Deep sediment heterogeneity from very low-frequency features from merchant ships

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Introduction

The very low-frequency (VLF) noise from merchant ships provides a wideband source to study the deep layers of the seabed. The nested striations which characterize ship spectrograms contain unique acoustic features (singular points) where the waveguide invariant (β) becomes infinite. In the New England Mudpatch, this occurs at frequencies between 20 and 80 Hz where pairs of modal group velocities are equal. These $\beta = \infty$ frequencies in ship noise spectrograms are independent of source-receiver range, ship speed, and source-receiver depth. They can be used to perform statistical inference for the deep layer sound speeds and thicknesses.

Experiment

The Seabed Characterization Experiment (SBCEX) of 2022 on the New England continental shelf had three vertical line arrays (Scripps:MPL VLA 1 and 2 and ARL:UT PROTEUS) strategically placed between two shipping lanes. The average water depth was 75 m with about 1 m bathymetry change between the VLA's. VLA1 and VLA2 were deployed at this location for three days; however, PROTEUS was deployed for 28 days of continuous data collection. During that time frame, 184 ships passed within 15 km of the arrays according to AIS data.

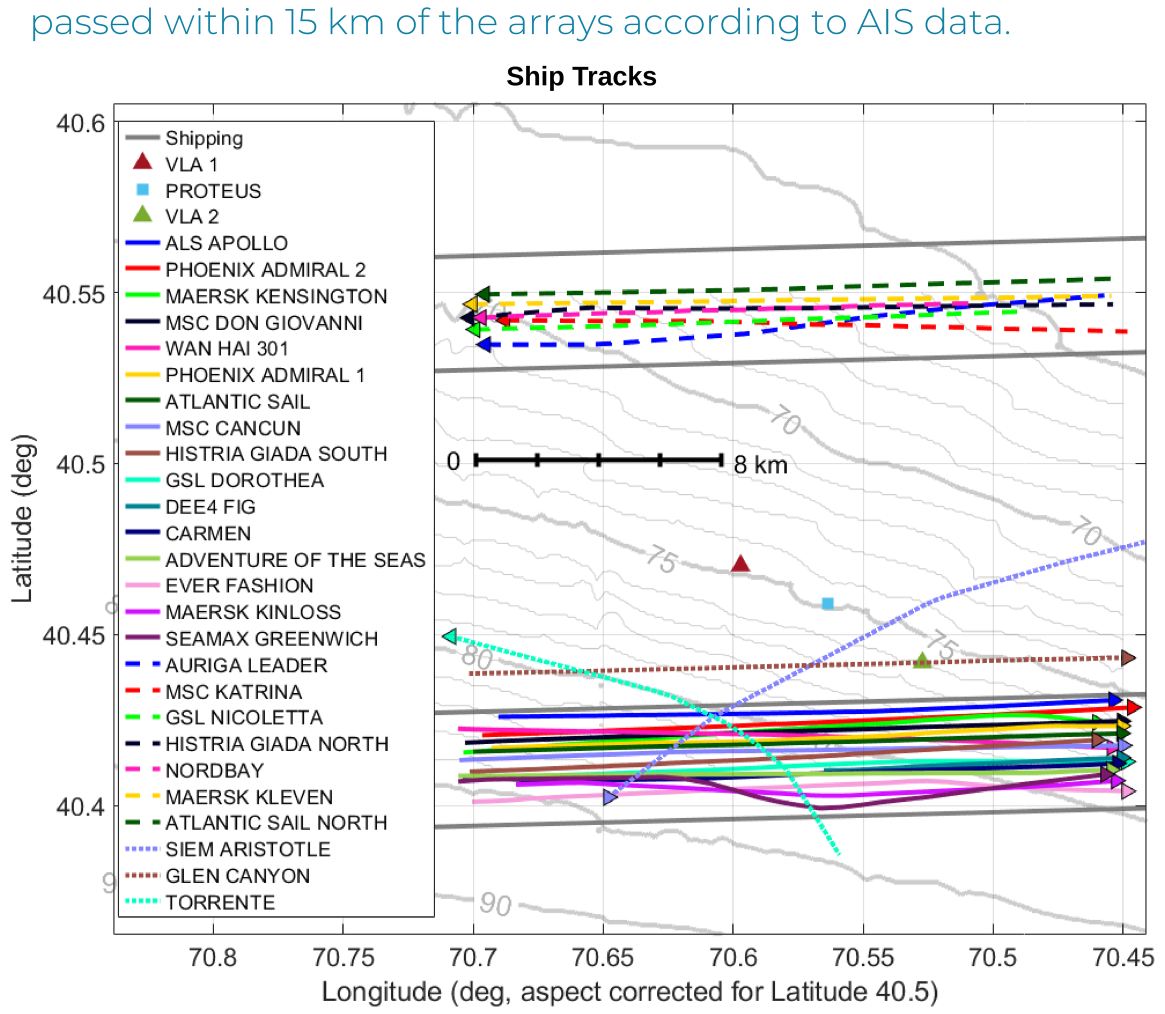

