Model-based ground-roll attenuation with updating quality factors

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SUMMARY

Model-based modeling and subtraction of surface waves have proven quite successful during the last few years. In a layered half-space viscoelastic model, each layer is characterized by its thickness, P- and SV-wave velocities, density, and P- and SV-wave quality factors. A method based on estimating the layer properties for each layer by matching the dispersion spectra of seismic and model-predicted synthetic data through genetic algorithm in surface-wave inversion has successfully been used. For computationally reasons, fixed quality factors have been used in the inversion process (Bai and Yilmaz, 2018). To mitigate the deficiencies due to this restriction, the synthetic data generated from the optimal model is adaptively subtracted from the shot gathers. However, since the quality factors can significantly attenuate amplitudes and cause phase shifts in seismic data, both practical applications and sensitivity analysis indicate that updating the quality factors are also important and necessary. In this paper, we illustrate the model-based method with the update of quality factors through a 3D seismic survey.

INTRODUCTION

Surface waves can generate coherent noise in seismic surveys. The coherent noise is usually known as ground roll, which is typically characterized by low frequencies, high amplitudes, and strong wave dispersion due to seismic attenuation. In practice, ground roll can significantly degrade data quality.

Based on the propagation properties of surface waves, various methods have been developed to attenuate such noise. Traditional filtering methods in f-k or τ-p domains (Carry and Zhang, 2009) are widely used to eliminate such noise. Despite their popularity, these methods suffer from problems such as irregular trace spacing, data aliasing and incomplete separation of signal and noise in the transform domain. As alternative to the filtering methods, different model-based techniques have been developed. The techniques usually implement surface-wave inversion to estimate an earth model, generate synthetic data from the model, and subtract the synthetic data from the seismic data. The dispersion spectrum of a shot gather can be calculated from its linear Radon transform (Luo et al., 2008). A dispersion curve, which expresses the relationship between frequencies and phase velocities, is extracted from the spectrum. By matching the dispersion curves obtained from seismic and synthetic data, an optimal earth model can be obtained (Park et al., 1998; Douma et al., 2014). However, it might be difficult to identify and pick the dispersion curves in practice. Alternatively, in order to obtain an optimal earth model in the surface-wave inversion, Dou and Ajo-Franklin (2014) presented a method which directly matches the dispersion spectra, while Groos et al. (2017) showed a method minimizing the misfit of the least-squares norm of the normalized wavefields.

The propagation properties of surface waves are directly related to the physical properties of near surface. Bai and Yilmaz (2018) simulated surface-wave propagation through propagator matrix method in layered viscoelastic media and generated synthetic data through Green's function. In a layered viscoelastic model, each layer is characterized by its thickness, P- and SV-wave velocities (V_p and V_s), density, P- and SV-wave quality factors (Q_p and Q_s). By updating the thickness, V_p and V_s while fixing the quality factors Q_p and Q_s in each layer, an optimal model is obtained through the match of dispersion spectra of seismic and synthetic data in surface-wave inversion. The synthetic surface wave generated from the optimal model is adaptively subtracted from its corresponding seismic data. However, practical applications of the method and sensitivity analysis of objective function indicate that updating Q_p and Q_s plays a crucial role due to fact that the quality factors can significantly attenuate amplitudes and cause phase shifts in seismic data. In this paper, we therefore update the thickness, V_p, V_s, Q_p and Q_s in each layer for an optimal viscoelastic model in surface-wave inversion. Like the previous work, we gradually remove ground roll from shot gathers via a multi-scale technique. We demonstrate the necessity of Q_p and Q_s updates and the success of such estimated models for ground-roll attenuation on a 3D seismic survey.

