Response to reviewer Milovan Urosevic

Dear Milovan Urosevic,

Thanks for the careful review of our manuscript. We have addressed all your remarks and below you find our point-to-point response outlined in blue.

Kind regards,

Sikelela Gomo Johannesburg, 14/09/2025

(Corresponding Author)

RESPONSE

Specific comments

MASW: Claimed depth of investigation of 360 m seems to be justified with very few data points (Fig. 8). From most of the displays provided the maximum depth appears to be around 200-220m, which is more likely to be the case, based on the acquisition parameters and the spread length over which surface waves could be traced on the low-res images provided.

We think that the transformation of our manuscript in pdf for the previous submission generated too low resolution figures and this has created some reasonable doubts in the reviewers. We will be careful to provide higher resolution figures in the corrected manuscript. Looking at the obtained models (Figure 10, 11, 12, and 13 of the manuscript) it is apparent that there are several zones in the investigated area where the deeper layers in the model have been updated with respect to the initial model value, thus confirming that the data are sensitive to the model throughout the selected investigation depth. In Figure 7 of the manuscript, we report the spatial distribution of the datapoints at different wavelengths, showing that there is a significant number of dispersion curves with wavelength well beyond 360 m, which we assumed as bottom of our model. Also to respond to the doubts of Samuel Zappalà (RC1), we carried out a sensitivity analysis (reported here in Figure 1 and that we do not plan to add to the paper) starting from a monte Carlo inversion of a dispersion curve taken from the dataset. The sensitivity analysis shows that the dispersion curves with longer wavelength are sensitive to the subsurface properties at the depth of our models. We also computed the wavelength/depth relationship according to Socco et al, 2017. This relationship depicts the skin depth of the surface wave propagation and confirms that the investigation depth is deeper than 200 m.

Nevertheless, we agree that only a limited portion of the curves reaches the wavelength needed to resolve the deeper layer of the model and that most of the estimated velocities below 300 m are generated by the spatially constrained inversion as a kind of interpolation of the available information at that depth. We have then decided to cut our model at 300 m. This change in our representation does not modify the interpretation that is based on the upper portion of the model.

