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REWARE: a seismic processing algorithm to retrieve geological information from the water column

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SUMMARY

When interpreting marine very high-resolution (VHR) single-channel seismic reflection data, the signal in the water column is generally considered as noise and is often eliminated by a water-mute application to focus on geological information under the seafloor. Alternatively, the signal in the water column can be used to study ocean currents or gas/fluid emissions. To provide images of the sedimentary formations and tectonic structures beneath the seafloor in shallow water regions, such as continental shelves and lakes, marine seismic reflection profiles are often acquired using a single-channel streamer and sparker-type source, providing VHR data, with limited penetration depth. To exploit the full potential of these single-channel data, we propose a simple algorithm, called REWARE (Recovery of Water-column Acoustic Reflectors). This algorithm allows to extract further geological information from the water-column data using open-source codes (Seismic Un∗x), adding the coherent signal from the previous shots, recorded in the water column, to the previous traces. The record length becomes longer while maintaining a very high trace-to-trace consistency. To demonstrate its efficiency, we present two examples of the REWARE processing in two different geological contexts: the East Sardinia shelf (Italy) and the North Evia Gulf (Greece). This method provides deeper images than with original data for seismic data acquired across steep slopes, such as canyons or continental shelf breaks. Thus, depending on the seafloor geometry and subseafloor structures, it is possible to image or map sediment layers and tectonic structures at depth, keeping a very high structural resolution.

Key words: Geophysical methods; Seismic instruments; Image processing; Seismic noise.

1 INTRODUCTION

Continental shelves and shallow water basins can be the locus of various sedimentary and tectonic processes leading to the development of complex organizations of sedimentary bodies and/or faulting and folding. Very high-resolution (VHR) seismic reflection is widely used for shallow water-depth investigations (<1000 m) to image these geological features. The source used is generally a sparker combined with a single or multichannel streamer. The processing of multichannel seismic data is widely detailed in the literature and several dedicated softwares exist (e.g. Yilmaz & Doherty 2001; Dondurur 2018; Kluesner *et al.* 2019). However single-channel processing is sometimes underestimated but is as essential as the processing of multichannel seismic data (Santos *et al.* 2021). Several authors have recently suggested (1) processing tools for single-channel data to improve the resolution of sparker seismic data, (2) new strategies of waveform analysis for deconvolution and random noise reduction, and also (3) complete processing workflows (e.g. Duchesne *et al.* 2007; Kluesner *et al.* 2019; Jun *et al.* 2020; Santos *et al.* 2021). These processing methods do not account for the signal in the water column. This signal is commonly used for oceanographic studies (e.g. Bakhtiari Rad & Macelloni 2020), current analysis, water temperature gradients (e.g. Ruddick *et al.* 2009) or gas and oil leaks. For subseafloor studies, the water-column data are generally ignored. However, the water-column data contain coherent signal, considered as 'noise' from the previous shot, which contains actual geological information. This information can be extracted to extend the trace length and observe geological features at greater depth than from the original data and typical processing.

The selection of acquisition parameters, such as record length, shot spacing and seismic energy output, for VHR single-channel seismic reflection data at shallow water depths can be challenging in the light of the quest for optimal seismic penetration depth and the complications due to bathymetric variations. For example, assuming acquisition parameters set for a water column of 50–100 m (sea-bottom is reached at 66 ms and its multiple at 132 ms) and a study area characterized by strong bathymetry variations (e.g. canyon heads or shelfbreak zones), the record time can be locally too short to record signal in the geological layers. An increase of the record length and shot interval would degrade the lateral trace-to-trace consistency of the data, that is, the lateral continuity of the geological signal. The objective here is to retrieve and use the coherent reflections from previous shots in the water column in order to obtain geological information at greater depth than from the originally acquired data.

