Surface wave analysis for heterogeneous geological formations in geothermal fields: effect of wave propagation direction

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ABSTRACT

We applied advanced surface wave analysis for multichannel and multishot seismic data to estimate S-wave velocity structure with high lateral resolution. Although a horizontally layered structure is typically assumed in surface wave analysis, this assumption might be violated in environments such as geothermal fields because of their heterogeneous geological formation. The lateral variation of phase velocity can be effectively estimated with common midpoint (CMP) cross-correlation (CMPCC) analysis. In this study, we introduced two additional approaches into the CMPCC analysis workflow, to further improve lateral resolution of phase velocity estimates. One approach is window-controlled CMPCC analysis, which applies a spatial window for the CMP gathers while maintaining the accuracy of the phase velocity estimates. In this analysis, we found that it is difficult to improve phase velocity estimates at lower frequencies, as a wider spatial window must be kept to maintain the accuracy of the dispersion curve. Therefore, we introduced another approach in which we consider the direction of surface wave propagation from sources to receivers. Selection of cross-correlations based on source–CMP direction provides a significant improvement in dispersion curve resolution in the presence of lateral velocity variations, for a wide frequency range. We applied direction-controlled CMPCC analysis to seismic data acquired in the Yamagawa geothermal field, Kyushu Island, southwest Japan, and obtained dispersion curves in the heterogeneous geological setting. We then obtained S-wave velocity profiles by applying genetic algorithm inversion to the dispersion curves. The S-wave velocity profiles in the geothermal field resolve shallow and local heterogeneous structures (e.g. volcanic ash, pumice and igneous intrusions) that cannot be identified on reflection seismic profiles.

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Introduction

Surface wave analysis is frequently used to estimate shallow S-wave velocity ($V_S$) structures in many scientific and engineering fields (Socco, Foti, and Boiero 2010; Tsuji et al. 2012a; Foti et al. 2014). In surface wave analysis, $V_S$ profiles are usually estimated from observed dispersion curves under the assumption of a horizontally layered structure (Xia, Miller, and Park 1999). Nazarian and Stokoe (1984) introduced spectral analysis of surface waves (SASW) to estimate surface wave dispersion curves from two receivers. In further developments, multichannel analysis of surface waves (MASW; Park, Miller, and Xia 1999) improves the stability of phase velocity estimation by using multichannel seismic data. In surface wave analysis, two-dimensional (2D) $V_S$ profiles are usually estimated by assembling one-dimensional (1D) layered structures estimated by inversion of local dispersion curves. Therefore, the key to the estimation of $V_S$ structure with high lateral resolution is to obtain local dispersion curves reflecting subsurface structure beneath the local points. In recent progress, common midpoint cross-correlation analysis (CMPCC) has been developed to enhance the accuracy in local dispersion curve estimation by taking cross-correlations between receiver pairs with the same CMP (Hayashi and Suzuki 2004).

Development of surface wave analysis available for laterally heterogeneous structures would be particularly important in geothermal fields due to the heterogeneous nature of such fields, which might include fractures, soft volcanic deposits (e.g. pumice) and hard igneous rocks (Tsuji et al. 2012b; Aoki et al. 2017). To obtain phase velocities with higher lateral resolution in geothermal fields, we introduced two extensions to CMPCC analyses. One is window-controlled CMPCC analysis (Ikeda, Tsuji, and Matsuoka 2013) in which we apply optimum spatial windows to the gathers for CMPCC analysis, and the second is to consider the wave propagation direction based on source–CMP location (i.e. direction-controlled CMPCC analysis). Although previous studies (Bergamo and Socco 2014; Ikeda and Tsuji 2016) utilised the wave propagation direction dependence of surface wave attenuation coefficients to identify localised heterogeneities, we propose to select wave propagation direction to reduce the influence of scattered surface waves on phase velocity estimation.

We applied the CMPCC analysis, with these two approaches, to multichannel seismic data acquired at
the Yamagawa geothermal field, Kyushu Island, south-west Japan. Our results show that window-controlled CMPCC analysis does improve the accuracy of dispersion curve estimation because it reduced phase velocity fluctuations generated by near-surface lateral heterogeneity. We further selected cross-correlations, taking into account wave propagation direction based on relative source-CMP locations, for the calculation of dispersion curves. Both numerical and field experiments demonstrate that wave propagation direction should be considered, particularly near geological boundaries, to improve the lateral resolution of dispersion curve estimates.

