

**VELOCITY ESTIMATION FROM SURFACE-CONSISTENT
STATICS**

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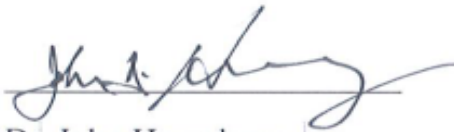
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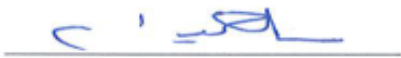
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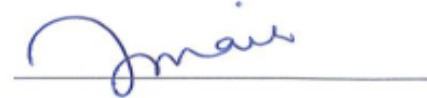
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I dedicate this work to my parents, siblings, teachers, and all those who contributed to my academic pursuit.

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LIST OF ABBREVIATIONS

AVO	:	Amplitude Variation with Offset
CDP	:	Common Depth Point
CMP	:	Common Midpoint
CVS	:	Constant Velocity Stack
FWI	:	Full Waveform Inversion
PP-wave	:	Mode Converted Compressional Wave to Compressional Wave
PS-wave	:	Mode Converted Compressional Wave to Shear Wave
NMO	:	Normal Moveout
SNR	:	Signal-to-noise ratio
SP-wave	:	Mode Converted Shear Wave to Compressional Wave
SS-wave	:	Mode Converted Shear Wave to Shear Wave
TWT	:	Two-way travelttime
V_{NMO}	:	Normal moveout velocity

ABSTRACT

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To optimally image the subsurface, geophysicists have developed numerous methods to determine the subsurface velocity. These methods have some limitations and assumptions and thus require constant improvement and development of new techniques to image complex geological structures. I propose and demonstrate a new approach for estimating subsurface velocity from residual static corrections. The technique is based on estimating the imperfect normal moveout (NMO) surface-consistent static component in a common midpoint (CMP) gather and inverting it for the correct NMO velocity.

The method was tested on a 2D elastic synthetic seismic dataset corresponding to a simple two-layer model with a sand dune that exhibited a vertical velocity resulting in considerable elevation and residual statics. The synthetic data were processed by an experienced processor through a conventional seismic data processing workflow including elevation and residual static corrections. Then, the imperfect NMO-correction component was estimated from the residual statics for a selected imperfectly NMO-corrected CMP gather located below the dune. The application of the proposed technique produced an NMO velocity value that is within 2.5% of the model (i.e., “true”) velocity value. The method worked also well with a dipping reflector model, obtaining an NMO velocity that is within

1 % error of the model (i.e., “true”) velocity of the medium. The procedure, unlike conventional NMO analysis, does not require prior knowledge of the dipping angle.

Furthermore, the method was also tested on a CMP gather from real 2D seismic data from southeast Texas, which exhibited a mild surface statics problem. The NMO velocity of a prominent reflection was correctly picked by an experienced processor. However, for testing purposes, a known incorrect NMO velocity was used instead for NMO correction of that CMP gather. Application of the proposed method on the resulting incorrectly NMO-corrected CMP gather estimated the correctly picked (i.e., “true”) NMO velocity with only 0.6% error. The technique has the added advantage of being independent of the initial (i.e., “wrong”) velocity value used for NMO correction before residual static correction, working well in both NMO overcorrected and undercorrected data. Statics correction affects the accuracy of the technique leading up to a 35% error in estimated velocity due to error in statics correction.

ملخص الرسالة

الاسم الكامل: محمد أحمد محمد

عنوان الرسالة: تقدير السرعة من احصائيات السطح المتسقة

التخصص: الجيوفيزياء

تاريخ الدرجة العلمية: 04/2023

لتصوير باطن الأرض على النحو الأمثل ، طور الجيوفيزيائيون طرقاً عديدة لتحديد السرعة تحت السطحية. هذه الأساليب لها بعض القيود والافتراضات ، وبالتالي تتطلب التحسين المستمر وتطوير تقنيات جديدة لتصوير الهياكل الجيولوجية المعقدة. أقترح وأظهر نهجاً جديداً لتقدير السرعة تحت السطحية من التصحيحات الثابتة المتبقية. تعتمد هذه التقنية على تقدير المكون الثابت الثابت المتسق مع السطح (NMO) غير الكامل في نقطة منتصف مشتركة (CMP) تجمع وعكسها من أجل سرعة NMO الصحيحة.

تم اختبار الطريقة على مجموعة بيانات زلزالية تركيبية مرنة ثنائية الأبعاد تتوافق مع نموذج بسيط من طبقتين مع الكثبان الرملية التي أظهرت سرعة عمودية مما أدى إلى ارتفاع كبير وثبات متبقي. تمت معالجة البيانات التركيبية بواسطة معالج متمرر من خلال سير عمل معالجة البيانات الزلزالية التقليدية بما في ذلك التصحيحات الثابتة والارتفاعية المتبقية. بعد ذلك ، تم تقدير مكون تصحيح NMO غير الكامل من الإحصائيات المتبقية لمجموعة CMP المختارة المصححة بشكل غير كامل من NMO الموجودة أسفل الكثبان الرملية. أنتج تطبيق التقنية المقترحة قيمة سرعة NMO في حدود 2.5٪ من قيمة سرعة النموذج (أي "حقيقية"). علاوة على ذلك ، تم اختبار الطريقة أيضاً على تجميع CMP من بيانات زلزالية ثنائية الأبعاد حقيقية من جنوب شرق تكساس ، والتي أظهرت مشكلة ثابتة في السطح. تم اختيار سرعة NMO للانعكاس البارز بشكل صحيح بواسطة معالج متمرر. ومع ذلك ، لأغراض الاختبار ، تم استخدام سرعة غير صحيحة معروفة بدلاً من NMO لتصحيح NMO لتجميع CMP. تطبيق الطريقة المقترحة على CMP الناتج المصحح بشكل غير صحيح NMO يجمع السرعة المختارة بشكل صحيح (أي "صحيح") NMO مع خطأ 0.6٪ فقط. عملت الطريقة بشكل جيد مع نموذج عاكس مغمور ، وحصلت على سرعة NMO في حدود 1٪ خطأ من السرعة الظاهرية الحقيقية للوسط. الإجراء ، على عكس تحليل NMO التقليدي ، لا يتطلب معرفة

مسبقة بزاوية الغمس. تتمتع هذه التقنية بميزة إضافية تتمثل في كونها مستقلة عن قيمة السرعة الأولية المستخدمة لتصحيح NMO قبل التصحيح الثابت المتبقي ، وتعمل بشكل جيد في كل من بيانات NMO المصححة بشكل مفرط وغير المصححة. يؤثر التصحيح الإحصائي على دقة التقنية مما يؤدي إلى خطأ بنسبة 35٪ في السرعة المقدرة بسبب خطأ في التصحيح الاستاتيكي

CHAPTER 1

INTRODUCTION

Velocity analysis in geophysics is the process of determining the speed with which seismic waves travel in the subsurface. The wave speed is usually called velocity and the estimation process is called velocity analysis (Gray, 2018). There are different methods by which this is achieved. The normal moveout (NMO) correction serves as one of the methods for obtaining velocities from seismic data. The NMO is the effect of the separation between source and receiver on the reflection arrival time of seismic waves of a horizontal reflector (“[Nmo](#)”). This separation induces a delay on the arrival time of a reflection from a horizontal surface at depth and is dependent on the velocity of the medium. NMO correction is the procedure in seismic processing that compensates for the effect of this separation. Stacking velocity can be computed from normal moveout or the change in arrival time produced by the source-receiver offset (“[Nmo](#)”). The computed velocities may then be used to correct for NMO to align the reflections before stacking. Velocity analysis in this case depends on observing the curvature of an event in a common midpoint (CMP) gather after repeatedly NMO-correcting it using a range of NMO velocities, with the correct NMO velocity having the most horizontal (i.e., flat) event. The cross-correlation of the traces of a CMP gather can also serve as a form of velocity analysis (Yilmaz, 2001). In these cases, the data need to be transformed into the stacking velocity and zero-offset time plane, on which the stacked cross-correlated gather with the best velocity shows the highest semblance amplitude (Taner and Koehler, 1969).

Numerous challenges are associated with the process of velocity determination. The choice of the initial velocity function is crucial because it determines the convergence of the iterative NMO velocity analysis. The accuracy of computed velocities is also limited with low SNR, as peaks may be generated by aligning random noise (Harlan et al., 1984; Yilmaz, 2001). In addition, the hyperbolic moveout assumption may fail due to anisotropy or heterogeneity in the subsurface, a steeply dipping layer or at large offsets (Tsvankin and Thomsen, 1994; Alkhalifah and Tsvankin, 1995; Fomel and Stovas, 2010).

The near-surface poses a long-standing challenge in the processing of seismic data, including velocity determination, due to the heterogeneous nature of the overburden (Marsden, 1993a). The loose nature of the material of it as well as the undulating nature of the surface cause seismic waves in the near-surface to deviate from the hyperbolic moveout (Taner et al., 1974; Yilmaz, 1987). This deviation appears on the seismic section as statics, an artificial change in reflection times of stacked traces. The effect of statics is usually computed and subtracted from the reflection times.

It has long been established that statics affect the accuracy of the velocity model (Cox, 1999; Zhang and Yilmaz, 2005). The estimate of the correction factor for the surface consistent statics consists of four components, one of which is associated with the NMO velocity function. Although this procedure has been in use for decades, the determination of velocity from surface-consistent statics has not been explored.

1.1 Statement of the Problem

Velocity analysis, a crucial aspect of seismic imaging, has been the subject of widespread research in geophysics for many decades. Despite these efforts, obtaining the exact subsurface velocity remains a challenging task for various reasons. For example, full waveform inversion (FWI) is resource intensive and requires heavy computing to perform on large datasets (Virieux and Operto, 2009). Similarly, conventional velocity analysis methods such as the semblance method and NMO analysis require many iterations and may produce inaccurate results if the starting velocity function is far from the actual velocity of a reflector and perform poorly in datasets with low SNR (He et al., 2021; AlAli and Anifowose, 2021). In addition, these methods need to be extrapolated from one subsurface point to another, affecting the accuracy. It is therefore necessary to improve these methods or develop new ones that can estimate subsurface velocity devoid of some of the constraints on the existing methods.

Statics problems affect velocity analysis negatively because they distort the velocity function in the near surface. Geophysicists correct this distortion by iteratively removing the statics effect and updating the velocity model until a threshold is achieved, but there has not been an attempt to estimate velocity from the statics. Therefore, this study derives a relation that enables the computation of the velocity of a reflector from the statics problem.

1.2 Objectives

The objective of this work is to conceptualize and demonstrate a novel approach to velocity estimation. Conventional velocity analysis (semblance method) will be used to

estimate the correct velocity of reflectors in a dataset by an experienced processor. By solving the surface consistent residual statics problem, a new relation will be derived that inverts the residual statics due to imperfect NMO analysis to find the correct NMO velocity. The performance of this technique relative to the conventional method will be investigated using synthetic and real seismic datasets.

1.3 Thesis Outline

In chapter 2, I review the current practice of velocity analysis and the effect of near-surface velocity variation. I explain the different methods of determining subsurface velocity and mitigating the statics problem. The surface consistent technique of statics correction is discussed in detail. I also highlight the challenges of the various velocity analysis techniques and the dependency of the NMO velocity method on good statics estimate. In chapter 3, I present the methodology used for both NMO velocity determination and surface consistent statics computation. I explain the various terms of the relevant equations. I then present my new methodology that estimates NMO velocity from surface-consistent statics using these equations, deriving a new relation between the two. Chapter 4 discusses the synthetic data used for testing the new method. The generation and processing workflow of the synthetics are also presented in this chapter. Chapter 5 presents the real dataset used for the validation of the method. I also discuss relevant information about the data, such as the acquisition parameters, processing techniques used, and quality of the data. In chapter 6, the application of the newly proposed method is tested on both synthetic and real datasets. The application procedure is explained, and the results are discussed. Chapter 7 concludes the study, discussing the performance of the new methodology and suggesting areas of possible improvement.

CHAPTER 2

LITERATURE REVIEW

2.1 Velocity Analysis

Velocity estimation is a crucial step in the processing workflow of seismic data. It provides the velocity information required to map the depth and thickness of various subsurface layers in a seismic section. An accurate velocity model is important for processing and interpretation steps, including migration and time–depth conversion. Different types of velocity estimates can be derived from seismic data (i.e., NMO velocity, stacking velocity, interval velocity). The stacking velocity that can reliably be estimated from seismic data usually yields the best stack (Yilmaz, 1987). Stacking improves the signal-to-noise ratio (SNR) by amplifying desired signals and suppressing noise, and the stacked section is used to migrate reflection events to their true position and collapse diffractions. A good stacked section and an accurate velocity model are also important for time-to-depth conversion. There are several ways in which velocity analysis is usually performed: conventional methods, panels, and picking (Sheriff, 2002).

2.1.1 Conventional Velocity Analysis

Conventional velocity analysis, based on the hyperbolic assumption, posits the two-way travel time (TWT) of seismic waves as a function of source-receiver offset to be approximated by a hyperbola. The hyperbolic assumption is better suited for horizontal or gently dipping layers and small spreads and collapses at far offsets or with increasingly dipping layers (de Bazelaire, 1988). The velocity value that causes the hyperbola to flatten is the normal moveout velocity, and the determination, by various methods, of this

particular value is one method of velocity analysis. The NMO velocity is equivalent to the stacking velocity at small offsets of a horizontal layer. Conventional velocity analysis depends on NMO correction, which is a dynamic correction. This means that the whole trace is not corrected with the same value; rather, each sample on the trace is corrected with a unique value. This introduces stretching of the data, particularly for shallow events and large offsets, causing an artificial increase in the wavelength and damaging the quality of the stacked data (Buchholtz, 1972; Barnes, 1992). The part of the data with severe stretching is muted, which affects the accuracy of subsequent processing steps in the stretched area, i.e., Amplitude variation with offset (AVO) analysis. Numerous methods have been developed to tackle the NMO stretch problem. By working with a wavelet-to-wavelet basis, Zhang et al. (2013) reduce the NMO-stretch effect at far offsets, which is typically associated with the sample-to-sample conventional NMO correction. Khoshnavaz et al. (2022) compensated for the eventual loss in frequency by increasing the dominant frequency before NMO correction. This method, however, failed to handle highly contaminated data.

Diffraction signatures (hyperbolas) can be used to estimate localized velocity and improve the velocity model (Khaidukov et al., 2004; Fomel et al., 2007; Coimbra et al., 2013). In most cases, diffraction events are treated as noise in conventional velocity analysis, and the information about the reflector associated with them is lost. In cases where diffractions can be reliably separated from reflection events, diffractions can be used to improve the velocity model (Zhang, 2005). This process involves iterative estimation of the velocity model and application of the NMO correction. By adjusting ellipses or hyperbolas to uncollapsed migration diffractions, Gonzalez et al. (2016) obtained a good velocity model

from diffraction events using the residual diffraction moveout method. This method does not require the complete separation of the diffractions from reflection events.

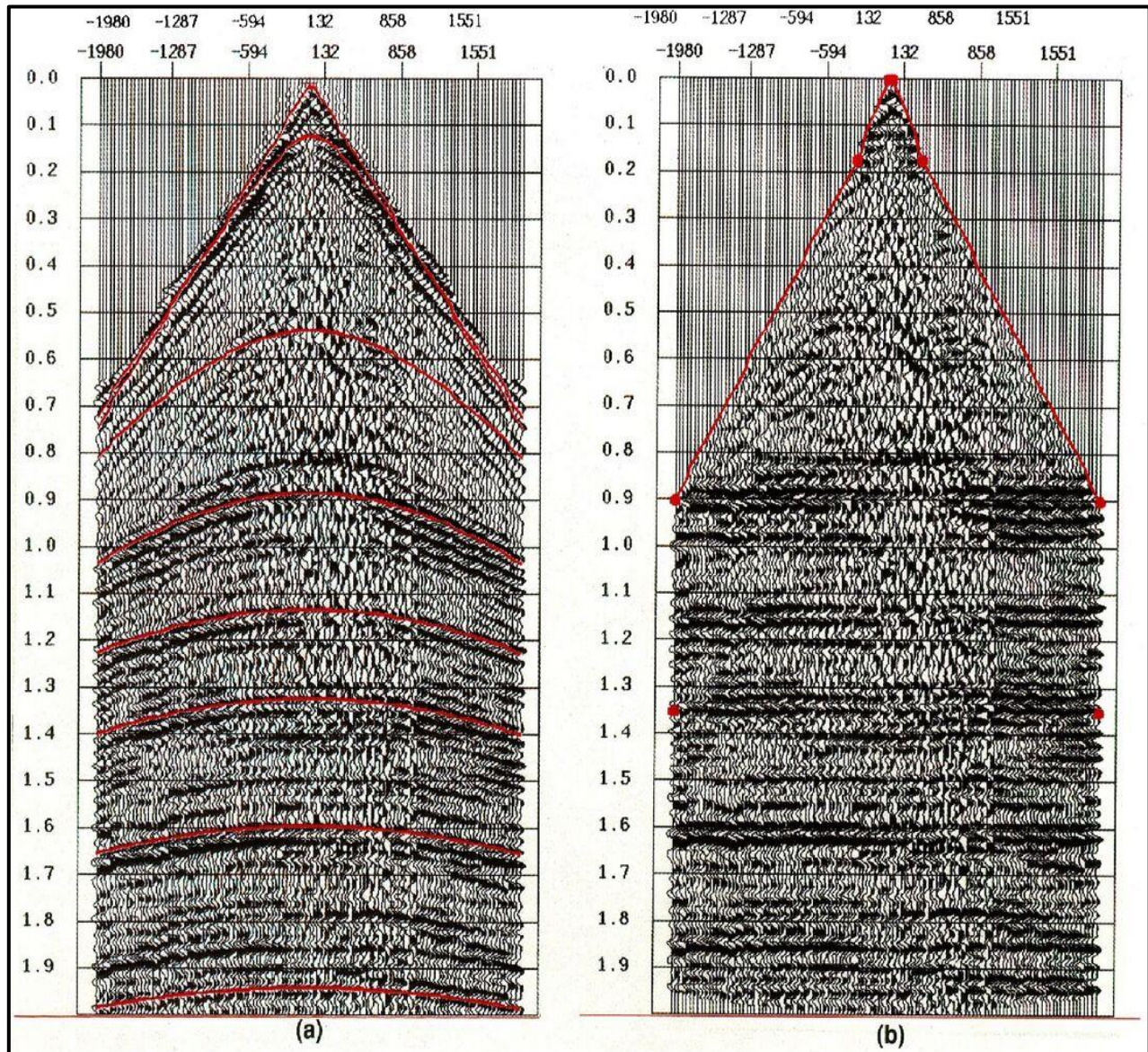


Figure 2.1 (a) A CMP gather before NMO correction. The same gather after the application of NMO is shown in (b). Conventional velocity analysis attempts to find the NMO velocity that best flattens the reflectors from (a) to (b). (Adapted from AAPG Wikii)

Velocity Spectrum

The velocity spectrum method, which is based on the cross-correlation of traces in a CMP gather, tries to find the stacking velocity for every reflector by mapping the time-offset data of a common midpoint gather onto a velocity-spectrum plane (Taner and Koehler, 1969). This is achieved by repeatedly NMO-correcting and stacking the seismic data using a range of velocity functions. The correct stacking velocity will produce the highest stacked amplitude (semblance) on this plane. This method is suitable for datasets with multiple reflection problems and less suitable for datasets acquired in areas of complex structure. Cross-correlation is adequate in measuring coherency, making this method efficient in separating signals from random noise in seismic data (Gadallah and Fisher, 2008). A low SNR also decreases the accuracy of the velocity spectrum method.

Semblance is a normalized, squared correlation of the NMO corrected seismic data with a constant or trend. The choice of the constant or trend affects the accuracy of the semblance method (Luo and Hale, 2012). The resolution of the velocity spectrum method's conventional semblance coefficient is not high, and its improvement has been the focus of continuous research. A high-resolution semblance method is important as it improves the process of picking peaks in the spectra. The use of weighted semblance, a technique that weighs the parameters for calculating semblance based on their response to velocity perturbations, was developed to improve the resolution of this method (Hale, 2009). Baros et al. (2014) improved the resolution by incorporating eigen value decomposition of the data into the weighted function. By working in the radon transform domain, sparsity enhancement technology improves the calculation accuracy of the velocity spectrum (Gong et al., 2016). Recently, the weighted similarity coefficient method, an extension of

conventional similarity, was introduced as an alternative to calculating a high-resolution velocity spectrum (Chen et al., 2015; Xu et al., 2020). Leite and Vieira (2019) considered the determination of an accurate semblance function as a nonlinear optimization problem and automated it for velocity analysis, using physical and mathematical constraints to obtain an initial velocity model.

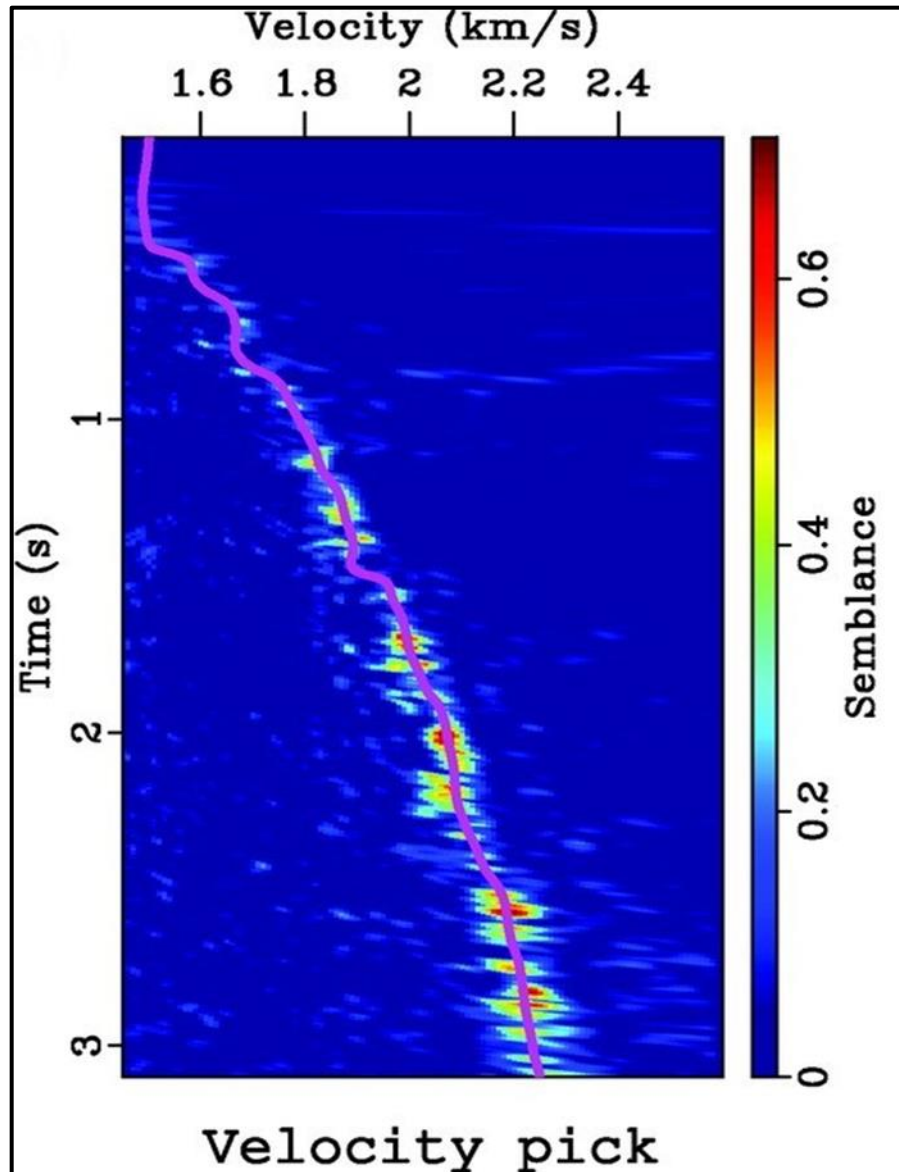


Figure 2.2 The semblance method. The region picked by the line denotes areas of high semblance. Adapted from Decker and Forel (2021)

2.1.2 Constant Velocity Stack

The constant velocity stack (CVS) method fits an NMO velocity to each reflector from repeatedly NMO-corrected CMP gathers using a range of constant velocities. This assumes that the optimal velocity will produce the best stack section. The constant-velocity stacks are displayed in panels and analyzed for the velocity that produces the most laterally continuous stack of reflectors. Stacking velocities are then picked directly from the CVS panel by choosing the velocity that yields the best stacked response at the selected time of interest (Yilmaz, 1987). Interpolation of NMO velocities, because the process is not performed for all CMP gathers, is a major drawback of this method. The method also strongly depends on the difference between adjacent test velocity values, as this should be chosen narrow enough to give sufficient discrimination of reflectors. This method is also sensitive to dipping events and sideswipes, which require abnormally high velocities. Side effects may also result in such high velocities in the relatively shallow parts of the dataset (Derman, 2018).

