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Wave Equation Datuming Applied to Seismic Data in Shallow Water Environment and Post-Critical Water Bottom Reflection

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Received: 1 August 2017; Accepted: 11 September 2017; Published: 15 September 2017

Abstract: Coastal areas are generally characterized by human manufacturing; thus, seismic data analysis is necessary to characterize the properties of the subsoil, the main purpose of which is to clarify risk situations. In the case of very shallow water environments, seismic multiple attenuation becomes a challenge when the reflection of the seafloor is post-critical, so it is not recorded because of the acquisition parameters. We propose an approach to attenuate the multiples by using wave equation datuming that does not require the detection of seafloor reflection and avoids the seafloor reflection prediction and related approximations in the post-critical conditions. Moreover, this approach allows for the enhancement of higher frequencies, and, consequently, an increase in resolution, demonstrating that it is a powerful tool to attenuate multiples and reverberations, especially where other approaches are found to be inefficient. An example of the application of seismic data acquired in the continental shelf of South Chile is reported.

Keywords: wave equation datuming; shallow water; post-critical; multiple

1. Introduction

A challenge for seabed industries operating in shallow water is to reduce the risk for the population living along the coastal area and to clarify the risk situation. In fact, main infrastructures related to gas and oil exploitation are located in shallow water in close proximity to the coast. It is clear that a deep knowledge of the seabed and subsoil structures is required for the development of such infrastructures. The geometry and petrophysical properties of subsoil structures are obtained from seismic data analysis. In shallow water, the critical point of seismic analysis is the attenuation of seabed multiples.

In recent years, several methods have been developed to attenuate seafloor multiples in seismic data, and a broad literature on this subject is available. Schematically, moveout and predictability are the two properties on which the most used algorithms are based. Algorithms that work in *x-t* and *tau-p* domains are able to separate primaries and multiples if they show different velocities (and thus, different moveouts). In addition, migration and wave equation approaches have been applied in many geological contexts to attenuate multiples.

The most-used method is surface-related multiple elimination (SRME), which has been employed since the pioneering work of Reference [1]. As pointed out by Reference [2], the main advantage of the SRME method is that it requires no prior information of the subsurface, i.e., the velocity structure or reflectivity, and it is effective to attenuate water-bottom-related multiples. Another advantage of this technique is that it works in any geological setting, using only surface data. Thus, this method is often chosen for multiple attenuation in complex geological settings [3]. On the other hand, the SRME method demands high coverage of sources and receivers to give an accurate result. SRME, though an effective method in deep water demultiple, usually shows limited success in shallow water situations [4]. In fact, in shallow water environments, problems have been encountered because the wave-field reconstruction to near offsets is inaccurate. When the offset approaches the distance where critical reflection occurs, the Normal MoveOut based extrapolation distorts the primaries, or introduces unwanted energies, such as refractions. So, many efforts have been made to overcome the disadvantages of the SRME method for shallow water.

In shallow water, short-period multiples have been usually attenuated by using predictive deconvolution in the *x-t* or *tau-p* domains (i.e., [5,6]). However, this approach attenuates all events with the period close to the water layer, including the primaries and interbed multiples. In fact, the separation of primaries and multiples can be performed by using Radon transforms, which are not optimal when complex wave-field propagation occurs in the subsurface; this occurs mainly because simple functions (parabolic or hyperbolic) do not correctly describe the moveout of primaries and multiples in such situations [7]. Therefore, the multiple attenuation requires more sophisticated methods, such as deterministic demultiple methods that design an operator to predict water layer multiples from the data [8]. The deterministic demultiple method predicts the amplitude accurately, but struggles with the complex water bottom due to the inaccurate model derived from the autocorrelation. An inversion-based SRME algorithm to avoid the multiple subtraction from the data was proposed by Reference [9]. In this instance, the primaries are estimated with the corresponding multiples to explain the data directly; consequently, the cost could be significantly high. In addition, model-based methods can be used to handle the near-offset issue properly with limited prior information, i.e., the Green's functions of the water bottom [10].

