

**SAND DUNE STATIC DELAY: A DATA DRIVEN
APPROACH AND ADJUSTMENT OF THE SAND CURVE**

BY

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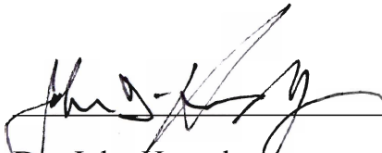
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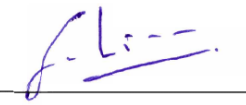

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Dedication

To my pure grandmother.

|

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LIST OF ABBREVIATIONS

S/N	:	Signal to noise ratio
QC	:	Quality check
AGC	:	Automatic gain control
BOS	:	Base of Sand

ABSTRACT

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Thesis Title : Sand Dune Static Delay: A Data Driven Approach and Adjustment of the Sand Curve

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Sand dune environments pose logistical challenges to seismic data acquisition and processing. The Rub-AlKhali of Saudi Arabia and Taklimakan of China are two desert regions where the first has the sand dunes interleaved by sabkha (salt flat) environment. Such environments present a range of complications from amplitude variation and surface multiples to near-surface static issues. Different methods have been suggested to address such near-surface static problems. Many of the methods would resolve the first-order effect in certain conditions; however, they fail to give proper solutions in other areas.

In this work, I offer a data-driven near-surface static solution. Unlike other methods, which require prior knowledge of the sand thickness, porosity, water saturation, or the existence of a smooth base of sand, the suggested method does not require any prior knowledge. Nonetheless, if available, they will aid in the assessment of the near-surface static solution from the technique I am proposing. The technique does not suffer from any source of error in the assumptions made in previously suggested empirical formulas. I generate an area-specific polynomial relation of thickness as a function of static delay times.

ملخص الرسالة

الاسم الكامل: علي فؤاد مهدي الجشّي

عنوان الرسالة: التأخر الساكن في الكثبان الرملية: حل مستوحى من البيانات وإصلاح منحى التأخير في الرمل

التخصص: الماجستير في الجيوفيزياء

تاريخ الدرجة العلمية: مارس ٢٠٢١

تطرح بيئة الكثبان الرملية تحديات لوجستية على البيانات السيزميّة من ناحية جمعها ومعالجتها. تعد منطقة الربع الخالي في المملكة العربية السعودية وتكلامكان في الصين منطقتين صحراويّتين ، فيما الأولى منهم تشكّل مثلاً لتداخل الكثبان الرملية والسبخات (المسطحات الملحية). تفرض هذه البيئة مجموعة من المضاعفات من اختلاف في السعة الموجية، والتردد في الموجات الناشئة داخل الكثبان السطحية (ناشئة من اختلاف كبير في المعاوقة السزمية بين طبقة الكثيب الرمي و سطح السبخة) إلى مشاكل التأخر الساكن في استقبال الموجات. تم اقتراح طرق مختلفة لمعالجة مشاكل التأخير الناشئ من طبقة الرمل السطحية أو القريبة من السطح. العديد من الطرق المتاحة ستحل تأثير المستوى الأولي لظروف سطحيّة معينة ؛ ومع ذلك ، فإنها تفشل في إعطاء حلول أمثل في ظروف سطحيّة أخرى.

في هذه الأطروحة، نقدم حلاً لمشكلة التأخير الساكن في الموجات مستوحى من البيانات ذاتها. على عكس الطرق الأخرى ، حيث يتطلب وجود معرفة مسبقة بسماكة الرمل ، المسامية ، تشبع الماء ، أو وجود علم مسبق عن مستوى قاعدة الرمل ، فإن الطريقة المقترحة لا تتطلب أي معرفة مسبقة. ومع ذلك ، إذا توقّرت ، فإنها ستساعد في تقييم الحل الذي نقترحه. لا تعاني التقنية من مصادر الخطأ كل الافتراضات المتضمنة في الصيغ [الرياضية أو] التجريبية المقترحة مسبقاً. نقوم بتوليد دالة كثيرة الحدود خاصة بالمنطقة وظروفها يكون السمك هو المتغير المستقل فيها ، فيما يكون المتغير التابع هو قيم التأخير الساكنة للموجات داخل الكثبان الرملية.

CHAPTER 1

INTRODUCTION

Desert areas with sand dunes have a slow velocity profile compared to the compacted sabkha layer (or other compacted sediments) around and/or beneath it. This leads to a very sharp contrast in acoustic impedance, resulting in reflections from the surface of the sabkhas (the base of sand). While the dunes are composites of unconsolidated quartz, the sabkhas are cyclic evaporations (flooding and evaporation) which leaves behind high-velocity salt deposits with clays. A site may contain sand dunes along with sabkhas as seen in Figure 1-1.

Reflections occur every time an event arrives at the topography because of the contrast between the sand and air, and sand and sabkhas. This type of dune reverberation (a type of surface multiples) is a source of noise or undesired signal in the seismic data and should be removed - when processing the data using methods such as variable predictive gap deconvolution (Ling et al., 1998). However, the reverberations are quite useful in revealing two-way-time in the sand dune, from the sabkha to the topography (Diallo and Chen, 2018).

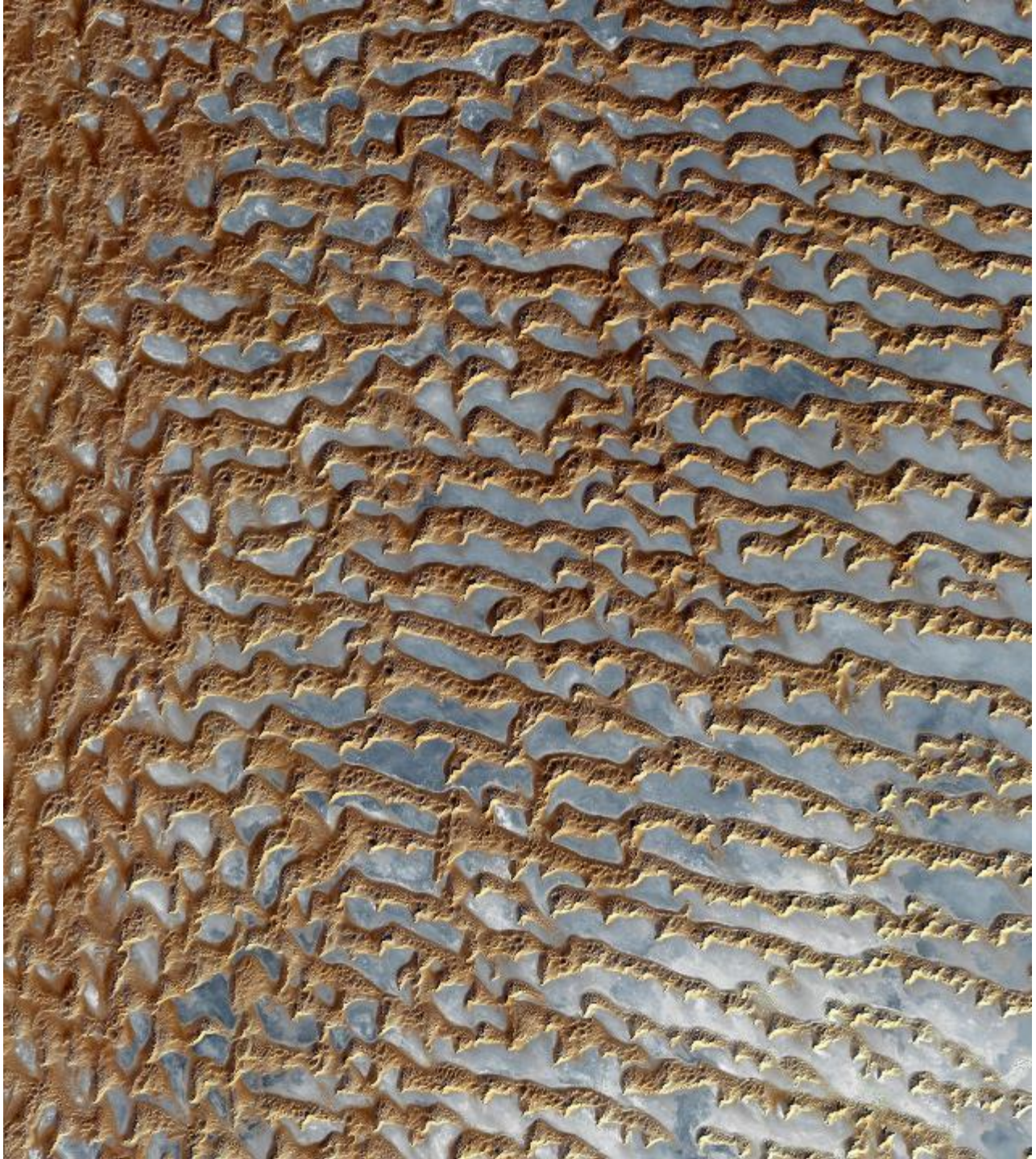


Figure 1-1: A satellite image of Rub-AlKhali showing surface topography variation. This image was acquired on Dec. 2, 2005 by the Advanced Spaceborne Thermal Emission and Reflection Radiometer, or ASTER, aboard NASA's Terra Earth-orbiting satellite. Image Credit: NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team

1.1 Statement of Problem

Sand dunes pose challenges in areas of oil and gas exploration. The low velocity of unconsolidated sands causes delays in the arrival of seismic waves. The delays vary from a source or a receiver to another. Solving the static issue (near-surface static solution) is essential to image and interpret continuous geological formations or/and assess with other attributes related to in-situ fluids and rock properties.

Refraction seismic data and refraction tomography will not solve the high lateral variation delays caused by the sand dune. Only after correcting for the time-in-sand can we proceed with refraction tomography to solve for weathering layer statics and put the data to a common reference datum in time and depth. Besides, a precise first arrival refraction picks are difficult to achieve without a reliable base of sand datuming requiring tedious analysis and indefinite results lacking in certainty.

The inaccuracy of methods currently in use led me to look for a more robust technique to attain a better time-in-sand delay.

1.2 Research Objective

Different solutions are available to solve this issue, one of which is the time-honored Sand Curve (Robinson and Al-Husseini, 1982) used in many areas, such as Rub AlKhali of Saudi Arabia and TaZhong of China. This research explores a data-driven approach designed to outline an independent way of solving for the near-surface static correction. By taking advantage of the order of the data and the autocorrelations, I will enhance the signature of

the two-way-time to pick the correct two-way-time in sand. In addition, the approach is very likely to help in assessing the other solutions that exist as a calibration. A thorough analysis of the proposed method and the sand curve will be done.

1.3 Thesis Organization

In this thesis, I examine the use of autocorrelation in seismic data of sand dune environment to correct for static delays required for further processing to produce a better image. I come up with an approach to generate an adaptive sand curve.

Chapter 1 gives a summary of the literature covering sand dune static delays and dune reverberation. I showcase the ideas associated with the classical Sand Curve and the main topic of this research that I expand on this thesis; the near-surface seismic reverberations.

In chapter 3, I give a brief introduction to the physical phenomena. I then describe key elements in producing the signature I am looking for and ways to enhance it.

Chapter 4 uses a finite-difference method of the wave equation to illustrate the idea-generating synthetic data followed by discussing the wave characters and the possible processes.

In chapter 5, I briefly discuss the conventional procedure in applying the traditional Sand Curve and its limitation. I present new models of alternative ways of achieving better results using the Sand Curve and I introduce a new concept of data driven sand curve. I give a complete flow for achieving this.

Chapter 6 presents real data acquired in sand deserts showing the problem and the results of applying the new methodology. Additionally, the adaptive sand curve approach is demonstrated.

In chapter 7, I give a short conclusion of the work presented and suggest future work. |

CHAPTER 2

LITERATURE REVIEW

In this chapter, I highlight some of the works related to the static delays, which provide insights to the approach I take in the following chapters.

2.1 Sand Curve

One of the best methods to strip out the time delays caused by the sand dune in desert environments in the Middle East is by using Sand Curves.

Shamlan et al., (1981) first used the elevation profile to generate ray-path refraction static corrections related and proposed tying them with upholes static values to achieve absolute values thereby solving for the time delays induced by the dunes. Following that work, Robinson and Al-Husseini (1982) generated a nonlinear sand curve correction; time-in-sand with respect to thickness using refraction time-thickness regression. This approach has a drawback because of the significant standard error typical in the estimated interval time with high R-squared regression variance. A scatter plot of the time-thickness initial data is shown in Figure 2-1.

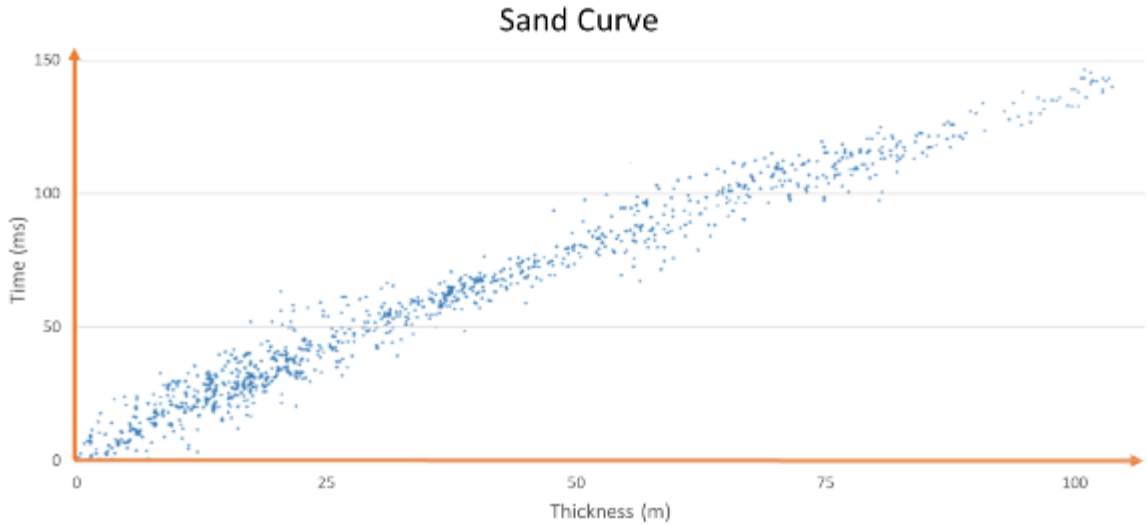


Figure 2-1: Measurements of thickness and time samples used to generate the Sand Curve.

Following the work of Shamlan, several studies have been carried out to confirm the time-thickness relationship and small tunings or adjustments to the final curve.

Al-Shuhail (2002, 2013) derived the sand dune curve analytically using Gassmann and Hertz-Mindlin theories. The resultant analytical expression depends on the porosity, density and saturation of the sand matrix. Later (Al-Shuhail, 2004), investigated the error in using a constant velocity profile against the widely accepted vertical velocity profile assumption in estimating the sand dune thickness using seismic refraction data. He concluded that introduced errors are not considerable. Furthermore, porosity variable has the most effect on the estimation.

Yanbin et al., (2006) uses an iterative velocity analyses approach that depends on the signal to noise ratio (S/N). At each iteration, the residual static improves the S/N using a pilot trace.

Liner (2008) acquired laboratory measurements to compare with the Sand Curve. The results were a good match between the lab and field data. However, the settings at which the lab measurements were performed (e.g., fluid saturation, porosity sand type... etc.), the constrained lab conditions and the environment's assumptions are sources of convergence. On the contrary, real environments are widely variable and inhomogeneous compared to the assumed lab conditions. One sand curve may not be appropriate for different areas.

Yilmaz (2011) conducted an iterative image-based effective-medium near-surface modeling method. The method uses depth migration with conditioned data, having no multichannel processing, that would generate image panels using a set of different appropriate near surface velocities. He then picks the shallowest horizon in any of the panels, perhaps, based on amplitude and pick velocity from the horizon semblance from the depth image volume to build an effective-medium velocity-depth model for the near surface. After that, he generates shot and receiver statics to datum to the picked horizons and with a replacement velocity to a floating datum. He applies these corrections and iterates again with multichannel signal processing to clean the data until the velocity variations are resolved followed with a residual statics pass. This approach complies very well with the vertical-ray assumption in static correction.

Bridle (2017) worked out an updated sand curve polynomial model for a dry sand as well. This polynomial basis is the empirical Sand Curve updated using residual time in sand decomposed from refraction tomography.

Al-Shuhail et al., (2018) has reviewed and compared three different velocity-depth functions used with the Sand Curve and uphole data from the Empty Quarter (Rub-

AlKhali); simple constant; a theoretical (Al-Shuhail, 2002) and an empirical function (Liner, 2008). He fitted the one-way time from Sand Curve and uphole data in a sand dune with each function and compared sum of squared errors.

Hanafy et al. (2020), conducted a field experiment using a high-resolution seismic to measure the velocity of the very few first centimeters to 1 meter. Combining it with a lower resolution seismic, the obtained velocities deeper than 1 m (to 7 m). They have concluded that although static corrections are very sensitive to the knowledge of velocities at very shallow depths, by comparing it with the results of Al-Shuhail et al., (2018), they concluded that it is general enough to be used.

2.2 Dune Reverberation

Dune reverberations are considered noise in the seismic data and should be removed. Ling et al., (1998) and Rujie et al., (2003) presented a predictive deconvolution approach with a variable predictive gap. In Figure 2-2, they show a synthetic source gather with pronounced reverberations in the time domain. Constant time intervals separate reverberations because of the use of a simple three-layer model.

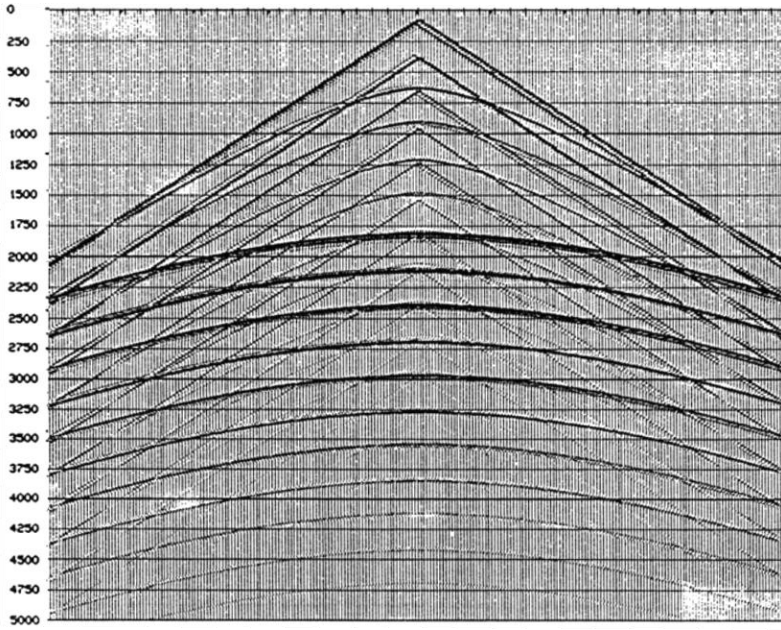


Figure 2-2: Source gather model of a three-layer earth with sand dune reverberations (Ling et al., 1998)

They also show, in Figure 2-3, real data autocorrelation panel. The autocorrelation panel exposes a signature that mirrors the topography. Many orders of reverberations can be outlined from the panel. Hence, they suppress the reverberations by deconvolution.

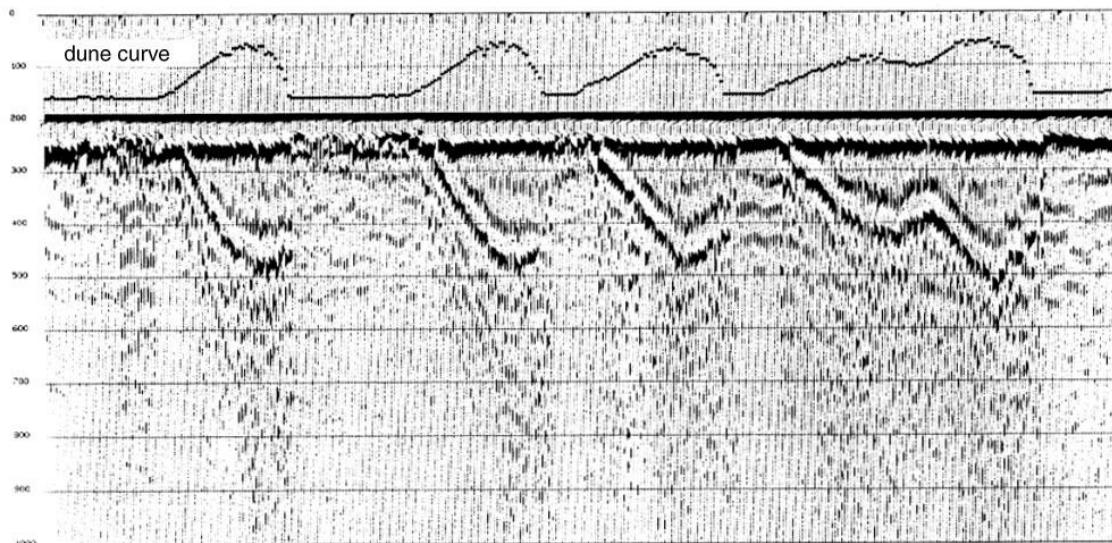


Figure 2-3: Statistical autocorrelation of the source gather from the field. The topographical variation of the dunes correlates well with the values of the autocorrelation mirror. (Ling et al., 1998)

Diallo and Chen (2018) realized the potential in stacked autocorrelation sections to data-driven static estimation. Figure 2-4, from Diallo and Chen (2018), shows a faint signature mirroring the surface topography in deserts of Saudi Arabia. The peaks, they confirmed, are about two-way-time delay in the sand portion. Figure 2-3, from Ling et al. (1998), shows a more apparent signature related to China's dunes in desert areas. Ling et al., (1998) worked to suppress these reverberations using a variable gap deconvolution.

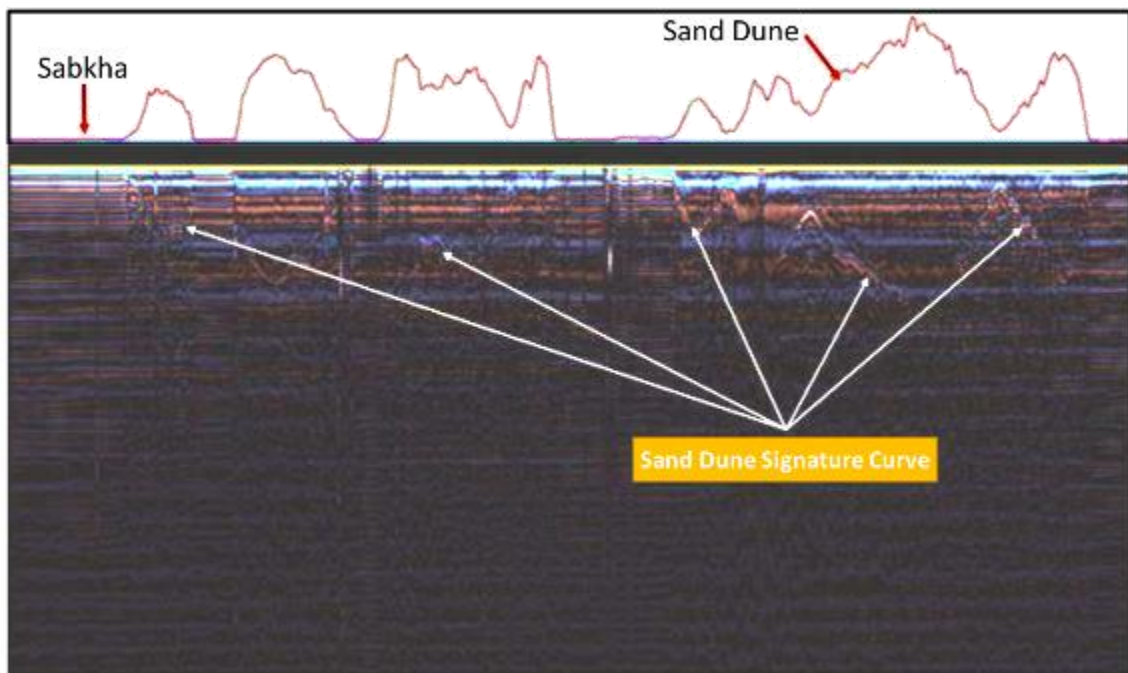


Figure 2-4: Autocorrelations along a receiver cable showing distinctive correlation between the sand dune signature curve and sand dune elevation. Peaks along the curve are approximately at twice the optimal absolute value of the dune statics on the time axis. (Diallo and Chen, 2018).