Figure 1: Map of the path of 24 ships that passed through the area. Most ships traveled in either the northern or southern shipping lane, with only a few ships departing from the shipping lanes. Several ships passed through the area multiple times during the 28 days. Signals from HISTRIA GIADA and ATLANTIC SAIL were captured from both the northern and southern shipping lanes. PHOENIX ADMIRAL passed through the area five times during the experimental dates, but only the two southern tracks showed clear signals due to the northern track being farther away.

Spectrograms from these merchant ships contain unique singular points where $\beta = \infty$ in the VLF band. Spectrograms from this study have exhibited as many as three singular points, which are associated with $\beta_{1,2}$, $\beta_{1,3}$, and $\beta_{1,4}$ where $\beta_{m,n}$ indicates that the modal group velocity V_m and V_n are equal at these frequencies. The frequencies where beta goes to infinity will be labeled as $f_{m,n}$ for the remainder of the poster.

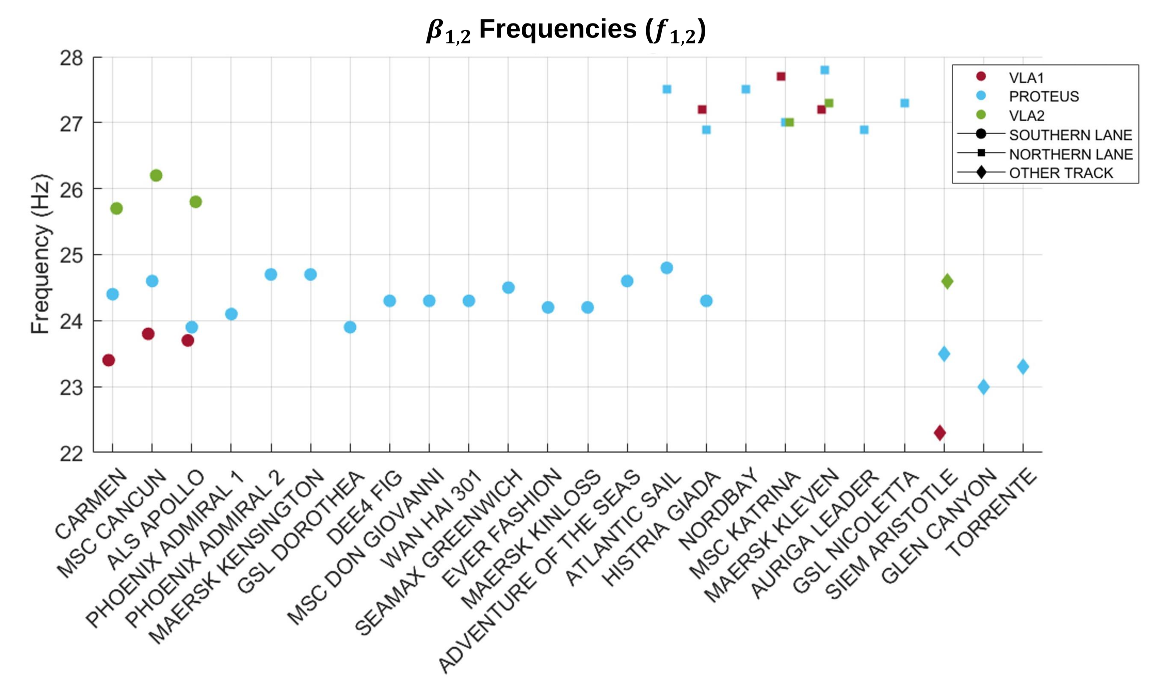

Figure 2: The frequencies ($f_{1,2}$) for 24 ships of interest. Ships with southern ship tracks are listed first followed by northern and other tracks. There are three distinct clusters in the singular points based on ship track. Furthermore, there are three groupings for ships in the southern lane associated with the three acoustic arrays.

