Study of the Serra do Mel in the Potiguar Basin: static correction vs. redatuming of the seismic data

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Abstract

The shallow part of the Serra do Mel region of the Potiguar Basin consists of Barreiras sandstones and Jandaira carbonates. Due to the poorly consolidated sandstone and carbonate alteration and the high impedance between the Barreiras and Jandaíra formations, the seismic signal is severely attenuated, which makes it difficult to obtain seismic images of the geological structures in the region. To study this seismic imaging problem, we build a synthetic model representing the geology of the region and then generate multi-coverage seismic data. Accurate determination of the low-velocity layer (LVL) model and static correction are essential for correct mapping of geologic structures. Using two LVL models, we present the comparison of the static correction with the Kirchhoff-type redatuming. We use PSDM migration to evaluate the accuracy of the results obtained by both techniques and their impact on depth imaging. Kichhoff redatuming is the best alternative to correctly map the geological structures in the region under study.

Introduction

The simplified lithostratigraphy of the Potiguar Basin in the Serra do Mel region is composed of the following formations: Barreiras (Tertiary sandstones) and Jandaíra (Upper Cretaceous carbonates), Açu Formation (Albian-Cenomanian sandstones and shales), Alagamar (Aptian sandstones, shales and calcarenites), Pendência (Rift phase sandstones, shales, and conglomerates). In its deepest sector the Graben reaches about 2,5 km of depth (Pessoa Neto et al., 2007).

Normally poorly consolidated rocks, such as the Barrier sandstones, strongly attenuate the seismic signal. On the other hand, due to the intrinsic characteristics of carbonate rocks and the conditions to which these rocks have been subjected over time (karstification and fracturing processes), they can strongly degrade the seismic signal, as happens in the Serra do Mel - Potiguar Basin area. This is the main reason for the study of this work.

The main step in seismic processing to remove distortions in the wavefield due to heterogeneity of the LVL model and topographic variations is static correction. Therefore, the accuracy of this correction is crucial for the correct mapping of geological structures. Statics correction in land seismic data processing involves the estimation and application of time shifts to align seismic data and to compensate for variations in topography and near-surface velocities; in other words, data recorded at the ground surface with varying topography is transferred to a given flat datum. This process includes first break picking, static shift estimation, statics correction, residual statics analysis, and iterative refinement (Cox, 1999). By removing the effects of near-surface velocity variations, statics correction improves the quality and interpretability of seismic data, enabling more accurate subsurface imaging and geological assessments.

Alternatively, to remove the effects of topography and near-surface heterogeneities on prestack seismic data, a redatuming method can be applied to transform the data from the ground surface to a new datum. In this paper, we apply the Kirchhoff-type redatuming method based on a single sum proposed by (Pila et al., 2014). An algorithm of this method for redatuming multi-coverage seismic data was presented in (Rocha et al., 2022). This method requires only knowledge of the velocity model near the surface or above the datum to transfer the data from the acquisition surface to the desired flat datum through a single stacking operation that implicitly includes the migration and demigration operations.

The objective of this paper is to study the seismic imaging problem of the Serra do Mel region, in the Potiguar Basin, by comparing the static correction with the Kirchhoff-type redatuming method. The near-surface velocity model or LVZ model is needed for both the static correction and the redatumation. Then, in this paper we first present the determination of the LVZ model using two well-known tomography methods. Using both ZBV models, we will apply the static corrections and Kirchhoff-type redatuming to the prestack data. To evaluate and compare the accuracy of both methods, we apply the Kirchhof prestack depth migration (PSDM).

Method

Synthetic model and data

In this study, we use a synthetic model to investigate a near-surface geological setting characterized by a layer with a vertical velocity gradient that can give rise to diving waves. This low-velocity layer (LVL) and the refractor also contain lateral velocity variations, which pose a challenge for tomographic inversion of first-arrival travel times. The construction of the synthetic model is based on the geological and geophysical knowledge of the Serra do Mel region in the Potiguar Basin, located in northeastern Brazil.