The advancement in machine learning techniques provides a means to tackle velocity analysis problems that conventional methods fail to address. Near-surface velocity constraints due to severe noise greatly affects the accuracy of conventional methods. Velocity reversal, anomalous high- or low-velocity layer intrusions into an otherwise increasing velocity with depth trend is one such problem that imposes a significant challenge to conventional velocity building models. Ma et al. (2022) proposed a deep-learning framework to estimate the near-surface velocity model with reversals. Their framework incorporates deep learning and FWI to estimate near surface velocity model from seismic data. Manual velocity picking is a time-consuming process and tedious. Using

a combined structure of You Only Look Once (YOLO) and Long-Term Short-Term Memory (LSTM) neural networks, Zhang et al. (2019) developed an efficient automatic velocity picking algorithm based on deep learning, formulating the problem as an object detection problem. Similarly, Biswas et al. (2019) used a preliminary NMO-velocity function and CMP gathers to train a recurrent neural network (RNN) to predict a velocity model through a supervised learning problem. In the training phase of their model, the estimated velocity is compared to the correct stacking velocity and the model's weights are updated. Ma et al. (2018) deployed a convolutional neural network (CNN) model to estimate the NMO velocity directly from prestack CMP gathers. The deployment of any machine learning (ML) model on a dataset different from the training data is a crucial step in validating the accuracy of the ML model. Transfer learning is a way to ensure that a model performs well across a range of unseen datasets. Park and Sacchi (2020) incorporate transfer learning in a CNN model to generalize its performance. Their model automatically picks the semblance, formulating the task as a classification problem. The output is a range of velocity semblance values with each regarded as a class. The method, trained with synthetic data extends its generalization to complex models using transfer learning. A test on a marine dataset set shows that the model performs reasonably well with unseen real data. AlAli and Anifowose (2021) reviewed the application of numerous ML models to the velocity estimation problem. They made a series of recommendations for building such models including the use of sufficient training data and considerations of anisotropic medium.

2.2 Static Correction

Reflection times often deviate from a hyperbola due to irregularities in the near-surface (Yilmaz, 1987). This leads to inaccurate reflection time on the stacked trace that affects subsequent processing steps and places events in the wrong position after migration. To apply NMO correction to reflection data correctly, static corrections are necessary to be applied in advance for the compensation of the time delays caused by the near-surface weathered layer and topography (Liu et al., 2005). Static corrections therefore are applied to seismic reflection data to compensate for the time shifts caused by changes in topography and variations in near-surface seismic velocities (Cox, 1999; Sheriff, 2002). It is an important aspect of seismic data processing to correct for the deviation from a perfect hyperbola that subsequently affects the computation of subsurface velocities. The velocity variation component of the correction pertains to the low-velocity layer (LVL), where the variable thickness of alluvial, aeolian, fluvial, or glacial material overlies bedrock. These deposits are unconsolidated; hence, the velocity of the seismic wave decreases significantly when it enters these layers, leading to time shifts in the trace. The amount of correction necessary is highly dependent on the velocity and thickness of the LVL and the offset between sources and receivers. The application of statics increases the quality of the seismic section (**Fig 2.3**) by placing events in their true position and producing a high-resolution image (Marsden, 1993a). Conversely, errors in static corrections lead to losses of seismic resolution, both temporal and spatial, and lead to difficulties in subsequent processing and interpretation steps (Zhu et al., 2014).

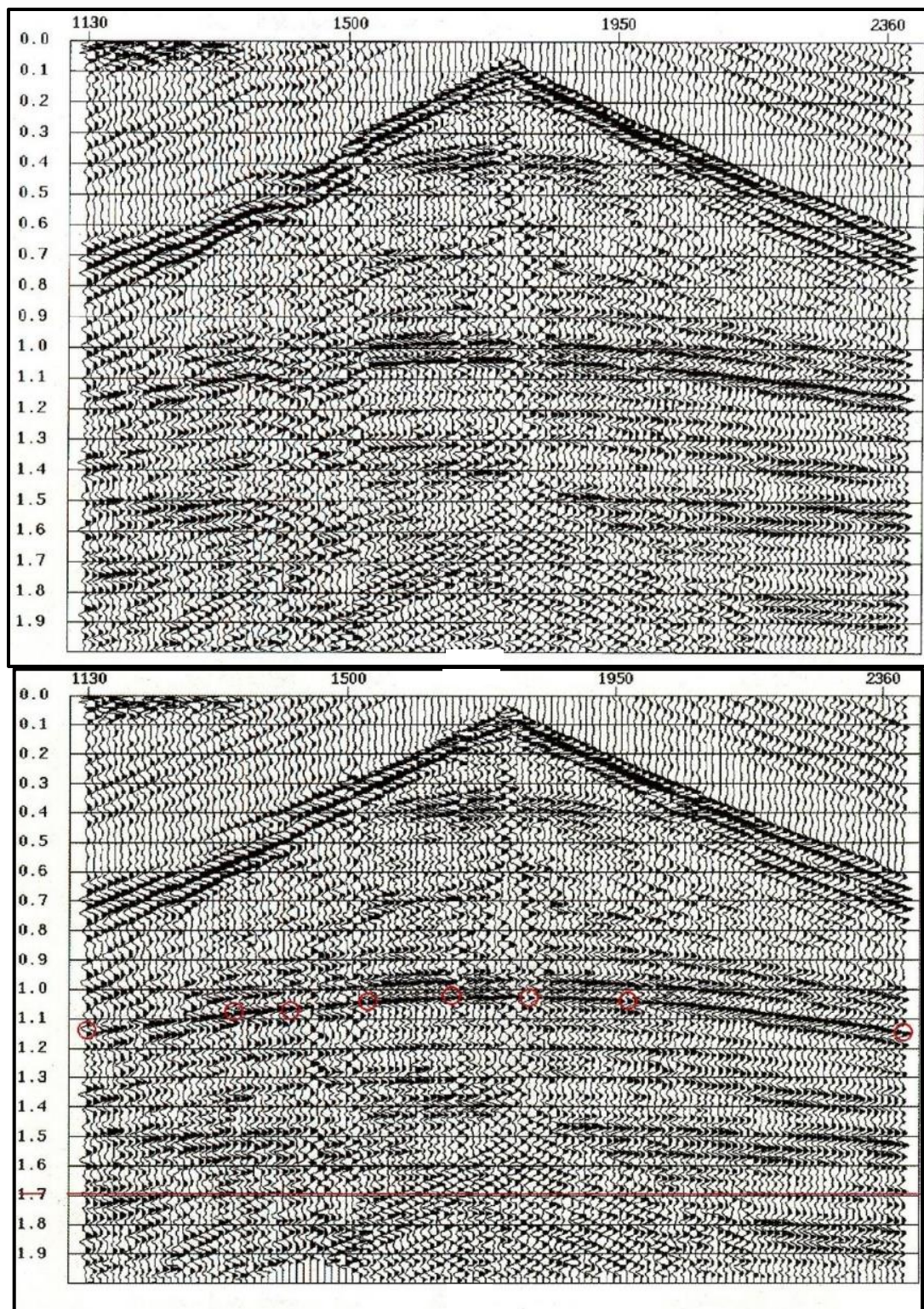


Figure 2.3 Statics effect. The figure above is distorted by statics, especially between CDPs 1130 and 1500. A static correction has been applied in the lower figure. (Adapted from AAPG Wiki: Adapted from: https://wiki.aapg.org/Seismic_processing_basics)

2.2.1 Elevation Statics

Elevation statics removes the deviations due to differences in the height of source and receiver locations by defining a common datum and assigning appropriate replacement velocities for the height above or below the datum at each source and receiver location. This method operates on the assumption that a simple time shift of the entire trace to a reference datum will yield a seismic record that is free from statics (Zhu et al., 2014). Luo et al. (2010) state that this assumption is not strictly true in most cases and that the correction works only in areas free of weathering layers and lateral velocity changes in the low-velocity layer. The relative elevation of each source and receiver location and the near-surface velocity model must be known to make this correction.

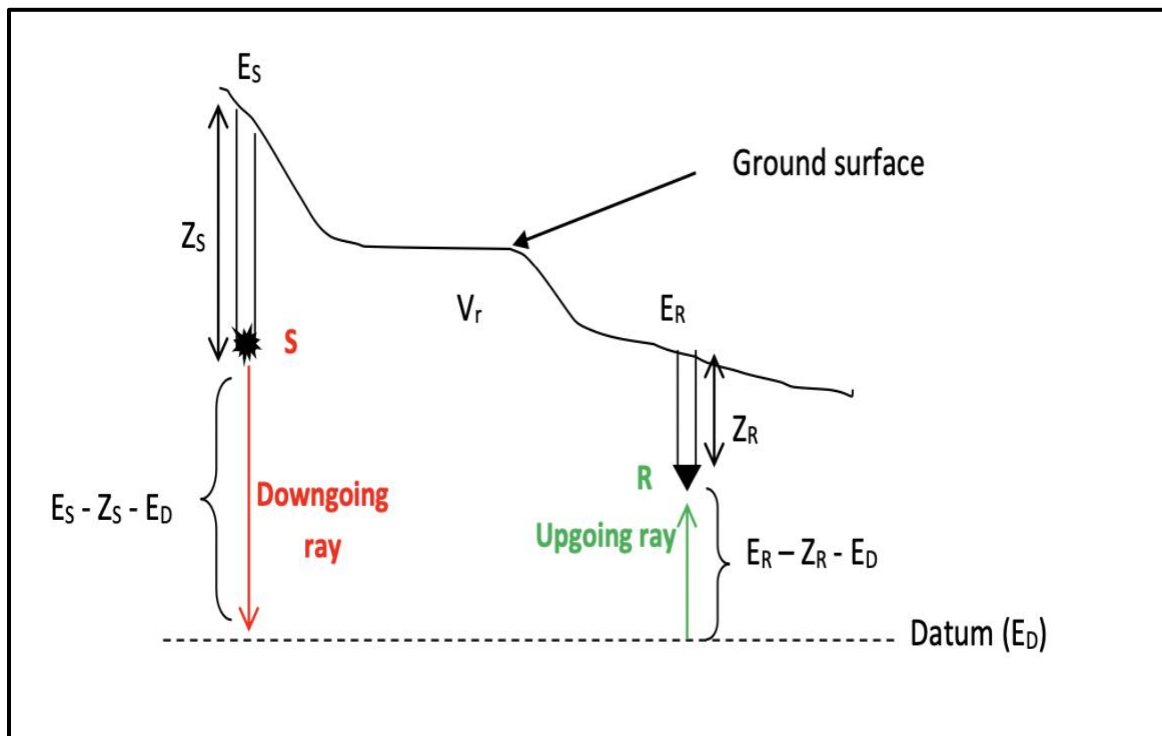


Figure 2.4 A scheme for the application of elevation (field) statics. A buried source is represented by the star and the receiver by the triangle. (Adapted from: Geop604 lecture notes).

The total field statics applied to each trace is the summation of the source and receiver time shifts of the trace. A datum is specified, and the distances from the positions of the source and receiver to the datum are computed as E_D according to Figure 2.4. The elevation of the source (E_S) and receiver (E_R) on the ground surface is used with the velocity of the replacement velocity (V_r) to compute the statics for the trace according to the relation below:

$$\Delta T_D = \frac{(E_S - Z_S - E_D) + (E_R - Z_R - E_D)}{V_r} \quad 2.1$$

The bedrock velocity (V_B) which is usually derived from uphole surveys, may be used in place of the replacement velocity (V_r). In land surveys, shots are not always buried. Vibroseis and other surface sources are instead used. In such cases, the refracted arrivals of seismic waves are used to compute the static corrections to a specified datum. Figure 2.5 shows the effect of the application of elevation statics correction.

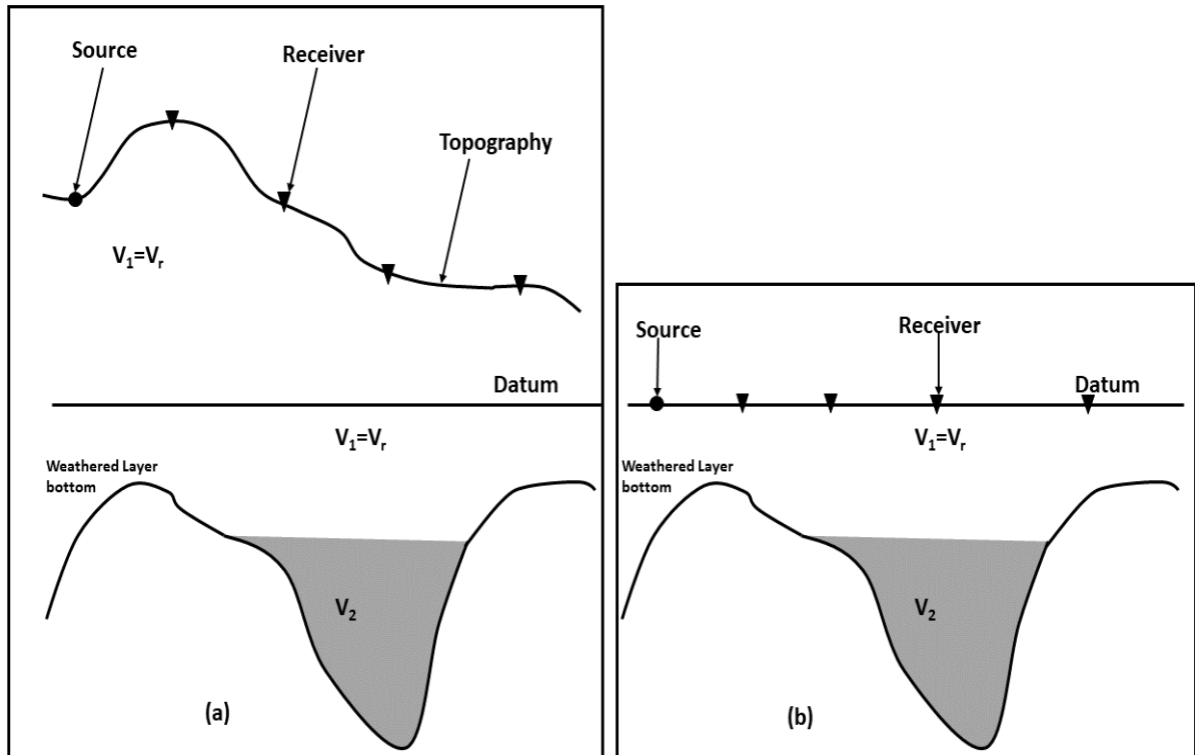


Figure 2.5 Schematics of data acquisition (a) before any statics correction and (b) after elevation statics correction.

2.2.2 Refraction Statics

Refraction statics depend on the analysis of the first breaks of seismic records to determine the thicknesses and velocities of the near-surface layers. When a seismic ray crosses a boundary between two reflectors, the ray bends according to Snell's law. The difference in velocity between the LVL and the underlying bedrock is such that the rays will travel along the boundary before reaching the receivers as the first breaks. This represents the base of the weathering layer, and the first break picks can be used to calculate the velocity of the sub-weathering layer.

Refraction statics correction is particularly useful to correct anomalies with long spatial wavelengths although it is also effective in correcting for short spatial wavelengths (Marsden, 1993b). The wavelength of the statics is the ratio of the width of the lateral velocity (or thickness) change in the weathering layer to the spread length (offset) (Adizua et al., 2019). Hagedorn (1959) and Knox (1967) pioneered the use of refraction statics correction using the Plus-Minus method and the Slope-Intercept method, respectively, which are both based on the delay time approximation of refracted travel times. The generalized linear inversion (GLI) method (Hampson & Russell, 1984) iteratively builds a model of the subsurface based on the information provided by the first breaks until some threshold is achieved between the model data and observed first breaks. The time-delay method (Lawton, 1989, 1990) derives the statics directly from the first breaks without building a near-surface model through a least squares approach.

2.2.3 Residual Statics

The application of elevation (datum) statics does not produce seismic sections that are completely free of remnant statics (Faquan and Yusheng, 2011; Marsden, 1993c). Residual statics are generated by the difference in thickness and lateral velocity changes of the highly variable weathering layer, which are unaccounted for by the application of field statics. This is a statistical process that is applied iteratively to the original gathers before NMO correction, which enhances the quality of the stacked traces by correctly aligning the reflections. Few iterations are needed, and each is followed by velocity analysis to improve the velocity picks (Gadallah and Fisher, 2008). The conventional residual statics is based on the cross-correlation of individual traces and CMP stacked traces. Each trace is cross-correlated with its CMP stacked trace, and the time shift of the maximum cross-correlation

value is taken to be the total statics to be applied to the trace. Areas with low SNRs pose a challenge, as it is difficult to obtain an accurate residual static correction.

Ronen and Claerbout (1985) compute the correct statics in data with low SNR by the method of stack-power optimization using a supertrace correlation. In this method, a supertrace is built from all the traces of the shot profile in sequence (trace F in **Fig.2.6**) which is then cross-correlated with another supertrace of all traces in the relevant stack section, in sequence, without the contribution of that shot (trace G in **Fig.2.6**). The maximum of this cross-correlation is then used to correct the stacked section, with the process repeated for each shot and receiver. Ren et al. (2016) developed residual statics estimation technology. It uses a searching method to scan the seismic trace and select the highest SNR portion of the trace to develop the supertrace. This trace is used with the model trace to compute residual statics. Koglin et al. (2005) approached the statics problem using the common reflection surface stacked-based imaging workflow. Here, the NMO-corrected traces and the stacked pilot trace are cross-correlated iteratively to ascertain the final estimate of the residual statics. The estimation of statics in noise-contaminated data is better treated as a nonlinear inversion problem (Rothman, 1985), as this handles errors associated with picking travel times. The nonlinear inversion technique transforms the cross-correlated traces' functions into probability distribution functions. Simulated annealing is then used to assign random numbers to these distribution functions and used to iteratively update the estimates of the statics until convergence with the optimal stack is achieved (Rothman, 1986).

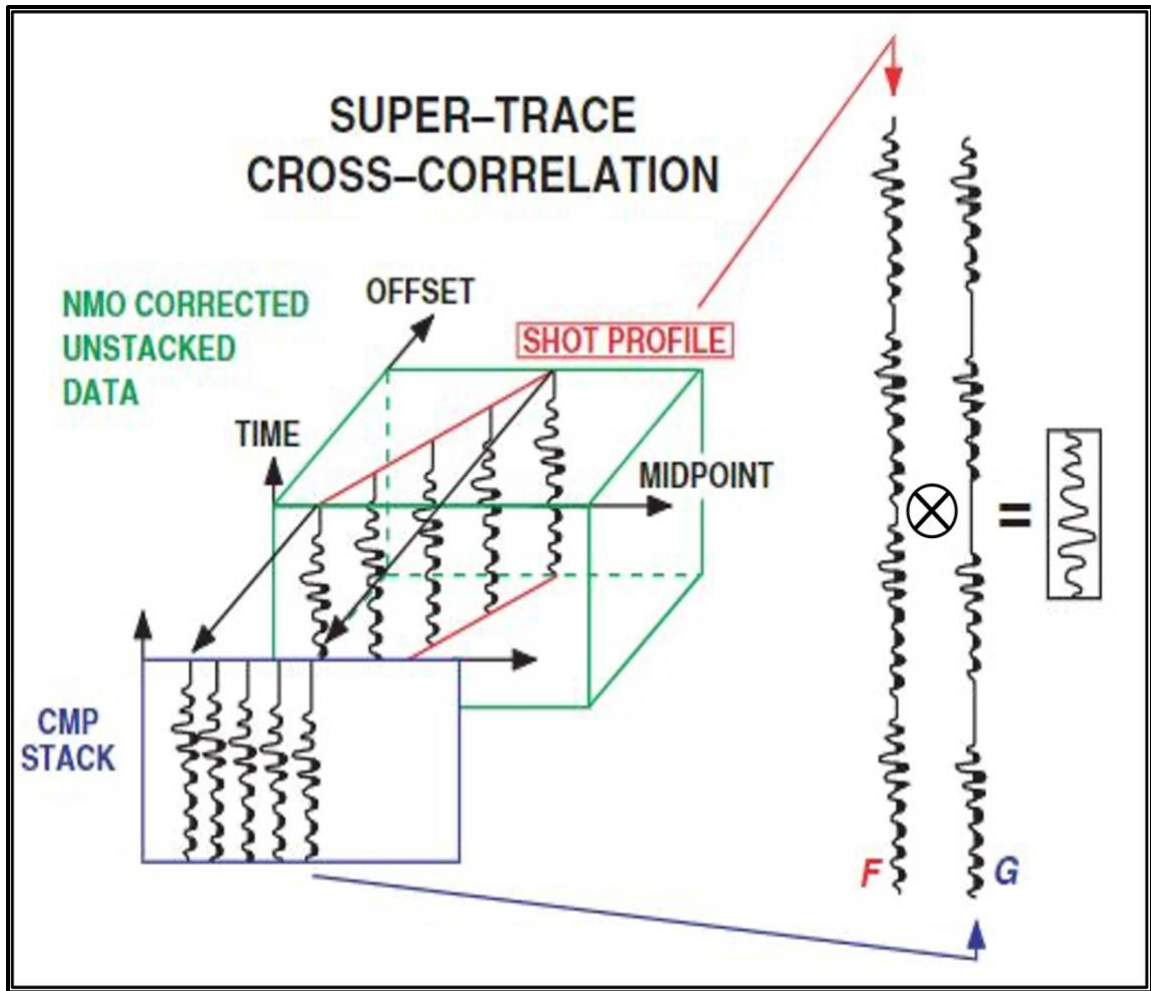


Figure 2.6 The super-trace cross-correlation method. Traces F and G, computed from stacking the shot gathers and relevant part of the CDP respectively, are taken as two super-traces. The correlation of the two traces maximizes the stack power of the CDP. (After Ronen and Claerbout, 1985)

The residual statics correction, due to its surface-consistent nature and dependence on NMO-velocity picking, is time-consuming and requires a considerable amount of effort. To avoid this, AlAli and Anifowose (2021) used a rank-based method that calculates statics independent of the surface-consistent assumption. Their method uses the rank property of frequency slices in the CMP domain, with statics resulting in a high-rank seismic section. This method also avoids the NMO stretch effect, which affects the conventional residual statics method.

2.2.4 Surface Consistent Residual Statics

The objective of static correction is to determine the reflection arrival times that would have been observed if all measurements had been made on a (usually) flat plane with no weathering or low-velocity material present. Hence, it leads to the concept of surface-consistent corrections, which are dependent on the location of the source or receiver but are independent of the source-to-receiver offset or time of the recorded data (Deere, 2009; Cox, 1999). Therefore, Surface-consistent residual statics correction assumes that static shifts are time delays that are solely dependent on the source and receiver locations on the surface and not the raypath trajectory in the subsurface (Taner et al., 1974). This assumption is only valid if all raypaths are vertical in the near surface. Yilmaz (1987) asserts that because of the low-velocity nature of the near-surface, rays entering the near surface tend to bend towards the vertical. The assumption breaks down in areas where raypaths bend away from the vertical in the near-surface (e.g., areas where permafrost is the topmost layer).

The perturbation in the travel time due to residual statics is associated with several contributing factors. Taner et al. (1974) and Wiggins et al. (1976) analyze the residual problem by decomposition of the differences in the travel time from a perfect hyperbola into the source, receiver, structural, and NMO components (see **Fig. 2.7**). They formulated the problem as a linear travel-time inversion. The procedure explained in Marsden (1993c), involves applying an approximate NMO correction to the data. The reflection events are considered to be misaligned due to the contribution of the source, receiver, and residual moveout. Then a time shift is obtained for each trace in each CMP gather which is used to optimize the stacked trace. Ronen and Claerbout (1985) tackle the statics problem using

the surface consistent assumption by optimizing the stack section of the CDP gathers using a super trace cross-correlation (see **Fig. 2.6**). Nagarajappa and Cary (2014) developed an improved stack power optimization method to incorporate and resolve both residual and phase correction.

The reflection method produces converted waves (PS, PP, SS, SP). The PS-converted wave, which is useful in exploration, requires statics correction in its processing workflow. PS velocities are more difficult to understand due to low SNR. Therefore, a modified residual statics method has been developed to correct the statics of PS waves (Strong and Hearn 2016).

Hanafy et al. (2020) showed the dependence of static corrections on the velocity estimate at shallow depths. The study shows that the computed statics can vary up to 44% from the correct statics when using replacement or tomogram velocity instead of an accurately measured velocity profile. Due to this dependency, multiple iterations of surface statics and velocity estimation become essential in determining the correct statics, which is resource-intensive and time-consuming. In areas with complex geologic formations, large statics associated with the source and receiver are caused by noise contamination in the seismic data. Abbas et al. (2018) applied the simulated annealing method to improve the quality of the statics computation in such complex areas, while the method of AlAli and Anifowose (2021) attempts to estimate the correct statics independent of NMO by using the rank property of frequency slices in the CDP domain.