We developed a processing algorithm called REWARE (Recovery of Water-column Acoustic Reflectors), using tools from Seismic Un∗x (Stockwell 1999; Cohen & Stockwell 2021) to retrieve the geological reflectors from the water-column data. This algorithm artificially increases the recording length, duplicating the data. It extracts the signal recorded in the water column of a seismic trace to add it after the previous trace to create a new seismic image down to greater depth than from the raw data. We tested this workflow on marine VHR seismic profiles from two examples: the East Sardinia shelf (Western Tyrrhenian Sea, Italy), dissected by deep canyons with a highly variable bathymetry (50–1000 m); and the North Evia rift basin (NW Aegean Sea, Greece), a sedimentary basin in a tectonically active system.

2 REWARE: PRINCIPLE

The resolution of the data mainly depends on the frequency band of the seismic source (Yilmaz & Doherty 2001). In particular, the vertical resolution is controlled by the signal frequency whereas the lateral resolution mostly depends on the width of the Fresnel zone, which is related to the signal frequency, but also the depth to the considered reflector and seismic velocities. Vertical resolution may be improved using deconvolution and 2-D migration helps improve lateral resolution (Yilmaz & Doherty 2001). Finer trace spacing increases trace-by-trace consistency (Dondurur 2018). In shallow water areas, it is important to record data with an optimal resolution and fine trace spacing. The shot interval dictates the record length, and thus the maximum depth of recorded reflections. When the bathymetry of the study area is variable, the record time can be too short in some places, and the signal of interest is cut by the end of the trace. In deep bathymetry areas, only the water column may be recorded on the seismic trace (Fig 1, down to time T). Variable bathymetry requires frequent changes in acquisition parameters leading to acquisition gaps, or the need to loop back during the survey, which is time-consuming. An alternative would be to set a longer shot interval to increase the signal penetration. However, an increase of investigation depth is usually associated with an increase of the source energy used—and thus the signal frequencies—and shot spacing. The expected vertical and lateral resolutions (lower frequency signal and trace-to-trace consistency) would be degraded.

When acquiring data of shots at a constant time interval, it is possible to set the record length equal to this shot time interval (T). With this acquisition parameter, the late arrivals from a shot n may still be recorded on the trace of shot $n + 1$ (Fig. 1). The useful observation of geological reflections from the previous shot in the water layer implies a sufficiently deep seafloor, which also avoids a too early multiple reflection, overlapping reflections of interest.

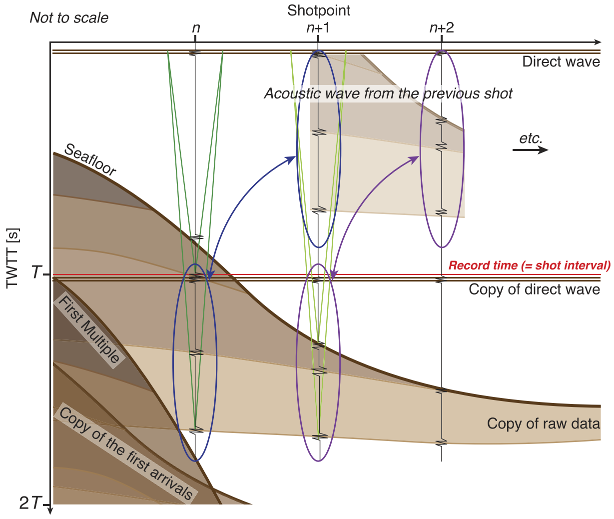

Figure 1. Diagram of the ray paths at increasing water depths illustrating the occurrence of reflections from previous shots, recorded in the water column, for short shot interval and record time of VHR seismic data. The record time is equal to the shot interval.

We consider a seismic section with N seismic traces, and a record length equal to the shot interval (T). The purpose is to extract the signal recorded in the water-column of traces 2 to N. This signal belongs to the traces 1 to $N - 1$, at times of T to $2T$.

3 PROCESSING ALGORITHM

The REWARE processing algorithm uses the open-source package Seismic Un∗x (Stockwell 1999; Cohen & Stockwell 2021). Shell scripts and further details about the procedure are presented in Supporting Information A.