THEORY

For a layered half-space viscoelastic model $\mathbf{m}$, the misfit between the dispersion spectra of seismic and model-predicted synthetic data is measured by an objective function J for a shot gather

$$J(\mathbf{m}) = ||\mathbf{s} - \mathbf{o}||_2, \tag{1}$$

where $\mathbf{o}$ is the dispersion spectrum of the shot gather, $\mathbf{s}$ is the dispersion spectrum of the synthetic data generated from $\mathbf{m}$, and $||.||_2$ is the L_2-norm of the differences between $\mathbf{o}$ and $\mathbf{s}$. In the model $\mathbf{m}$, each layer is characterized by its thickness (h), V_p, V_s, density, Q_p and Q_s. We calculate multimode phase velocities at each frequency through secular equation, simulate surface-wave propagation through propagator matrix method (Thomson, 1950; Haskell, 1953), and generate the synthetic data through Green's function from the model $\mathbf{m}$. The spectra $\mathbf{o}$ and $\mathbf{s}$ are obtained through high-resolution linear Radon transform from the shot gather and the synthetic data, respectively. Each spectrum is normalized by its maximum spectrum amplitude in order to preserve relative amplitudes.

The surface-wave inversion is a bound-constrained optimization problem, for which we seek an optimal model $\mathbf{m}$ that minimizes the objective function $J(\mathbf{m})$

$$\begin{aligned} &\underset{\mathbf{m}}{\text{minimize}} \quad J(\mathbf{m}) \\ &\text{subject to} \quad m_i^l < m_i < m_i^u,\ i = 1, 2, ..., n, \end{aligned} \tag{2}$$

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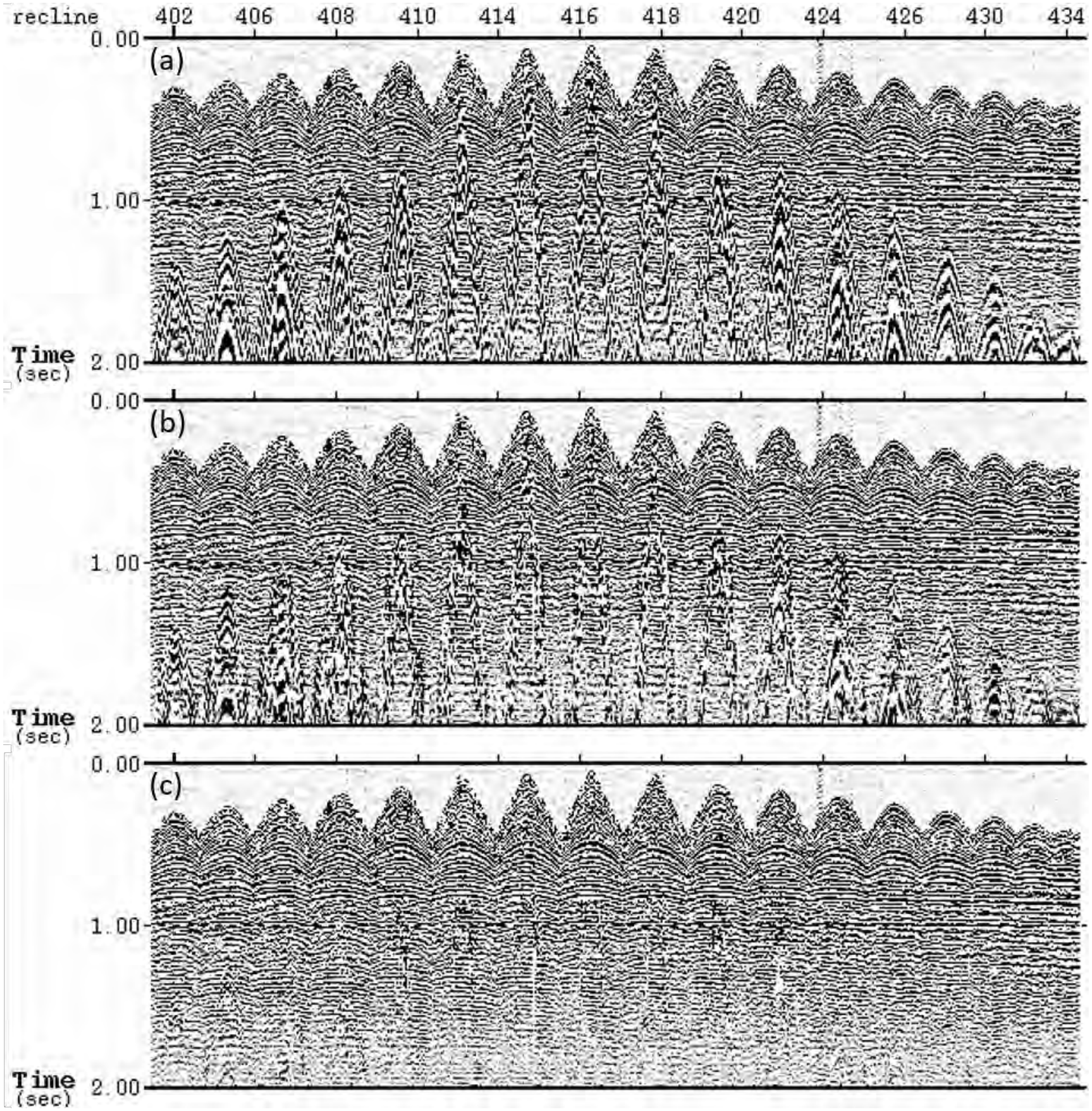

