ATTENUATION OF MULTIPLES IN 2D SHORT STREAMER LENGTH MULTI-CHANNEL SEISMIC DATA, GULF OF CALIFORNIA

By

MUHAMMAD SALMAN ABBASI

Master of Science in Geophysics

Quaid-i-Azam University

Islamabad, Pakistan

2004

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2014

ATTENUATION OF MULTIPLES IN 2D SHORT STREAMER LENGTH MULTI-CHANNEL SEISMIC DATA, GULF OF CALIFORNIA

Thesis Approved:

Dr. Priyank Jaiswal

Thesis Adviser

Dr. Mohamed Abdelsalam

Dr. Todd Halihan

ACKNOWLEDGEMENTS

I would like to extend my gratitude to Boone Pickens School of Geology, for offering me an opportunity to study. I have genuinely gained intellectually and have wonderful experience with working my lab mates. I would like to thank my advisor Dr. Priyank Jaiswal for selecting a wonderful project. He encouraged me in experimenting new ideas and guided me in all aspects of seismology. Also, I would like to thank Dr Mohamed Abdelsalam and Dr. Todd Halihan for being part of my thesis committee. I express my Sincere appreciation for all the good advice, that the committee members have given me during the process of finalizing my thesis. I thank my lab mates, Raj, Pouyan and Iftekhar for their assistance in improving my work and help outside the lab. Finally, I would like to thank my family for their support during my time at Oklahoma State University.

Name: MUHAMMAD SALMAN ABBASI

Date of Degree: MAY, 2014

Title of Study: ATTENUATION OF MULTIPLES IN 2D SHORT STREAMER LENGTH MULTI-CHANNEL SEISMIC DATA, GULF OF CALIFORNIA

Major Field: GEOLOGY

Abstract: Marine seismic data are typically imprinted with multiples energy, which is undesirable in seismic imaging. Due to the coherent nature of multiples, even if the data are long-offset, they are difficult to remove. Here, we present a comparison of four methods for attenuating long-period multiples energy in short–offset 2D streamer data from Gulf of California. Multiple attenuation methods include deconvolution, Linear Radon (Tau-P), Parabolic Radon Transform, and 2D Surface Related Multiple Elimination (SRME). Multiple attenuation entailed selection of most apt method or combination of methods for optimum results, without compromising quality of the primaries in the data. Results suggest that any kind of deconvolution based approach is the least effective. The Linear Radon filtering is effective in selective parts of the model. Both Parabolic Radon transform and SRME appear to be the most effective methods, but not free of inherent pitfalls. The sub-seafloor velocity model appears to be playing a key role in the Parabolic Radon Filtering. We conclude that while there is no general rule in processing multiples attenuation, tailoring methods based on acquisition and subsurface geology often produces the most acceptable result. In our case, we interpret the stack that was produced after application of SRME method. The resulting stack shows new magmatic bodies that were suppressed by multiples energy.

TABLE OF CONTENTS

Chapter Page

LIST OF FIGURES

CHAPTER I

For deep crustal imaging, reflection seismology is one of the most popular methods, mainly due to its intrusive nature and ability to sample large areas with relatively low cost. A seismic survey involves generating external energy pulses through sources such as dynamite, air guns or vibroseis and recording them at increasing distances away from the source. A recorded wave field is the result of interaction between the source and the subsurface rock and fluid types. The recorded data contain random and coherent space-time signals. Of interest to an interpreter is the coherent portions of the wave field that can be linked to subsurface properties. Random signals can arise from traffic or wind in a land survey and sea-mammals and waves motion in a marine survey. The coherent signal can be divided into two broad categories - the desirable part, which typically corresponds to primary reflections and the undesirable part, which interferes with the primary reflection and includes a broad range of modes of energy propagation such as ground roll (land), multiples (marine), and mode-converted waves (both land and marine).

A large portion of the effort in crustal imaging is expended in the removal of the undesirable parts of the recorded wave field while minimizing effects on the desirable parts. This thesis concerns testing four methods of processing marine-seismic data for attenuating coherent multiples energy in a marine seismic dataset. The data have been acquired through a short-offset (maximum source- receiver offset is 2500m), multi-channel (96 channels) survey over undulating seafloor in the Gulf of California where seismic characterization of the

Precambrian crust was intended. The purpose of processing was to ensure that no primary reflections have been obscured by multiples energy prior to crustal interpretation.

Due to the physics of wave-propagation, multiples, which are typically the undesirable part of the seismic coda, become an automatic byproduct of marine survey (Ellsworth, 1948) . In general multiples refer to reverberating seismic energy. In a marine environment, the reverberation occurs between the seafloor and air-water interface which are strong reflectors. Unless the reflection arrivals from the deepest stratigraphy of interest arrive before the first reverberation, the reflection coda is bound to be contaminated with multiples energy. Removing multiples energy through processing is critical prior to imaging (time or depth migration) because most of the imaging algorithms assume that all energy present in the seismic coda are primary.

In principle, multiples can be generated across any interface with strong impedance contrast. Kinematically, multiples can have a varied origin such as from water bottom (reverberation between seafloor and sea surface) or internal (reverberation within one or more layer). Multiples can also be categorized on the basis of their arrival time with respect to their primaries. Short -period multiples immediately trail their respective primary signal. Peg-leg reflection or a pulsating air gun bubbles can create short period reverberations. Longer-period multiples arrive close to twice or later of their primary arrivals. The “order” of multiple is the number of times the energy has reverberated. Fig. 1 illustrated ray paths corresponding to Short and Long Path Multiples. This thesis particularly focuses on water-bottom multiples. The term “water bottom” means ringing of the reflection coda in between the sea floor and air-water interface.

By definition, multiples are periodic in nature, i.e., they keep occurring at regular interval of time in the seismic trace. The property of "repeatability" is used in processing to identify and attenuate the multiples. At zero-offset, the primaries (of deeper interfaces) typically have higher velocity than coincident multiples (of shallower interfaces). Therefore at non-zero offsets, multiples separate out from the primaries due to the difference in their move-outs (trajectory in the time-offset domain). A number of multiple removal algorithms are designed such that this difference is accentuated by transforming the data into other domains (as described below).

Periodicity is deterministic in flat stratigraphy. For example, when the seafloor is flat, the first order water-bottom multiple arrives at approximately twice the time of its primary. However, in an uneven stratigraphy, although periodicity is still prevalent, arrival time of multiples depends on the seafloor geometry. In practice, the time difference (lag) between the repeatable part(s) within the seismic trace can be determined using autocorrelation. The lag can be in turn used to design filters to attenuate multiples. Reflection from the air-water interface reverses the reflection polarity. Therefore, with increasing orders of the multiple, the polarity alternates; the peak of the primary reflection becomes the trough of the first order multiple. The traces are shifted with estimated lags and added to themselves within an appropriate time window attenuated the multiples. It is common for these types of "predictive" filters to be applied in smaller time windows in a running average sense across the whole seismic trace. The predictive filters can be done in time-offset domain or intercept time - ray parameter domain.

When the seafloor is rugged, such as in this case study, the periodicity of the multiple is not definitive. Additionally, when the seafloor is deep (>500 meter), also as in this case study, there is a slight shift in the receiver location (ship movement) which further invalidates the assumption of periodicity. Therefore, the predictive filter is often not effective for attenuating long period multiples in time-offset domain. Taner (1980) showed that data transformed in the domain of intercept (t) and ray parameter (p), can sometimes show better periodicity. The trajectory of reflection in time-offset domain is hyperbolic. When traces in time-offset domain are summed together along paths tangential to the hyperbola, the hyperbola turn into an ellipses(Stoffa et al., 1981); the slope of the tangents is the ray parameter (apparent slowness), and the intercepts of the tangential trajectories at time axis is the intercept. The t-p transform essentially involves approximating a spherical wave by a combination of multiple plane waves (Tatham et al., 1983) . Hyperbole with similar curvatures, such as primary and multiple from a common interface, create similar looking ellipses. Due to a higher curvature of ellipse with respect to corresponding hyperbolas, difference between coincident primary and multiples in this domain is greater than the time-offset domain. As a result, the periodicity can also be exploited in a much better manner. When the predictive filters are applied in this domain, the overall process is known as Linear Radon.

Besides periodicity, move-out times are another important characteristic of seismic multiples. Move-out is velocity dependent which increases with offsets. Methods such as stacking (Mayne, 1962), FK Filtering (Ryu, 1982) and Parabolic Radon (Hampson, 1986) utilize this attribute. Seismic acquisition sources generating seismic energy are recorded at receivers that are typically laid out at regular intervals. To minimize random noise as well as obtain information on the formation velocity, traces from hypothetical, common-reflection points are sorted together in gathers, referred to as the common-mid-point (CMP) gathers. Assuming a flat, layer-cake Earth, individual reflection trajectories in every gather can be corrected for their move-out, referred to as Normal Move-out Correction (Mayne, 1962) and summed into a single trace. This process is known as stacking and has traditionally been an elementary technique in removing multiples. When transformed into frequency (cycles per unit time) and wavenumber (cycles per unit distance) domain, multiples that travel with lower velocity compared to coincident primaries have lower wavenumbers. Ryu (1982) showed that for coincident reflections, deliberately picking velocity which is lower than primary and higher than multiple for Normal Move-out Correction (NMO) followed by domain transformation provides a visible difference between primaries and multiples. The multiples can be muted in the FK domain and the remaining coda can be transformed back into time-offset domain.

The parabolic radon transform (Hampson 1986) is an extension of linear radon transformation which additionally utilizes the move-out attribute. The data are NMO corrected to the best of interpreter's ability (so that the reflections are flat) and then transformed into t-p domain. In principle, a primary reflection from a flat interface which has been appropriately corrected will appear as point amplitude in the t-p domain. The transformed multiples, on the other hand, will have a curved trajectory which is easy to identify. Parabolic radon transform has had numerous successful applications in removing multiples provided the velocities are estimated correctly (Foster and Mosher, 1992; Hampson, 1986; Russell et al., 1990; Sacchi and Porsani, 1999; Sava and Guitton, 2005).

In certain conditions, both periodicity and move-out assumptions can be violated. Marine acquisition is carried out by detonating air guns with receiver cables (streamers) towed at the back of the ship. The air gun generates pulses at regular interval of times, while the ship moves. In deep marine acquisition, due to the ship movement, the receiver position shifts between recording of its primary and multiple, which violates the assumption of periodicity. In additions, if the reflecting interface has complex topography the ray paths are not intuitive. Regardless of the interface complexity, the separation between coincident primary and multiples increases at larger offsets. Thus, removal of multiples in datasets with deep and complex seafloor and small streamer length are the most difficult in processing to address.

Anstey & Newman (1966) introduced a method wherein auto-convolution of a trace predicts multiples for a flat-Earth. Berkhout (1982) extended this concept for laterally varying media. Verschuur (1992) further extended this method to determine ray paths of the multiples through simultaneous spatial-temporal convolution of coincident traces in source and receiver gathers, and called it the Surface Related Multiple Elimination (SRME) method. The SRME methods seem to be the most versatile (Alvarez et al., 2004; Berkhout and Verschuur, 2006; Dragoset et al., 2010; Matson and Abma, 2007; Verschuur, 2006). The concept behind SRME is fairly intuitive. Considering a seismogram as a convolution between the source wavelet and the primary reflectivity series, multiples could be thought of repeated convolutions of the wavelet with the same reflectivity series. For example, the first order multiple is an auto-convolved primary and higher order multiples are convolution of primary with lower order multiples. The receivers at shorter offsets can be used to estimate lower order multiples.

The amplitudes of multiples obtained through SRME have to be strongly conditioned, as the synthetic data obtained through cascading cycles of spatial-temporal convolution, has high amplitudes. SRME estimates multiples by convolving traces of shot gather with primary only response (created by muting) response at common receiver gathers. Since muting rarely ensures removal of all multiples, in practice, a multiple-only response can never be generated by SRME. As a result the SRME is done iteratively. The predicted synthetic multiple coda is subtracted from the real coda in using a least squares method, and the filtered data is used to re-estimate the multiples. In each iteration, the amplitudes of the predicted multiples get closer to the real data.