CHAPTER 3

APPROACH/METHODOLOGY

In this chapter, I label the main modules and their importance to the method that I plan to pursue. I start by highlighting the geological setting that allows for this particular event or signature to be present. Next, I discuss the main module to articulate the signature. Then I explore methods and domains where the enhancement can be done best coherently.

3.1 Multiple Occurrence

The high variations in acoustic impedance between layers causes the seismic wave to reflect as the wave propagates to the layers' boundaries. If it happens to be a layer between two layers of high acoustic impedance contrast at both ends (e.g., Figure 3-1), we will observe reverberation with partial transmission at each end of the layer. The transmitted wave is recorded in the receiver field. The first-order reverberation time arrival is equal to twice the layer thickness over the layer's velocity. The second-order wave arrives at four times that and so on. This may also occur between multiple layers of low acoustic impedance contrast between two high impedance contrast layers.

Depending on the interface dip, the time it takes the reverberation to cross the layer may vary. In addition, the overburden layer would cause the arrival times to vary. However, in a near flat sequence of layers, these occur at constant time intervals. Many reverberations may occur in the sequence of layers.

These reverberations, so called multiples, occur in different ways. As there are multiple paths, the wave may travel after it reflects or refracts from any layer. In this work, I am concerned with near-surface multiples. Near-surface multiples occur between the weathered layer's lower boundary and the high contrast in acoustic impedance with the air at the weathered layer's upper boundary.

$$Velocity_1 \cdot Density_1 > Velocity_2 \cdot Density_2 > Velocity_3 \cdot Density_3$$

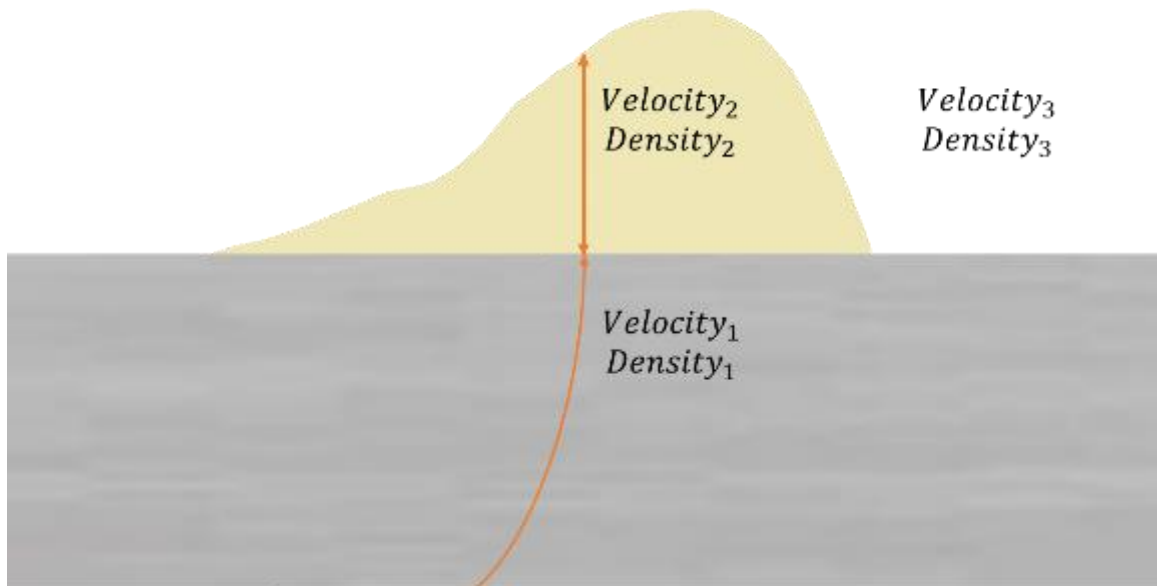


Figure 3-1: a schematic showing a wave traveling through layers with high impedance contrast in two ends.

3.2 Introduction: Correlation

Autocorrelation is a measure of a trace's resemblance to itself lagging in time at each time step. Consequently, it is an indication of randomness as well. Auto-correlating each time-series gives high amplitudes at times that the trace resembles itself. The autocorrelation, by virtue, disrupts any random processes keeping only same processes characterized by

periodicity. When doing so, the phase is lost and the only information left is independent of the origin time. Since the trace is at a perfect match with itself at zero lag, the autocorrelation is symmetric over the zero-lag time. Moreover, the maximum resemblance happens at zero lag, presenting the signal's energy, therefore the maximum peak in the series.

I use the definition of autocorrelation of a discrete function for a time-series $X(t) = (X_1, X_2, X_3 \dots X_n)$ as follows (Priestley, 1967, 1981; Tukey, 1967):

$$\hat{R}(k) = \frac{1}{(n-k)\sigma^2} \sum_{k=0}^{n-k} (X_t - \mu)(X_{t+k} - \mu) \quad (3-1)$$

Where k is the lag time $< n$, μ is the mean and σ^2 is the variance.

The energy of a signal can be written for simplicity as:

$$E_s = \sum_{t=1}^n |X_t|^2 \quad (3-2)$$

In summary, the autocorrelation approach utilizes the sampling order of the time-series to articulate correlation between data points separated by certain time lags pronouncing temporal patterns within the time-series.

To best observe this, we can inspect a periodic function. For example, consider the sinusoidal sine wave decaying with time over 6 seconds with a sampling rate of 2ms shown in Figure 3-2: a. If we auto-correlate the time series with itself at the same sampling rate

as the lagging (or leading) time interval, we obtain the results in the correlogram of Figure 3-2: b. We observe the periodicity still existing and the character of the sine wave is preserved. Whenever a peak occurring in the original trace is aligned with the one in the lagged (or leaded) signal, or a trough of the first with one of the second, we obtain a high local correlation in the correlogram. On the other hand, when the peak is aligned with a trough or vice versa, we get local minimum correlations that are negative in values, due to the opposing amplitude signs. The decay of the original signal is preserved in the correlogram as the amplitudes of peaks and troughs correlated differ in amplitudes as we increase the lag or lead even more and more.

In contrast to the above periodic function, we examine that of a random signal. Figure 3-3a shows a randomly distributed Gaussian noise time series with the same sampling rate and length of the previous decaying sine wave example. The correlogram, shown in Figure 3-3b, provides an insight to the randomness. At the zero lag or lead time, we find perfect correlation of the time series with itself. The value at this origin is the signal energy of the series. As soon as the copied series is lagged or led, the correlogram value drops tremendously and would be near zero until the maximum lag or lead sample is reached.

Next, I take the two presented signals, the decaying sinusoidal sine wave and add the random Gaussian noise to it at 80% ratio, Figure 3-4a. We can visually perceive the high amplitude sine wave character in the first segment of the time-series. As we approach the end of the series, however, we cannot identify or point-out peaks from troughs visually. Nonetheless, comparing correlogram of this new series (noisy single), shown in Figure 3-4b, with that of the clean signal, in Figure 3-2: b, shows the similarity in the

autocorrelation by disrupting the random noise leaving only the periodic decaying sine wave features with amplitude difference related to relative signal energy.

The results are consistent with the expectation. All show the highest energy at the zero lag or lead time. The random noise is smeared as soon as the time-series is shifted one time sample (Figure 3-3b). The autocorrelation of the pure decaying sine wave and the one with the added noise shows consistent sinusoidal behavior, with a minor difference in correlation amplitudes due to the Gaussian noise added.

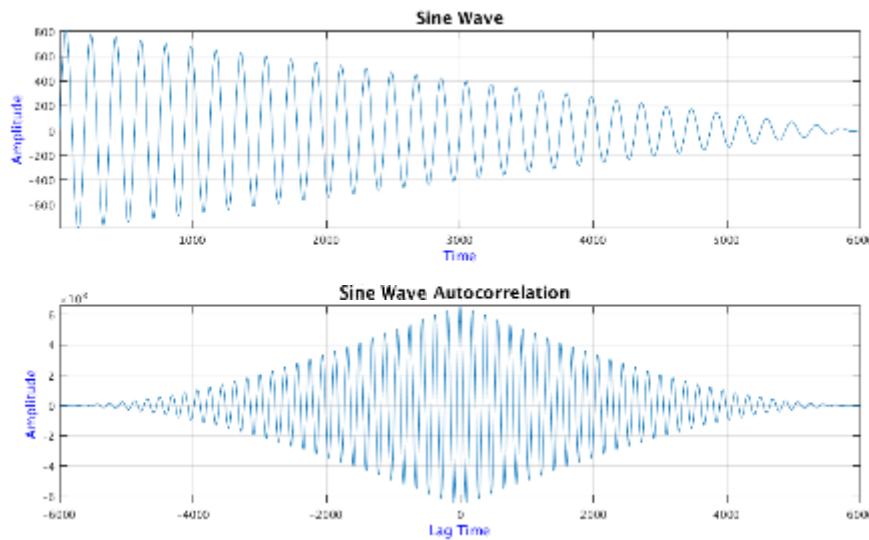


Figure 3-2: a) Single frequency decaying sinusoidal wave. b) Autocorrelation panel of the synthetic sinusoidal wave.

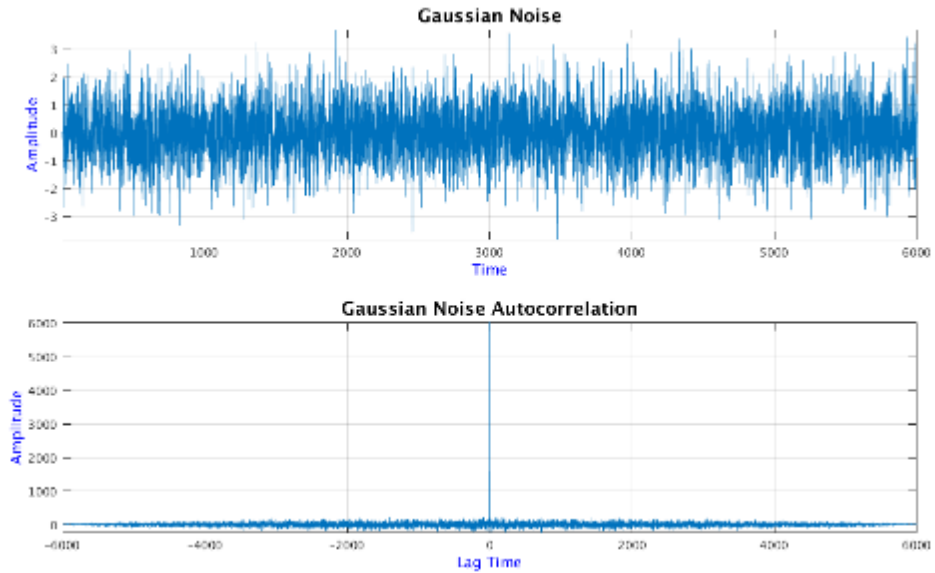


Figure 3-3: a) Random Gaussian noise. b) Autocorrelation panel of the Gaussian noise.

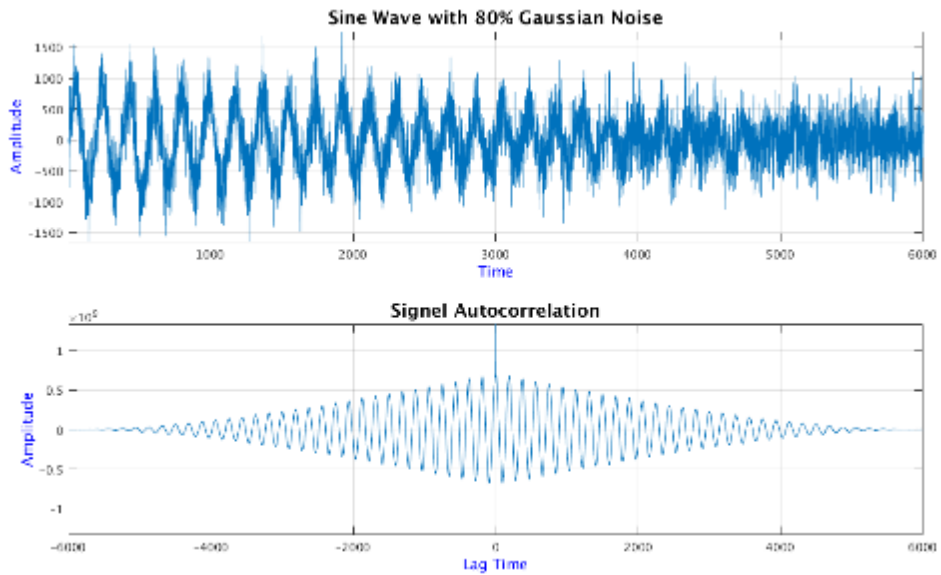


Figure 3-4: a) Single frequency decaying sinusoidal wave with 80% random Gaussian noise. b) Autocorrelation panel of the synthetic signal.

Because we have a symmetric time series, we only use the positive side (lag) of the autocorrelation. This leaves us with one-half of the samples.

3.3 Sorting and Common Domain

Since we are interested only in near-surface multiples, we need to eliminate any others that are coming from other layers. Moreover, we are interested in enhancing the signature of this multiple occurrence.

The autocorrelations are independent of the ensemble sort; the autocorrelation of each trace is produced only one time throughout the process. This happens at the raw data level before any induced sorting.

For our purpose, we stack in order to enhance the identification and attenuation of the undesired multiples. We must do this in a common domain that allows us to detect and recognize this particular event from others. Common source gathers are the set of time series recorded by multiple receivers from one source point. On the other hand, common receiver gathers are the set of time series recorded by a single receiver from different source points. Figure 3-5 illustrates common source and common receiver gathers.

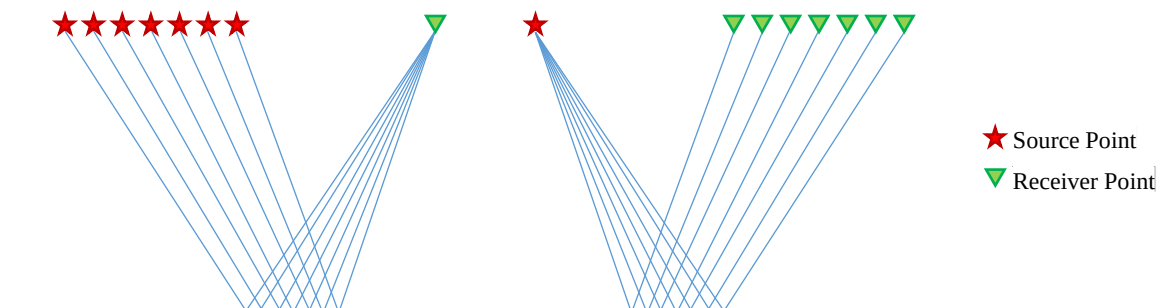


Figure 3-5: Illustration of common domain gathers. a) Receiver gather and b) Source gather.

In exploration seismology, numerous receivers are laid out to acquire the reflections produced by one source point. Likewise, numerous different source points are recorded by the same receiver station.

A wave travels through the high contrast layer in the near-surface twice for a reflected or refracted transmitted and received wave. Once in the source field and another in the receiver field. There could be high lateral variation in the surface conditions between the source and receiver points, where the source side undergoes different impedance characters than the receiver side. This is part of the case I am interested in; when the source occurs on a sabkha and the receiver on the dune, or vice versa. The topography may also change between the two points causing the wave to travel different time in each side.

Traces that are recorded at one receiver station should be impacted by the receiver field in all the traces. While traces that are recorded by multiple receivers from one source are impacted by the source field in all traces. This said, each trace exhibits a source and a receiver field impact (influence).

For a near-surface multiple at the source field, we may have multiples recorded at all receivers for that source. For a near-surface multiple at the receiver field, we may have multiples recorded at all receivers for all sources received at that receiver. Figure 3-6 shows an illustration of two different one side occurrence near-surface multiples (sand reverberation).

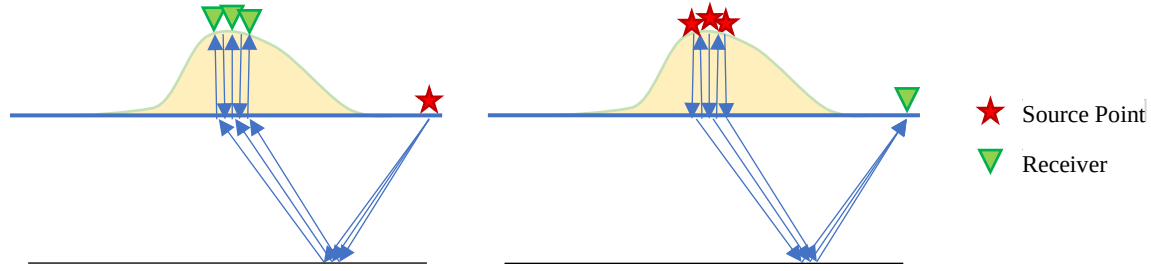


Figure 3-6: Illustration of dune static delays and reverberation of dune effect a) Receiver field (side) b) source field (side)

Figure 3-7 shows a wave traveling through the high acoustic impedance contrast boundary in both the source and receiver wave fields.

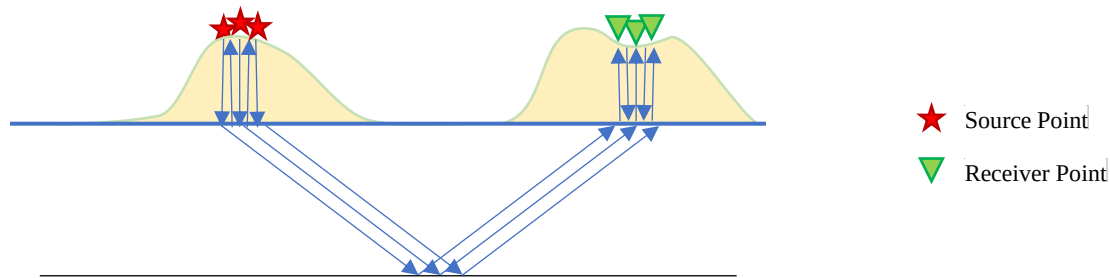


Figure 3-7: Occurrence of reverberation and dune static delay on both source and receiver sides.

The main sorting orders I use are the source and receiver. After autocorrelations, I sort the same data set to common source point gathers and common receiver gathers separately. This gives me a view of coherent events that relate to either the source side or the receiver side. The second step is to stack each source gather and receiver gather independently. This step stacks constructively any coherent resemblance and cancels out any other random events that are not related to the near-surface field in the common gather domain. Figure 3-8 shows different scenarios where the wave field departing from one source point, or arriving at a receiver point experiences different near source effect.

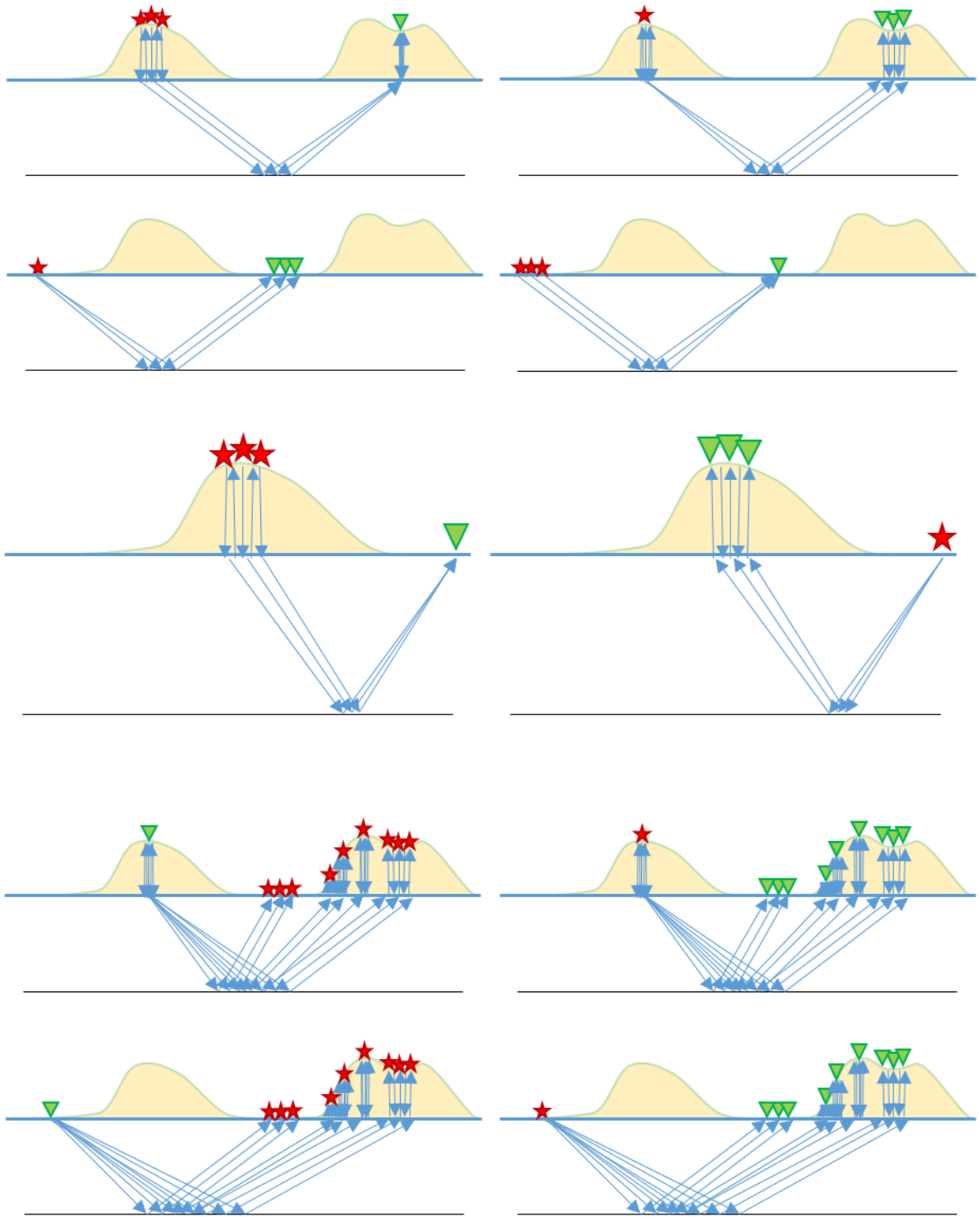


Figure 3-8: Different source and receiver point placements

The other significant implication of expressing the multiple signature at these two common field domains is to achieve a surface-consistent static correction. Surface consistency relies on having one value for all traces that are common to a surface point; source points and receiver stations. Since I am able to identify multiples in these common fields, I fulfil this by virtue.

3.4 Enhancement in the common field domain

There are many processes that can enhance the event I am trying to detect as well as to reduce the amount of undesired signals.

3.4.1 AGC (AGC normalization)

Since individual source wave fields are different for a common receiver wave field and individual receivers in a common source wave field, the energy varies in a set of common time series. Normalization of the wave field may improve the coherency of the event within an ensemble and between ensembles. Moreover, Automatic Gain Control (AGC) pronounces common events and asserts that they exist in most, if not all the common set at relatively close amplitude.

