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Random and coherent noise attenuation for 2D land seismic reflection line acquired in Iraq

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ABSTRACT

Noises are common events in seismic reflection data that have very striking features in seismograms, affecting seismic data processing and interpretation. Noise attenuation is an essential phase in seismic processing data, usually resulting in enhancing the signal-to-noise ratio (SNR) and improving the subsurface seismic image. Groundroll presence is a major fashion of significant noise in land seismic surveys. It is a type of coherent noise present in seismograms that appears as linear events, in most cases overlapping the reflections and probably making it challenging to recognise. There are several domains used in noise attenuation techniques. The domain transformations are a complex algorithm used commonly during the processing of seismic data; Therefore, a large number of methods have been developed to attenuate these types of noise to preserve the frequency bandwidth and enhance the SNR of the seismic data. In the time-offset domain, the noise wave such as groundroll and random noises overlap over time; a different domain makes it easier to successfully isolate coherent, random noise and reflection events. We have used effective algorithms in different domains such as (shot, receiver, t-x, f-x, f-k, R-T, and offset class) to attenuate coherent and random noises present in the data. The results indicate that the different domains can reveal features and geological structures that have been masked by the noises present in current data. Because these filtering techniques encourage significant improvements in the final image quality in the 2D seismic section, possibly giving the interpreter an advantage, particularly in structural and stratigraphic interpretation.

1. Introduction

The seismic exploration technique is the most frequently used and well-known geophysical method among several methods of geophysical prospecting. The seismic data can be processed to expose details information on geological structures on scales from the dozens of metres of the crust to the central core of the earth (Yilmaz 2001; Kearey et al. 2002). A major part of most of its continued success is that raw seismic data is processed to yield accurate subsurface images of the geological structures. Oil exploration and production companies use several methods to evaluate and attempt to recognise hydrocarbon reservoirs so the processing of seismic data becomes significantly important (Yilmaz 2001; Aminzadeh and Shivaji 2013; Onajite 2013; Dondurur 2018; Abdel Fattah et al. 2020; Nanda 2021; Ismail et al. 2021; 2021). Several elements can affect the accuracy of seismic data to initially ensure successful drilling and later to contribute a clearer understanding of the characteristics of the reservoir. Appropriate and acceptable noise attenuation strategies help increase seismic data's potential advantage and significant impact on exploration, production, and development.

Advancements in signal processing methodologies have meaningfully impacted the geological interpretation of data for the interested area. Seismic data processing requires the applied several successive algebraic, statistical, and signal processing methodologies, which are usually mixed with experienced and skilled geophysicists in specific interpretation. These seismic data processing stages include such as geometric spreading compensation, static correction, frequency/wavelength filtering, velocity analysis, deconvolution, time/depth migration, etc (Yilmaz 2001). After all, the processed data is delivered to the interpretation analysis, which principally targets to generate a simple, credible geological represented model that fully corresponds with the measured data.

Seismic data generally contain seismic noise, which should be removed to increase the signal-to-noise ratio (S/N) (Liu and Chen 2013; Nazari Siahsar et al. 2017). The noise in seismic exploration specifically implies an uninterpretable or undesired portion of recorded seismic signals due to several reasons. These undesirable events may probably be considered signals, but generally, these undesirable noise events give inadequate or Confusion info about the subsurface and are usually referred to as random noise and coherent noise.

The first step in noise attenuation is analysing seismic data to identify the sources and physical characteristics of noise regardless of the noise source, the characteristics usually fall into two categories: the first is Coherent Noise (Ground Roll, Guided Waves, Multiples, and Power line) while the second is random (Incoherent) noise (e.g. spikes) (Carolyn 2010). Incoherent noise, most of which is known as random noise, contaminates the seismic data, and the resulting data can lack coherency between different seismic traces. Many seismic processes can be corrupted, if the noise is not eliminated such as in the geologic interpretation and velocity analysis (Chen and Fomel 2015).