Method

In the CMPCC method, a CMP is defined as the mid-point between two receivers (Hayashi and Suzuki 2004). Possible receiver pairs with the same CMP are collected from multishot and multichannel data (Figure 1a). The cross-correlations of each pair with the same CMP are grouped, and the resulting CMP gather of cross-correlations is defined as a CMPCC gather. Local dispersion curves at CMPs can be estimated by applying MASW to each CMPCC gather. In this section, we explain concepts of window-controlled CMPCC analysis and direction-controlled CMPCC analysis that we have developed in this study.

Window-controlled CMPCC analysis

Because the lateral resolution of local dispersion curves depends on the receiver spacing, the effect of lateral variation can be suppressed by removing cross-correlation data with longer receiver spacing. However, decreasing the number of cross-correlation pairs decreases the accuracy of dispersion curve estimation. In window-controlled CMPCC analysis (Ikeda, Tsuji, and Matsuoka 2013), we reduce longer receiver spacing data as much as possible, while maintaining the accuracy of phase velocity estimation. In the following, we describe how we define wavenumber resolution for a given receiver configuration, and how many receiver pairs we remove considering the wavenumber resolution.

Assuming the observed seismic data are composed of only the fundamental mode of surface waves, the dispersion image can be described as the convolution of the array smoothing function (ASF) (Johnson and Dudgeon 1993) and the true dispersion image as
follows:

\[ U(k,f) = |ASF| \ast P(k,f), \quad (1) \]

\[ ASF = \sum_{j=1}^{N} W(x_j) e^{\text{i}kx_j} \]

where \( U \) is the observed dispersion image, \( P \) is the true dispersion image for fundamental mode surface waves, \( k \) is the wavenumber, \( N \) is the number of cross-correlation pairs, \( f \) is frequency and \( x_j \) is the receiver spacing for \( j \)th receiver pair. \( W(x_j) \) is a spatial weighting function defined as a function of receiver spacing. The effects of receiver geometries (i.e. receiver spacing) on the observed dispersion image can be

\begin{table}[h]
\centering
\begin{tabular}{|l|c|}
\hline
Parameter & Value \\
\hline
Size of grid cell & 1 m \\
Number of cells & 1500 (horizontal) \times 300 (vertical) \\
Time interval & 0.0002 s \\
Number of grid of absorbing layer & 100 \\
Time duration & 8 s \\
\hline
\end{tabular}
\caption{Parameters of numerical simulation displayed in Figure 2.}
\end{table}

Figure 3. Examples of CMPCC gathers at CMPs of 5089 m, 5199 m, and 5399 m. (a) CMPCC gathers constructed from both positive- and negative-offset data; (b) CMPCC gathers from positive-offset data; and (c) CMPCC gathers from negative-offset data. We applied a 4–12 Hz bandpass filter to each CMPCC gather. Positive time indicates the wave propagating from the source to the CMP, and negative time indicates the wave propagating from the CMP to the source. Arrows indicate the noise (i.e. reflection energy) derived from the geological boundary.
Figure 4. Observed dispersion curves for simulation data from (a) the CMPCC gathers using both-offset data for positions 5089 m, 5199 m, and 5399 m. (b) As (a) but from the CMPCC gathers using positive-offset data. (c) As (a) but from the CMPCC gathers using negative-offset data. The grey scale in (a)–(c) represents the normalised amplitudes in the dispersion images scaled from 0 to 1 (Ikeda and Tsuji 2015). The value of 1 indicates a perfect match between the observed data and predicted phase velocities. Red dots are picked phase velocities with largest amplitude at each frequency. (d) Amplitude of the dispersion images at the picked phase velocities for all cases in (a)–(c). At each CMP, the number of receiver pairs is 594, 297 and 297 for both-, positive- and negative-offset data, respectively.
evaluated from the ASF (Bergamo, Boiero, and Socco 2012; Ikeda, Tsuji, and Matsuoka 2013). Wavenumber resolution can be defined by the value of the wavenumber when the absolute values of the ASF fall to half maximum (Johnson and Dudgeon 1993) for a given receiver geometry. This wavenumber resolution ($k_{\text{min}}$) can be converted into the maximum detectable wavelength ($\lambda_{\text{max}} = 2\pi / k_{\text{min}}$). To improve lateral resolution, we gradually remove cross-correlation data at each CMP, beginning with longer receiver spacings. While removing cross-correlation data, we compute the maximum detectable wavelength for each receiver spacing configuration. For an observed wavelength ($\lambda_{\text{obs}}$) at each frequency and CMP, we remove longer receiver spacing pairs where possible, while satisfying the following relationship (Ikeda, Tsuji, and Matsuoka 2013):

