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Non-Hyperbolic Velocity Analysis of Seismic Data from Jequitinhonha Basin, Northeastern Brazil

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Abstract: Normal moveout (NMO) velocity is used in seismic data processing to correct the data from the moveout effect. This velocity depends on the medium above the reflector and it is estimated from the adjustment of a hyperbolic function that approximates the reflection time. This approximation is reasonable for media formed by isotropic layers. For deeper exploration targets, which effectively behave as anisotropic media, the NMO velocity estimate from the hyperbolic approximation becomes imprecise. One possibility is the use of non-hyperbolic approximations for the reflection time and deeming the medium to be anisotropic. However, these approximations make the NMO velocity estimation a more complex problem, since the anisotropic parameters are unknown. In this study the NMO velocities for a vertical transverse isotropy medium are estimated using two non-hyperbolic reflection time approaches. For comparing the two methodologies that estimate NMO velocity, a 2-D dataset from Jequitinhonha Basin is used and it presents anisotropic behavior. The results show that this approach produces more consistent results than the conventional approach, which ignores the anisotropy of the medium.

Key words: NMO velocity, non-hyperbolic reflection time, anisotropic media.

INTRODUCTION

After the seismic reflection data acquisition, the same data is processed, so that the final product is the seismic section, to be interpreted by geophysicists and geologists. There are three main steps in seismic data processing: deconvolution, stacking and migration, in their usual order of application (Yilmaz 1987). Deconvolution removes the effects of the wavelet, which is the wave generated by the seismic source, from the seismic trace recorded at the surface receivers. With the deconvolution increases the temporal resolution of the seismic trait. After deconvolution, there is the stacking which is a compression procedure, so that the volume of data is reduced to a stacked seismic section. This is done by applying the normal moveout (NMO) correction to seismic traces sorted in groups or families of common midpoints (CMPs), and then the traces are summed along the offset axis. An important parameter required for stacking is the so-called stacking velocity, which in turn is obtained through a velocity analysis or a statistical process of consistency maximization. Finally, migration is a step that eliminates diffractions and maps the events in a stacked section to their correct subsurface positions. To obtain the stacked image the data is transformed from source-receiver coordinates to CMP families. A CMP family consists of several seismic traces that have different source and receiver positions, but all have the same midpoint.

The velocity used to correct the effect of the moveout on CMP gathers, called NMO velocity, is considered equal to the stacking velocity. In conventional seismic data processing this velocity is estimated from the data by an optimal fit between the observed reflection time and a hyperbolic approximation of this same time. However, for shallow events with large offsets, the hyperbolic approximation of the refection time fails, and the velocity estimation and NMO correction will generate significant distortions in the high frequencies of the seismic data (Yilmaz 1987), compromising the stacking and imaging from these data. A number of studies have attempted to compensate for these distortions (Al-Chalabi 1973, 1974, Malovichko 1978, Blias 1982, Goldin 1986, Alkhalifah & Tsvankin 1995) by using non-hyperbolic approximations for the reflection time computation.

Seismic anisotropy is a consequence of ordered small-scale heterogeneity (Thomsen 2002). In general, sedimentary basins have layers with thicknesses much smaller than the wavelength. In other words, a medium composed of thin multilayer isotropic materials can be considered homogeneous and anisotropic if the wavelength of the elastic waves which propagates in it is much larger than the thickness of the layers, causing changes in the seismic response. In seismic data processing these changes are observed in the difference in the reflection time curve and the first procedure in which the anisotropy can identified is through NMO correction.

Media formed by thin layers or that encompass a fault system, as is the case for several hydrocarbon reservoirs, behave as effective anisotropic media (Helbig 1994). Among the various types of anisotropy, a medium is type VTI anisotropic if it is stratified or has a system of horizontal flat faults. For anisotropic media, it is more complex to estimate the NMO velocity since the approximation of the reflection time must take into account the anisotropic parameters of the medium (Alkhalifah & Tsvankin 1995, Alkhalifah 1997, Fomel 2004, Aleixo & Schleicher 2010). These parameters are generally unknown.

In this work, two methodologies are used to estimate the NMO velocity of a real 2-D marine data, without the need to estimate the anisotropic parameters of the medium. The two methodologies use the approaches of Al-Chalabi (1973) and Castle (1994) for reflection time computation. We show that even when the medium presents anisotropy it is possible to estimate a consistent NMO velocity model without the knowledge of the anisotropic parameters of the medium, with better results than the conventional approach.

MATHEMATICAL MODELS FOR THE REFLECTED TIME COMPUTATION

For a medium formed by two layers separated by a flat reflector, and when the medium above the reflector is homogeneous and isotropic, the reflection time is given by

$$t(x)^2 = t_0^2 + \frac{x^2}{v^2}, \tag{1}$$

where $t(x)$ is the reflection time along the source-reflector-receiver path, x is the distance between the source and receiver, t_0 is the reflection time at position $x = 0$ and v is the medium velocity. The reflection time in equation (1) describes a symmetric hyperbole with respect to the time axis, whose asymptotes intersect at the position of the source, which is the origin of the coordinate system.

For a medium formed by *N* layers the traveltime of the reflected wave generated by the source is given by (Taner & Koehler 1969):

$$t_s(x)^2 = C_0 + C_1x^2 + C_2x^4 + C_3x^6 + \ldots + C_kx^{2k-2}, \qquad (2)$$

in which $C_0 = t_0^2$, $C_1 = 1/v_{RMS}^2$, C_2,... are functions of the thickness and wave velocity of the layers. The root mean square (RMS) velocity is an average of the interval velocities and is given by (Dix 1955):

$$v_{RMS}^2 = \frac{\sum_{k=1}^{N} \tau_k v_k^2}{\sum_{k=1}^{N} \Delta\tau_k}, \qquad (3)$$

in which v_k is the interval velocity and $\Delta\tau_k$ is the double traveltime (reflection time) in the k-th layer. Thus, the RMS velocity is an average of the velocities of the layers above the reflector.

