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Improvement of stacking image by anisotropic velocity analysis using P-wave seismic data

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Summary

Anisotropy (e.g., directional dependence of velocity at a fixed spatial location in a medium) plays a very important role in seismic imaging. It is very difficult to know the presence of anisotropy in the subsurface geological formations only from P-wave seismic data and special analysis is required for this. The presence of anisotropy causes two major distortions of moveout in P-wave seismic reflection data. First, in contrast to isotropic media, normal moveout (NMO) velocity differs from the vertical velocity; and the second is substantial increase of deviations in hyperbolic moveout in an anisotropic layer. Hence, with the help of conventional velocity analysis based on shortspread moveout (stacking) velocities does not provide enough information to determine the true vertical velocity in a transversely isotropic media with vertical symmetry axis (VTI media). Therefore, it is very much essential to estimate the single anisotropic parameter (η) from the longoffset P-wave seismic data. The long-offset P-wave data has observable non-hyperbolic moveout, which depends on two parameters such as normal moveout velocity (V_{nmo}) and the anisotropy parameter (η). It has been demonstrated here with long-offset P-wave seismic data that suitable velocity analysis using V_{nmo} and η can improve the stacking image obtained from conventional velocity analysis.

Introduction

The most important and difficult step for seismic data processing and inversion in anisotropic media is to identify the medium parameters hidden within the reflection P-wave seismic data. The subsurface geological targets of interest are dominated by horizontal or subhorizontal layers. Hence, the seismic reflection data provides important information about these layers. Moveout from these horizontal and subhorizontal reflectors provides useful information about subsurface velocity. Fortunately, reflection moveouts from horizontal interfaces are generally well represented by truncated Taylor series-type characterizations of moveout in transversely isotropic (TI) media with a vertical symmetry axis (VTI) (Hake et al., 1984; Tsvankin and Thomsen, 1994). These representations are accurate to and beyond the large offsets often used in practice. Here we have tried to obtain the improvements in the stacking image by suitable anisotropic velocity analysis as compared to the conventional stacking velocity analysis. This method also provides a measure of the anisotropic parameter obtained from the P-wave velocity analysis of VTI media for the long-offset seismic data. The improvements in the stack section after anisotropic velocity analysis is substantial as compared to its counterpart of pure isotropic conventional velocity analysis with short-spread NMO. Alkhalifah and Tsvankin (1995) demonstrated that for VTI media just two parameters are sufficient for performing all time-related processing, such as NMO correction (including nonhyperbolic moveout correction), dip-moveout (DMO) correction, and prestack and poststack time migrations.

Methodology

NMO velocity for layered VTI media

Reflection traveltimes (moveout) provide the most reliable information for building velocity models using surface seismic data both in isotropic and anisotropic media. If the medium is anisotropic, an attempt to fit the traveltimeoffset relationship using a purely isotropic velocity field may lead to misstacking of reflection events and distortions in

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seismic images. Hence, understanding the influence of anisotropy on the kinematics of reflected waves is of primary importance in seismic velocity analysis and processing. Moveout of pure (non-converted) modes on common-midpoint (CMP) gathers is conventionally approximated by the Taylor series expansion near the vertical (e.g., Taner and Koehler, 1969):

$$T_x^2 = A_0 + A_2 x^2 + A_4 x^4 + ..., \quad (1)$$

where x is the source-receiver offset, T_X is two-way traveltime at offset x, and the coefficients are given by

$$A_0 = T_0^2, A_2 = \left.\frac{d(T_x^2)}{d(x^2)}\right|_{x=0}, A_4 = \frac{1}{2}\frac{d}{d(x^2)}\left[\frac{d(T_x^2)}{d(x^2)}\right]_{x=0} \quad ;(2)$$

T_0 is the two-way zero-offset traveltime. Equation (1) does not include odd powers of x because CMP moveout of pure modes is symmetric with respect to zero offset (e.g., it remains the same when one interchanges the source and receiver) (Tsvankin, 2005).

