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How robust is Rayleigh-Marchenko imaging?

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Abstract

Rayleigh-Marchenko redatuming estimates up- and down-going Green's functions from virtual sources in the subsurface given band-limited pressure and vertical particle velocity seismic data and a smooth velocity model. The calculated Green's functions enable both focused and multiple-free structural imaging, as well as precise subsurface angle gathers. We achieve this by creating focusing functions that concentrate energy at any virtual subsurface place. It is not necessary to have prior knowledge of the source wavelet. This redatuming approach can be a powerful tool to eliminate free-surface and internal multiples, provided the media are acoustic and lossless. We assessed the robustness of Rayleigh-Marchenko redatuming and subsequent imaging by utilizing both synthetic elastic data and ocean-bottom cable field data, anticipating interference from mode-converted waves. Rayleigh-Marchenko redatuming can achieve a reasonable multiple-free subsurface seismic structure, given its acoustic assumption. The Rayleigh-Marchenko redatuming and subsequent imaging are especially suitable for ocean bottom, source-over-spread streamer, and horizontal borehole seismic data.

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Article Highlights

- This study assessed the robustness of Rayleigh-Marchenko redatuming and imaging on elastic data.
- To what extent does the application of Rayleigh-Marchenko redatuming affect the interpretation of seismic data that contains mode-converted waves?

Introduction

Geoscientists use seismic images to map hydrocarbon deposits. Traditional and popularly used methods, namely Kirchhoff migration, wave equation migration, reverse time migration (RTM), and least-squares migration, require that the input reflected seismic waves consist of primary events only, that is, events that have one reflection point. Multiples that have more than one reflection point must be removed first. Effective methods to remove free-surface-related multiples are available for marine pressure streamer data, ocean-bottom cable (OBC), and multi-component marine streamer data. This is not the case for internal multiples. Many internal multiple removal methods need a model of the subsurface. Some prerequisites are manual identification of primaries. The inverse scattering series (ISS) method correctly evaluates the kinematics of multiples, but knowledge of seismic source wavelets is vital. Additionally, the subsequent step of reducing multiples by subtraction can sometimes fail or negatively impact the primary signals.

Imaging methods that use both primaries and multiples to create subsurface seismic images were first published in 1991. They produced a seismic image by migrating both the primaries and deepwater multiples using ray-based Kirchhoff migration. Another method formulated a pre-stack depth migration that uses a model-based estimate of internal multiples. The following imaging methods also utilize internal multiples but are data-driven; these are least-squares migration, interferometric imaging, one-way wave equation migration, reverse time migration (RTM) for internal multiples, full

wavefield migration , and generalized internal multiple imaging . All these imaging methods, including the most popular ones mentioned earlier, require a fairly accurate and detailed velocity model to function effectively.

Marchenko and Rayleigh-Marchenko redatuming ; conversely, obtain focusing functions from the measured reflection response at the surface and an estimate of the direct arrivals between the focal point and the surface receivers, relying solely on a smooth subsurface model. Unfortunately, Marchenko redatuming requires co-location of sources and receivers and accurate knowledge and deconvolution of the source wavelet. Thus, Marchenko redatuming has so far limited real field applications. Marchenko redatuming acoustic approximation analysis was extensively done by . They compared a 2D marine field application with a representative synthetic model. They concluded that mode conversions can have a substantial impact on the recovered multiple-free reflection response. Nonetheless, acoustic multiple elimination significantly improves the images.

In this paper, we investigated the robustness of Rayleigh-Marchenko redatuming and subsequent imaging on elastic synthetic and field OBC data, where mode-converted waves are expected to interfere. Rayleigh Marchenko redatuming can manage both surface and internal multiples using dual-sensor, band-limited seismic data with an unknown source signature, for instance, ocean-bottom cable (OBC) seismic data.

Material and methods

For a detailed derivation of the Rayleigh-Marchenko equation, the reader is referred to . In this study, we created acoustic and elastic OBC synthetic data and compared the results. The acoustic case is intended as a reference when the Rayleigh-Marchenko theory presumptions are adequately met. The 2D synthetic reflection data was made using P-wave and density models (Fig. 1) that were changed after . We