The topography of the synthetic model was defined using information from the terrain topography of a specific seismic line (L230-401) that crosses the Serra do Mel in a SW-NE direction. The near-surface velocity model or LVL depth (V0, V1, Z1) were obtained from geological information and refraction tomography using a proprietary static correction software, according to the methodology previously described by Gonçalves and Garabito (2021). Although the horizons below the LVL model along the

L230-401 line were originally derived from regional seismic data interpretation, they were subsequently simplified for the purposes of this study. Therefore, the synthetic model below near-surface velocity model is composed of homogeneous layers separated by straight interfaces. The complete velocity model (near surface and deep layers) can be seen in Rocha et al. (2022).

The synthetic multi-coverage seismic data were generated by modeling the acoustic wave propagation by means of the finite difference numerical solution, applied to a velocity model with a grid of 5x5 m, in which the Ricker wavelet was used with a frequency peak of 30 Hz. We generate 270 shot gathers, each with 201 traces, using split-spread source-receiver geometry. The interval between shots is 80 m, and interval between the receivers is 20 m, with a maximum absolute offset of 2000 m. The time sample interval is 4 ms. The shot gather shown in Figure 1 is an example of the synthetic data when the refraction and reflection events are regular, i.e., without significant distortions, because the topography of the terrain and the base of the LVL have smooth variations.

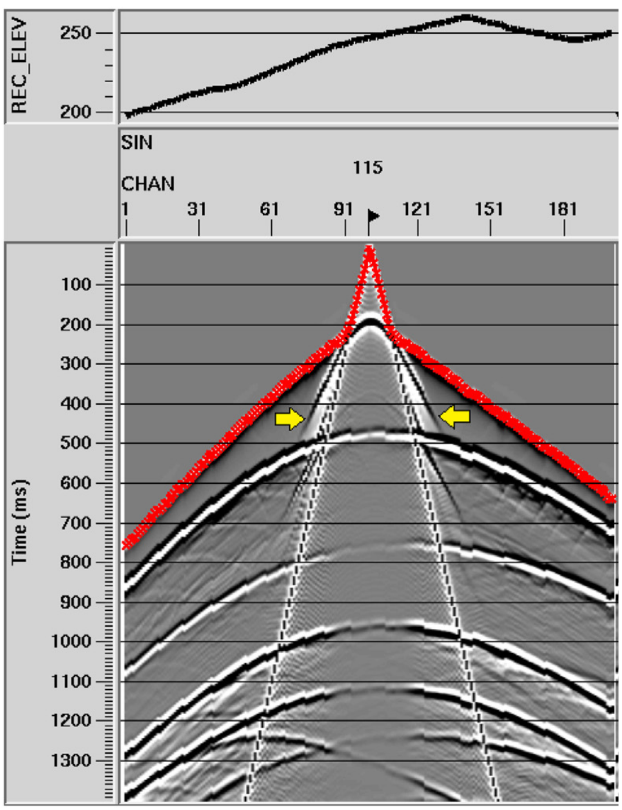

Figure 1 – Shot gather at 9120 m. The upper part shows the receiver's elevations and lower part the recorded wavefield. The red dots are the first break picks, and the yellow arrows indicate the diving waves beyond the first arrivals (modified from Goncalves & Garabito, 2021).

Near-surface velocity model estimation

The workflow for obtaining a near-surface velocity model is as follows: (1) input data, (2) first break picking and interpretation, (3) initial model definition, and (4) refraction tomography (Goncalves & Garabito, 2021).

The synthetic shot gathers are used as the input data to perform the first break picking operation (Figure 1). The data picking step is essential for ray-based refraction tomography because it requires a supply of travel times of the seismic waves that reach the receiver first. In addition to being used in the tomography inversion, the picks are also used to estimate initial velocities and refractor depths.

The interpretation of the first break picks starts with the estimation of the crossover points, which was performed for each arm of the split-spread arrangement to better account for changes in topographic relief, refractor relief (presence of layer dips), and lateral velocity variation in the refractor. The definition of crossover points is used not only for determining velocities, but also for Delay Time calculation and ray tracing in tomography, since these points separate the arrival of the wave type (refraction, reflection, or main wave) for each layer of the model. Therefore, if the crossover identification is incorrect, tomography is compromised, and filters can be applied to smooth crossover values if necessary.