This act enhances many periodic events common in a certain set, as well as common with other sets of common wave fields. The enhancements include second-order multiple occurrences as well, which is more noticeable with short window AGC.

3.4.2 Offset

Considering that near-surface multiples can be generated from refractions, as well as transmitted reflections, events from different offsets in a common field may come at slightly different times. This depends mostly on the impedance contrast and the layer in which the seismic wave is transmitted. This is because a very low impedance layer would result in a near vertical kickoff angle. To mitigate this, we should correct for offset angles. However, for a high channel count setting, we could limit the offsets and still achieve a good fold coverage making it unnecessary to correct for offset angles.

We can also apply an offset dependent gain. Since signal amplitudes of the near offsets are higher than those of the far, we can apply an offset dependent amplitude scaling. Dunes further decreases amplitude with offset (AlJishi et al., 2019). However, trace by trace AGC can be sufficient most of the time to equalize trace amplitudes with offset.

An offset study should be designed prior to the offset limitation choice. In high elevation sand dune environments, the source and receiver layout might be very different from those in the acquisition pre-plan. This is because accessibility to locations could be limited only to receivers while highly inaccessible to sources like vibrators. Thus, some source or receiver points may lack the short offsets or the long offsets. This may cause surface points to drop of the data set. In spite of this, we could still interpolate static values knowing the elevation of these points with high accuracy.

3.4.3 Stacking

Stacking is the summation of traces in an ensemble major sort key. Different stacking normalization can be used.

As mentioned in the previous sections, stacking the autocorrelations in a common field increases the common signal in this field for each ensemble. At the same time, it cancels out (or decrease) the events that are only present in some time series within an ensemble (destructively summed). Hence, this process increases the confidence of the targeted event by expressing the typical value/s on the ensemble set.

3.4.4 Post-Stack Enhancement

FK filters are very effective signal processing tools. In the post-stack domain, many events that were common in all wave field domains are attributed to non near-surface multiples. In a flat, or near flat, geological multiple generator, inter-bed multiples have the same time interval across most of the time series. In addition, they include features such as those generated by water table -which is particularly flat. Therefore, they have the same occurring time. FK filters can help in rejecting these flat events (or pass non-flat events) with infinite velocity. This is the most effective approach or technique with highly varying surface topography to reduce rejection of near-surface occurring events.

We can also use the FK filter in the pre-stack domain to remove the highly dipping events. However, this is more prone to errors and stacking should be sufficient to deal with the high dips.

It can be handy as well to filter using the Karhunen-Loève (K–L) transform to extract unwanted linear events that are coherent across the volume and suppress them without harming the near-surface signature (Londoño et al., 2005).

3.4.5 Background Noise Subtraction

Background noise resulting from geological features mentioned in the section 3.3.4, similar to that present in Ground Penetrating Radar (GPR) data, is typically common to the whole set of data.

Background noise subtraction is done by summing all the time series together and averaging to approximate the background noise. After that, we would subtract this single averaged time series from the individual input time series. Normalization and/or AGC could be an important step prior to this. This approach yields a similar result to the FK infinite velocity rejection used to remove the flat events. Since it is a non-deterministic technique, it can oversee events of different frequencies that may not be very visible. Such normalization process is done in the time domain.

In contrast to the FK filtering, background removal can be executed in the pre-stack domain as well as in the post stack or both. In general, the noise will have a subtle very low frequency character.

3.4.6 Ensemble Alignment

Applying an ensemble residual delay correction may remove offset delays. It may address the geometry terms that are not accounted for deterministically (like the offset angle). To do this, we should stack each common field ensemble. We may apply some post stack enhancements to clean the data, such as applying a low-cut filter, or a stochastic (in-deterministic) spiking deconvolution. Then, using this stacked trace, we apply a cross correlation based residual statics correction with the unstacked ensemble set. The window should be very small, maybe within a sample. Before cross correlation is done, the first samples (which is zero autocorrelation lag; the signal energy) have to be damped so the solution does not freeze at zero or secondary maximum amplitudes would be picked. I can also apply an offset angle correction deterministically.

3.5 Behavior of Source and Receiver Field

The data cleanness varies from offset to other due to different sorts of noise, varying amplitudes, and different types of waves. Therefore, we should examine the reverberations characters, not only with thickness, but also with offset. We have to evaluate different offset ranges that best address the reverberations coherently in each of the source or receiver domains.

Moreover, the source and receiver sides show different strengths of the signature. These could be used together or separately. In addition, some of the enhancements may be applied on both domains at the same time.

3.6 Chapter Summary

I have highlighted the physical principal and kinematics of seismic events under investigation. I discussed the domains in which these events can coherently be distinguished. I provided a description of the noise, possibly, present and some techniques to increase the S/N of the event.

CHAPTER 4

APPLICATION TO SYNTHETICS

I perform a simple synthetic modeling to illustrate the multiple occurrence discussed in chapter 3. First, I present modeling parameters that are similar to the geological settings of the real data, followed by the outcome of the forward model. Then I highlight the event in a single selected domain.

4.1 Synthetics Generation

Modeling is imperative to acquiring a better understanding of the behavior of the surface multiples and hint at the autocorrelation outcome of real data. A synthetic model, which is free of noise and with known parameters, makes it possible to identify events and analyze their kinematic and dynamic behaviors.

I used a finite-difference wave equation method to do the modeling. For the same model parameters, I have generated elastic and acoustic forward models.

4.2 Model Space

The model space is designed to have elastic properties that mimic field conditions. The same velocity and density contrast must be present to be able to associate and anticipate the modeling outcome with that of real data.

We must place our source/s and receiver/s functions at the boundary between sand and air, or have a free surface half-space model. This is necessary to achieve the free surface effect (reflection from the sand-air boundary).

The sand velocity is inhomogeneous and is a function of depth related to the compaction of the overburden. Thus, it has a gradient increasing with depth. The velocity can be assumed from the Sand Curve by dividing the thickness over the time for a finite gradient at each depth thickness or by using any of the velocity-depth functions for sand. However, for the simplicity of our model, I use a constant velocity for the sand equal to the average of sand at corresponding thickness (I average over the slowness) from the Sand Curve. This is appropriate because of the high contrast of the sand-sabkha boundary resulting in a near right angle onset. Accordingly, the minimum bending ray that may potentially exist away from the zero-offset has not been observed in the pre-stack correlogram gathers.

The layers underlying the sand bodies are the sabkhas, which are composed of highly compacted salt flats. Hence, I assign them a constant velocity.

As I am interested to model the refractions and reflections, I choose to insert multiple layers of constant velocities with a sharp acoustic impedance contrast. Consequently, I have multiple reflections and refractions surface-based multiples. This enables to predict the practical benefits of either or both of them. The last (deepest) layer will have neither reflection, nor refraction as I am using an absorbing boundary condition in all of the model's directions except its upper boundary, which is a free surface.

4.2.1 Source and Receiver Layout and Layer Parameters

The model consists of five layers. The total depth is 800 m and the distance covered is 2000 m. The source is located in the middle of the space making a split-spread having maximum offset of 1000 m. The receiver array is placed on top of the sand layer along the air-sand contact boundary. The model parameters are given in Table 4-1. A schematic illustration of the model space is demonstrated in Figure 4-1.

Table 4-1: Forward modeling parameters of the layers including depth, P velocity and S velocity.

Layer	Depth (m)	P Velocity (m/s)	S Velocity (m/s)
Air	50	300	0
Sand	100	500	300
Sabkha	150	1700	700
Layer 1	200	1950	1400
Layer 2	300	2400	1850

Velocity model

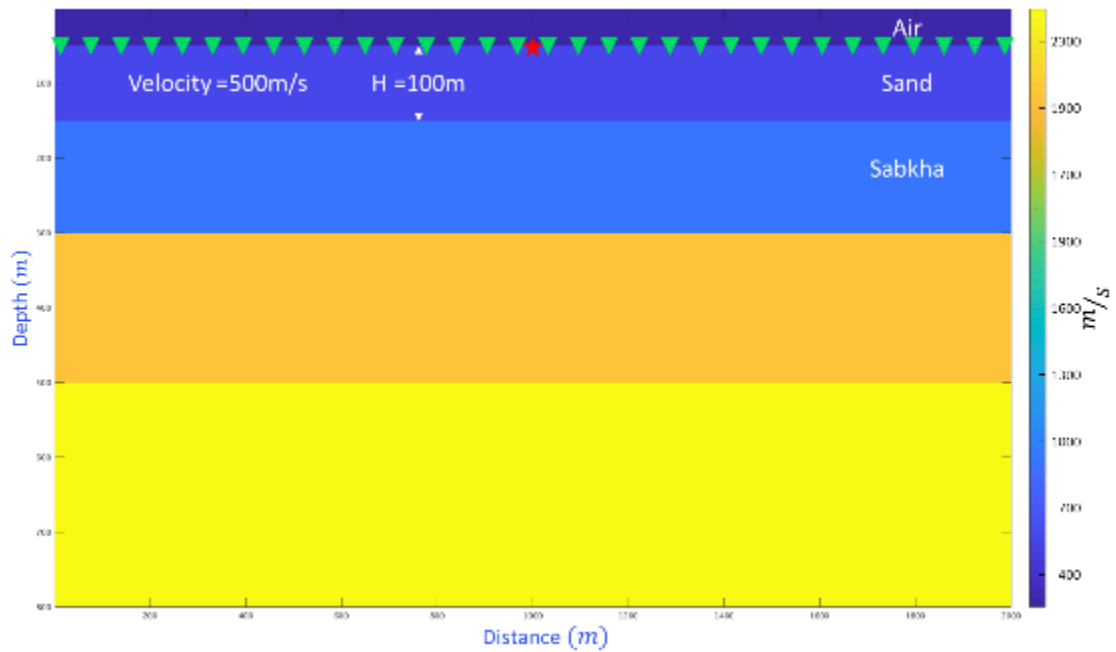


Figure 4-1: P wave velocity model used in the generation of the synthetic data showing a layered-cake model consisting of five layers with velocities from Table 4-1.

4.2.2 Modeling Expectation

From the given parameters in Table 4-1, I computed the normal incident times the wave takes to travel across each layer. In addition, I computed the two-way travel time for each layer. Then I summed these to compute the times it takes to travel to each of the layers' boundaries and reflect to reach the surface. Table 4-2 shows the layers and the travel times.

Table 4-2: Model layer travel times including normal incident time, two-way time and the zero-offset reflection cumulative two-way time

Layer	Normal Incident time (ms)	Two-way-time (ms)	Cumulative Two-way time (ms)
Air	166	333	Receiver locations
Sand	200	400	400
Sabkha	88	176	576
Layer 1	102	205	781
Layer 2	125	250	(absorbing boundary; no reflection)

The events that I anticipate are reflections and refractions at the base of the sand layer, as well as from the base of the sabkha layer. A simplified schematic ray diagram for each of these events is shown in Figure 4-2. The velocity model has one source at the center and receivers at fixed intervals.

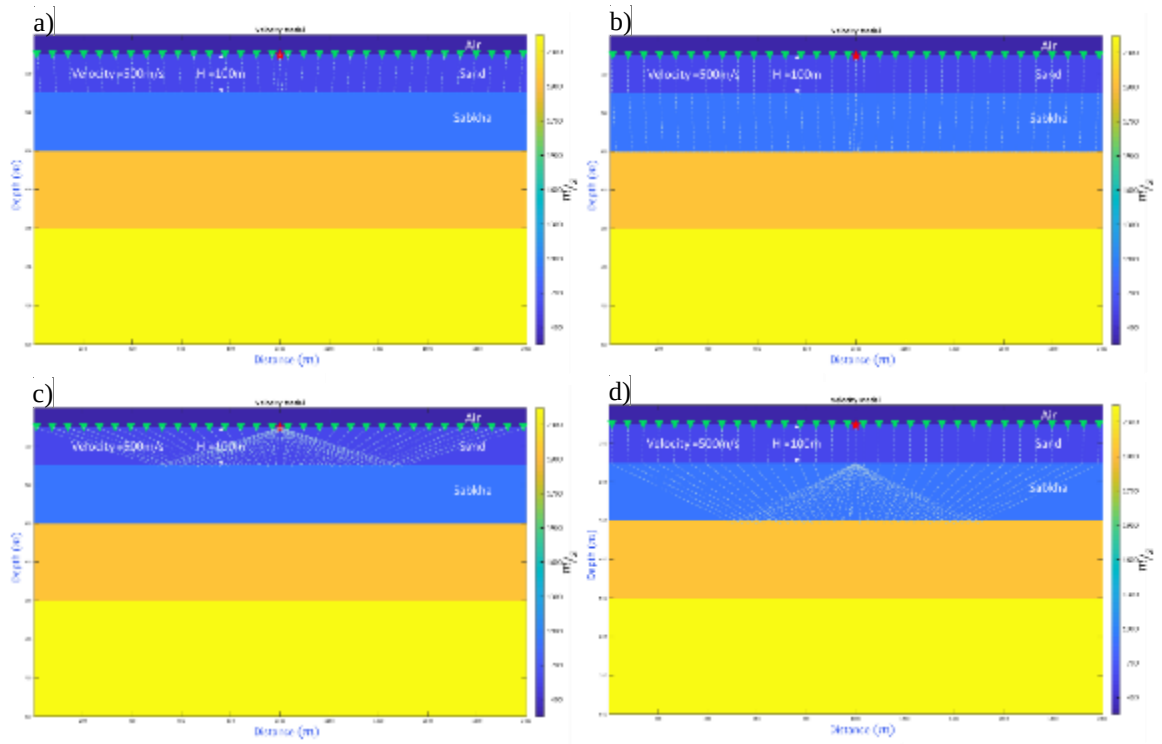


Figure 4-2: A schematic ray-diagram on the velocity model. a) Refraction rays at the base of the sand dune. b) Refraction rays at the base of the sabkha layer. c) Reflection rays at the base of the sand dune. d) Rays from the reflection of the base of the sabkha.

4.3 Forward Modeling Recorded Seismic

Figure 4-3 shows 1.5 second recording time of the continuous array on the air-sand boundary. This result is derived from the acoustic modeling.

Looking at the source gather, we can observe reflections happening at zero-offset vertex at 400 ms. The wave reverberates within the layer due to the sharp impedance contrast in both the top and bottom of the layer. The vertex of the first reverberation within the layer from the reflection occurs at twice the first reflection time. The second reverberation occurs at 3

times that of the first primary reflection and so on. Away from the vertex, the reverberation time diverts from this behavior following a normal move-out hyperbola.

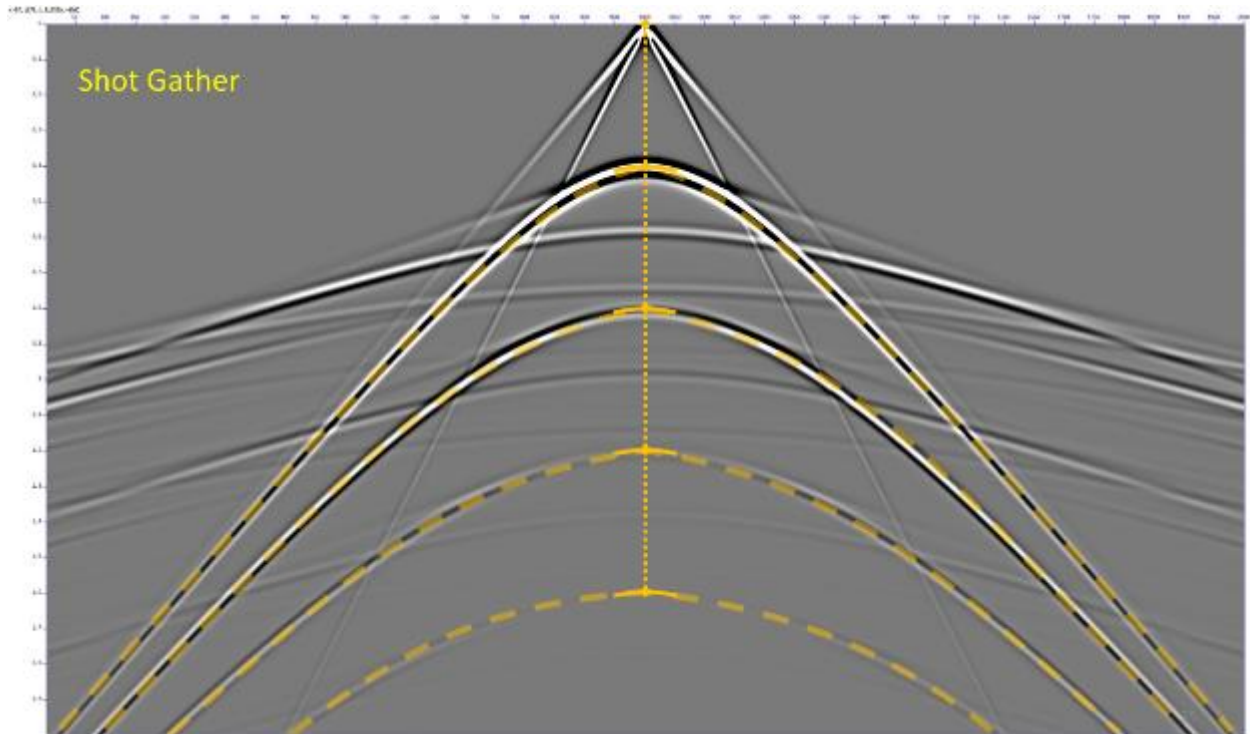


Figure 4-3: Acoustic modeling results for one source point. The dashed orange are the extent of the dune reflection and the reflection reverberations while the cusp of the reflection and reverberations are shown in solid orange.

We also observe refractions happening at the base of the sand. Away from the vertex of the reflection from this layer, we can track the linear refraction event. The reverberation from this refraction can be observed at twice the time of the original event. Additionally, the higher order reverberations are present as well, as highlighted in Figure 4-4. At the zero-offset time, the linear refraction is absent because it only starts at the critical offset. Across the offsets, away from the zero offset, the events can be tracked within this finite offset scheme.

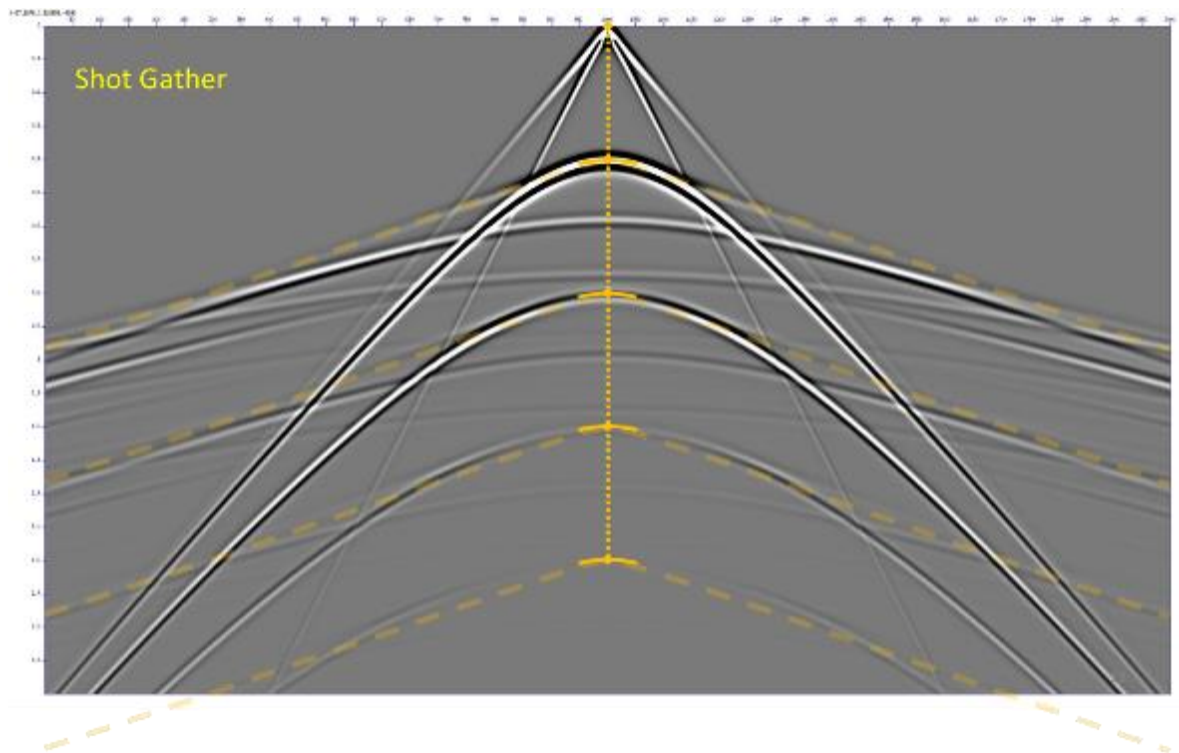


Figure 4-4: Acoustic modeling results for one source point. The dashed orange is the refraction and the refraction reverberation while the cusp of the reflection is shown in solid orange.

Moving down to the sabkha layer, the reflections happening at zero offset vertex is the cumulative sum of the sand and sabkha two-way-time. This is 400 ms and 176 ms adding to 576 ms. Since there is a sharp acoustic impedance contrast at the sand/air boundary, the wave reflects back after it is recorded by the receiver. At the base of sand, the wave encounters a sharp impedance contrast resulting in the wave bouncing back to the sand. The wave reverberates within the layer as it reaches these boundaries. The vertex of the first reverberation within the layer from this reflection occurs at an additional time equal to twice the first layer reflection time. This is 576 ms and 400 ms adding to 976 ms. Each additional order of reverberation occurs at an additional 400 ms. Figure 4-5 highlights the reflection from the base of sabkha followed by the reverberation within the sand layer.

Away from the vertex, the reverberation time diverts from this behavior following a normal move-out hyperbola.

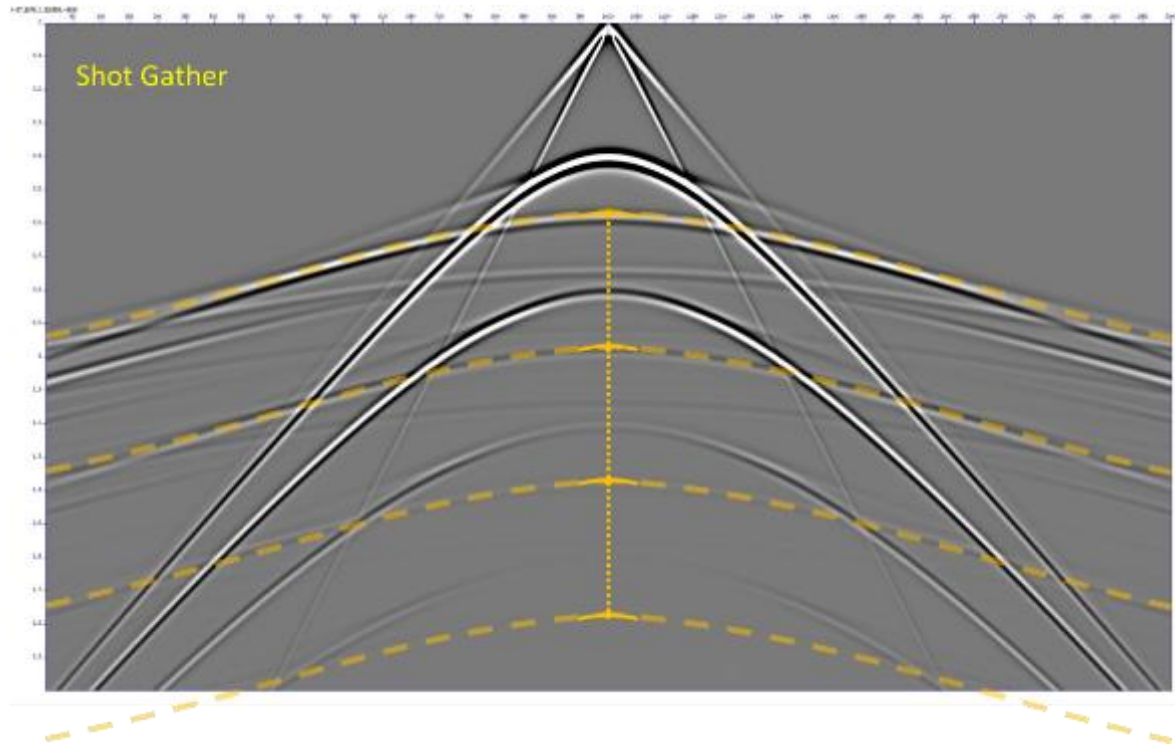


Figure 4-5: Acoustic modeling results for one source point. The dashed orange is the reflection and the reflection reverberation while the cusp of the reflection is shown in solid orange.