In this thesis I have attempted multiple removals in a marine dataset that was acquired in the Gulf of California (Fig 2), in Guaymas basin. The acquisition was intended to image the rift and associated deep-crustal features, which includes magmatic bodies and sills. Conventional stacking (Fig 3), shows the presence of strong multiples energy that could be coincident with deep crustal reflections. The magmatic sills and magmatic bodies which are anticipated close to the rift gets overwhelmingly obscured by the multiples energy. (Fig. 3). Due to the short streamer length (2500 m), relative to a deep (900 - 1900 m) and complex seafloor structure, multiples removal is not straightforward. We have tested 4 methods of multiple removal – 1) Predictive filter for short period reverberations (such as bubble pulse), 2) Linear Radon 3) Parabolic Radon and 4) 2D SRME for long period multiples. We have found that 2D SRME provided the highest signal-to-noise ratio in an image which enables improved interpretation of sub-seafloor stratigraphy.

CHAPTER II

2. BACKGROUND

The dataset processed in this thesis is 2D in nature and was acquired across the Guaymas trough, located in Gulf of California (Fig. 2). The intent of the acquisition was to image deep crustal and mantle features associated with the spreading center. The full acquisition was comprised of a 2D Multi-Channel Seismic (MCS) and Ocean bottom seismometer (OBS) layout. While the MCS data provides structural information, the OBS data provides velocity information. However, to obtain velocity information using the OBS data through first arrival or reflection tomography (Morgan et al. 2010), it is first important to obtain structural control. The 2D streamer used in this acquisition is short (2500 m) and is not adequate to image deeper stratigraphy of interest (>1 km depth). The biggest challenge of obtaining structural information is the overwhelming presence of multiples (Fig.3) in the data. Unfortunately, the short streamer length with respect to seafloor depth, makes multiple removal challenging.

2.1 GEOLOGY

The Gulf of California rifting began ~ 4 million year ago (Larson, 1972) with an estimated spreading rate of 6 centimeter per year (Moore, 1973). Presently, Guaymas Basin is actively spreading and is part of the transform fault system that extends from the East Pacific Rise to the Saint Andreas Fault. The Guaymas basin is characterized by high sedimentation rate (Douvere, 2008). The source of sediment is mainly the Colorado River which has been draining the North American continent since the late Miocene (Fuis et al., 1984). A relatively less deformed sedimentary sequence of up to 200 m, which is fairly continuous across the basin suggests that the deformation may have slowed down in the current times (Bischoff and Henyey, 1974). At the base of sedimentary sequence, magmatic sills which are resulted from magma upwelling and intrusion can be found. The sills also mark the top of basement rocks which could be oceanic in composition (Fisher and Becker, 1991). Occasionally, sills are also found interfingering within the sedimentary package. In seismic data the sills typically appear as high amplitude horizons, due to their large acoustic contrast with respect to their host sediments. Multiple episodes of magma ascent is also expected to create intrusive features within basement rocks (Fisher and Becker, 1991).

2.2 DATASET

The seismic profile in this thesis has a NE-SW trend, and passes directly over the Guaymas trough. The sea floor in my profile ranges from 900 to 1900 m depth. Other parameters relevant to acquisition and processing are as follows:

1. Separation between two consecutive air gun fires (source interval): 75 meters
2. Separation between two consecutive hydrophones (receiver interval): 25 meters
3. Fold (number of traces which include reflections from common spatial location): 16
4. Distance of closest hydrophone from source (Near Offset): 125 meters
5. Distance of furthest hydrophone from source (Far offset): 2500 meters
6. Sampling Interval= 4msec
7. Dominant Frequency=30 Hz
8. Dip Limit for Spatial Aliasing at sediment velocity=30

A key challenge in processing is to ensure that recorded data are not aliased, i.e., the spatial sampling is adequate for reconstruction of the steepest dip. In our dataset, with 30 Hz dominant frequency, dips greater than 70 degrees could be aliased. As a result, in comparing the images after processing, we have been skeptic towards the steeply dipping interfaces.

The Guaymas Basin is characterized as complex and deep, which impedes the accurate imaging and multiple estimation with the acquisition constraints (short streamer length). The non-flatness of the sea-surface introduces amplitude and phase perturbations to the source and receiver responses and these can affect the time-lapse image (Laws and Kragh, 2002). Rough sea floor can also be categorized in seismic acquisition, by the wayward diffracted energy. The 2D seismic profile will not be able to capture diffracted wave energy, and this leads to less resolved features even after accurate processing .A rugged sea bottom causes significant changes of the lateral velocity and makes the seismic wave propagate along a complicated seismic path. Also time difference curve is not a hyperbolic, the common mid-point (CMP) gather associated with conventional processing is not the common reflected point gather (Chang et al., 2008).The hyperbolic gathers are pre-condition for effective application for linear (Tau-p) and parabolic radon.

Depth of sea can be categorized as shallow and deep and is relative. Shallow marine acquisition comprises of continental shelf and part of continental slope. Generally, a depth greater than 500 m is considered deep in seismic acquisition. This categorization in seismic depends on acquisition geometries and seismic processing tools being employed. For instance, for shallow marine acquisition smaller source is used compared to deep sea marine acquisitions, as propagating waves incur spherical divergence. Longer streamer lengths and record time is required for deeper acquisitions. Distinction between shallow and deep sea acquisition is prominent in seismic processing tools. The amplitude gains applied to seismic signals for deeper acquisition are more compared to shallower acquisitions. The stretching factor which is stretch of seismic traces at far offsets after application of normal move-out (NMO) is more for longer streamer length (deep sea) compared to shorter streamer lengths (shallow sea). In attenuating multiples, it is observed that prediction filter in linear radon (τ-*p*) fails since multiples are not periodic due to their longer paths, which is attributed to deep sea. In shallow water, where the water bottom is very flat, τ-p deconvolution is alone very effective. .In general deconvolution methods are less effective in deep water. Another problem is that long period requires longer operators. Since primaries can be periodic over long tie windows, long operators have the potential to suppress primaries as well as multiples (Xiao et al., 2003).

The long streamer length is a natural choice for acquiring deeper stratigraphy. The performance of parabolic radon in attenuating long period multiples enhances, as longer streamer presents more delay time (move-out), between primaries and multiples.

Therefore, in seismic processing distinction between shallower and deep seismic acquisitions depends on performance of multiples attenuation algorithms. However, this is not limited to multiple attenuation algorithms. Seismic processing projects are tailored to produce optimum results, by best selection of parameters which best addresses complex and deep seafloor imaging challenges.

CHAPTER III

3. THEORY

The seismic wave field has both desired (signal) and undesired (noise) parts. The primary objective of processing is to enhance Signal-to-Noise (S/N) ratio. In general noises are of two kinds – Incoherent, which is generally random in nature and Coherent, which could be a byproduct of geology or acquisition. My thesis focuses on attenuating a type of coherent noise, which is the reverberating multiple energy between the seafloor and air-water interface. I have tried four methods that are based on periodicity, move-out or a combination of both. These methods are described below in detail.

3.1 Predictive Filtering:

In principle, multiples are predictable using any method that can determine the internal repeatability within a seismic tract; auto-correlation (comparison of the trace to itself) is one method. It helps in visualizing how similar the trace is to itself at different lags. Since first order multiples have opposite polarity with respect to its primary, when the primary is shifted and added, the multiples energy can be attenuated. This method is called predictive filtering. In practice it operates in pieces; a part of the trace which contain the primary is added to the part which contains the multiple.

3.2 LINEAR RADON/*τ-p*:

This method was first introduced by Taner (1980). A shot gather in time-offset domain can be transformed into Linear Radon (intercept-time τ, and ray-parameter, *p*) using the following transformation (Verschuur, 2006):

$$M\ (p_x, \tau) = \int_{-\alpha}^{+\alpha} d(x, t = \tau + p_x \mathbf{x})\ dx$$

where

τ = o- intercept time of tangent to hyperbolas (reflections) in time-offset (t-x) domain

p_x= slope of tangent

M-= Transformed Data

d=Original Data.

In practice, shot gathers in the t-x domain are stacked along dipping trajectories. The dip, p_x, which also serves as a slope of a hypothetical tangent can be quantified as: $p_x = \partial t(x)/\partial x = 1/V_{app}$. The intercept on the time axis is known as *τ*. A flat even such as ground-roll and direct arrival in shot gather transform to a single point, when plotted in terms of in τ-*p*. A hyperbolic event in the t-x domain, on the other hand, is mapped onto an ellipse in the τ-*p* domain (Stoffa et al., 1981). Mapping in the τ-*p* domain is essentially decomposing a spherical wave into plane waves. This transformation has an important benefit. The separation between the ellipse of the primary and its co-incident multiple is much greater in the τ-*p* domain. Further, the periodicity of long period multiples are also preserved. The periodicity can be used as a differentiating tool using predictive filter (Yilmaz, 2001).

The application of Predictive Filter in τ-*p* domain is similar to its application in the t-x domain. Data in the shot gather are transformed into τ-*p* domain and then are auto-correlated to determine the prediction lag (time period after which the multiples energy occurs). After careful selection of prediction distance (lag), an operator length (the length of the window on which the summation has to be done) is selected. Operator length should be long enough so that multiples for a particular primary are accommodated.

The linear radon method has been widely used along with other multiple attenuation methods in both land and marine datasets. In marine data, the bathymetry of the sea bed plays a crucial role. The assumption that the reflection is a hyperbolic event, may easily break down with the seafloor topography is complex which mainly affects the prediction lag in the *τ-p* domain. Alam and Austin (1981) suggests a scaling the lag as:

$$\alpha(\mathrm{p}) = \alpha(0)(1 - \mathrm{p}^2\,\mathrm{V}_\mathrm{w}^2\,)^{1/2}$$

where

α (p) = Prediction lag

$\alpha(0)$= Prediction lag at p= 0

V_W=Water Velocity.

The scaling has met with a limited degree of success in complex seafloors. Over the years, τ-*p* has been used as one of the important methods in eliminating long-period multiples. Since, the efficacy of this method is based on preserving periodicity of multiples; it is rather successful in shallow marine seismic surveys. The τ-*p* has not been a reliable multiple attenuation method for deep water seismic data or where the sea bed has rough topography, since periodicity could not be preserved.

3.3 Parabolic Radon Transform:

Parabolic Radon Transform was introduced by Hampson (1986). This method exploits the move-out of multiples in the CDP domain.The NMO correction compensates the delayed time caused by source-receiver offset, so that all events seismic trace have vertical time. The NMO correction is preceded by sorting the seismic traces in the CDP domain. The NMO equation is given in (Yilmaz, 2001):

$$\mathrm{t} = \tau^2\ + (4\mathrm{h}^2\,/\mathrm{V}^2)^{1/2}$$

where

t = time after NMO correction

τ = two-way zero offset time

h = half offset

V= Stacking Velocity.

After the NMO correction, the CMP gather primaries are flattened or over-corrected, whereas the multiples remain under-corrected. This transformation is called Parabolic Radon Transform, since the NMO correction leaves under-corrected multiples with a parabolic trajectory. This plot assists in separation of multiples which are not separable in time-space domain.

Hampson(1986), introduced this transform as an effective tool for multiple attenuation. Below is the equation from (Verschuur, 2006):

$$M\ (q, \tau) = \int_{-\infty}^{+\infty} d(x, t = \tau + qx^2)\ dx$$

where

q= curvature

τ= two way zero offset time

t= time after NMO correction

M=radon transformed data

d=original Data.

The data, when plotted in terms of zero-offset two way time (τ) and curvature (q), which is the degree of roundness, will have the positive curvatures representing the under-corrected multiples and negative curvatures presenting the over-corrected primaries. The positive curvatures can be removed from the transformed data by filtering and the remaining data can be transformed back in the t-x domain. This method is effective in datasets which have large move-out differences between primaries and multiples. The parabolic radon transform equation can also be expressed in frequency domain, where the wave field is decomposed into plane waves, after which the result is inverse transformed from frequency to time (Verschuur, 2006):

$$\mathrm{M}\ (\mathrm{q},\ \mathrm{f}) = \int_{-\infty}^{+\infty} d(\mathrm{x}, \mathrm{f})\mathrm{e}^{(-2\pi \mathrm{fq}x^2)}\ \mathrm{dx}$$

However, inverse parabolic radon transform i.e. bringing the data from parabolic radon space to t-x domain causes problems. When transforming data in parabolic domain, smearing effect is seen, that cannot be properly reconstructed in time domain, after the application of Inverse radon transform. This is due to the fact that the offset range in the input data is limited and each limitation in the space-time domain yields a smearing effect in the transform domain (Verschuur, 2006).