	Thickness (m)	Sound Speed (top) (m/s)	Sound Speed (bottom) (m/s)	Density	Attenuation
Mud	9.2	1445	1446	1.62	0.04
Transition	3.0	1446	1750	1.80	0.15
Sand	7.5	1750	1750	1.83	0.15
DL1	[50, 300]	[1700, 1810]	$DL1\_SS_{top}$	2.00	0.15
DL2	[50, 300]	[1815, 2050]	$DL2\_SS_{top}$	2.20	0.15
DL3	100.0	2100	2100	2.20	0.15
Basement	--	2350	2350	2.60	0.22

Table I: Prior model of seabed. Because the VLF sound travels into the deep sediment layers, the singular points from the merchant ship spectrograms can be used for a statistical feature-based inversion for these deep layers. For DL1 and DL2, the numbers in brackets correspond to the upper and lower bound values.

Results

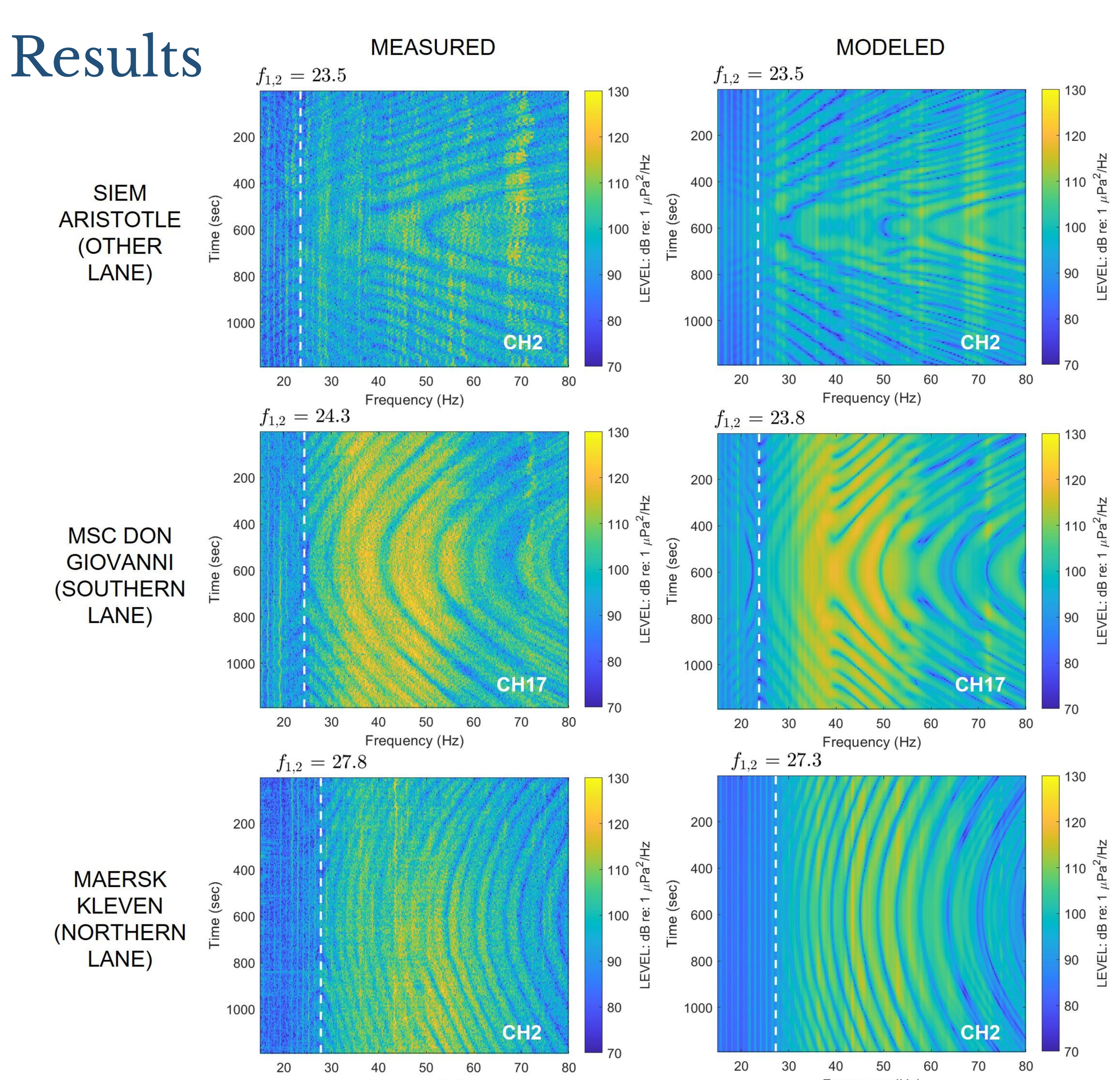

Figure 3: (Left) Measured spectrograms for three different ships collected by PROTEUS. The frequencies of all singular points observed in the measured data are used in a maximum entropy inversion to estimate the optimal deep layer parameters. (Right) Spectrograms modeled using optimal deep layer parameter values. The white dashed-lines show $f_{1,2}$.