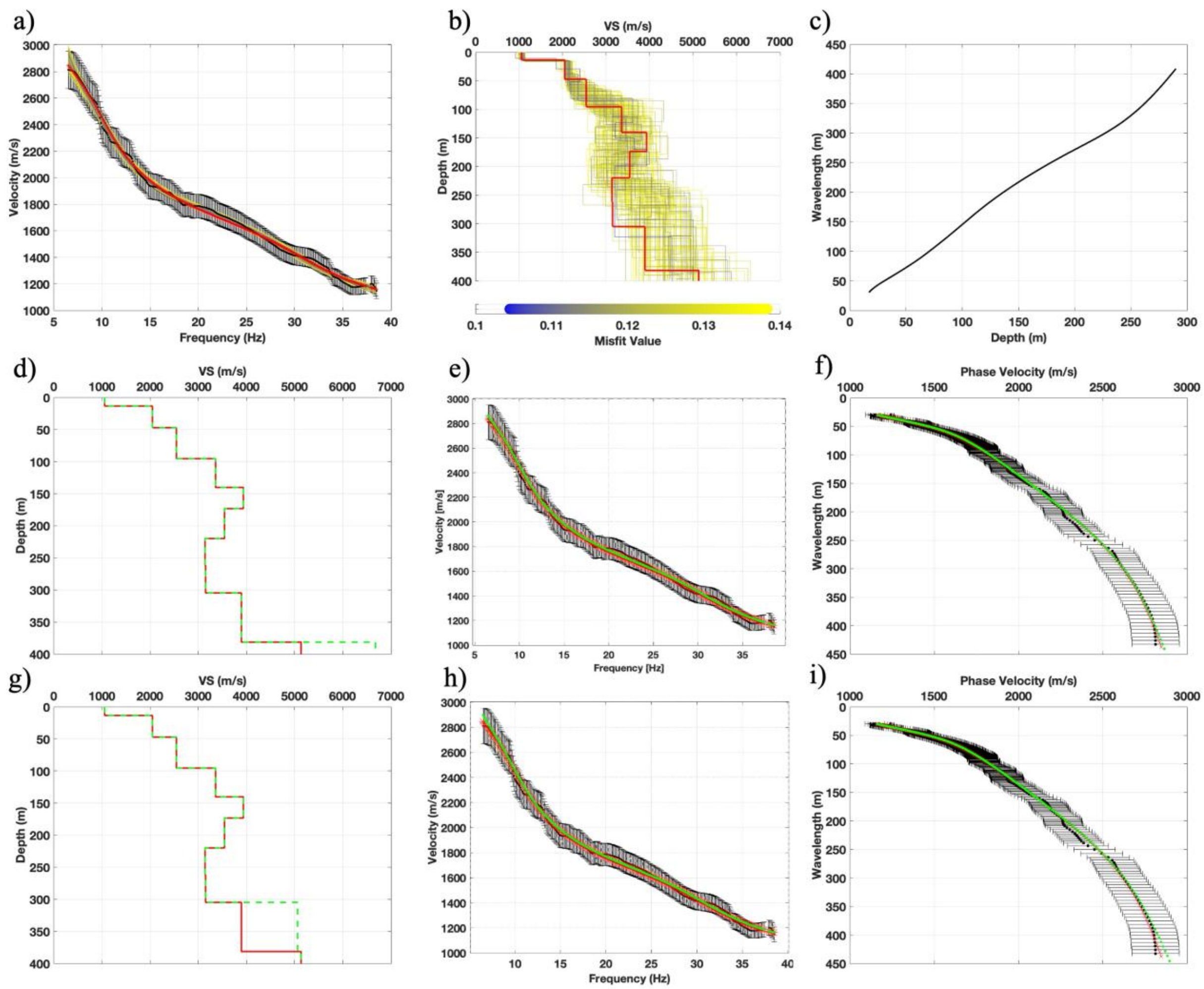

Figure 1: Sensitivity analysis of the medium-frequency band dispersion curve from the dataset (Line P1) to velocity variations in the deeper layers. (a–b) Selected dispersion curves and corresponding VS models from 1D Monte Carlo inversion (Socco and Boiero, 2008). (c) W/D analysis (Socco et al., 2017) indicating the investigation depth as a function of wavelength. (d–f)

Sensitivity of the dispersion curve to a 30% perturbation of VS in the half-space. (g–i) Sensitivity to a 30% perturbation of VS in the layer above the half-space.

Socco L.V., C. Comina, F. Khosro Anjom, 2017, Time-average velocity estimation through surface-wave analysis: Part 1 — S-wave velocity: GEOPHYSICS, 82, 3, U49–U59, https://doi.org/10.1190/GEO2016-0367.1

Socco, L.V, D. Boiero, 2008. Improved Monte Carlo Inversion of Surface Wave Data: Geophysical Prospecting, 56, 357-371 https://doi.org/10.1111/j.1365-2478.2007.00678.x

Fig.8 phase velocities are reasonable. The inverted velocities go to 5000 m/s, seems much to high at depths of 200-300 m. Pretoria complex: Vp (5.0-6.5 km/s), Dolerite intrusions 6.0-6.8 Km/s. Hence Vs higher than 3.8 km/s can hardly be expected.

Thanks for this comment. We have thoroughly analyzed the results and in fact the value of 5000 m/s is associated to the deeper layer of the model which is the one that presents the lower sensitivity. We have hence changed our data representation and limit our representation to 4000 m/s. In Figure 2 we show some examples of lines with the new color scale and we show that this representation allows the investigation depth of the different portions of the model to be outlined. This change in the data presentation does not change the velocity model in the upper portion of the model on which our interpretation is based.