included an S-wave velocity model based on the

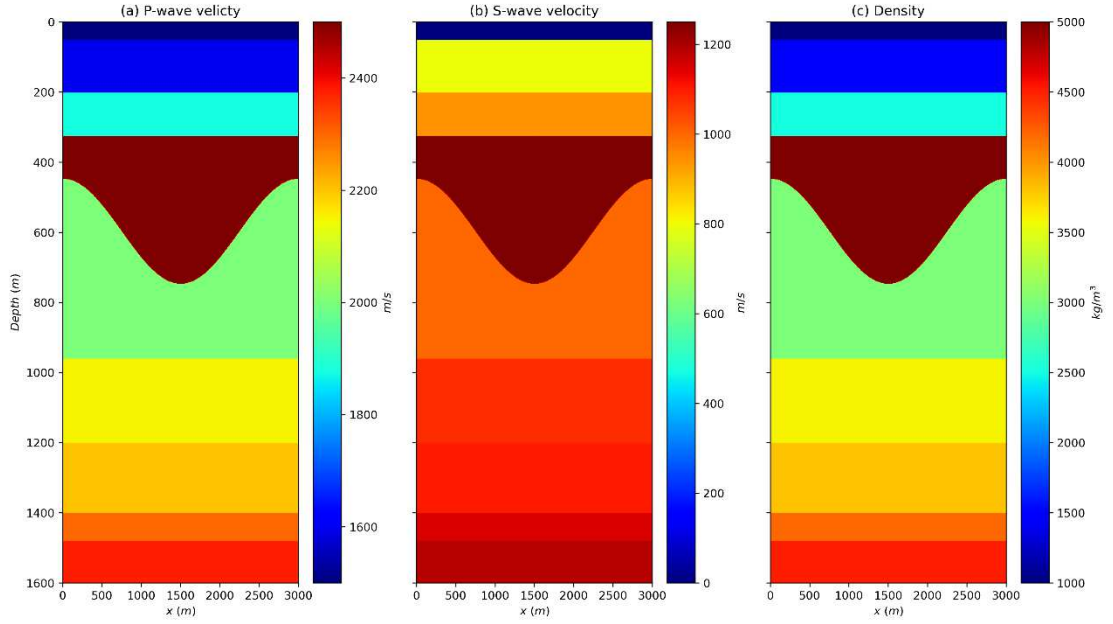


Fig. 1 (a) P-wave velocity, (b) S-wave velocity, and (c) density model used to create a synthetic acoustic and elastic OBC reflection dataset.

empirical relationship indicating that S-wave velocity is roughly half of the P-wave velocity . We acquired the OBC synthetic data by firing 376 shots at 8 m intervals and at a depth of 10 m. 376 receivers were distributed on the seafloor at 50 m every 8 m (Fig. 2). The two input data sets needed for the Rayleigh Marchenko technique were created using two models. The true model has been used to create the reflectivity from surface sources measured at the receivers near the sea bottom, including free-surface multiples. We used a finite-difference modeling program, *fdelmodc* , to simulate the acoustic and elastic reflection responses. Fig. 3 shows a comparison between the multiple-free zero-offset time section and zero-offset time sections of the acoustic and elastic pressure reflection data. Note the severity of the multiples in the data, especially the elastic reflection data, where s-waves are also present. As the Rayleigh-Marchenko formulation integrated free-surface multiples into the upgoing and downgoing particle velocity data, both surface-related and internal multiples were modeled to create the surface pressure (Fig. 4) and vertical particle velocity (Fig. 5) seismic reflection data.

The input data were detached into their upward and downward components in the frequency-wavenumber domain, utilizing

$$v_z^\pm = v_z \pm k_z/(\rho\omega)p$$

A smooth model has been used to estimate the direct arrival between the surface and the image point. Since the true model is not available in practice, we have used a smoothed version for our direct arrival calculations, assuming that an initial or reference velocity model is available or can be built via, for example, stacking velocity picking.

The acoustic Rayleigh-Marchenko redatum and imaging methods were also applied to a 2D line of a North Sea OBC dataset (Fig. 6). The red rectangle in Fig. 7 shows the imaging zone. The field Rayleigh-Marchenko imaging result is compared with a single-scattering imaging result.

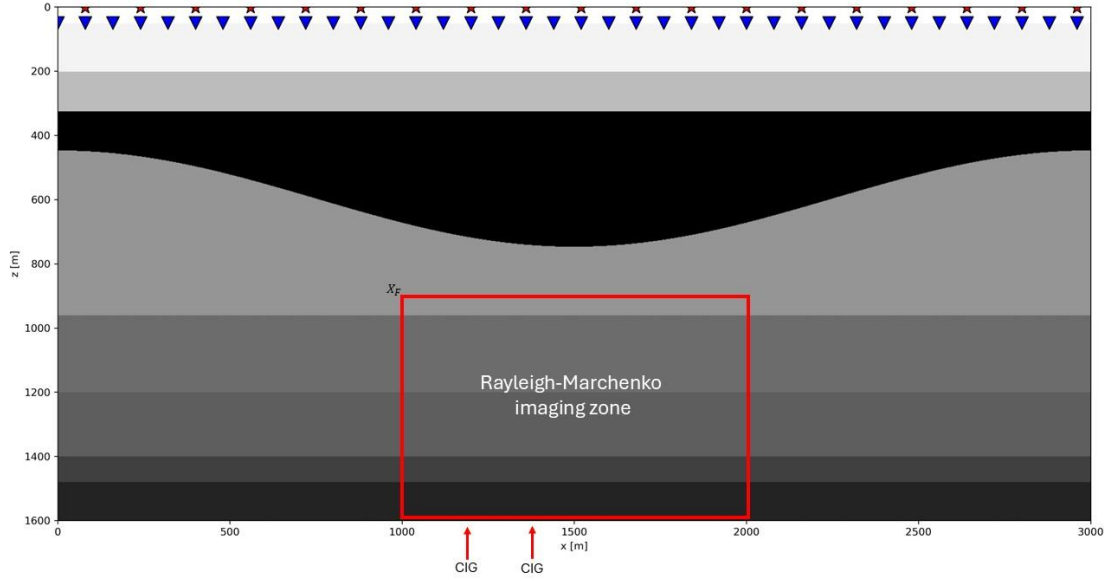


Fig. 2 Synthetic OBC acquisition. Blue triangles are receivers placed at the water bottom (50 m). Red stars indicate the shots taken near the sea surface (10 m).