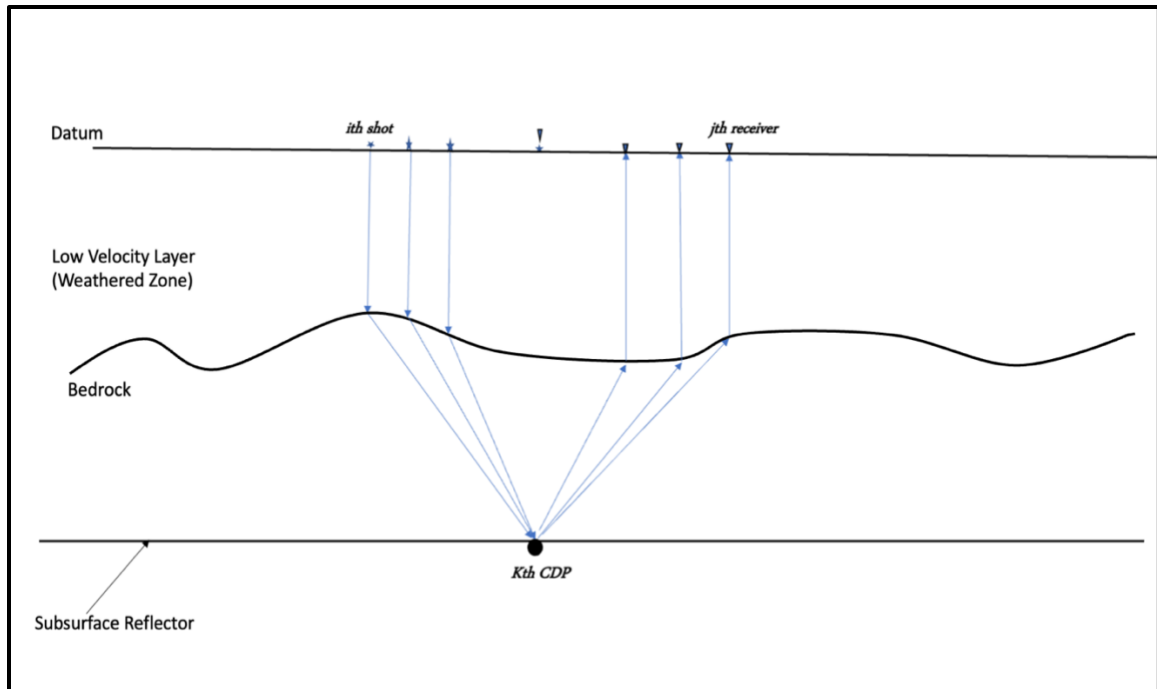


Figure 2.7 The surface-consistent statics assumption. It decomposes the static problem into the source term due to source i , the receiver term due to receiver j , the structural term due to CDP K , and the NMO term associated with the velocity at CDP K

CHAPTER 3

METHODOLOGY

3.1 Offset-Time Equation

In a reflection survey, waves reflect from the interface between layers (**Fig 3.1**). The angle of incidence and angle of reflection are the same. Using Pythagoras' theorem, the distance traveled by the seismic signal on the downward leg of the journey is:

$$d^2 = Z^2 + \left[\frac{X}{2}\right]^2$$

$$d = \sqrt{Z^2 + \frac{X^2}{4}} \quad (3.1)$$

The signal travels the same distance on the upward journey, covering a total distance of $2d$ from the source to the receiver. The whole journey is traveled at the velocity of the medium V . Therefore, the total travel time from the source to the receiver X distance (offset) apart is given by:

$$T(X) = \frac{2d}{V}$$

$$T(X) = \frac{2\sqrt{Z^2 + \frac{X^2}{4}}}{V}$$

$$T(X) = \sqrt{\left[\frac{2Z}{V}\right]^2 + \frac{X^2}{V^2}}$$

$$T(X) = \sqrt{T_0^2 + \frac{X^2}{V^2}}, \quad (3.2)$$

where $T(X)$ denotes the two-way travel time at offset X , $T_0=2z/v$ denotes the two-way travel time at zero offset and V denotes the velocity of the medium.

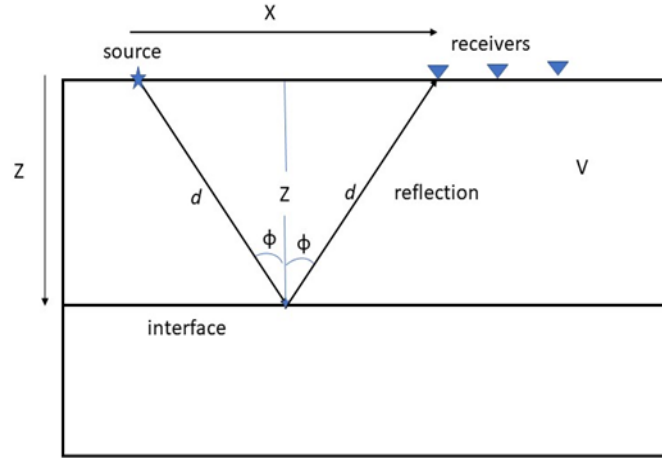


Figure 3.1 Wave trajectory from source to receivers showing the distance travelled ($2d$), the depth of the reflector Z and the offset X .

3.2 Normal Moveout

$T(X)$ is dependent on (X) and increases with an increase in the offset (X) . This increase, termed the normal moveout causes the reflector to form a hyperbola at far offset (**Fig. 3.2**). The time increase due to the normal move out, $\Delta T_{NMO}(X)$ is usually removed from $T(X)$ to flatten the hyperbola. To obtain $\Delta T_{NMO}(X)$, consider equation 3.1 and the fact T_0 is the time it takes for the wave to travel vertically from the source to the receiver making an angle of 90° with the interface. Therefore, $T_0=2z/v$ where z is the depth of the interface, v is the velocity of the medium and it is multiplied by 2 because T_0 is a two-way travel time. Inserting T_0 into **eq. (3.2)** and re-arranging gives:

$$T(X) = \frac{\sqrt{4Z^2 + X^2}}{V} = \frac{2Z}{V} \sqrt{1 + \left(\frac{X}{2Z}\right)^2} = T_0 \sqrt{1 + \left(\frac{X}{2Z}\right)^2}$$

$$T(X) = T_0 \left[1 + \left(\frac{X}{VT_0}\right)^2\right]^{1/2} \quad (3.3)$$

We can simplify **eq. (3.3)** by expanding it using power series expansion (Taylor's series) and assuming that X/VT_0 is relatively small so that the higher terms can be ignored:

$$T(X) = T_0 \left[1 + \left(\frac{X}{VT_0}\right)^2\right]^{1/2} \approx T_0 \left[1 + \frac{1}{2} \left(\frac{X}{VT_0}\right)^2 + \dots\right]$$

$$T(X) \approx T_0 \left[1 + \frac{1}{2} \left(\frac{X}{VT_0}\right)^2\right] \approx T_0 + \frac{X^2}{2V^2T_0}$$

Therefore;
$$\Delta T_{NMO}(X) = T(X) - T_0 \approx \frac{X^2}{2V^2T_0} \quad (3.4)$$

3.3 Normal Move Out Correction

The normal moveout effect increases $T(X)$ by the value of $\Delta T_{NMO}(X)$ which is a function of X , V , and T_0 (**eq. 3.4**). For NMO correction, this value is removed from $T(X)$ so that the two-way travel time at any offset X after NMO correction, $T_{NMO}(X)$, is approximately equivalent to the two-way travel time at zero offset. T_0 .

$$T_{NMO}(X) = T(X) - \Delta T_{NMO}(X) \approx T(X) - \frac{X^2}{2T_0V^2} \approx T_0 \quad (3.5)$$

This approximation works better at small offsets. The velocity in **eq. (3.5)** that best approximates $T(X)$ to T_0 horizontally flattens all events in the seismic section and is called the NMO velocity, V_{NMO} (see **Fig. 3.2**). The determination of this velocity function is an important aspect of seismic data processing.

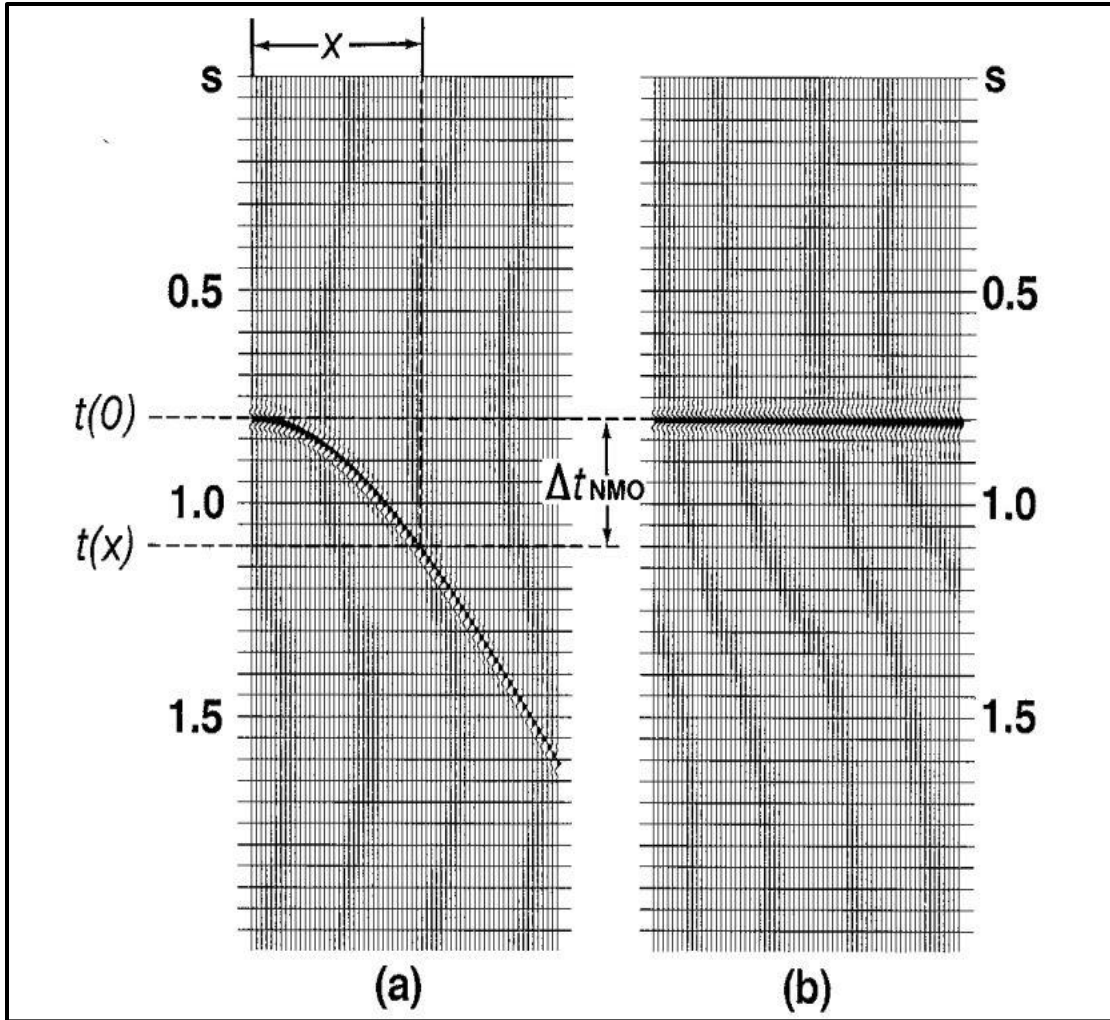


Figure 3.2 Normal moveout causes the reflector to form a hyperbola (a). Δt_{NMO} is the time shift that flattens the reflector (b). This is dependent on an appropriate NMO velocity function during velocity analysis. (After Yilmaz, 2001)

3.4 The Surface Consistent Statics

As discussed in section 2.2.2, surface consistent statics correct for the time delays caused by the variations in elevation and weathering thickness of the near surface. Surface consistency assumes that a given location on the surface is associated with a constant time delay regardless of the wave path in the subsurface. This correction is applied on a trace-by-trace basis and the total time shift applied to a trace has several contributing factors one of which is associated with the NMO corrections discussed in section 3.3.

The total surface consistent residual statics (T_{ijk}) depends on four components:

$$T_{ijk} = R_j + S_i + G_k + M_k X_{ij}^2 \quad (3.6)$$

where T_{ijk} denotes the total time shift due to statics associated with a trace originating from a source at i , reflected from subsurface location k , and detected by a receiver at j . R_j denotes the residual statics time delay due to the receiver located at j ; S_i denotes the residual statics time delay due to the source located at i ; G_k denotes the difference in two-way travel time (due to subsurface structure) between T_{0k} at the k^{th} CMP and $T_{0\text{ref}}$ at a reference CMP, and M_k is the residual NMO effect associated with the trace generated by the i^{th} source and recorded by the j^{th} receiver (**Fig. 2.7**).

The NMO term (M_k) accounts for possible imperfect NMO correction due to using an incorrect NMO velocity for the k^{th} CMP according to **eq. (3.5)**. This term is related to T_{NMO} and it can give useful information about the NMO velocity at the K^{th} CDP as explained in the next section.

3.5 Velocity from Surface Consistent Statics

3.5.1 Equations for Normal Moveout

The M_k term in **eq. (3.6)** shows the interdependence of statics correction and velocity analysis. The effect of this term is most pronounced along the CDP plane. Isolating the effect of M_k in a CDP position can give some information about the time delays associated mainly with NMO.

Consider the K^{th} CDP, NMO corrected with an initial stacking velocity function (V_{wNMO}). The statics computed for all traces of this CDP will have a negligible structural term (i.e., $G_k=0$), because the application of a constant shift to all the traces in the CDP gather, has no effect on the alignment of reflection times within the CDP. Furthermore, after the application of the source and receiver static corrections (i.e., subtracting R_j and S_i from T_{ijk}), the time shifts should be zero if a correct stacking velocity was used during velocity analysis. Therefore, the remaining time shift associated with the traces of the CDP gather after the application of the source and receiver statics must be due to the effect of the initial NMO velocity function used during velocity analysis. This collapses **eq. (3.6)** into:

$$T_{ij} = M X_{ij}^2 \quad (3.7)$$

This is the equation of a parabola relating T_{ij} to X_{ij} . All values of X are known from the geometry of the survey and T_{ij} can be obtained through picking. Fitting a parabola to the picks can give an estimated value for M . The values of T_{ij} and M obtained from picking and curve fitting can be used to obtain the correct velocity of the medium (V_c) as described below.

Substituting equation (3.2) into (3.5), the NMO correction time $T_{NMO}(X)$ will be given by:

$$T_{NMO}(X) = \sqrt{T_0^2 + \frac{X^2}{V^2}} - \Delta T_{NMO}(X) \quad (3.8)$$

The velocity V in **eq. (3.8)** is the correct velocity of the medium which will be termed V_c subsequently. If the correct velocity (V_c) is used to compute $\Delta T_{NMO}(X)$, the expression in **eq. (3.8)** will result in $T_{NMO}(X) \approx T_0$ as alluded to in **eq. (3.5)**. However, as with the case of our CDP of interest (i.e., K^{th} CDP) and **eq. (3.7)**, the computation of $\Delta T_{NMO}(X)$ is incorrect due to the remnant time shifts observed in **eq. (3.7)**. This is due to the use of a wrong NMO velocity function (V_{wNMO}) leading to both wrong NMO correction ($\Delta T_{wNMO}(X)$) and time T_{wNMO} . This results in the expression:

$$T_{wNMO}(X) = \sqrt{T_0^2 + \frac{X^2}{V_c^2}} - \Delta T_{wNMO}(X)$$

$$T_{wNMO}(X) = \sqrt{T_0^2 + \frac{X^2}{V_c^2}} - \frac{X^2}{2T_0 V_{wNMO}^2} \quad (3.9)$$

where the first term in **eq. (3.9)** is the two-way travel time at offset X , V_c is the correct NMO velocity of the medium (which is unknown), and V_{wNMO} is the wrong NMO velocity, which is known from velocity analysis.

Note that $T_{wNMO} \neq T_0$ in this case, which is due to the imperfect NMO correction. In particular,

$$T_{wNMO}(X) = a + bX^2. \quad (3.10)$$

To obtain the correct velocity of the medium from **eq. (3.9)**, all the traces of the CDP are picked for a particular reflector of interest, a parabola is fitted to these picks according to **eq. (3.10)** and equated to **eq. (3.9)**, resulting in:

$$a + bX^2 = \sqrt{T_0^2 + \frac{X^2}{V_c^2}} - \frac{X^2}{2T_0V_{wNMO}^2} \quad (3.11)$$

where $a \approx T_0$ and $b \approx M$ as in **eq. (3.7)** and the approximation is due to fitting. The actual T_0 should be that at which the “incorrect” velocity was picked. Equation (3.11) can be solved for the correct (unknown) NMO velocity as follows:

$$\begin{aligned} \left[a + bX^2 + \frac{X^2}{2T_0V_{wNMO}^2} \right]^2 &= T_0^2 + \frac{X^2}{V_c^2} \\ \frac{X^2}{V_c^2} &= \left[\frac{2aT_0V_{wNMO}^2 + 2bT_0V_{wNMO}^2X^2 + X^2}{2T_0V_{wNMO}^2} \right]^2 - T_0^2 \\ \frac{X^2}{V_c^2} &= \frac{[2aT_0V_{wNMO}^2 + 2bT_0V_{wNMO}^2X^2 + X^2]^2 - 4T_0^4V_{wNMO}^4}{4T_0^2V_{wNMO}^4} \\ V_c^2 &= \frac{4T_0^2V_{wNMO}^4X^2}{[2aT_0V_{wNMO}^2 + 2bT_0V_{wNMO}^2X^2 + X^2]^2 - 4T_0^4V_{wNMO}^4} \end{aligned} \quad (3.12)$$

Expanding **eq. (3.12)**, simplifying, and grouping like terms yields:

$$V_c = \frac{2T_0V_{wNMO}^2X}{\sqrt{A+BCX^2+C^2X^4}} \quad (3.13)$$

Where:

$$A = 4(a^2 - T_0^2)T_0^2V_{wNMO}^4$$

$$B = 4aT_0V_{wNMO}^2 \text{ and}$$

$$C = 1 + 2bT_0V_{wNMO}^2$$

Equation (3.13) can be used to estimate the correct NMO velocity of the medium from the time shifts resulting from the imperfect NMO application.

3.5.2 Equations for Dip Moveout

So far, the scenario discussed has been based on a horizontally layered earth. This is an approximation that is not always correct. When the layers dip considerably, the time-offset equation changes accordingly to accommodate for the dip. Levin (1971) derived the time-offset equation for a dipping reflector with dip angle ϕ , which is given by:

$$T(X) = \sqrt{T_0^2 + \frac{X^2 \cos^2 \phi}{V_m^2}} \quad (3.14)$$

Where V_m is the velocity of the medium above the dipping reflector and other variables retain their definitions. Equation (3.14), like eq. (3.2) is the equation of a hyperbola, with the dip angle ϕ only affecting the apparent velocity. The velocity that will flatten a dipping event is greater than the velocity of the medium through which the waves travel (Yilmaz, 2001). This is computed by dividing the medium velocity by the cosine of the dip angle:

$$V_c = \frac{V_m}{\cos \phi} \quad (3.15)$$

The equation for estimating velocity from surface consistent statics for a dipping reflector, following eq. (3.11), will therefore be:

$$a + bX^2 = \sqrt{T_0^2 + \frac{X^2 \cos^2 \phi}{V_m^2}} - \frac{X^2}{2T_0V_{wNMO}^2} \quad (3.16)$$

Inverting (3.16) for the velocity of the medium V_m yields:

$$V_m = \frac{2T_0V_{wNMO}^2 X \cos \phi}{\sqrt{A + BCX^2 + C^2X^4}} \quad (3.17)$$

With A, B and C retaining their definitions.

For NMO correction, V_{NMO} is required according to **eq. (3.15)**. Therefore **eq. (3.17)** will be divided by $\text{Cos } \phi$:

$$V_c = \frac{2T_0 V_{\text{wNMO}}^2 X \text{Cos } \phi}{\text{Cos } \phi \sqrt{A + BCX^2 + C^2 X^4}}$$

$$V_c = \frac{2T_0 V_{\text{wNMO}}^2 X}{\sqrt{A + BCX^2 + C^2 X^4}} \quad (3.18)$$

Equation **(3.18)** is the same with **eq. (3.11)** for a flat reflector and shows that the method will work fine for a dipping interface.

The processing steps for the application of the new methodology are described in **Fig 3.3**.

Next, I apply the steps described in this section to synthetic and real datasets.

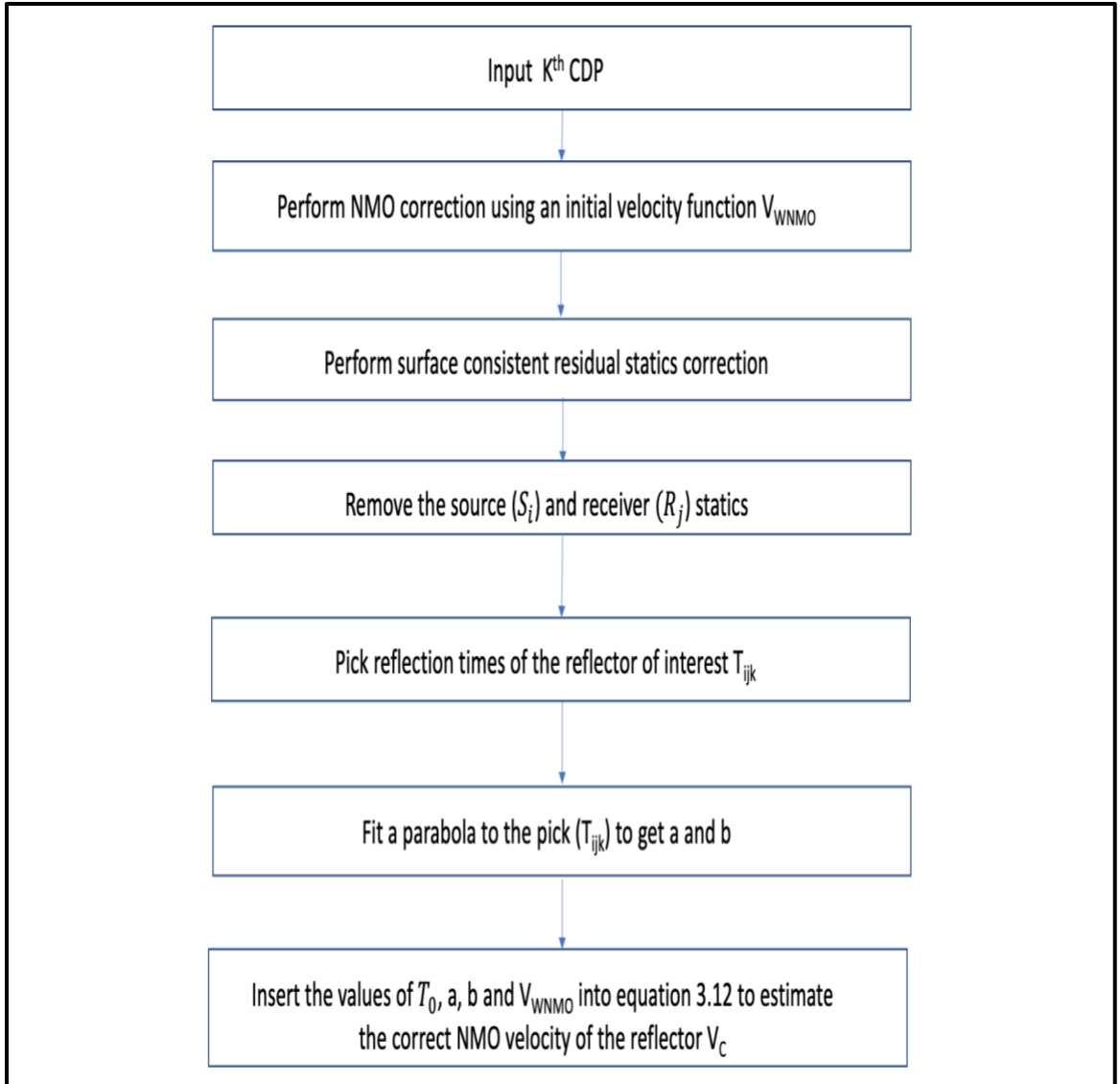


Figure 3.3 Processing workflow of the proposed methodology

CHAPTER 4

SYNTHETIC DATASETS

4.1 Horizontally Layered Earth Model

4.1.1 Data Generation

The synthetic data are 2D elastic seismic data generated using a conventional 2D acquisition geometry. The profile length is 5 km with a sand dune between $X=2$ km and 3 km that has a maximum height of 100 m above a flat top interface of the uppermost layer. This serves as the source of the statics problem, as the velocity of the dune differs significantly from the velocity of the underlying layer. The velocity within the dune is governed by the equation:

$$v(z) = v_0 \sqrt{1 + kz^{1/3}}, \quad (4.1)$$

where z is the depth from the surface of the dune, $v_0=15$ m/s, and $k=1500 \text{ m}^{-1/3}$ are constants typical in a quartz-rich slightly saturated dune (Al-Shuhail, 2002, 2006).