To estimate the velocities of the LVL layer, we calculate the direct wave (V0) by taking the average of the inverse of the travel time slopes, one for each arm of the split spread geometry. To define the velocities of the refractors (V1, V2, etc.), we use the principle of reciprocity and the direct versus reverse shot method. Then, in the next step, the Delay Time method is used to determine the refractor depths. The interpretation output is an initial near-surface velocity model.

Refraction tomography

We used two different refraction tomography methods to determine or refine the near-surface velocity model: Rayinvr and Refratom (Goncalves & Garabito, 2021). The initial velocity model used in both tomography methods is the result of interpreting the first break picks.

Rayinvr uses a model with segmented layers formed by trapezoids to form the interfaces. This method does not require a uniform grid and allows for flexibility in model construction since the vertices of the trapezoids do not need to be sampled at regular intervals. Rayinvr tomography is based on ray tracing and simultaneously invert the travel times of the direct, refraction and diving waves to obtain both the 2D velocity and the interface structure (Zelt, 1992). On the other hand, Refratom uses a numerical equivalent model solution for refraction tomography (Amorim et al., 1987). This method parameterizes the model into vertical prisms with constant velocities but allows lateral velocity variations. Each prism represents a block of equal horizontal length with an unknown constant velocity. This straight ray tomography focuses on inverting the travel times to obtain only the 2D velocity, while keeping the depth of the refractor fixed, i.e., it is not updated during the inversion process.

The near-surface velocity models from the two tomography methods are shown in Figure 2. Figure 2a shows the true model used for comparison, Figure 2b the Refratom result, and Figure 2c the Rayinvr result. In this work, these two velocity models are used to evaluate and compare the static correction and redatuming of the pre-stack data.

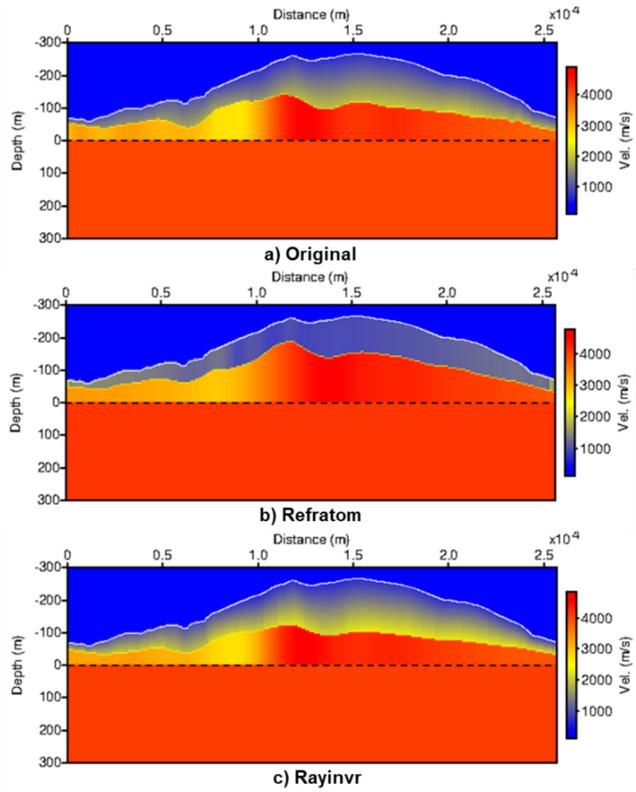

Figure 2 – Near-surface velocity models of the synthetic model representing the geological setting of the Serra do Mel region of the Potiguar Basin, Brazil: a) true model, b) obtained with Refratom tomography, and c) obtained with Rayinvr tomography (modified from Rocha et al., 2022).