Using the optimal seabed parameters for MSC DON GIOVANNI, a plot of the modeled modal group velocities shows that frequencies where the group velocities of modes are equal correspond to frequencies of the singular points.

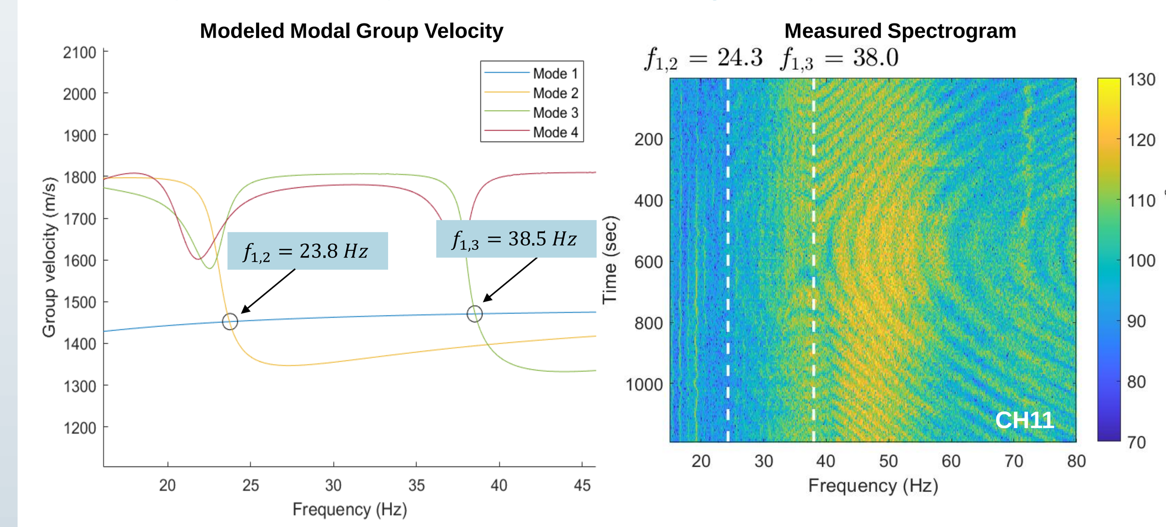

Figure 4: For the MSC DON GIOVANNI measured on PROTEUS, modeled modal group velocities (left) and measured spectrogram (right) show similar $f_{1,2}$ and $f_{1,3}$. Although the modeled spectrogram, as shown in Fig. 2, shows both singular points, different channels from the measured data show the singular points with varying clarity.

Marginal probability distributions of the inversion indicate that using singular points only provides enough information to find the sound speed of the first deep layer. All ships had clear peaks for the sound speed of deep layer one. Only a few ships had informative distributions for other parameters.