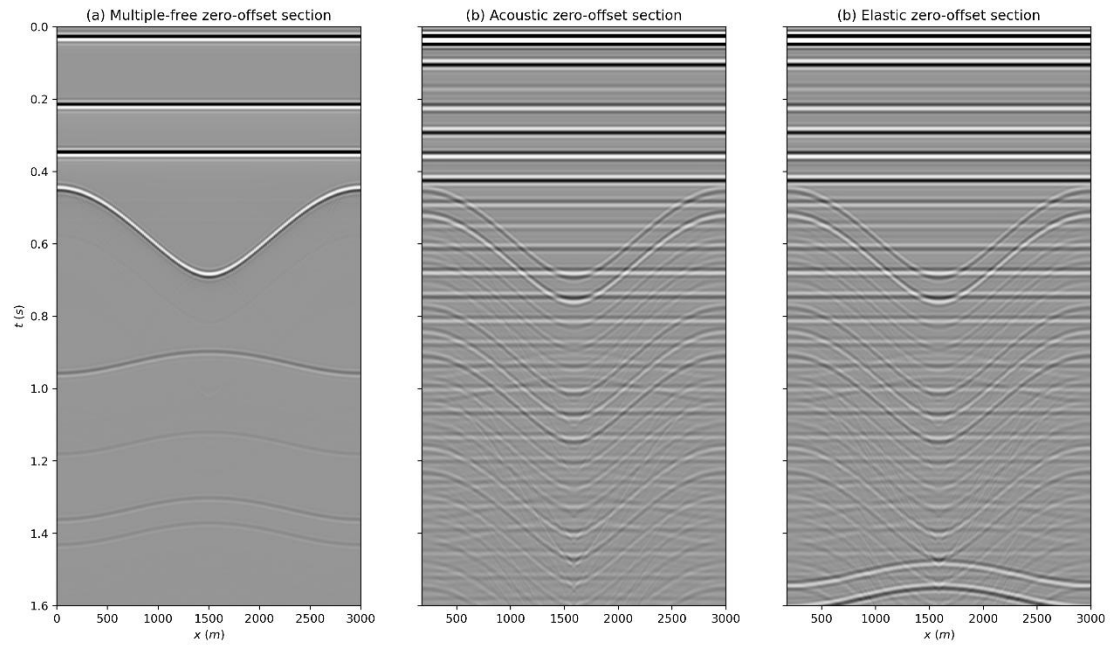


Fig. 3 Zero-offset gather: (a) multiple-free, (b) acoustic, and (c) elastic. Note the severity of the multiples in (b) and (c).

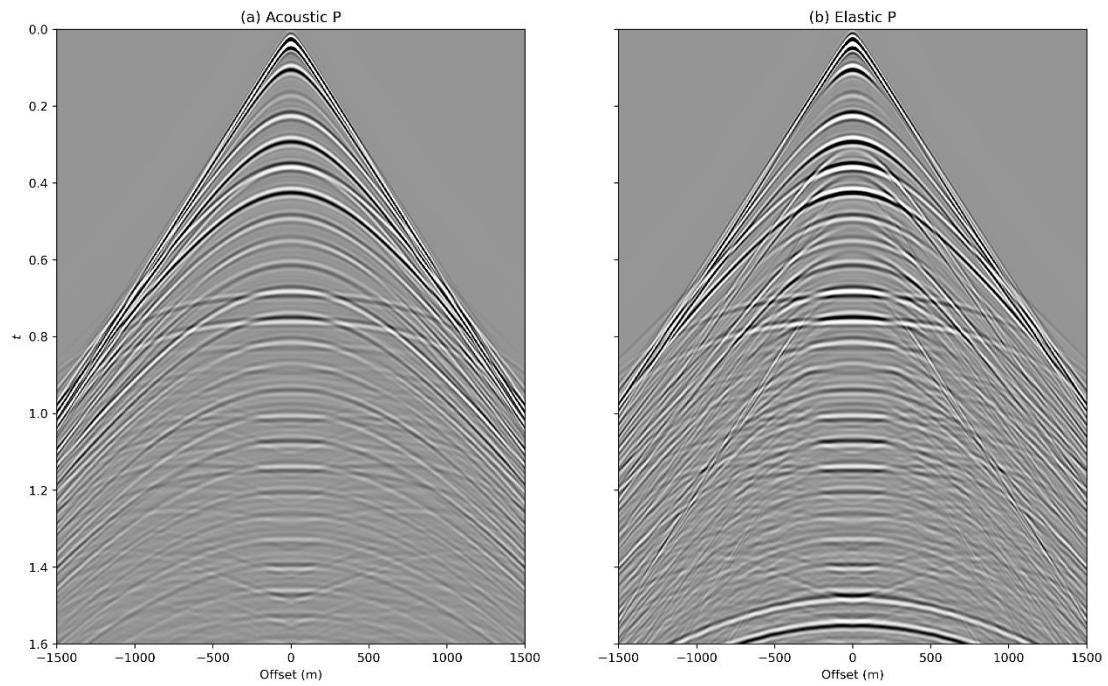


Fig. 4 (a) Acoustic pressure wavefield, P and (b) elastic P.