Figure 1: Ground-roll removal. (a) A raw shot gather with strong ground roll throughout receiver lines. (b) The shot gather after one cycle of GA and adaptive subtraction of ground roll. Ground roll is partially removed. (c) The shot gather after 8 iterations of GA and adaptive subtraction. Ground roll is almost fully removed.

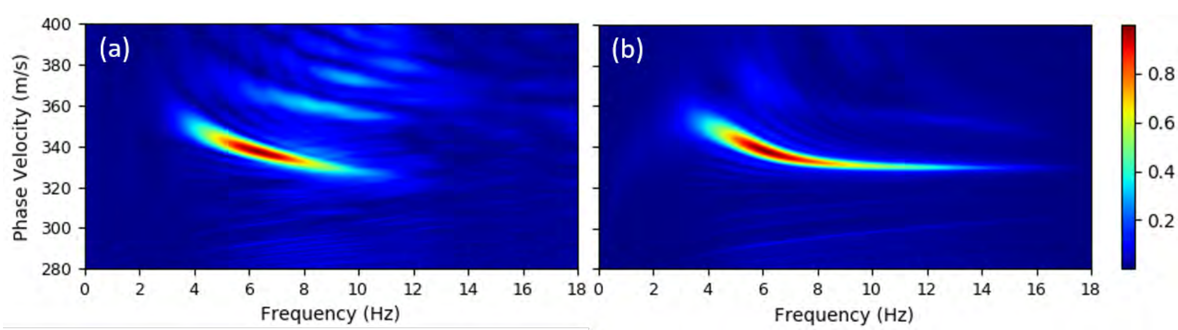

Figure 2: Dispersion spectra obtained from seismic and synthetic data. (a) The spectrum obtained from the shot gather shown in Figure 1(a). (b) The spectrum computed from the synthetic data modeled from the optimal layer parameters.