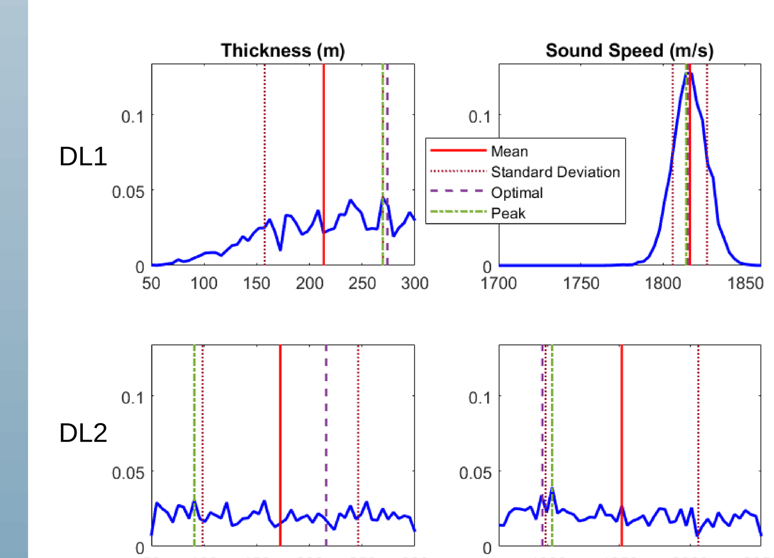

Figure 5: Marginal probability distributions for MSC DON GIOVANNI from PROTEUS CH17. Deep layer 1 (DL1) is the only parameter with an informative probability distribution.

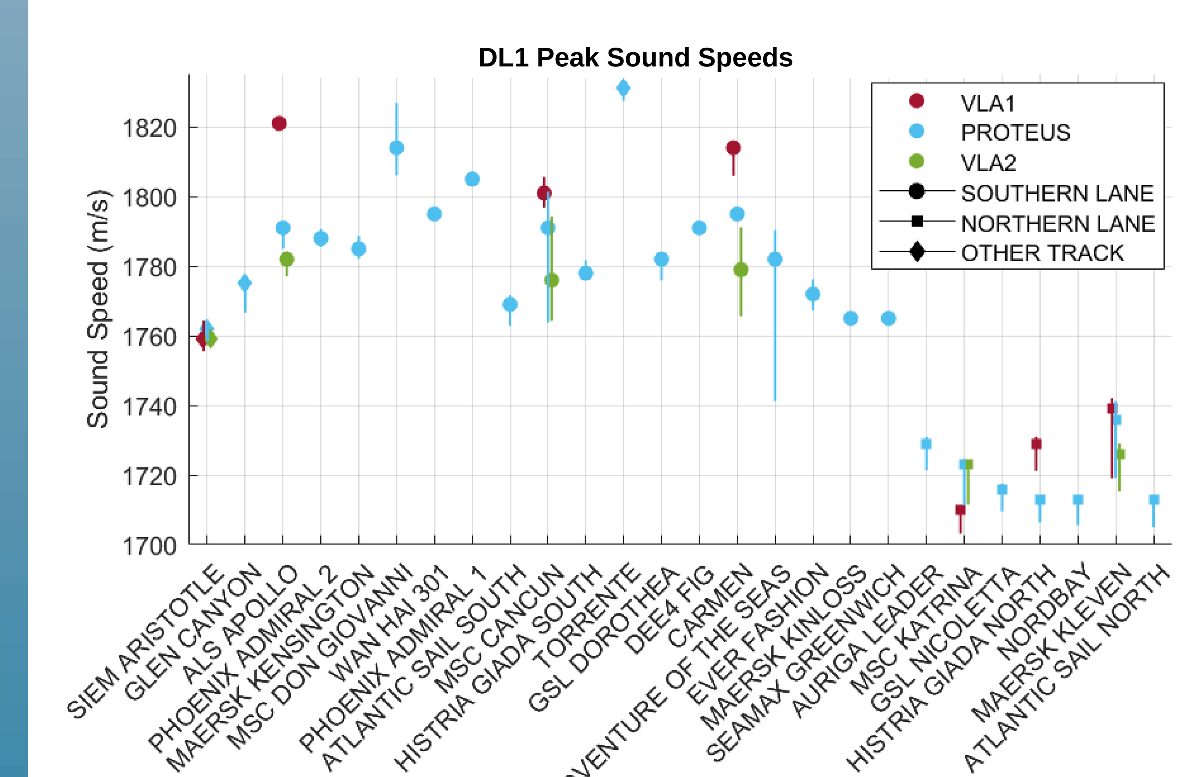

Figure 6: The peak sound speeds for all ships of interest based on the marginal probability distributions. The ships are ordered from closest to farthest from PROTEUS at the time of closest point of approach (CPA). The bars indicate the standard deviation of the marginal probability distribution for the sound speeds. Clear clusters distinguish the sound speeds inferred from ships traveling in the northern versus southern shipping lane.