Several authors have proposed a combination of few methods in order to enhance the attenuation of multiples in shallow water. Recently, an approach that combines the model-based method with the conventional SRME method to attenuate multiples of broadband data, the so-called shallow-water multiple elimination (SWME) method, was proposed by Reference [2]. This approach predicts the multiple model by using a broadband wavelet and proper aperture. The Green's function is limited in offset in order to ensure that post-critical energies are not convolved. Two multiple models from both source- and receiver-sides are adaptively subtracted from the input data with an enhanced hybrid subtraction method, such that no high-order multiple term is solved explicitly. After the water-bottom-related amplitude is removed, a conventional SRME is employed to remove residual surface-related multiples. Finally, a combination of deterministic water-layer demultiple (as proposed by Reference [11]) and general surface multiple prediction to predict all free-surface multiples (as proposed by Reference [12]) was suggested by Reference [13]. Following this technique, the two predictions are subtracted from the data, improving the final result.

Several authors have proposed the usage of the pre-stack depth migration to discriminate coherent noise in offset gathers (i.e., [14]). For example, in the angle domain, only the primaries are flat as suggested by Reference [15]. Therefore, they proposed to transform the migrated data in that domain. Then, the data sorted in angle gathers are mapped using a Radon transform in order to separate the signal from the noise. Other migration methods use free-surface-related multiples, but most approaches need to predict multiples (i.e., [16]). In order to avoid multiple prediction, a pre-stack reverse time migration (RTM) approach that uses the primaries and the free-surface-related multiples simultaneously can be applied as recently suggested by Reference [17]; in this way, the imaging is improved in the complex geometry cases. A similar approach was proposed by other authors, such as Reference [18], obtaining successful results.

In the case of a very shallow water environment, the challenge in multiple attenuation arises when primary water-bottom reflection is not recorded because acquisition parameters allow for the detection of only post-critical reflection. When water-bottom reflections are missed, different authors demonstrated that a good solution to attenuate multiples is to estimate primaries from those multiples [19,20]. For instance, a multichannel prediction operator can be adopted to estimate the water-bottom reflections from the water-layer multiples [21]. Then, the modeled seafloor reflection is added to the recorded seismic data and the SRME method can be applied to attenuate multiples (i.e., [22,23]).

Here, we propose an approach to attenuate multiples by using wave equation datuming (WED; i.e., [24]) that does not require the presence of seafloor reflection and avoids the seafloor reflection prediction and related approximations in post-critical conditions. Compared with other methods used in the literature for multiple attenuation, WED allows for the attenuation of incoherent and coherent noises, and is particularly strong in the case of shallow water environments, independent of acquisition parameters. Note that there are no restrictions in the case of post-critical water-bottom reflection. Moreover, this approach allows for the enhancement of higher frequencies, consequently increasing resolution and the final imaging of the subsoil.

2. Materials and Methods

In this study, we applied our proposed procedure on seismic data acquired in the continental shelf of South Chile, where the average water depth is about 20 m. This line, located in the Arauco Basin, was already partially processed by Reference [25] in order to characterize the gas reservoir located in this area. It is important to notice that gas reservoirs are present in the Arauco Basin. So, it is important to have a good image of the subsoil in this area in order to preserve the built infrastructures and evaluate the related risks for the coastal population.

This line was previously acquired by the project "Subduction Processes Off Chile (SPOC)" [25]. The near offset is equal to 150 m, while 120 hydrophones, spaced every 25 m, were used; the shooting was every 25 m. As already mentioned, the very shallow water is very critical because the bottom reflection is post-critical. So, we decided to apply WED in order to improve the signal-to-noise ratio, attenuate multiples, and enhance higher frequencies, so increasing the resolution.

WED is a powerful method that can be used to increase the signal-to-noise ratio and the resolution of marine and land seismic data. In the terrestrial environment, it has been used to improve the static corrections on crustal (i.e., [24]) and high resolution (i.e., [26]) seismic data; recently, it was applied successfully to process S-wave data [27]. In the marine environment, WED was used to process sparse ocean bottom seismometer (OBS) data for deep crustal prospecting [26]. After WED, shots and OBSs were relocated at the same datum (sea level), allowing for processing with the use of commercial software, and improving the final result with respect to the conventional approach.