The source and receiver spacings are 20 m and 1 m, respectively. All sources and receivers were buried 15 m beneath the surface to avoid the effects of surface-related ghost reflections. The P-wave velocity is assumed to be the average P-wave velocity from the surface to the source or receiver depth. It is calculated by dividing the source or receiver depth (i.e., 15 m) by the vertical one-way time from the surface to this depth calculated from **eq. (4.1)** to be 0.0197 s (Al-Shuhail et al., 2018). This resulted in a P-wave velocity in the dune ranging from approximately 900 to 1250 m/s. The corresponding minimum S-wave velocity range is 450 to 625 m/s, as it is assumed the S-wave velocity is half the P-

wave velocity for all model layers. The velocity of the layer underlying the dune and the lowermost layer are 3000 and 5000 m/s, respectively. The maximum velocity is the P-wave velocity of the lowermost layer, which is 5000 m/s. The density of all layers and the dune is constant at 2000 kg/m³.

A 10-Hz zero-phase Ricker wavelet is used with a corresponding maximum usable frequency of 25 Hz for the simulation. The grid cell size is 2.8 m, rounded down to 2.5 m along the x- and z-axes, calculated from the minimum velocity (350 m/s) and maximum usable frequency (25 Hz). The grid cell size is then used with the maximum model velocity to calculate the simulation time step to be 0.000355 s, which was also rounded down to 0.0003 s. This is to satisfy the Courant–Friedrichs–Lewy (CFL) stability criterion. **Fig. (4.1)** shows the wavelet, and **Table 4.1** summarizes the acquisition parameters of the model. The model is depicted in **Fig 4.2**.

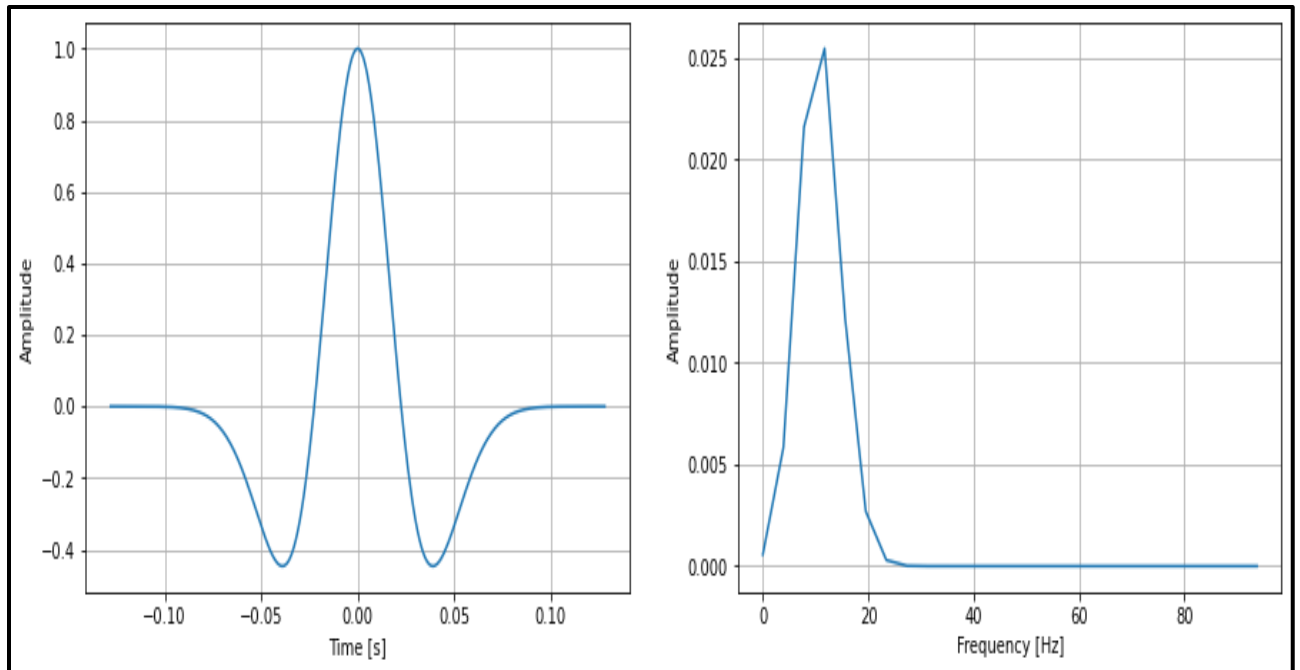


Figure 4.1 A 10-Hz Ricker wavelet with its frequency domain representation showing a maximum frequency of 25 Hz. This wavelet was used to generate the synthetic data.

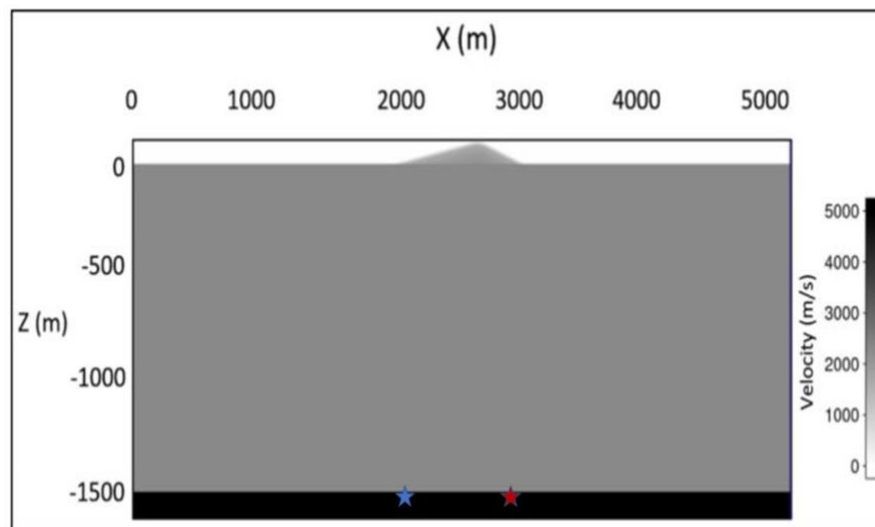


Figure 4.2 Velocity model of the synthetic data. The blue and red stars indicate the positions of CDP2000 and CDP2900, respectively.

Table 4.1 Acquisition parameters of the synthetic data

Parameter	Value
Shot spacing	20 m
Receiver spacing	1 m
Receiver depth	15 m
Shot depth	15 m
Number of Receivers	5001
Number of Shots	251
Minimum offset	-5000 m
Maximum offset	5000 m
Source wavelet	Zero-Phase Ricker with 10-Hz peak frequency
Sampling interval	2.1 ms
Recording time	2.5 s

4.1.2 Processing Workflow

The synthetic data required little processing. The data were processed using a conventional 2D land seismic data processing workflow that involves the following basic steps:

1. Gain application using automatic gain control (AGC) with a gate = 0.1 s.
2. Frequency Wavenumber (F-K) filtering to remove prominent linear events.
3. Spiking deconvolution using a prediction lag = 2.1 ms, operator length = 0.125 s, pre-whitening noise = 0.1%, and auto-correlation window = 0-2.5 s.
4. CDP sorting
5. NMO correction with the correct velocity function (V_c) used to generate the data (i.e., $V_c=3000$ m/s and $T_0= 1.0$ s).
6. Static correction to obtain the source (S_i) and receiver (R_j) statics within the dune ($X= 2000$ - 3000 m). See Fig 4.5

The data was sorted into the CDP domain to select the CDP of interest (i.e. K^{th} CDP). The CDP2000 is selected because it is close to the dune exhibiting a considerable amount of statics. **Figure (4.3)** shows the selected CDP gather after these processing steps until step 4. **Figure (4.4)** shows the same CDP after NMO correction of the dataset using a velocity of 3000 m/s which is the P-wave velocity of layer 1 below the dune. **Figure (4.6)** shows the CDP after the application of the computed statics (**Fig 4.5**).

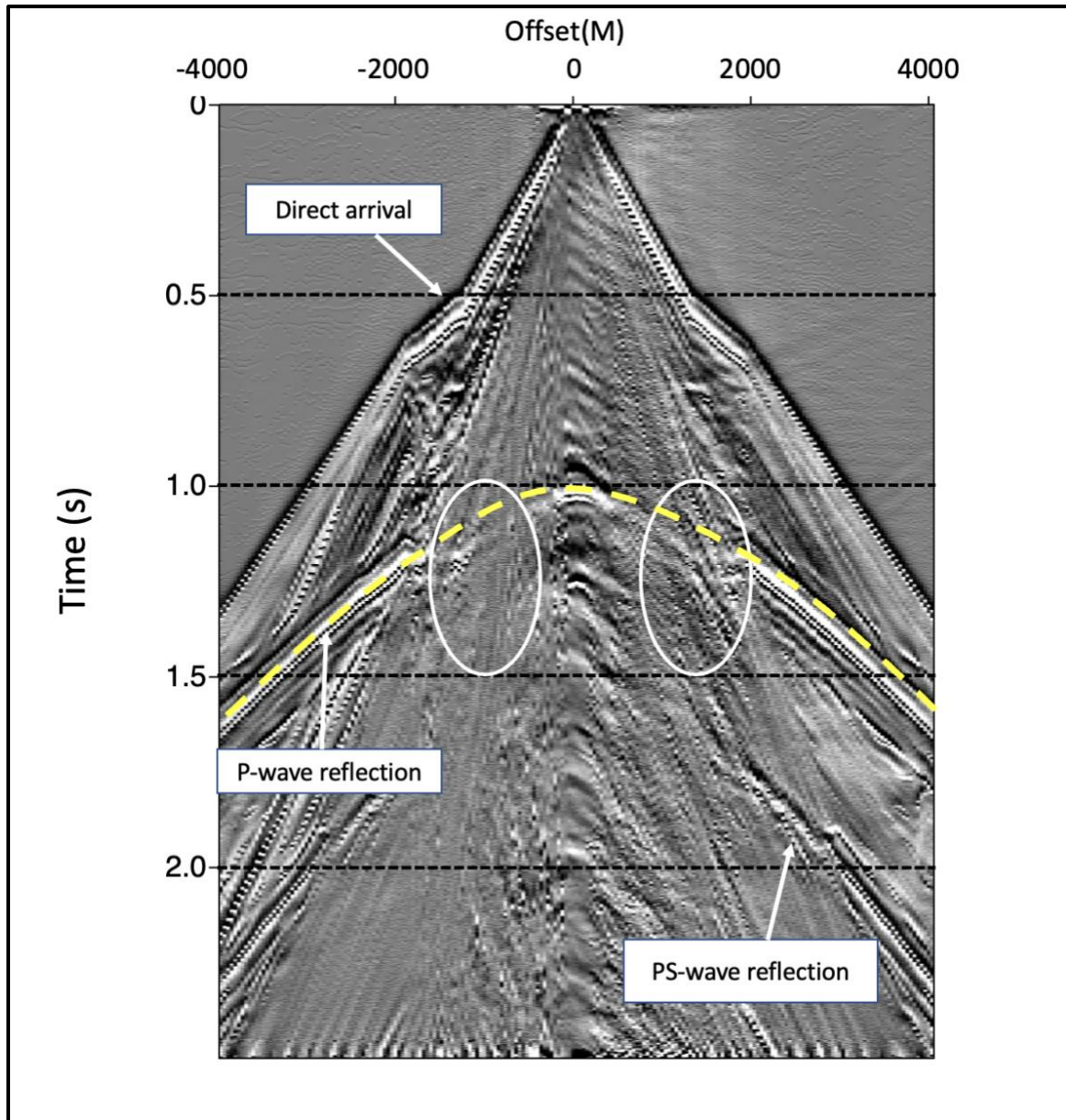


Figure 4.3 CDP2000 after processing steps (1-4). The circles show the effect of statics between $X=-2000$ m to $X=2000$ m while the yellow curve shows the reflection of interest at $T_0=1.0s$

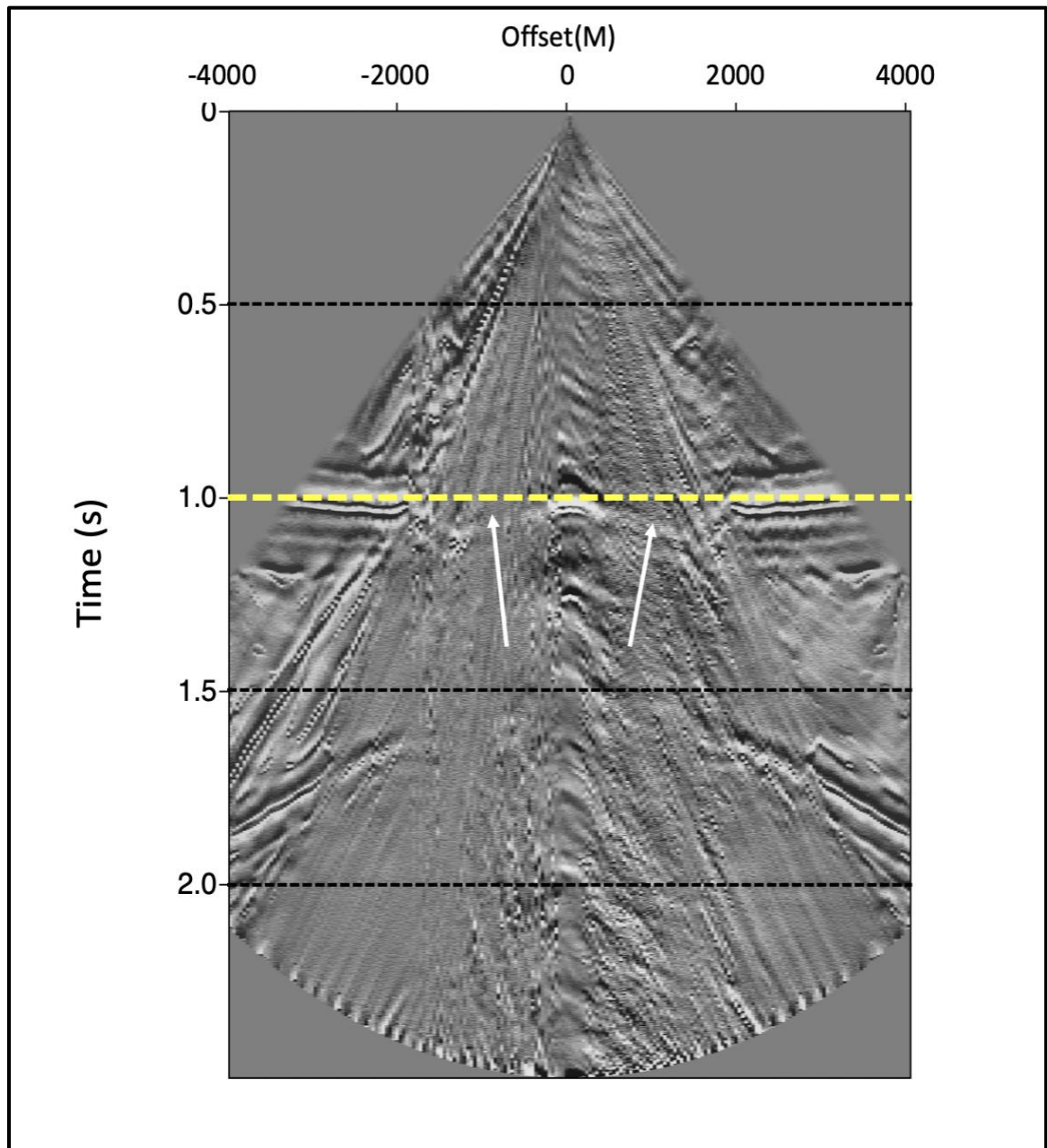


Figure 4.4 CDP2000 after NMO correction with the correct velocity of 3000 m/s. The reflection of interest is flattened except for the effect of statics caused by the dune shown by the arrows

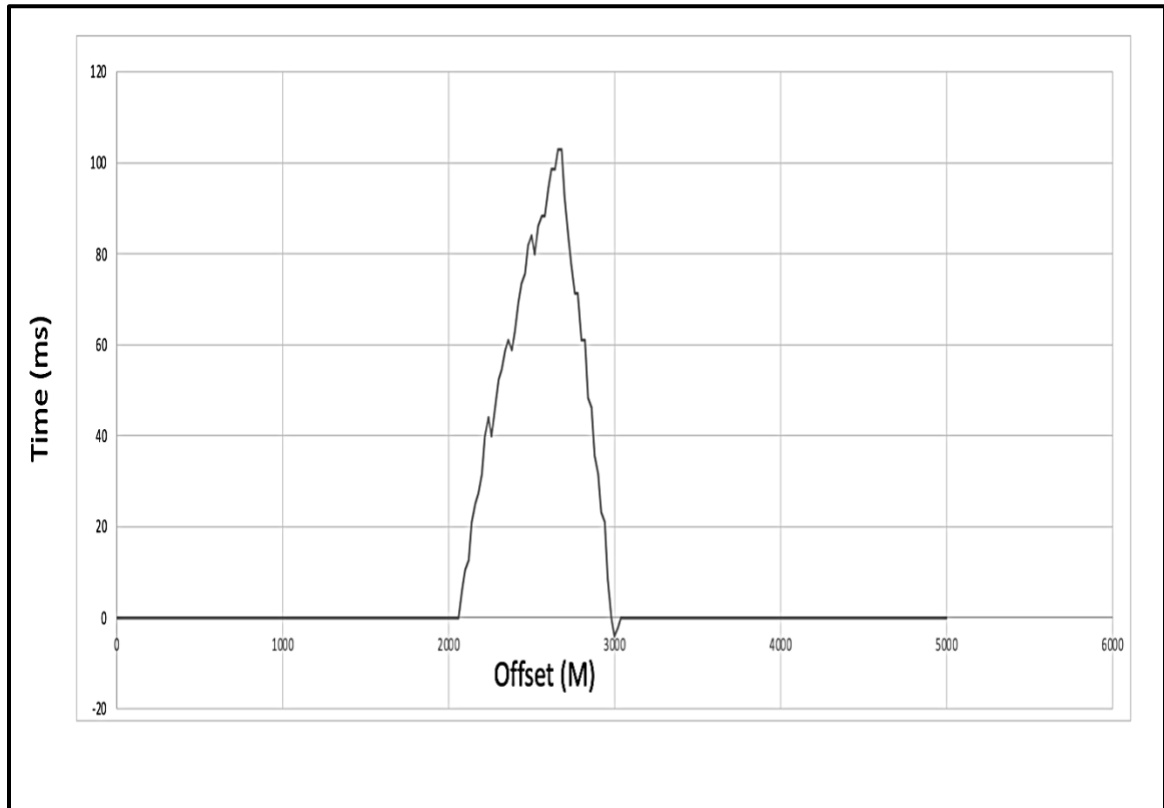


Figure 4.5 Computed source and receiver statics obtained from surface-consistent residual statics.

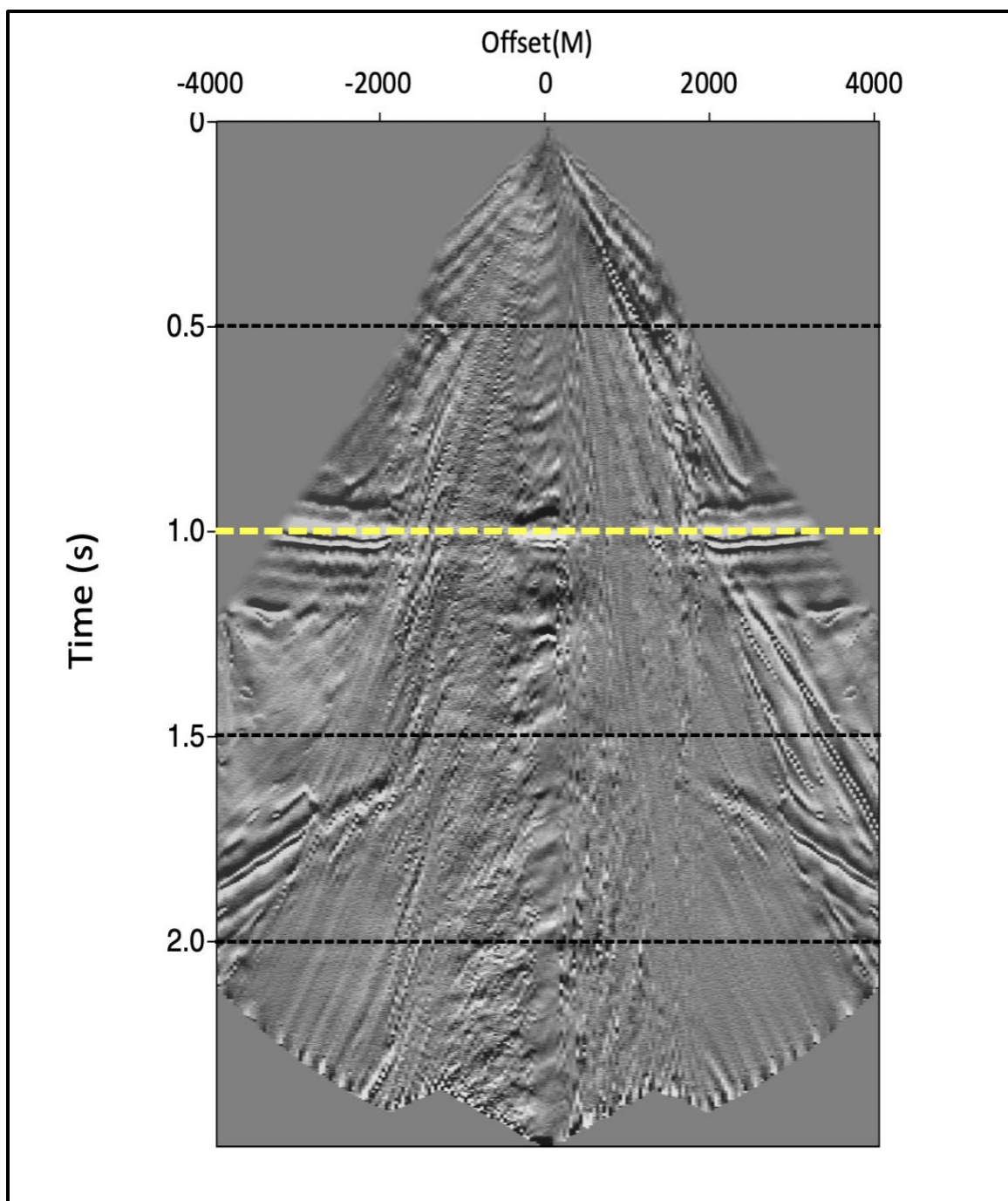


Figure 4.6 CDP2000 after NMO correction and application of source and receiver statics.

4.2 Dip Model

4.2.1 Data Generation and Description

A 2D acoustic synthetic dataset was generated to test the methodology on a dipping layer. The model length is 6 km with a depth of 2 km. The model consists of three layers, with two dipping reflectors (**Fig. 4.7**). The velocities of the layers are 2500 m/s, 3015 m/s and 4000 m/s. A 2D seismic line was acquired using 40 shots with source stations from $X=2$ km to $X=3.95$ km and a shot spacing of 50 m and a source peak frequency of 12 Hz. The receiver spread has 60 receivers with a spacing of 50 m. The record time and sampling interval are 2.0 s and 2.0 ms, respectively.