Considering small offsets, that is, when $x << z$ where z is the depth of the reflector, an approximation of the reflection time for a stratified medium is given by (Yilmaz 1987):

$$t_c(x)^2 = C_0 + C_1x^2 = t_0^2 + \frac{1}{v_{RMS}^2}. \qquad (4)$$

In a CMP gather, the data are under the effect of the moveout due to the distance between source and receiver. The correction of the moveout Δt_{NMO} is given by:

$$\Delta t_{NMO} = t(x) - t_0, \qquad (5)$$

Equations (1) and (4) are similar, such that for a stratified medium the reflected wave velocity is given by the average RMS of the layer velocities above the reflector. The velocity required to correct the NMO effect in a stratified medium is made equal to the RMS velocity, that is, $v_{NMO} = v_{RMS}$.

The NMO correction, expressed by equation (5), is further improved the closer the curve $t(x)$ is to the observed reflection times. In conventional processing the velocity estimation for NMO correction is based on equation (4). However, the equation for the reflection time in (4) fails for media with some degree of anisotropy and large offsets**.**

AL-CHALABI APPROACH FOR REFLECTION TIME APPROXIMATION

Equation (4) assumes that the RMS velocity is equal to the NMO velocity. Al-Chalabi (1973) proposed a third term in equation (2) that includes medium characteristics, which have an NMO velocity different from than RMS velocity, with the following condition:

$$C_2x^4 > 2(t_c^2 - t_s^2). \qquad (6)$$

In practice, the value of C_2x^4 is very close to the value of $2(t_c^2 - t_s^2)$ which makes the third term generate satisfactory results. In this study, the Al-Chalabi method will be referred to as the velocity estimation for the NMO correction, which uses the velocity analysis given in equation (2), truncated up to the third term. The coefficient of this term in equation (2) is given by:

$$C_2 = (a_2^2 - a_1a_3)/4a_2^4, \qquad (7)$$

where $a_i = 2\sum_{k=1}^{N} v_k^{2i-3} h_k$ with i = 1, 2, 3, ... and h_k is the thickness of the k-th layer.

Castle Approach for Reflection Time Approximation

Another mathematical expression to compute the reflection time is presented in Malovichko (1978) and used by Castle (1994), according to the equation:

$$t=\tau_s+\sqrt{\tau_0^2+\frac{x^2}{v^2}}, \tag{8}$$

where $\tau_0=\frac{t_0}{S}$, is expressed as

$$\tau_0=\frac{t_0}{S}, \tag{9}$$

and τ_s is the intersection time of the asymptotes and the time axis:

$$\tau_s=\tau_0(S-1). \tag{10}$$

In the equations above, t_0 is the zero offset reflection time and v is an auxiliary variable, so that

$$v^2=SV_{RMS}^2, \tag{11}$$

where S is the heterogeneity factor and is expressed as

$$S=\frac{\mu_4}{\mu_2^2} \tag{12}$$

The value of μ_j is expressed by

$$\mu_j=\frac{\sum_{k=1}^{N}\Delta\tau_k v_k^j}{\sum_{k=1}^{N}\Delta\tau_k}, \tag{13}$$

and is called the time weighted moment of time. The termis v_k the interval velocity and $\Delta\tau_k$ is the vertical time of the $k-$ th layer.

Synthetic Data

Figure 1 shows the exact reflection time (purple curve) and its different approximations. The simple model is formed by a flat reflector located at a depth of z = 0.5 km. The medium above the reflector is the Greenhorn shale where the vertical velocity of the P wave v_p, is 3.094 km/s and the Thomsen parameters are ε = 0.256 and δ = -0.051 (Jones & Wang 1981). The reflection time is the sum of the travel time between the source and the reflection point with the time between the reflection point and the receiver. The time computed by the equation (1) is shown in Figures 1a and 1b by the green color curve. Note that this reflection time curve is hyperbolic in nature, and this is in accordance with equation (1), that is, the behavior of the curve is consistent with the hyperbolic dependence of the reflection time t(x) as a function of the offset x. It is observed that for small deviations, with the receiver near the source, the reflection time is slightly greater than 0.3 s. For large deviations, the reflection time is around 1.7 s.

This figure shows that the approximate reflection time calculated in (5) is inconsistent with the exact reflection time when the offset-depth ratio $x/z > 2.0$. These results compromise the NMO correction provided by equation (5).

A second model, shown in Figure 2, is formed by five layers with VTI anisotropy whose anellipticity parameter η, defined by Alkhalifah & Tsvankin (1995), ranges from 0 to values greater than 0.2. This variation is a function of the layer depth, such that the last layer has the highest anisotropy value.