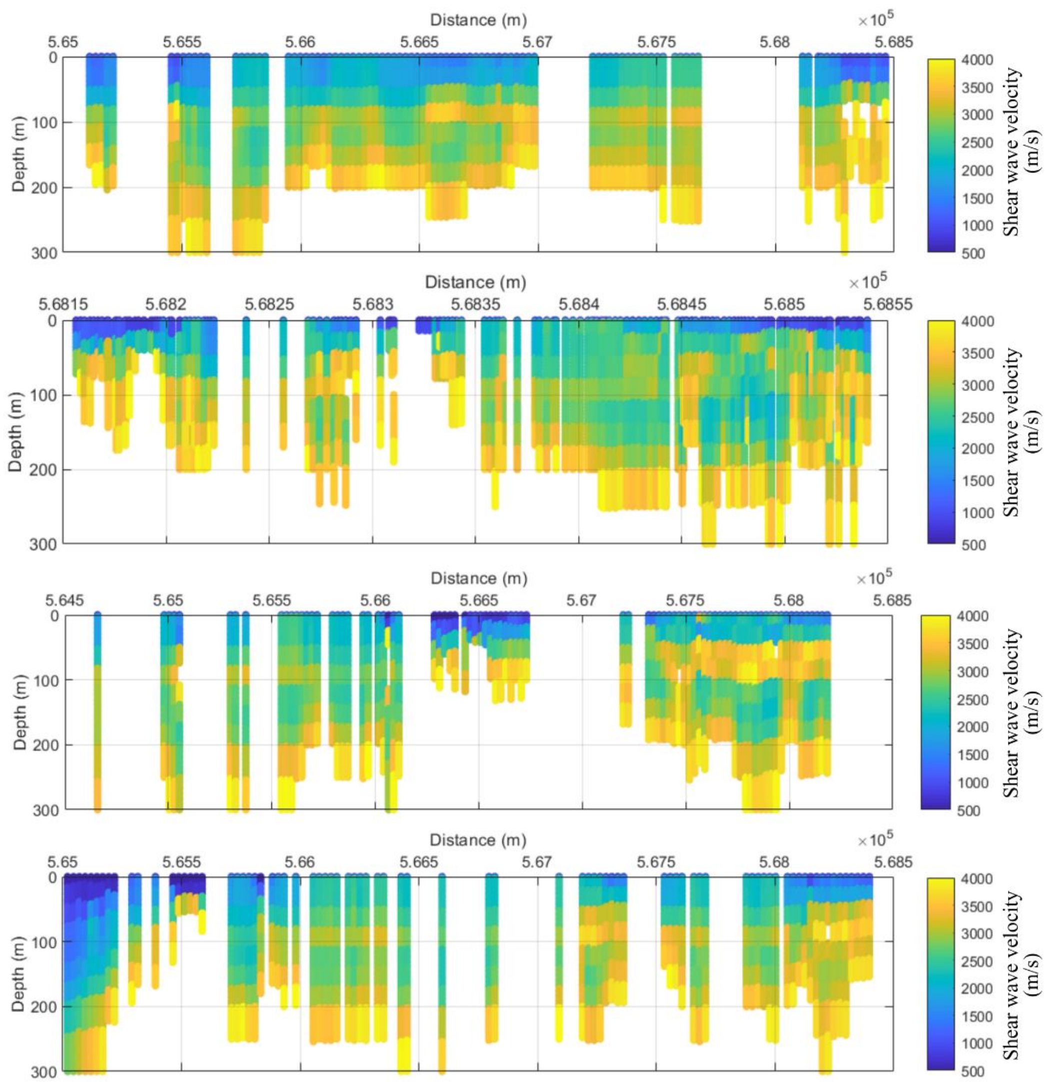

Figure 2. Vs profiles extracted from the 3D grid. The profiles are limited to shear Vs of 4000 m/s and illustrate the variable nature of the depth penetration of the data.

Receiver spacing of 10m risks spatial aliasing of surface waves. A frequency–wavenumber (F-K) analysis of both the newly acquired and legacy datasets would significantly strengthen the validation of the applied methods. If remedial steps were taken to mitigate aliasing risks, they should be documented to increase the confidence in the findings.

Rayleigh waves are highly energetic and easy to recognize in the spectra. If the source is in end off mode and hence the Rayleigh waves travel in one direction along the receiver spread used for the dispersion curve computation, this allows to compute the spectrum beyond the Nyquist wavenumber. The aliased part of the propagating wavefield will then appear unwrapped and picking beyond Nyquist limitation will be possible (see Socco and Strobbia, 2004 for details). Anyway, in the present dataset, the information content in the high frequency band is very limited and in most of the picked dispersion curves we do not have energy in the wavelength range that would produce spatial aliasing. Here below we show a fk spectrum of a selected shot as example (Figure 3). The spectrum is computed up to 3 times the Nyquist wavenumber and we show that, with our spatial sampling, no aliasing is expected. To explain that the aliased part, if present, can be easily recovered, we resampled the same record with coarser spatial sampling and computed again the fk spectrum. The dispersion curve picked from the original data is superimposed on the spectrum and extends beyond the Nyquist wavenumber. We do not think to add this figure in the revised version of the paper, but we will add a sentence to explain that aliasing is not an issue even though the receiver spacing is quite large with respect to usual SW data.