The moveout parameter of most practical significance in exploration seismic is the NMO velocity V_{nmo}, responsible for the hyperbolic moveout on conventional spread lengths that do not exceed the distance between the CMP and the reflector as per Dix (1955):

$$T_{hyp}^2 = T_0^2 + \frac{x^2}{V_{nmo}^2} \quad (3)$$

and

$$V_{nmo}^2 = \frac{1}{A_2} = \left.\frac{d(x^2)}{d(t^2)}\right|_{x=0} \quad (4)$$

If the traveltime is plotted in the T^2 - x^2 coordinates, the factor I/V^2_{nmo} determines the initial slope of the moveout curve. With increasing offset T^2 (x^2) curve deviates from a straight line due to the influence of the quartic (A^4x^4) and the higher-order moveout terms. Hence, stacking velocity estimated using finite-spread moveout in conventional processing (i.e., moveout velocity) may differ from the analytic NMO velocity defined by equation (4).

Anisotropy causes two major distortions of reflection moveout. First, in contrast to isotropic media, NMO velocity generally differs from the vertical velocity (in a single layer) or from the root-mean-square (RMS) of the interval vertical velocities (in layered media). This is the main reason for mis-ties in time-to-depth conversion and the erroneous depth scale of seismic images often produced by conventional migration algorithms. Second, anisotropy may substantially increase deviations from the hyperbolic moveout since T(x) curve becomes non-hyperbolic even in a single homogeneous anisotropic layer (Tsvankin, 2005).

The standard NMO equation (3) used in the industry applies only the first two terms of the Taylor series expansion (equation 1). Although seismic data of all offset ranges strictly speaking is non-hyperbolic. Hence the use of first two terms only for NMO equation, which describe a perfect hyperbola, is adequate for small to medium angles/offsets. Long-offset data or data from VTI media, however, may have observable non-hyperbolic moveout, and so higher order terms must be included to accurately obtain the moveout correction. It has been shown that such moveout depends on only two parameters, normal moveout velocity V_{nmo} and the anisotropy parameter η (Alkhalifah, 1997).

Alkhalifah (1997) suggested an approximation to the truncated Taylor series terms by including η in the fourth order term, which provides a better estimate of the exact formulation of the infinite series. The corresponding nonhyperbolic NMO equation for P-waves in a single VTI layer can be represented as

$$T^2(x) = T_0^2 + \frac{x^2}{V_{nmo}^2} - \frac{2\eta x^4}{V_{nmo}^2\left[T_0^2 V_{nmo}^2 (1+2\eta) x^2\right]} \quad (5)$$

where T(x) is the two-way traveltime at offset x, T_0 is the zero offset two-way traveltime, V_{nmo} is the NMO velocity, and η (coefficient of anisotropy) is the VTI medium parameter. For homogeneous media

$$V_h = V_{nmo}\sqrt{1+2\eta} \quad (6)$$

where V_η is the horizontal velocity. The first two terms on the right of equation (5) correspond to the hyperbolic portion of the moveout, whereas the third term approximates the non-hyperbolic contribution. Note that the third term (fourth order in x) is proportional to the coefficient of anisotropy η, which therefore controls nonhyperbolic moveout directly.

The NMO interpolation now requires to access a time-rms velocity (T - V) function that has been stored in seismic database prior to running the program. The time-velocity pairs stored in the database are not directly used to calculate NMO. Instead, the following sequence is used in the calculations (i) the velocities are horizontally interpolated, (ii) the velocities are vertically interpolated, (iii) the moveout is calculated for each sample. For η analysis the corresponding module stores η functions in the seismic database. The functions are in the form of time-η (T - η) pairs defined for specified CDP locations along the seismic line. The corresponding T-η functions are always associated with predefined T-V functions stored in the same seismic database. Therefore, the T-η functions are stored under the same seismic database name as the stacking velocities. The NMO application using the corresponding η-analysis will apply the NMO correction including the 4^{th} order term (equation 5), which takes into account non-hyperbolic moveout of long-offset seismic data and help in anisotropic velocity analysis for VTI media.