The reflection data of the synthetic models were obtained through SU (Seismic Unix) (Stockwell 1997, Cohen & Stockwell 2010). The velocity spectrum of a CMP gather of the data is shown in Figure 3a. Figure 3b shows the results of the NMO corrected velocity used in equation (5), which considers the medium to be isotropic (i.e. η = 0). According to this figure, when η ≠ 0 (i.e. for anisotropic media), the events are not horizontal, even for small offsets. Thus, other

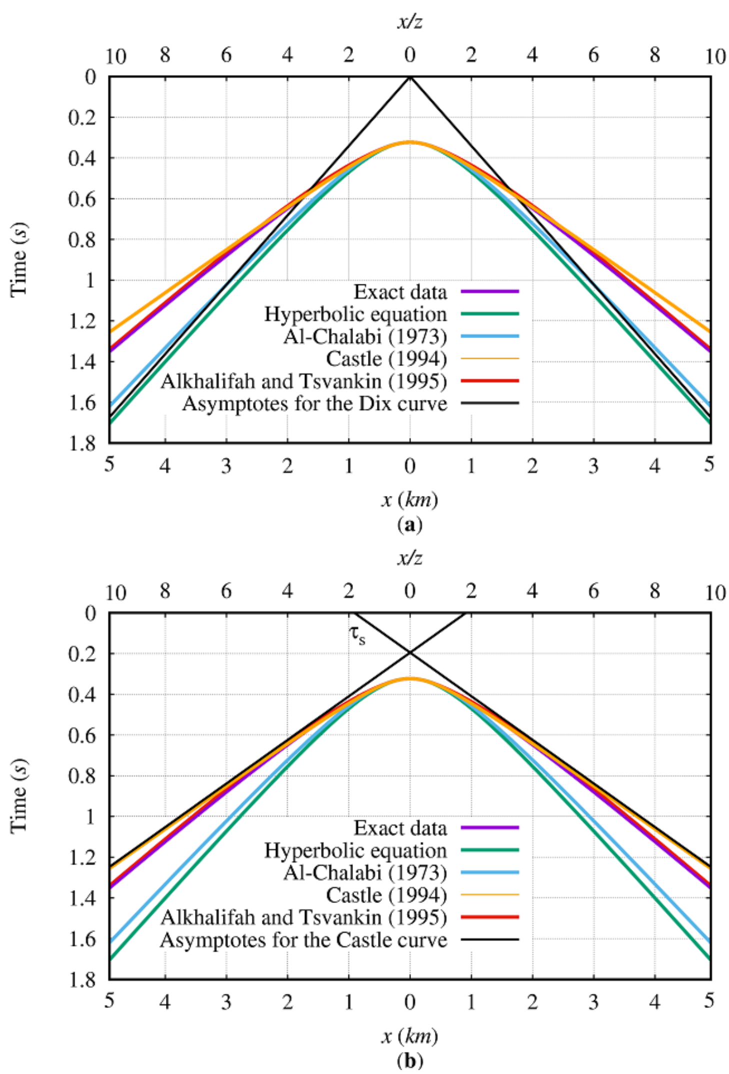

Figure 1. **Reflection time for a model with a horizontal reflector at 0.5 km depth, whose incident medium is VTI (Greenhorn). On the horizontal axis, the distance is shown at the bottom of the graphic and the offset depth ratio of the reflector is shown at the top of the graphic. The reflection time is indicated on the vertical axis. The exact reflection time is the purple curve and the conventional hyperbolic approximation (equation (5)) is the green curve. Three non-hyperbolic approximations are also shown: Al-Chalabi (blue curve), Castle (orange curve) and Alkhalifah and Tsvankin (red curve). In (a) the asymptotes of the conventional approach and in (b) Castle's asymptotes are both shown in black.**

approximations are required for the reflection time in anisotropic media.

Figure 1b shows the geometry of equation (8) for the same model shown in Figure 1a; a horizontal reflector in an anisotropic medium. The approximation given by equation (8) describes a shifted symmetric hyperbole with respect to the time axis, and its asymptotes intersect at the point $(x=0, t=\tau_s)$. Figure 1b also shows the non-hyperbolic reflection time approximation curves: Al-Chalabi's (blue curve), Alkhalifah & Tsvankin's (red curve) which depend on the anisotropic parameter η of the medium, and Castle's (orange curve).

Figure 1b shows the similarity between Castle's and Alkhalifah & Tsvankin's approaches for the exact reflection time when the offset-depth ratios are up to 4.0 (x/z < 4.0). When the range is 4.0 < x/z < 6.0 Castle's approximation presents different results from the exact data, although the difference is small and still within this range. For values of *x*/*z* > 6.0, Castle's approximation is faulty. The approach of Alkhalifah & Tsvankin produces better results than Castle's approach in all situations.