We consider a seismic section with N seismic traces and a raw record length, T, in two-way traveltime (TWTT, Fig. 2a). The coherent signal, in the water column of a trace $n + 1$ between the sea level ($t = 0$) and the seafloor reflector, corresponds to late arrivals from the previous shot (trace n). The operation consists in adding the data of trace $n + 1$ at the end of trace n, starting from the record time T, and obtain a trace n with an extended record length of $2T$.

The algorithm comprises two steps (Fig. 2):

1) Extract two copies of the data: the first with traces 1 to $N - 1$ extracted (D1), and the second with traces 2 to N (D2) (Fig. 2a).

2) Merge both data sets D1 and D2 by concatenation of D2 after D1, in time (Fig. 2b). We obtain an updated seismic section with an extended record length, called SD. Note that a copy of the direct wave appears in the middle of the SD seismic profile.

The conditions to use REWARE are (1) a bathymetry allowing for the observations of coherent geological reflections from the previous shot above the seafloor reflector, and (2) equal record length and shot interval. Meeting this condition is mandatory to receive the late arrivals directly on a trace $n + 1$. Existing public data sets also check those conditions (e.g. see profiles HC-12; SB-102 and SB-143 in Sliter *et al.* 2008)

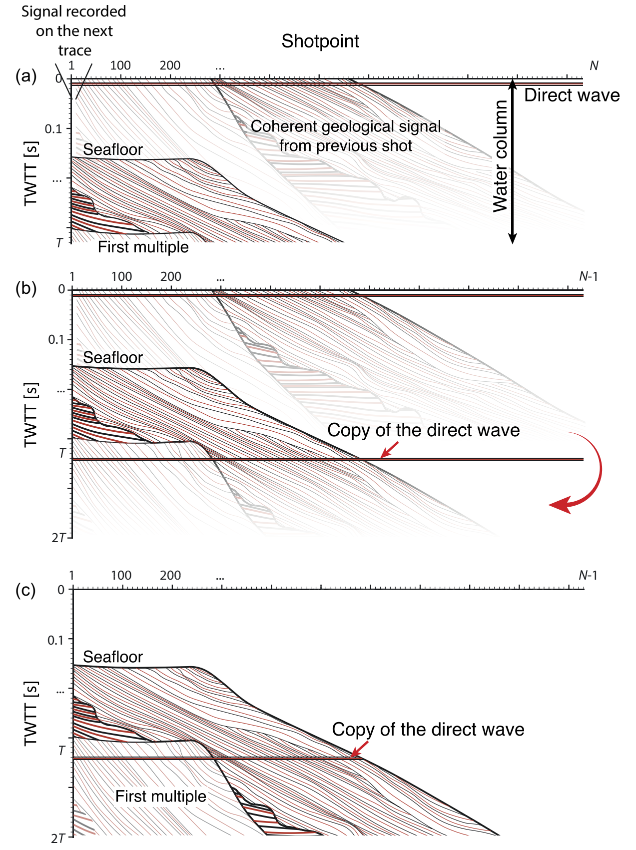

Figure 2. Sketches of the REWARE algorithm: (a) raw data, (b) merging of D1 and D2 and (c) resulting seismic section after muting of water-column information.

4 APPLICATION ON TWO EXAMPLES

The seismic processing workflow, incorporating the REWARE algorithm, applied to marine VHR single-channel seismic data, enables the utilization of signals typically regarded as noise in the water column. This workflow reduces the need for changing the acquisition parameters (shot interval, vessel speed and record length) during the acquisition surveys, when bathymetry varies rapidly, keeping a high trace-to-trace consistency, even in deeper areas.

We present applications of the REWARE algorithm to two VHR sparker seismic profiles acquired during two different surveys:

1) The METYSS 4 cruise (Gaullier & Watremez 2019) is dedicated to the architecture of submarine canyons of the Eastern Sardinian continental shelf (Western Tyrrhenian, Italy).

