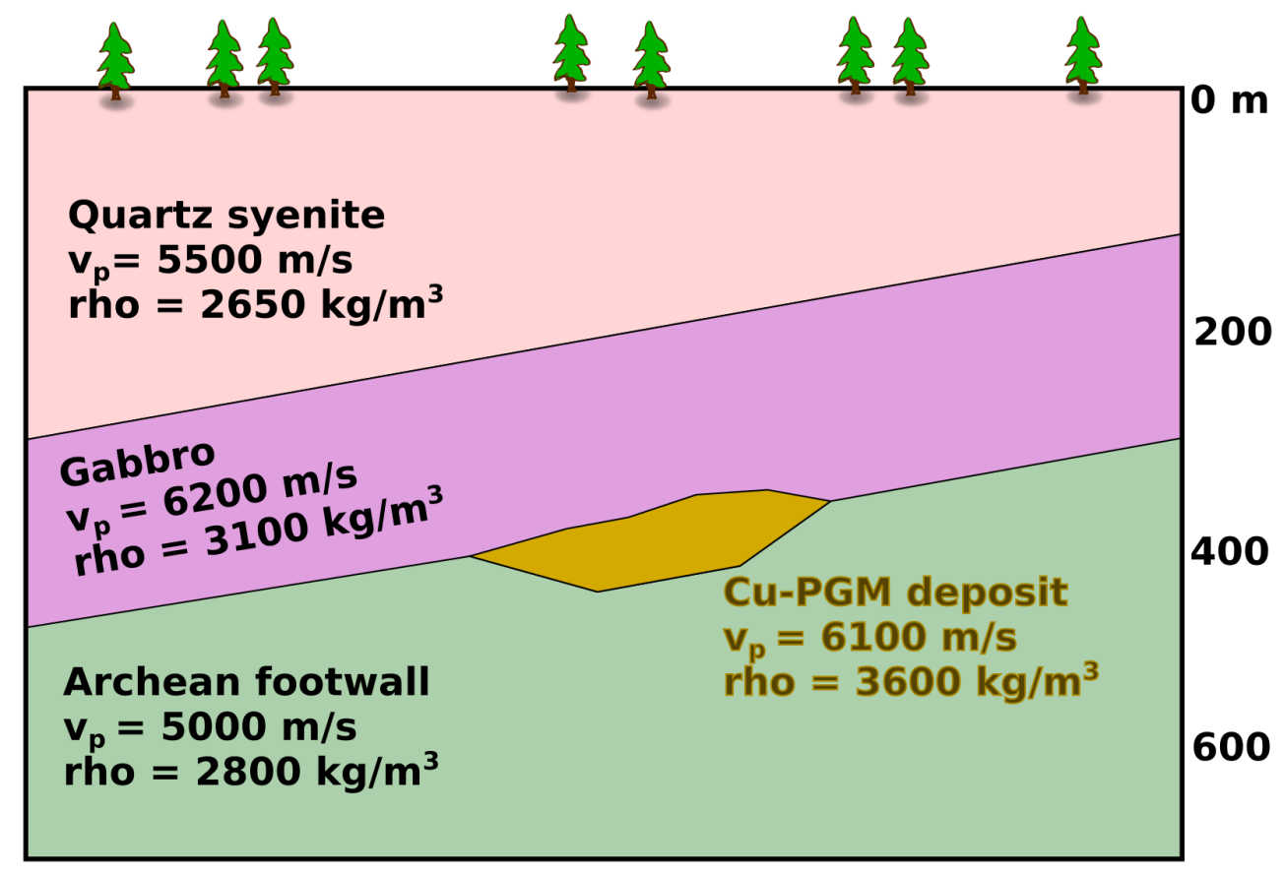

Figure 3: Cartoon depiction of ore-body geometry.

Seismic reflection theory

The ability to detect a deposit is determined by the impedance contrast (ore versus the surrounding rock) and the geometry of the deposit (size and depth of burial) relative to the source frequency (Salisbury and Snyder, 2007).