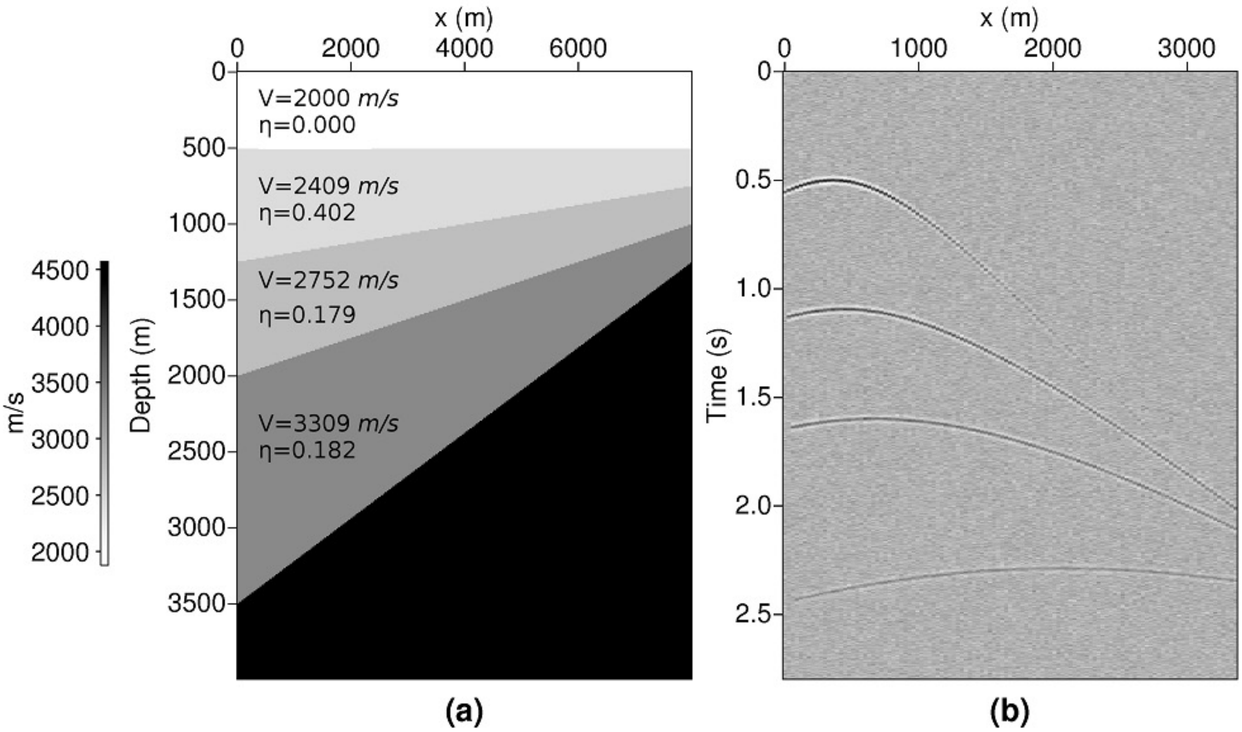

Figure 2. a) Geometry of the model 2 formed by five layers with dipping reflectors, whose degree of anisotropy increases with depth. b) A CMP family of the synthetic data obtained through SU.

However, as previously mentioned, using the reflection time approximation presented by Alkhalifah & Tsvankin requires that the medium has anisotropic parameters (Ortega et al. 2018). Figure 1b shows that for offset-depth ratios $x/z < 2.0$, the Al-Chalabi's approximation presents a behavior close to the observed reflection time, which was already expected for small offsets. Other tests were done where the medium was considered to have a weak degree of anisotropy, that is less than 10% according to Thomsen (1986), and showed that all approaches analyzed here presented the same behavior, but more accurately in relation to the observed reflection time.

According to Figure 1, the estimated velocity from the approach presented in Castle (1994) presents satisfactory results when the medium displays a moderate degree of anisotropy, approximately 20% according to Thomsen's parameters, and offset-depth ratios of 4.0. Conventional hydrocarbon reservoirs can reach up to 5 km deep, and in exceptional situations they can reach a depth of 9 km (Al-Harrasi et al. 2011); furthermore the anisotropy does not exceed 20% in the Thomsen's parameters. For data acquisitions with offsets greater than 2 km, the offset-depth ratio $x/z < 4.0$. Therefore, it is reasonable to consider the approach presented in Castle (1994), even for media with anisotropy, instead of the conventional approach; because in addition to producing better results, it still has the advantage of not needing the anisotropy parameters of the medium

Velocity Estimation for a Real Anisotropic Data

The Jequitinhonha Basin is located in the northeastern region of the Brazilian coast, on the southern coast of the State of Bahia (see Figure 4). It occupies an area of approximately

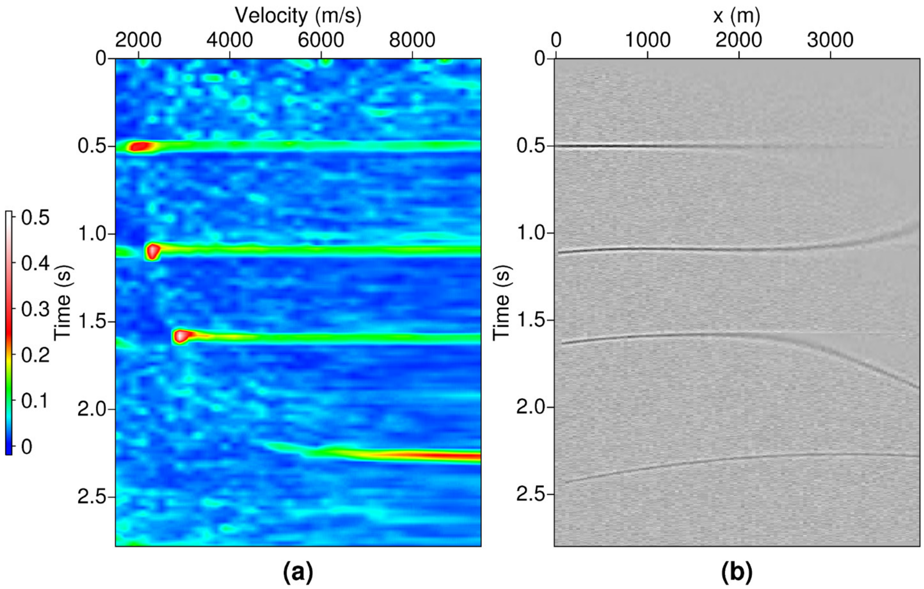

Figure 3. a) CMP family semblance panel shown in Figure 2b. b) The same CMP family after the conventional velocity analysis corrected for the NMO effect.

10,100 km^2, of which 9,500 km^2 are submerged. In relation to the offshore portion, an area of 7,000 km^2 is between 0 to 1,000 m water depth and an area of 2,500 km^2 is between 1,000 and 2,000 m. This basin is located on the southern border of the São Francisco Craton, and is mainly comprised of granitic rocks, totally or partially reworked by the Transamazonian cycle (Santos et al. 1994).