In essential, WED is based on Kirchhoff integral solution to the scalar wave equation (using both near-field and far-field terms), as described in the literature [28–31]. It is important to recall that because of the use of Kirchhoff method, WED cannot be used if amplitude analysis is planned, such as amplitude versus offset analysis. One of the main requirements of the WED method is a regular acquisition geometry, i.e., constant distances between receivers and seismic sources. In a marine environment, this request is almost always satisfied; if not, it is necessary to add shots with zero traces and/or zero traces if receivers are missed. For details about the practical use of WED, see References [24,26] and the references therein.

WED was applied first in the common-source domain (moving the receivers to the datum plane; in our case, 50 m above sea level) and, successively, in the common-receiver domain (moving the shots to the datum plane; i.e., 50 m above sea level) by using the velocity model obtained from velocity analysis. Operating on a common-source domain has the effect of extrapolating receivers from sea level to 50 m above it. Also, because of reciprocity, operating on a common-receiver domain changes the datum of the source to 50 m above sea level. Basically, WED is a process of upward or downward continuation of the wave-field between two arbitrarily shaped surfaces. Recalling the main principles of the theory, we should consider the importance of distinguishing between migration and WED (e.g., [28–31] and the references therein). WED produces an un-migrated time section at a specified datum plane; migration involves computing the wave-field at all depths from the wave-field at the surface. In addition to downward continuation, migration requires the imaging principle. In this respect, WED is an ingredient of migration, when we apply migration as a downward-continuation process. Seismic Unix package, a free software developed at the Colorado School of Mines, and in particular the code developed by Reference [32], and home codes were used to perform WED.

Before applying WED, we recovered the amplitudes and deleted partial or total noise traces. Moreover, the mute of the refracted events was applied before WED. Along the analyzed line, we selected some shots to show the improvement obtained by WED (Figure 1), as will be discussed in the following section. A band-pass filter was applied to all shots.