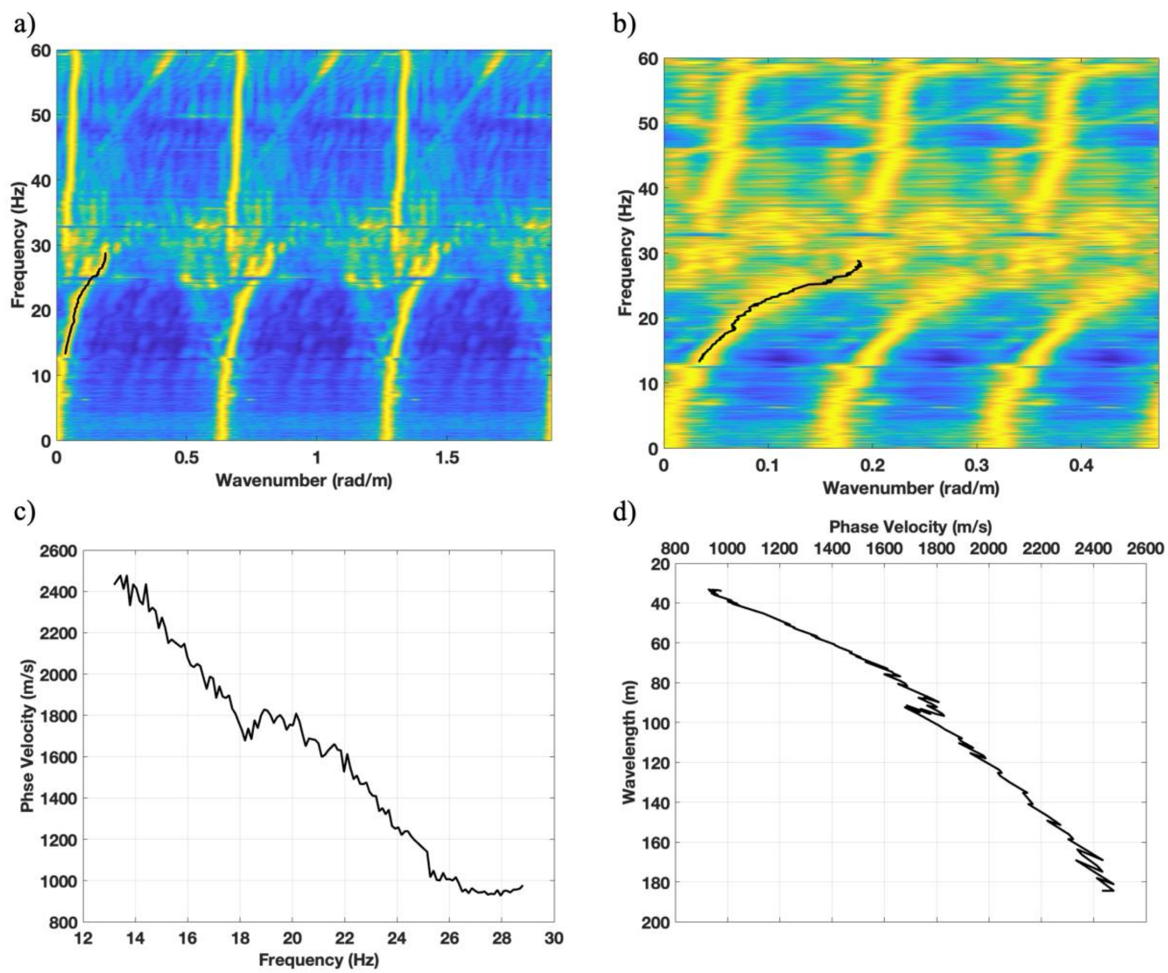

Figure 3. f–k analysis for dispersion-curve picking along line P1 using a 300 m spatial window with (a) every receiver and (b) every 4th receiver. The f–k spectrum is unwrapped to extend the analysis beyond the Nyquist wavenumber. In (a), the black curve marks the picked dispersion curve, which is superimposed in (b) for comparison. (c–d) Dispersion curves expressed as functions of frequency and wavelength, respectively.

Socco, L.V., C. Strobbia, 2004, Surface-wave method for near-surface characterization: a tutorial: Near Surface Geophysics 2,4 165-185 https://doi.org/10.3997/1873-0604.2004015.

It remains unclear why P-wave refraction arrivals, which are visibly present in the provided shot records, were not incorporated into the geophysical analysis. Integrating these data with shear-wave profiles would offer a more robust inversion framework. Furthermore, by linking P- and S-wave velocity models, the authors had the opportunity to compute additional elastic parameters, particularly Poisson's ratio, which could enhance aquifer characterization.

We definitely agree that it will be interesting to compare P-wave data with the VS data from SW analysis. This comparison, with the addition of surface wave attributes (Colombero et al., 2019) that correlate very well with the velocity models, is the object of a paper in preparation. We decided not to include this part of the work in the present paper, as the actual paper is already quite extensive and lengthy. We also like the suggestion of computing the Posson's ratio from the computed P and S wave velocity models, and this will be incorporated in the future work. Future work also includes the SW analysis of the surface DAS and broadband MEMS-based sensors that were co-located with the data from the 5 Hz geophones presented here.