The seismic line used in this study is 0214-0270. It extends a length of 27.625 km and is located on the slope region, between the continental shelf and the oceanic platform (Figure 4). Data from line 0214-0270 was acquired by a marine tower streamer type vessel, whose haul was 3,125 m in length and had 120 channels. Details of the acquisition geometry are provided in Table I.

The seismic processing performed up to the stacking step is shown in a flowchart (Figure 5). In the velocity analysis step for the NMO correction, three approaches for estimating NMO velocity were applied: (i) conventional analysis according to equation (4); (ii) the formulation by Al-Chalabi (1973) presented in this study in equation (2) up to the third term; (iii) and the formulation by Castle (1994) presented here in equation (8). Multiplicative seismic events that appear in the seismic sections are called multiple reflections and are mainly caused by the surface of the water layer, which is subject only to atmospheric pressure. In other words, the seismic wave propagates to all directions in subsurface, and it will also rise until reaching the free surface and will be reflected by it. No procedure was adopted for the attenuation of these multiple reflections, which could be applied before the velocity analysis step. We chose not to deal with the multiples, because the main objective of this work is to show the effects of the NMO correction on the stacked image.

Velocity analysis is a step in the seismic data processing with the objective to determine the seismic velocity of a given medium, for example, a medium arranged in layers. Its result directly influences the steps of stacking and migration. In the velocity analysis we try to obtain a velocity function that results in a better NMO correction, and consequently a better stacking. In this work

Figure 4. Map indicating the location of the Jequitinhonha Basin. The seismic line used (indicated on the map in red) is located on the slope region, between the continental shelf and the abyssal plain. Source: Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (2018).

velocity analysis was implemented through the velocity spectrum, which in turn is obtained by means of a measure of coherence or semblance. Coherence is a measure that represents the degree of similarity between the seismic traces of a CMP family. The graphical representation of the velocity spectrum is by means of color maps, in which the amplitude peaks represent the greatest coherence measurements.

Figures 6 to 8 show the CMP gather 977, velocity spectrums with selected velocity curves and the CMP gather correction that takes into account the estimated velocity. Muting was not applied to the results after the NMO correction so that the effects of each velocity estimate could be observed.

In the velocity analysis discussed in this work, the reflection time was calculated with the hyperbolic traveltime formula of equation (1) as shown in Figure 6, with the non-hyperbolic approximation of Al-Chalabi (1974) according to Figure 7 and Figure 8 shows the result using the non-hyperbolic approximation of Castle (1994). The semblance values are directly associated with the coherence of events, so that the most coherent events will have semblance values close to 1, corresponding to the peak of the spectrum. The events associated with noise will have values close to zero.

Table I. **Acquisition geometry of seismic line 0214-0270 in the Jequitinhonha Basin.**

Parameter	Value
Number of sources	981
Distance between sources (*m*)	25
Number of channels	120
Distance between channels (*m*)	25
Minimum offset (*m*)	150
Maximum offset (*m*)	3125
Register time (*s*)	5.0

In traditional velocity estimation approaches, frequency distortions occur as a result of NMO correction. This can be seen in Figure 6, where the data overcorrected for large offsets and shallow events. For Al-Chalabi's (1973) approach, the result of NMO correction shows an improvement in stretching, but the data are now under-corrected for large offsets (Figure 7). The Castle approach (1994) is shown in Figure 8, along with the results of the NMO correction. A comparison between Figures 6 through 8, demonstrates that Castle's velocity estimation provides the best results.

In Figures 9 and 10 the results are shown as stacked sections of the data from using the estimated velocities according to, respectively, the traditional approach in Figure 9a, Al-Chalabi's approach in Figure 9b, and Castle's approach in Figure 10. The approach of Castle (1994) presented the best results, because the shallower reflectors have a higher resolution and lateral continuity. Thus, even if the data presents moderate anisotropy, it is possible to estimate the velocity with better results than those obtained from conventional processing by using Castle's approach where the medium anisotropy of the medium are not required. There is no much difference between Figures 9a and 9b. However, the blue rectangle captures a small region where we can see the result of frequency distortions due to NMO correction. For this particular region Figure 9b is slightly better than Figure 9a, but the best coherence can be seen in Figure 10.

We used the conventional methodology, as well as Castle's and Al-Chalabi's, for 2-D marine data from the Jequitinhonha Basin which has a water depth greater than 2 km. We assume that the data refers to a VTI medium, based on the behavior of the distance-depth ratio (Tsvankin & Thomsen 1994). In this type of medium the horizontal velocity is faster than the vertical velocity, and in fact, faster than the NMO velocity. The presence of VTI seismic anisotropy produces significant distortions in the seismic images, obtained from the velocities of conventional velocity analysis. NMO correction in this type of medium produces distortions in the frequency called stretching, which manifest themselves significantly in large distances ($x/z > 1$), in low-velocity shallow events and in anisotropic media. This is because the horizontal velocity in this type of medium is faster than the vertical velocity, and in fact, faster than the NMO velocity. This means that by correcting this stretch hyperbolic analysis, there will be an overcorrection, making stretching more evident. One solution to this problem is to remove the overcorrected traces and stack the others, thus obtaining a more adequate image. It should be emphasized that the stretching is not an undoubted diagnosis of the presence of anisotropy in the subsurface, since isotropic layers may produce similar effects. However, this latter situation is a special case. On the other hand, the simulation with the synthetic data showed that the anisotropy factor η, used in the Alkhalifah & Tsvankin (1995) approach, was quite adequate to the extent that the result was close to Castle's (1994) approach, used both in the synthetic data and in the real data. Thus, it is valid to use an equation for the reflection time that has a correct asymptotic behavior in small and large deviations for the velocity analysis. The non-hyperbolic behavior of reflections is not visually clear in raw data, and is more evident when hyperbolic corrections are made (Thomsen 2002).