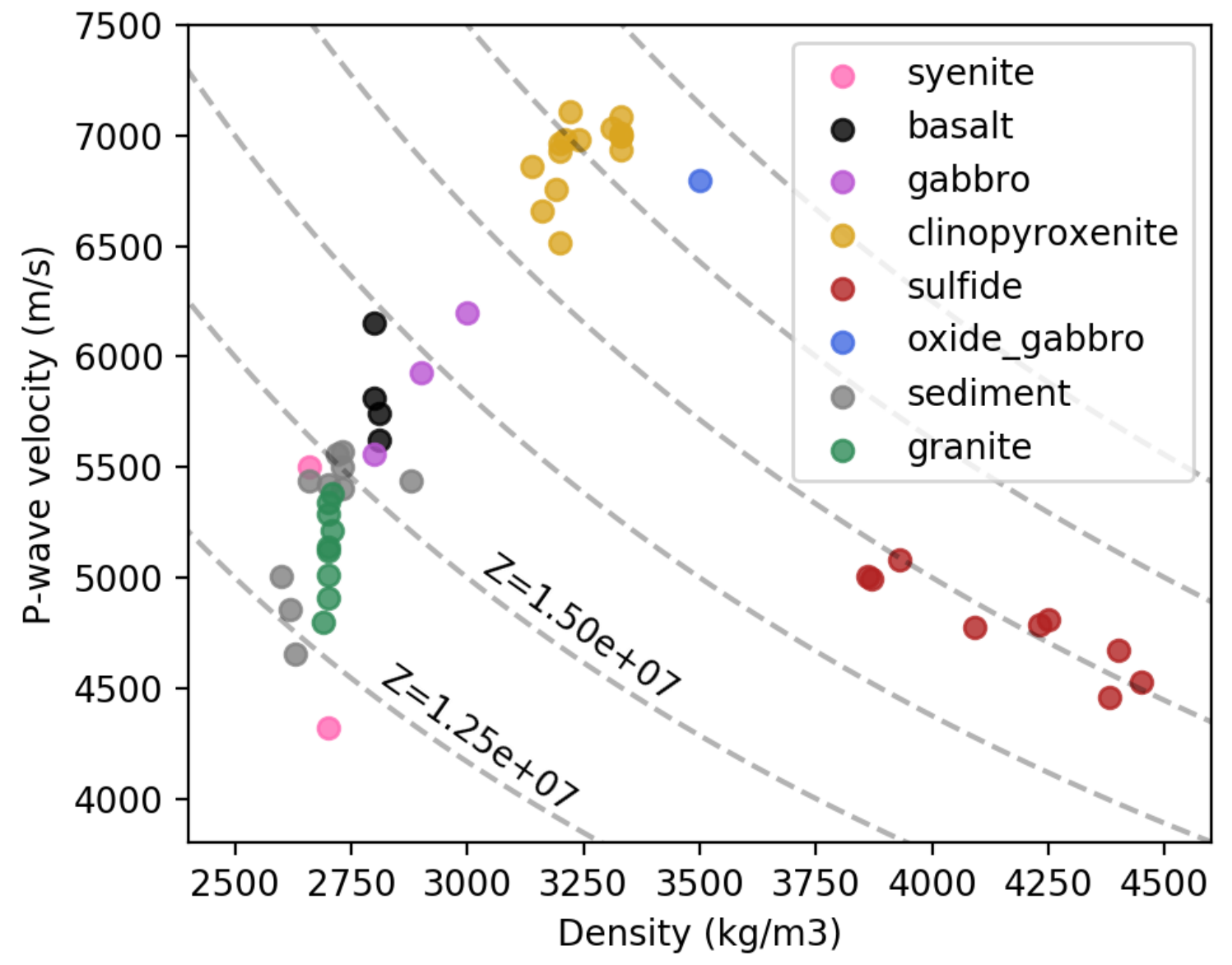

Figure 4: Density and P-wave velocity for common rocks.