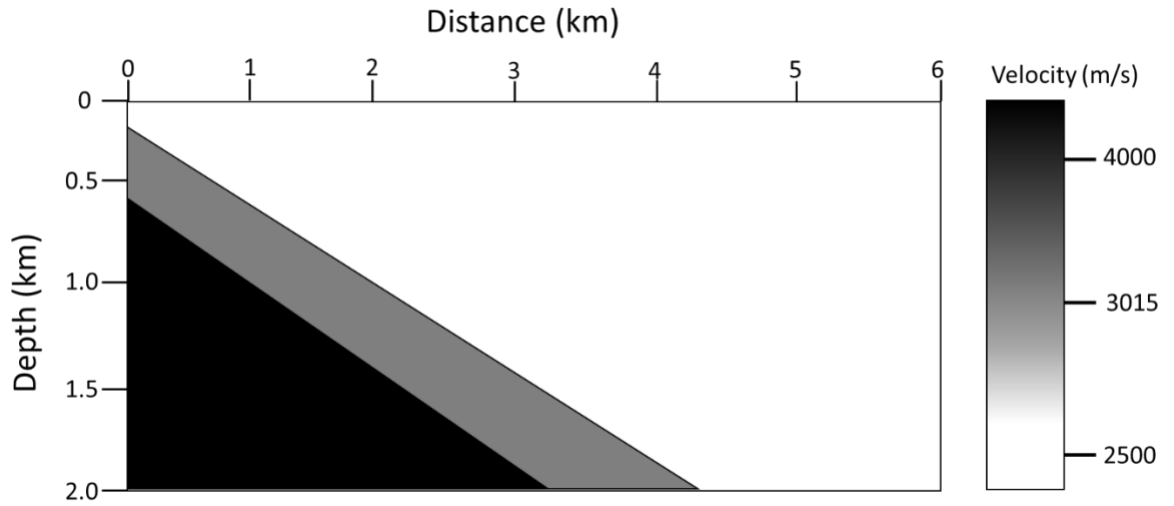


Figure 4.7 Dipping reflector model.

Figure (4.8) shows a shot gather from the model. The two-way zero-offset (T_0) and the two-way time at the apex of the hyperbola (T_a) are shown on the shot gather. The values of T_0 and T_a are then used to compute the dip angle:

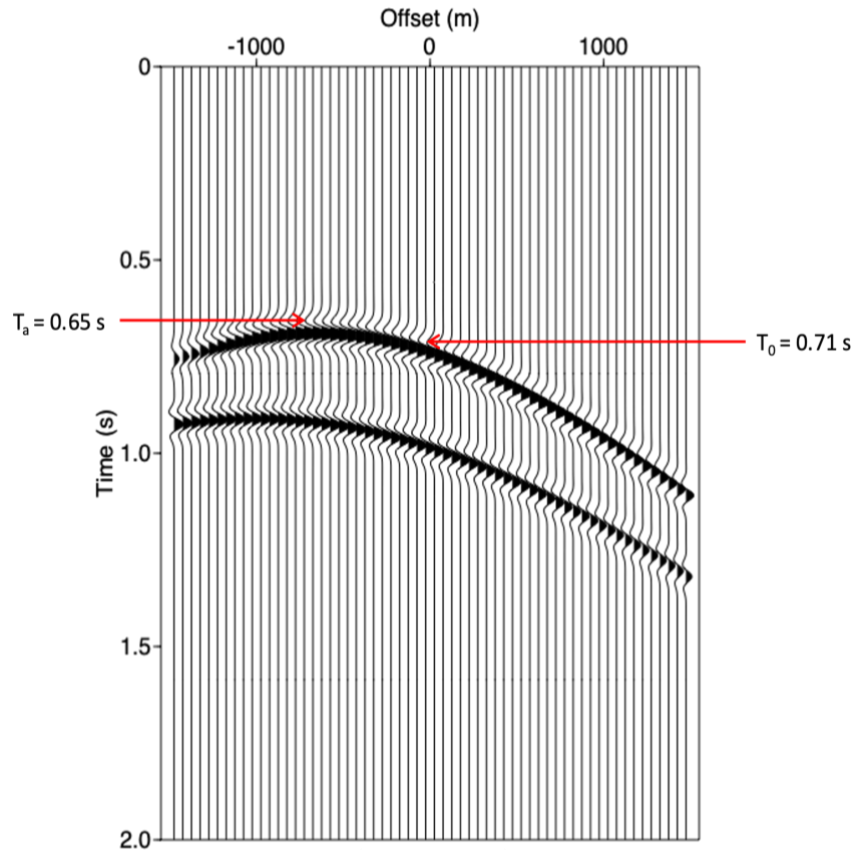


Figure 4.8 Sample shot gather from the dipping reflector model.

$$\phi = \cos^{-1}\left(\frac{T_0}{T_a}\right) \quad (4.2)$$

$$\phi = \cos^{-1}\left(\frac{0.65}{0.71}\right)$$

$$\phi = 23.7^\circ$$

Using the value of 23.7° as the dip angle and the velocity of the medium above the dipping reflector (i.e., 2500 m/s), the apparent NMO velocity required to correct for the reflector can be computed according to **eq. (3.15)**:

$$V_{NMO} = V_c = \frac{V_m}{\cos \phi}$$

$$V_c = \frac{2500}{\cos 23.7^\circ} = 2730 \text{ m/s.}$$

Figure (4.9a) shows a pre-NMO corrected CMP from the dataset and **(4.9b)** shows the same CDP after NMO correction with an apparent $V_{NMO}=2730 \text{ m/s}$.

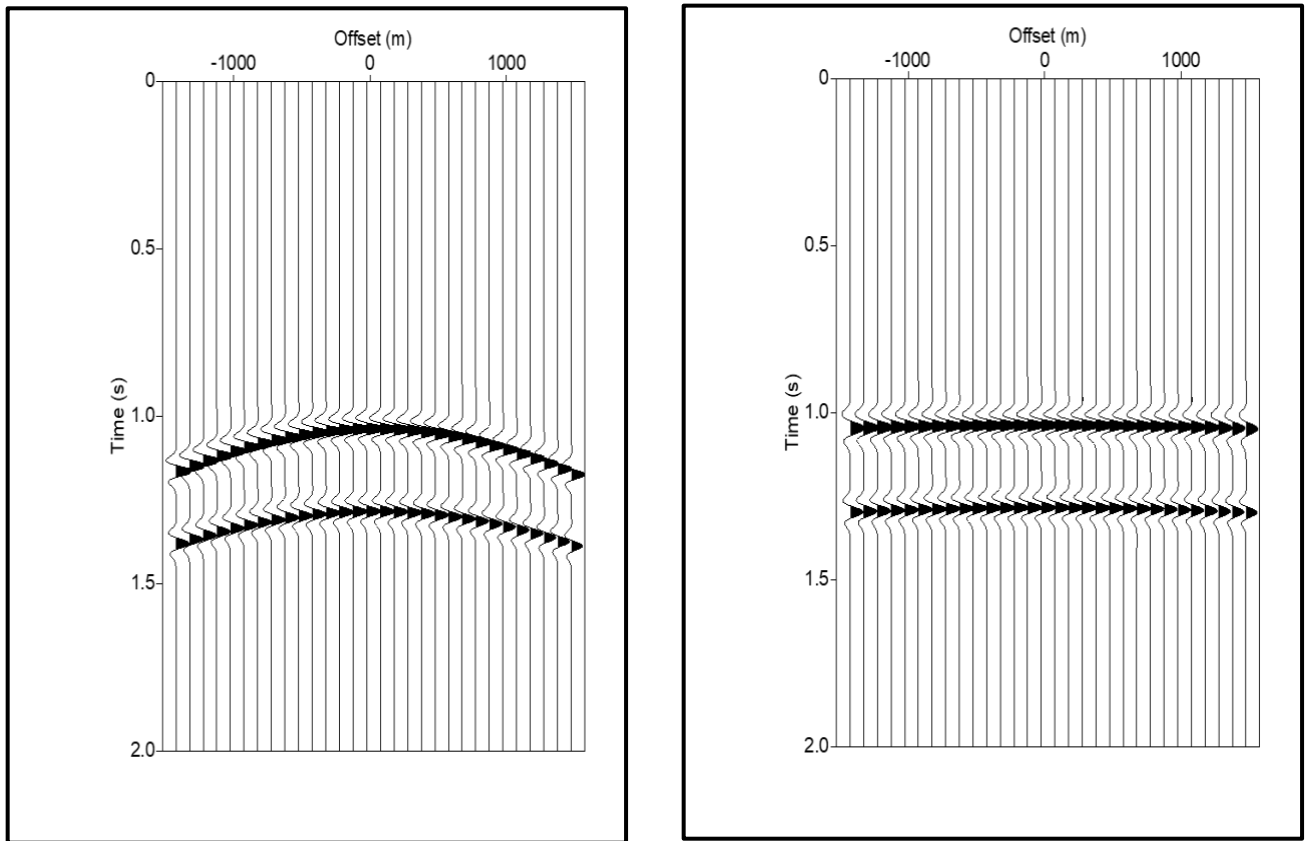


Figure 4.9 (a) Pre-NMO corrected sample CMP and (b) NMO corrected sample CMP

CHAPTER 5

REAL DATA

5.1 Data Description

The real dataset used is a well-studied 2D seismic land data from east Texas, USA (Mousa and Al-Shuhail 2011; Al-Mashhor et al., 2019). The dataset was demultiplexed, and an 8-64 Hz bandpass filter was applied to the data during recording. The data have the following acquisition parameters:

- 18 shot records
- 33 channels per shot
- 594 traces
- 2 ms sampling rate
- Variable shot interval
- 67 m receiver interval.
- 1501 samples per trace

5.2 Processing Workflow

I processed the data using a conventional 2D processing workflow and derived the best velocity that flattens the events using the velocity spectrum method. First, the data were gained to enhance the reflection events and mitigate the effect of geometrical spreading. Next, ground rolls were filtered using FK filtering to improve the SNR of the dataset. To spike the data and improve the vertical resolution, I deconvolve the data and balance the amplitudes. **Fig. 5.1** shows sample CDP gathers after these processing steps before NMO correction, while **Fig. 5.3** shows the same gathers after NMO correction using a velocity function derived from velocity picking on velocity spectra (**Fig. 5.2**). **Table 5.1** shows the time picks for all reflectors from the CDP.

Table 5.1 Velocity picks of CDP225

Time (s)	Velocity (ft/s)
0.076	5720.93
0.28	6162.79
0.55	6697.67
0.86	7232.56
1.24	7790.7
1.65	8465.12
1.91	9581.14
2.22	11186
2.26	12555
2.69	13814

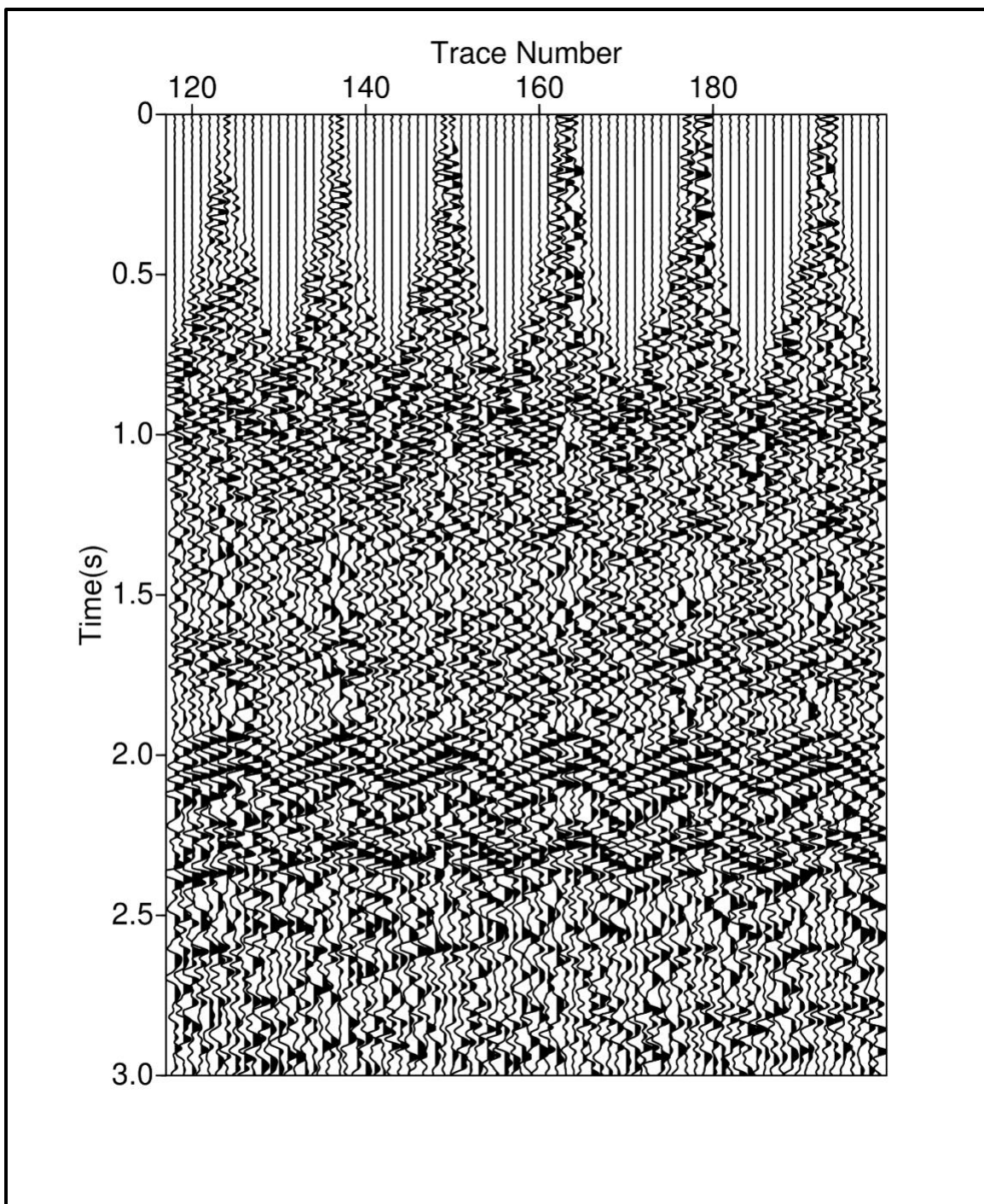


Figure 5.1 CDP223 - 228 from the real data set from east Texas before NMO correction

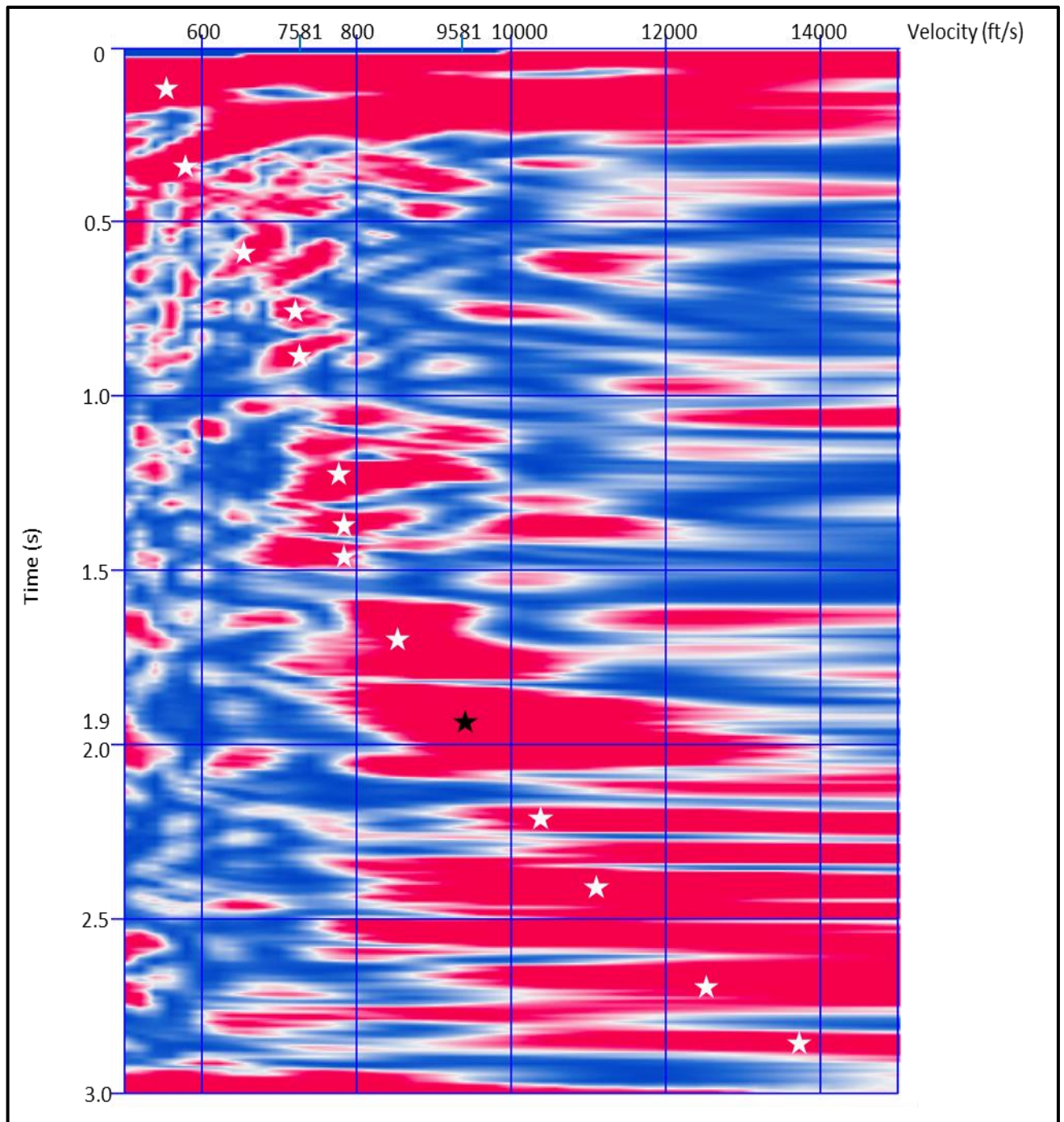


Figure 5.2 Velocity spectrum of CDP225 showing the picks (white stars) and the pick of the reflector of interest at $T_0=1.9$ s (Black star).

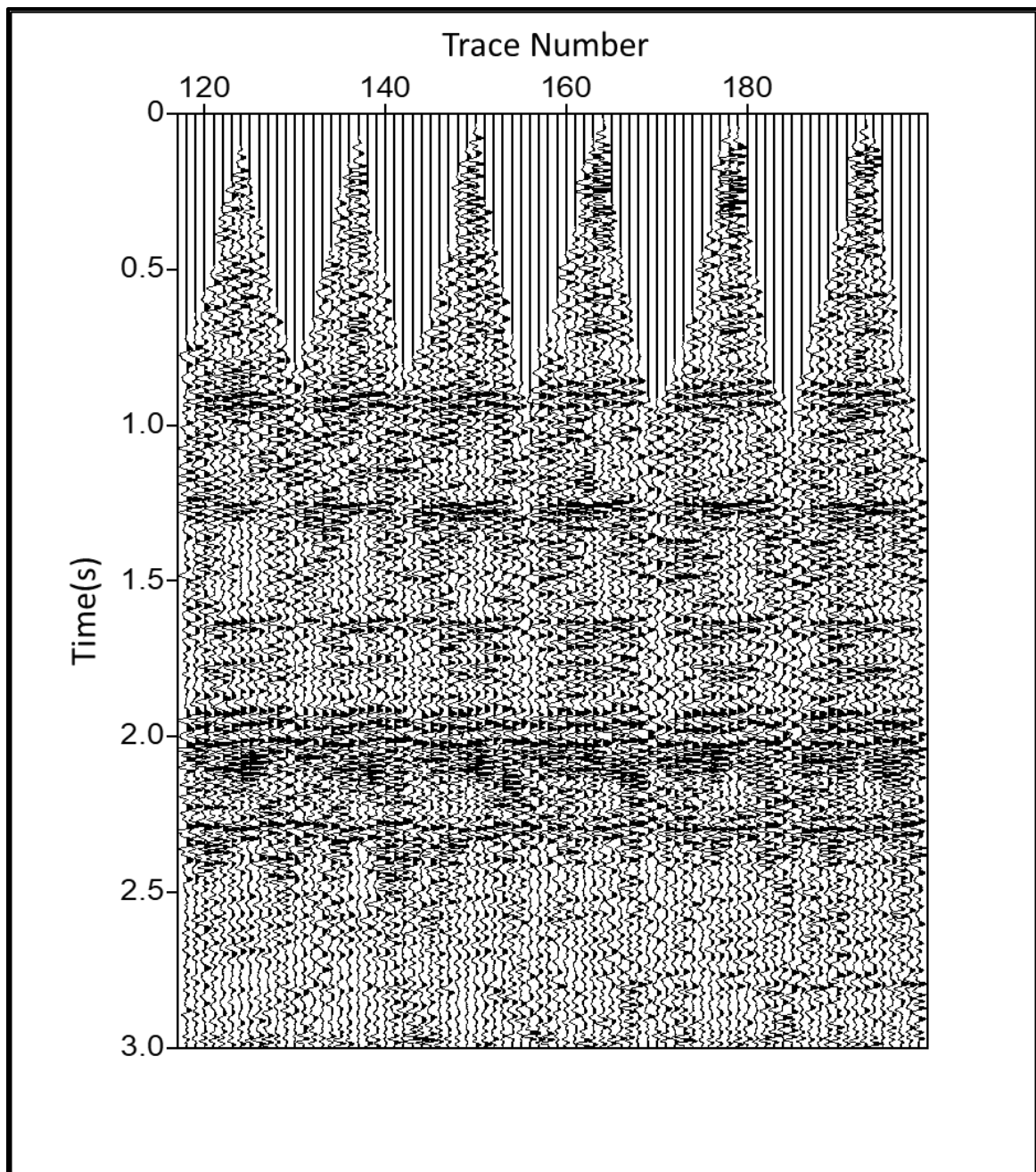


Figure 5.3 CDP223 - 228 from the real data set after NMO correction. The reflection events have been considerably flattened. The velocity function used for this process is considered the correct NMO velocity (V_c).

CHAPTER 6

METHODOLOGY APPLICATION AND RESULTS

6.1 Application to Synthetic Data and Results

I applied the proposed methodology to CDP2000 of the synthetic data reflected at $X=2000$ m. This CDP was selected because it is close enough to the dune to have a considerable amount of statics (see **Fig. 4.2**). I first NMO-correct the pre-NMO corrected data (**Fig. 6.1**) with an initial velocity (V_{WNMO}) of 4000 m/s, which is greater than the correct NMO velocity of 3000 m/s for this reflection. This causes the reflection at $T_0=1.0$ s to curve downward instead of being horizontally flattened (**Fig. 6.2**). The static time delays visible in **Fig. 6.2** is due to both the effect of the dune and the imperfect initial NMO velocity used to NMO correct the data. I then compute and apply the source and receiver statics to remove the time delays due to the dune. This resulted in the CDP containing only time delays that are associated mainly with the wrong NMO application (**Fig. 6.3**). I then pick the reflection times on all the traces of this CDP at the reflector of interest. Fitting a parabola to the picks (**Fig. 6.4**) gives a value of $\mathbf{a} (\approx T_0) = 1.04075$ s and $\mathbf{b} (\approx M) = 1.73909 \times 10^{-8} \text{s/m}^2$. I then inserted the calculated values of $\mathbf{a}$ and $\mathbf{b}$ from the fitted parabola and $T_0 = 1.0$ s and $V_{WNMO}=4000$ m/s into **eq. (3.13)** for each offset to estimate the correct velocity (V_c) at the reflector of interest. These estimated velocity (V_c) values ranged between 2700 m/s and 3200 m/s, which are within 10% of the correct NMO velocity value of 3000 m/s. The mean estimated V_c value is 2924 m/s, which is only about 2.5% error from the correct V_c value of the reflector. I then use this velocity as the NMO velocity to flatten the pre-NMO corrected CDP gather (**Fig. 6.5**). The procedure can be repeated on any CDP for any reflector of interest.