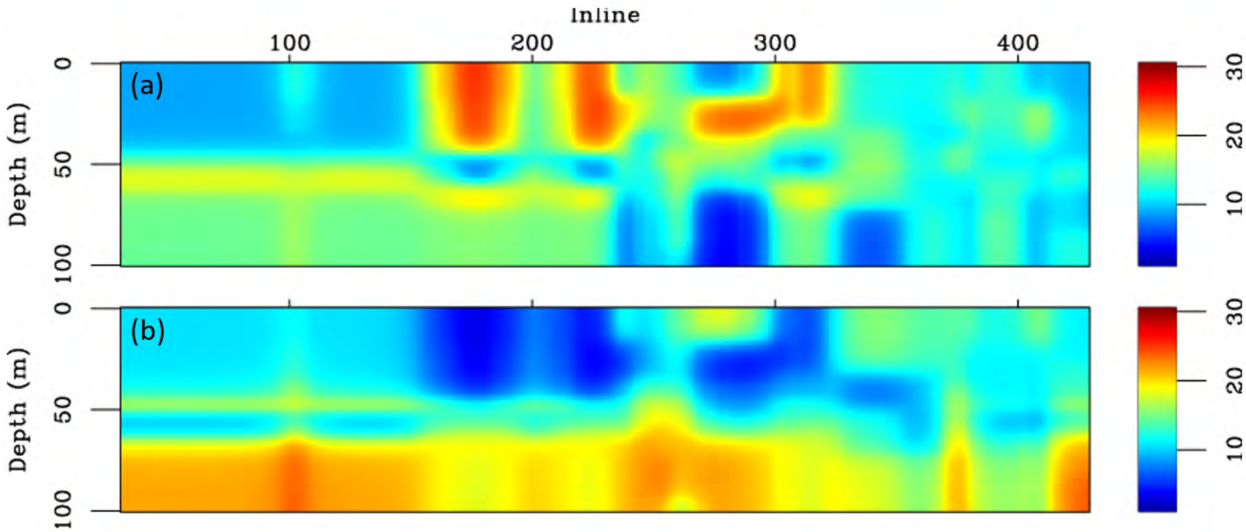

Figure 3: (a) Q_p and (b) Q_s sections along a cross-line from the 3D survey. Q_p and Q_s are extracted from the optimal models which are obtained from the surface-wave inversion.

where m_i is the i^{th} parameter of the layered model $\mathbf{m}$, m_i^l and m_i^u are the lower and upper bounds of m_i, respectively, and n is the number of parameters in $\mathbf{m}$. In each layer of $\mathbf{m}$ we update its h, V_s, γ, Q_p, and Q_s, where γ is V_p/V_s. According to the propagator matrix method, the thickness of the bottom layer is infinite. As a result, we do not update h in the bottom layer. Since surface-wave propagation is more sensitive to the SV-wave properties, we directly update V_s. By setting the lower bounds of γ as 1, we make sure that V_p is always greater than V_s. Consequently, we update γ instead of V_p for each layer. Gardner's equation is used to calculate density from V_p (Gardner et al., 1974). The inversion is a nonlinear problem and, hence, $J(\mathbf{m})$ can have multiple local minima. To avoid local minima, we use genetic algorithm (GA) method (Whitley, 1994), a derivative-free search approach toward globally optimal regions, for the solution of the inversion problem.

Once an optimal model is obtained from GA, synthetic data is generated from the model and is adaptively subtracted from a shot gather. With the updated shot gather, we repeat GA and adaptive subtraction so that ground roll is gradually removed from the shot gather. The multi-scale technique mitigates the limitations of 1D modeling to make sure that this method is applicable in practice. Moreover, in the objective function $J(\mathbf{m})$, we compare the complete signal content of dispersion spectra, including fundamental mode, high-order modes, leaky modes, acquisition geometry, and processing effects for the model $\mathbf{m}$. This also makes the method suitable in practice.

EXAMPLES

The method is demonstrated on a 3D seismic survey. A shot gather is shown in Figure 1(a). Ground roll, characterized by low frequencies, low velocities and high amplitudes, is observed on each receiver line. We use 5-layer models for ground-roll attenuation. Given a 5-layer half-space model, a vertical force is applied to generate synthetic surface-wave data with frequencies up to 18 Hz. To evaluate the extent to which we can constrain each parameter for GA, we first specify some reference values for each parameter according to first arrivals and ground-roll cones. Next we perturb one parameter while fixing other parameters, do forward modeling, and compare resulting synthetic data with seismic data to determine the parameter's bounds. As a result, the thicknessns are limited between 3 meters and 30 meters, γ ranges from 1.3 to 5.2, and the lower and upper bounds of Q_p and Q_s are 1 and 30, respectively. Table 1 shows the bounds of V_s in each layer for GA in the surface-wave inversion. An optimal model for a shot gather is obtained by the surface-wave inversion. The synthetic shot gather generated from the optimal model is adaptively subtracted from the shot gather. 30-point filters are designed and applied in sliding windows of 150 ms for the adaptive subtraction.