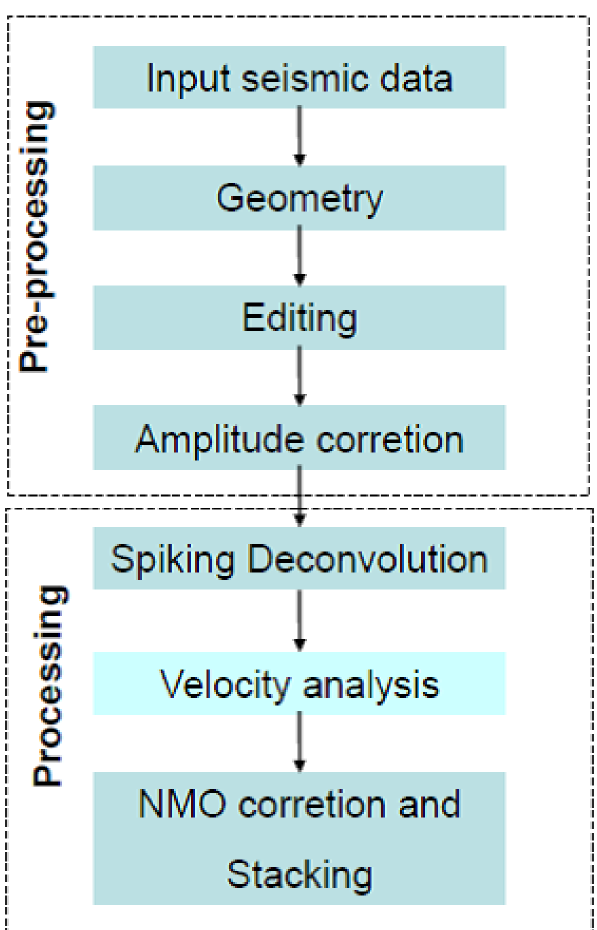

Figure 5. Processing flowchart of the marine seismic line 0214-0270 in the Jequitinhonha Basin.

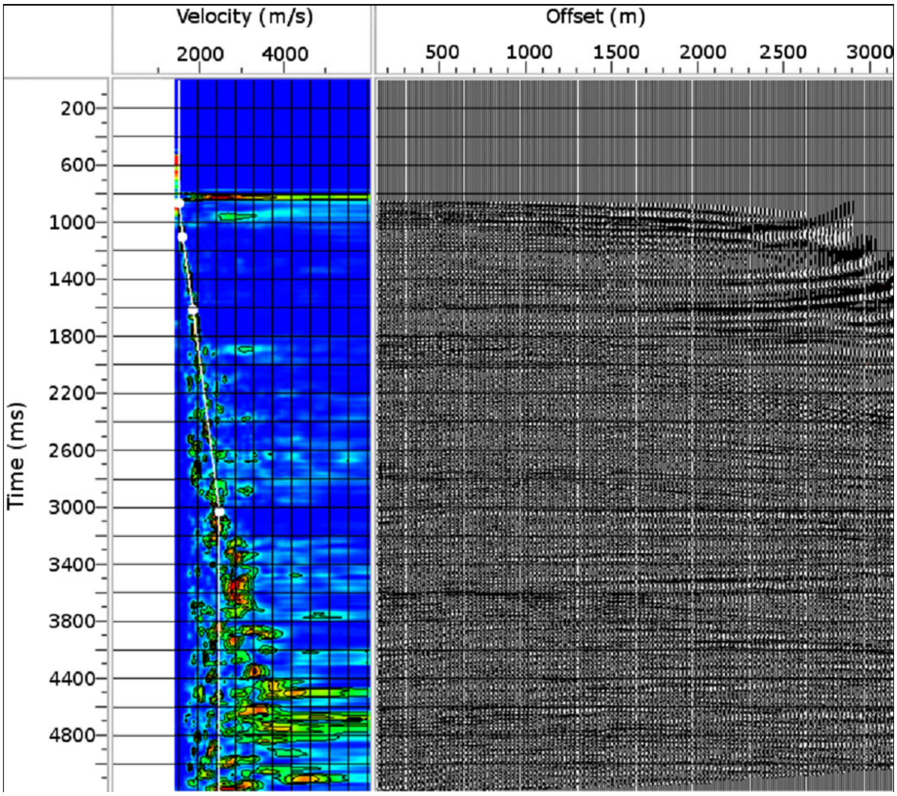

Figure 6. Velocity spectrum (left) and NMO correction (right) for the CMP gather 977. Estimated velocities (points on the white curve) were obtained through the hyperbolic approximation of the traveltime, equation (4).