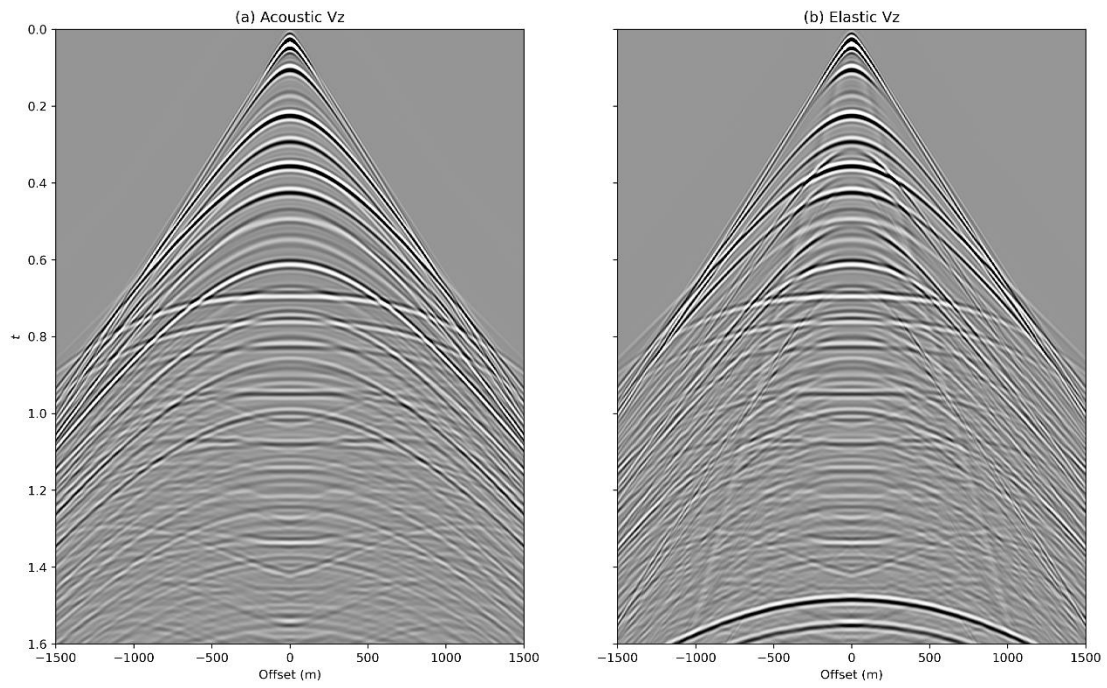


Fig. 5 (a) Acoustic vertical particle velocity gather and (b) elastic V_z .

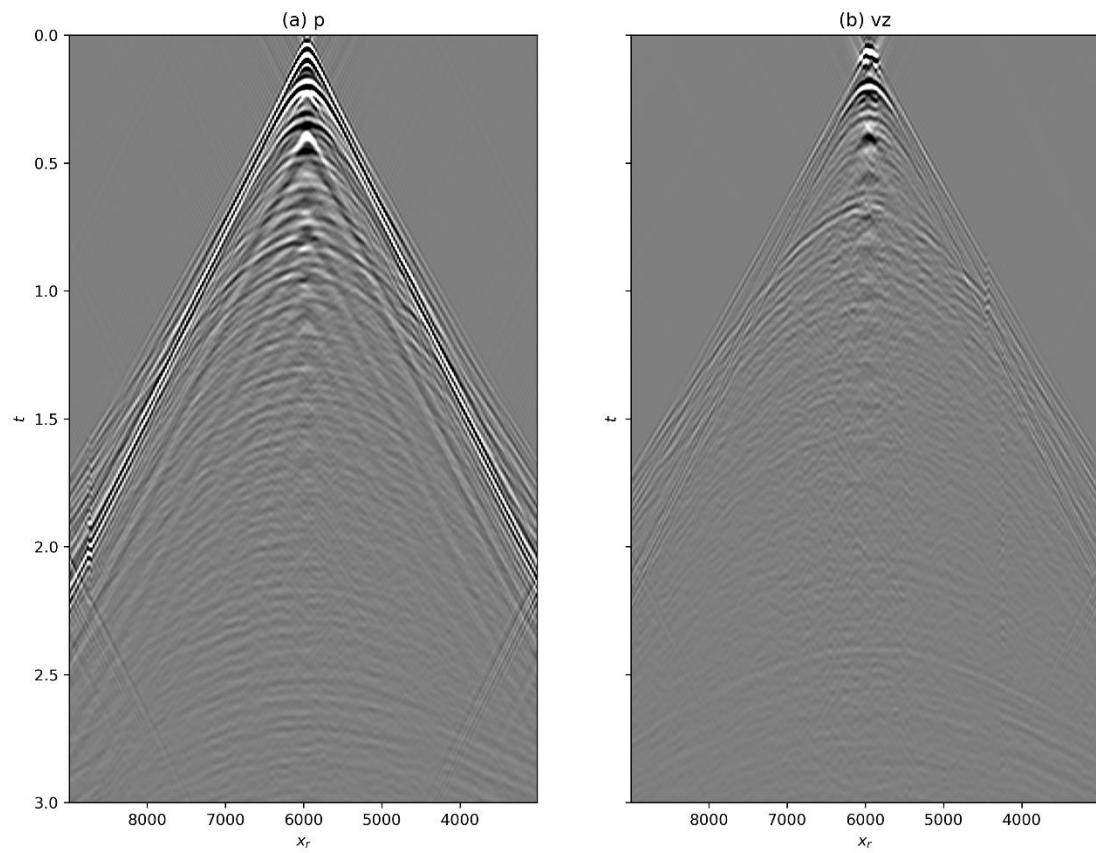


Fig. 6 OBC field data. (a) a full pressure shot gather and (b) a vertical particle velocity shot gather.