$$\lambda_{\text{obs}}(f) < \alpha \lambda_{\text{max}}(f),$$  

where $\alpha$ is a parameter to be set depending on the data. $\lambda_{\text{obs}}$ is obtained from the dispersion curves at each CMP estimated by conventional CMPCC analysis, without the window-controlled analysis. A larger value of $\alpha$ implies a sharp spatial window or more cross-correlation pairs to be removed. On the other hand, a smaller $\alpha$ extends the spatial window around the CMP, resulting in more cross-correlation pairs being kept for the phase velocity estimation. The key of window-controlled analysis is to find the optimum $\alpha$ to improve lateral resolution of phase velocity estimates, without reducing their accuracy.

**Direction-controlled CMPCC analysis**

The direction-controlled CMPCC analysis is based on the differing behaviour of surface waves, depending on the direction of wave propagation from source to receiver (Figure 1b). The differences are due mainly to the presence of geological boundaries, and attention has focused on surface wave attenuation properties (Bergamo and Socco 2014; Ikeda and Tsuji 2016). Bergamo and Socco (2014) estimated attenuation coefficients from positive- and negative-offset data separately. In horizontally layered media, the trend of energy decay (i.e. attenuation coefficient) should be the same. However, when surface waves propagate through sharp lateral or dipping discontinuities (i.e. geological boundaries), the scattering and transmitting behaviour of surface waves depends on the source to receiver direction (Bergamo and Socco 2014; Ikeda and Tsuji 2016). If the trend of the attenuation is different for positive- and negative-offset directions, an abrupt change in the attenuation can be used as an indication of the presence of a sharp lateral discontinuity (Bergamo and Socco 2014). In CMPCC analysis, Ikeda and Tsuji (2016) obtained attenuation coefficients that were dependent on the source to CMP direction, and distinguished geological discontinuities and localised fractures using phase velocities and attenuation coefficients.

We performed numerical simulations to investigate the effectiveness of the direction-controlled CMPCC analysis. We constructed a geologic model (Figure 2a) by considering the geological heterogeneity predicted at the Yamagawa geothermal field. It should be noted that our actual simulation model is larger than that displayed in Figure 2(a) to avoid the effect of artificial reflection from the boundaries (see Table 1). To generate synthetic waveforms, we used the elastic finite difference method with velocity-stress staggered grids for a 2D P-SV wavefield (Virieux 1986). The source was a Ricker wavelet with a 7 Hz central frequency, applied to the vertical normal component of stress. We applied a free surface boundary condition (Levander 1988) at the top of the model, and absorbing boundary conditions (Cerjan et al. 1985) on the other boundaries. We defined the source and receiver intervals to be 10 m along the surface. P-wave velocities and densities for numerical modelling are computed from the empirical relations of Kitsunetzaki et al. (1990) and Ludwig, Nafe, and Drake.
Figure 6. (a) Geological map of the Yamagawa geothermal area (modified from Okada et al. (2000)). (b,c) Area of surface wave analysis in this study (marked by a black rectangle).

(1970). Other parameters in the numerical simulation are summarised in Table 1. We observe surface wave (Rayleigh wave) propagation of vertical particle velocity on the shot gather derived from the numerical simulation (Figure 2b and 2c). When the source is located at the right side on the low $V_s$ material, we observe clear reflections from the vertical (or dipping) velocity boundary (arrow in Figure 2c). However, reflections are barely seen when the wave propagates through the velocity boundary from rigid to soft material (Figure 2b).