The random (Incoherent) and coherent noise attenuation is an important step in reflection seismic data processing and interpretation (Yilmaz 2001). Random noise should be attenuated before seismic interpretation, to improve the signal-to-noise ratio of seismic data (Saad and Chen 2020), and the quality of seismic images; hence, seismic events interpretation is greatly facilitated. However, the main challenge is to remove the noise while preserving the seismic signals. Several methods have been developed to attenuate random noise in seismic data, e.g. the t-x and f-x prediction methods (Abma and Claerbout 1995; Liu et al. 2012; Naghizadeh and Sacchi 2012), f-x deconvolution based on signal predictability (Canales 1984), median filtering methods (Liu, 2013; Gan et al. 2016), the sparse transform-based methods (Fomel and Liu 2010; Chen and Song 2018), Singular value decomposition methods (Bekara and Van der Baan 2007), Wavelet (Donoho et al. 1996) and curvelet transform (Starck et al. 2002). The coherent noise appearing on a seismic record includes surface waves (ground roll), airwaves, guided waves, body waves, etc. Ground roll is one of the main types of coherent noise inland seismic data. It has the significant characteristics of relatively low velocity, low frequency, high amplitude, and strong energy (Sheriff and Geldart 1995). several techniques have been developed to attenuate Coherent noise. the conventional methods can be divided into two groups based on the suppression of undesired parts of recorded data in the spectral domain, including high-pass and bandpass filtering, f-k filtering (Yilmaz 2001) and the adaptive ground-roll attenuation method (Wang et al. 2012; Hosseini et al. 2015), the radial trace (R-T) domain (Henley 2003), curvelet transform for Coherent and random noise (Neelamani et al. 2008).

In this work, the data set is selected for processing to obtain better seismic images. Various noise suppression techniques are utilised to attenuate random and coherent noise exhibited on raw shot gathers. We are focused on using Frequency-dependent to attenuate random noise in the (t–f) domain, adaptive ground-roll attenuation method to attenuate ground roll in the (f-x) domain, radial trace (R-T domain) methods to attenuate coherent noise in seismic data, structurally consistent filtering to reduce random noise and enhancement of structural continuity while protecting geological structures, dip-dependent median filtering in the (x-t domain) to suppress random noise and increase trace-to-trace coherency and

2. Materials and methods

The variability of noise types sometimes certainly makes separating signal and noise a problematic and not easy procedure. However, effective noise suppression is essential for high-resolution imaging. Subtracting the noise from seismic data is a significant step towards super confident interpretations. In seismic processing data, there is no single processing algorithm that can remove all noise types. Nearly all denoising methods have the common methodology of easily transferring the data to any domain where the signal and noise components can be separated. Practically all denoising methods have the common methodology of easily transferring the data to any domain where the signal and noise components can be separated. The recognised noise is therefore removed before the data component is transformed back into a typical (t–x) domain. Therefore, the challenge is to find a domain in which noise and signal are well detached (Elboth et al. 2008).

To process the Seismic data, the processing software of Geovation by CGG was used. Several shots of the data were selected from the first, middle, and last records to decide which parameter is suitable for the seismic data. Then, these parameters were applied to all datasets. The seismic survey was shot in 1981 using a dynamite source with a record length of 5 seconds, sample interval of 2 ms, 30-fold coverage, trace spacing, and shot point spacing (70 m). Below we will briefly explain the step-by-step data processing sequence for noise attenuation that is directly relevant to a 2-D seismic data set that will come later in this article. The processing flow was created by testing parameters, methods, and algorithms (Figure 1). The processing sequence applied to the current data was reformatting and Geometry up-data, Static correction, Bandpass filtering, geometric spreading correction, initial velocity analysis 1 km × 1 km, and noise attenuation.