Hampson (1986) proposed a least-square method, by improving the data in radon space, and minimizing the difference between the re-constructed T-X data and the original one. This minimization is done on root mean square (RMS) values of difference of two datasets, and modification in radon space. For this implementation to become efficient, the process of inversion is carried in frequency domain. The input data are a function of x and the model space is function q [Verschuur, 2006]. The frequency Equation can be written as:

$$\mathrm{L} = \mathrm{e}^{-2\pi \mathrm{fq}x^2}$$

where

L= operator that transforms data into parabolic radon domain
2*pi*f=angular frequency
q=curvature
x=offset

The Radon panel is constructed as per frequency component for all possible curvatures at all offsets. As described, the optimization is carried in least square`s sense and the Radon space can be described as:

$$\mathbf{M} = (LL^{H})^{-1}\mathbf{Ld}$$

where

M=transformed data

d=original Data

The data are reconstructed using the equation:

$$\mathbf{d} = L^{H}\mathbf{m}$$

The reconstructed data are very similar to the original data. Thus, multiples are muted in the Parabolic Radon transform and are re-constructed into T-X domain. Radon has been very effective if correct velocities are used to distinguish between primaries and multiples. Radon is a successful technique used in the petroleum industry. But it is pertinent to mention that radon works under two assumptions (Verschuur, 2006):

1. Primaries and multiples map into different areas in the Radon domain, after which they can be separated.

2. Primary and multiples events can be described efficiently by hyperbolas and parabola in the NMO-corrected CMP offset domain.

The first assumption holds true in most geological settings. In terms of velocity, the velocity increases with depth. Multiples have lower velocities compared to the primaries at the deeper depth. But in case of velocity inversion, when we have higher velocities at the shallower depth compared to the deeper, this assumption will not hold. High velocity associated with the shallower horizons, will exhibit multiples which cannot be distinguished by lower velocity primaries at the deeper depth. So the NMO corrected multiples will not have hyperbolic and parabolic curvature, and thus cannot be filtered-out in Radon space.

Secondly, in dipping and complex geological setting, events do not have a hyperbolic and parabolic occurrence. The more lateral variations are present in the Earth, the more the assumption of hyperbolic move-out in the CMP-offset will break down (Verschuur, 2006).Therefore, the multiples not exhibiting parabolic and hyperbolic pattern will not be muted in radon space. Further research remains necessary to extend the Radon transform methodology such that it becomes applicable for complex media [Verschuur, 2006]

In my thesis I have used the ProMax data processing software which uses the semblance Weighted Radon (Bradshaw and Ng 1987). Semblance weighted radon first transforms the data into radon space and runs coherency to plot major clusters of energy into a new radon panel. The coherency scan of high energy clusters to lower energy clusters is again carried out in radon space using Gauss-Seidel iterative method for making a complete radon panel. The high resolution radon was proposed by Ng and Perz (2004) which performs the same procedure, but after first scanning, it subtracts the energy taken out in radon space and return to shot gather for a new round of transformation into radon space, where it is rescanned for coherency and the new cluster of energy is again added to the previous radon panel. The process is iterative and uses Gauss-Seidel sparse matrix operation until convergence is done. The back and forth transformation from shot gather to radon space at each iteration, prevents smearing in radon space and has proven to be more efficient than semblance weighted radon. Synthetic tests in the published literature have shown that the method achieves excellent τ-p localization and multiples attenuation (Ng and Perz, 2004).

3.4 Surface Related Multiples Elimination

Surface related Multiples elimination (SRME) is a unique method in removing surface related multiples. Unlike, the aforementioned methods, this method use the concept of simultaneous space and time convolution (Verschuur, 2006). Assuming that the seismic wave field convolves with the earth' reflectivity series to produce seismic trace, the equation for SRME is given as:

$$Po\ (t) = p(t) - a(t)*p\ (t)*p\ (t) + a\ (t)*a(t)*p(t)*p(t)*p(t) - \ldots$$

Where

p(t) = Seismic date

Po(t) = Seismic Data without multiplies

A(t) =surface operator a(t) acts as a source de-convolution filter

* =symbol of convolution.

Verschuur derived the above formula for practical application of SRME, considering the premise of convolution. The aforementioned formula exhibits an effective method of prediction multiples from a seismic data, by convolving to itself. Each convolution predicts multiples for 1st order and so forth. The alternate positive and negative signs indicate downward reflectivity from the surface. The surface operator a(t) is the de-convolution filter, which de-convolves the signal receiving at the surface, before it is used for the convolution with reflectivity of earth and predicting multiples. Theoretically, true impulse response is required, and therefore each signal at the surface is de-convolved before the consequent convolution to the reflectivity. SRME can also be operated in frequency domain. The equation is given by (Verschuur, 2006):

$$Po\ (f) = P(f) - A(f)P2(f) + A2\ (f)P3(f) -$$

The predicted surface multiples are then added to the original trace and the multiples are removed. The same practice is exercised for seismic data. The aforementioned method was derived considering a flat layer or 1D Earth model.

In practice the theoretical 1D (horizontal layer) SRME model has to be tailored for estimating all order of surface multiples. The real subsurface does not have horizontal stratigraphy. Verschuur (1992) proposed a new methodology for estimating multiples using the aforementioned SRME methodology. Common receiver traces are convolved trace by trace to corresponding common shot gather, to estimate all order of multiples. Multiples constitute primary as well as multiples paths. Common shot gather traces represent the primary path and common receiver traces represents the addition multiples paths for that particular primary trace. The convolved traces are summed to predict all order of multiples. 2D SRME is a practical method in seismic processing to estimate most surface multiples for a shot gather.

It is also evident from the methodology that higher orders of multiples are estimated at further offsets. Note that location of the stationary reflection point at the surface will vary for each type of multiple. Therefore, a pre-selection of traces to flow into this summation may limit the accuracy of the prediction process (Dragoset et al., 2010). It is difficult to estimate source signature for all traces in 2D case, which involves common shot and common receiver gather. Each combination of traces represents wave field with different paths. So in practice de-convolution at each receiver is not done. Therefore, 2D SRME gives accurate arrival time of multiples, but its amplitudes are not accurate to match the multiples occurring in real dataset. This problem will be addressed in 2D SRME subtraction by using adaptive filtering.

3.4.1 Adaptive version of SRME:

A better estimate of source signature is required for effective removal of multiples energy, otherwise remnant multiples energy will be left in seismic data. The best estimate is proposed by Verschuur et. al (1992) which is an adaptive method. Practically, the seismic shot gathers are matched with the predicted multiples (which are added at this stage of SRME), by virtue of defining windows in the original seismic data with multiples for accurate estimation of source signature. Filters are estimated in the least square sense. The windows are shifted in time and space and a new matching filter is calculated.

3.4.2 Iterative SRME

The amplitudes of multiples obtained through SRME have to be strongly conditioned, as the synthetic data obtained through cascading cycles of spatial-temporal convolution, has high amplitudes. SRME estimates multiples by convolving traces of shot gather with primary only (created by muting) response at common receiver gathers. Since muting rarely ensures removal of all multiples, in practice, a multiple-only response can never be generated by SRME. As a result the SRME is done iteratively. The predicted synthetic multiple coda is subtracted from the real coda in using least squares method, and the filtered data is used to re-estimate the multiples. In each iteration, the amplitudes of the predicted multiples get closer to the real data.

The iterative 2D SRME can be expressed below (Verschuur, 2006):

$$\mathbf{Po\,(i + 1) = P - A(f)Po(i)P}$$

where

Po (I + 1)= next iteration for multiple estimation

A (f) = surface operator in frequency domain

Po (i) = multiples estimate of previous iteration

Hence multiples of different order are predicted in the first iteration are subtracted and then undergoes subsequent iteration of SRME and subtraction. The number of iterations is not fixed and varies for different datasets. Each subtraction round also affects the quality of primary energy. So a compromise has to be met, to preserve primaries and attenuate multiples so that deeper stratigraphy is less obscured by multiples energy and is interpretable.

The dataset can be categorized as deep and complex. It is worthwhile to mention that deep and complex dataset has its implications for optimum utilization of the aforementioned algorithms, especially Linear Radon (τ-p) and Parabolic Radon.Both algorithms require hyperbolic trajectory of shot gathers. The reflection events are hyperbolic because waves propagates with hyperbolic trajectory.

Shallower sea floor reflections are more hyperbolic, but due to delayed arrival times and inhomogeneity`s in the propagating medium, the hyperbolic trajectory for deep seafloor and underlying stratigraphy could not be preserved. Linear Radon transforms, require construction of tangents (inverse of velocity=slowness=p) along hyperbolic trajectory of events, and then plotting p with respect to 0-intercept times of these tangents. Irregular or non-hyperbolic events violate this condition. This result in inaccurate transformation, and periodicity of multiples could not be preserved. Similarly, parabolic radon entails application of Normal Move-out (NMO), so that delay time due to offsets will be taken care of. The algorithm states that once hyperbolic events are corrected using NMO, multiples depict parabolic trajectory. This parabolic path of multiples is mapped in radon space using parabolic equation. But if shot gathers are not hyperbolic, NMO correction will lead to non-parabolic trajectory of multiples, and parabolic radon transform will be inaccurate.

The above conditions for hyperbolic events holds true for complex seafloor as well. Seismic energy reflecting from complex strata is wayward, and do no depict hyperbolic trajectory. Reflected events have irregular geometry and also depict cross-dips and diffractions. Therefore, accurate transformation of these reflected events in Linear Radon (τ-p) and Parabolic Radon are impossible. This leads to inaccurate multiples estimation and attenuation.

CHAPTER IV

APPLICATION & RESULTS

The dataset was first loaded into seismic processing software from Halliburton Inc. ProMax and acquisition geometry is setup. The data was pre-processed for selection of gains, frequency spectrum and predictive de-convolution. Although Automatic Gain of 500 msec is selected for display purposes, it had been removed for the ensuing multiples removal techniques. Spectral analysis was carried out for selection of bandwidth of frequency to be processed (Fig. 6). A bandwidth of 8 to 10 to 60 to 70 Hz, using Ormsby filter was selected.

4.1 Application of Prediction Filter

Predictive filtering was used for attenuating short period reverberations. This was preceded by auto-correlation of traces selected from different locations and making estimate of the best lag for prediction distance (Fig.7). A lag of 20 msec was selected. Using the aforementioned pre-processing parameter, prediction filter is applied on the dataset. This resulted in attenuating short period reverberations. The magmatic bodies were resolved and shown in Fig.8. A comparison between raw stack and stack obtained after application of prediction filter is shown in fig.8.

4.2 Application of Linear Radon Filter:

The linear Radon or τ-p transforms hyperbolic events into ellipse and linear events into points. The dataset was pre-conditioned by applying top mute. A new set of headers for τ and p were added into ProMax, for invoking τ-p parameters during processing. A number of(slowness) values were tested. A relation can be made which accounts for all frequencies upto maximum frequency and time range , to estimate P values:

$$\textbf{Number of P values} = (\mathrm{Dt}_{\mathrm{max}} - \mathrm{Dt}_{\mathrm{min}}) * \mathrm{F}_{\mathrm{max}}$$

However, after checking transforms from T-X domain to τ-p domain and simultaneous inspection of effective de-convolution, p values of -50 msec/meter to250 msec/meter were selected (Fig. 9). A bulk shift of 628msec was estimated for accurate transformation of events from 0-offset intercept time in Tau-P domain to shot gather T-X domain. The Tau-p domain of shot gathers were auto-correlated (Fig. 9) to estimate long period lags, a procedure carried out for estimating short period reverberations in pre-processing step. The rough sea floor could not preserve perfect hyperbolas in shot gathers, a condition necessary for a perfect ellipse formation in Tau-p domain. In addition, deep-water bottom with combination of short streamer could not preserve multiples in periodic fashion. Therefore, lags could not be picked in auto-correlation of τ-p domain.

Also an attempt was made to estimate and apply prediction distance which varies with sea bed depth, by taking into account changing seabed (Alam and Austin, 1981).

$$\textbf{Prediction Lag} = \textbf{Water Bottom Time} * (1 - \mathrm{p}^2 \mathrm{V}_{\mathrm{w}}^2)^{1/2}$$

A stack was made using water velocity and water-bottom is marked for estimating the travel two way time of the water bottom. Austin formula (yilmaz) accounts for the changing depth of sea floor and thus lags were estimated, which were not constant throughout the dataset. These lags were then used using ProMax module-Targeted De-convolution. The rough seafloor caused inaccurate transformation into τ-p domain, and also impeded in preserving periodicity in τ-p domain. After application of τ-p, shot gathers were NMO corrected using appropriate velocity in CDP domain. The stack (Fig.10) obtained had long period surface multiples. Linear Radon had not proven to be an effective method for attenuating long period surface multiples, in deep and rough seafloor.