Because the scattered and transmitted surface waves at a geological boundary might depend on the direction of wave propagation (Hyslop and Stewart 2015), we applied the direction-controlled CMPCC analysis to reduce the scattering effect by selecting cross-correlation pairs for particular wave propagation directions. We constructed CMPCC gathers from the simulation data. We computed cross-correlations between each pair of traces so that the receiver nearer the source became a virtual source. We defined cross-correlation data as being positive offset (i.e. positive-offset data) when the virtual source is located on the west side of the CMP (the left side in Figure 1), and negative-offset data to result when the virtual source is located on the east side of the CMP (the right side in Figure 1). Cross-correlation traces with the same receiver spacing are stacked. Figure 3 shows examples of CMPCC gathers from both-offset, positive-offset and negative-offset data at CMPs located in the high $V_s$ zone (position 5089 m), in the transition zone from high $V_s$ to low $V_s$ (5199 m), and in the low $V_s$ zone (5399 m). In the CMPCC gathers, we observed the effect of scattered and transmitted surface waves depending on the offset direction. At the
Figure 7. Examples of shot gathers from raw field data. Stars indicate the positions of the shotpoints, whereas circles represent the receivers contributing to the shot gather.

CMP at 5089 m, reflections could not be observed at all. However, strong energy reflection is observed in the CMP gathers near the geological boundary at CMP 5199 m and CMP 5399 m, for both-offset and negative-offset cases (arrows in Figure 3). This result indicates that the influence of the geological boundary (Figure 2a) upon the CMP gather is small for positive-offset data. In this model, selecting wave propagation from the direction of high velocity to low velocity (rigid to soft material) seems effectively to suppress the reflected wave in the CMP gather. The energy of the transmitted wave, compared with that of the reflected wave, is stronger when the wave propagates from rigid to soft materials (Hyslop and Stewart 2015).

We then extracted dispersion curves at each CMP by applying MASW to CMP gathers derived from the numerical simulation (Figure 4). To validate our result, we compared the estimated phase velocities with theoretical values computed using the compound matrix method for horizontally layered structure (Saito and Kabasawa 1993) at each CMP. Our result (Figure 4) indicates that source direction influences phase velocity estimation. It can be seen that positive-offset data contribute to improving the stability of the phase velocity estimation (Figure 4b), as shown by high normalised amplitudes in the dispersion images (Figure 4d), compared with the both-offset case and the negative-offset case (Figure 4a–4d), especially near the velocity boundary. It should be noted that the CMP of 5199 m is located in the low velocity zone \( (V_S = 200 \text{ m/s}) \) but the CMP gather includes cross-correlations across the geological boundary, so the estimated phase velocity (red in Figure 4) is different from the theoretical one (cyan in Figure 4).

In Figure 5, we display dispersion curves from the simulation data estimated at all CMPs. To image the sharp lateral variation in the synthetic velocity model at \( \sim 5200 \text{ m} \) horizontal distance (Figure 2a), it is desirable to obtain a sharp lateral variation, as shown in Figure 5(d). The lateral variation in phase velocities estimated from positive-offset data showed clearer lateral variation (Figure 5b), compared with both-offset (Figure 5a) and negative-offset analysis (Figure 5c). Phase velocity fluctuations at the geological boundary in the both-offset and negative-offset data are possibly generated from surface waves reflected at the geological boundary. The effect of the dip of the geological boundary also contributes to generating more noise, associated with energy reflected back from the boundary.

The numerical simulation (Figure 5) demonstrated that if we observe a clear lateral variation in phase velocities, then using either positive- or negative-offset data (relative to the high-to-low phase velocity direction) contributes to improving the accuracy of phase velocity estimation.
Figure 8. Comparison between dispersion curves obtained from conventional CMPCC analysis and those from window-controlled CMPCC analysis. (a) Without window control. (b) With window control ($\alpha = 0.5$). (c) With window control and median filter. The location of each CMP is shown in the map in (d). Because of the limited interval between CMPs from south to north in our processing (every 12.5 m), the positions of the CMPs do not coincide exactly with the source–receiver line.

Application to field data

Data and results

We performed window-controlled and direction-controlled CMPCC analyses on a three-dimensional (3D) seismic data set acquired in the Yamagawa geothermal field (Figure 6), located close to the Kagoshima Graben, Ata Caldera and a volcanic–tectonic depression. Although this survey was originally designed as a seismic reflection investigation, we can use the
multichannel data for our surface wave analyses. The Yamagawa geothermal power plant is located on host rock (i.e. dacite) in a depression surrounded by faults (Aoki et al. 2017). Near-surface deposits such as scoria from the Kaimondake volcano, followed by a 100 m layer of pyroclastic rocks (composed of pumice flows, and sand and gravel deposits), can be identified from the surface (Okada et al. 2000). The information about heterogeneous shallow formations is crucial in geothermal exploration, because it allows us to relate outcrops with subsurface geothermal reservoirs, and to design efficient drilling operations.