2.1. Data import, reformatting and geometry up-data

Data import and geometry are in the pre-processing part, which lay the foundation for the following processing steps such as static corrections and CMP sorting. The Input data was in SEG-D format. The data are converted from SEG-D to the specific internal
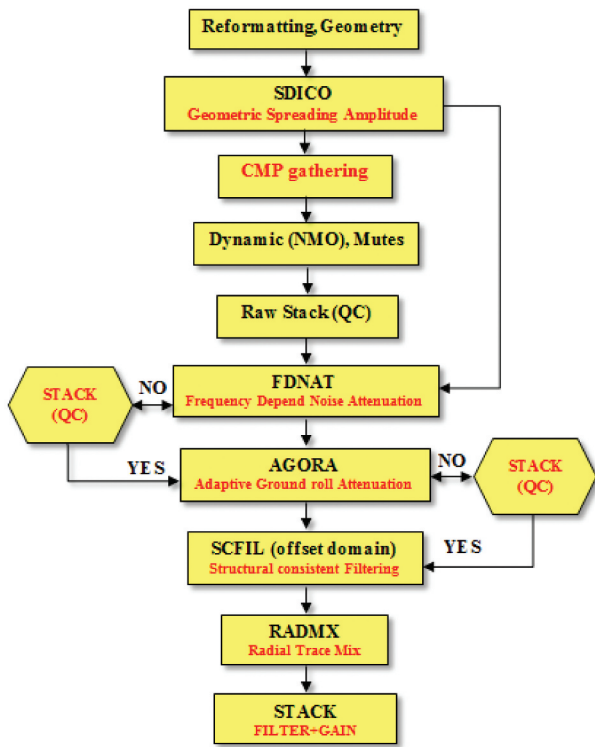
Figure 1. Noise attenuation processing Flowchart used in processing current data.

Geovation data format (SDS) that is used during the seismic processing. The geometry builds–up by using onset (CGG application). We were Identifying the information about the acquisition geometry needed to process seismic data e.g. Common Mid-Point, nominal fold, CMP spacing, Shot interval, Trace interval, spreading type, etc. Then these parameters were exported to update certain header attributes. The QC for the shot records by checking the start time curves above shots. The input and output record numbers matched with the observer information. Finally, seismic data is merged with the field geometry file.

2.2. Static corrections

We are preparing Field statics (uphole static) calculations to use in the next steps e.g. QC Stacks and modules that required it. The Brute stacks were created using uphole statics correction only.

2.3. Velocity analysis and normal move-out correction

The Velocity analysis is one of the prime aspects of seismic data processing and is used at different stages of processing. The velocity picking is vital for further processing steps (Li et al. 2009). Normal move-out (NMO) is crucial for picking velocities in order so that reflections are lined up in CMP gathers (Yilmaz 2001). Velocity analysis was performed using CGG's Interactive Velocity Analysis (Pacesetter). These

analyses require an initial velocity field, but in a virgin area, it is required, to estimate this, from the seismic data itself. we are employing CVS (Constant Velocity Stack) methods. Stacking velocities are picked directly from the constant velocity stack (CVS) panel by choosing the velocity that yields the best stack response at a selected event time (Yilmaz 2001). CVS has been computed using a range of velocity from 1500 m/s to 5000 m/s on a group of CDP gathers chosen for analysis. Interactive velocity analysis is carried out for (1 km x 1 km).

As a result of the NMO correction, a frequency distortion occurs, particularly for shallow events and at large offsets (NMO stretching) (Miller 1992). This problem can be circumvented by muting the stretched zones in the gather (Yilmaz 2001). To obtain the stacked image the data is transformed from source-receiver coordinates to CMP gathers, the velocity is used to correct the effect of the move out on CMP gathers. NMO correction methods often suffer from the problem of NMO stretching, which nonlinearly increases with offsets and decreases with zero-offset travel time. The NMO stretching can be quantified by frequency distortion, so stretching is confined mainly to large offsets and shallow times. To reduce the effect of the stretching on the result of the stacking procedure, the part with severe stretching of the data is muted from the data ("stretch-mute") after the NMO correction.