Anisotropic Velocity Analysis

It is now well known to the exploration community of reflection seismic that the presence of anisotropy in the subsurface geological horizons cannot be neglected during seismic data processing and inversion. If the effects of anisotropy are neglected during the processing, this will definitely lead to mis-positioning and mis-focusing of the layers of interest. It is also important to note that the general complexity of the processing algorithms that include anisotropy is more difficult to implement than that those ignore it. The main concern however is the difficulty in estimating the anisotropy parameters required by the processing algorithms. Only recently Alkhalifah and Tsvankin (1995) showed that the influence of vertical transverse isotropy (VTI) on NMO, DMO, and time migration is governed by the normal-moveout (stacking) velocity V_{nmo} from horizontal reflectors and the single anisotropic parameter η. The fact that time processing is controlled by just two parameters, one of which, V_{nmo} is routinely determined by conventional velocity analysis, making the anisotropic imaging a practical understanding. The inversion of η requires either the NMO velocity of a dipping event with a dip of at least 25° or long-spread (nonhyperbolic) moveout from a horizontal reflector. Therefore a correct time image for a VTI media can be generated using only P-wave seismic reflection data.

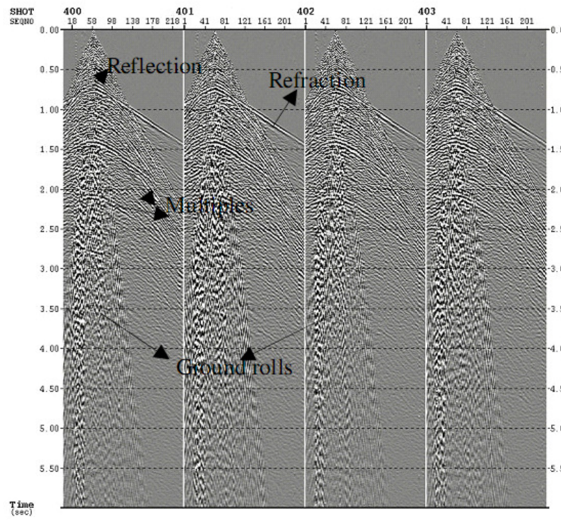

Figure 1: The geometry corrected raw shot gathers of long-offset seismic data showing different phases (refractions, reflections, multiples and ground rolls etc.) having good S/N.

The 2-D seismic data used for the analysis is acquired in a sedimentary basin of western India (land) with asymmetric split spread configuration of 240 channels having shot interval of 50 m and receiver interval of 25 m. The CDP data is acquired by radio frequency telemetry (R-F Telemetry) sercel SN-388 seismic data acquisition systems of NGRI with maximum fold of 60. The typical shot gathers after application of geometry is shown in Figure 1. The seismic data shows various prominent phases as well as dominated by low frequency ground rolls which obscure the deep reflections. The data is acquired with maximum charge size of 6 - 8 kg in shot holes of maximum depth 20 – 30 mts. We have tried to eliminate the low frequency ground rolls and other surface related noises by applying different filters. The corresponding stack section is obtained with conventional processing flow (Geometry, Editing, Spherical divergence correction, Statics, Filtering, Deconvolution, CMP Sorting, Velocity analysis, NMO, Muting, DMO, and Stacking) (Yilmaz, 1987) without incorporating anisotropic velocity analysis of long-spread moveout shown in Figure 2. The stack section shows overall gross structural features along with very clear reflectors at 1.0 s and 1.5 s and up dip toward CDP 100. There is a prominent thrust faulting at CDP 2960-3050 having significant throw but poorly focused. The deeper reflections are not very prominent in the stack section. Also the shallow structural features are neither very prominent nor well focused in the stack section because of conventional velocity analysis by ignoring the effect of anisotropy if at all it exists in the seismic data. Since the dipping layer is lying below horizontal layers of sediments, the conventional velocity analysis could not improve the stack section by ignoring the presence of anisotropy in the seismic data. The conventional velocity analysis which is based on short-spread moveout (stacking) velocities does not provide enough information to determine the true vertical velocity in transversely isotropic media with a vertical axis of symmetry (VTI media). Shale is one immediate example of a VTI media. The velocity in VTI media varies with direction of propagation away from the vertical, but not with azimuth (Alkhalifah et al., 1996). The supergather, zero-offset stacking panels of CDP's of the supergather formed by applying NMO to flatten the reflectors with velocities picked from velocity spectra of the coherency semblance picks shown in Figure 3 for short-spread moveout. The analysis shows very good estimation of corresponding stacking velocity (Figure 4), which is used to obtain the stack section (Figure 2). The velocity field (Figure 4) shows continuous increase of velocity with vertical time and the corresponding velocity contours with the estimated values displayed at different CDP locations.