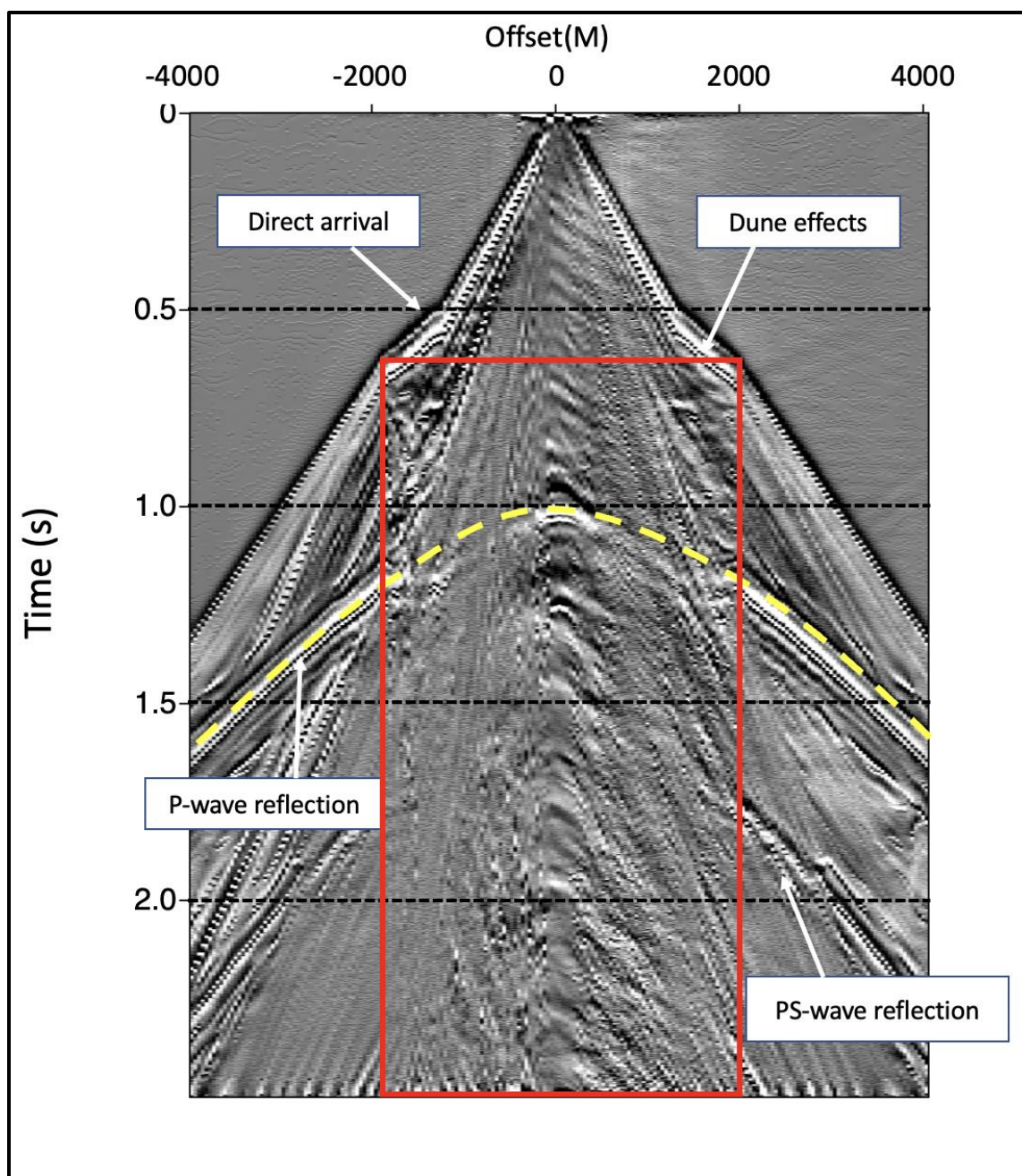


Figure 6.1 CDP2000 before NMO correction and statics correction. The area within the red rectangle shows the effect of the dune. The yellow curve shows the reflection of interest.

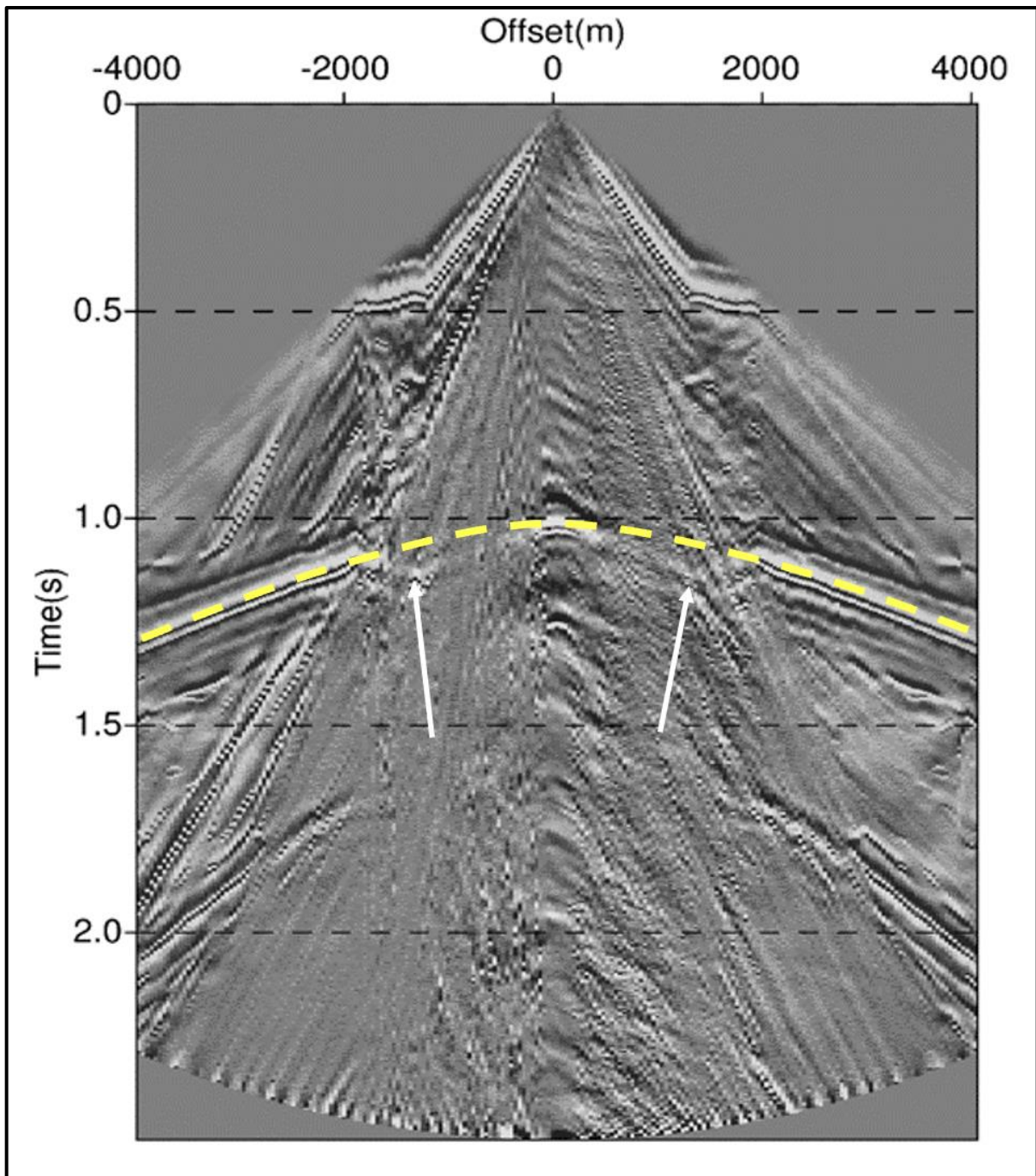


Figure 666.2 CDP2000 after NMO correction with $V_{WNMO}=4000$ m/s. Notice that dune statics are still present (white arrows). The reflection of interest (yellow curve) is not flat due to the use of high NMO velocity.

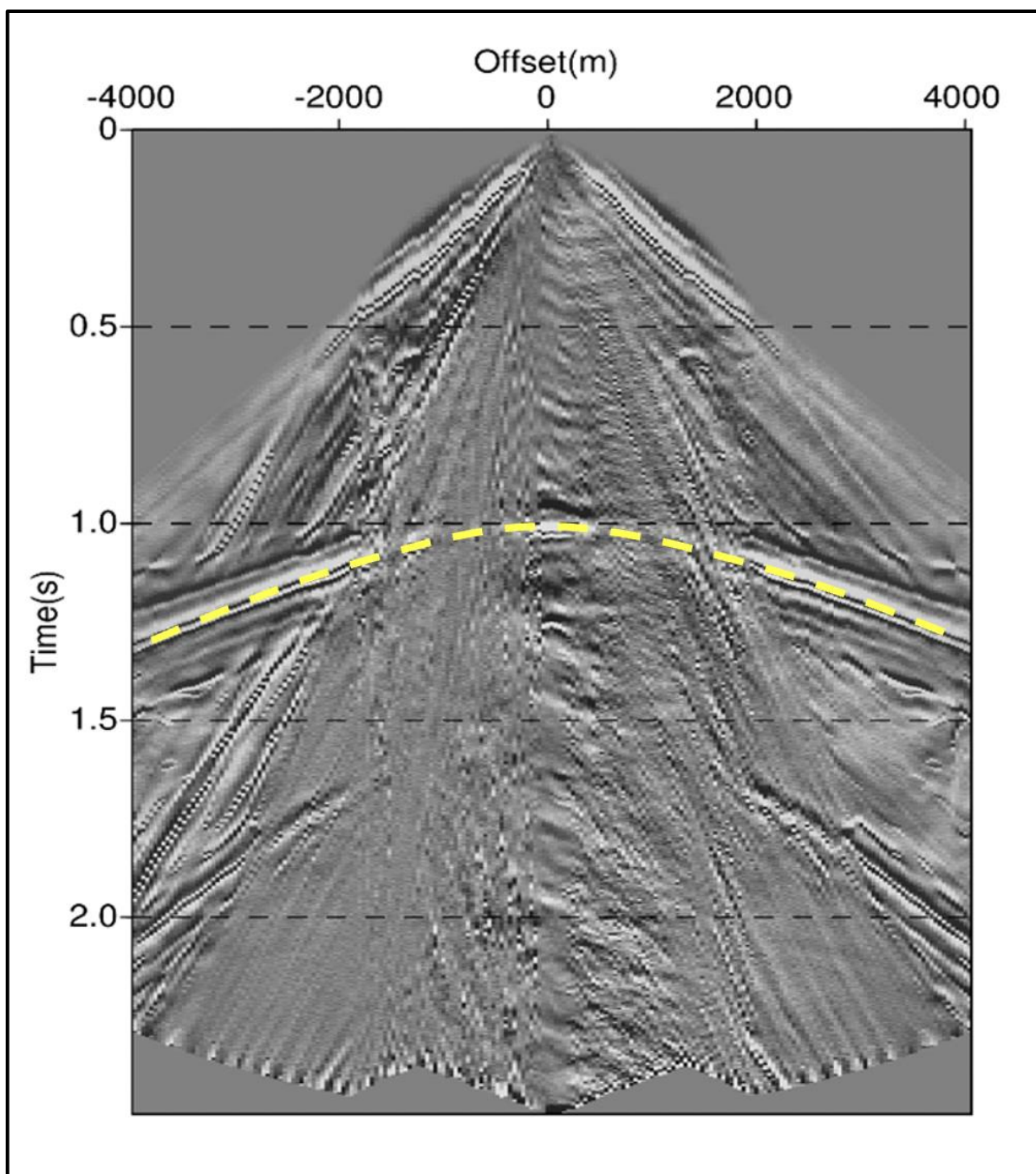


Figure 6.3 CDP2000 after NMO correction using V_{WNMO} followed by application of source and receiver static. The dune statics in Fig. 6.2 have been removed and the only time delay is due to the imperfect NMO correction.

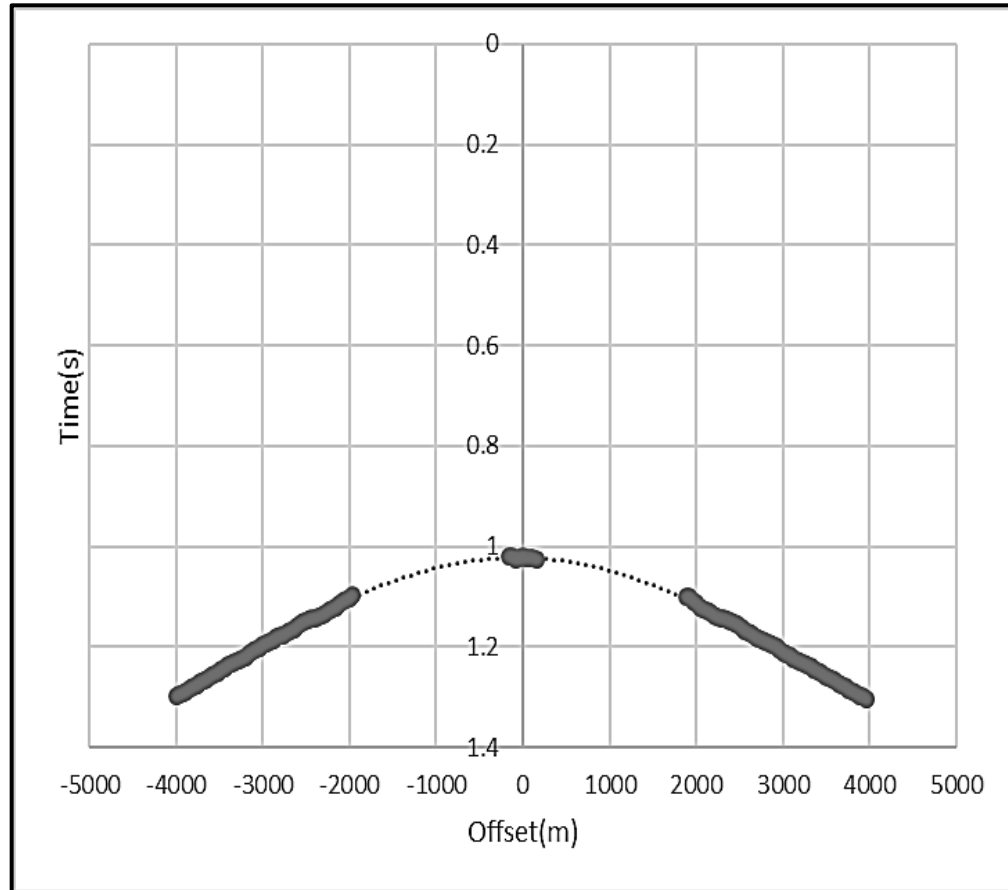


Figure 66.4 Plot of time picks as a function of offset for CDP2000. The dotted line indicates the best-fit parabola. Gaps in picking are due to excessive dune noise.

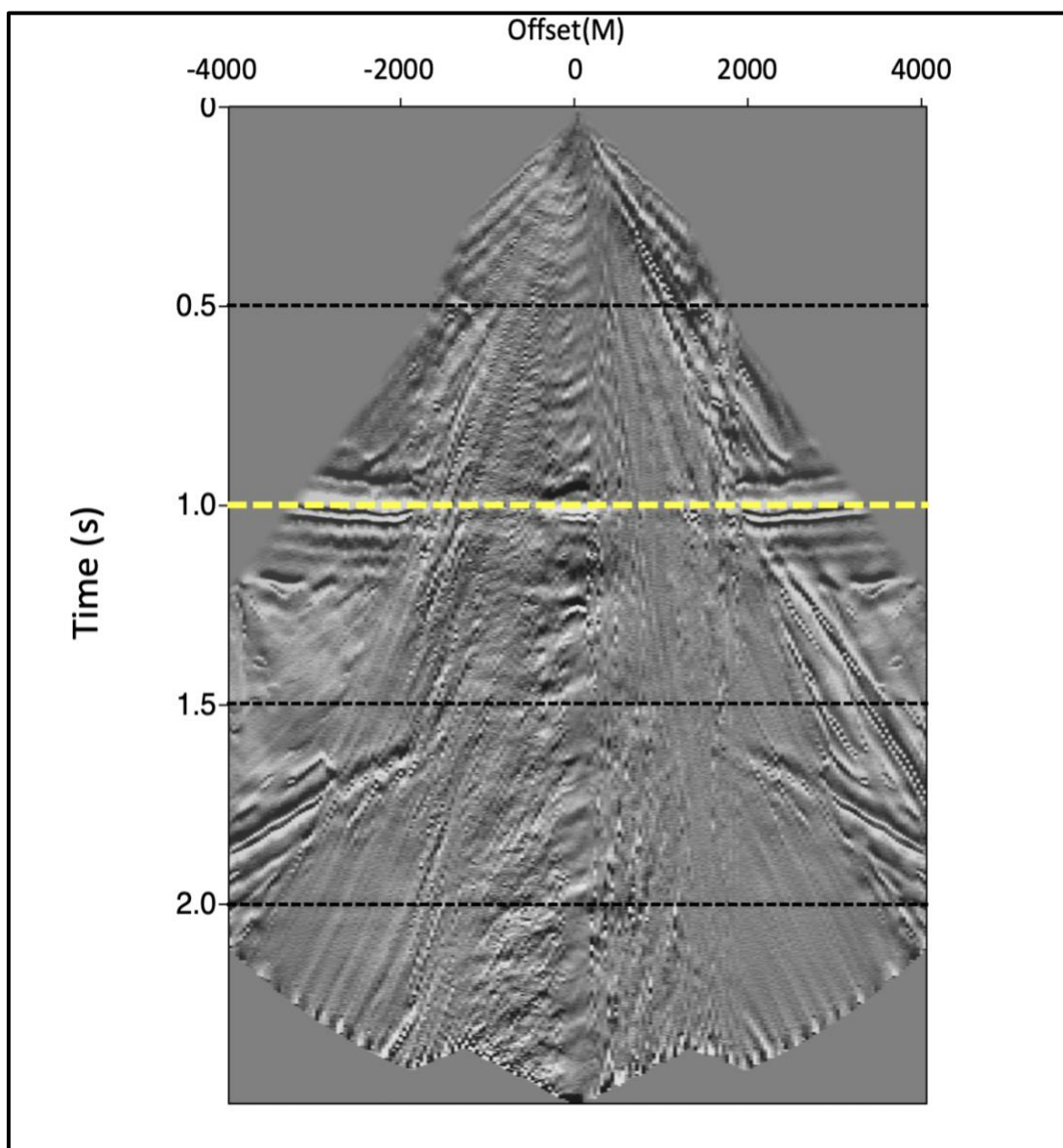


Figure 666.5 CDP2000 after applying the mean estimated NMO velocity of 2924 m/s. Note the almost perfect flattening of the event of interest at $T_0=1.0$ s.

6.2 Application to Dip Model and Results

I selected CMP150 (**Fig. 6.6**) to apply the proposed method on a dipping reflector. The dataset has been processed and has no statics effects. I introduce the effect of imperfect NMO-correction by NMO-correcting the first dipping reflector with a low velocity (V_{wNMO}) of 2000 m/s. This causes the reflector to be overcorrected and concave upwards (**Fig. 6.7**).

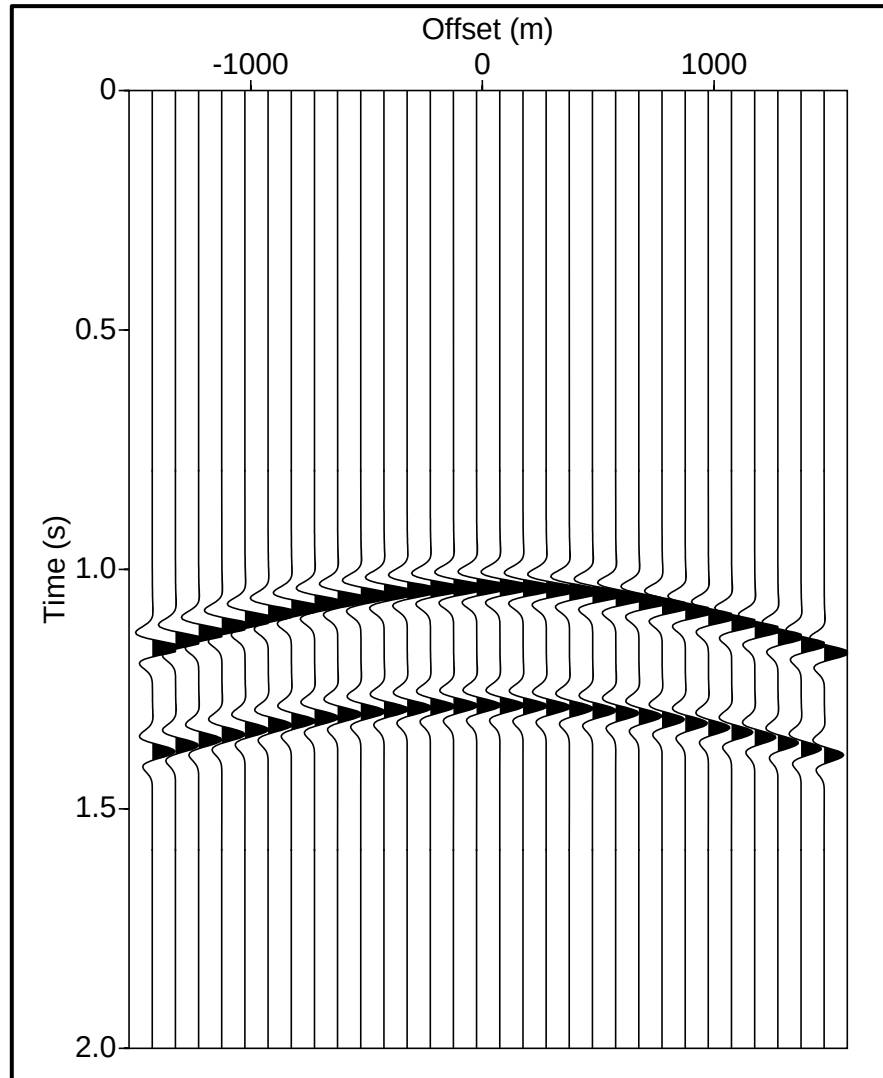


Figure 6.6 Pre-NMO corrected CMP 150

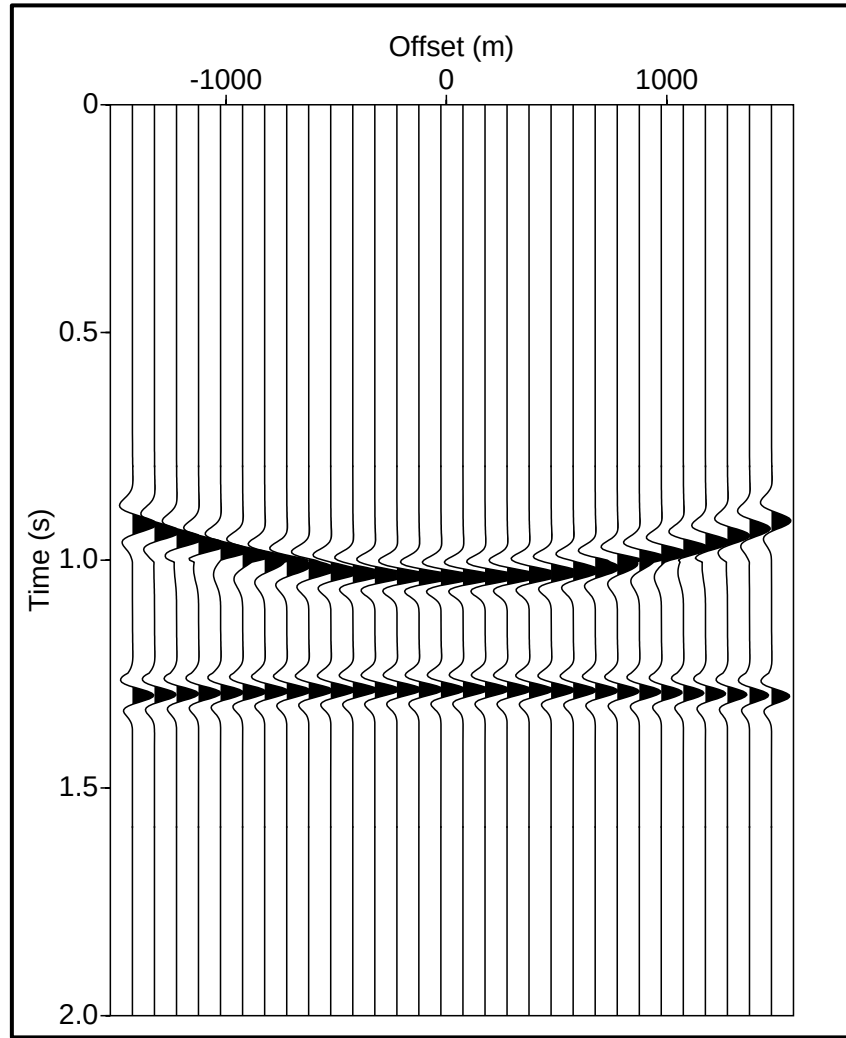


Figure 6.7 Imperfect NMO corrected CMP150 with $V_{wNMO}=2000$.

I then picked the reflection times of the CMP at the reflection of interest (i.e., $T_0=1.0s$) and fitted a parabola to the picks (**Fig. 6.8**). The results from the curve fitting gives the values of $a (\approx T_0) = 1.00348 s$ and $b (=M) = 6.08 \times 10^{-8} s/m^2$. I insert these values with $V_{wNMO} = 2000 m/s$ and $T_0 = 1.0013 s$ (from manual picking on the pre-NMO corrected CMP gather) into **eq. (3.13)** to obtain the value of V_c that will correctly flatten the reflector.

The statistical summary of this analysis is shown in table (6.1). The mean V_c value is 2763.79 m/s which is about 1.24% from the apparent NMO velocity value (i.e., 2730 m/s).