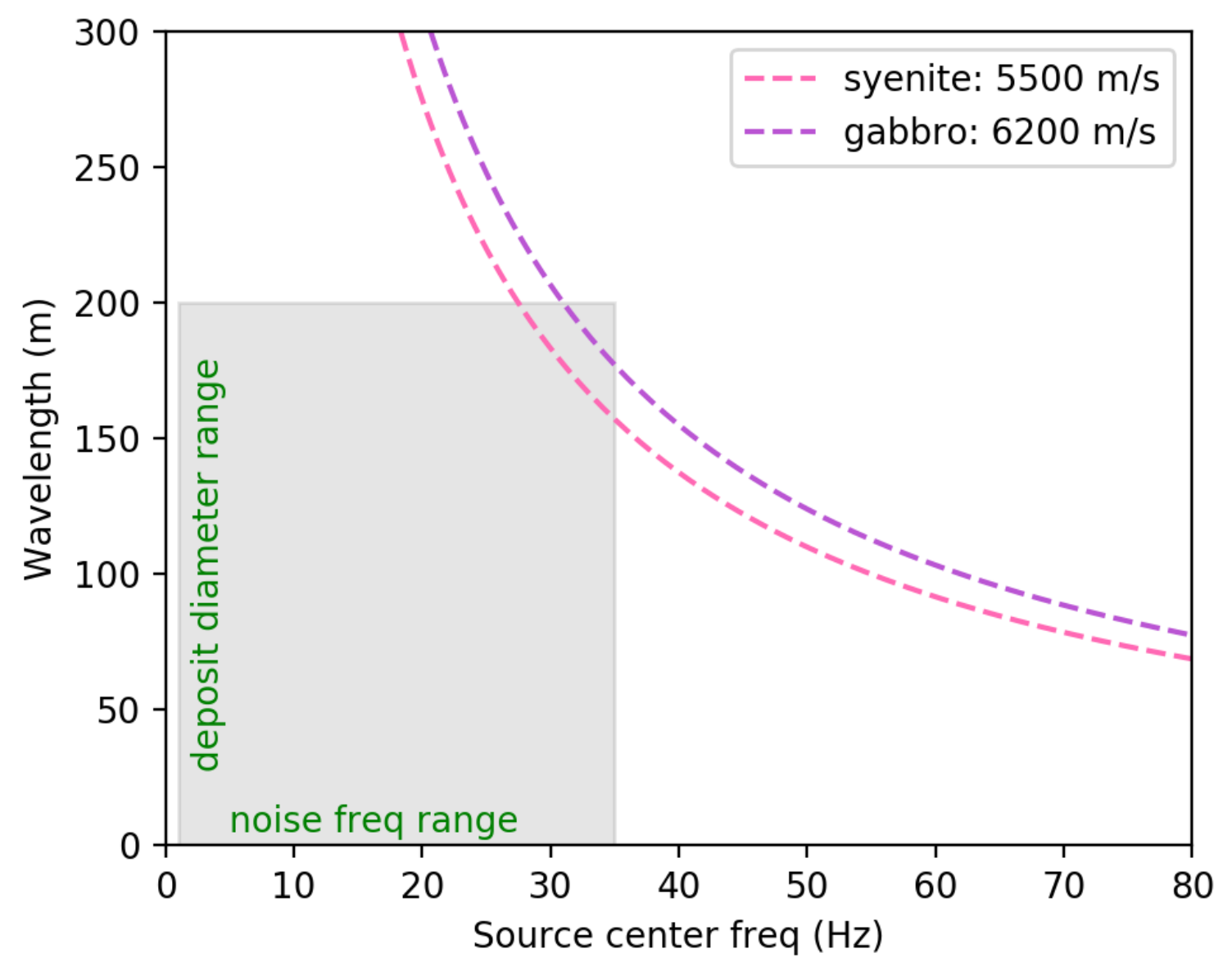

Figure 5: Wavelengths for different rocks with our expected parameter range shaded.

The portion of reflected energy is described by

$$reflection\_coeff = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

where $Z = vp$ is the material's impedance property. The impedance difference between adjacent contours corresponds to a 0.07 reflection coefficient.

Vertical resolution is controlled by the the Rayleigh limit, which gives the minimum resolvable thickness for a tabular deposit:

$$min\_thickness = \frac{v}{4f}$$

where v is P-wave velocity of the deposit and f is the source frequency.

Horizontal resolution is dictated by the width of the first Fresnel Zone, which gives the minimum diameter of a deposit that can be imaged as a surface rather than a diffractor:

$$min\_diam\_surface = \sqrt{\frac{2zv}{f}}$$

In our case, where the diameter of the deposits will be less than or equal to the wavelength, we expect only to be able to image them as diffractors.

Ambient noise cross-correlation

Ambient noise processing involves computing and stacking inter-station correlations over long time periods to recover estimated Green's Functions (Shapiro and Campillo, 2004).

We expect the primary sources of ambient noise will be waves in Lake Superior, trucks on the nearby highway and wind-induced tree oscillations. For this study we are primarily interested in the body waves that are reflected off geological boundaries. These arrivals will be the weakest and therefore the most difficult to extract.