Colombero, C., C. Comina, L.V. Socco, 2019, Imaging near-surface sharp lateral variations with surface-wave methods — Part 1: Detection and location: Geophysics, 84, 6, EN93-EN111 DOI: https://doi.org/10.1190/geo2019-0149.1

Figure 4 shows Rayleigh waves that are barely visible and limited to a spread length of approximately 200 m. Based on standard MASW practices, this propagation range does not support the claimed investigation depth of 360 m, especially when employing 5 Hz geophones and assuming realistic shear wave velocities for the site.

We again are sorry for the low resolution of the first submission. We modified Figure 4 of the manuscript, improved resolution, and zoomed image of the surface wave train has been added for improved clarity. The aim of the figure was to show a typical example of the seismic records obtained in the study area. The seismic records, however, characteristics of the study area are very varied, as shown in Figure 4. Likewise, the surface wave propagation and their clarity vary considerably, mainly depending on the geology. As seen in Figure 4 and 5 below, several dispersion curves that support the claimed investigations depth are obtained.

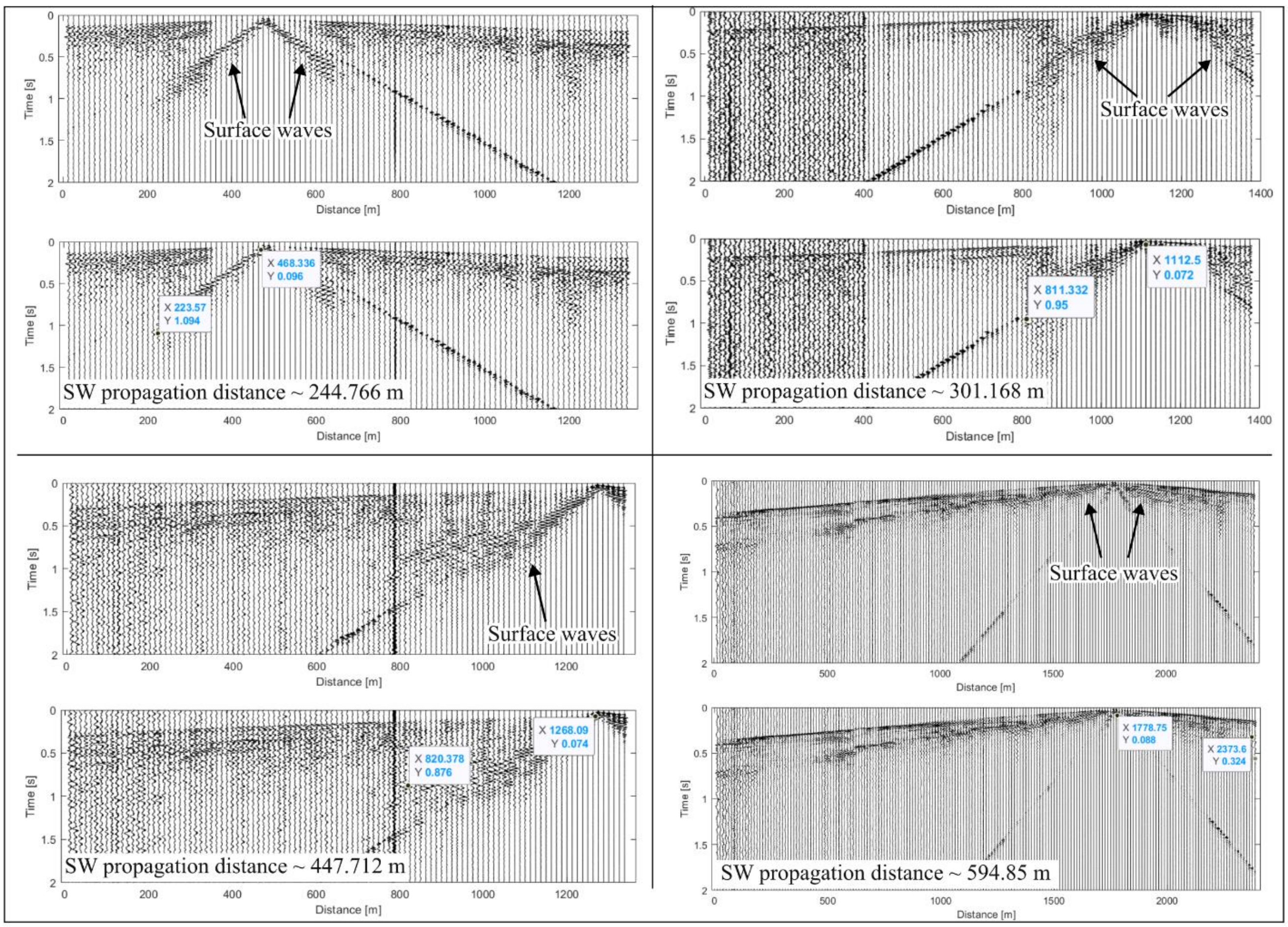

Figure 4: Typical seismic records obtained in the study area.