4.3 Application of Parabolic Radon Filter:

The dataset was then used for application of parabolic radon. Since parabolic radon discriminates primaries and multiples on basis of the curvature. Hampson (1986) proposed that multiples depict parabolic curvature after application of NMO on the primaries. Therefore, it was pre-condition for estimation of relatively accurate estimation of RMS velocity for NMO correction. Super-gathers were formed and were sampled with an increment of 50 CDP intervals. The velocity was meticulously picked by keeping distinction between primaries and multiples. Since strong water bottom reflections also preserved strong water bottom multiples, multiples were conspicuous in semblance plot which appear right at the bottom of the primaries above.

This resulted NMO corrected primaries and multiples remained under-corrected (Fig. 11), which is a pre-condition for muting multiples in radon space. The CDP domain NMO corrected data was tested for various q (slope of curvature) values, which are essentially move-out times. A range of -622- to 1407 msec, was selected for optimum transformation and results. The transformed dataset was then muted (Fig. 12), along positive positive q values, since multiples depict positive curvature. The muted data were then transformed back into the time-space domain (Fig. 12), and were stacked (Fig. 13).

Due to the rough sea bed the NMO corrected CDPs had multiples which were not periodic in geometry. This resulted in smearing of multiples energy with primaries, even with the state of the art High Resolution Radon. Unlike Tau-P, where deep water-bottom presented problem in preserving periodicity of multiples, the inaccurate parabolic radon transformation was only due to rough sea bed and complex structural geology. Also, short streamer length could not offer distinction among primaries and multiples in terms of move-out. Thus inaccurate transformation and less move-out due to short streamer length resulted in muting of primaries along with the multiples. Multiples were muted at the cost of removing primary energy and the stack obtained had low resolution, with less primary energy and more smearing effect.

4.4 Application of SRME Filter:

SRME does not depend upon the periodicity and velocity for surface related multiples and thus is an ideal method for the present dataset. It was evident that rough sea bed and depth of water bottom had impeded in effective attenuation of multiples for both Linear and Parabolic Radon. SRME is based on the concept of convolution and multiples were estimated for each source-receiver combination.

The aforementioned theory is practical for flat Earth, where the reflectors are considered flat. However, in complex structures, which represents a more realistic geological setting, multiples estimate is carried out by convolving common shot gathers with common receive gathers. A shot record for which multiples are predicted is first interpolated, to meet the cardinal requirement of SRME, that receivers and sources should be co-located. This is carried out first taking into account all original shot gathers which appear on the shot gather. In this case, 31 previous shots for each shot gather were used and then interpolated. A set of common receivers were formed which were then convolved with the respective traces of common shot gather forming common receiver gathers, for which multiples are to be estimated. This process forms Multiple Contribution Gather (MCG). When this process was repeated for different common-receiver gathers, the predicted multiples for all receivers locations could be obtained [Dragoset et al., 2010].

The 2D SRME was run on ProMax to handle large datasets. The dataset has receiver interval of 25 meter, which was an acceptable interval to avoid spatial aliasing. The dataset was regularized (trace interpolation) for 12.5 meter, but there was no distinction between the outcome of estimated multiples for 25 meter and 12.5 meter. Therefore, no interpolation was carried out to save processing time. However, the shot gathers were regularized to interpolate near offsets of 125 meter. Missing Near offset had considerable effect in multiples suppression (Dragoset, 1999). This would enable to estimate multiples at near offset. A 2D SRME was run, on the principal cited above, and an estimate of multiples was achieved. These multiples were then un-regularized and were merged in one file along with its respective shot gathers (Fig. 14). This was essential for ensuing subtraction process in ProMax.

Once the multiples were estimated and were merged in one file, the dataset was ready for subtraction. The local filter approach was carried out for subtraction cited in previous passages. The filter estimate was carried out using least square approach, and was used for subsequent subtraction subsequent subtraction.

Since, the structural and geological setting varies along the 2D profile, it was worthwhile to test the datasets with different window lengths and filter for a more accurate surface operator. After series of test and parameterization, the data were divided into two datasets. I have used the following:

1. 1-725 shot gathers

Window Length: 1000 msec

Filter Length: 200 msec

2. 726-1819 Shot gathers

Window Length: 3000 msec

Filter Length: 600 msec.

The multiples attenuation (Fig. 15) in this fashion had been more efficient, less time consuming and had rendered better preservation of primaries. The optimum result was achieved in 2 iterations. The final stack depicts better resolution and attenuation of multiples (Fig. 16)

In my thesis I have used four methods (Prediction Filter, Linear Radon, Parabolic Radon and 2D SRME), for resolving features such as magmatic bodies and sills. The magmatic sills have been resolved using prediction filer, which were obscured by short period reverberations. Linear Radon and Parabolic Radon which used periodicity and move-out respectively could not attenuate long period Multiples. 2D SRME have been most efficient in attenuating long period multiples and have resolved subtle features which can be characterized as magmatic bodies (Fig.16).The illuminated magmatic sills and bodies were consistent with the literature of the area.

CHAPTER V

5.1 DISCUSSION

The pre-processing is carried out adhering the conventional seismic steps. Predictive lag estimation for short period reverberations is consistent throughout the seismic profile. The 20 msec prediction lag, has attenuated short period reverberations, and enhanced resolution. The Linear Radon transformation could not preserve multiples with periodicity, because of the deeper marine acquisition. Also rough seabed topography caused reflections associated to deeper depths to be preserved as non- hyperbolic, in shot gathers domain, which resulted in inaccurate transformation from time-offset domain to Linear Radon domain.

Parabolic Radon is used to distinguish between primaries and multiples by using the move-out time (delayed time). This method was partially effective. The rough topography of seabed could not preserve multiples with parabolic trajectory, after application of NMO. This impeded correct transformation in the Radon Therefore, even High Resolution Radon Transform, which is efficient for avoiding smearing, attributed to its iterative selection of cluster of energy, could not perform well and remnant multiples energy is present in the final outcome stack (Fig.13). Also, short streamer length, did not allow separation of primaries and multiples at shorter offsets, resulting in primaries removal.

2D SRME has proven to be the most successful method in removing surface related multiples. This method does not depend on the periodicity and move-out. It uses the principle of convolution, and has predicted surface related multiples of all orders. The attenuation of multiples at shallower depths have resolved magmatic sills and bodies, which were not visible before multiples attenuation. Although multiples are removed in the same fashion at deeper depths, magmatic sills and bodies are not visible. This can be attributed to either absence of these features at depth or due to short streamer length.

Multiples attenuation methods have made advancements over the years. Present topic of research also includes better subtraction algorithms and using multiples for imaging. The subtraction of multiples poses problems, since it results in subtraction of primary energy. Estimation of primaries by sparse inversion (EPSI) is based on the same primary –multiple model as SRME. Unlike SRME, EPSI estimates the primaries as unknowns in a multi-dimensional inversion process rather than in a subtraction process (van Groenestijn and Verschuur, 2009).

It is worthwhile to mention that multiples are being used to enhance signal to noise ratio of dataset, and credible work has been done in which horizon resolution in enhanced by application of migration algorithms on datasets with multiples. However, the final product requires elimination of multiples for interpretational work. Imaging with multiples is then merged with conventional processing for resolving events, which are not resolved with conventional processing (without multiples). This idea is introduced by Ysing who used ray-equation based Kirchhoff depth migration to image primary reflections and deep-water multiples (Reiter et al., 1991).Use of multiples energy is still a relatively unexplored domain, and considerable work is being carried out to understand its performance, before being used as an industry practice.

5.2 CONCLUSION

We have attempted to attenuate multiples energy in a marine dataset that was acquired using short streamer over structurally complex and deep sea floor. Four methods for multiples attenuation: Prediction Filter, Linear Radon, Parabolic Radon and SRME are compared. The methods generally exploit two characteristics of multiples: periodicity and move-out (delayed time arrival). SRME also uses the concept of spatial-temporal convolution. The depth of water bottom and rugged seabed has significant influence on the outcome of the methods. Knowledge of the geology and structural complexity of the area under investigation is essential in determining the efficacy of these methods. For this datasets, Prediction Filter and 2D SRME appears to be most effective in attenuating, short period and long period surface multiples respectively. Seismic profile from a combination of Prediction Filter and 2D SRME appears to be showing geologically expected features. Although the multiples were removed effectively, resolving geological features at depths greater than ~4s TWT, was difficult because of very low fold and short streamer length. In the end, after multiple removal using SRME, reflectivity packages that are interpreted as intrusion within the oceanic crust have become very clear. Velocity modeling from the OBS data using the profile constructed in this thesis can further resolve these features.

Due to complex seafloor, the seismic energy is diffracted and is not captured by receivers in 2D plane. A more accurate resolution of geological features is attained, if 3D acquisition is carried out. The diffracted energy is collapsed to its true temporal-spatial position using Migration algorithms. Kirchhoff Migration which is known for its optimum performance for steep and dipping stratigraphy can be used. However, the diffracted energy needs to be captured by receivers for optimum application of this algorithm. 3D acquisition geometry enables capturing of diffracted energy for optimum resolution of geological features.

REFERENCES

Alam, A., and Austin, J., 1981, Suppression of multiples using slant stacks: Ann. Soc. Explor. Geophys. Mtg.

Alvarez, G., Biondi, B., and Guitton, A., Attenuation of diffracted multiples in angle domain common image gathers, *in* Proceedings 2004 SEG Annual Meeting2004.

Anstey, N. A., 1966, THE SECTIONAL AUTO-CORRELOGRAM AND THE SECTIONAL RETRO-CORRELOGRAM*: Geophysical Prospecting, v. 14, no. 4, p. 389-426.

Berkhout, A., and Verschuur, D., 2006, Imaging of multiple reflections: Geophysics, v. 71, no. 4, p. SI209-SI220.

Bischoff, J. L., and Henyey, T. L., 1974, Tectonic elements of the central part of the Gulf of California: Geological Society of America Bulletin, v. 85, no. 12, p. 1893-1904.

Calvert, S., 1966, Accumulation of diatomaceous silica in the sediments of the Gulf of California: Geological Society of America Bulletin, v. 77, no. 6, p. 569-596.

Cao, Z. N., and Bancroft, J. C., Radon transforms and multiple attenuation of White Rose data.

Chang, X., Liu, Y. K., DU, X. D., and LI, X. X., 2008, Seismic imaging under the irregular deep water bottom: Chinese Journal of Geophysics, v. 51, no. 1, p. 160-167.

Dix, C. H., 1948, The existence of multiple reflections: Geophysics, v. 13, no. 1, p. 49-50.

Douvere, F., 2008, The importance of marine spatial planning in advancing ecosystem-based sea use management: Marine Policy, v. 32, no. 5, p. 762-771.

Dragoset, B., 1999, A practical approach to surface multiple attenuation: The Leading Edge, v. 18, no. 1, p. 104-108.

Dragoset, B., Verschuur, E., Moore, I., and Bisley, R., 2010, A perspective on 3D surface-related multiple elimination: Geophysics, v. 75, no. 5, p. 75A245-275A261.

Ellsworth, T. P., 1948, Multiple reflections: Geophysics, v. 13, no. 1, p. 1-18.

Foster, D. J., and Mosher, C. C., 1992, Suppression of multiple reflections using the Radon transform: Geophysics, v. 57, no. 3, p. 386-395.

Hampson, D., Inverse velocity stacking for multiple elimination, *in* Proceedings 1986 SEG Annual Meeting1986.

Kelamis, P., Chiburis, E., and Shahryar, S., 1990, Radon multiple elimination, a practical methodology for land data. , 60th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded

Abstracts, p. 1611–1613.

Laws, R., and Kragh, E., 2002, Rough seas and time-lapse seismic: Geophysical Prospecting, v. 50, no. 2, p. 195-208.

Lokshtanov, D., Suppression of water-layer multiples-from deconvolution to wave-equation approach, *in* Proceedings 2000 SEG Annual Meeting2000.

Matson, K. H., and Abma, R., 2007, Method of multiple attenuation, Google Patents.

Mayne, W. H., 1962, Common reflection point horizontal data stacking techniques: Geophysics, v. 27, no. 6, p. 927-938.

Moore, D. G., 1973, Plate-edge deformation and crustal growth, Gulf of California structural province: Geological Society of America Bulletin, v. 84, no. 6, p. 1883-1906.

Ng, M., and Perz, M., High resolution Radon transform in the tx domain using" intelligent" prioritization of the Gauss-Seidel estimation sequence, *in* Proceedings 2004 SEG Annual Meeting2004.