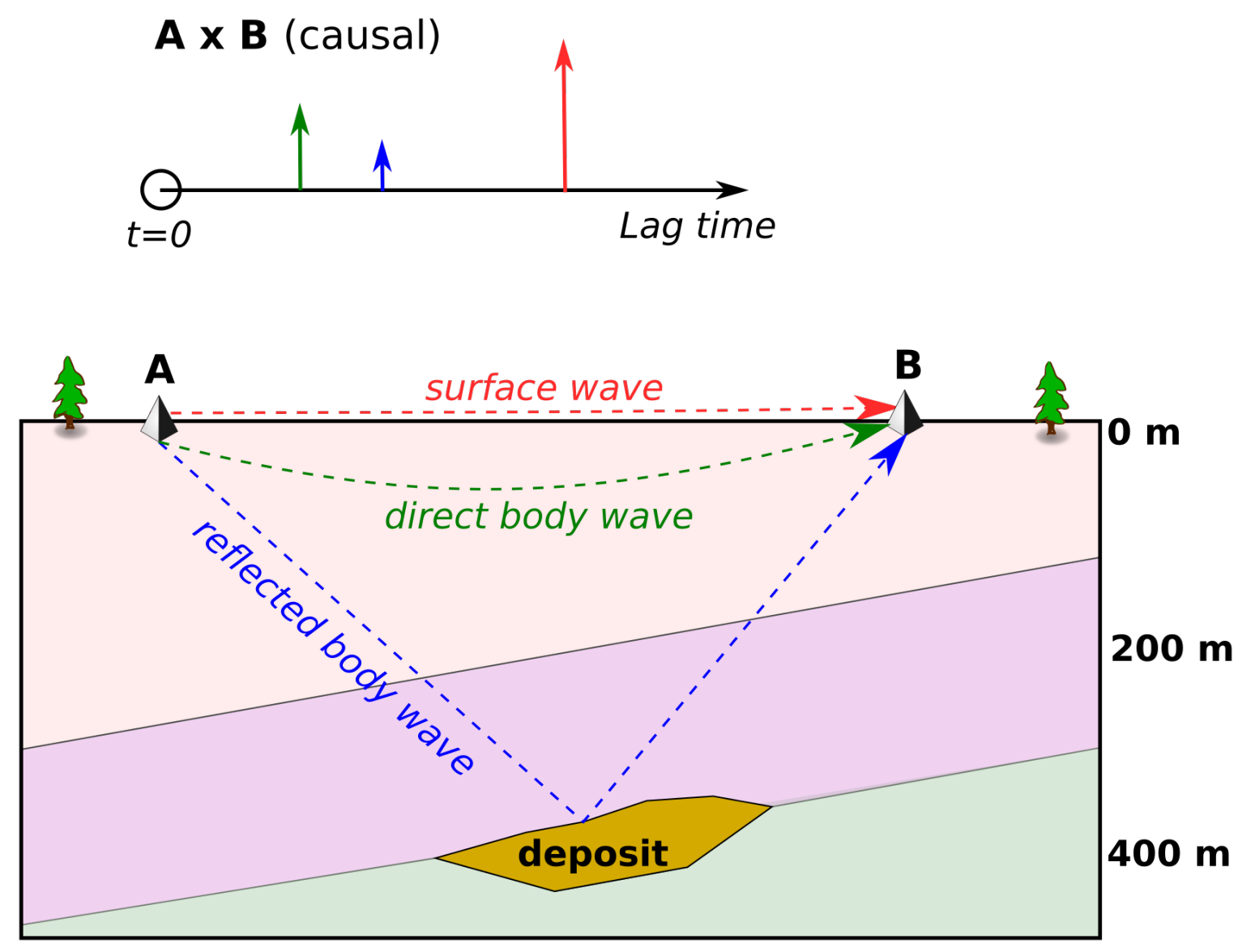

Figure 6: Expected times and amplitudes for the different arrivals in a given CCF.

Double-Beamforming

To isolate the weak arrivals from reflected body-waves, we divide the array into many small sub-arrays and use a double-beamforming method to effectively 'steer' pairs of these sub-arrays towards a common potential reflector location. The steering process involves time-shifting and stacking the raw station waveforms within each sub-array based on travel-times to a target location.

This results in one CCF per sub-array pair which are then used to localize the dominant reflectors through regular cross-correlation beamforming.

The drawback of this method is the high computational cost of re-computing all CCF's in the 30-day period for each potential reflector location.