2) The WATER cruise (Chanier & Gaullier 2017; Chanier & Watremez 2021) aims to delineate the fault systems in thick sedimentary basins in the shallow North Aegean Sea (Greece).

The data used in these studies were acquired with a sparker source device. It generates controlled seismic energy by creating a spark in the water, which vapourizes the surrounding water and creates a plasma bubble. The collapse of the bubble produces an acoustic wave that propagate and reflect on the geological layers. In general, the frequency of a sparker source ranges between 0.3 and 5 kHz, depending on the type of electrode, the energy level and the depth of tow. In the two case studies presented below, the frequency of the sparker source ranges between 0.3 and 2 kHz.

After a correction of the acquisition geometry, each seismic profile is examined to look for geological reflectors recorded in the water column. The REWARE algorithm is used when the water column contains coherent signal, before applying a bandpass filter. For both examples, we chose not to apply further common seismic processing workflows, such as deconvolution, migration and gain recovery as these processes are time-consuming and the resulting enhancement in signal quality does not justify the effort.

4.1 Continental shelf crosscut by canyons

During the METYSS 4 survey (Messinian Event in the Tyrrhenian from Seismic Study, Gaullier & Watremez 2019) onboard the R/V Téthys II, more than 280 seismic profiles were acquired along and across the Eastern Sardinian continental shelf of the hyperextended Western Tyrrhenian margin (Rehault *et al.* 1987; Jolivet & Faccenna 2000; Gaullier *et al.* 2014; Lymer *et al.* 2018). The acquisition system comprises one seismic source (sparker SIG 300 Joules), a digital single-channel streamer and the SonarWiz6 acquisition software. The great variability in bathymetry along the profiles required frequent changes in acquisition parameters, particularly the shot spacing dictating the record length. Two sets of acquisition parameters have been applied:

1) Mode 1: on the continental shelf at shallow water depths (c. 50–100 m): the shot interval is 0.533 s (i.e. shot spacing of 1.1 m in using a ship speed of four knots). The record length is 533 ms TWTT with a sampling rate of 0.25 ms. The energy output is 150 J for the sparker source. The vertical resolution is approximately 0.6 m.

2) Mode 2: on the upper continental slope at deeper water depths (c. 600–1000 m), the shot interval is 1 s (i.e. shot spacing of ∼2.1 m in using a ship speed of four knots). The record length is 1 s with a sampling rate of 0.25 ms. The energy output is 300 J. The vertical resolution is around 1 m.

Some seismic profiles acquired in Mode 1 show heterogeneous bathymetry, as the area of the canyon heads (Fig. 3d) reaches deeper water depth (c. 1000 m).

The selected seismic profile (Fig. 3a) shows the Diedda Canyon along the Western Sardinian platform (Fig. 3d). The acquisition parameters of this profile were set to Mode 1, adapted to obtain a high spatial resolution for a maximum investigation depth of approximately 400 m. The record length of 0.533 s does not show the thalweg of the canyon, which occurs at ∼800 ms TWTT (600 m water depth). However, an image of this geological feature appears clearly in the water column (Fig. 3a, shot points 5500–6500). The REWARE algorithm (Fig. 3b) complements the infill reflectors in the canyon with an optimal vertical resolution and trace-to-trace coherence. Various discontinuities in the Diedda canyon (coloured lines on Fig. 3c), including the Messinian Erosion Surface (Lymer *et al.* 2018; Sylvain *et al.* 2023), and separating several Plio-Quaternary sedimentary units (Fig. 3c) are delineated thanks to the high vertical resolution of this data set.