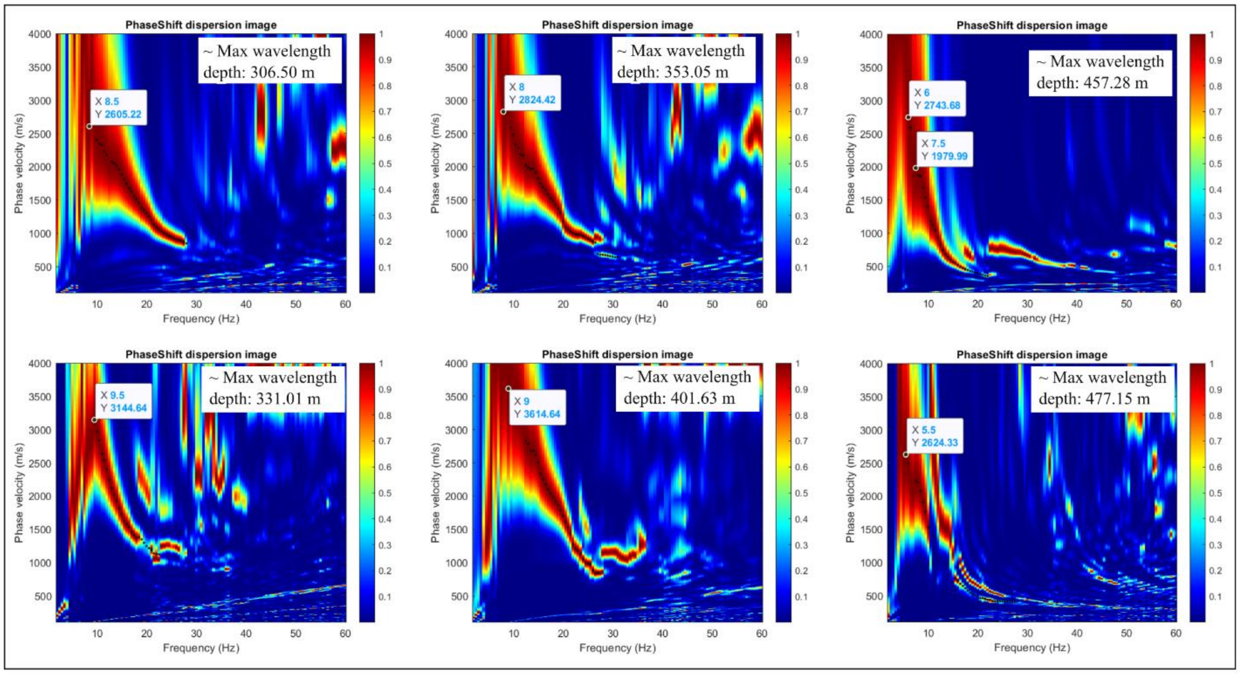

Figure 5: Typical dispersion curves obtained from the seismic record of the study area.

Moreover, the vibroseis source utilized in the survey is known to produce relatively weak surface wave energy. Its long-duration sweep increases the risk of mixed wavefields, which may affect dispersion curve extraction.

We humbly disagree with this statement. There is no reason to think that vibroseis would produce a weak energy surface wavetrain. Our personal experience in comparing impact and vibrating sources did not evidence significant difference in the two kinds of source at the same site. We also made extensive test with a light vibrator with different sweep lengths and also analyzed the difference of the results obtained on raw or deconvolved data. No evident differences were found and longer sweeps always increased the data quality. Unfortunately, these analyses have never been used for a publication so we cannot provide a reference, but in Figure 6 we show two records that are part of those analyses. The first is the record of a 90 kg vibroseis shot and the second is the stack of 11 shot with a hammer. These data are not completely comparable to those acquired for the present study, but show that in the same condition vibrating sources generate data completely comparable with impact sources. It is also worth noting that the behavior of the source (coupling, harmonics, etc.) and the wavefield propagation are dependent on-site conditions.