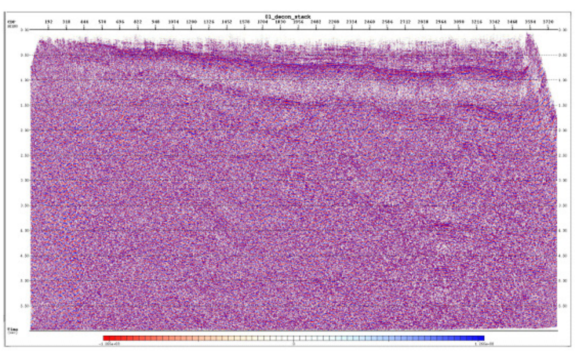

Figure 2: Stacked section of the seismic data acquired in a sedimentary basin of western India.

The velocity field (Figure 4) is used in NMO correction of CDP gathers. The events are virtually flattened across the near offset range (Figure 3) i.e., the offset effect has been removed from traveltimes. However, as a result of moveout correction, traces are stretched in a time-varying manner, causing their frequency content to shift toward the low end of the spectrum. Frequency distortion increases at shallow times and large offsets (Yilmaz, 1987). To prevent the degradation of especially shallow events, the distorted zone is muted before stacking (Figure 3). The CDP stack section is obtained by summing over the offset (Figure 2). The conventional velocity analysis taking into account nearoffset NMO could not incorporate the presence of VTI anisotropy due to the dipping layers. To accommodate the effect of VTI anisotropy, it is essential to incorporate non-hyperbolic moveout (fourth order terms of equation 5) in the velocity analysis.

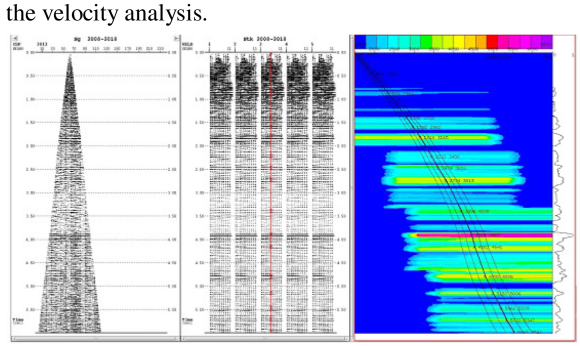

Figure 3: Supergather after NMO with mute of long-offset data to avoid stretching, CDP stacks of the same supergather with the picks of reflected phases and the corresponding coherency semblance spectra display used in conventional velocity analysis.

To accommodate fourth order term in the anisotropic velocity analysis, we have used the same set of supergathers as used in the conventional velocity analysis without muting the long-offset data (Figure 5). The corresponding η-analysis is carried out for all the supergathers formed in the similar way as used for the conventional velocity analysis, but this time with the coherency semblance spectra computed for η instead of V_{nmo}. This analysis is interactive for the estimation of the long-offset/VTI medium anisotropy parameter η (Alkhalifah, 1997) and is semblance based. The values of η are picked from the coherency semblance spectra of timeh display with maximum semblance and stored those in the same databases as used for V_{nmo}. These η values are used this time for flattening the reflected events for CDP stacks as shown in Figure 5. The application of NMO will be considered as η-NMO instead of V_{nmo} and described in equation 5.

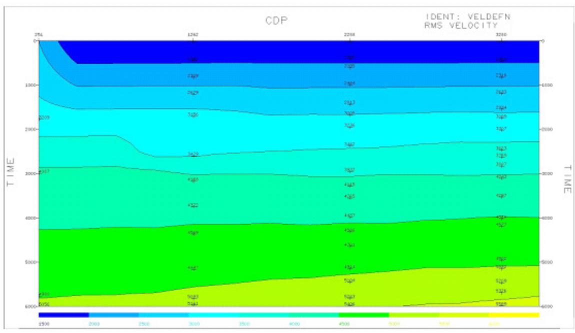

Figure 4: The stacking velocity derived from velocity analysis using small spread hyperbolic moveout. The velocity field is used to obtain the above stack section (Figure 2).