Table 1: V_s Bounds for GA

Layer	$V_{s,min}$(m/s)	$V_{s,max}$(m/s)
1	30	600
2	100	700
3	150	800
4	150	800
5	150	800

In surface-wave inversion, an optimal model is obtained by matching the dispersion spectra obtained from seismic data and synthetic data which is generated from the optimal model. Figure 2(a) shows the dispersion spectrum obtained from the shot gather shown in Figure 1(a) and 2(b) shows the spectrum of the synthetic obtained from the optimal model after inversion for the gather given in Figure 1(a). Notice the similarity of the two spectra. Optimal model estimation is based on matching the dispersion spectra but the ground-roll removal is done in the time-space domain by adaptive subtraction of the modeled ground roll. As shown in Figure 1(b), ground roll is partially removed from the shot gather after the first iteration. The Q_p and Q_s sections shown in Figure 3 are extracted along a cross-line from the optimal models obtained from the first surface wave inversion carried out on the entire survey. We observe very low Q_s in the middle parts of top layers which can cause very strong attenuation.

We examine the objective functions sensitivity to different model parameters in order to determine which parameters are significant. We have 5 independent parameters in each layer: h_i, V_{pi}, V_{si}, Q_{pi}, and Q_{si}, where the subscript i denotes the layer number. We investigate the influence of each parameter on the objective function $J(\mathbf{m})$ by perturbing them by $\pm 50\%$ while keeping the other parameters at their reference values as shown in Table 2.

Figure 4 shows how the perturbation effect of each parameter on the objective function $J(\mathbf{m})$ for the optimal model given in Table 2 obtained from the shot gather shown in Figure 1(a). We make several observations from these plots. The depth and sharpness of the valleys are proportional to the sensitivity of its corresponding parameter. The asymmetric shape of each valley suggests that the perturbation at different directions have different contributions; parameters less than the correct values usually result in larger errors in the objective function.

Table 2: Material property values of a 5-layer earth model

Layer	h	V_p(m/s)	V_s(m/s)	Q_p	Q_s
1	21.51	1056.10	274.64	19.38	19.06
2	22.27	1612.96	402.86	14.41	22.31
3	19.95	1273.17	431.29	12.12	3.92
4	22.96	2087.13	552.65	12.75	11.08
5	∞	2385.09	527.64	14.50	1.51

Clearly, V_{s1}, V_{s2}, h_1, V_{s5}, V_{s3} and V_{p1} are the most sensitive parameters. Among them, the objective function also demonstrates multiple local minima. Specially V_{s5} shows several local minima in the perturbation range. This is the reason why we chose the global optimization method in surface-wave inversion. Figure 4 also indicates that Q_{s1}, Q_{s2} and Q_{s3} have significant contributions to the objective function. As expected, small quality factors have more impact on the objective function than large quality factors. Practical applications verify that updating the quality factors is very important for the removal of ground roll for challenging dataset. As a result, beside updating h, V_p and V_s, we also update both Q_p and Q_s in each layer for ground-roll removal.

A total series of 8 GA and adaptive subtraction are implemented. As the iterations go on, ground roll is gradually removed from seismic data. Figure 1(c) displays the final shot gather. Compared to the raw shot gather, the removal of ground roll is very significant. The signal-to-noise ratio is greatly improved. Desired seismic events are recovered and, thus, are more continuous.

We demonstrated the necessity of including the quality factors in the inversion process and showed a successful implementation of the method on a real data. However, we have 24 independent parameters which need to be updated for a 5-layer model. Specifying the parameter bound for GA still remains as a challenge. GA is a derivative-free search method. Therefore it is necessary to evaluate as many models as possible in order to obtain a globally optimized solution, which leads to high computational costs. Additionally, more work is also needed to address the challenges such as the simplicity of model parameterization and speeding up the convergence of the non-linear optimization problem through different optimization methods and objective functions.

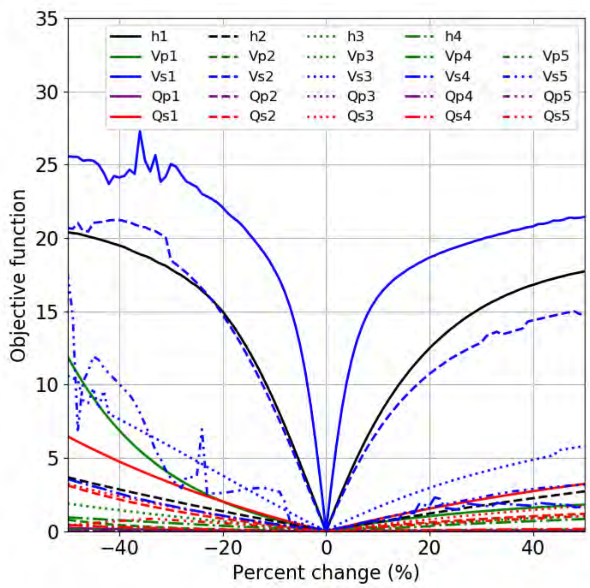

Figure 4: Objective function versus the perturbation of each model parameter. The horizontal axis is relative perturbation, with zero values corresponding to reference values in Table 2 for each parameter.