2.4. Spherical divergence correction

A field record describes a wavefield produced by an individual shot. Theoretically, the individual shot is considered a point source that yields a spherical wavefield. The earth has two impacts on a propagating wavefield: (1) inhomogeneous geology (medium), energy intensity decreases proportionately to the square wavefront radius. The amplitude of the wave is proportional to the square root of energy intensity; it decays as 1/r. In practice, velocity generally increases with depth, which simply causes further wavefront divergence and significantly fast decay amplitudes with distance. (2) The frequency components of the source signal vary with time as it propagates. In particular, the high frequencies are absorbed earlier than the low frequencies. This is due to the intrinsic attenuation in rocks. Therefore, to bring up any signal that may be present in the deep portion of the record, this earth effect must be removed. By using the primary velocity function to correct geometric spreading, the amplitudes of the dispersive coherent noise and multiples have been overcorrected(Yilmaz 2001). The factor (1/r) that explains the decay of wave amplitudes as a function of the spherical wavefront radius is relevant for a homogeneous medium without attenuation. Amplitude decay can be described approximately

by $1/[v^2(t) t]$ for layered earth (Newman 1973). Where (t) is the two-way travel time and V(t) RMS velocity of the primary reflections (those reflected only once) averaged over a survey area. The function gain of geometric spreading correction is expressed by:

$$g(t) = \frac{v^2(t)t}{v_\circ^2 t_\circ} \qquad (1)$$

Where (v_0) refers to the reference velocity at a definite time (t_0)

SDICO module applies compensation for the effects of geometrical spreading calculated using Newman's formula. The amplitude correction process was utilised in seismic data to compensate for the amplitude decay which develops from the propagation of the seismic wave from a point source in a layered medium. For optimum amplitude compensation, SDICO CGG programs were applied for data. SDICO program applies compensation for the effects of geometrical spreading computed using P. Newman's formulae. Each sample is multiplied by the following equation:

$$T^n V^m (T_\circ) \qquad (2)$$

Where (T) is the TWT of the sample in (seconds), (T_o) is the NMO corrected time, V (T_o) is the stack velocity at the time T_o for the CDP being considered, (n & m) are the user-defined powers of T and V. Figure 2 shows shot gather before and after applied Spherical divergence compensation.

2.5. Frequency-Dependent noise attenuation

In seismic reflection data, random noise can be generated from several sources, such as poorly fixed geophones, wind motion, human activities, traffic, and transient movements neighbouring recording cable or electrical power noise. Some random noise invariably exhibits spike-like properties (Yilmaz 1987); it also can be generated by scattering from near-surface anomalies such as gravel, boulders, or vuggy limestone (Dobrin and Savit 1988). Although stacking can at least relatively attenuate random noise in shot gathers data, remaining random noise after stacking will significantly reduce the accuracy of final data interpretation (Yilmaz 1987).

Noise characterised by anomalous amplitudes is removed from pre-stack seismic data by transforming the seismic data into the frequency domain and then applying a spatial median filter. Frequency bands with amplitudes that deviate from the median amplitude by a specified threshold are either scaled (multiplied by a specified scale factor) or replaced with an interpolated band using neighbouring traces. Frequency-Dependent RNA removes unwanted noise (anomalous amplitude) while preserving the signal and enhancing the seismic image. The method is an adaptive automated frequency-dependent amplitude threshold method to distinguish and remove high amplitude "spiky" and some of the coherent noise.