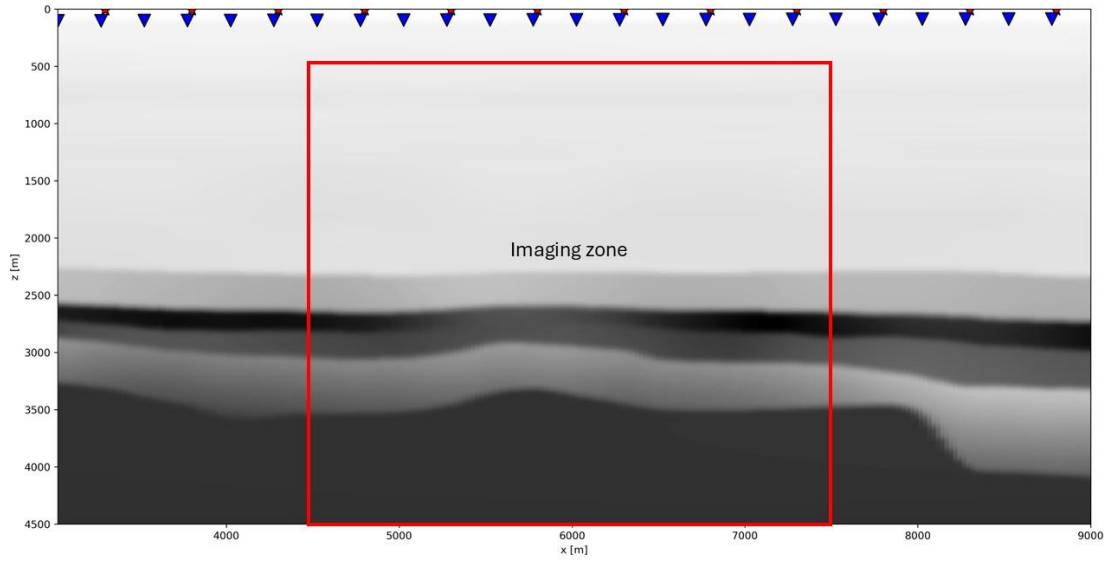


Fig. 7 Field OBC acquisition. Blue triangles are receivers placed at the water bottom (~ 80 -100 m). Red stars indicate shots taken near the sea surface (6 m).

Brief Theory

In order to get a target reflection response free of overburden-related multiples, Rayleigh-Marchenko redatuming deconvolves up- and downgoing Green's functions ($G^\pm$). Thus, Green's functions must be obtained before moving on to the multiple-elimination stage. The approach to addressing the scattering relationships between Green's functions and focusing functions ($f_1^\pm$), referred to as representation theorems, is motivated by fundamental physics. The Green's functions are attenuated with a temporal mute, save for two intersections with the focusing functions. The first (f_1^+/G^+) is indispensable and mandated by the program as a preliminary estimate, whereas the second is presumed to be negligible (f_1^-/G^-). These assumptions may be valid for sufficiently uncomplicated acoustic media where the initial overlap can be assessed, hence completely restricting the problem. On the contrary, in elastic redatuming, the first overlap encompasses a forward-scattered transmission coda, which is a transmission created by the overburden, incorporating conversions between

compressional and shear modes as well as so-called “fast multiples” . Currently, it is impossible to determine the forward-scattered transmission without a thorough understanding of the overburden. Additionally, the multiple-elimination technique raises the likelihood of a non-zero second overlap, which is nearly certain in an elastic medium due to the significant difference between P- and S-wave velocities. A comparable restriction on the elastic ISS is called monotonicity .

Here, we applied an acoustic Rayleigh Marchenko redatuming and subsequent imaging to synthetic acoustic, elastic, and field OBC data to analyze how severe the effect of mode conversion on acoustic Rayleigh Marchenko redatuming and imaging results is.

Results and discussion

Fig. 8 compares an acoustic green’s function obtained by a finite-difference modeling program at a focal point $X_F = (1000, 900) m$ (see Fig. 2) versus the acoustic Rayleigh-Marchenko estimates. We can see that the acoustic Rayleigh-Marchenko estimate is fairly accurate. Fig. 9 compares the result of an elastic Green’s function obtained by a finite-difference modeling program versus an acoustic Rayleigh-Marchenko estimate of the Green’s function but with the input of elastic data. Again, we can see a satisfactory match between the acoustic Rayleigh