The 3D seismic data were acquired using vibrators as sources and geophones as the recording system. Both source and receiver intervals are $\sim 10$ m. We analysed seismic data for which source–receiver distance was $< 200$ m. To apply the CMPCC analysis to the 3D seismic data, we followed the processing workflow of Ikeda and Tsuji (2015). Because sources and receivers were spatially distributed on the ground surface, we collected cross-correlations into CMP bins, with a bin size of $25 \times 25$ m. To increase the spatial resolution, we overlapped the bins, and defined 34 CMPs at every 12.5 m around the survey line (412.5 m from west to east direction) (Figure 6). We then calculated dispersion curves at each CMP (every 12.5 m). Examples of the shot gathers from the field data around the survey line can be seen in Figure 7.

In the window-controlled CMPCC analysis, we tested the wavenumber resolution parameter $\alpha$ in Equation (2) from 0.4 to 1 (every 0.1). Considering the trade-off between the accuracy of phase velocity estimation and lateral resolution, we decided on $\alpha = 0.5$ as the best compromise. Comparisons of the dispersion curves obtained before and after applying the window-controlled analysis are displayed in Figure 8.

To distinguish positive-offset and negative-offset directions in the direction-controlled CMPCC analysis, we selected cross-correlation data based on the angle of the source-CMP line with respect to the west–east direction ($\phi$ in Figure 9). Because the sources and receivers were not in a straight line, we defined sources positioned within $-10^\circ < \phi < 10^\circ$ to give positive-offset data, and we defined negative-offset data as resulting from source-CMP angles less than $-170^\circ$ or more than $170^\circ$ (Figure 9). The first and the last CMP positions in our survey line are shown in Figure 10(a) and 10(b). The number of receiver pairs at the end of the west side is limited due to the bending line geometry (Figure 10c). The dispersion curves in Figure 11 were obtained using the conventional CMPCC gathers, the positive-offset CMPCC gathers, and the negative-offset CMPCC gathers. We show the dispersion curves derived both from the window-controlled analysis and direction-controlled analysis in Figure 12. We also display the phase velocity distribution derived from positive-offset data with the window-controlled analysis and all CMPs in the west–east direction in Figure 13(a). From the observed phase velocity distribution, we roughly estimated the $V_S$ distribution by transforming $1.1 \times$ observed phase velocity vs. one-third of observed wavelength into an apparent $V_S$ vs. depth section (e.g. Heisey et al. 1982; Foti et al. 2014) (Figure 13b).

To estimate $V_S$ structures from the dispersion curves, we applied genetic algorithm (GA) inversion (Goldberg 1989), using dynamic mutation and elite selection (Yamanaka and Ishida 1996) for dispersion curves derived from CMPCC analysis using both window-controlled and direction-controlled approaches (Figure 13a). Because phase velocities at high frequencies cannot be estimated at some CMPs (e.g. on the western side), the inversion results at shallower depths were not stable. To stabilise the inversion, we interpolated and extrapolated phase velocities in higher frequencies by using the inverse distance weighting interpolation (white shaded area in Figure 13a). We applied the moving average filter to the dispersion curves to remove velocity fluctuation.

In our inversion, we compared observed dispersion curves with theoretical fundamental mode dispersion...
curves of Rayleigh waves computed by the compound matrix method (Saito and Kabasawa 1993). The search range for \( V_S \) and the thickness of each layer were set to \( \pm 30\% \) for the five-layered reference models, which were defined from the apparent \( V_S \) model in Figure 13(b). P-wave velocity and density were obtained from empirical equations of Kitsunezaki et al. (1990) and Ludwig, Nafe, and Drake (1970). In the GA inversion, we set 100 and 200 as the initial population and generation, respectively. We applied 20 trials with different initial populations. The final inverted \( V_S \) models were defined as the average of these 20 trial models (Figure 14a and 14b). We compare the GA inversion results (Figure 14a and 14b) with the P-wave seismic reflection profile (Figure 14c).