4.2 Tectonically active rift basin

The second example of data is a seismic profile acquired in the North Aegean Sea during the WATER cruise (Western Aegean Tectonic Evolution and Reactivations; Chanier & Gaullier 2017; Chanier & Watremez 2021), which is dedicated to the study of fault patterns at the junction of active rift basins and the western prolongation of the North Anatolian Fault (Caroir *et al.* 2024). This area is mostly characterized by shallow water depths (30–60 m) locally displaying

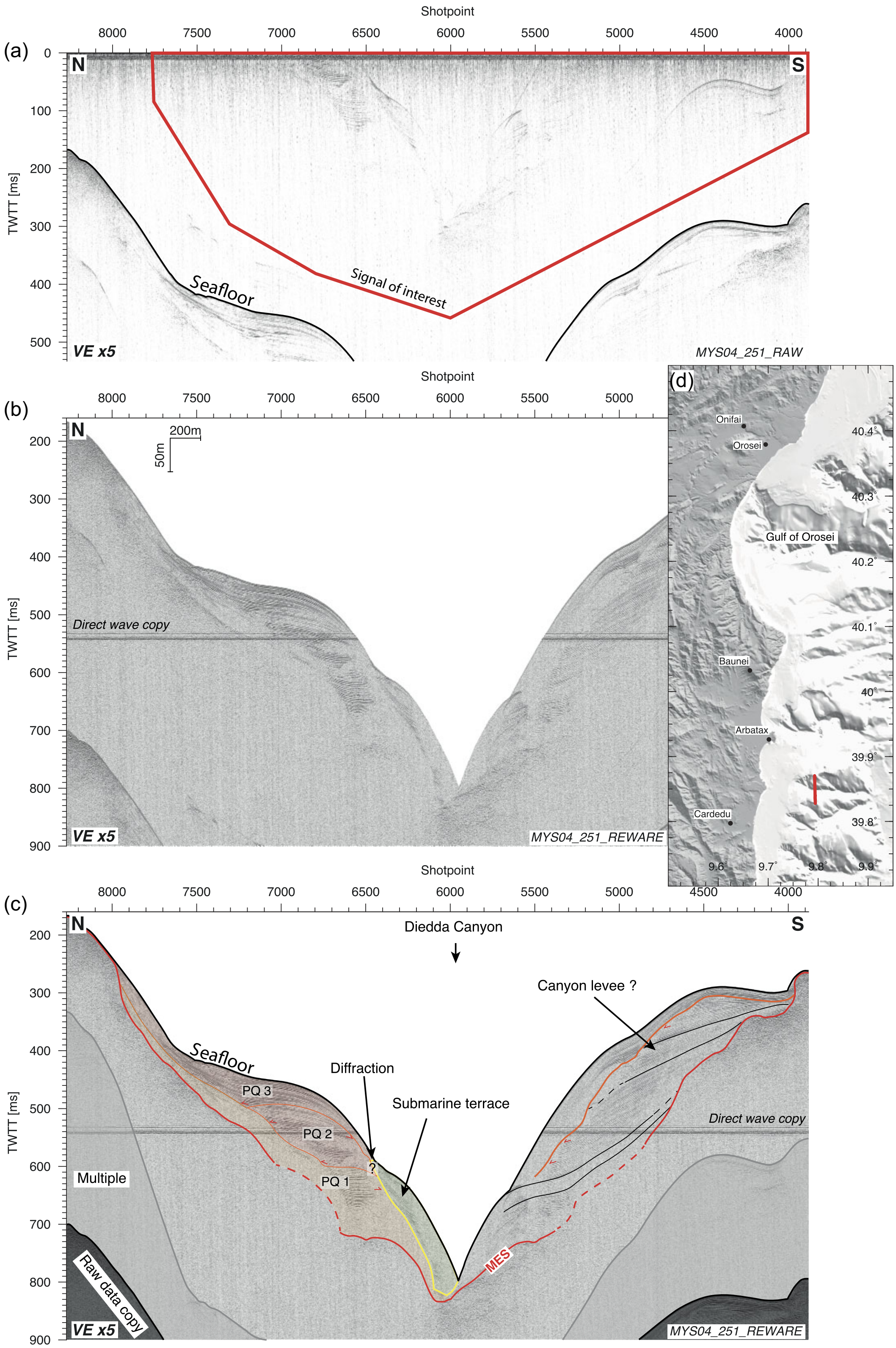

Figure 3. (a) Raw seismic section of the MYS04_251 profile illustrating the presence of coherent signal from previous shot recorded in the water column. (b) Uninterpreted and (c) interpreted REWARE section of the MYS04_251 seismic profile (Sylvain *et al.* 2023). A geometry correction, the REWARE algorithm, a bandpass filter and a water mute were applied. The restored part of the Diedda Canyon is under the 'direct wave copy' between 533 and 800 ms TWTT. The line labelled as MES corresponds to the Messinian Erosion Surface, the other lines delineate the discontinuities limits between PQ 1, PQ 2 and PQ 3 units, and highlight the discontinuity between PQ units and the submarine terrace. (d) Location of the profile (thick line), along the eastern Sardinia shelf. The map shading highlights the relief. Bathymetric data are extracted from the MAGIC (*MArine Geohazards along the Italian Coast*) project (Chiocci *et al.* 2021). Topographic data are extracted from the ALOS (*Advanced Land Observing Satellite*) database (Tadono *et al.* 2014).