O'doherty, R., and ANSTEY, N. A., 1971, Reflections on AMPLITUDES*: Geophysical Prospecting, v. 19, no. 3, p. 430-458.

Peacock, K., and Treitel, S., 1969, Predictive deconvolution: Theory and practice: Geophysics, v. 34, no. 2, p. 155-169.

Reiter, E. C., Toksöz, M. N., Keho, T. H., and Purdy, G., 1991, Imaging with deep-water multiples: Geophysics, v. 56, no. 7, p. 1081-1086.

Russell, B., Hampson, D., and Chun, J., 1990, Noise elimination and the Radon transform, Part 2: The Leading Edge, v. 9, no. 11, p. 31-37.

Ryu, J. V., 1982, Decomposition (DECOM) approach applied to wave field analysis with seismic reflection records: Geophysics, v. 47, no. 6, p. 869-883.

Sacchi, M. D., and Porsani, M., 1999, Fast high resolution parabolic Radon transform: 69th Ann. Mtg., Soc. Expl. Geophys., Expanded Abstracts, p. 1477-1480.

Simoneit, B. R., 1985, Hydrothermal petroleum: genesis, migration, and deposition in Guaymas Basin, Gulf of California: Canadian Journal of Earth Sciences, v. 22, no. 12, p. 1919-1929.

Stoffa, P. L., Buhl, P., Diebold, J. B., and Wenzel, F., 1981, Direct mapping of seismic data to the domain of intercept time and ray parameter-A plane-wave decomposition: Geophysics, v. 46, no. 3, p. 255-267.

Taner, M., 1980, LONG PERIOD SEA-FLOOR MULTIPLES AND THEIR SUPPRESSION*: Geophysical Prospecting, v. 28, no. 1, p. 30-48.

Tatham, R., Keeney, J., and Noponen, I., 1983, Application of the tau-p transform (slant-stack) in processing seismic reflection data: Exploration Geophysics, v. 14, no. 4, p. 163-172.

van Groenestijn, G., and Verschuur, D., 2009, Estimating primaries by sparse inversion and application to near-offset data reconstruction: Geophysics, v. 74, no. 3, p. A23-A28.

Verschuur, D. J., 2006, Seismic multiple removal techniques: past, present and future, EAGE publications.

Weglein, A. B., Gasparotto, F. A., Carvalho, P. M., and Stolt, R. H., 1997, An inverse-scattering series method for attenuating multiples in seismic reflection data: Geophysics, v. 62, no. 6, p. 1975-1989.

Xiao,C., Bancroft,J,C. Brown J., and Cao,Z.,2003, Multiple Suppression: A literature Review

Yilmaz, Ö., 2001, Seismic data analysis: processing, inversion, and interpretation of seismic data, SEG Books, v. 10.

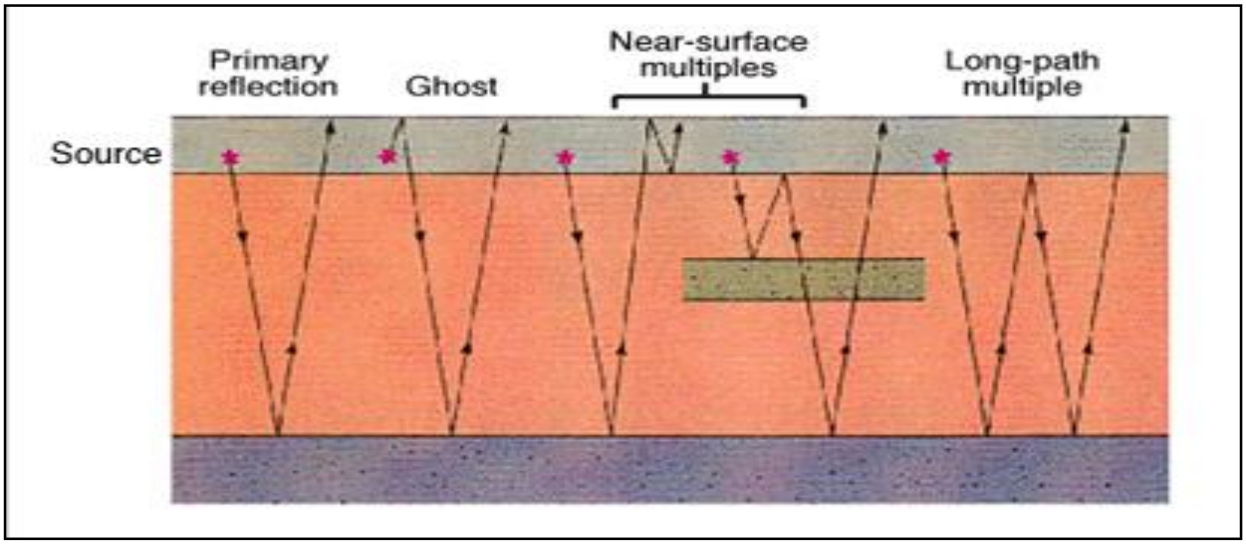


Figure 1: Primary Reflection (Signal); Ghost (Noise)-wave reflects from surface before its downward travel path; Near surface Multiples (in this figure peg-leg) in which seismic energy is first reflected and then encounter multiple bounces at shallower stratigraphy before being recorded; Long path Multiples: Multiple reflection with longer path within a single bed or many beds.(Verschuur 2006)

Figure 2: Guaymas Basin-Seismic Profile is trending NE-SW across the Rift

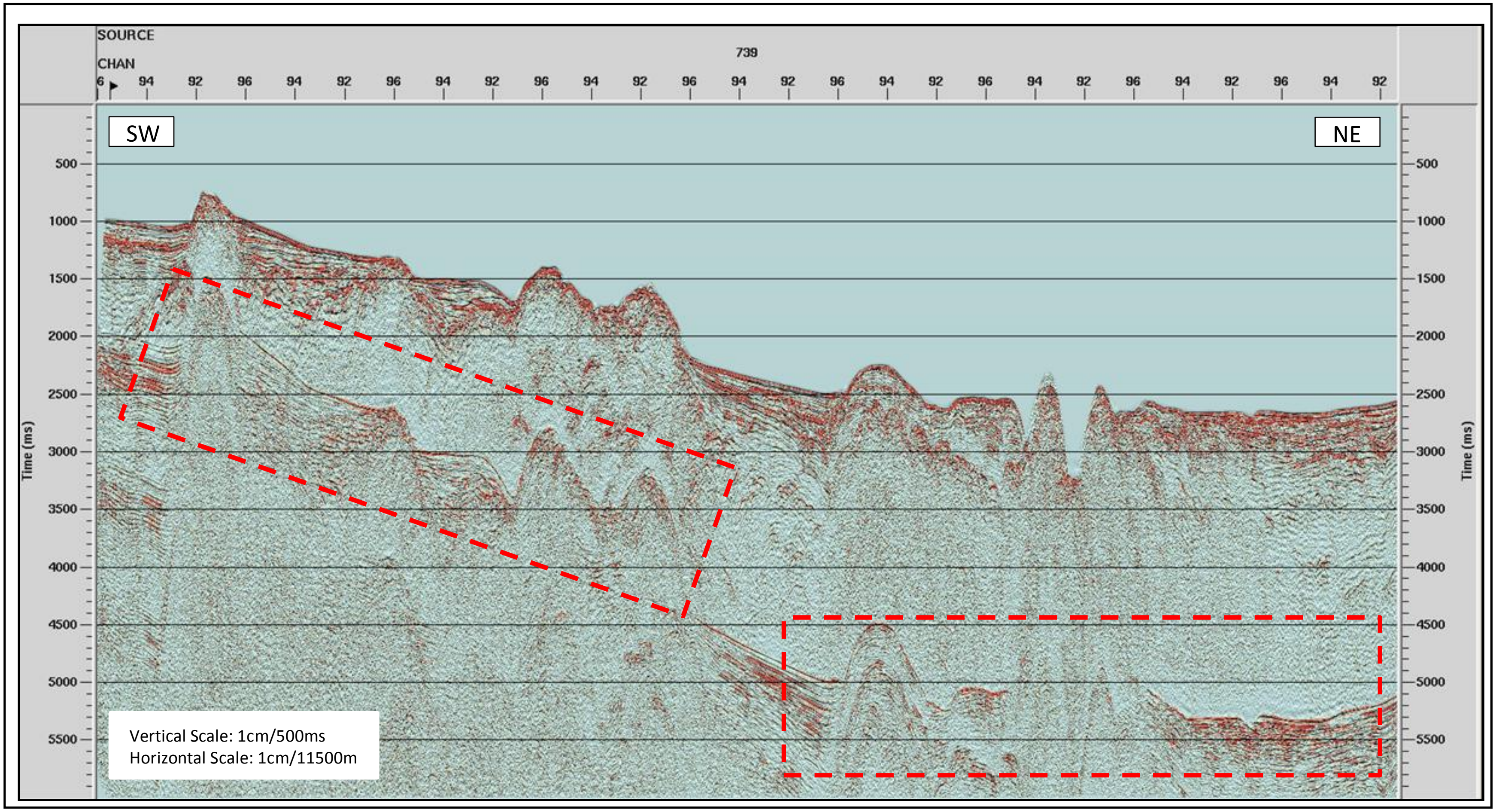


Figure 3: Raw Stack. First order multiples are highlighted within dashed red boxes

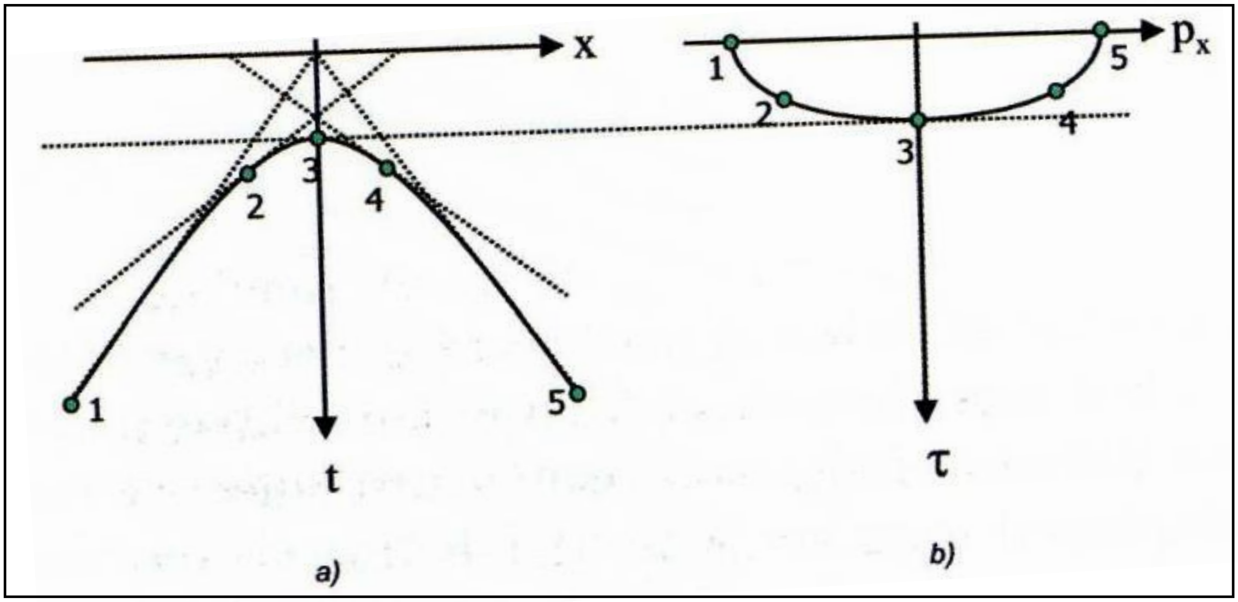


Figure 4: a. Shot Gather-Hyperbolic Trajectory. b. Linear Radon Transform .Green dots represent points along which tangent is drawn. Each tangent represent inverse of velocity or slowness (p).Hyperbolic Trajectory in time-space domain is transform into ellipse in Linear Radon(τ-p) domain, by plotting 0-intercept time along y-axis and p along x-axis.