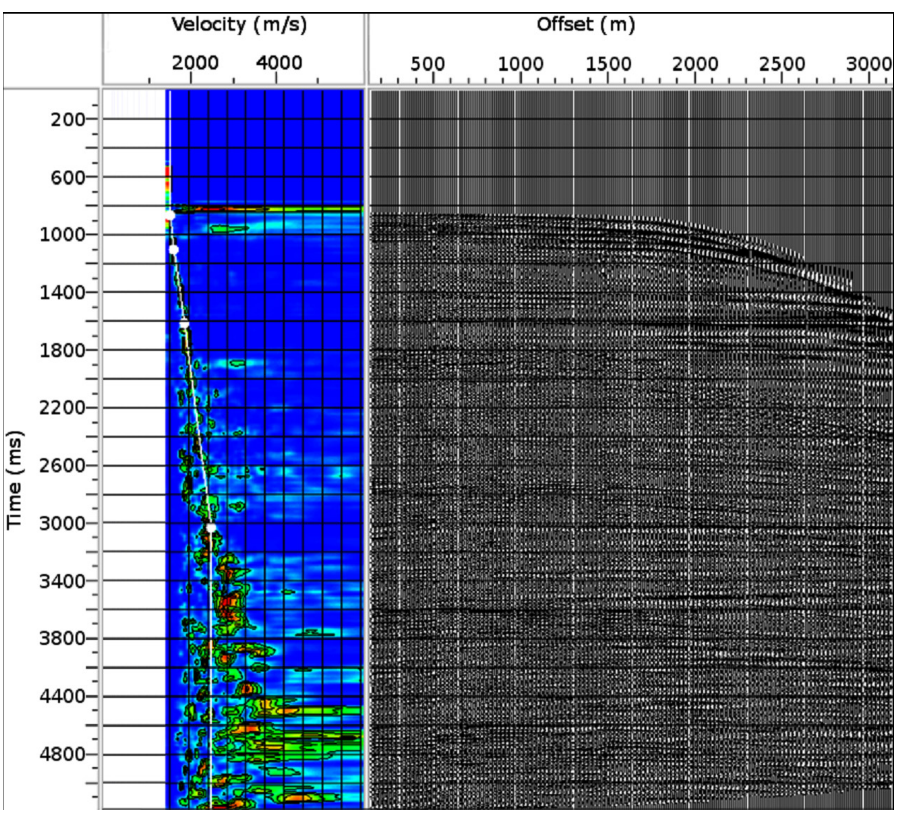

Figure 7. Velocity spectrum (left) and respective NMO correction (right) for the CMP gather 977. Estimated velocities (points on the white curve) were obtained through the non-hyperbolic approximation of Castle (1994).

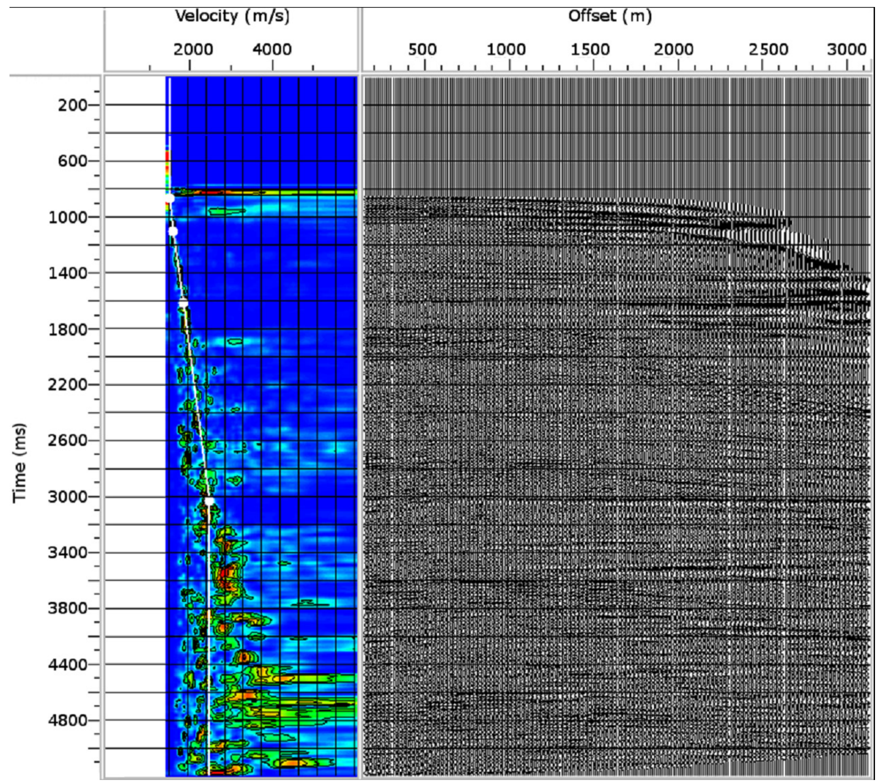

Figure 8. Velocity spectrum (left) and respective NMO correction (right) for the CMP gather 977. Estimated velocities (points on the white curve) were obtained through the non-hyperbolic approximation of Al-Chalabi (1973).