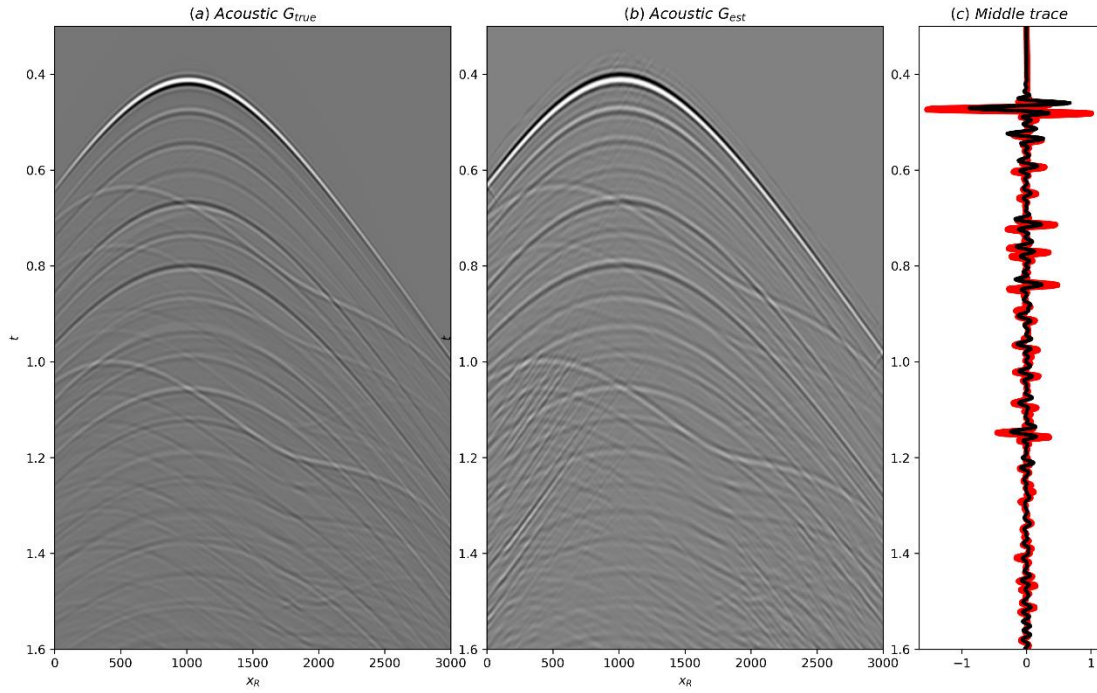


Fig. 8 (a) True acoustic green's function via forward modeling, (b) estimated green's function calculated by Rayleigh-Marchenko redatuming using acoustic data, (c) middle trace comparison of (a) against (b).

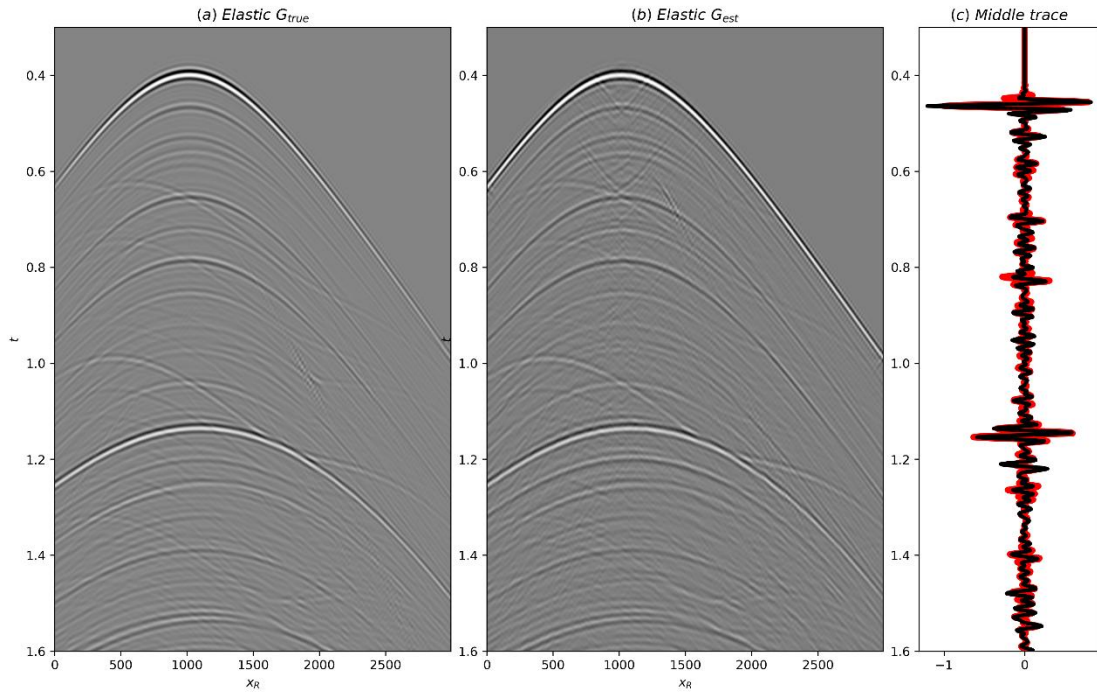


Fig. 9 (a) True green's function via forward modeling, (b) estimated green's function calculated by Rayleigh-Marchenko redatuming using elastic data, and (c) middle trace comparison of (a) against (b).

-Marchenko estimate and the true Green's function. For the target-oriented imaging, we produced a set of Green's functions at each depth level inside the red rectangle in Fig.