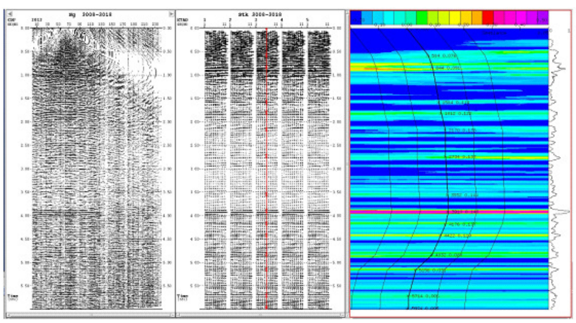
Figure 5: The supergather after η-NMO, CDP stack panels of the same supergather with reflector picks, and coherency semblance spectra for η-analysis.

The application of NMO with η and corresponding NMO without η is prominent by flattening the long-offset shallow reflectors (Figure 6) for an example CDP-1900. The hockey stick effects of long-offset non-hyperbolic events are flattened after applying η-NMO. The corresponding η values picked for different CDP locations during η-analysis is displayed in Figure 7. This shows the η values ranges from 0 – 0.3 with maximum values (0.25 – 0.29) lying between 3 – 4 s range toward CDP 100. This zone may be considered as highly anisotropic. This region is also structurally complex and the reflectors both in the shallow and deeper zones could not be imaged with the help of conventional velocity analysis as shown in the stack section (Figure 2).

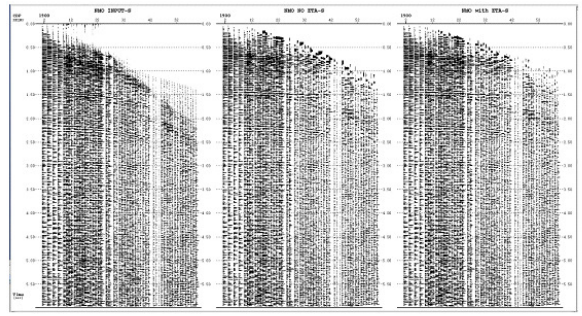
Figure 6: Comparison of CDP-1900 before and after application of η - NMO.

The same processing flow is followed as mentioned above to obtain the stack section after η-NMO instead of only NMO as used in conventional processing. The final stack section after anisotropic velocity analysis of long-offset data is shown in Figure 8. The anisotropic stack section has considerable improvements in delineating the shallow structural features of syncline between CDP 500-950, more focusing of the thrust fault between CDP 2960-3050, and focusing of other shallow and deep reflectors as compared the conventional stack section (Figure 2). The anisotropic stack section also shows much better continuity of the reflectors and the fault planes with better focusing of isolated deeper events at 3.5-4.0 s.

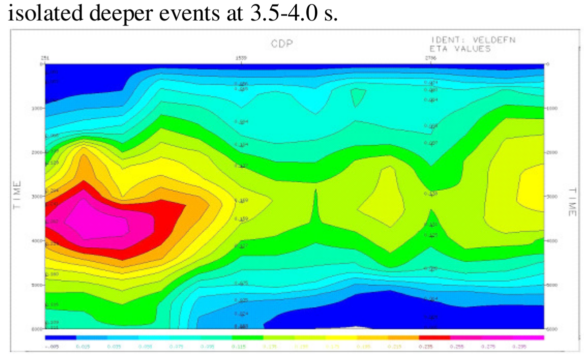

Figure 7: The η plot obtained after non-hyperbolic velocity analysis and coherency semblance analysis for η at different CDP locations.

Most of the artifacts developed in the normal stack section are not seen in the anisotropic stack section. This also helps the interpreter to understand and correlate with true subsurface geological targets of interest without incorporation of other geophysical/subsurface geological informations, which sometime are difficult to obtain. By seeing the nature of improvements in the anisotropic stack section, we can infer that the η values computed (Figure 7) by η-analysis for non-hyperbolic moveout of long-spread seismic data cannot be considered as anomalous. Although the anisotropic time section (Figure 8) is clearly superior to its isotropic counterpart (Figure 2), it cannot be readily converted into an accurate depth section. While the time processing provides knowledge about the coefficient η, but the vertical velocity is the key parameter needed to obtain a depth image. Unfortunately, the surface P-wave seismic data alone are not sufficient to recover the true vertical velocity.