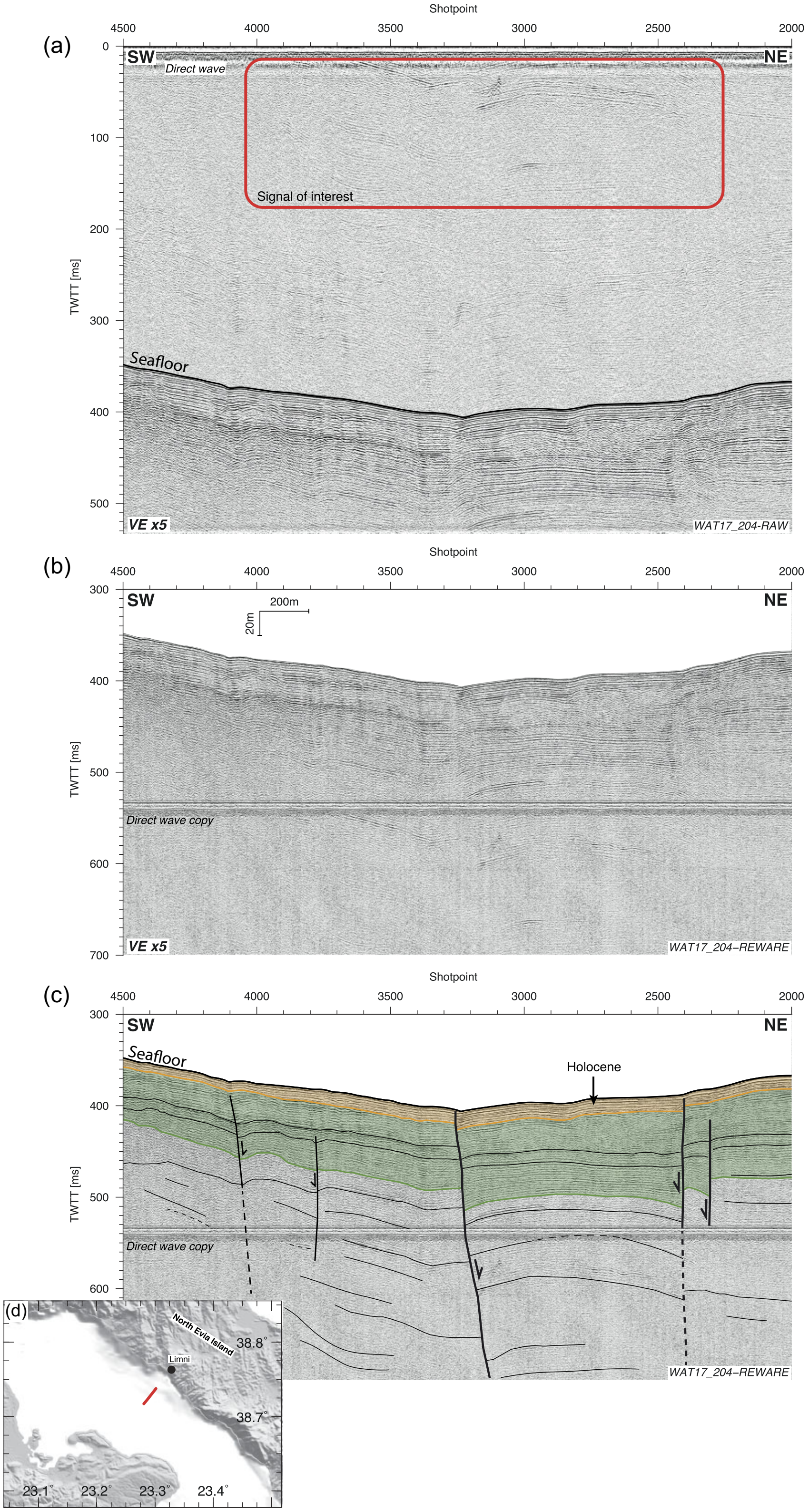

Figure 4. (a) Raw seismic section of the WAT17_204 profile illustrating the presence of coherent signal from previous shot recorded in the water column. (b) Uninterpreted and (c) interpreted REWARE section of the WAT17_204 seismic profile. A geometry correction, the REWARE algorithm, a bandpass filter and a water mute were applied. The seismic part added under the 'direct wave copy', between 533 and 700 ms TWTT, is the signal of the water column. (d) Location map of the seismic section (thick line), south of North Evia Island. Bathymetric and topographic data are extracted from GMRT (*Global Multi-Resolution Topography*, Ryan *et al.* 2009).

very heterogeneous seafloor morphology, with steep slopes towards deep troughs that can reach water depths down to 500 m. To obtain a VHR image of tectonic deformations and associated sedimentary structures, the acquisition system and configuration were similar to the ones used during the METYSS 4 cruise.

The great variability in bathymetry along the profiles would have required frequent changes in acquisition parameters. However, a high trace-by-trace consistency was favoured by using a short shot interval of 0.533 s (i.e. 1.1 m shot spacing at a vessel speed of four knots). Therefore, the areas at water depths >400 m were neglected.

The selected seismic section from the WATER survey (Fig. 4) shows the benefits of applying the REWARE algorithm to the seismic profile. The deeper seismic section has been restored, highlighting thick faulted sedimentary sequences, while maintaining the high spatial resolution. On the raw section (Fig. 4a), the seafloor is located between 350 and 410 ms TWTT (i.e. 262–307 m water depths). To keep the very high spatial resolution, the record length was limited to 533 ms TWTT, allowing for only 150 ms TWTT of geological record beneath the seafloor to be imaged. In addition, several normal faults are observed with a limited vertical extension, and therefore their dip directions remained relatively unclear. The REWARE data extend the observations relative to the faults and the offsets of the corresponding reflectors at depth, only by adding the reflections from previous shots recorded in the water column. For instance, on the REWARE data (Fig. 4c), the central fault can be followed more than 200 ms TWTT longer than on the raw data (Fig. 4a). Not only the faults, but also the architecture of the sedimentary deposits, are revealed thanks to the integration of REWARE into the seismic processing workflow.

5 DISCUSSION

Here we discuss how to best combine REWARE with other standard steps of single-channel seismic processing, such as filtering, deconvolution, migration and static correction (Yilmaz & Doherty 2001; Dondurur 2018; Santos *et al.* 2021).