2 and used them directly to create images as well as true-amplitude common-image gathers (CIG) in the subsurface as described by . Fig. 10 shows a comparison of the targeted imaging results of acoustic data versus elastic data. The elastic input zero-offset section and a depth seismic reflectivity section are included as a reference for the imaging results. On Fig. 10d, we can see faint artifacts (top 2 red arrows ~ 1050 m & 1110 m), possibly remnants of shear multiples incorrectly handled by the acoustic Rayleigh-Marchenko redatuming. Similarly, the bottom two red arrows (~ 1520 m & 1590 m) are possibly artifacts caused by strong shear wave events corresponding to events 1.5 s and 1.75 s in Fig. 10a. Nonetheless, referring to the reflectivity section (Fig. 10b), all primary events in Fig. 10c and 10d were successfully imaged. Cancellation of all multiples is almost perfect in Fig. 10c. Fig. 11 shows CIG for acoustic input versus elastic input. Shear wave events obviously have some effect on the CIG. Still, all reflectors in the subsurface, as shown in Fig. 10d were successfully imaged.

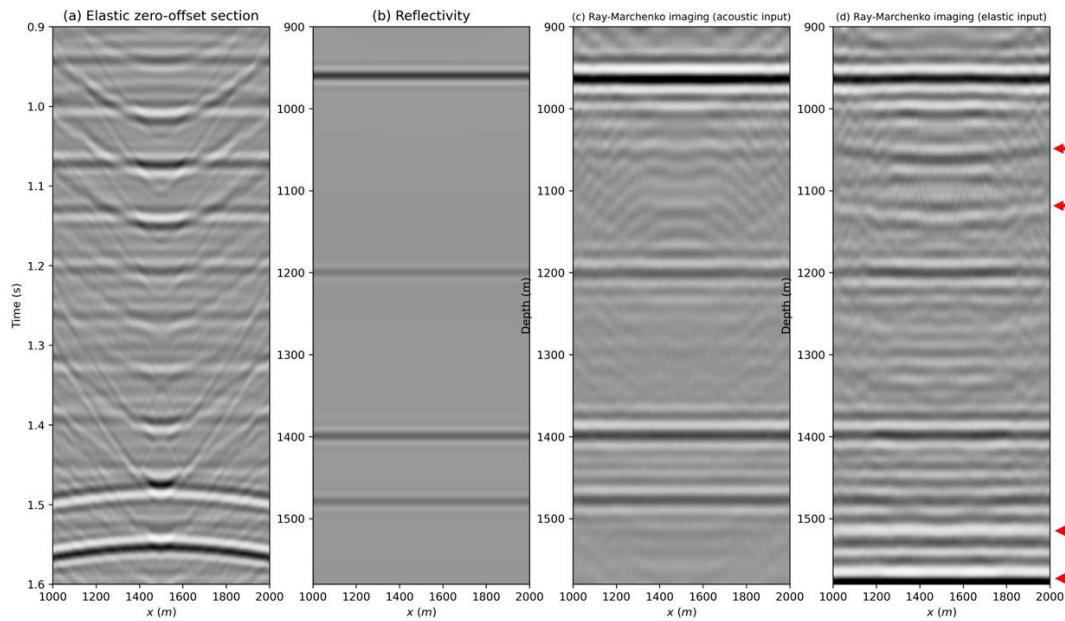


Fig. 10 (a) The input zero-offset section, (b) reflectivity (c) acoustic Rayleigh-Marchenko imaging on

acoustic data, (d) acoustic Rayleigh-Marchenko on elastic data.