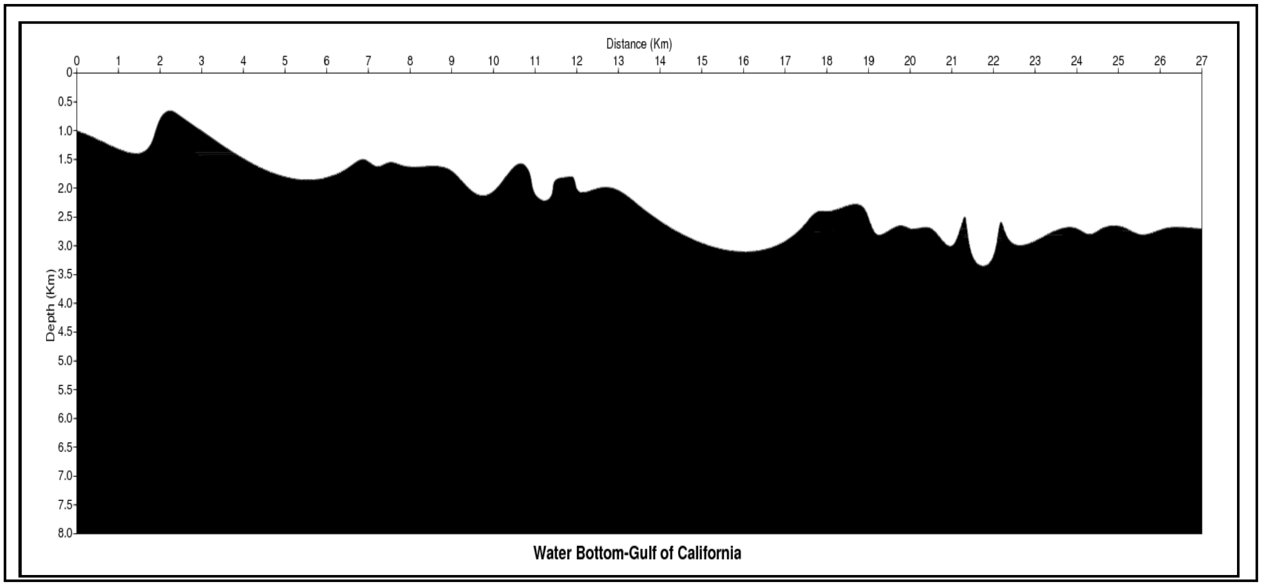


Figure 5: Seafloor topography modelled using Finite Difference Wave Propagation in Seismic Unix.

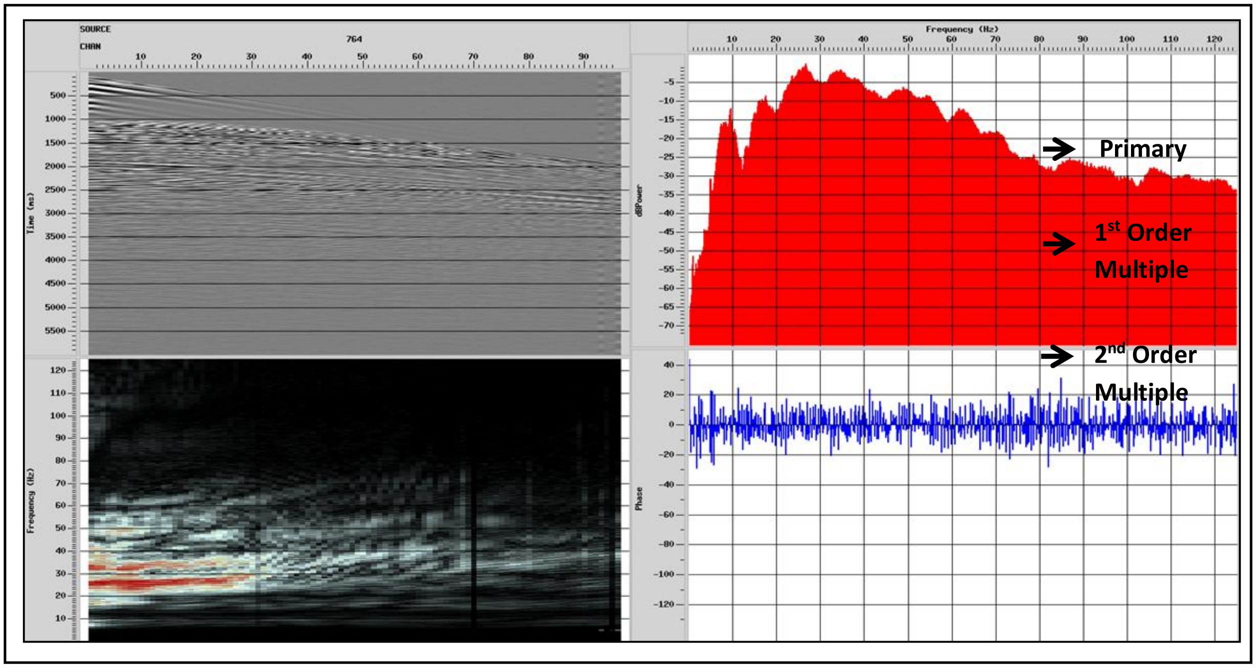
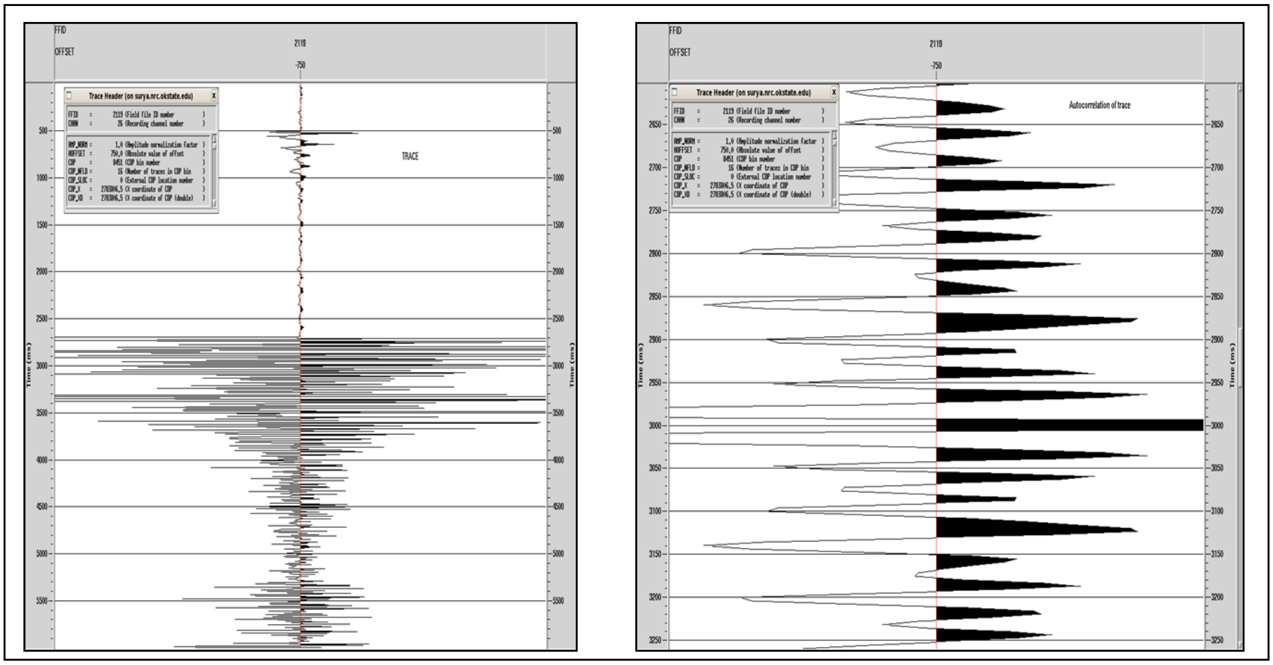


Figure 6: Spectral Analysis to determine prominent frequency in data. Shot gather in Time-Space is Fourier transformed into Frequency Wave number domain



```
Trace Header (on surya.nrc.okstate.edu)
FFID     =        2119 (Field file ID number            )
CHAN     =          26 (Recording channel number        )

AMP_NORM =         1,0 (Amplitude normalization factor  )
AOFFSET  =       750,0 (Absolute value of offset        )
CDP      =        0451 (CDP bin number                  )
CDP_NFLD =          16 (Number of traces in CDP bin     )
CDP_SLOC =           0 (External CDP location number    )
CDP_X    =   2783046,5 (X coordinate of CDP             )
CDP_XD   =   2783046,5 (X coordinate of CDP (double)    )
```

Figure 7: Trace (Left) is auto-correlated (*Right*), to estimate lags of short period reverberations.

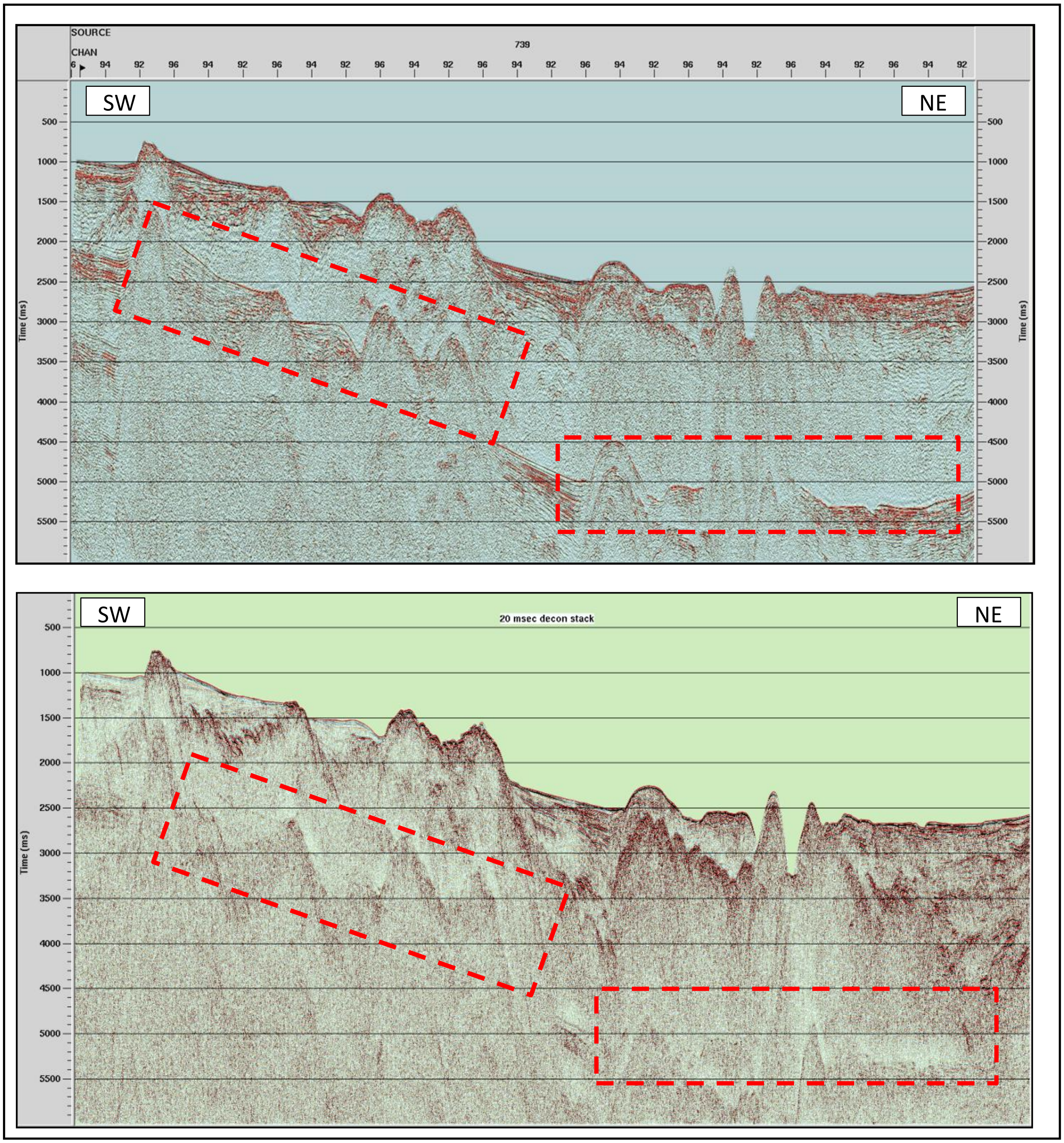


Figure 8: Stack after accurate velocity and Prediction Filter. Short Period Reverberations are attenuated. Remnant multiples are highlighted in dashed red box.