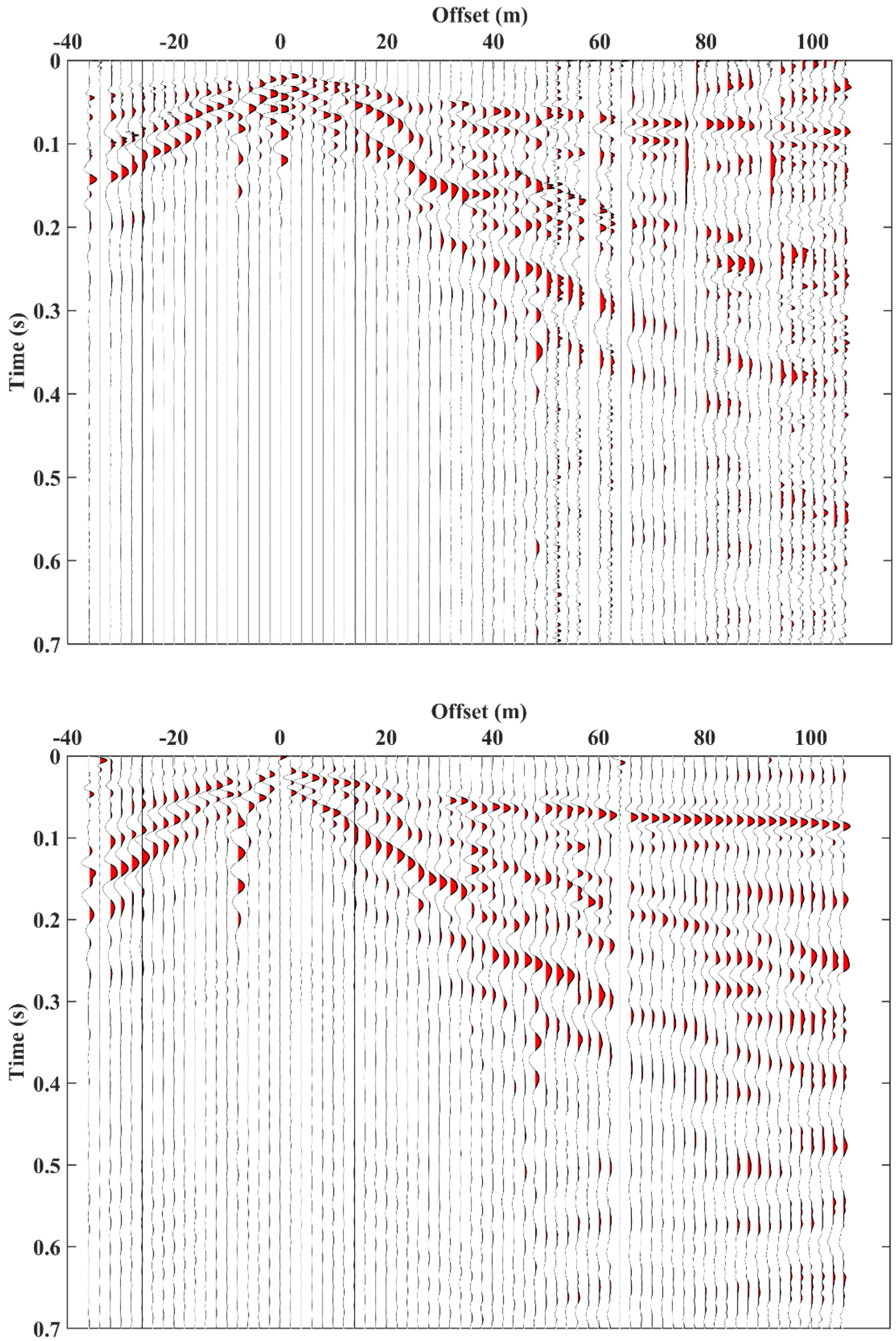

Figure 6. At the top is a deconvolved record acquired with a light vibrating source, and at the bottom is a record obtained by stacking 11 hammer (5kg) source repetitions at the same source

point. These data are not related to the present work and are just aimed at supporting the above statement with experimental evidence.

Figure 6 exhibits well-developed P-wave refractions extending across the full 2 km spread. Surface waves appear to be present, at best over 200m length, and/or spatially aliased. The small display scale and low resolution of the field data images severely hinder a proper assessment of wavefield characteristics in both Figures 4 and 6.

Resolutions of figures in the manuscript have been improved. Due to the large number of Figures constituting the manuscript already, we avoided adding more images, however, examples of seismic records showing varied and large surface wave propagations in the analysed data are shown in Figure 4 above.

To allow for accurate interpretation of all wave types, significantly improved display quality is necessary. I recommend that representative shot records from both the new and legacy surveys be shown independently, without additional overlays, so that readers can assess signal quality and wavefield content with greater clarity.