In addition to the reflection, a refraction event exists at low amplitudes.

Moving down to the first layer, the reflections happening at zero offset vertex are the cumulative sum of the sand, sabkha and first layer two-way-time. These are 400 ms, 176 ms and 205 adding to a total of 781 ms. Since there is a sharp impedance contrast at the air boundary, the wave reflects back after it is recorded by the receiver. At the base of sand, the wave encounters a sharp impedance contrast resulting in the wave bouncing back to the sand. The wave reverberates within the layer as it faces these boundaries. The vertex of the first reverberation within the layer from this reflection occurs at an additional time equal

to twice the first layer reflection time. This is 781 ms and 400 ms adding to 1181 ms. Each additional order of reverberation occurs at an additional 400 ms. Figure 4-6 highlights the reflection from the base of sabkha event followed by the reverberation within the sand layer. Away from the vertex, the reverberation time diverts from this behavior following a normal move-out hyperbola.

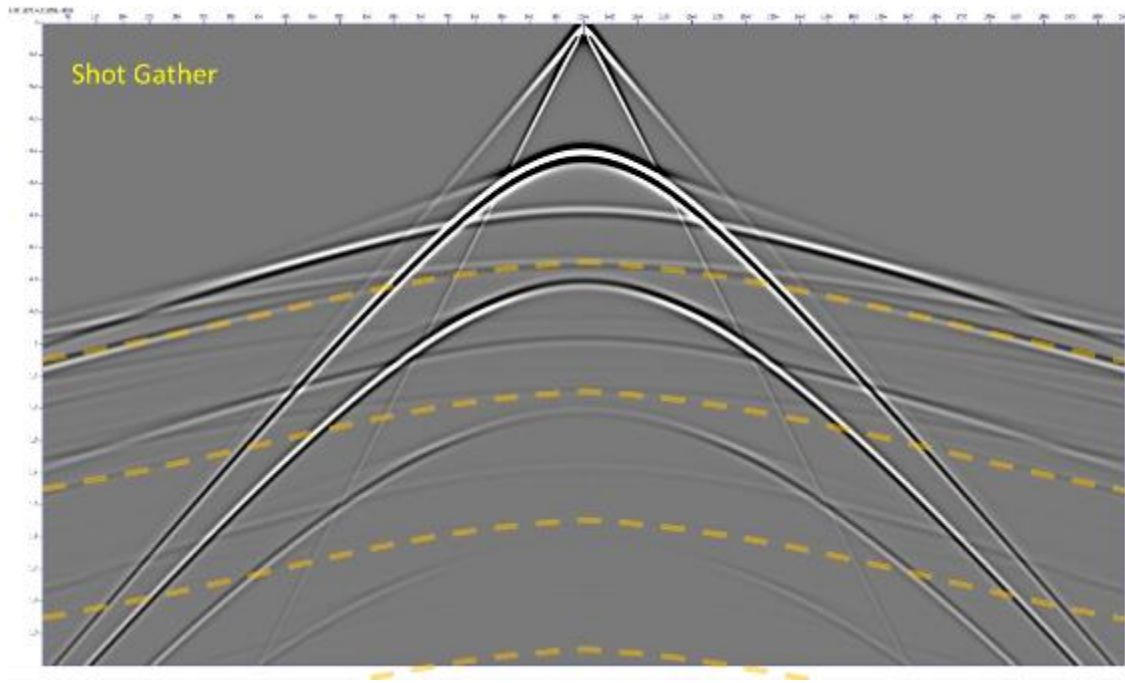


Figure 4-6: Acoustic modeling results for one source point. The dashed orange is the reflection and reverberation from the first layer beneath the sabkha.

The elastic forward modeling also shows the events highlighted in the acoustic modeling in Figure 4-3 to Figure 4-5. In addition, many different linear events and converted phases are present. This presents an effective illustration showing the power of correlation and stacking in pronouncing the desired reverberation. Although at the center of the gather many different events appear to have redundant occurrence, not all of them have the same moveout. Figure 4-7 shows the elastic modeling result. The elastic forward modeling

shows dispersion due to improper modeling parameters needed to account for the very low S-velocity.

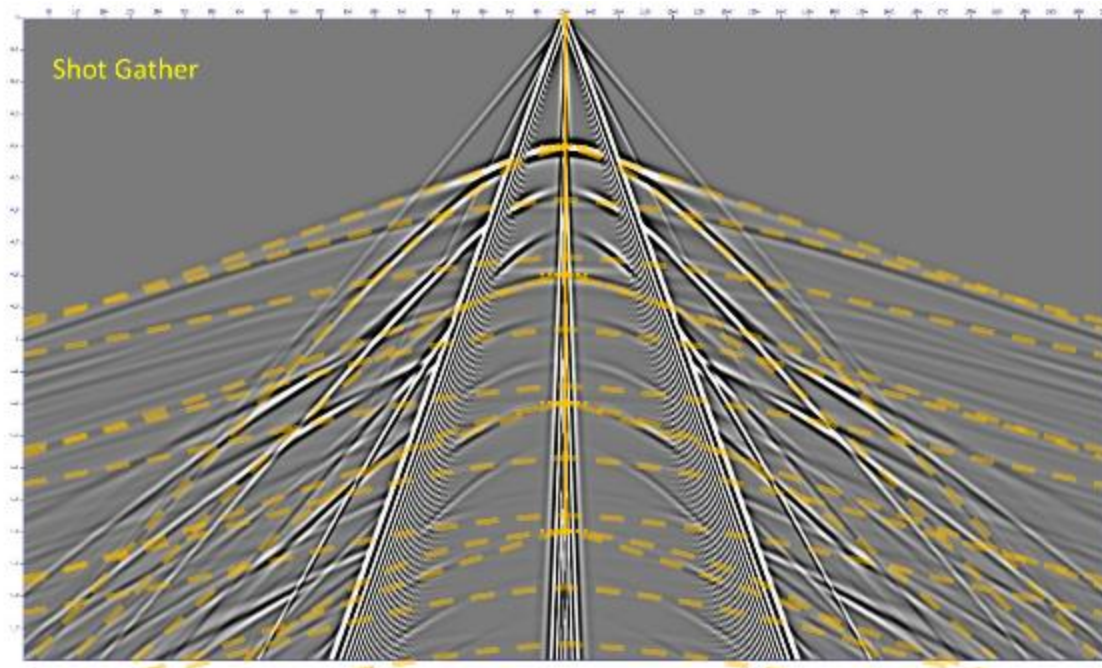


Figure 4-7: Elastic modeling recorded wave field results for one source point. The dashed orange lines are the different vents discussed in earlier figures.

It is important to notice that at the air-sand boundary and the sand-sabkha, we observe polarity reversals each time the wave is reflected. This is combined with a slight phase shift.

In addition to the events highlighted, there is the coherent linear noise. Figure 4-8 highlights the noise cone of the acoustic wave field.

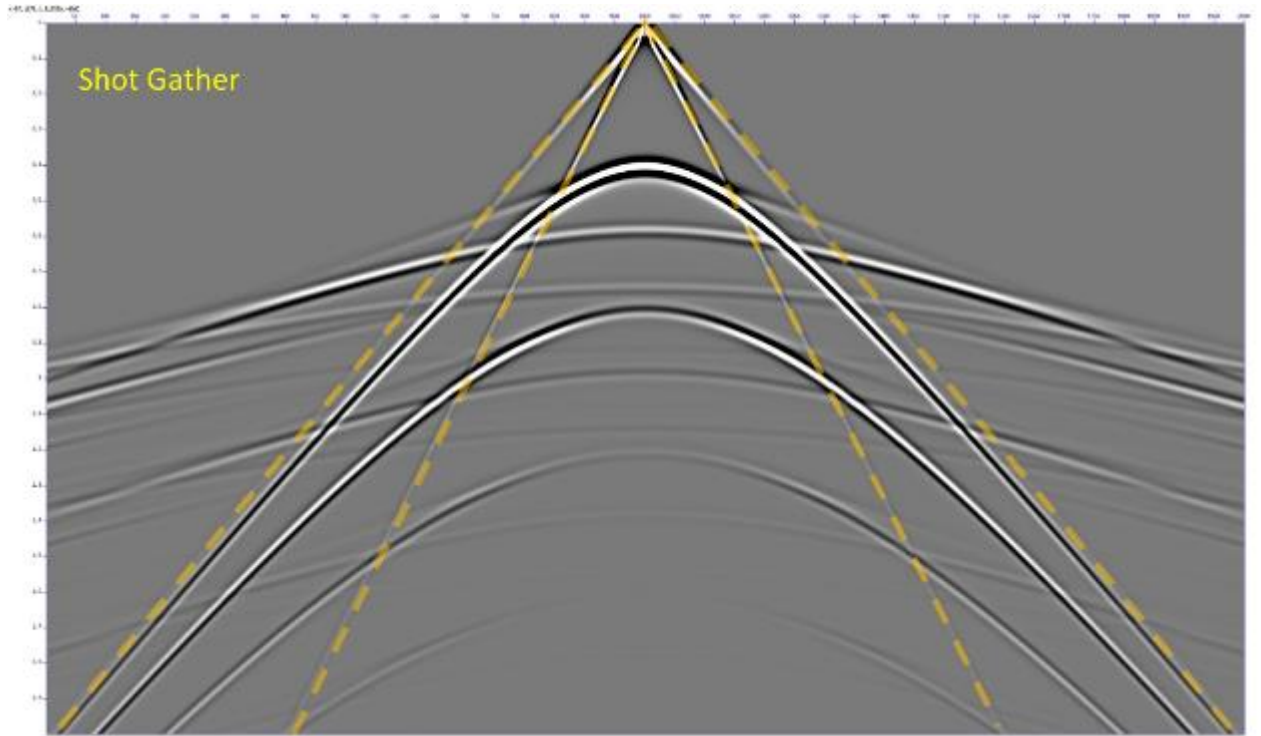


Figure 4-8: Acoustic modeling results for one source point. Highlighted in orange is the linear noise cone.

4.4 Autocorrelation of Recorded Seismic

Figure 4-9 shows the autocorrelation of each of the traces recorded by the array for the single source in the elastic scheme. The data includes all the events with coherent arrivals (e.g., ground roll). Different traces exhibit different events that, when sampled temporally, can be spaced uniformly and therefore have different periodicity pronounced. Traces at the center, for example, do not have refractions recorded because they fall below the critical offset. However, the rest of the traces do have them. On the other hand, the short offsets have high linear noise present. Looking along a single time through the different offsets, we observe very few continuous events consistently in the different traces. Highlighted in orange are the expected times of the events and the second and third harmonics. At the

center of the autocorrelation, where the strongest reflection is present and the multiples, we observe the highest amplitudes of the first reverberation.

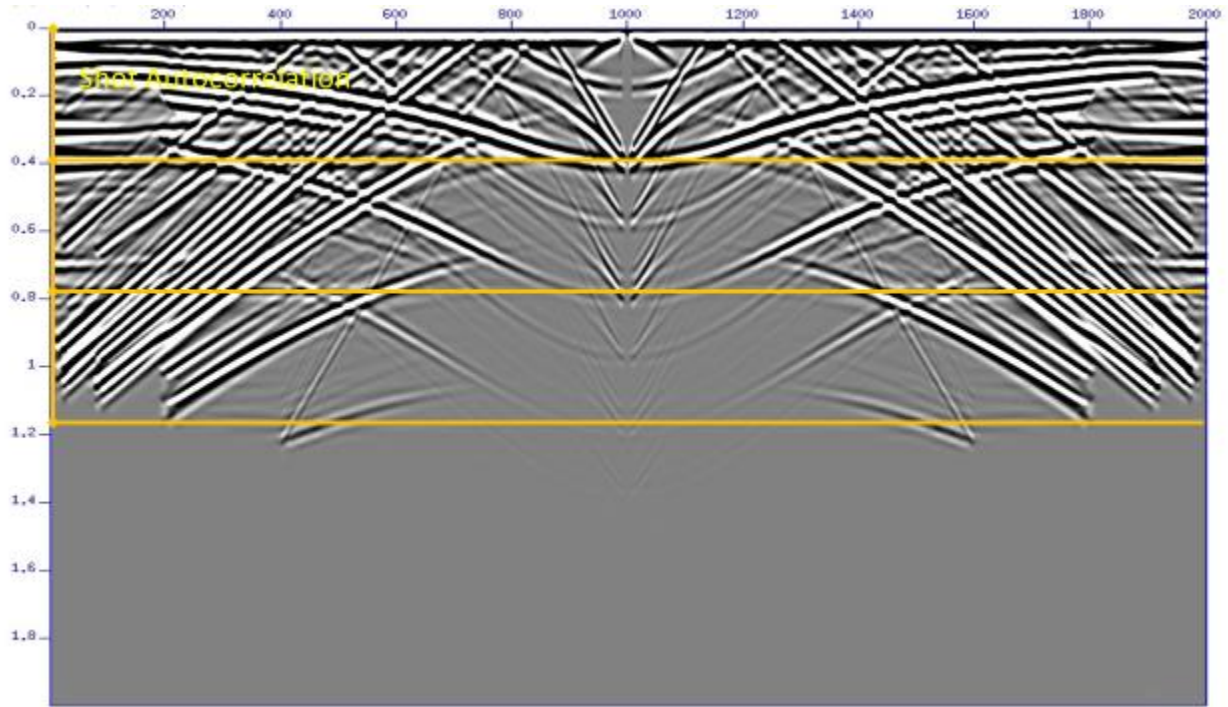


Figure 4-9: Individual autocorrelations of the source gathers. The multiple occurrences highlighted with solid orange are with the first-order coming first.

Figure 4-10 is a variable display stack of all of the autocorrelations traces. The strongest event, after the one at zero-lag, is the reverberation signature presenting the two-way travel-time. In addition, the first and second harmonics are present at significantly lower amplitudes.

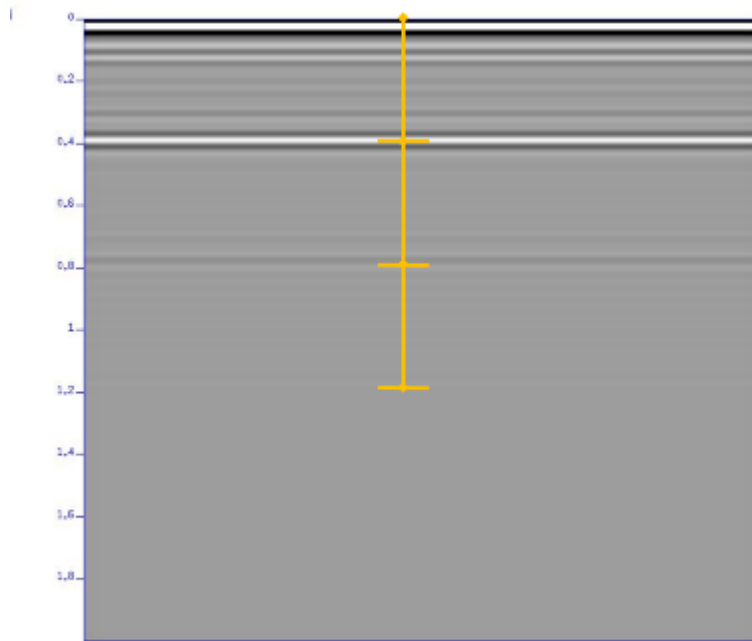


Figure 4-10: A stack of the autocorrelations in Figure 4-9.

Figure 4-11 shows a wiggle trace, instead of the previous variable display. Figure 4-11a shows the central (zero offset) trace from the autocorrelation panel. While Figure 4-11b shows the stacked trace of all offsets. The reverberation is clearly distinguished by the high amplitude.

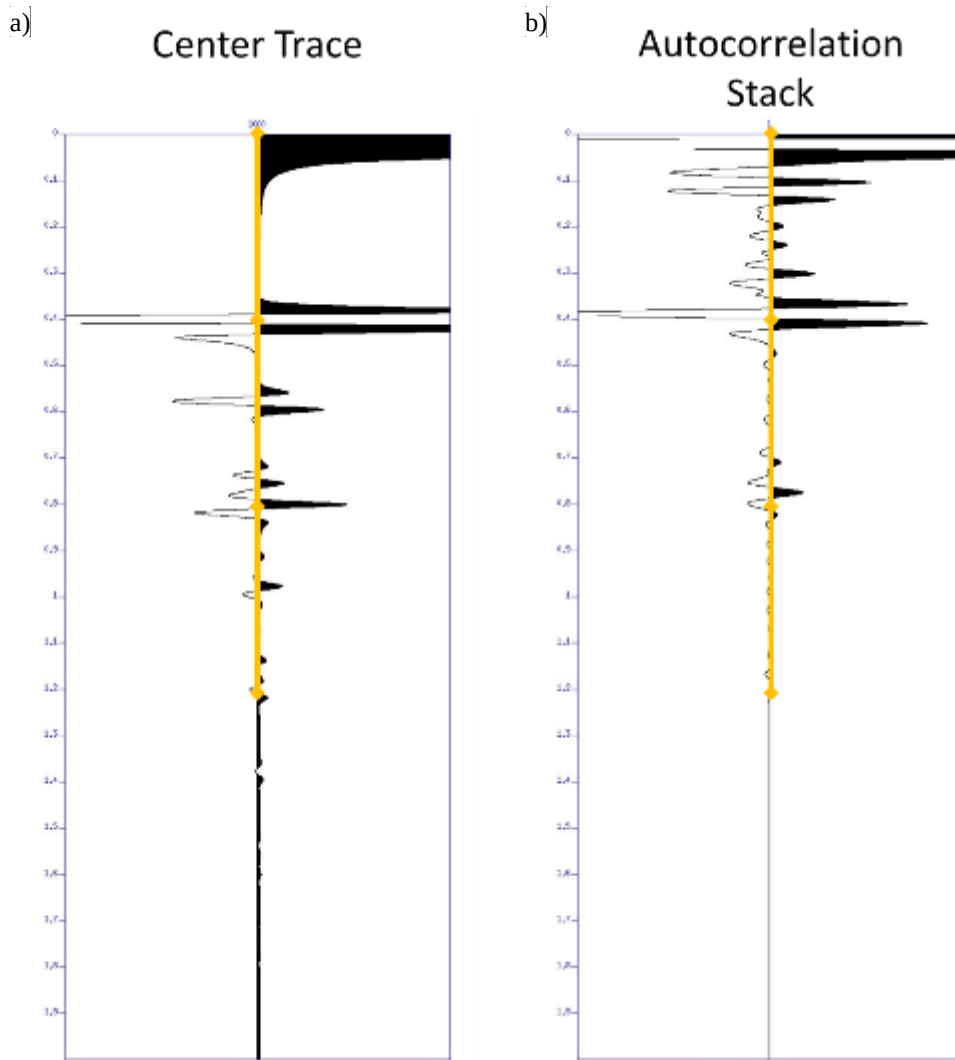


Figure 4-11: A wiggle representation a) A trace at the center of the acoustic recorded wave field. b) A stack of the autocorrelations in Figure 4-9.

4.5 Discussion

Linear noise attenuation of the direct arrival, the surface wave, could be removed with F-K rejection filter. This improves the correlograms in the offsets in which it is present. Especially in elevations where the signature is distorted by them.

Looking at the reflections, we are able to see the periodicity at the vertex. However, as stated earlier, periodicity away from the vertex is not the same travel time. To be able to utilize the reflections based surface reverberation across the full offset range we can apply a Normal Move Out correction (NMO) using a velocity suitable to stack the lower surface multiples. In other words, we are using a velocity lower than the stacking velocity for the events that occur at the same time the multiple is recorded. This velocity is identical to that of the original event. A non-stretch NMO benefits the correlogram most to present a sharp signature. On the other hand, a regular NMO is recommended to be followed by a wavelet distortion recovery to preserve the signature sharpness. This is true for a flat layer or sand dunes with slightly varying surface topography. It is possible to limit the use to the near offsets since the event is almost flat at the vertex. This is what is observed to stack well as having got the highest energy.

The refraction is perhaps distorted if we apply an NMO correction. Thus, we can segregate the refractions and auto-correlate them separately. We can choose to stack the reflections and refractions or use only one of them. We can stack the two volumes, refraction and reflection, or stack all the auto-correlogram from both refraction and reflection at once.

Since refractions are only observed within the first layer, we anticipate that other reflections will contribute very little constructively or destructively to the signature in the correlogram. Further, stacking with the other offsets will further decrease the contribution.

4.6 Summary

The synthetic model shows that high velocity contrast results in reverberation. We can predict the reverberation times if we have an insight about the geology. Knowing the velocity, density and depth of the sharp contrast boundary allows to estimate the arrival time of seismic events.

It also showed that the auto-correlation is very effective in enhancing the targeted reverberations' signatures. Further, stacking the common gather reduced the noise and increased the reverberation clarity. I have confirmed the effectiveness for a single source gather with positive results. Synthetic modeling gave us good insight of what to expect in the real data.

More options were to use ray-tracing methods to examine acoustic refraction and acoustic reflection only and impose the events on the gather to confirm the highlighted events. Looking at each of those separately for each layer would have been useful.

Additionally, modeling a variant topography with alternating surface geology (sand and sabkha) would have resembled real conditions. In addition, modeling multiple source points with variable topography would show the power of stack to eliminate the receiver side reverberation in a source point stack, and the source point side reverberation in the receiver point stack.

CHAPTER 5

ADAPTIVE SAND CURVE AND BASE OF SAND

PICKING

5.1 Introduction

In this chapter, I discuss the utilization of the recorded and processed reverberations. I explain the limitations of the existing Sand Curve as well as benefiting from the surface reverberations. In the end, I introduce a new method of generating an empirical adaptive sand curve.

5.2 Problem Description

The static solution involving a highly variable topography and high impedance contrast between the unconsolidated layer and the underlying layer requires a two-step static solution. The initial step removes the high frequency delays caused by the low velocity/density and highly varying topography, while the second step removes the long and medium wavelengths caused by the underlying weathered layer. Typically, velocity inferred from upholes precedes the sand delay removal. Tomography or advanced wave equation datuming are also commonly in use nowadays.

Applying the steps from chapter 3, that have been discussed using synthetics in chapter 4, allows us to estimate the time it takes the wave to travel across the sand layer

Using the good source and receiver autocorrelation stacks for each surface point, we can directly pick the static-delay values from each source or receiver stacked traces. This yields a surface consistent static solution.

This satisfies the first static correction step in such area with the stated conditions. However, this introduces an obstacle when trying to proceed forward with completing the full-static solution steps. To proceed to the next step, the elevation at which the initial step was able to datum the source or receiver points to is required. Hence, I propose the following steps in the next sections.