**Discussion and interpretation**

When we applied the conventional CMPCC analysis or the window-controlled analysis (Figure 8a and 8b), one can see that phase velocity on the west side (e.g. the CMP at 5175 m) is higher than that in the east area (the CMP at 5350 m), indicating the presence of high \( V_S \) material on the west side of the survey line. At the CMP 5175 m, a phase velocity discontinuity in the frequency range of 11–14 Hz can be improved by applying the window-controlled analysis (Figure 8a and 8b). Similar improvement can also be seen at other CMPs. Although the window-controlled analysis modified phase velocity fluctuations that are probably related to lateral heterogeneity, it is difficult to improve phase velocity estimation at lower frequency ranges. This is because we need to keep receiver pairs with longer receiver spacing to maintain the accuracy of phase velocity estimates at longer wavelengths.

In direction-controlled analysis (Figure 11), we could see that positive-offset data at the 5337.5 m CMP (close to a geological boundary) derives more reliable phase velocity in the 4–12 Hz frequency range than the others (note the large and continuous amplitude value in dispersion image) (Figure 11b). At higher frequencies at the 5175 m CMP, phase velocity discontinuities in both-
and negative-offset cases (Figure 11a and 11c) were suppressed in the positive-offset analysis (Figure 11b). The dispersion curve for window-controlled CMPCC and direction-controlled CMPCC analyses combined (Figure 12) demonstrates that the positive offset case (Figure 12b) showed higher stability and greater amplitude in the dispersion image at selected phase velocities, compared with both-offset data and negative-offset data (Figure 12d).

We identify a phase velocity trend decreasing from west to east along the survey line (in dispersion curves at all CMPs; Figure 13a). A clear lateral variation in phase velocity around 5250 m could be caused by the geological boundary (Figure 13a and 13b). The $V_S$ distribution results derived from GA inversion of positive-offset data with the window-controlled analysis (Figure 14a and 14b) also demonstrate the high $V_S$ lithology on the western side of the geological boundary. The seismic reflection profile (Figure 14c) showed that a lateral discontinuity (i.e. a geological boundary) is located from $\sim 5150$ to $\sim 5250$ m at greater depths. Because the boundary between the softer and harder materials shown in our $V_S$ model (Figure 14a and 14b) is consistent with the location of the discontinuity imaged on the reflection profile (Figure 14c), the local geological heterogeneity we revealed in this study could be related to the discontinuous features deeper in the section. Furthermore, on the eastern side of the geological boundary, $\sim 10$ m of soft sediment ($V_S < 350$ m/s) seems to cover the higher $V_S$ formation shown in the GA inversion results (Figure 14a and 14b). These shallow lithology variations could not be identified in the low-frequency reflection profiles (Figure 14c) and possibly reflect local volcanic deposits recognised in boreholes (Okada et al. 2000).

**Summary**

To characterise heterogeneous geological structures in geothermal fields, we proposed extending CMPCC
Figure 12. Observed dispersion curves with (a) window-controlled analysis using both-offset data, for CMPs at 5175 m, 5337.5 m and 5350 m. (b) As (a) but with window-controlled analysis using positive-offset data only. (c) As (a) but with window-controlled analysis using negative-offset data only. (d) Amplitude of dispersion images at picked phase velocities for all cases in (a)–(c).

analysis with either or both of a window-controlled CMPCC analysis and a direction-controlled CMPCC analysis. In the direction-controlled analysis, we extract surface wave phase velocities from CMPCC gathers limited to either positive- or negative-offset direction data. Our numerical simulation study demonstrated that using the direction-controlled CMPCC analysis improves the stability of phase velocity estimation near a geological boundary. By applying these analyses to field seismic data acquired at the Yamagawa geothermal field, we identified clear lateral variation in phase velocity at the western end of the survey line. The inverted $V_S$ profile
from our CMPCC analysis reveals local heterogeneous structure, which cannot be imaged on the reflection seismic profile. Both simulation and field experiments show that by selecting the direction of wave propagation we are able to improve the lateral resolution of surface wave dispersion curves, reducing the influence of scattering effects at sharp lithological boundaries and of the dip of the boundary. CMPCC analysis using either positive- or negative-offset data would work well if lateral variation of phase velocities can be clearly observed. In conclusion, our proposed CMPCC analysis could be effective in revealing sharp lateral variations with higher spatial resolution in the geothermal field.

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