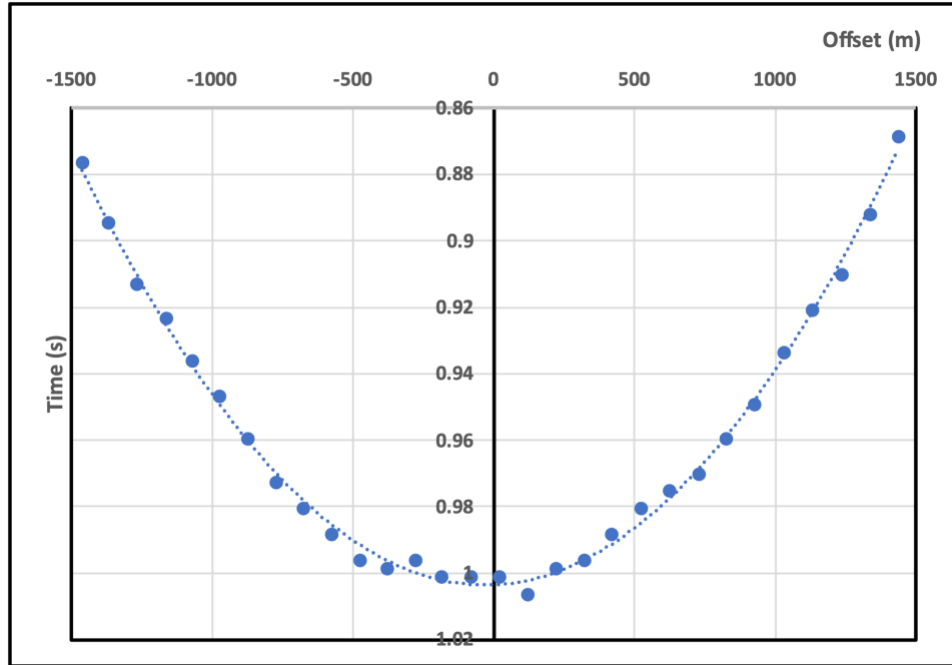


Figure 6.8 Parabolic fit to reflection times of CMP 150 of the dip model after imperfect NMO correction

Table 6.1 Statistical parameters of calculated velocity values of CMP 150

Min	Max	Mean	Median	Standard Deviation
2705.85 m/s	2796.04 m/s	2763.79 m/s	2771.33 m/s	28.44 m/s

I then use the calculated velocity value ($V_c = 2763.79$ m/s) to NMO correct the pre-NMO corrected CMP 150 (Fig.6.9).

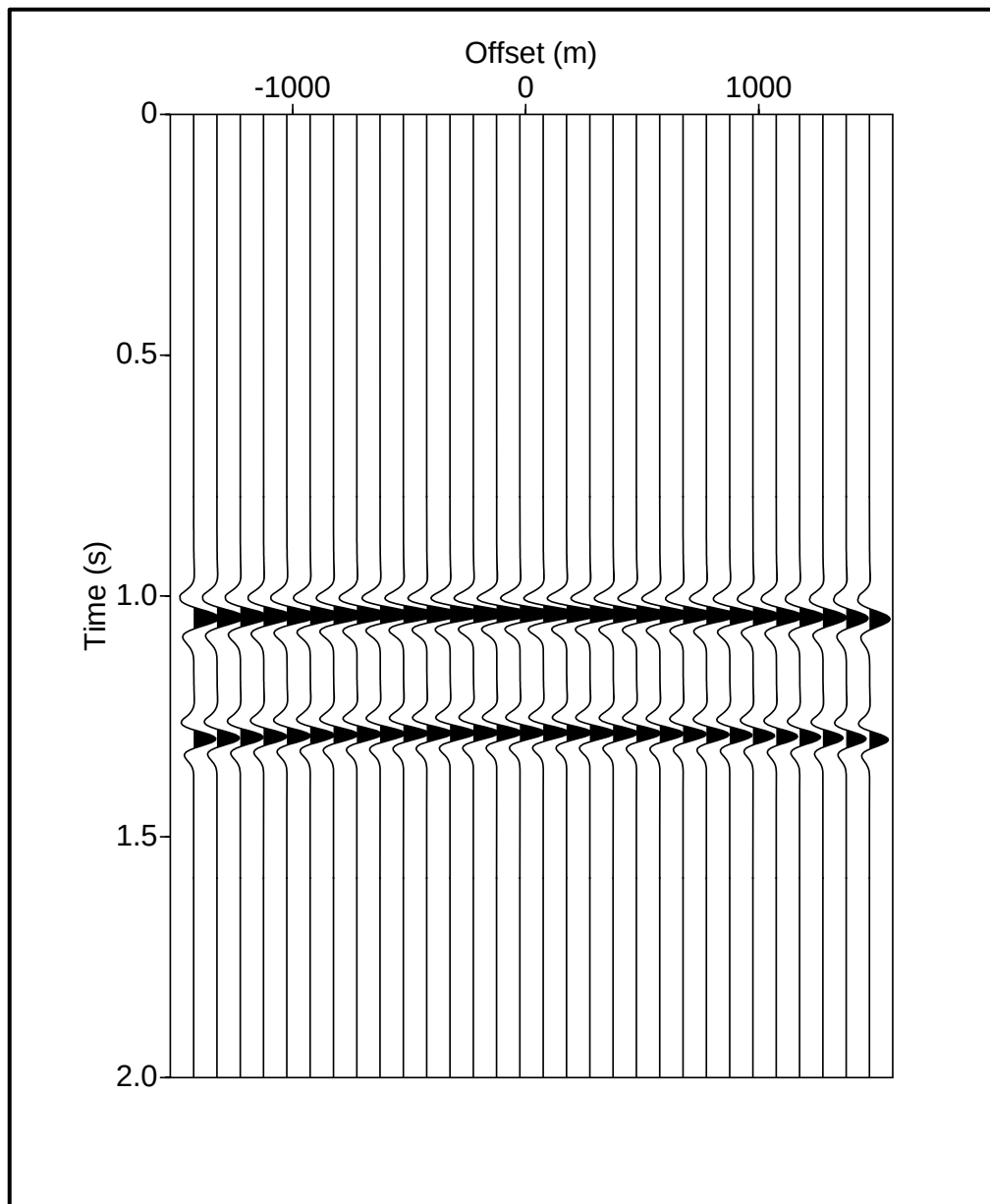


Figure 6.9 NMO-corrected CMP 150 with $V_c = 2763.79$ m/s

6.3 Application to Real Data and Results

I selected CDP225 to apply the proposed method for estimating the correct NMO velocity from residual statics corrections. The major concern in processing real datasets is the SNR. Therefore, the choice of this CDP is due to its higher fold and SNR. After processing the dataset up to the step described in section 5.2 (**Fig 6.10**), I used the super trace correlation method to compute and apply the correct source and receiver statics to the traces of this CDP. Next, I NMO correct this CDP with the correct velocity function (**Fig. 6.11**). The correct velocity of the reflection of interest (i.e., at $T_0 = 1.9$ s) in this CDP is $V_c = 9581$ ft/s. I arrived at this value through conventional velocity analysis. This is the value that best flattens the reflector of interest.

I then introduce time delays due to imperfect NMO by using a lower velocity of **7581 ft/s** at $T_0 = 1.9$ s to perform NMO correction on the pre-NMO corrected CDP. The incorrect low velocity causes the event to depart from a hyperbola and bends upward (**Fig. 6.12**). **Figure 6.13** shows the velocity spectrum of CDP225 with the positions of the correct and wrong NMO velocities indicated at $T_0 = 1.9$ s by black and yellow stars, respectively. I then compute and remove the source and receiver statics from the traces of the CDP. **Figure 6.14** shows the traces after removal of the source and receiver statics and NMO correction using an incorrect velocity of 7581 ft/s at $T_0 = 1.9$ s.

Next, I manually pick the time shifts of this CDP at the reflector of interest (**Table 6.2**) and fit a parabola to the picks (**Fig. 6.15**) according to **eq. (3.10)**. This results in $a (\approx T_0) = 1.89409$ s and $b (\approx M) = 1.7701 \times 10^{-9}$ s/ft². I use these a and b values as well as $V_{wNMO}=7581$ ft/s and $T_0=1.9$ s and input them into **eq. (3.13)** to estimate the correct NMO

velocity (V_c) that will flatten the event at $T_0 = 1.9$ s on each trace using the offset value (X) of that trace obtained from the trace header. The estimated V_c values ranged from 9580 ft/s to 9671 ft/s (**Table 6.3**) with a mean value of **9635 ft/s**. The mean estimated V_c value is within 1% of the true V_c value of 9581 ft/s. **Table 6.3** shows other statistical parameters of the calculated V_c values. **Figure 6.16** shows the positions of various NMO velocities at $T_0 = 1.9$ s on the velocity spectrum. The NMO corrected CDP225 using the mean calculated velocity from surface-consistent statics (V_c) is shown in **Fig 6.17**.

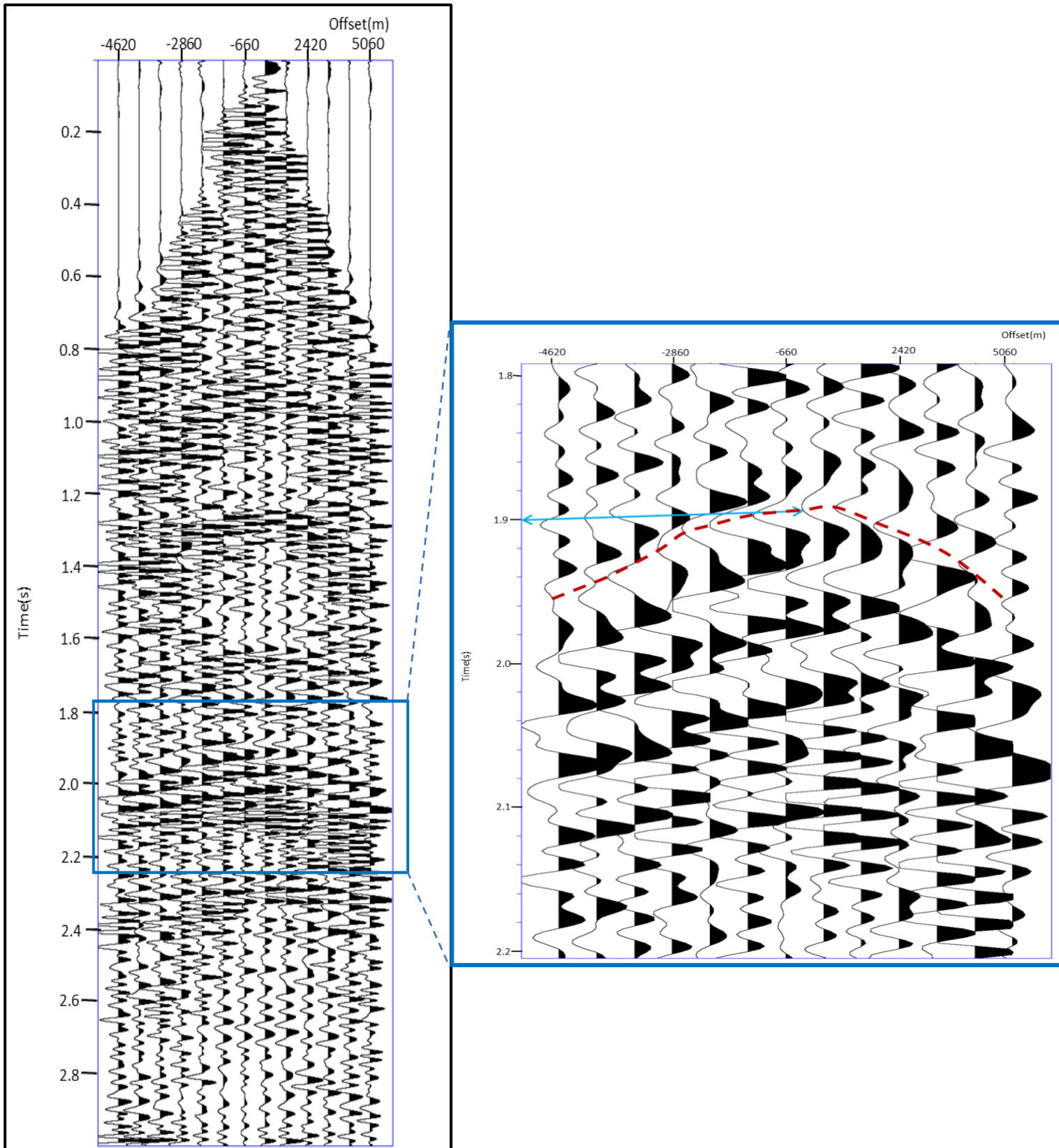


Figure 6.10 Pre-NMO corrected CDP225 before removal of source and receiver statics. Notice the hyperbolic event of interest at $T_0=1.9$ s indicated by the red curve.

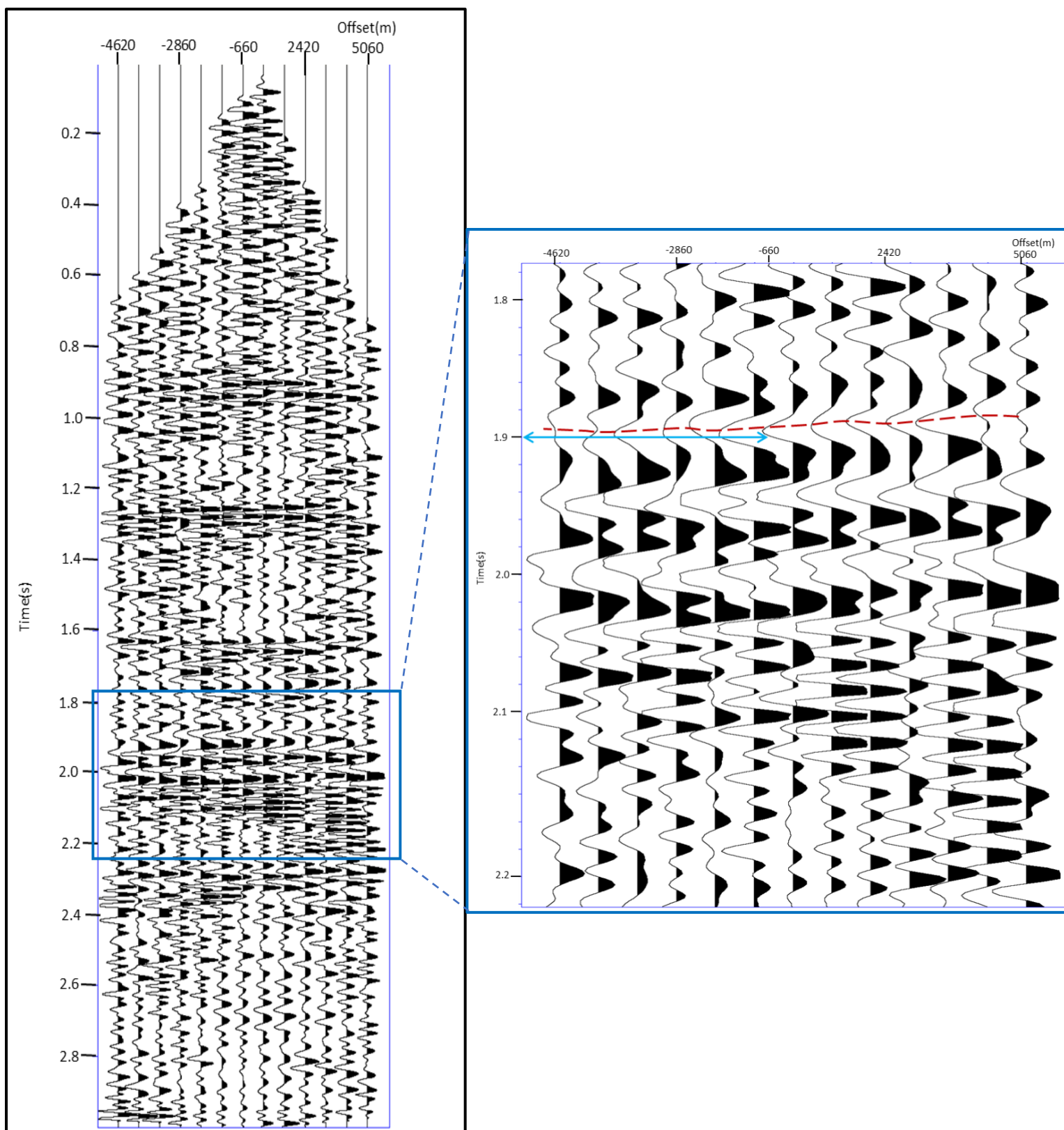


Figure 666.11 CDP225 after NMO correction with a correct velocity value of 9581 ft/s at $T_0 = 1.9$ s. This is the velocity value that best flattens the event at $T_0 = 1.9$ s.

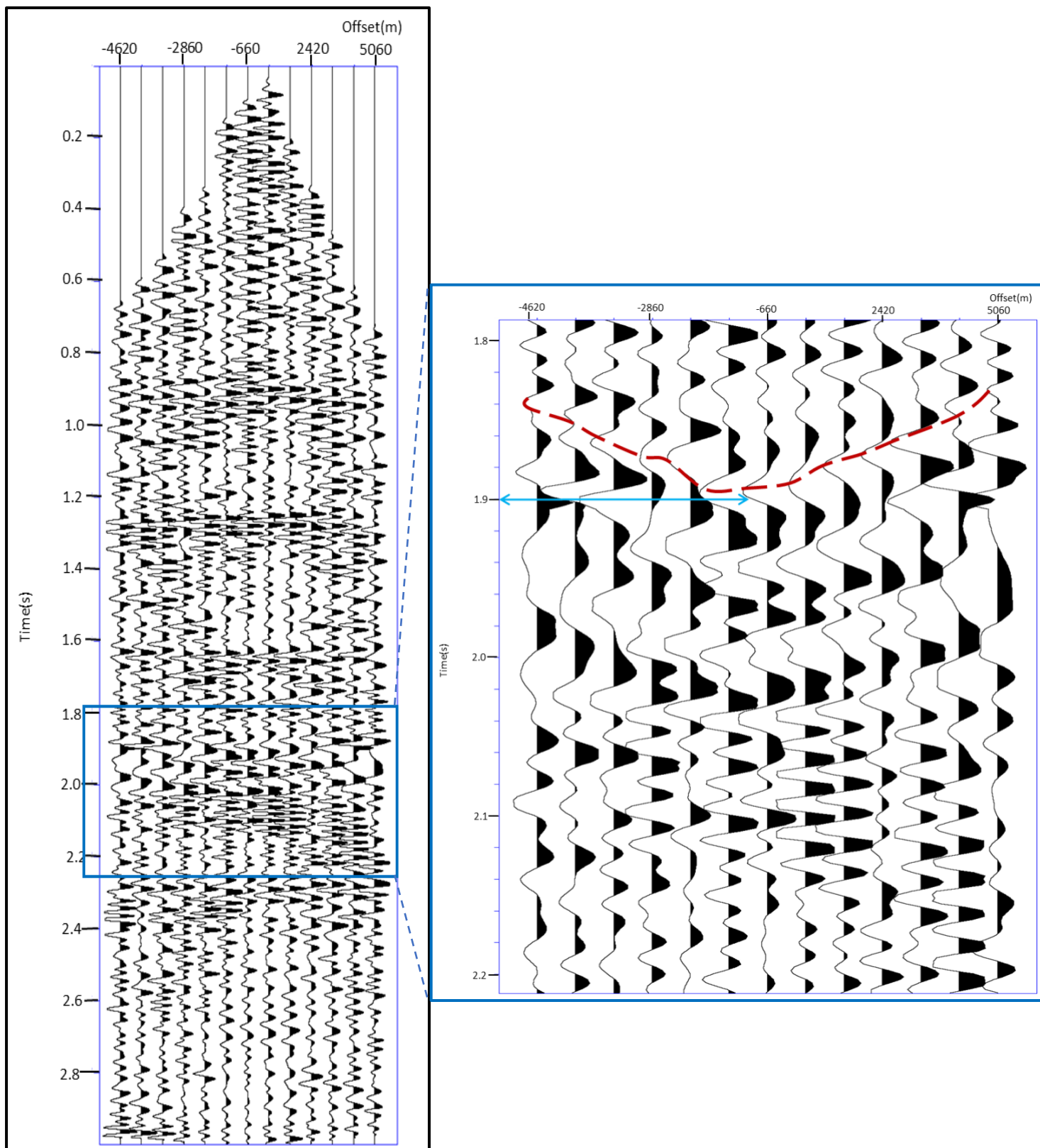


Figure 66.12 CDP225 after NMO correction with $V_{wNMO}=7581$ ft/s at $T_0 = 1.9$ s. Notice the concave upward curve of the event of interest indicated by the red curve.

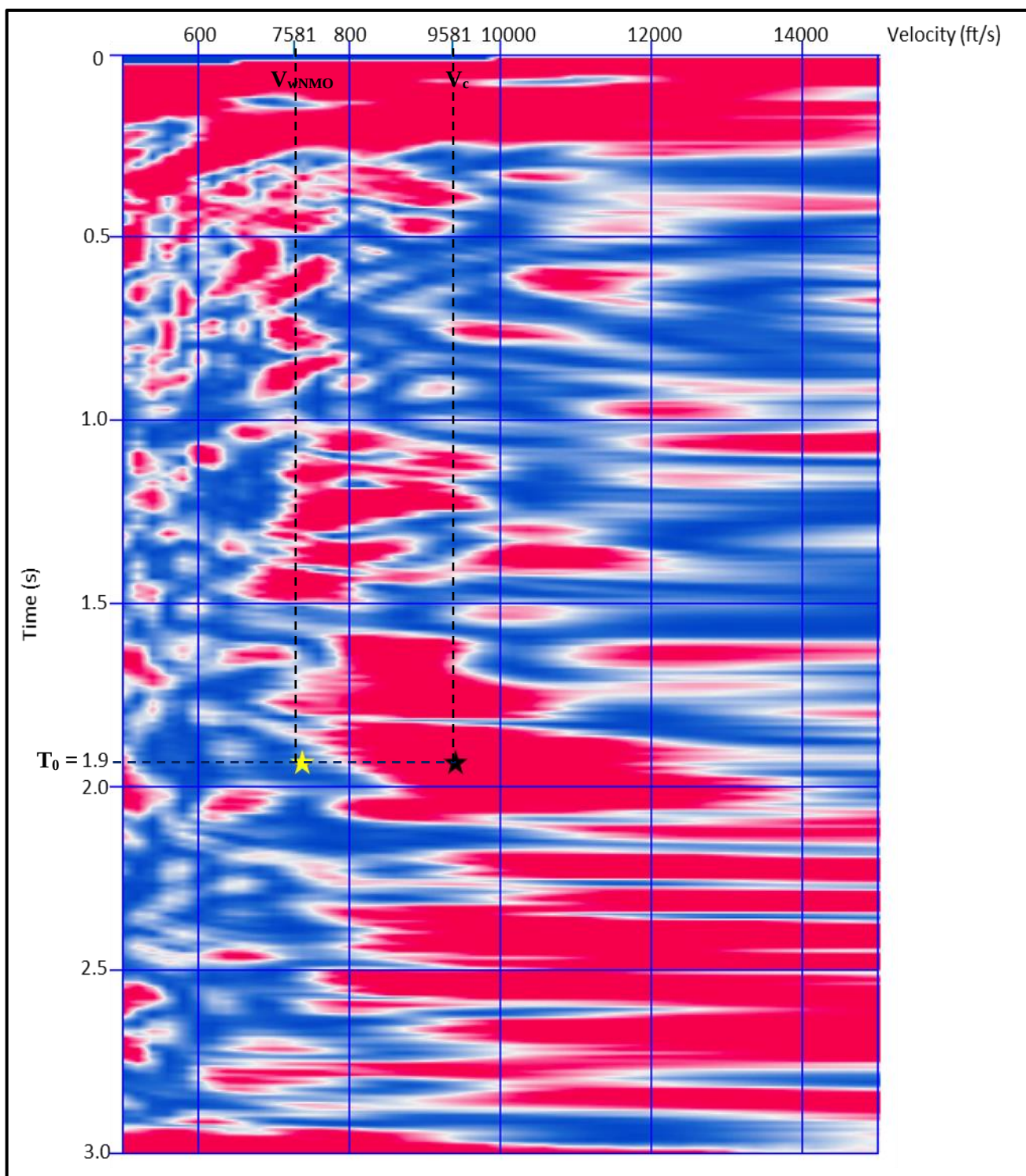


Figure 6.13 Velocity spectrum of CDP225 showing the correct velocity pick (black star) and wrong velocity pick, V_{wNMO} (yellow star). Both are picked at the reflection time of interest (i.e., $T_0=1.9$ s) but the wrong velocity has a considerably lower semblance as indicated by its blue color compared to the high semblance value associated with the correct NMO velocity indicated by the red color.