5.3 Solution Steps

5.3.1 Inverse Sand Curve and Elevation QC

The Sand Curve gives back a static correction once we know the sand dune thickness. The independent variable is the sand dune thickness while the dependent one is the one-way travel time. In chapter 6, I provide a detailed evaluation of the Sand Curve and its reliability. For now, I use the time-honored Sand Curve in plotting the independent variable as the Y-axis and the dependent variable on the X-axis at an interval equal to the significant digits (measurement accuracy) of the acquired elevation data points. Next, I fit a polynomial through the points plotted to best reconstruct the curve. Figure 5-1 shows the points and the fit. The result is an inverse sand curve that is able to take one-way travel

time and yield a thickness equal to the corresponding sand thickness. Figure 5-2 shows both, the Sand Curve and its inverse.

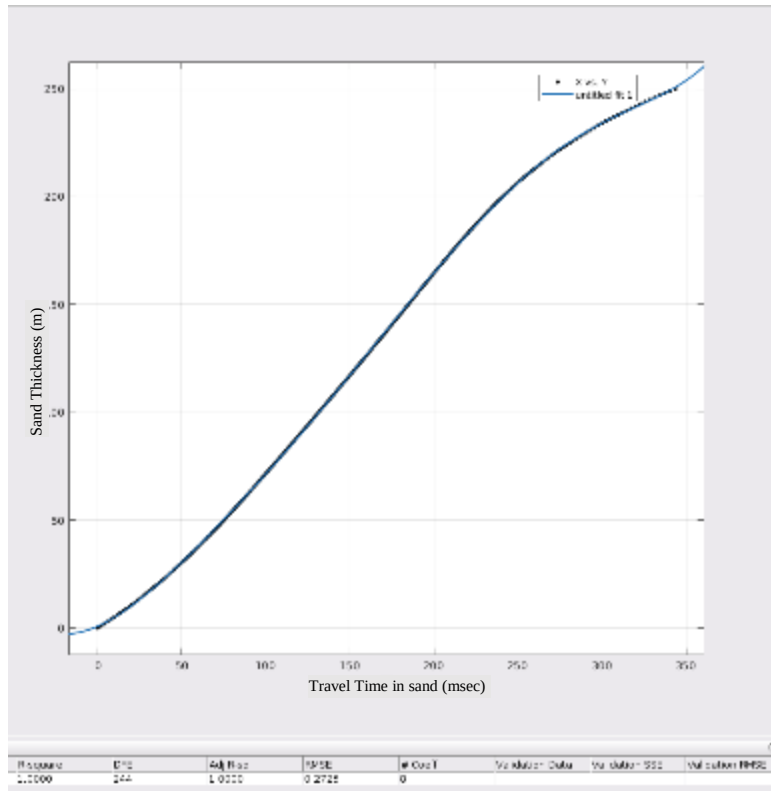


Figure 5-1: Inverse sand curve fitted using the independent and dependent variable interchanged.

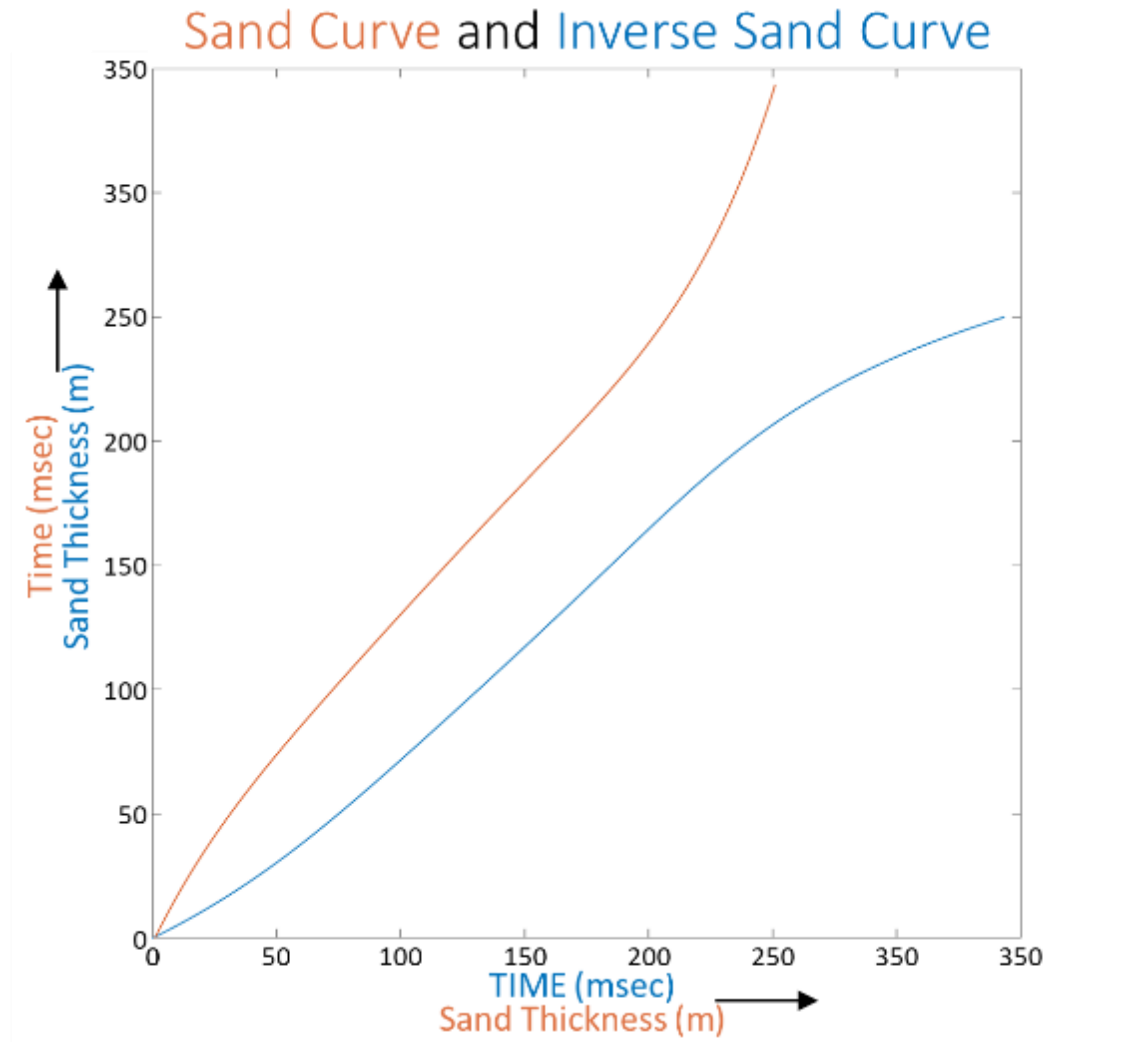


Figure 5-2: Inverse sand curve fitted using the independent and dependent variable interchanged. Sand Curve is in blue and inverse sand curve is in orange.

Using this inverse function, we are able to know the thickness of the sand body from the picked times. By subtracting this obtained thickness from the surface elevation, we arrive at the elevation point the picked static solution modified (re-datumed by a vertical time shift) the trace to.

Among the benefits of this approach, is that we are able to QC the static correction times we picked. This is because it is more intuitive to judge an elevation surface than to judge a time thickness surface (time in sand). The high-frequency statics resulting from picking the time signature dune reverberation may convert to a highly variable elevation surface rather than the expected (or assumed) smooth one.

In light of this, I can proceed with the next steps in the full-static solution having the new updated elevation surface of the data points.

In this special environment, we apply several static steps. The initial step is the sand curve, the next could be any, but not limited to single layer, multilayer statics or tomography-based static solution

Since the single or multilayer static solution from up-holes is usually gridded and interpolated to a single or multilayer velocities, then thicknesses from a common datum are used to compute time using these velocities. A poorly picked surface reduces the quality of the short statics solution causing a defocusing effect to the seismic stacks. In many cases, this can be resolved with surface-consistent cross-correlation based residual statics. In the case of the sand dunes, we observe medium-wavelengths static issues related to the large sand bodies. These wavelengths are unresolved after surface-consistent cross-correlation residual statics. This is because they will still exist in the pilot stack that is used to correlate with. Besides, high residual values coinciding with sand geo-bodies will seep to any depth conversion or depth imaging.

We also know that a smooth surface is important to arrive at an appropriate tomography-based static delay. This is because the computation tomography relies on is sensitive, in terms of cost and time, to the grid size. Hence, a grid size small enough to represent the high variation in surface elevation of the sand dunes is usually inconvenient. Additionally, small sized grid requires huge computational capacity beside the long run times. Even then, we are limited by the acquisition spatial parameters.

Depending on the evaluation of the new surface elevation, we can apply a smoother length that gives a better-smoothed surface. Then, we can use the same sand curve to regenerate the one-way-time statics of the sand dune. However, in areas with exposed sabkhas, smoothing is likely to alter the sabkhas elevations or even cause the surface to be above the surface topography. An outcome that we need to avoid.

5.3.2 Updating the Elevation Picks

To resolve the sand statics, I go back to the picked times or elevations produced from the picked times. I then sort the correlograms to the picked times or corresponding elevations. Either values should give us the same sort order. At this point, we see the sabkhas traces clustered at one side and the traces acquired on the sand dunes in an increasing sort order. This can be verified by plotting the sand curve on top of the correlograms, multiplying it by two to achieve the two-way time in sand.

At this point, we are able to pick a new sand curve. If we see a consistent high discrepancy between the correlogram values and that of the sand curve for this specific location, we

could estimate a new sand curve (discussed next). Another reason for the discrepancy is inaccurate picked times or inaccurate thickness.

Next, I perform stacking based on common elevation or static time delays. Based on the number of data points and sampled elevation fold, we can choose to stack a number of elevation intervals or static time delays (e.g., a quarter or half a meter, or one or two milliseconds). If the elevations were sampled equally, we can stack each tenth of a meter (if that is the measurement accuracy). However, there is no control over the elevation distribution.

At this stage, I can pick a sand curve for this specific area or site. Since sand composition varies from one area to another, and water saturation could vary from one season to another, I assume that the accuracy of the static time delays will increase by selecting a more specific sand curve.

5.3.3 Limitation of the Existing Sand Curve

One of the limitations of the time-honored Sand Curve is that it was constrained by 105 meters in thickness. This is due to the heights estimated elevation point in the refraction survey initially conducted (Robinson and Al-Husseini, 1982). The fitted polynomial is extremely dependent on the constrained data at the high elevation. Thus, I can control it better by introducing points from elevations higher than those in the Sand Curve and of those in this location that reach 250 meters in elevation. This makes the new curve much reliable around the 100 meters thickness interval. Yet, it may move the error tendency somewhere between the 170 and 250 meter elevation. The accuracy of the high elevation

corrections depends on how many points are sampled having the highest elevation and the fold thickness distribution of the points. A secondary limitation is that the elevation of the points that were used in fitting the existing time-honored Sand Curve were assumed with an unknown precision or observational error. The elevation points may not have been very precise as the elevation/time readings. This is shown in the scattered points in the Sand Curve inferred plot (Figure 2-1).

Errors due to extrapolation to high elevation and observational thickness errors in the construction of the curve will likely be solved with surface-consistent cross-correlation based residual statics. Especially, for small dunes or for areas with good distribution of sand thickness and/or sabkhas. However, a prerequisite to the surface-consistent cross-correlation based residual statics is linear noise attenuation and variable adaptive gap deconvolution (optional) which benefit from a precise sand thickness solution -eliminating the need to iterate- and for reasons discussed in section 5.3.15.3.1.

Since stacking smears the events, we can apply a spiking deconvolution to have a better signature of the event. The new stack can then be interpolated using a 2D interpolation to produce correlograms at intervals of the original unstacked set. The final result is a new sand curve picked from the final stack and fitted with a polynomial.

The new interpolated data can now be used as a pilot to be cross-correlated with the individual source and receiver set with the corresponding elevation. The resultant are residual values due to errors in reverberation signature time picking (or surface elevation picks). I add these values to the two-way static time correction we initially picked and then re-sort to the newly updated times. This improves the elevation surface that was produced

from the un-updated time. The stacking, deconvolution, interpolation and cross-correlation steps can be iterated until we converge to minimum residual values.

It is not necessary to pick the two-way times from the correlograms. Where a trusted picked base of sand is available, it is possible to use its elevation surface, sort by thickness, and do the iterative scheme defined above to enhance the existing elevation surface.

It is also possible to pick a smooth elevation that fits the two-way time correlogram event using the sand curve function derived earlier. Going this route, we might have to iterate the pick so that our picking is spatially consistent. This is because the source and receiver points are different from the acquisition pre-plan, hence, a 2D picking may not converge to the real -sought after- surface at the first pick. This also assures that we do not violate the surface elevation or sabkha elevation by crossing them.

Furthermore, in areas where acquisition is carried around all year long for multiple years, we are able to produce sand curves varying with season. This takes into account the variations in fluid content through different seasons as one dataset is acquired. Although this is a second or third order effect, it reduces potential residual errors.

5.3.4 Adaptive Sand Curve Flow Diagram

A diagram in Figure 5-3 shows the proposed flow. The elements enclosed in the dashed line are repeated if the residual values are high. Until the values converge to zero or stabilize, the iterations should continue.

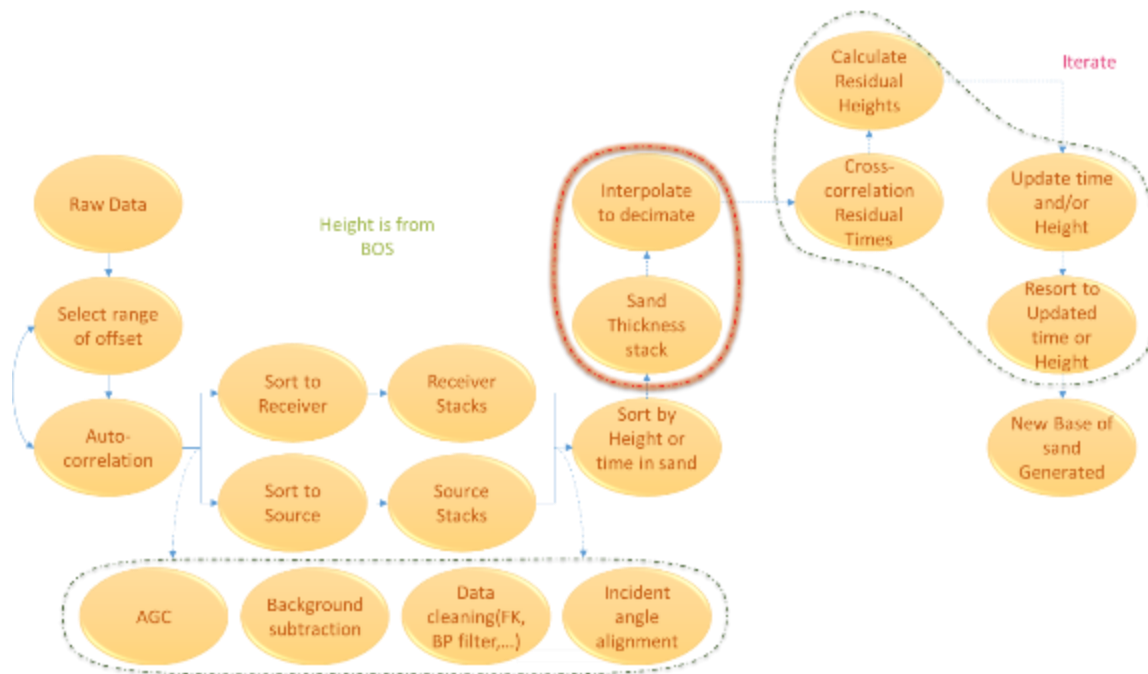


Figure 5-3: A diagram of the proposed flow.

5.4 Elevation Picking

5.4.1 Conventional Elevation Picking

The base of sand picking is usually done on 2D elevation profiles. Source or receiver east-west elevation profile lines are usually used. Since it is a time consuming and labor intensive process, the lines are picked sparsely. As a result, the gridded lines are likely to cross elevation values in between, depending on how sparsely the lines are picked (and how accurate the depth interpretation is). In addition, further smoothing maybe mandatory if simple triangulation is used in the process. This increases the spreading of the elevation crossings to more points.

The residual tomography static residual polynomial curve derived by Bridle (2017) is highly influenced by the legacy picking technique. Thus, different interpretation of the base of sand will require a very different curve updating polynomial correction. Furthermore, my analysis indicates that the under correction of the static-delays of the Sand Curve displayed by Bridle (2017) is associated with the base of sand, rather than the empirical curve.

5.4.2 Proposed Elevation Picking

I have examined a more reliable elevation picking strategy for mixed surface geology areas. The solution integrity increases if the sabkha bodies are uniformly distributed. The more the sabkhas, the higher the accuracy of the surface. The assumption is that the base of sand, which is the sand-sabkha contact layer, is highly smooth under the sand bodies.

The proposed solution relies on the accuracy of the elevation points acquired in the field of the seismic source and receiver points by the surveying unit. Based on elevations, we chose to pick sabkha boundaries enclosing the points of individual sabkhas bodies. Between the sabkhas, under the sand bodies, we interpolate the sabkha elevations. As a result, we generate a connected smooth base of sand spanning the field. This approach may require multiple iterations of sabkha edge editing and the right choice of interpolation algorithms. A short smoother could be necessary for the previously discussed reasons. These two last points are site-specific. Figure 5-4 shows an example of the picking process of an area with a uniform sabkha distribution. The interpolated surface shows a general

slope of the base of sand in the area, and some anomalous points and polygon-related imprints. These are easily improved with a short smoother as mentioned.

As a byproduct, I am able to use picked sabkha points to reclassify surface geology. This said, it is possible to utilize, if exists, the surveying report for each source and receiver point that also tells if the it is placed over sabkhas or sands and interpolate using these. Unfortunately, experience shows that the surveyors classify surface acquired points very poorly, thus requiring extensive editing in preparation. I tried this using cross-plots of elevations and slope angles. This may not eliminate all errors because the points in such environment are highly deviated from the acquisition preplan.

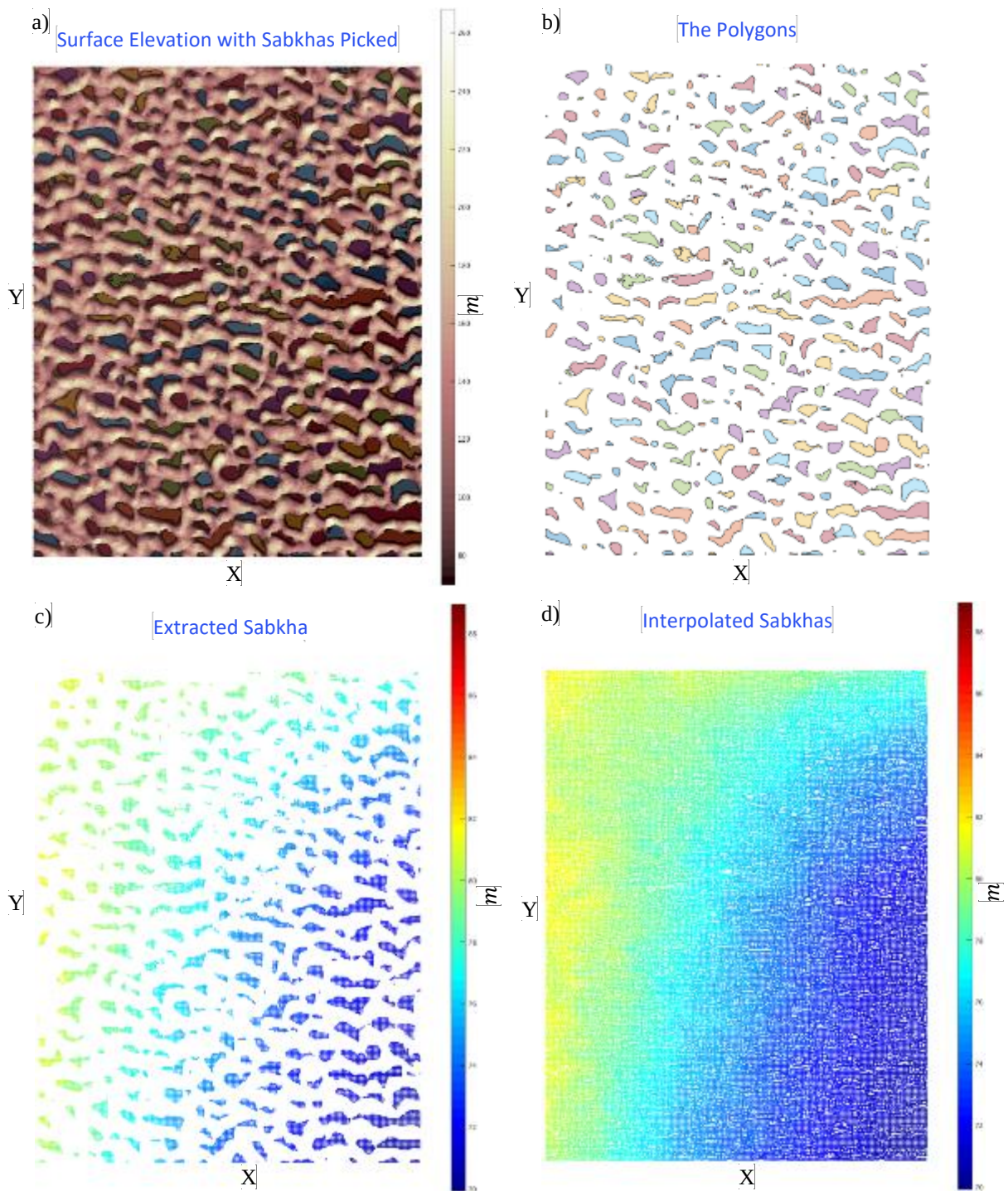


Figure 5-4: Polygon picking on elevation surface. a) Elevation surface with polygons. b) Polygons picked. c) Extracted elevation points from the elevation surface. d) Interpolated elevation surface form the extracted points

In fully sand covered areas, we propose the use of north-south lines in addition to the conventional east-west lines. It is more important that the QC be done in north-south lines than the signature picking itself. This is especially important for acquisitions where dunes are elongated in the east-west direction

This newly picked base of sand may be used as an initial picking for the cross-correlation residual updating the proposed scheme. Depending on the reliability, it can also be used with the time-honored Sand Curve or the new adaptive sand curve to calculate static time delays. After that, the second step in the static solution will use this new elevation surface for the weathering layer time-delay calculation.

Satellite data are very useful in terms of elevation values and actual sand body images. Since sand dunes can change location over time, utilizing historical acquired data of elevations and images from satellites is an added benefit allowing less interpreted base of sand points.

5.4.3 Essential Base of Sand QC

The following is a list of major QC points that yields a better base of sand:

- In a map view of elevation, no North-South or East West lineation are observed.
- Elevation profile shows no medium wavelengths.
- The generated base of sand does not go above the surface elevation.
- Applying gap-deconvolution is able to remove the sand reverberation using the time-in-sand calculated using the generated base of sand.

- Dune de-amplification correction is not amplifying sabkahs (no edge effects) due to classification as sand dune.
- Cross-correlation-based residual static values are very small and do not coincide with the sand dunes.
- The stack response shows good focusing, continuity and resolution.
- Preserving a smooth surface.

5.5 Summary

In this chapter, I discussed limitations of the current Sand Curve approaches. I also explained the importance of a smooth reliable base of sand elevation in the static solution. Then I proposed a new adaptive sand curve and a cross-correlation scheme for updating the picks elevation to mitigate the 2D picking errors. In the end, I proposed a new map view polygon picking of the sabkhas to construct the base of sand.

CHAPTER 6

REAL DATA APPLICATION

In this chapter, I consider a real data acquired in the Rub al Khali desert of Saudi Arabia. A detailed study of the data is presented. Afterward, the methods in chapter 3 are applied and the approach developed in chapter 5 is demonstrated. A comparison of the synthetic data and the derivation of the adaptive data driven sand curve is shown. Finally, the application of the solution on the real data is illustrated.