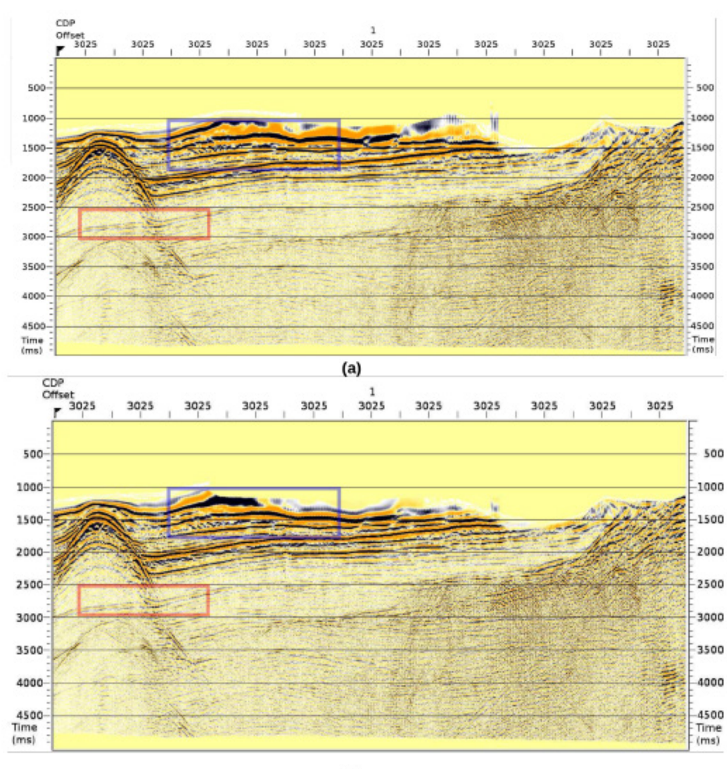

Figure 9. a) Stacked seismic section where the NMO velocity was estimated using conventional velocity analysis. b) Stacked seismic section where the NMO velocity was estimated using Al-Chalabi (1973) method. The blue rectangle show a region in detail where the frequency distortions due the NMO correction can be seen. The image using Al-Chalabi (1973) method is slightly more coherent than Figure 9a. In both images, the water-bottom multiples of first order, indicated by the red rectangle, are always present.

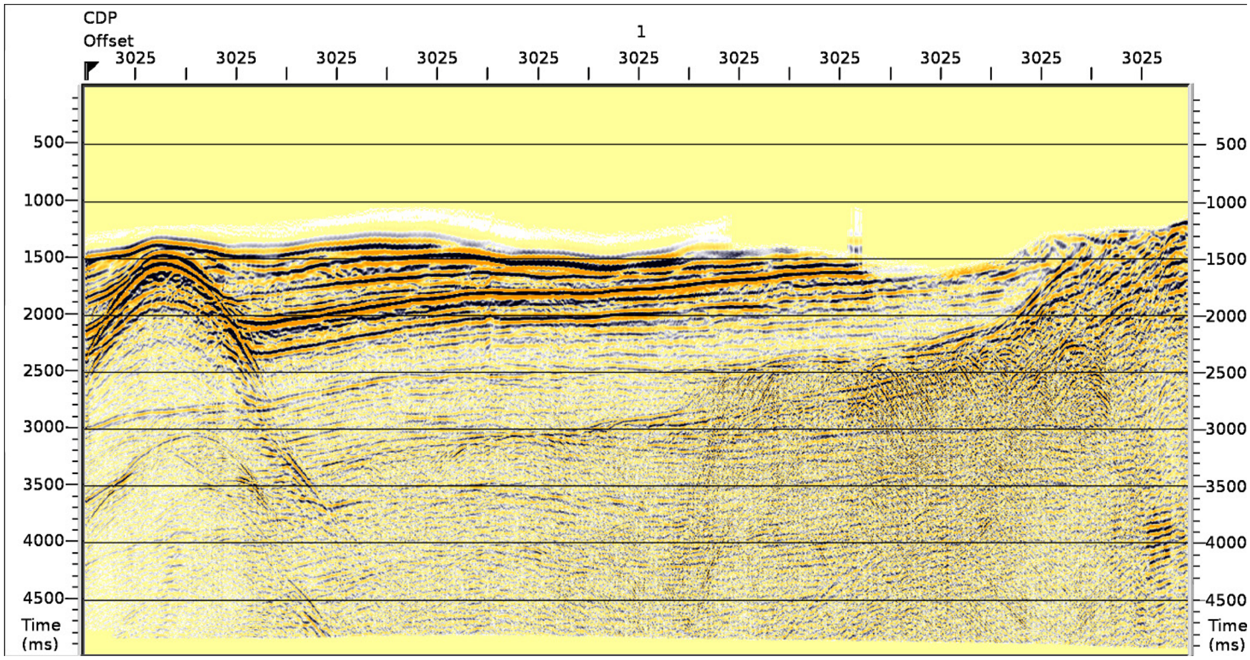

Figure 10. Stacked seismic section where the NMO velocity was estimated using the method of Castle (1994). Note a higher resolution and reflector continuity between 1500 and 2000 ms.

CONCLUSIONS

We applied different methodologies to estimate the velocity of NMO correction for 2-D marine data with large offsets. The medium was considered anisotropic, and a common procedure to obtain velocity estimation is the methodology presented in Tsvankin & Thomsen (1994). However, this methodology requires that the anisotropic parameters of the medium be known, which is information that is generally not available. As alternatives, three approaches to obtain velocity estimation were tested. In the first one that is the conventional approach, the estimation is made taking into account the hyperbolic reflection time curve. The two other approaches (Al-Chalabi 1973, Castle 1994) consider a non-hyperbolic curve for the reflection time. The residual curve of the NMO correction with large offsets is properly corrected for using Castle's displaced hyperbola method. It results in a better quality stacked seismic section compared to the conventional velocity and the Al-Chalabi methods. These results were applied to large offsets in data from the Jequitinhonha Basin, without using NMO stretching of the traces after NMO correction. Thus, according to these three tests, it was shown that, for an anisotropic medium it is possible to estimate the NMO velocity without knowing the anisotropy parameters of the medium, with better results than those obtained using the conventional approach. In addition, it was shown that for media with a moderate degree of anisotropy, using Castle's approach provides reasonable results for distance-depth ratios up to 4.0.

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FG Ortega developed this study, processed the seismic data, generated the figures, interpreted the results and wrote the first version of the manuscript. A Bassrei idealized and supervised the research, translated the manuscript, contributed to the results discussion and to the text review. ENS Gomes co-supervised the research and contributed to the results discussion and to the text review. AG Oliveira helped with the seismic data processing and contributed to the results discussion and to the text review.

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