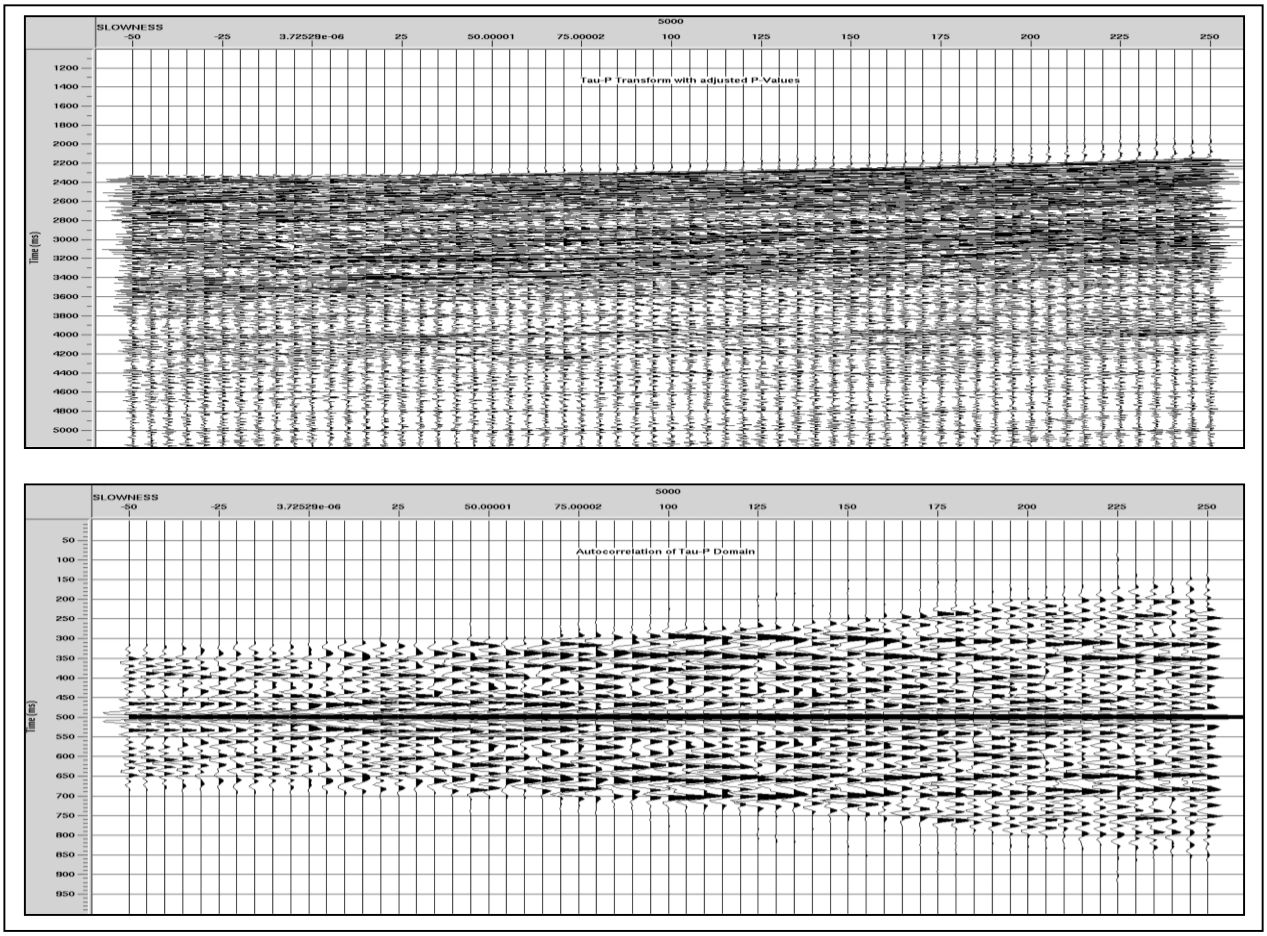


Figure 9: Shot Gather in Tau-P Domain (*Above*), p-range -50 to 250 msec, and its auto-correlation (*Below*).Lags are not periodic

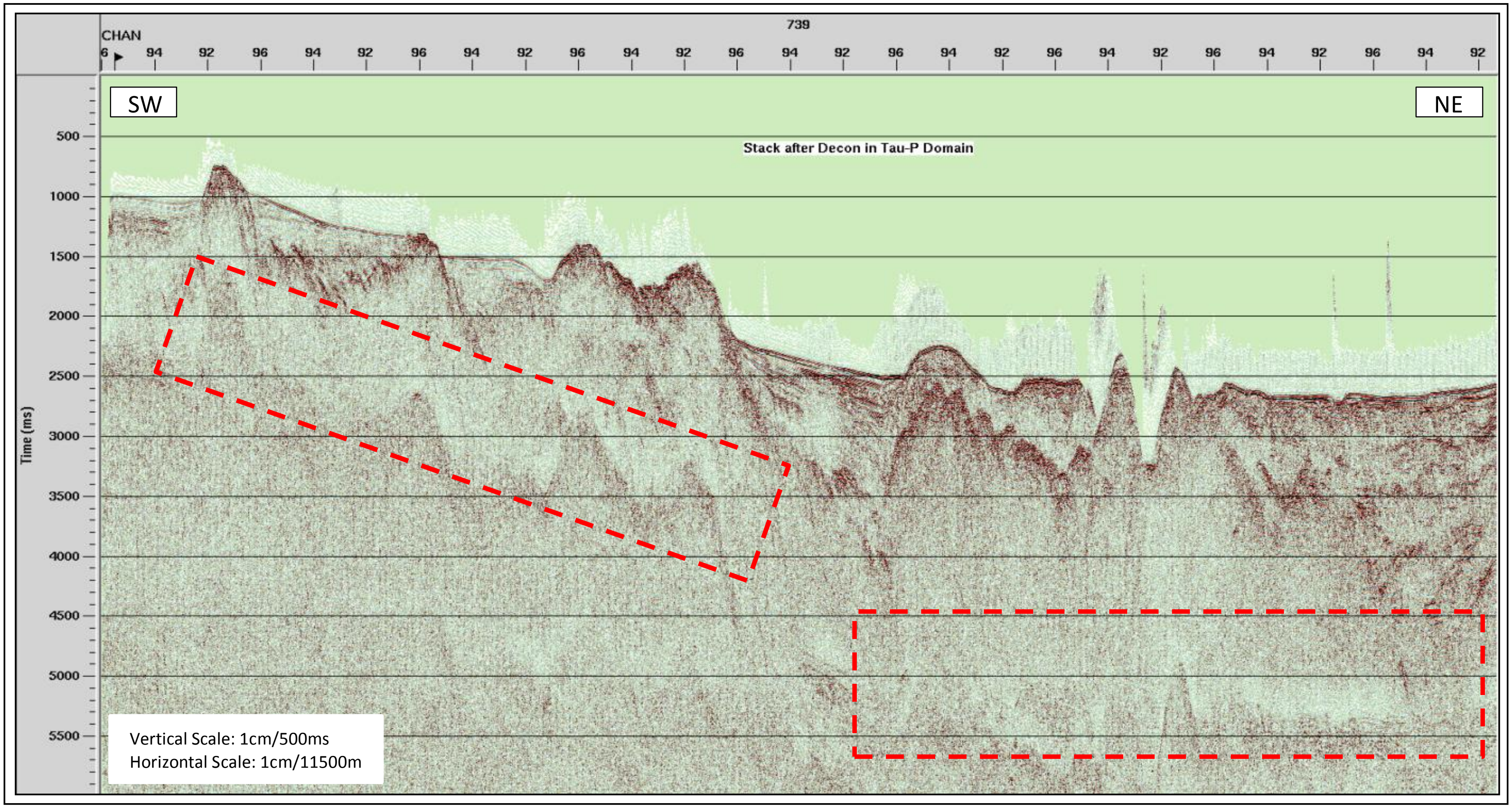


Figure 10: Tau-P Filter. Remnant multiples are highlighted in dashed red box.

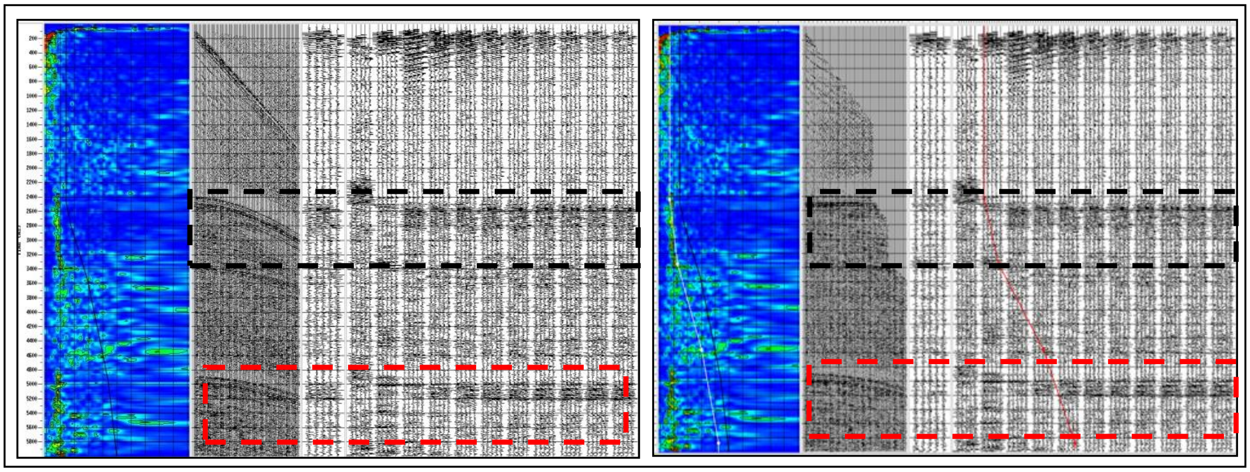


Figure 11: Velocity Analysis before Parabolic Radon. Left Panel shows Under-corrected Primary *(Black Box*) and Multiples (*Red Box*); Right Panel shows Corrected Primaries (*Black Box*) using NMO, while Multiples (*Red Box*) are under-corrected

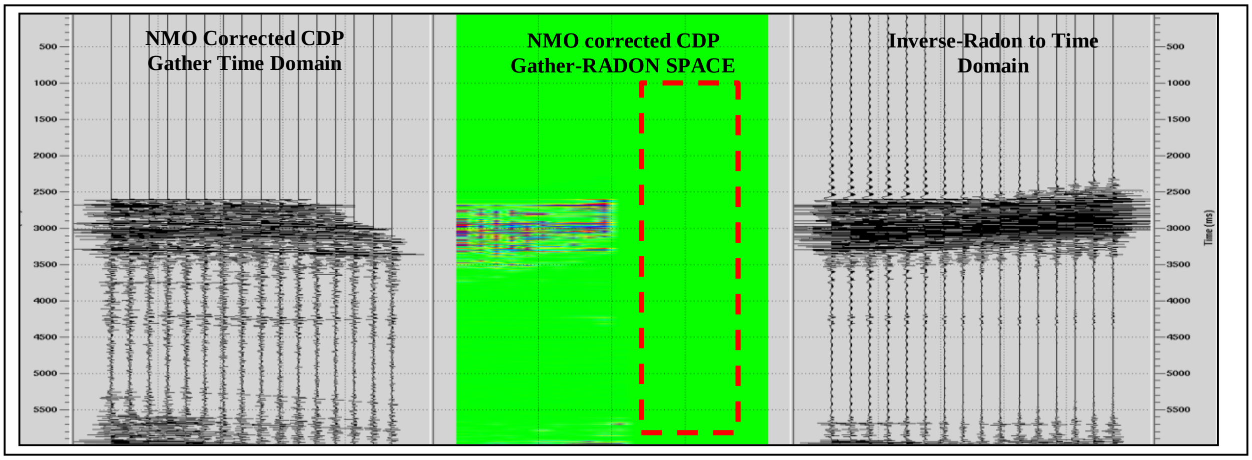


Figure 12: NMO corrected CDP (*Left*), Parabolic Radon Transform, Multiples Muted(*Center*), Inverse Radon to Time-Space Domain(*Right*)