6.1 Introduction about the Data

The presented data set is acquired in Rub al Khali of Saudi Arabia. The sand dunes are distinctive in terms of the elevations ranging from few meters to 250 meters. They spread spatially across several kilometers and have different shapes across the region with sabkhas. Figure 6-1 shows different types of sand and sabkha shapes and sizes. These sabkhas mark the baseline for the first step in a statistic solution for such an environment. The sabkhas have no static correction values when removing that of the sand bodies; which is the first step in the static solution. There are also areas where sabkhas disappear and only sand covers the topography.

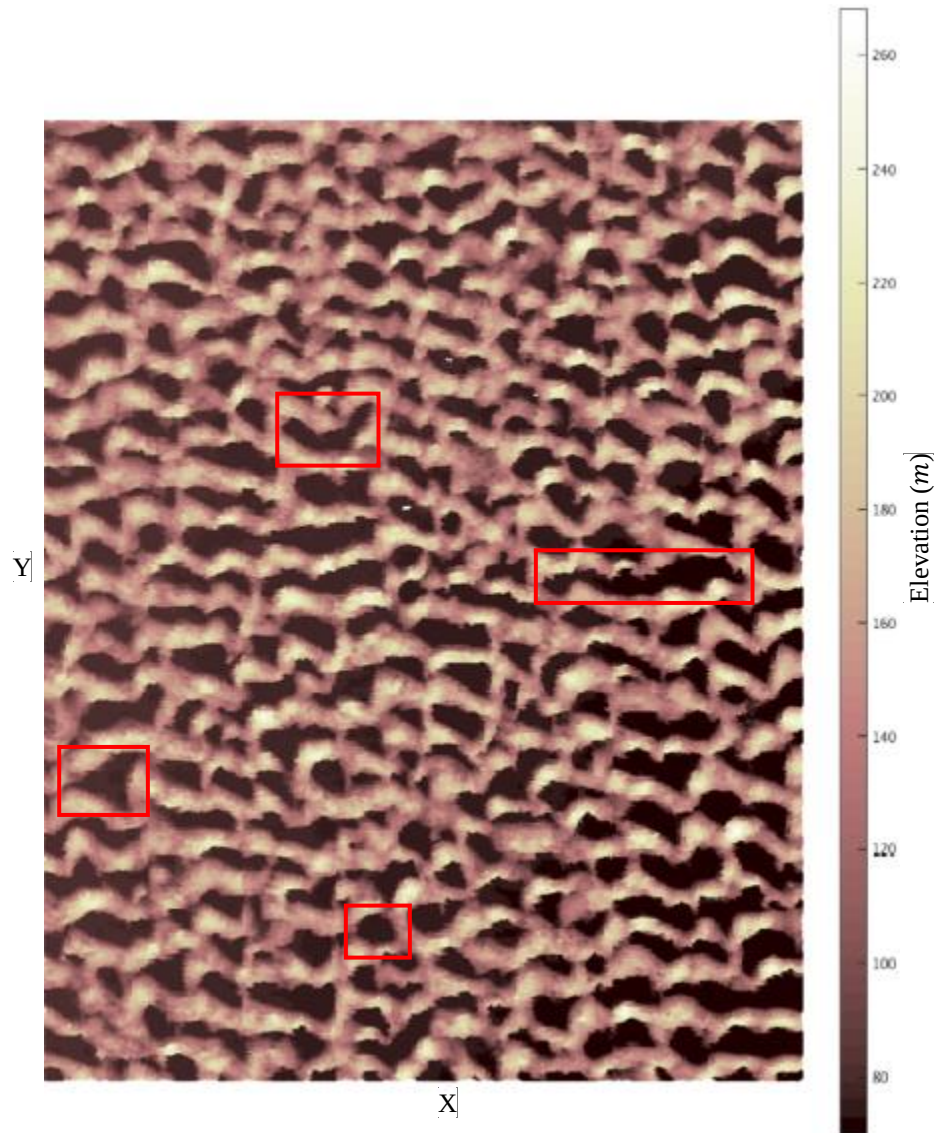


Figure 6-1 Different size and shapes of sand dunes in desert area of Saudi Arabia highlighted with red boxes.

These dunes make the acquisition very difficult to carry on as per blueprint. Accessing dunes from one side is very different from another side; slip face is different from wind ward face for example. Thus, the receiver lines can be very difficult to maintain straight, even to keep smooth at times. In addition, when acquiring multiple blocks, it may not be possible to lay receiver points on the same location that one block has been laid when the

dune was accessed from the other block. For vibrators, it is impossible to reach to the crest of many of the dunes. Thus, the points have to be skidded (moved from the preplanned location). In some seasons, placing sources points would not be possible in sabkhas. This is due to sabkhas being flooded with precipitation that are likely to cause the vibrators to be stuck. These points have to be skidded as well. Figure 6-2 shows a blueprint of the intended source and receiver points, and the actual acquired points. A consequence of this is an imperfect offset coverage. Figure 6-3 shows the variable offset distribution caused by the skidded source points. It also shows the block acquisition boundaries where the fold offset is building in the overlap areas the end blocks.

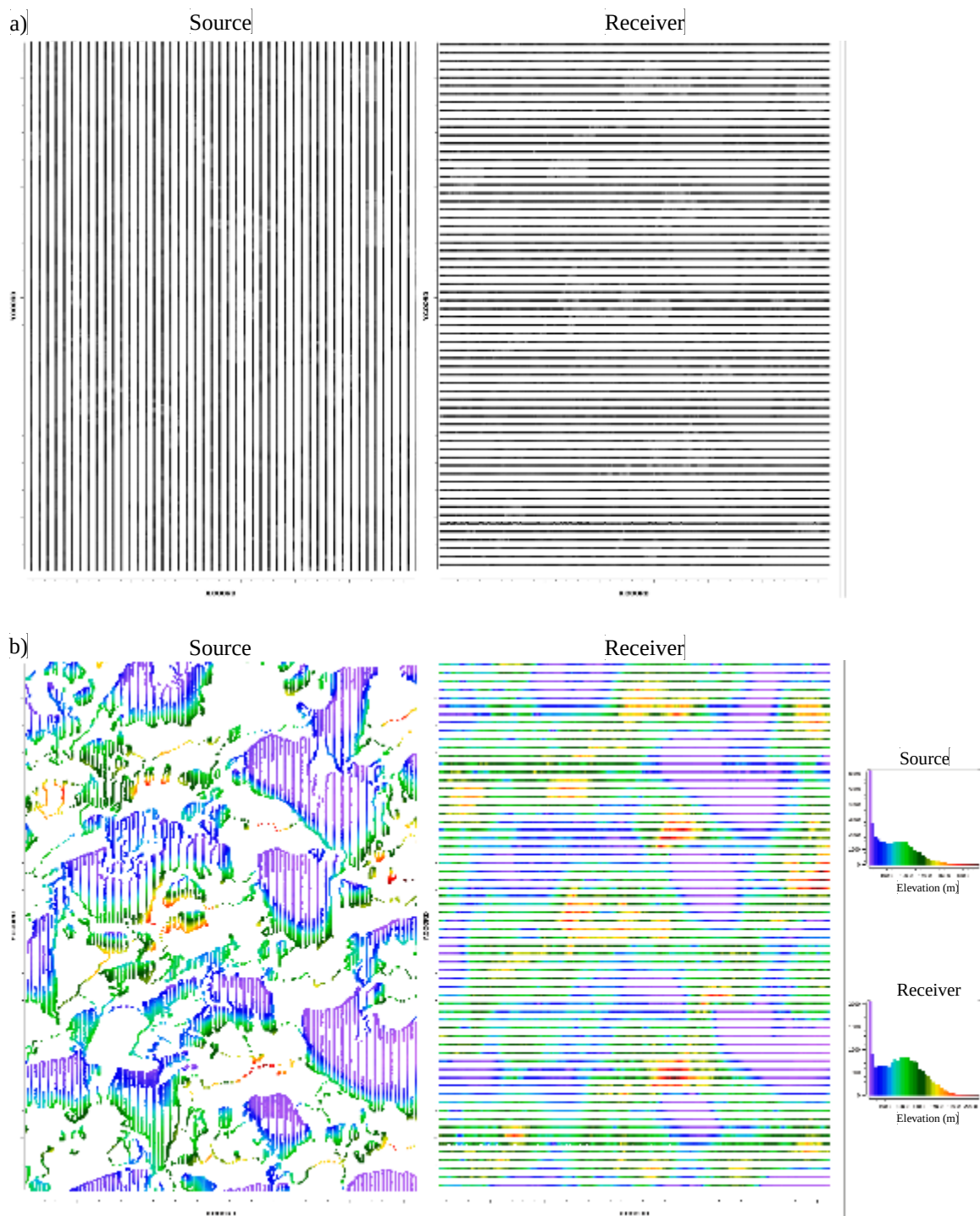


Figure 6-2 a) Shows the blue print of source and receiver points b) The actual acquisition layout for the source and receiver points caused by high elevation dunes in the area.

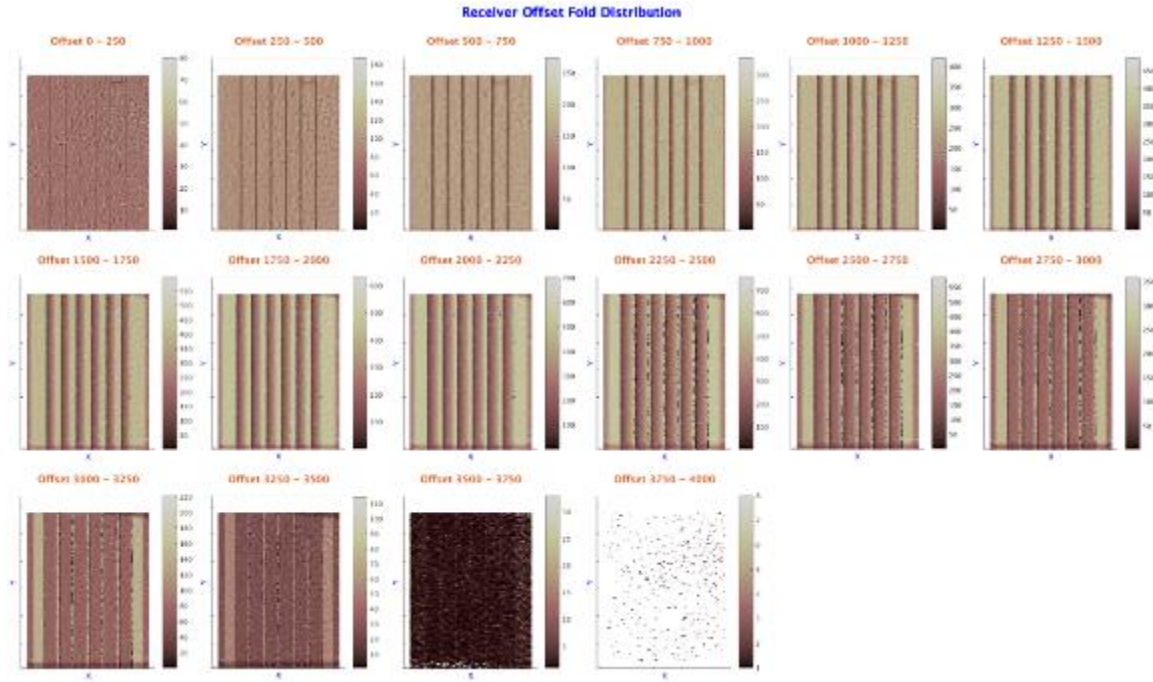


Figure 6-3 Offset distribution of data acquired in desert areas.

As a result, the data has unique characteristics. Although some of the mentioned points could make positive events in our requisite, they degrade the data quality. For example, having to lay receiver points in different non-overlapping points results in a more surface coverage. One point that was accessed from one side of the dune recorded or shot at the highest thickness and another geospatially close point but is recorded or shot on the sabkha forming cross spreads for noise attenuation challenging.

6.2 Application of the flow

The modules introduced in chapter 3 and the approach developed in chapter 5 are applied in this section.

Figure 6-4 shows seismic gather of a near cable acquired on sabkhas and sand dunes. The sand dunes have variable elevation across the line. The areas with the hot amplitudes are those occurring on the dunes (Al-Marzooq et al., 2019). The reverberations are not clear when examining the gather visually.

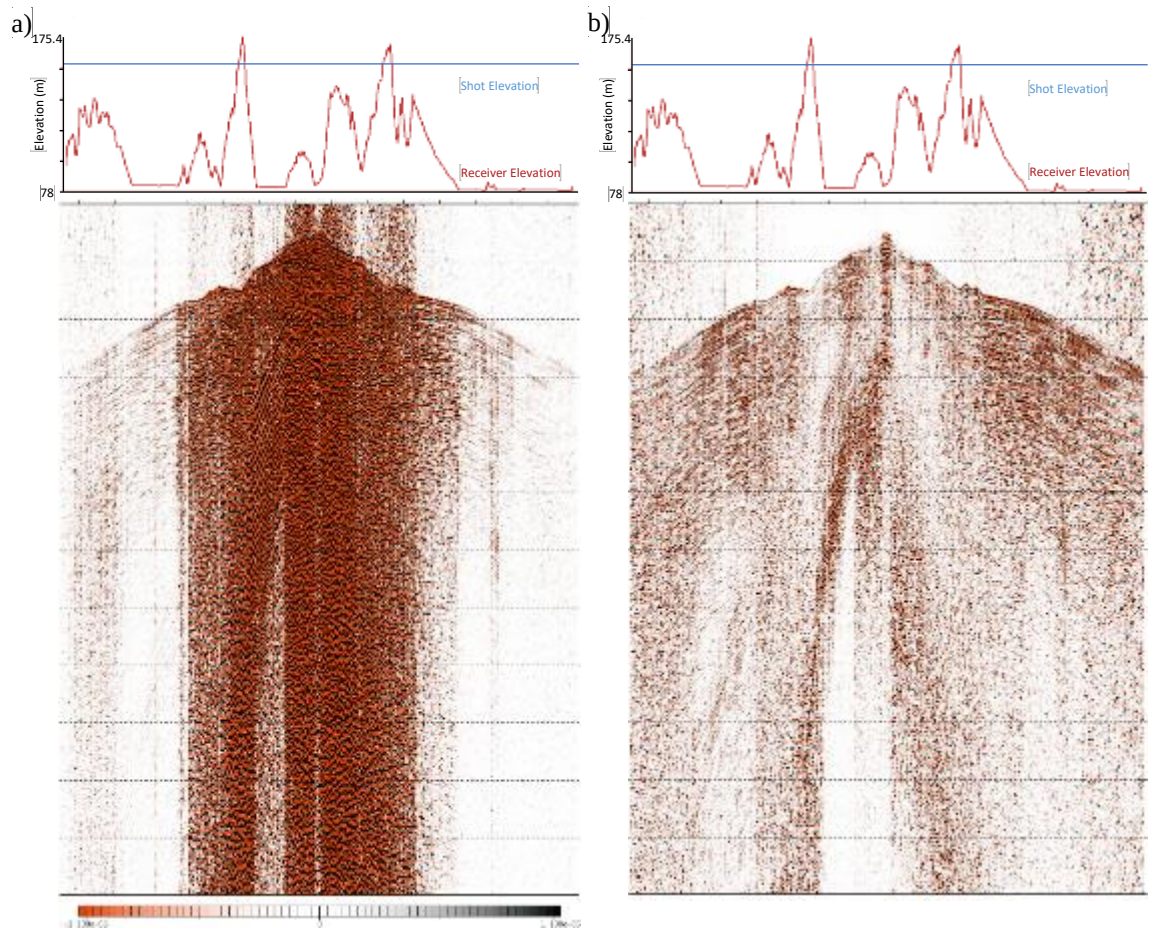


Figure 6-4: A single receiver line traversing dunes and sabkha areas showing amplitude amplification. a) Raw. b) After trace-by-trace equalization. In red is the Receiver elevation profile and in blue is the source.

Figure 6-5 shows the auto-correlogram of the same gather presented in Figure 6-4 with elevation profile plotted on top. The auto-correlogram of the gather shows the signature of

the sand dunes but are very hard to track consistently across the whole line and for the whole offset range or across different elevation values.

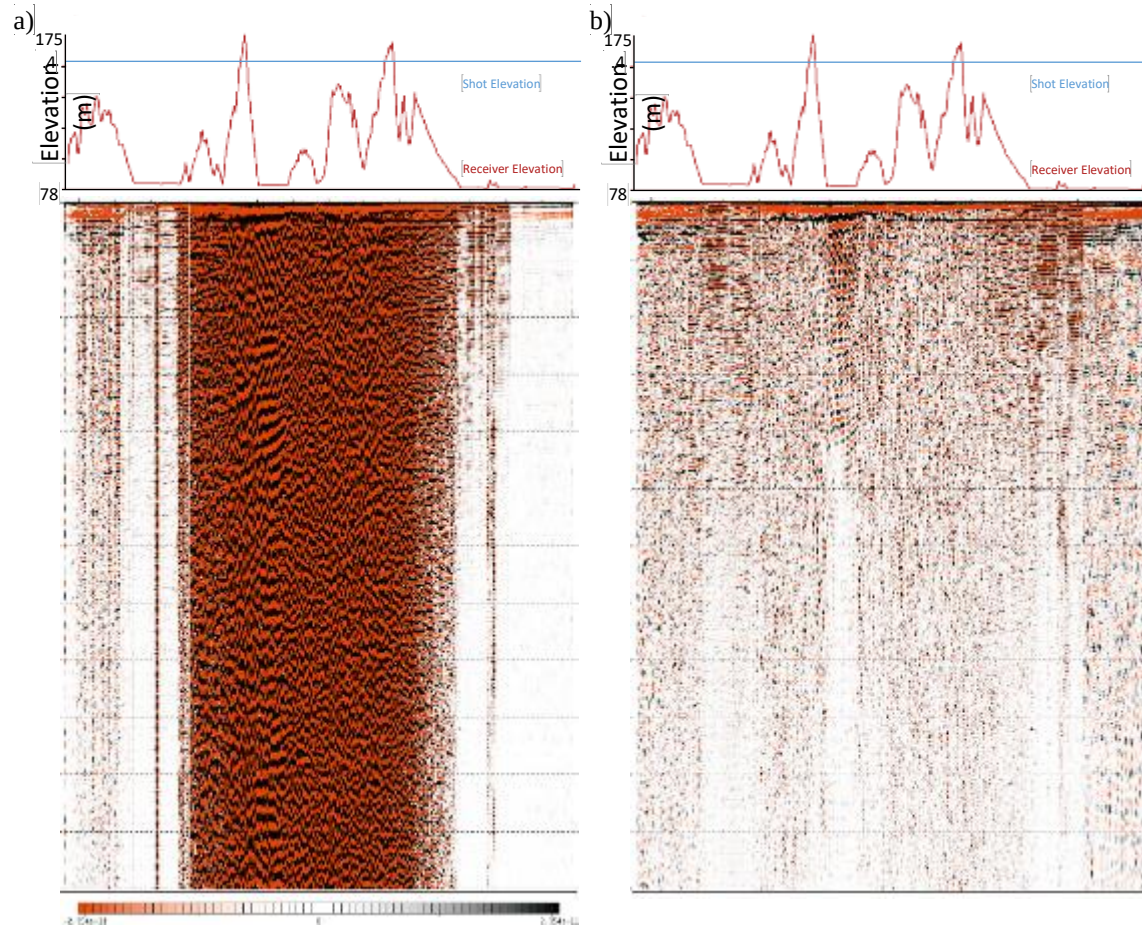


Figure 6-5: a) Auto-correlogram of the raw data in Figure 6-4(a) b) Auto-correlogram of the raw data in Figure 6-4(a)

Figure 6-6 shows pre-stack correlogram highlighting the events. The zoomed-in area illustrates the flatness of the event. This indicates a near-vertical take-off angle of the waves crossing the sand-sabkha boundary and travel the sand body from the source and to the receiver. For this reason, correcting for any offset variation may not be necessary.

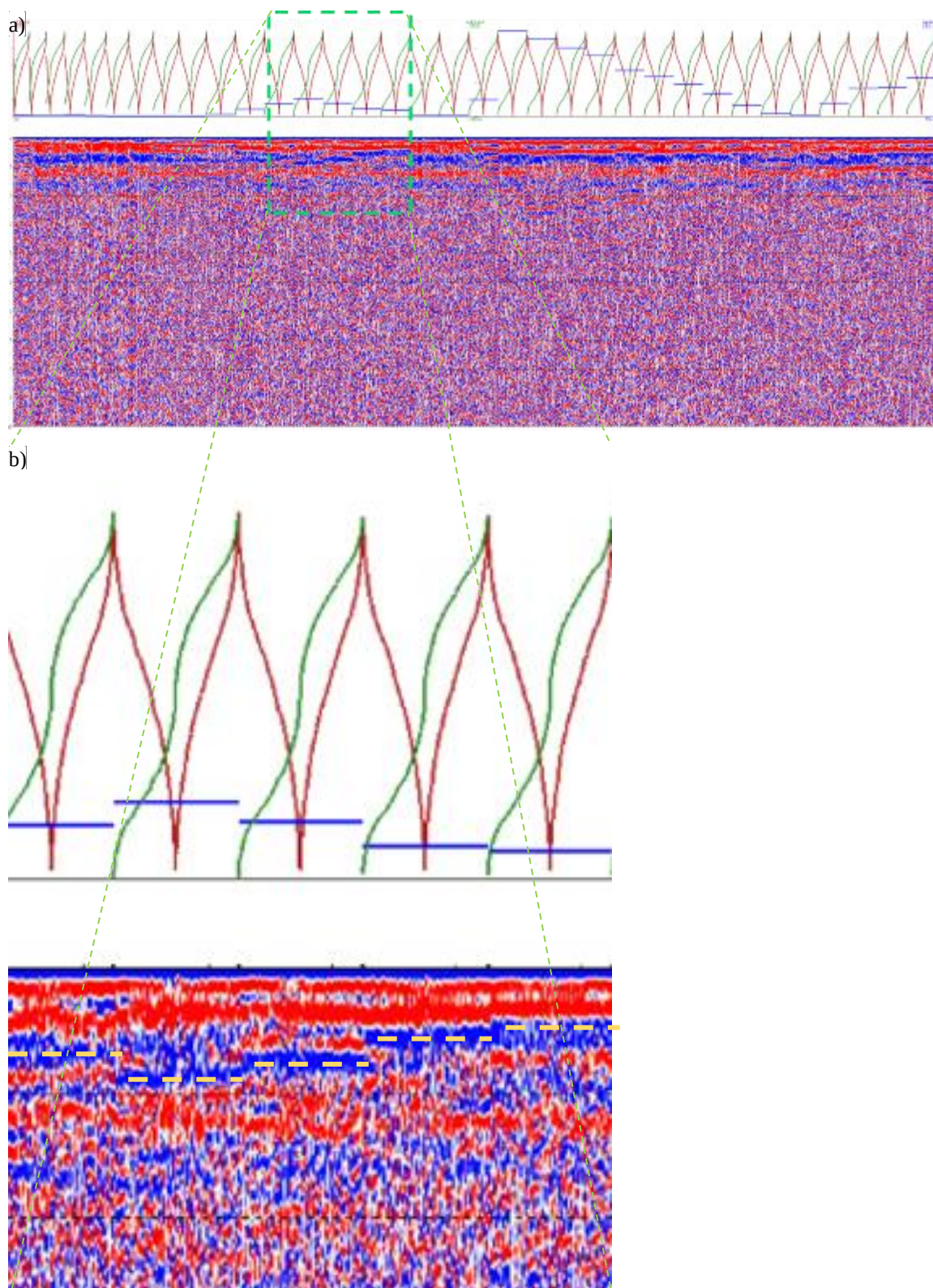


Figure 6-6: a) Pre-stack auto-correlograms sorted by common receiver and signed offsets. b) The green box area zoomed highlighting the sand reverberation signature with dashed orange. In green is the signed offset, in red is the absolute value offset and in blue is the receiver elevation.