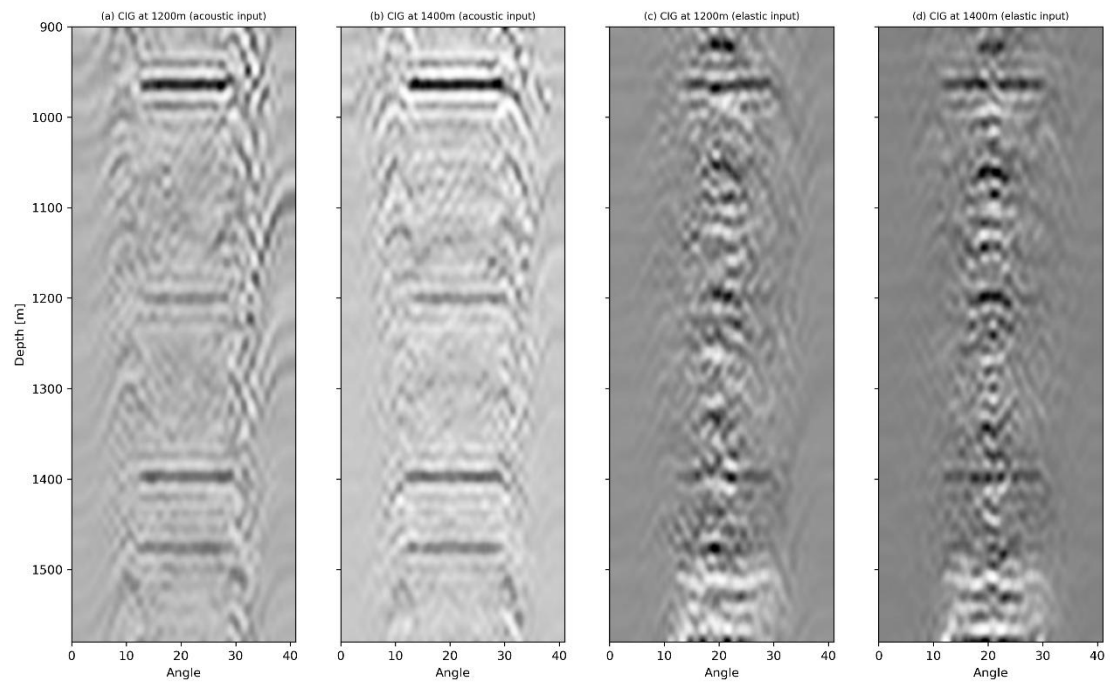


Fig. 11 CIG gathers (a) at 1200 m (acoustic input), (b) at 1400 m (acoustic input), (c) at 1200 m (elastic input), and (d) at 1400 m (elastic input).

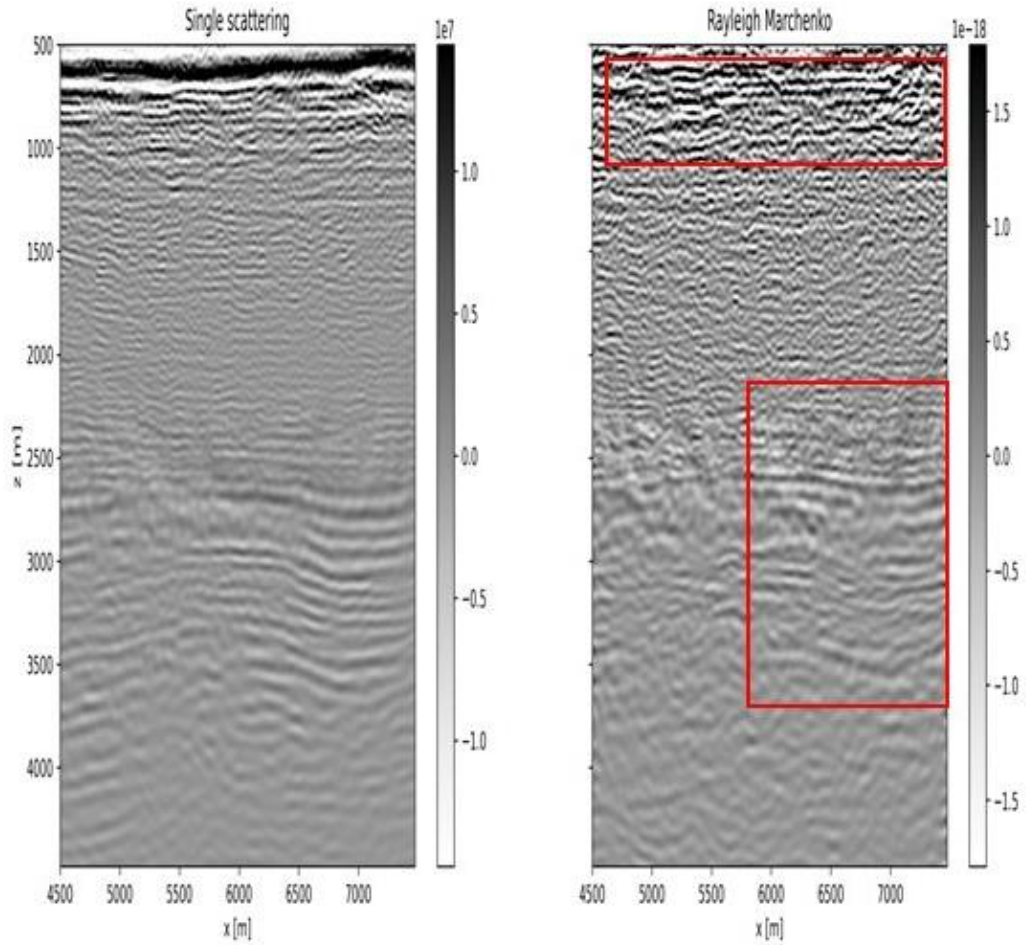


Fig. 12 Rayleigh-Marchenko imaging on a 2D field OBC data (a) single-scattering and (b) Rayleigh-Marchenko.

Fig. 12 displays the image created from Rayleigh-Marchenko redatuming and imaging that we applied on a 2D line OBC from the North Sea. For comparison, we also produced a single-scattering image of the up-going component of the particle velocity data. Fig. 12b shows that the Rayleigh-Marchenko image has reduced artifacts related to improper handling of multiples.

Conclusions

An investigation on elastic synthetic data confirms that acoustic Rayleigh-Marchenko redatuming can provide interpretable subsurface seismic images containing mode-converted waves. Nonetheless, significant shear wave events will influence the resultant CIG and amplitude versus offset analysis. Fortunately, the resulting seismic

image is adequate for a reasonable seismic interpretation. Additionally, the input data have undergone no preprocessing other than up- and down-going vertical particle wavefield separation. This is a huge cost saving in seismic processing, as no prior multiple removal is required.

Author contributions

Dr. Abdul Halim proposed the concept. Abdul Rahim performed the experiments. Dr. Abdul Halim and Abdul Rahim co-wrote the manuscript. Both authors participated in data analysis and manuscript discussion.

Competing financial interests

The authors declare no competing financial interests.

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