We agree with this recommendation. All the raw data from both old and new datasets are available to the authors. However, we believe that this suggestion should be incorporated into the current work by the PhD candidate, which involves processing the latest 3D seismic data for comparison with the legacy 3D seismic data. The legacy data presented are included solely for final interpretation purposes, and SW analysis is provided to complement the legacy data and other geological data, characterizing the near-surface geology. Thus, the presentation of the shot records does not fall within the scope of the current paper and will definitely be considered for the future paper.

Figure 13 suggests that the legacy data may have undergone excessive (signal-to-noise ratio) SNR enhancement, potentially resulting in an overly smoothed image that masks subsurface discontinuities. If access to the raw legacy dataset is possible, reprocessing it with modern imaging techniques could yield a significantly different structural interpretation. Moreover, the reprocessing may bring more clarity in the near surface, possibly up to 200 m depth.

This is possible and the legacy seismic is currently being re-processed using latest imaging techniques, particularly focusing on depth imaging. We also plan to analyze the diffractions on the stacked data that may be related to faults and dykes that are not well observed on the current legacy data. Additionally, we observe that the limitation for near-surface imaging may be related to the acquisition parameters (e.g., RI, RLI, SI, and SLI) and the bandwidth-limited sensors and sources used during data acquisition.

Lows in Vs at the position of interpreted dykes could be related to the computations since dolerite dykes are likely to have a higher velocity than the surrounding rocks.

In general, yes, but at South Deep Mine and the Witwatersrand goldfields, the dykes can be weathered and competent – these can vary along the length of the dyke. The dykes can be less competent in the near-surface compared to silicate rocks, and therefore breakdown more than the surrounding metasedimentary rocks, when exposed to weathering processes, resulting in lower seismic velocities relative to the surrounding metasedimentary rocks (Evans et al., 1998). The emplacement of dykes at South Deep mine often occurs along weak zones (i.e., faults and fractures). In these zones, the subsurface is often characterized by intensified weathering and alteration, due to the presence of increased fracturing, porosity, and fluids, which accelerate the breakdown of rock in these zones, including both in-situ rock and the associated dykes. Thus, it is possible that the dykes in the area are highly weathered. It is also possible that the low-velocity zone on the Vs model is due to faulting, rather than the dyke. Two alternative explanations are presented in the discussion section. However, the spatial correlation of this velocity zone and the dyke location (as confirmed through drilling and underground mapping) may suggest that the dyke might have intruded into the fault zone that crosscuts the overlying aquifers, implying that the deeper mining level and overlying aquifer systems are structurally connected, thus these structures may transport water to the mining level. This is the main objective of integrating the legacy and SW analysis, i.e., to enhance our understanding of the near-surface geology.

Recommendations

The investigative approach is conceptually appealing yet suffers from poor presentation of field data. High-quality visual displays are crucial for transparent interpretation. This needs to be corrected.

The quality of the displays presented has been improved.

I believe that the analysis would be strengthened by incorporating P-wave refraction tomography, given that refraction images already span the full spread length.

F–K (frequency–wavenumber) plots should be included to assess the integrity of surface wave sampling and verify spatial aliasing.

Please, see the responses to your previous remarks on this concern. We do not plan to add the fk that we have included in this response to the paper, since the number of figures is already very high and the paper very long. Moreover, we did not use fk for extracting dispersion curves so this would risk creating confusion about the dispersion images used in the processing. The improved resolution of the figures with respect to the previous submission should allow the reader to assess the presence of the surface waves in the raw data and on the dispersion images.

Concerning the analysis of P-wave travel times, beside the response above, it is useful to remark that the availability of P-wave arrival along the records does not guarantee a larger investigation depth with respect to that obtained by dispersion curve analysis and that low velocity layers that are retrieved from SW analysis in large portion of the area would be very difficult targets for P-wave analysis.

The stated depth of investigation needs more rigorous justification. I recommend including a brief overview of MASW methodology and the commonly accepted rule of thumb for depth estimation.

After working for more than 10 years on rigorous estimation of investigation depth of surface waves we tend to avoid using rule of thumbs but to assess directly the investigation depth from the data. The wavelength-depth plot presented on the response above (Figure 1) and the sensitivity analysis represent the skin depth of the data and show the capability of the chosen parameterization to exploit the sensitivity of the data also at depth. We do not plan to report the sensitivity analysis in the paper but we will add a paragraph to discuss these aspects. Moreover, we have cut the model at 300 m.

The geology chapter could be much more concise and related to the analysis shown. Geological referencing is way to extensive for a little benefit to the reader.

The chapter has been revised to provide a summary of previous work done in the area, particularly related to the lack of near-surface characterization, and to focus on the timing of activity of faults and dykes in the region that link the shallow geology and deeper mining levels.