CONCLUSIONS

We present a model-based method for ground-roll attenuation. This method is based on a layered half-space model in which each layer is characterized by its thickness, V_p, V_s, density, Q_p, and Q_s. Given a viscoelastic model, we simulate surface-wave propagation through propagator matrix method and generate synthetic data through Green's function. By matching the dispersion spectra obtained from seismic and synthetic data, an optimal model is found for each shot gather. The synthetic data generated from the optimal model is adaptively subtracted from its corresponding seismic data. The sensitivity analysis indicates that Q_p and Q_s are very important to the objective function used in this method. As a result, beside updating the thickness, V_p and V_s, we also update Q_p and Q_s in each layer. Q_p and Q_s can significantly attenuate amplitudes and cause phase shifts in seismic data. We demonstrated the need and success of estimating these parameters in the inversion process through a real data example.

REFERENCES

Bai, J., and O. Yilmaz, 2018, Model-based surface wave analysis and attenuation: 80th Annual International Conference and Exhibition, EAGE, Extended Abstracts, 1–5.

Carry, P., and C. Zhang, 2009, Ground roll attenuation with adaptive eigenimage filter: 79th Annual International Meeting, SEG, Expanded Abstracts, 3302–3305, doi: https://doi.org/10.1190/1.3255545.

Dou, S., and J. Ajo-Franklin, 2014, Full-wavefield inversion of surface waves for mapping embedded low-velocity zones in permafrost: Geophysics, **79**, no. 6, EN107–EN124, doi: https://doi.org/10.1190/geo2013-0427.1.

Douma, H., E. Jenner, R. Kumar, and J. Al-Kanderi, 2014, Rayleigh-wave filtering through phase-velocity dispersion inversion and modeling: Application to north kuwait 3D seismic field data: 84th Annual International Meeting, SEG, Expanded Abstracts, 4279–4283, doi: https://doi.org/10.1190/segam2014-1173.1.

Gardner, G., L. Gardner, and A. Gregory, 1974, Formation velocity and density — The diagnostic basis for stratigraphic traps: Geophysics, **39**, 770–780, doi: https://doi.org/10.1190/1.1440465.

Groos, L., M. Schäfer, T. Forbriger, and T. Bohlen, 2017, Application of a complete workflow for 2D elastic full-waveform inversion to record shallow-seismic Rayleigh waves: Geophysics, **82**, no. 2, R109–R117, doi: https://doi.org/10.1190/geo2016-0284.1.

Haskell, N., 1953, The dispersion of surface waves on multilayered media: Bulletin of the Seismological Society of America, **43**, 17–34.

Luo, Y., J. Xia, R. Miller, Y. Xu, J. Liu, and Q. Liu, 2008, Rayleigh-wave dispersive energy imaging using a high-resolution linear radon transform: Pure and Applied Geophysics, **165**, 903–922, doi: https://doi.org/10.1007/s00024-008-0338-4.

Park, C., R. Miller, and J. Xia, 1998, Imaging dispersion curves of surface waves on multi-channel record: 68th Annual International Meeting, SEG, Expanded Abstracts, 1377–1380, doi: https://doi.org/10.1190/1.1820161.

Thomson, W., 1950, Transmission of elastic waves through a stratified solid medium: Journal of Applied Physics, **21**, 89–93, doi: https://doi.org/10.1063/1.1699629.

Whitley, D., 1994, A genetic algorithm tutorial: Statistics and Computing, **4**, 65–85, doi: https://doi.org/10.1007/BF00175354.

10.1190/segam2020-3426983.1