Static correction

In standard seismic data processing, after estimating the near-surface velocities, the field static corrections must be calculated and applied to the seismic shot and receiver records. The static correction involves a vertical time shift of the data from the topography to a final datum, which is typically sea level. It is therefore calculated using the near-surface velocity to determine the travel time shift for each shot and receiver.

The field static correction is then applied to move the data referenced on the ground surface to a plane datum (sea level), i.e., the sources and receivers are positioned on the flat datum at 0 m. If the static correction is accurate, you can proceed with depth domain imaging.

In the time domain processing, after applying the field static corrections to the seismic shot and receiver records, the data is repositioned to a floating datum calculated by averaging the statics (we use 51 CDP points to smooth values) and using a replacement velocity of 2000m/s. The prestack data positioned at the floating datum is corrected for high-frequency static and will be close to the acquisition surface, which will not affect subsequent velocity analysis and migration procedures.

Kirchhoff-type redatuming

Seismic data Redatuming is a process that transforms the input data from the acquisition terrain surface to a new desired datum, typically a flat datum below the LVL model (sea level). Redatuming corrects for surface topography and near-surface heterogeneity distortions in the seismic data. There are several methods to perform this transformation, and, in this work, we use the Kirchhoff-type single-stack redatuming algorithm for prestack data presented in Rocha et al., (2022).

The Kirchhoff-type single-stack redatuming method, originally introduced by Pila et al. (2014), requires only a good approximation of the near-surface velocity model above the new datum, and a representative homogeneous velocity model below. A detailed description of the method and the algorithms can be found in the two cited articles.

After redatuming the field data to the flat datum (sea level) using one of the velocity models shown in Figure 2, the pre-stack data in the new flat datum can be used as input for depth imaging, as we will do in this work.

Results

Here we present the results of applying static corrections and Kirchhoff-type redatuming to the synthetic data representing the geology of the Serra do Mel region.

To apply the static correction to the prestack data, we use the near-surface velocity models of Figures 2b and 2c to calculate the travel time for vertical trajectory for each shot and receiver. The vertical time-shift is applied to each shot and receiver to move its location vertically from the surface to the flat datum at 0 m. The output of the static correction is prestack data as if it were acquired at level zero, but to avoid too many figures we will not show this data.

To evaluate the accuracy of this correction, we applied the Kirchhoff prestack depth migration (PSDM) to these data using the true velocity model below the datum, i.e., below 0 m. Figure 3a shows the PSDM image obtained from prestack data with static correction using the Refratom near-surface velocity model and Figure 3b shows the PSDM image obtained from data with static correction using the Rayinvr near-surface velocity model. In these results, the true reflector interfaces are shown as blue dashed lines and serve as a reference for evaluating the inaccuracy of the migrated images. Therefore, Figure 3a shows the focusing errors for all reflections in the area highlighted with a yellow rectangle. This is because the accuracy of the static correction is poor in this part of the seismic line. On the other hand, the PSDM image obtained from the data with static correction using Rayinvr's near-surface model shows no significant distortions.

We apply the Kirchhoff-type single-stack redatuming algorithm to the pre-stack data also using the models shown in Figures 2b and 2c. As we can see from these models, this method of redatuming does not need the knowledge of a correct velocity model below the datum. We also applied the PSDM to the redatumed data using the true velocity model below the datum. Figure 4a shows the depth migrated image obtained from the redatumed data using the near-surface velocity model of Refratom tomography and Figure 4b shows the PSDM image obtained from the redatumed data using Rayinvr's model.

The migrated image in Figure 4a also shows the distortions or bad focusing for all the reflectors in the area that is marked with a yellow rectangle. This error is due to the inaccuracy of the near-surface velocity model that is determined by the Refratom tomography. On the other hand, the migrated image in Figure 4b shows the correct position of the reflectors, as indicated by the overlapping dashed lines. This confirms that the velocities obtained by Rayinvr tomography are very close to the real model.