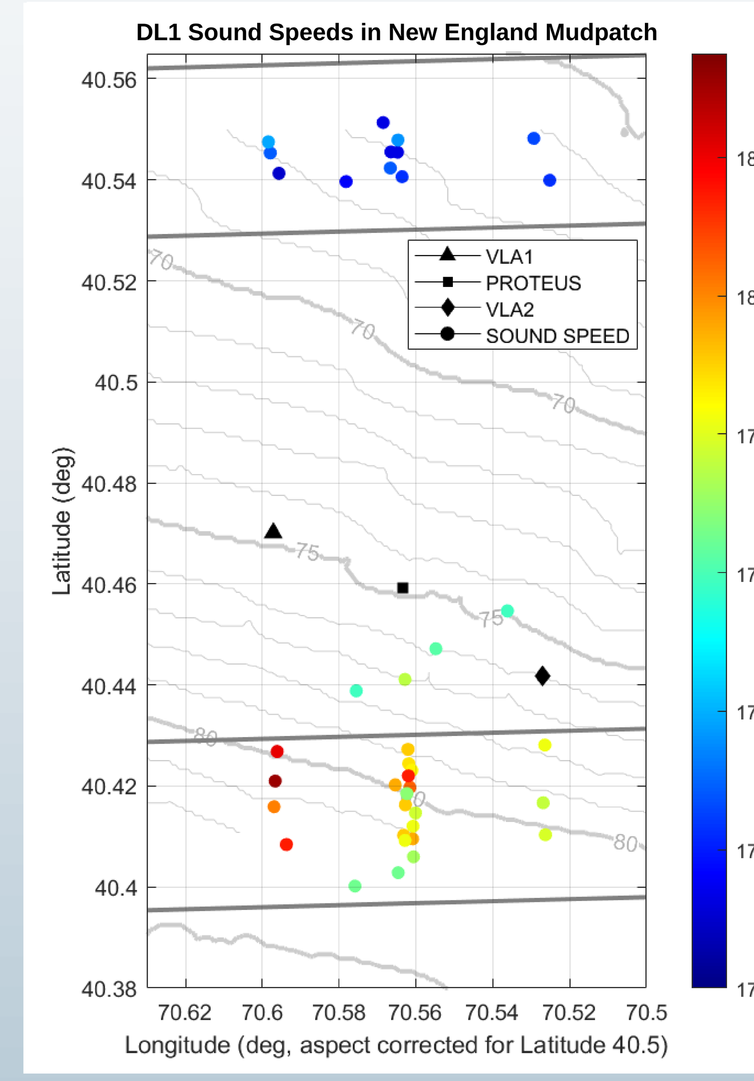

Figure 7: The sound speed of DL1 at the discrete latitude and longitude coordinates at CPA. For a horizontally stratified environment, one would expect the sound speed of the deep layer to be the same throughout the geographical area. These results point to sediment heterogeneity.

Conclusion

Estimates of the deep layer sound speeds were inferred for 24 ships based on $\beta = \infty$ points observed in VLF spectrograms. The resolution of the singular points is sufficient to observe a statistical difference between the northern and southern shipping lanes. Based on the ships CPA, sound speeds in the northern section of the Mudpatch are greater than the southern sections. In the southern shipping lane, there is also indication of a gradual shift in the sound speed going from east to west. Because propagation from the southern and northern tracks are statistically distinguishable, there is enough resolution to infer heterogeneity in the seabed .

Accomplishments

- DL1 sound speeds between northern and southern lane ships are statistically distinguishable.
- Discovered shifting trends in DL1 sound speed based on location, including from east to west in southern lane.
- The heterogeneity in the deep sediment layer sound speeds span from 1710 m/s to 1820 m/s.
- The uncertainty in determining the frequency values for singular points is low enough to determine heterogeneity.

References

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