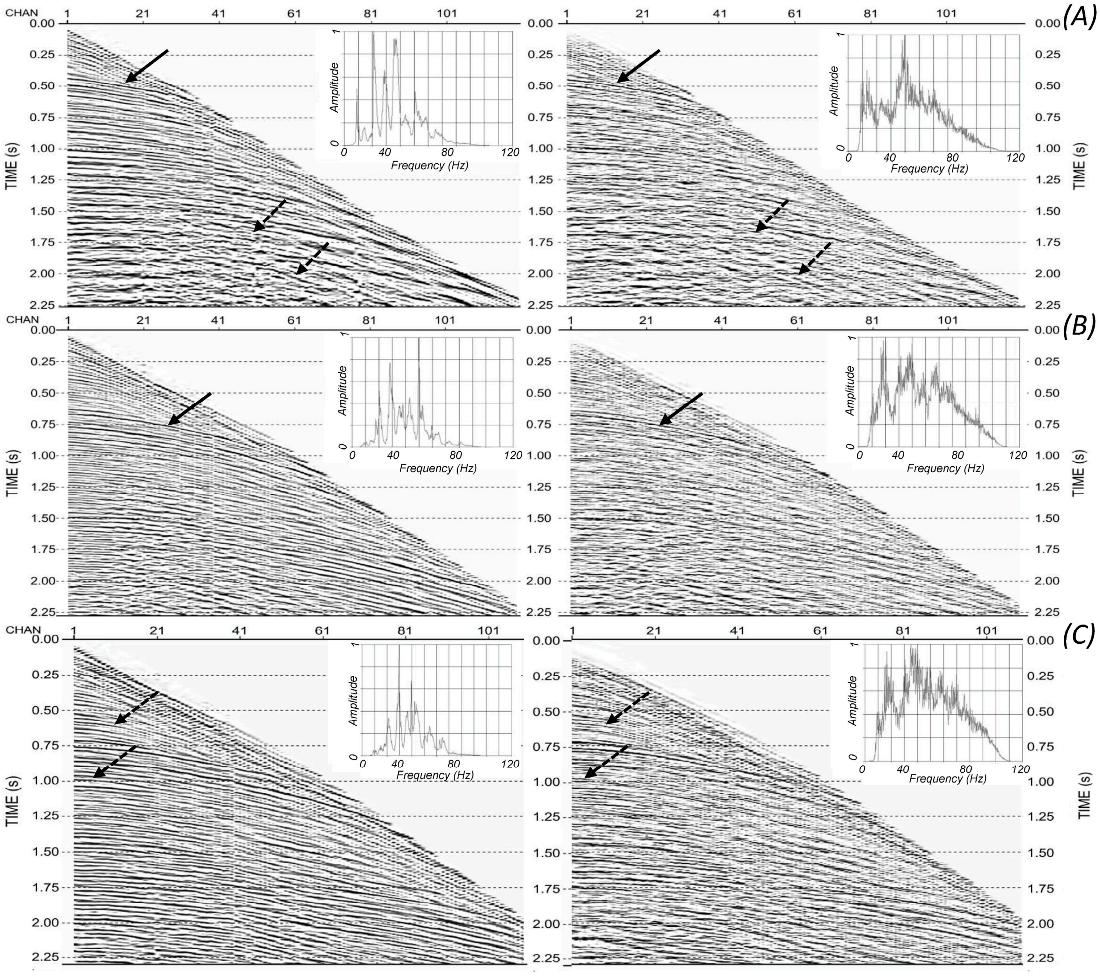

Figure 1. An example of three shot gathers and their amplitude spectra (insets) (panel (**A**–**C**)) before (left panels) and after WED (right panels) along the seismic lines. The black arrows indicate the main reflections, while the black dotted arrows indicate the attenuated noises as discussed in the text.

3. Discussion

WED is proven to be a very flexible and useful tool to increase the signal-to-noise ratio and, consequently, improve the seismic imaging in many contexts of geophysics, including shallow water environments where multiples dominate the record and the water-bottom reflection is post-critical. In Figure 1, some examples of analyzed shots without and with the application of WED are reported, while, in the insets, their amplitude spectra are included.

The shots show an improvement of the signal-to-noise ratio with a strong attenuation of the multiples and the increase of the resolution, as shown on the amplitude spectrum. For example, in Figure 1A, the reflection at about 500 ms Two Way-Time (TWT), indicated by black arrows, is more recognizable after the WED application (right panel). In Figure 1B at about 700 ms TWT, it is possible to identify the same reflector indicated by black arrows. Moreover, dip events below 1 s TWT, more evident between channel 21 and 61, are attenuated, and some are indicated by black dotted arrows. Comparing the two spectra of the shots, it is clear that another advantage of the WED application is the increase of resolution due to the relative increase of high frequencies. Also in this case, the multiples are strongly attenuated. The last example (Figure 1C) shows the same results, i.e., a strong attenuation of the multiples (see black dotted arrows) and an increase of the resolution highlighted by the amplitude spectra.

In order to show the advantage of this technique, we reported the stack sections without (panel A in Figure 2) and with (panel B in Figure 2) the application of WED. The strong reflector emerging westwards at about 500 ms represents the base of late Pliocene-Quaternary deposits, as interpreted in the literature (i.e., [33]). This reflector is affected by reverse faults, as confirmed by different authors (i.e., [33]).