The next step is to sum all trace auto-correlations in the designated offset range for each receiver point and each source point. This improves the signature drastically and makes it trackable. Figure 6-7(a) shows a receiver stack for a segment of a seismic line that includes a sabkha and variable sand dune thickness. The mirror image of the elevation profile is very distinguishable. Figure 6-7 (b) shows the application of different enhancements (highlighted in section 3.4) to the same line.

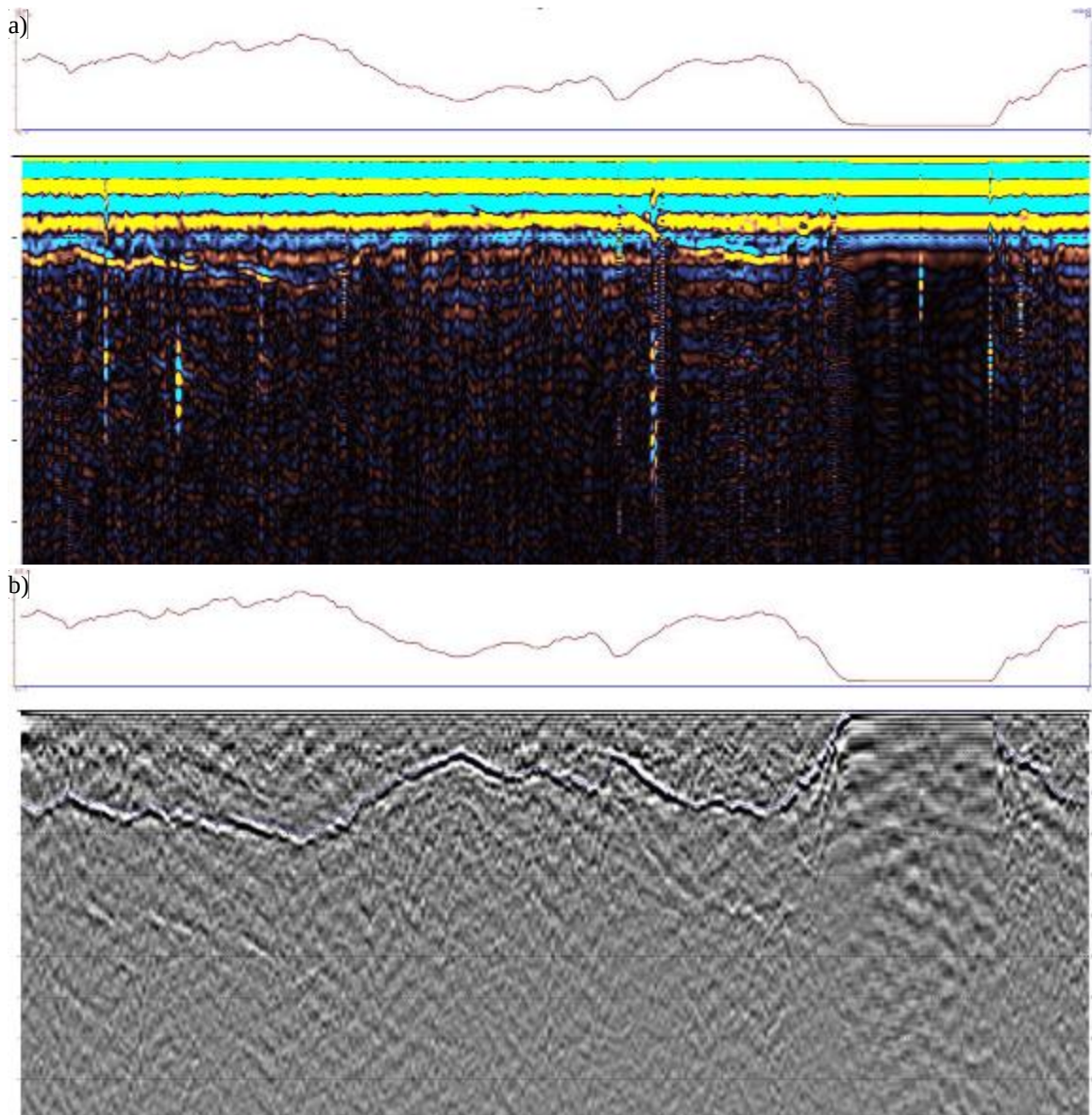


Figure 6-7: a) Raw receiver stack data and b) after enhancement. Plotted in red is the receiver elevation.

Given that autocorrelation gives the highest resemblance to each trace at time zero, we always have the peak of the amplitude at time zero interfering coherently. As we move away from zero time, we observe a mirror of the surface topography in time. This is the indicative signature of the sand reverberation.

Depending on the thickness of the sand dune, the signature may well be buried within the high amplitudes low frequency in the autocorrelation stacks at the low-thickness part. To be able to identify the correct static time delays, we have to design an adaptive deconvolution operator to remove the flat events seen in the autocorrelation stacks. Figure 6-10 shows the operator from this data set. This operator is designed by averaging all the traces after normalization.

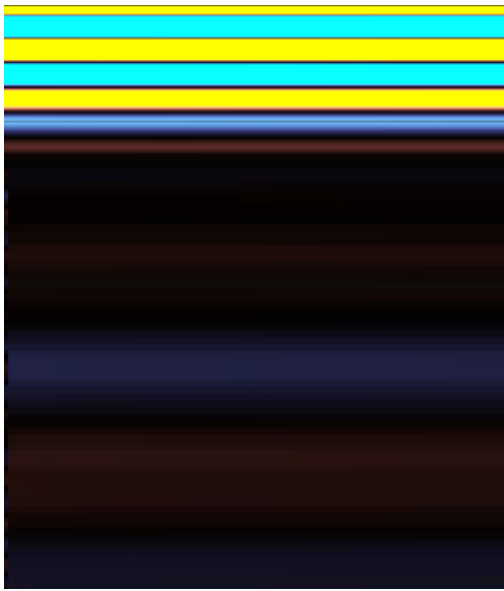


Figure 6-8: The deconvolution operator to remove the background noise.

The base of sand can now be picked on the elevation profile or on the time signature (using the inverse sand curve function). Figure 6-9 shows a long profile that crosses many blocks. While the legacy method was a pure interpretation, the zoomed area shows the benefit of the new method having the signature as a guide. The elevation that was picked gives a two way time in sand that is on the peak of the signature.

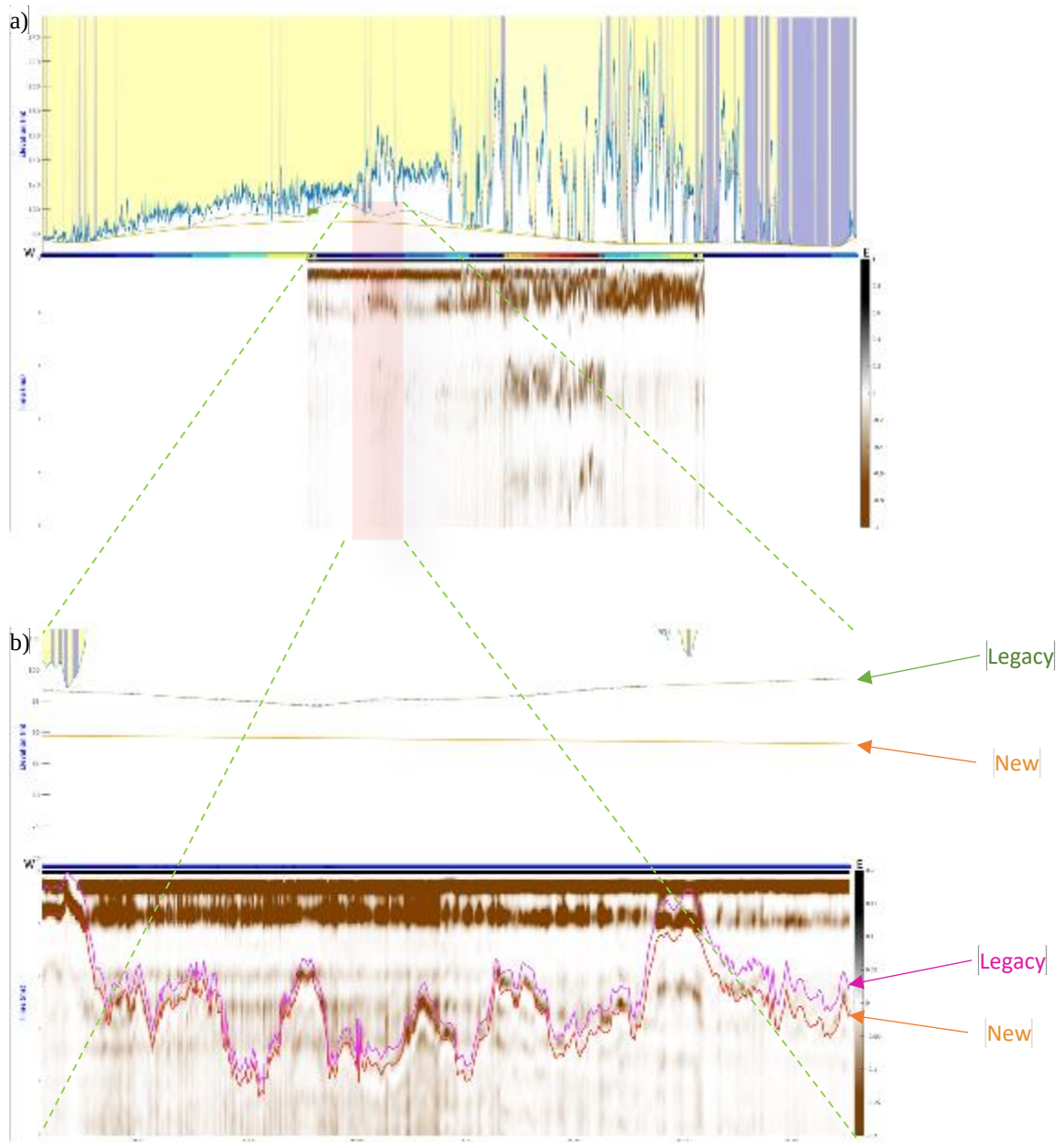


Figure 6-9: a) A long receiver elevation profile that crosses many acquisition blocks with the correspondent auto-correlogram. b) the pink highlighted area is zoomed and the correlogram is gained. In magenta is the two-way-time in sand (using the Sand Curve) corresponding to the green base of sand elevation. In dark orange is the two-way-time in sand (using the Sand Curve) corresponding to the orange base of sand elevation.

Figure 6-10 shows source points sorted by sand thickness based on the legacy base of sand picking (a) and the new (b), as in Figure 6-9a. Figure 6-10b for the same data after using the approach presented in chapter 5. A coherency improvement is clear with the new sort.

As indicated before, this is one way to testify that the new base of sand is better, more consistent, or closer to where the real surface is. Figure 6-11 is shows the same coherency improving for the receiver but to a less degree. Figure 6-12 shows the receiver (a), source (b), and both the source and receiver combined in one panel (c). At first glance, the transit time in sand (the two-way-time delay) appear to go abruptly high when reaching the high elevations at a certain reading. This impression comes from the fact that numerous amounts of the data are distributed in the mid thickness and less of those at the low and high thicknesses. Thus, the uneven distribution of the number of traces is causing this deceptive behavior.

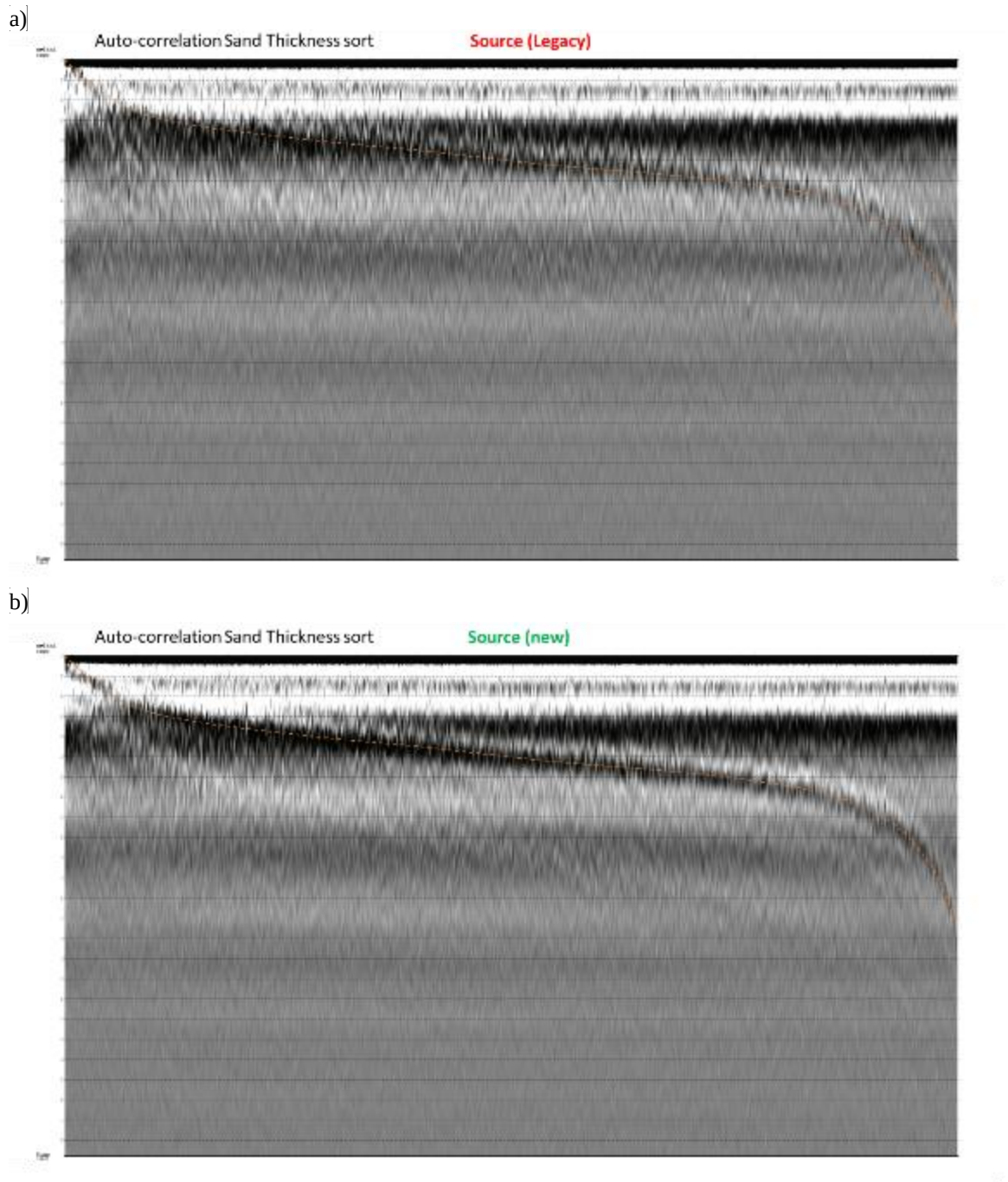
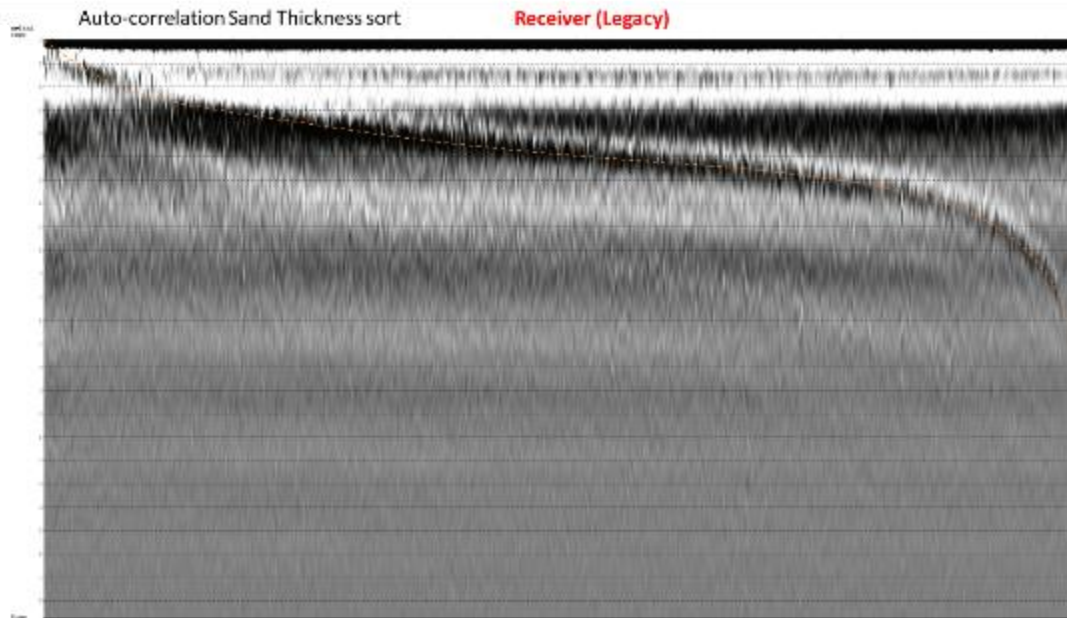


Figure 6-10: Stacked source auto-correlograms sorted by: a) legacy sand thickness and b) new sand thickness.

a)



b)

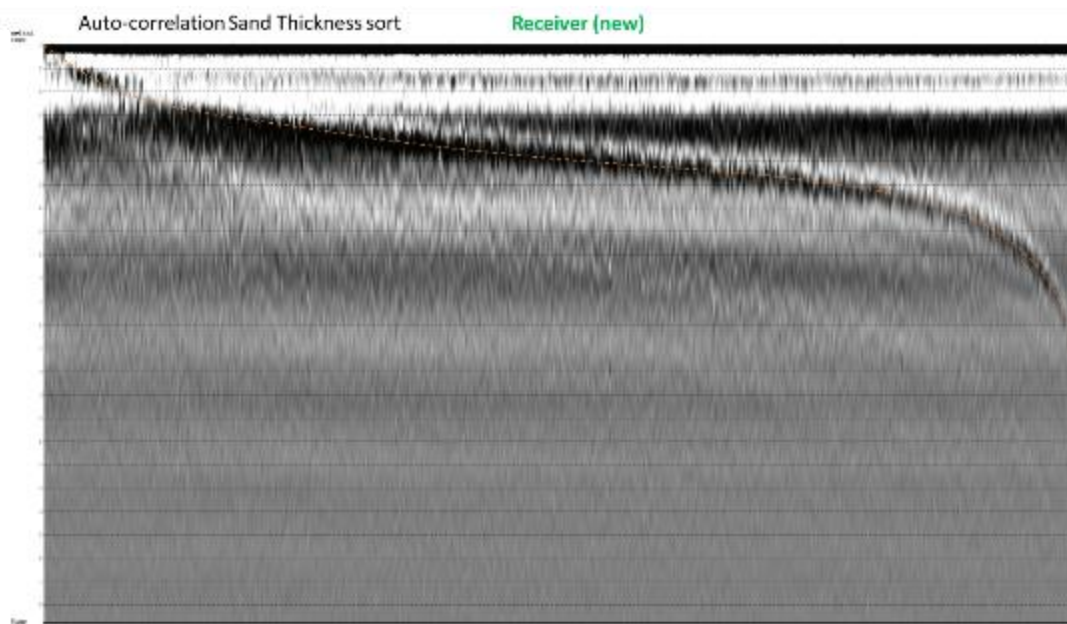


Figure 6-11: Stacked receiver auto-correlograms sorted by: a) legacy sand thickness and b) new sand thickness.

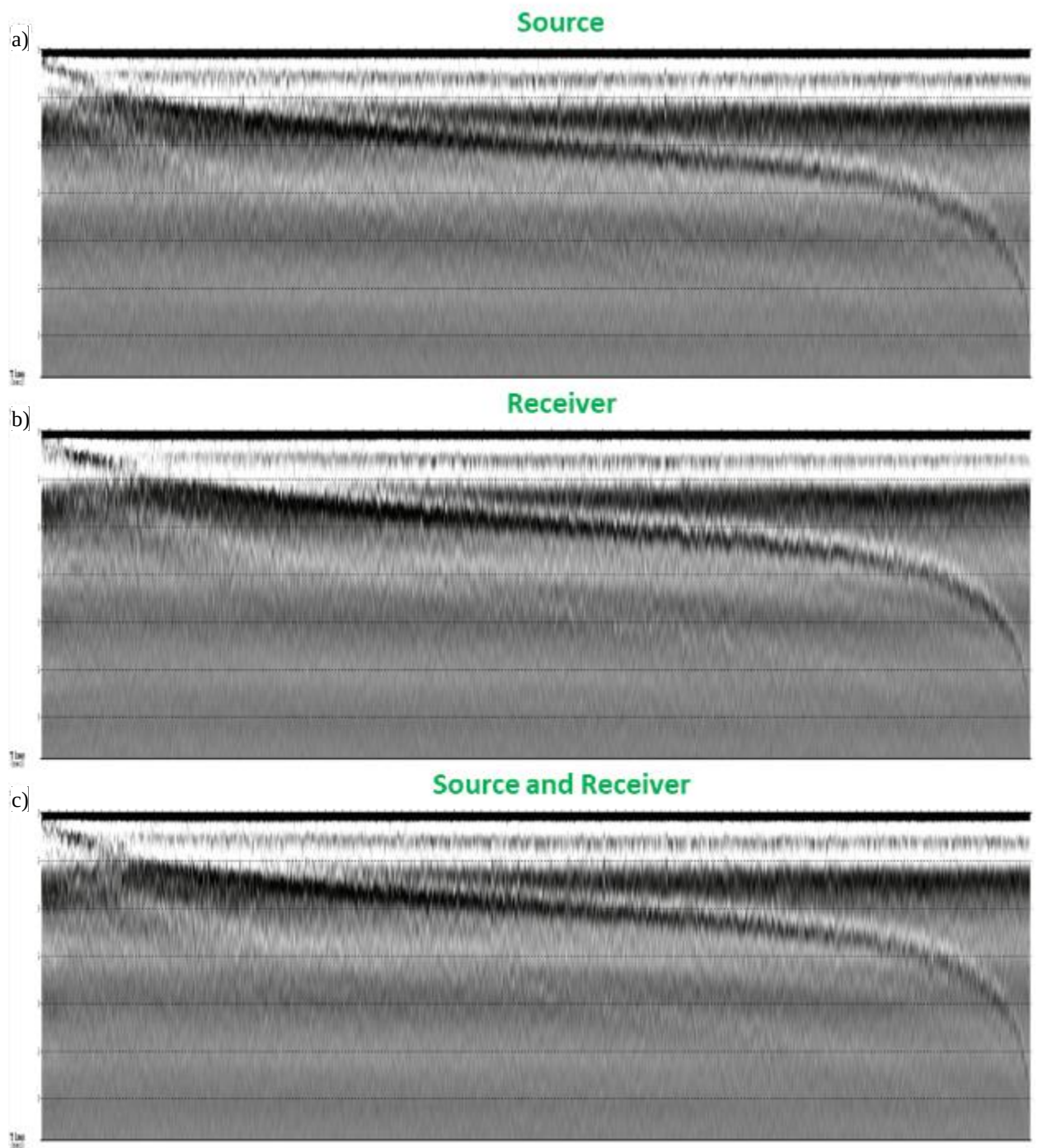


Figure 6-12: Auto-correlograms sorted using the new sand thickness. a) Stacked source b) Stacked receiver C) Both stacked receiver and source combined.