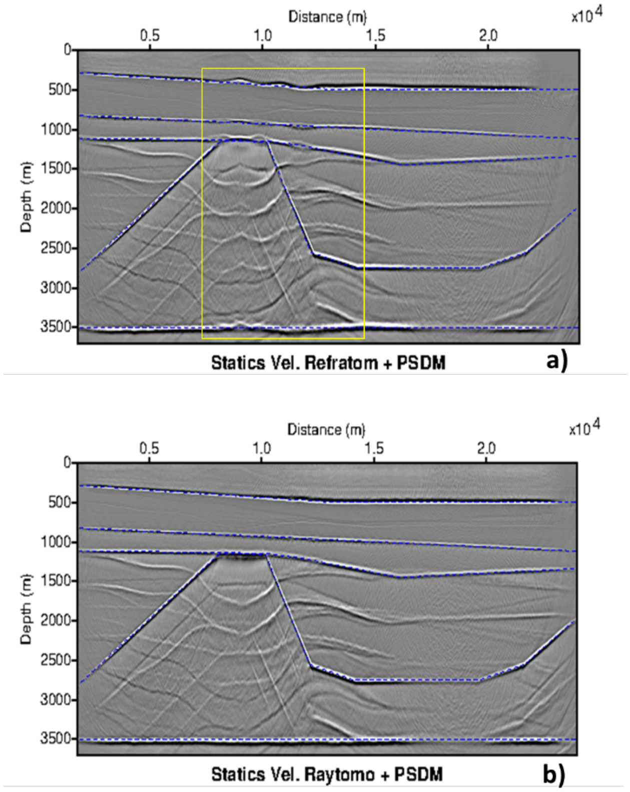

Figure 3 – PSDM images obtained for the synthetic prestack data with static correction to the final datum (0 m): a) migrated image from data with static correction using Rafratom's near-surface velocity model and b) migrated image from data with static correction using the Rayinvr's near-surface velocity model.

Conclusions

This paper presents a study of depth seismic imaging using a synthetic seismic data representing the geologic setting of the Serra do Mel region in the Potiguar Basin.

The results showed that errors in reflector focusing occur when static correction is applied to the final flat datum with an inaccurate near-surface velocity model. A similar error occurs when redatuming is applied with an inaccurate near-surface velocity model.

However, in data with static correction applied using the inaccurate near-surface velocity model, the focusing errors are larger at the shallower reflectors, resulting in greater error propagation when using any method to determine the depth velocity model. For data with more variable topography, these errors may increase.

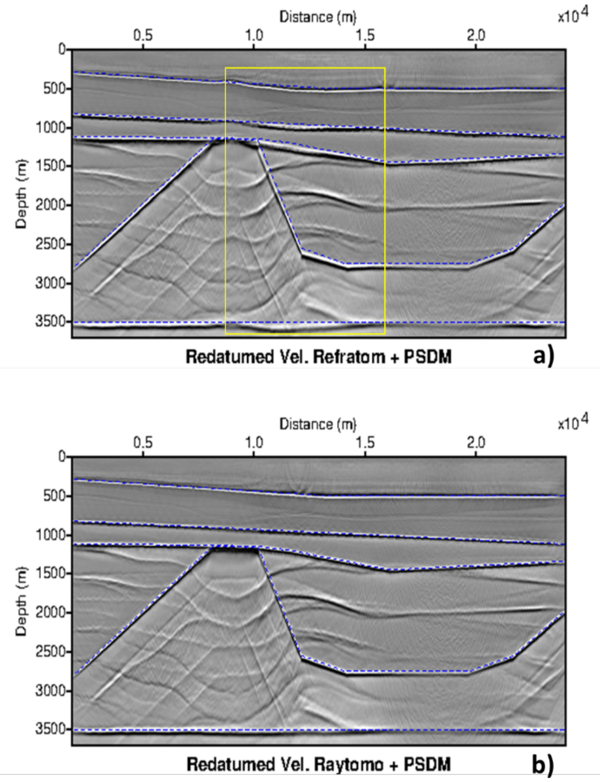

Figure 4 – PSDM images obtained for the synthetic prestack data redatumed to the flat datum at 0 m: a) migrated image from redatumed data using Rafratom's near-surface velocity model and b) migrated image from redatumed data using the Rayinvr's near-surface velocity model.

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