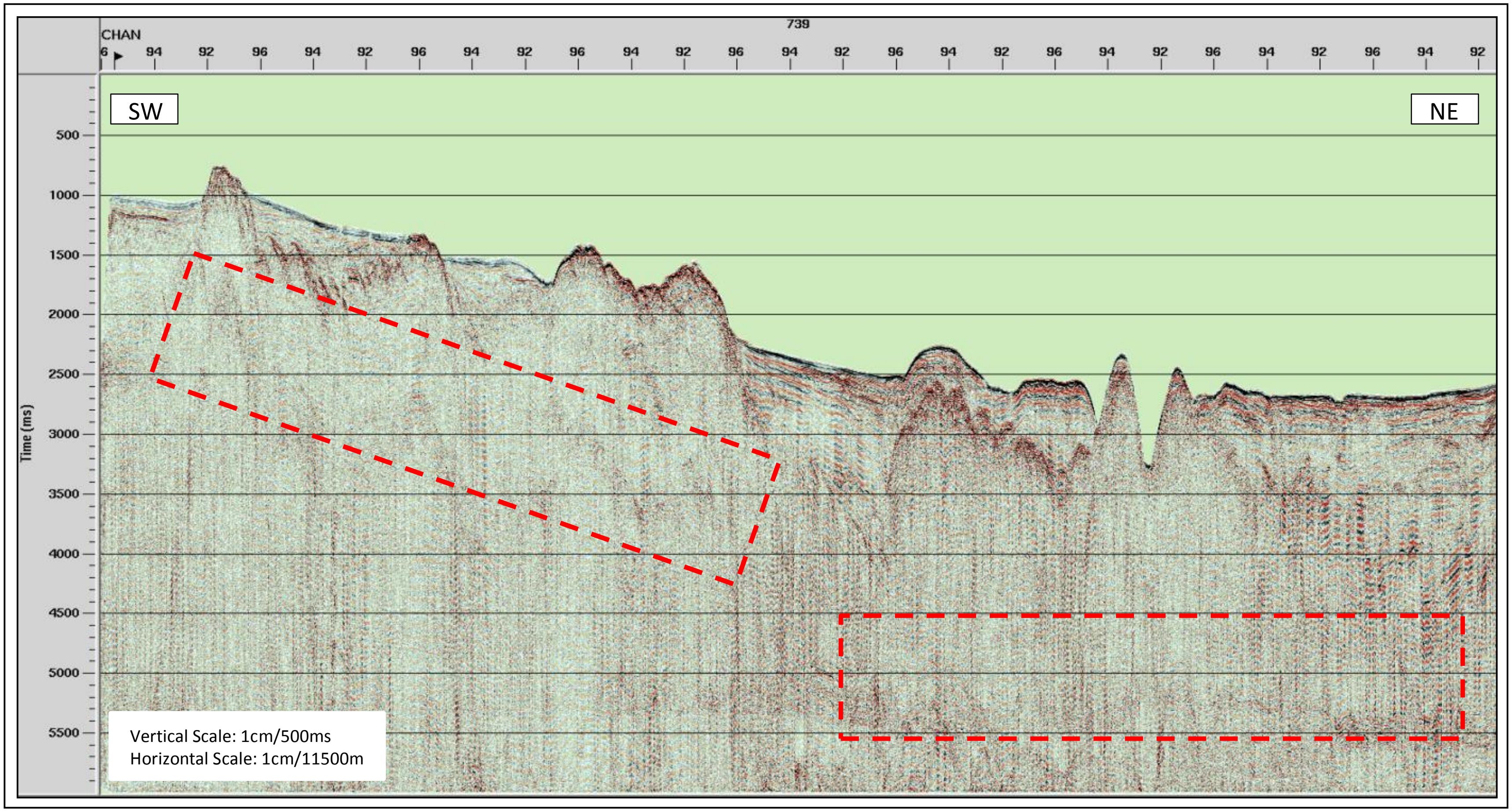


Figure 13: Parabolic Radon Stack. Primary Energy is also muted along with multiples (Short Streamer length). Remnant Multiple Energy is also present.

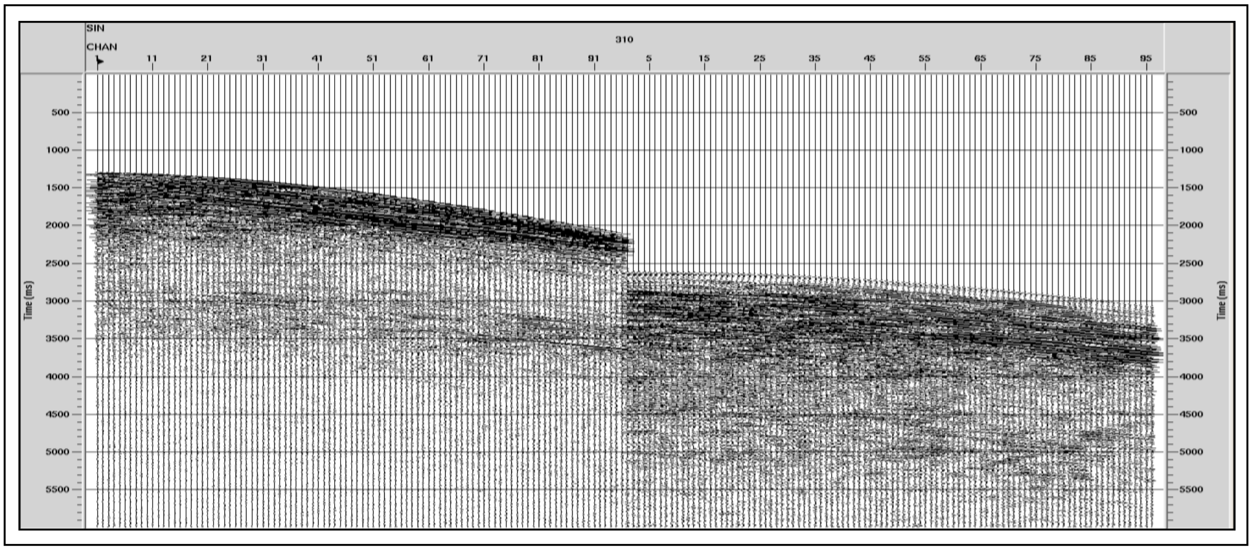


Figure 14: Shot Gather *(Left*) and its Estimated Multiples *(Right*) using 2D SRME

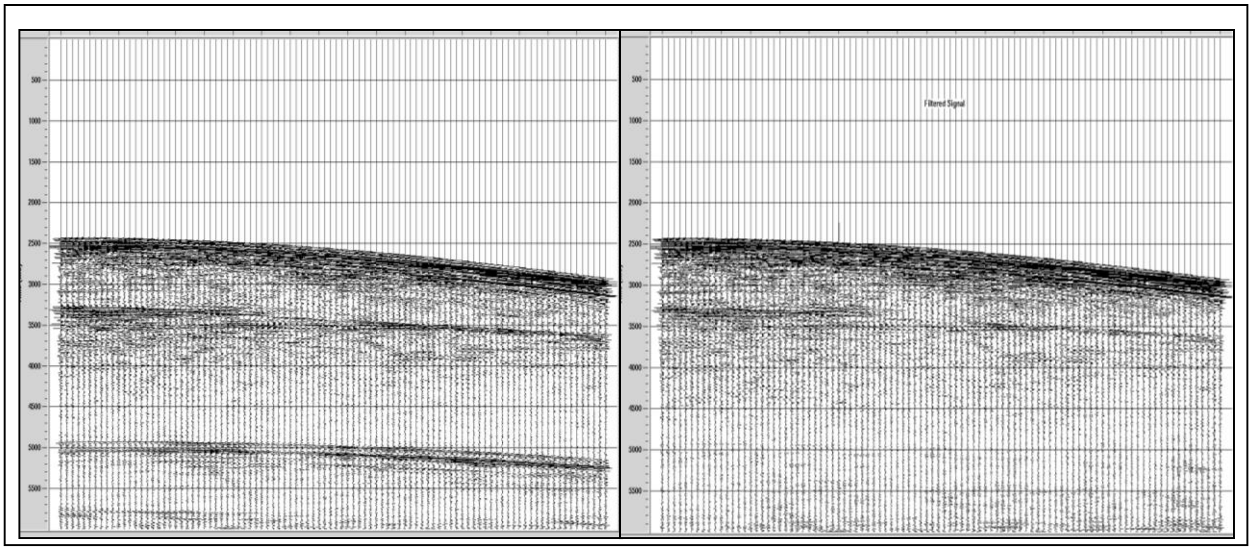


Figure 15: Shot Gather (Left) and Filtered Shot Gather (Right) after adaptive Subtraction

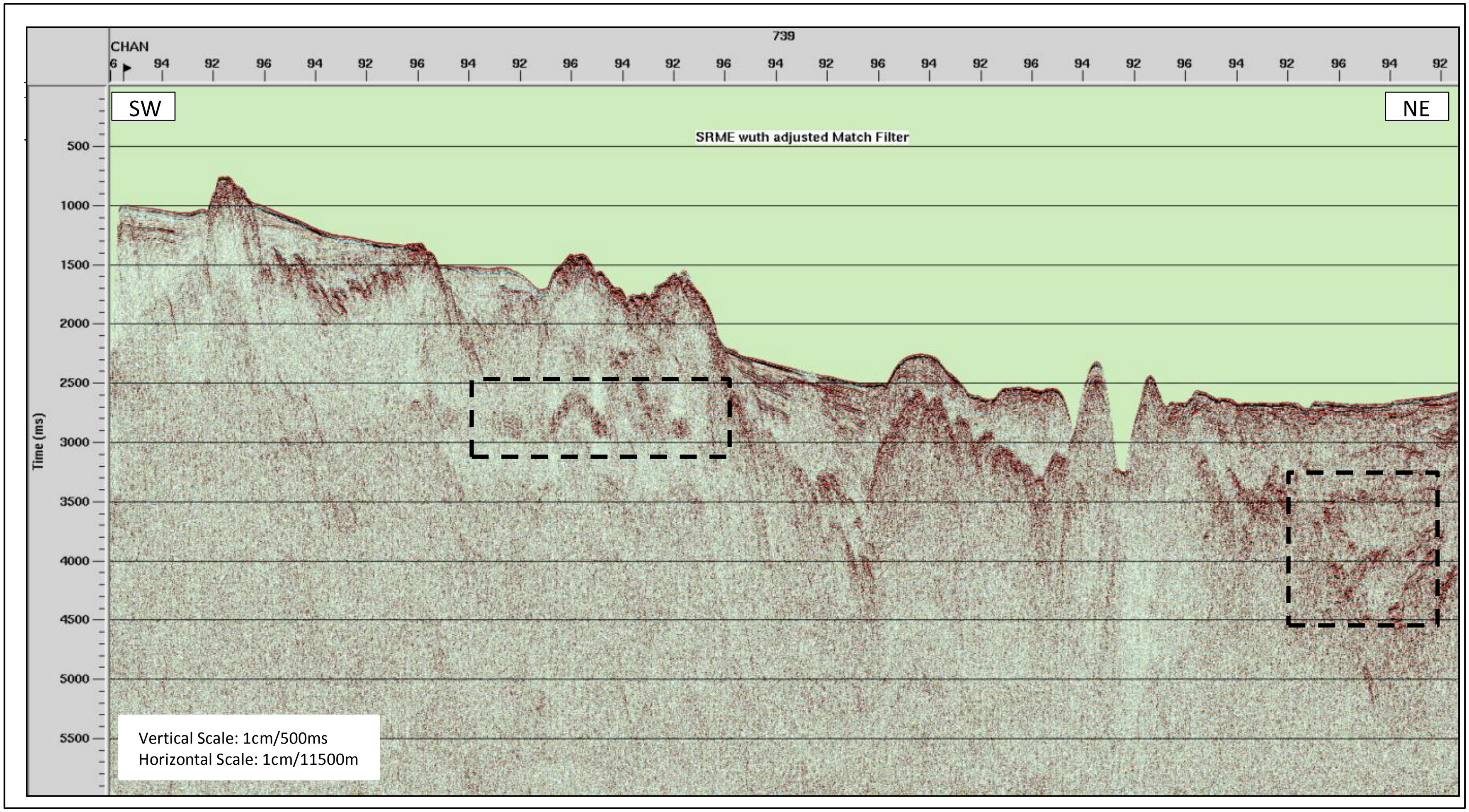


Figure 16: SRME Stack. The resolved magmatic bodies are highlighted within dashed Black Box. Multiples are reasonably well attenuated

VITA

MUHAMMAD SALMAN ABBASI

Candidate for the Degree of

Master of Science

Thesis: ATTENUATION OF MULTIPLES IN 2D SHORT STREAMER LENGTH MULTI-CHANNEL SEISMIC DATA, GULF OF CALIFORNIA

Major Field: GEOLOGY

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma, in May, 2014.

Completed the requirements for the Master of Science in Geophysics at Quaid-i-Azam University, Islamabad, Pakistan in 2004.

Experience:

Worked in Oil & Gas Development Company (OGDCL) as Geophysicist

Professional Memberships:

Society of Exploration Geophysicist (SEG)
American Association of Petroleum Geologists (AAPG)