The next step is to design a stacking interval that can best give a high S/N, as well as to give a compressed wavelet. Figure 6-13 is a one-meter interval thickness stack. The stack shows the event signature more coherently. Picking this signature gives the new adaptive sand curve.

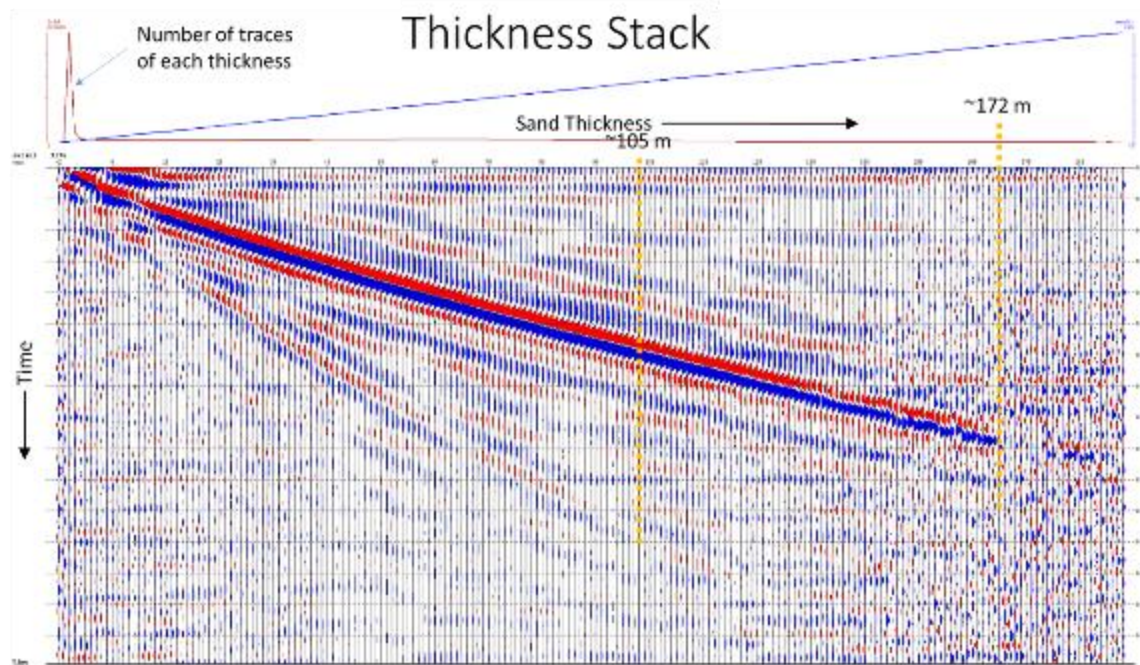


Figure 6-13: Stack of receiver and shot stacks using one-meter interval.

The dashed line occurring at 105 meters corresponds to the heights estimated thickness presented by the data that constructed Sand Curve. The other highlighted dashed line at 172 meters is a conservative cutoff to the extended data we can use to pick a new sand curve. Although, we can pick further up to 200 meters in this data set. Figure 6-14 shows the thickness stack based on the legacy picking method and the proposed one. The signature is more compressed and has a better match with the Sand Curve.

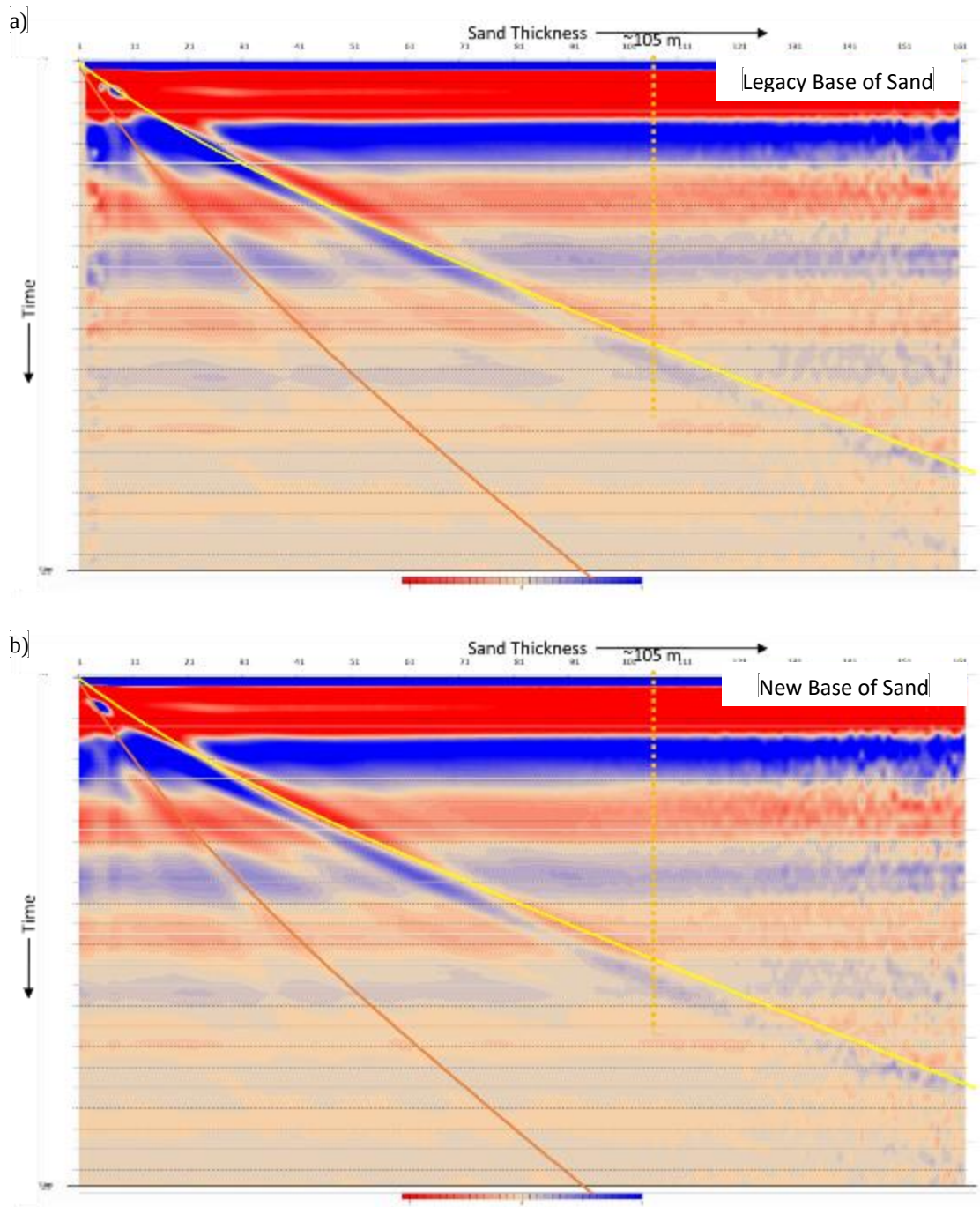


Figure 6-14: Stacked auto-correlograms sorted by: a) legacy sand thickness and b) new sand thickness. The yellow profile is the Sand Curve and the orange is twice the Sand Curve.

Figure 6-15 shows low-cut filter applied on the stacked correlograms based on the new sand thickness. In yellow is the Sand Curve. The olive green is a proposed sand curve.

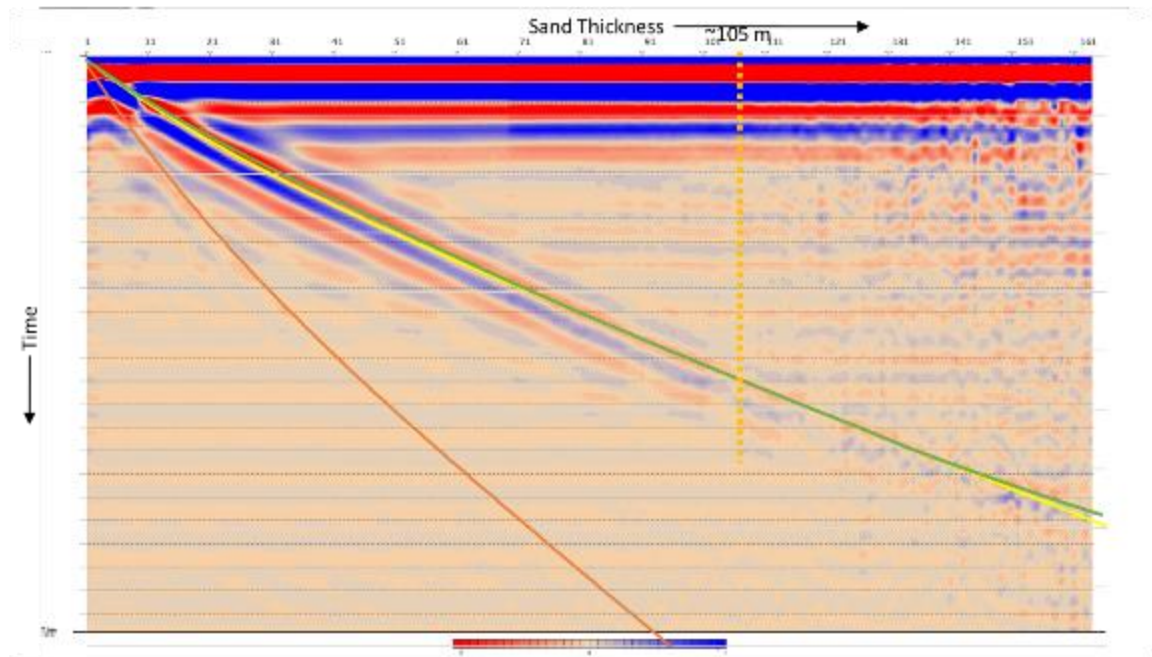


Figure 6-15: Stacked auto-correlograms sorted by sand thickness using the new sand thickness. The yellow profile is the Sand Curve and the orange is twice the Sand Curve. The olive green is a proposed sand curve

Figure 6-16 shows base of sand elevation resulting from the new approach compared with that of the legacy approach. We can see that the developed approach presents a smoother and noise free surface. Figure 6-17 presents CDP stacks representing the two different elevation datums. This shows an example of how the base of sand can exert a long wavelength static. Figure 6-18 is another example of the short wavelength statics that are common in base of sand static.

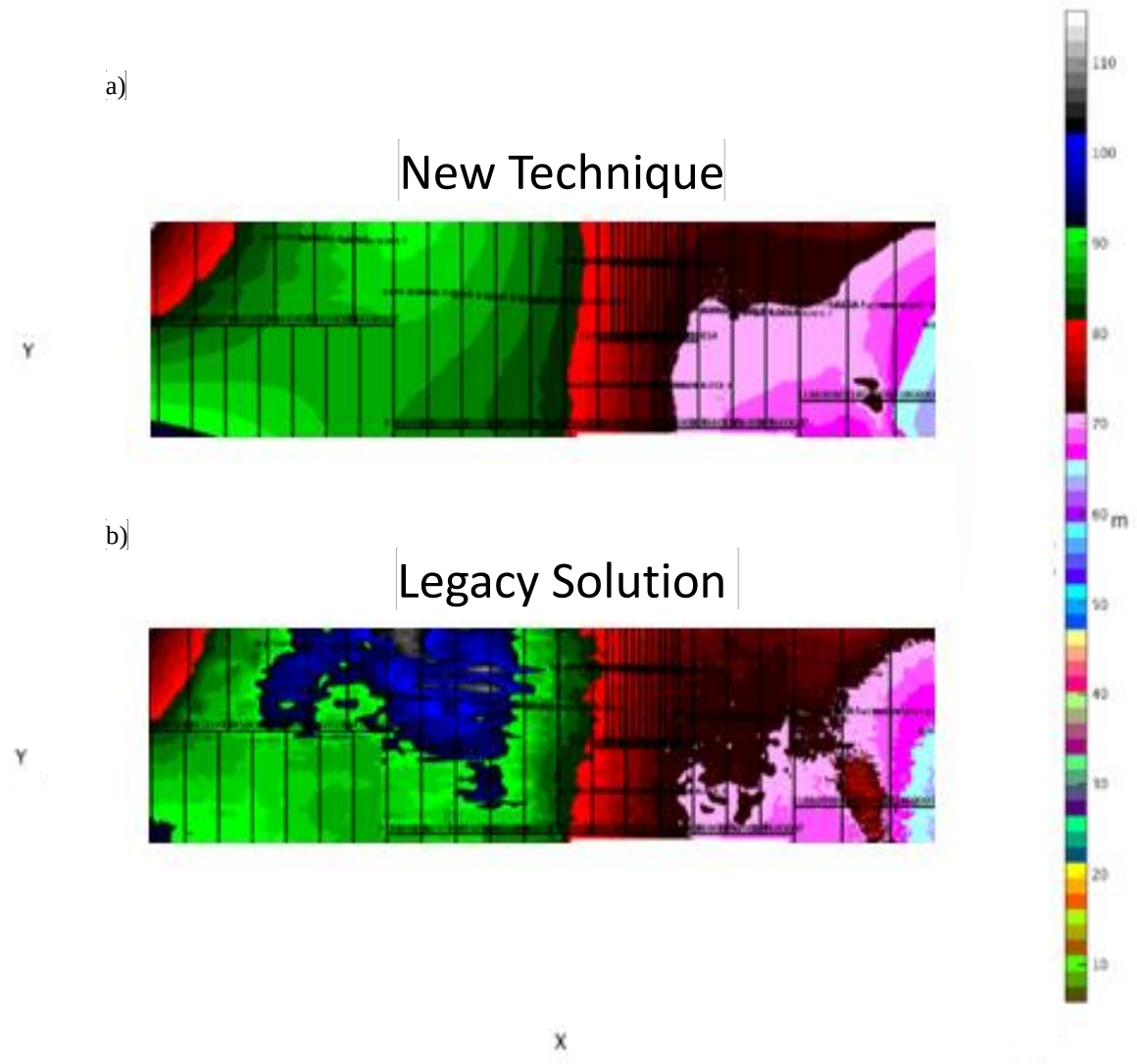


Figure 6-16: Base of sand elevation a) legacy and b) new method.

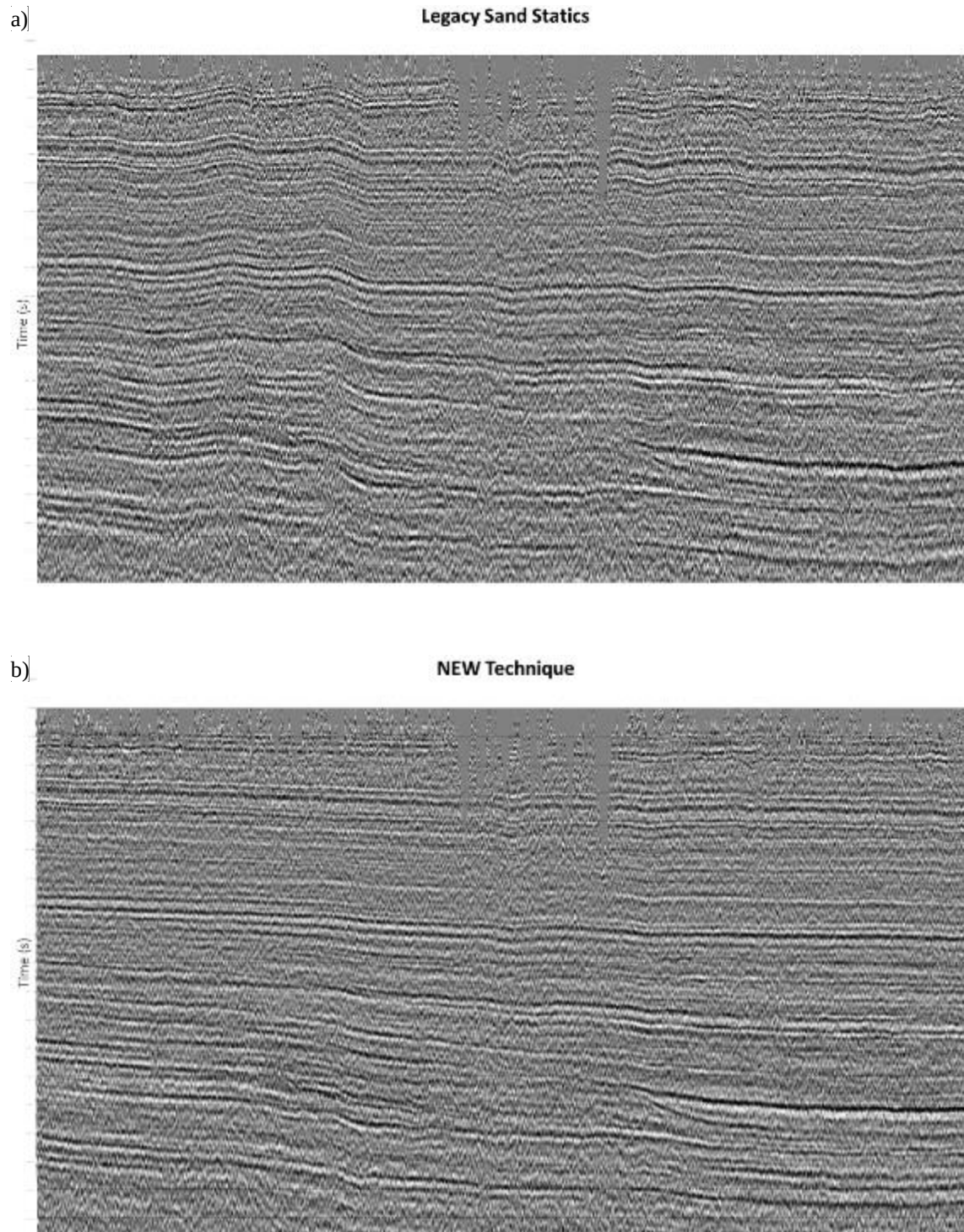


Figure 6-17: CDP stacks with base of sand showing effect on long-wavelength statics a) legacy and b) new

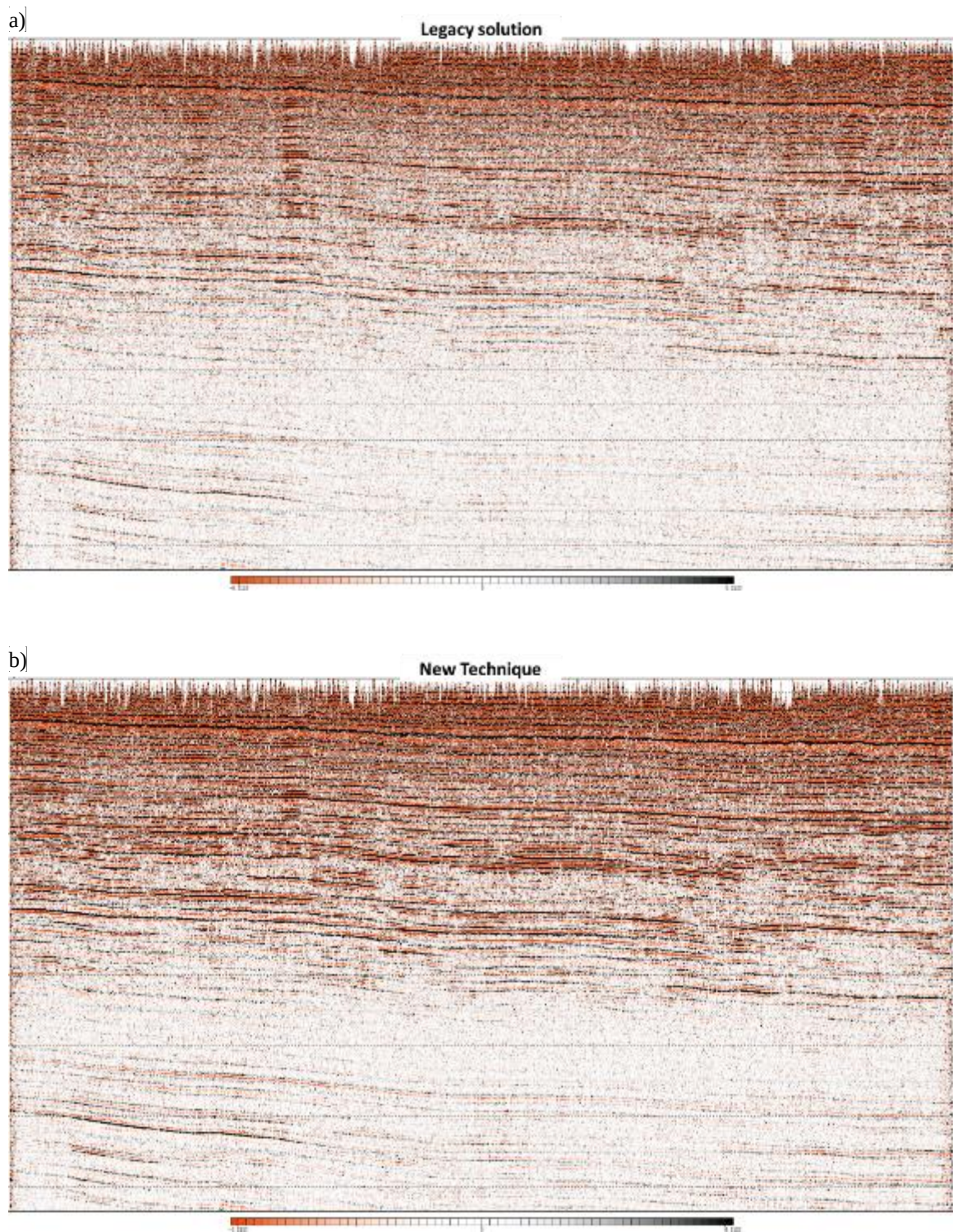


Figure 6-18: CDP stacks with base of sand showing effect on short-wavelength statics a) legacy and b) new. The display is using global amplitude scaling.

6.3 Summary

The developed approach shows a great stack response emphasis. The emphasis in the past is on the stack response. However, the actual relationship is important. This is because a good stack with a poor reference elevation datum will cause harm to imaging or time-to-depth conversion.

CHAPTER 7

DISCUSSION AND CONCLUSION

7.1 Summary

In this thesis, I have covered the literature associated with the sand static delays and sand dune reverberation. I proposed a new methodology to derive the static correction and I covered the fundamentals used in the workflow of the methodology.

7.1.1 Proposed Elevation Picking

I have discussed ways to better utilize the use of the Sand Curve and the application of the sand statics is by picking an appropriate base-of-sand that is smooth and well interpreted. I have shown that the proposed elevation picking will result in first-order improvement. I included a list of QC steps that are responsible in getting the desired outcome.

7.1.2 Data Driven Sand Curve

I showed that the time-honored Sand Curve is a very robust polynomial to solve sand dune static delays. However, it could be improved using the proposed approach. The approach is able to extend the span of the thickness of the original curve. The approach also uses more data points, to better constrain the fit of the curve. In addition, error that is associated

in the thickness present in the points collocated to construct the Sand Curve is no longer a concern.

7.1.3 Adaptive Sand Curve and Base of Sand Building

I have shown an iterative approach to build the sand dune static model including the static delays and the new datum which is the base of sand. The iterative scheme yields a more robust base of sand which is important for the application of the weathering layer statics and for depth imaging. This workflow can be automated and can utilize a more global base of sand to converge to the appropriate base of sand and generate the sand-static-delays.

7.2 Future work

I anticipate that there may be a seasonality associated with seismic wave velocity in sand dunes due to the variability in water saturation levels. I hypothesize that through utilizing precipitation data to evaluate sand static delays, one can build a better-fitted curve for each season in an area.

Likewise, I observed that the sand composition and grain size varies in the region. This may be a source of velocity variation in the sand body. I suggest that different sand curves can be constructed for areas with different sand composition.

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