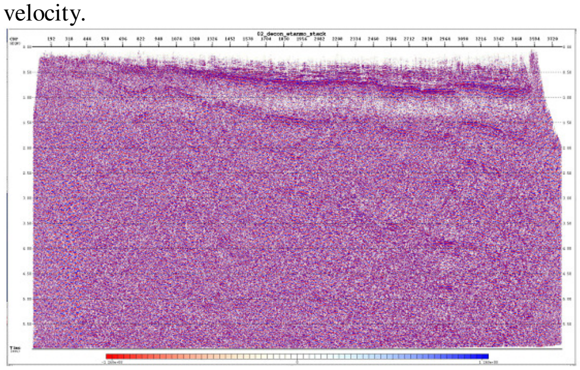

Figure 8: The stack section obtained after anisotropic velocity analysis for non-hyperbolic moveout of the same seismic data.

Discussion and Conclusions

The most common type of anisotropy in sedimentary basins is vertical transverse isotropy (VTI media), usually associated with shale formations. Anisotropy induces such distortions in conventional isotropic processing as inaccurate reflector depths, blurry images, lateral mispositioning of dipping events, misstacking of moderate- and large-offset reflections. While sometimes it is possible to make a corrections for anisotropy in conventional isotropic processing by artificially adjusting the velocity, but this approach represents only a partial solution to seismic imaging problems and creates unrealistic velocity models. P-wave time processing in VTI media is controlled by two parameters – the short-spread moveout (stacking) velocity V_{nmo}, produced by conventional semblance velocity analysis, and the anisotropic parameter η. The most stable method for obtaining η is based on velocity analysis of dipping events. Also η can be estimated using long-spread (non-hyperbolic) moveout from horizontal reflectors. Note that η has the potential of becoming an important tool in lithology discrimination from surface seismic data, especially in sedimentary sequences containing shales and sands.

Once the importance of anisotropy in seismic data processing is accepted, two further impediments to taking its presence into account must be overcome: (1) processing algorithms that include anisotropy are more complex than those that ignore it, and (2) even with such processing capability at hand, estimating the anisotropy parameters required by these algorithms is highly challenging task. The second problem has always seemed to be especially intimidating for the exploration seismologists.

If a medium contains a dipping target reflector beneath a laterally homogeneous (e.g., horizontally layered) VTI overburden, all P-wave time domain processing steps (NMO, DMO correction, prestack and poststack time migration) are controlled by just two parameters – the NMO velocity from a horizontal reflector [$V_{nmo}(0)$] and the anisotropic parameter η - in each layer. The two timeprocessing parameters govern both long-spread (nonhyperbolic) moveout from horizontal reflectors and NMO velocity of dipping events. Therefore, it should be possible to obtain them from surface P-wave data without using other seismic data sets like shear waves or borehole measurements. This analysis shows a practical understanding for estimating the parameters $V_{nmo}(0)$ and η from P-wave reflection moveout of 2-D seismic data acquired in a sedimentary basin and confirmed the presence of anisotropy which is truly VTI in nature and the effect of anisotropy cannot be ignored.

The fact that the parameter η is a function of $V_{nmo}(0)$ and the horizontal velocity V_h(equation 6) points to an alternate way of performing velocity analysis in VTI media, which is not yet explored in the literature. If it is possible to obtain an accurate value of V_h (e.g., from head waves traveling along a horizontal reflector or from crosshole tomography), then $V_{nmo}(0)$ and V_h can be used to carry out time-domain processing of P-wave data. Dipping events or non-hyperbolic moveout – the main sources of direct information about η - then are not needed at all. Of course, head waves can help in estimating the horizontal velocity for only the shallow part of the section.

Time-to-depth conversion and depth imaging, however, cannot be performed without the vertical-velocity function that is not accessible from surface seismic P-wave data alone and hence not attempted. To build anisotropic velocity models in depth, it is essential to have well information (e.g., check shots), with subsequent spatial interpolation of the results, or include reflection moveout of shear or mode converted (PS) waves in velocity analysis. If V_{nmo} and η have been recovered from the data but vertical velocity is unknown or is determined with error, the image produced by the sequence of NMO, DMO, and poststack depth migration will be well-focused but may have the wrong depth scale. Hence, the present study of obtaining the stack section with anisotropic velocity analysis bears significant improvements in imaging subsurface structural details as compared to the conventional stack and can be adopted in routine analysis for sedimentary basins where anisotropy plays a vital role. The η-analysis and the corresponding η-functions combined with V_{nmo} can be suitable for lithology estimations of sand-shale sequences or other isotropic geological formations where no other geophysical/geological informations are available.

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