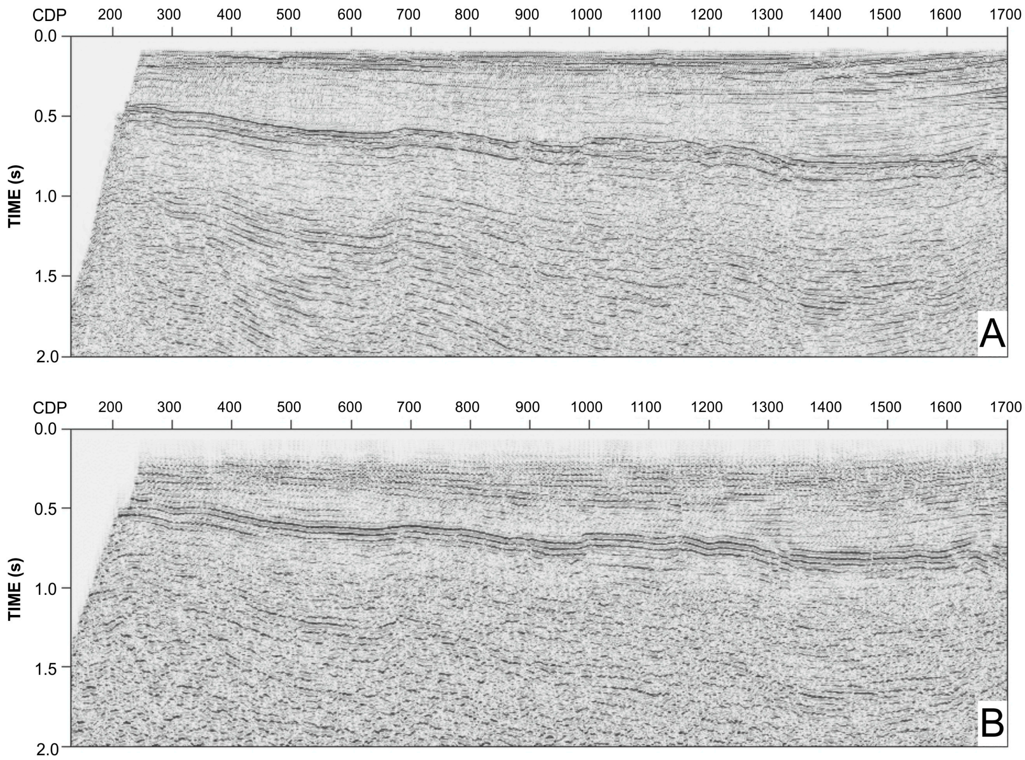

Figure 2. Stack section without (panel (**A**)) and with (panel (**B**)) the application of WED.

The comparison of the two stack sections shows that the reflector associated with the Pliocene-Quaternary deposits is better resolved in panel B. Moreover, the faults affecting the reflector and their trends are better imaged. In the shallow portion of the stack section in panel A, it is not possible to recognize reflections because the presence of multiples related to the seafloor. On the contrary, on the stack section in panel B, it is possible to clearly recognize some reflections because multiples are strongly attenuated by the WED.

Below the base of late Pliocene-Quaternary deposits, the multiples are strongly attenuated, so it is possible to recognize the reflections related to deeper deposits. In conclusion, WED is a powerful tool to attenuate multiples and reverberations, especially where other approaches are found to be inefficient.

4. Conclusions

In this paper, we demonstrated that WED is a very flexible method that can be used in many contexts to attenuate incoherent and coherent noises. In fact, it can be applied successfully not only to land or OBS data, as demonstrated in the literature (i.e., [24,26]), but also in the case of marine seismic data. It is worth underlining that one of the main requirements of WED (i.e., constant distances between receivers and seismic sources) is satisfied in this last case. In this paper, we analyzed seismic data acquired in very shallow water, considering a case when primary water-bottom reflection was not recorded because the reflection was post-critical due to the acquisition parameters. In conclusion, WED gives good results, allowing for a better interpretation and better imaging of the subsoil.

Acknowledgments: We acknowledge the CINECA award under the ISCRA initiative (project HP10C7EZAE-WEDIONIO), for the availability of high performance computing resources and support. This work is partially supported by the Ministry of Education, Universities, and Research under the grant for the Italian participation to the activities related to the international infrastructure PRACE—The Partnership for Advanced Computing in Europe (www.prace-ri.eu). We are grateful to CONICYT (Fondecyt de Iniciación N°11140216), which partially supported this work.

Author Contributions: All authors contributed to the writing of the manuscript. Umberta Tinivella performed the WED, Michela Giustiniani processed the seismic data, while. Ivan Vargas-Cordero interpreted and contributed to the choice of the processing flowchart applied to the seismic data.

Conflicts of Interest: The authors declare no conflict of interest.

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