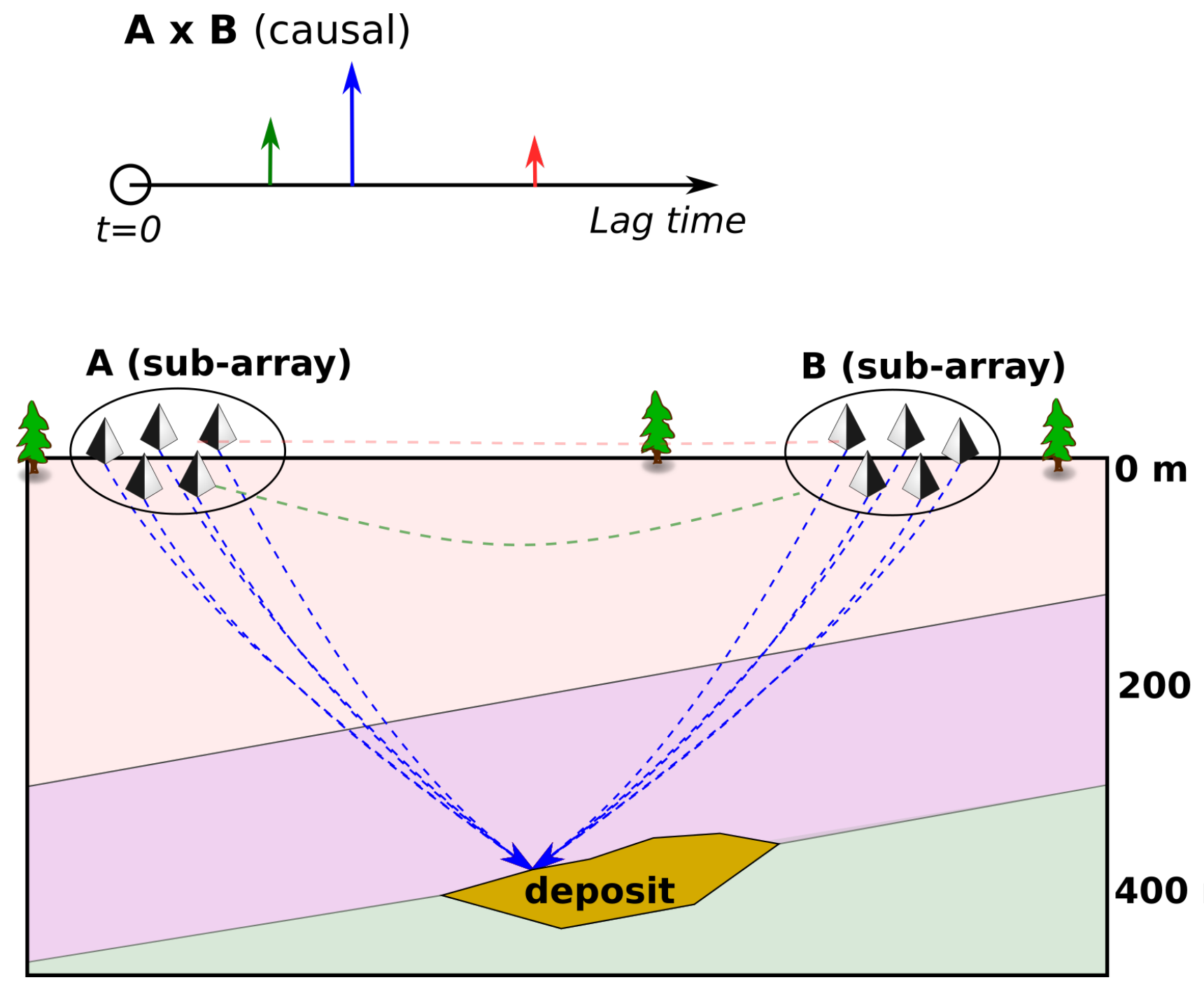

Figure 7: Double-beamforming involves steering sub-arrays towards each potential reflector location resulting in a single CCF per sub-array pair in which the reflected body-wave has been enhanced.

Going forward

1. Develop the double-beamforming reflection technique using synthetic data with perfect ambient noise conditions
2. Determine best methods for removal or reduction of coherent surface wave energy
3. Understand and quantify properties of the real ambient noise
4. Introduce this realistic noise into our synthetic model to understand the limitations it imposes
5. Apply our processing method to the real dataset

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