When REWARE is applied first in the processing workflow, the occurrence of the copy of the direct wave in the middle of the section has consequences on further processing. (1) A migration in the T-K domain may be applied on this single-channel data set (equivalent to a 2-D post-stack migration with constant velocity; Stockwell 1999). However, the copy of the direct wave causes overmigration ('smile') artefacts (Dondurur 2018), which will corrupt the reflectors above this event. Please note it is also important to check for the presence of random spikes (electronic noise) that may also happen with sparker data, also leading to overmigration artefacts. Thus, the migration should be applied prior to the REWARE algorithm, and on data showing no random spikes. (2) Some algorithms for gain recovery are affected by REWARE. An automatic gain control (AGC) is not recommended with REWARE due to the high amplitude of the direct wave. Indeed, the AGC will lower the amplitude above the seabed but also above the direct wave copy, resulting in a quiet zone affecting the reflectors. (3) Another gain recovery algorithm, such as the spherical divergence correction, corrects the loss of amplitude of the acoustic wave due to the increasing distance from the source. The amplitude of late arrivals becomes more visible with this correction, which does not affect the relative amplitude variations at depth (Dondurur 2018). A spherical divergence spreading correction (Yilmaz & Doherty 2001) has been tested before REWARE, but it decreases the amplitudes of the coherent signal in the water column, which is incompatible with the purpose of the REWARE processing algorithm. However, using the spherical divergence spreading correction after applying the REWARE algorithm will increase the amplitude of the late arrivals without modifying seismic facies. (4) A deconvolution may be applied to a data set. For air-gun data, the deconvolution is well known and easy to apply as the wave source is the same for each trace. However, for sparker data, the deconvolution is complex and time-consuming as the wave source is different from one shot to another (Duchesne *et al.* 2007). A single operator can be used along an entire profile, although this is not optimal for sparker data. This solution works best for airgun data. The deconvolution may be applied on the data either before the REWARE algorithm, or after. Static corrections include suppression of the action of tides and waves affecting the sea surface (Lacombe *et al.* 2009; Kim *et al.* 2017).

We propose a processing workflow for single-channel data, modified from Santos *et al.* (2021). This processing workflow implements the REWARE algorithm and allows to use common processing tools, such as deconvolution, migration, gain recovery or filtering, to their full potential.

In summary, the seismic processing workflow proposed follows:

(1) Geometry correction.
(2) Filtering (e.g. bandpass filter, F-K filter, etc.).
(3) Deconvolution.
(4) Static corrections.
(5) Migration.
(6) REWARE.
(7) Spherical divergence correction.
(8) Water mute (amplitudes are set to zero above the seafloor).

6 CONCLUSION

REWARE is a very simple and rapid method using the late arrivals from the previous shot recorded in the water column to obtain further geological information. This method can be applied to marine VHR single-channel seismic reflection profiles. The REWARE algorithm is an open-source code provided as a Shell script and using Seismic Un∗x modules (Supplementary materials) to integrate in the seismic processing workflow. For each seismic trace, it retrieves the coherent signal from the previous shot, recorded in the water column, and add it at the end of previous traces, artificially extending the record length. This processing allows to optimize the acquired marine VHR seismic data. Moreover, this method solves the conflict between the need to obtain more information at depth below the seafloor (long record length) and maintaining an initial high spatial resolution (high source frequency and short shot interval).

From two case studies, we demonstrate that the coherent signal recorded in the water column of the seismic section may be retrieved and can provide useful information on the geological structures beneath the seafloor. We show the potential of this processing for sedimentology or structural geology studies at variable water depths, on the continental shelves and associated slopes and canyons, while maintaining good resolution of sedimentary sequences, unconformities and tectonic features.

In offshore areas, with low to moderate bathymetry and especially with high morphological variability, this processing limits the need to changes in acquisition parameters each time bathymetry varies, thus optimizing acquisition times. The approach minimizes seismic gaps where water depth increases, without additional acquisition time.

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AUTHOR CONTRIBUTIONS

Romain Sylvain: Writing—original draft; Writing—review & editing; Visualization; Methodology

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Frank Chanier: Writing—review & editing; Supervision; Data acquisition

Fabien Caroir: Writing—review & editing; Visualization; Data acquisition

Virginie Gaullier: Writing—review & editing; Supervision; Data acquisition

SUPPORTING INFORMATION

Supplementary data are available at *GJIRAS* online.

DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

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