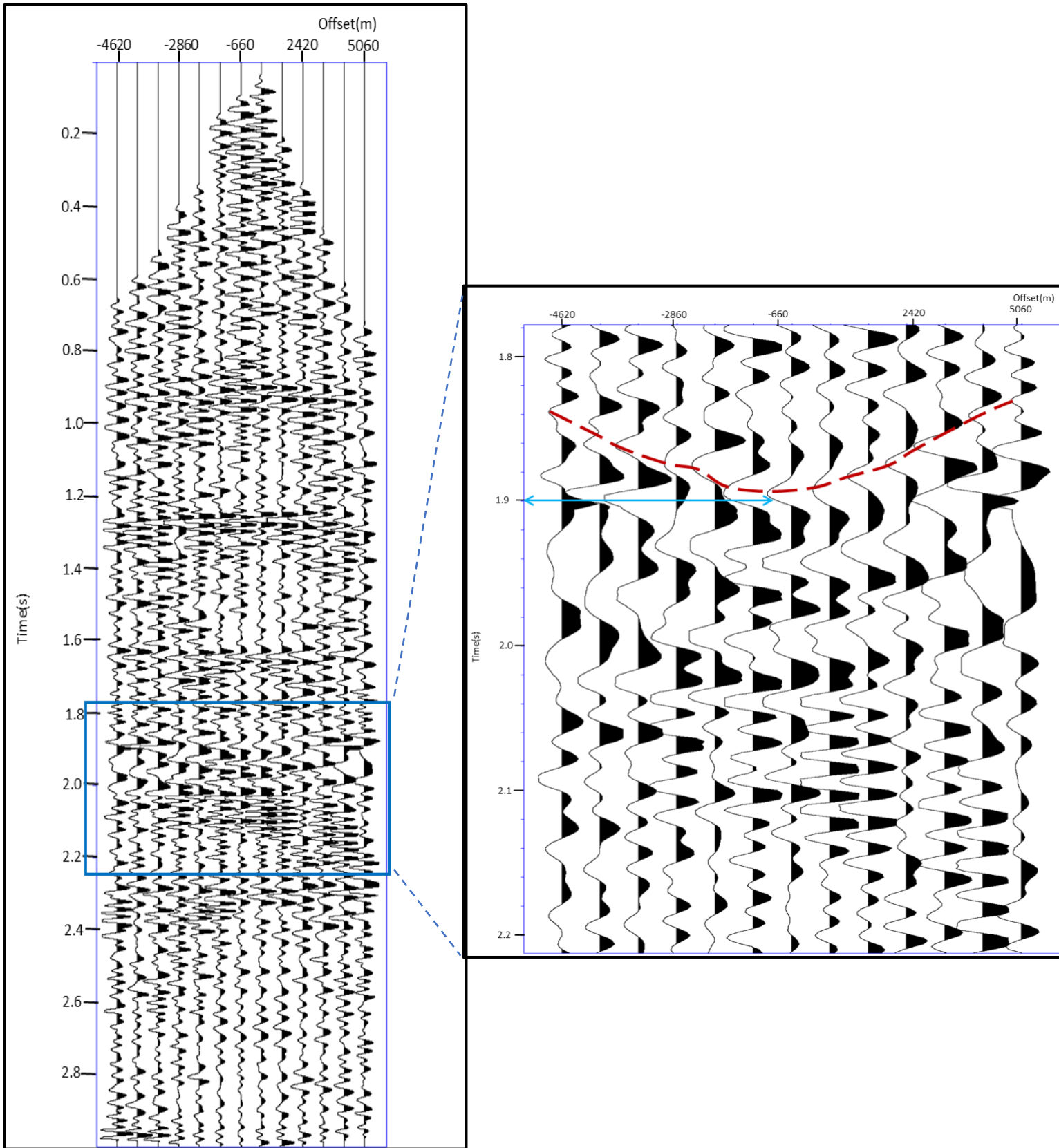


Figure 6.14 CDP225 after incorrect NMO correction and application of source and receiver statics. The arrival times at $T_0 = 1.9$ s were picked and used to calculate the correct NMO velocity (V_0) of the reflector.

Table 6.2 Manual time picks and calculated correct NMO velocities (V_c) of CDP225 after statics application and incorrect NMO correction (Fig 6.14).

Offset (ft)	Manual picks (s)	Calculated Velocity (ft/s)
-4620	1.85714	9595
-4180	1.86065	9608
-3740	1.87645	9621
-2860	1.88102	9641
-2420	1.88066	9650
-1100	1.89611	9666
-660	1.89611	9669
-220	1.89366	9671
1540	1.88628	9662
2420	1.88207	9650
3300	1.87294	9632
4180	1.85714	9608
5060	1.85152	9580

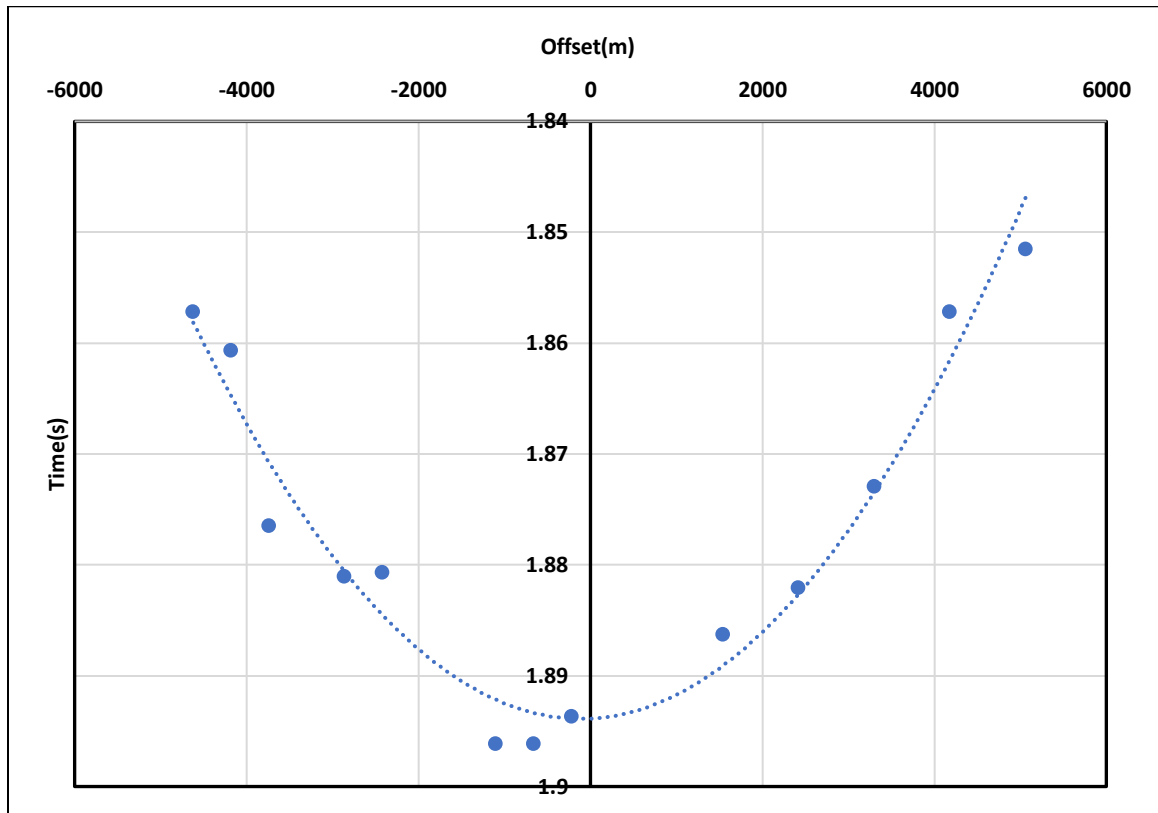


Figure 6.15 Parabolic fit to time picks of CDP225 after statics application and wrong NMO correction at $T_0 = 1.9$ s.

Table 6.3 Statistical parameters of the calculated velocities (V_c) in Table 6.1.

Max (ft)	Min (ft)	Mean (ft)	Median (ft)	Standard Deviation (ft)
9671	9580	9635	9641	24.77

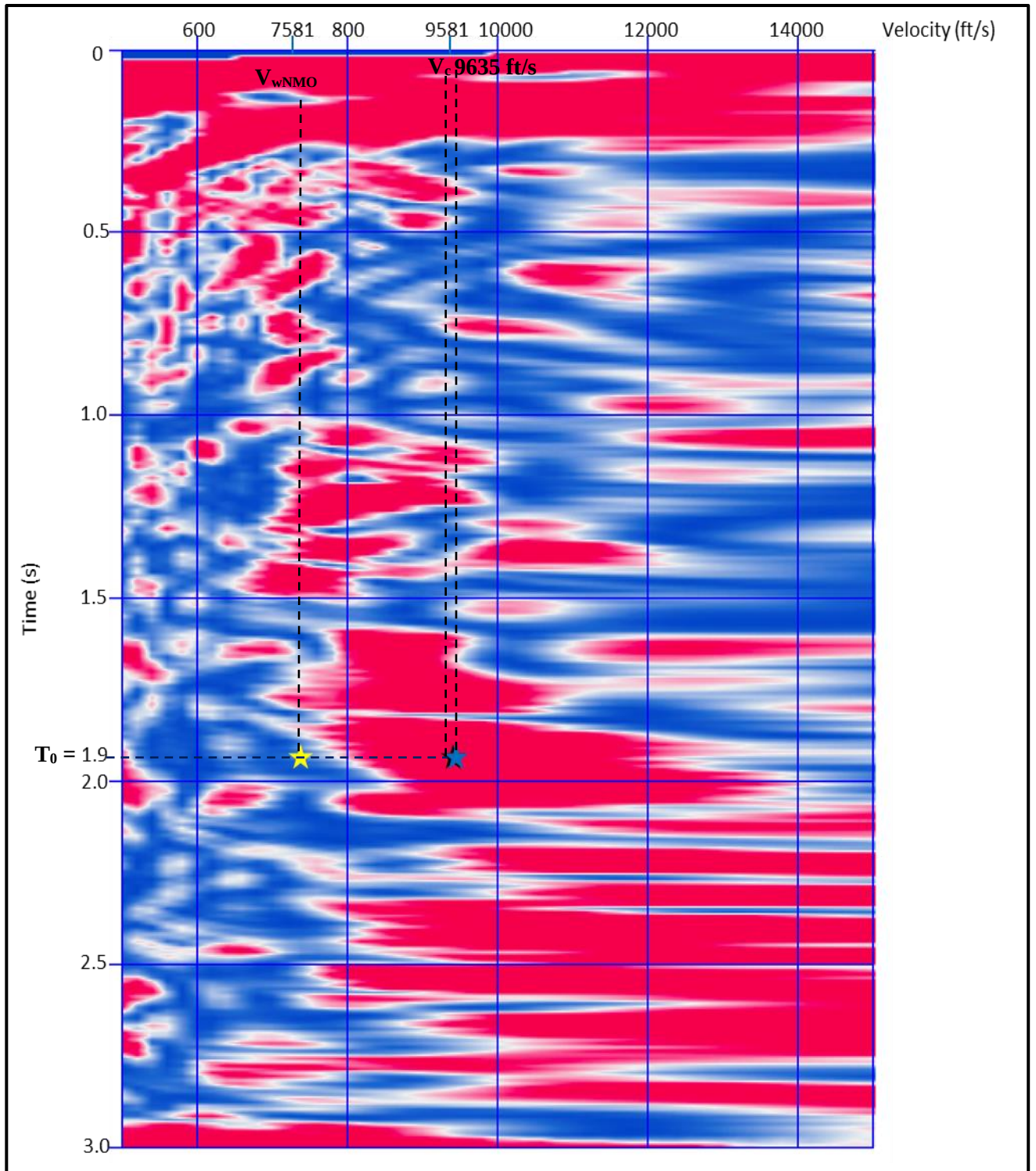


Figure 6.16 Velocity spectrum of CDP225 showing the correct NMO velocity pick from conventional velocity analysis (black star), the wrong velocity pick V_{wNMO} (yellow star), and the mean of correct NMO velocities (V_c) estimated from the new method (blue star) at $T_0=1.9$ s. Note the very proximity of the blue star to the black star showing the accuracy of the calculated value.

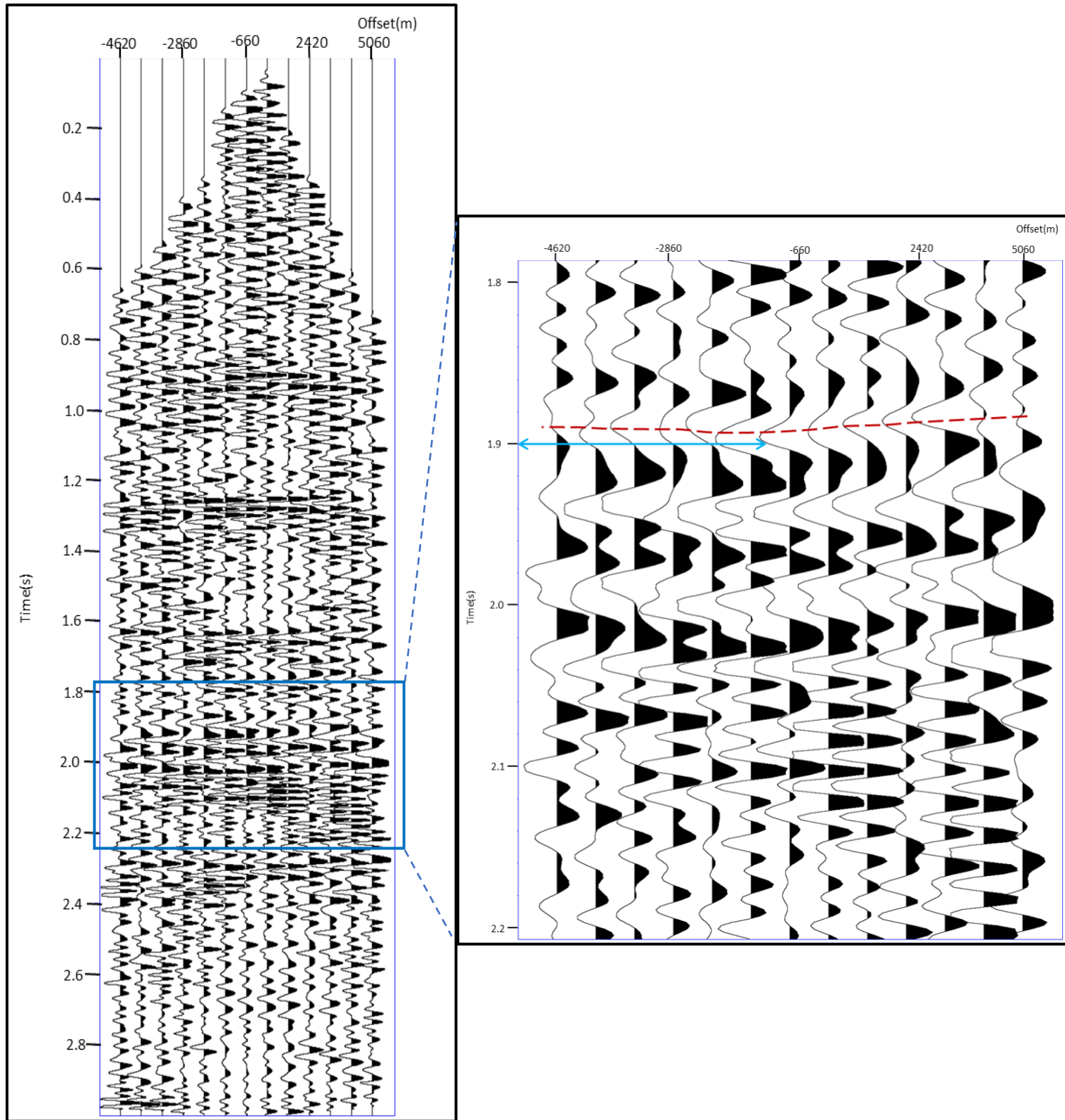


Figure 6.17 CDP225 after NMO correction with the velocity obtained from the new method and statics correction.

6.4 The Effect of Statics Correction on Velocity Estimation

The derivation of the equations that govern the methodology (section 3.5) relies on the estimation and application of the correct statics to the traces of the CDP. This suggests that errors in the statics computation and application have a direct effect on the accuracy of the proposed method. To test for this effect, I did the analysis on CDP2000 of the flat synthetic model (section 6.1) with different levels in statics application on the CDP. Figure 6.18 shows the CDP with different levels of application in statics correction. The result shows that although the parabolic fit shows changes in the parameters **a** and **b** (Fig. 6.19), the accuracy of the method remains fairly well (**about 2.5%**) (Table 6.4).

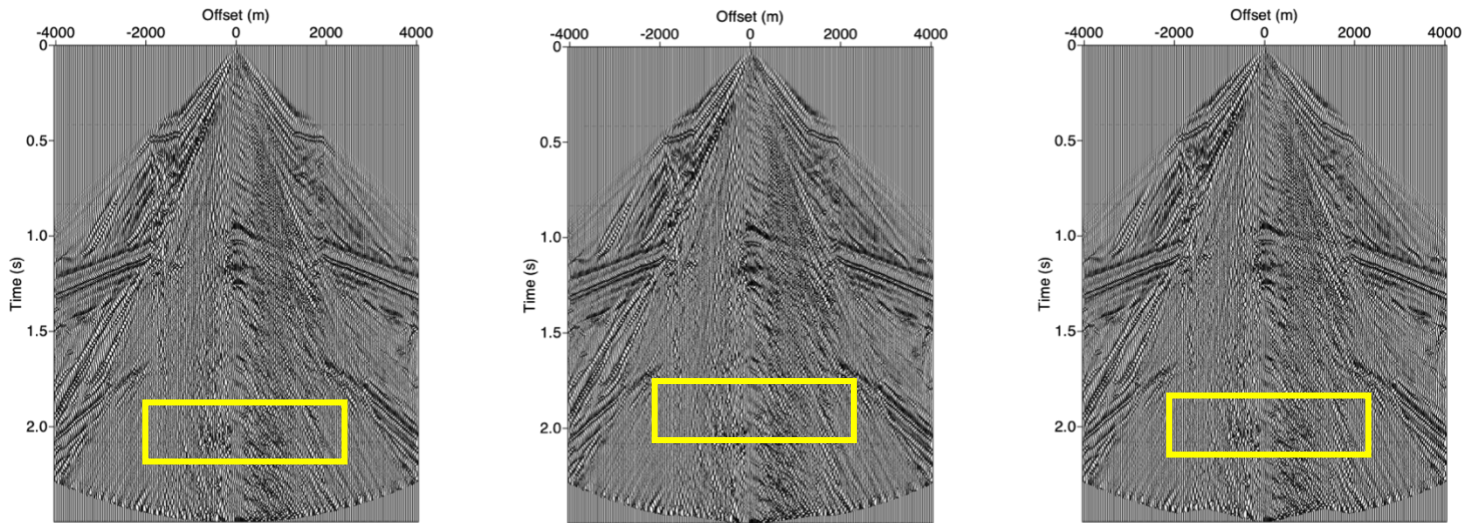


Figure 6.18 Incorrectly NMO-corrected CDP2000 with no statics applied (left) (i.e., 0% statics correction), 20% statics correction (center) and 50% statics correction (right). The yellow boxes show the effect of statics correction.

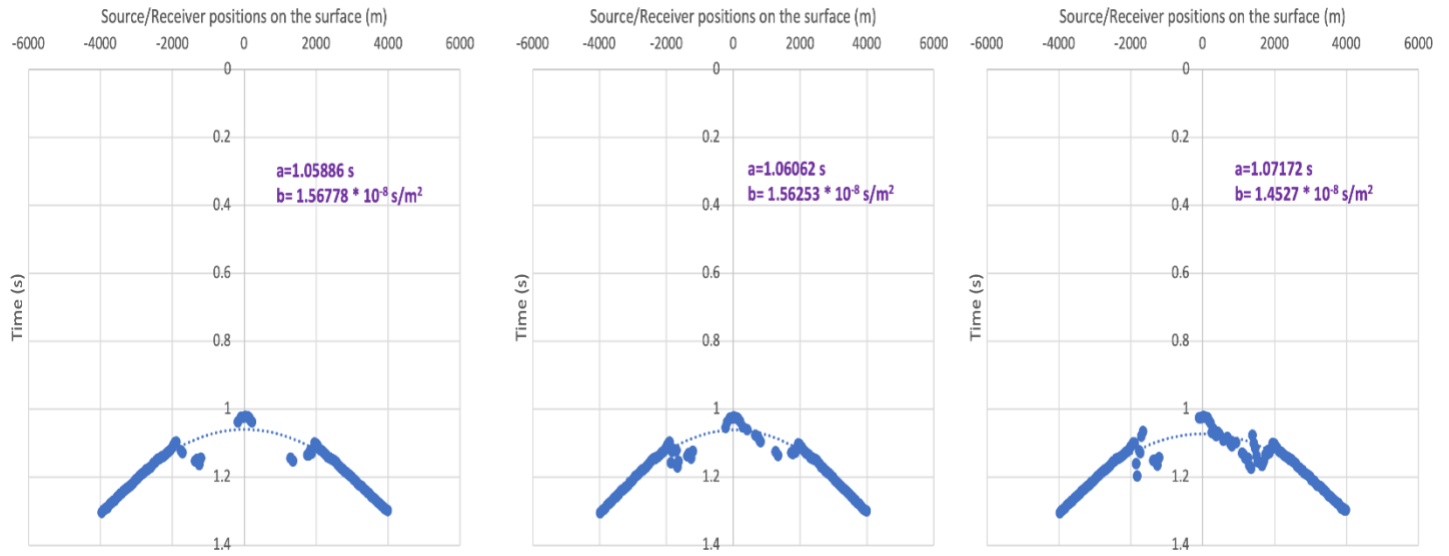


Figure 6.19 Curve fitting showing the values of parameters a and b for CDP2000 with no statics applied (left), 20% statics correction applied (center) and 50% statics correction applied (right).

Table 6.4 Statistical values for different levels of in statics correction.

Statics correction (%)	Min (m/s)	Max (m/s)	Mean (m/s)	Median (m/s)	Standard Deviation	Absolute Error (m/s)	Error (%)
100	2725	3183	2924	2780	120	76	2.5
50	2840	3268	3076	2910	129	76	2.5
20	2795	3233	3021	2795	128	21	0.7
0	2794	3233	3004	3004	123	4	0.1

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Discussion and Conclusions

The surface consistent statics computation established the relation between the statics and NMO velocity, showing the dependency of the accuracy of static correction on a good NMO velocity model. Surface consistent static correction assumes that time shifts caused by variations in the velocity and thickness of near surface layers are primarily due to four main contributing factors: statics at the source and receiver, statics due to subsurface structure, and a NMO static component. In practice, only the source and receiver components of the surface consistent statics decomposition are applied to mitigate the effect of statics in conventional processing of seismic data. The NMO component and structural term are neglected. In this study, I demonstrate a novel approach to estimating the correct NMO velocity from surface-consistent statics by inverting the NMO static component for NMO velocity. This method is based on fitting a parabola to the residual static that is due to imperfect NMO correction after the application of the other static components.

The proposed methodology works on individual CDPs, making the structural term zero i.e., $G_k=0$. In addition, it isolates the effect due to the NMO by applying the computed source and receiver statics corrections (i.e., making $R_i=0$, $S_j=0$). To test the proposed methodology, I first apply it to 2D elastic synthetic suffering from NMO under correction due to using an incorrect high NMO velocity. I then apply the method on a 2D real seismic dataset suffering from NMO overcorrection due to using an incorrect low NMO velocity. Thirdly, I apply the method to a 2D synthetic dataset with dipping reflectors. These tests

showed that the method is independent of the initial (incorrect) NMO velocity applied to the CDP. The method is also independent of the dip angle, working well even when the dip angle is not known.

The same datasets were processed using a conventional processing workflow to evaluate the proposed methodology. The processing was done by an experienced processor, obtaining the NMO velocity through the semblance method. Results show that within the selected CDPs, the new method achieved a good velocity estimate in the synthetic dataset, with an error of 2.5% relative to the correct velocity of the model. In comparison, the method achieved errors of 0.6% and 1.24% in the case of the real and synthetic dipping reflectors datasets, respectively. The higher error in the synthetic dataset of the flat model might be attributed to the severe statics introduced by the complex shape and velocity distribution within the dune.

7.2 Limitations and Recommendations

7.2.1 Limitations

The new technique demonstrated in this study has some limitations including the following:

- The method requires prior removal of the source and receiver statics from the data.
- The method requires picking after removal of the source and receiver statics.

7.2.2 Recommendations

The following are some recommendations for the future development of this technique:

- Use an auto-picking algorithm to pick T_{ijk} times at all offsets after removal of the source and receiver statics.
- The method was tested on datasets with simple geology. It is recommended to test its performance in more structurally complex environments.
- The method was tested on dip models that have gentle dips ($\phi \approx 24^\circ$). The robustness of the model should be tested using layers with steeper dips.

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