The FDNAT module attenuates high-amplitude noise in decomposed frequency bands. It uses frequency-dependent and time-variant amplitude
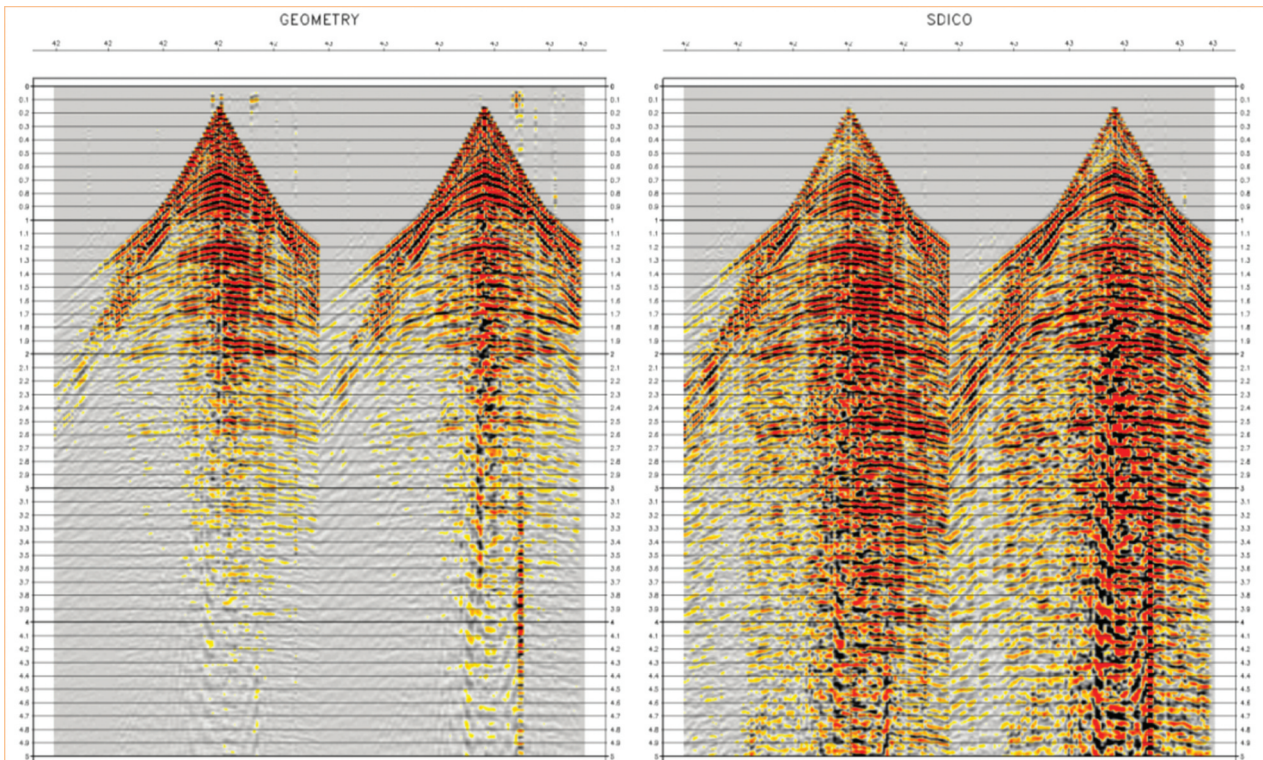

Figure 2. Shot gather before and after (SDICO).

threshold values in defined trace neighbourhoods to detect and suppress noise specific to different frequency ranges and different times. Defining different threshold values for different frequency ranges at different times often produces better results based on the knowledge of the distribution of signal and noise. The threshold is typically determined by different algorithms e.g. the average amplitude, envelope amplitude average, average root-mean-square (RMS) amplitude, and decibel criteria (Wang et al. 2011; Zhang 2011; Kong et al. 2017). Here average amplitude criterion (AMC) used to calculate threshold values:

$$TH = \frac{1}{N} \sum_{i=0}^{N-1} fabs(x(i)) \qquad (3)$$

Where: (TH) threshold, (N) number of sampling points in the time window, X(i) the amplitude of the i-th sampling point, and (fabs) an operator with absolute values.

A threshold value is used to compare the ratio between the strength of a sample and the median strength of the neighbourhood of the sample (Figure 3a). The strength, as absolute values, are always positive values. The time variation of TH values is necessary for suppressing noise that changes dramatically with time. The time variation defined at each given FREQ location is independent of other FREQ locations. Parameter TH is defined as a function of time by linear interpolation between given T locations. Parameter TH is also interpolated linearly and laterally between different FREQ locations. The interpolation scheme is illustrated in (Figure 3b). The first TH values are linearly interpolated at each given FREQ value between consecutive time locations. At each time level, TH values are linearly interpolated between neighbouring FREQ locations. The Input pre-stack seismic data is usually shot-ordered or CMP ordered. Traces within each gather must be in a spatial order such as offset. Because noise attenuation is typically applied early in the processing sequence, non-NMO corrected, shot-ordered data is usually input.

Appropriate threshold values should be set to obtain a good compromise in preserving the seismic signal, removing random noise, and avoiding the existence of any undesired patterns such as artefacts. With several tests, we found the optimum thresholds 8, 6, 2, and 1 for specific frequency bands 10, 20 40, and 60 Hz
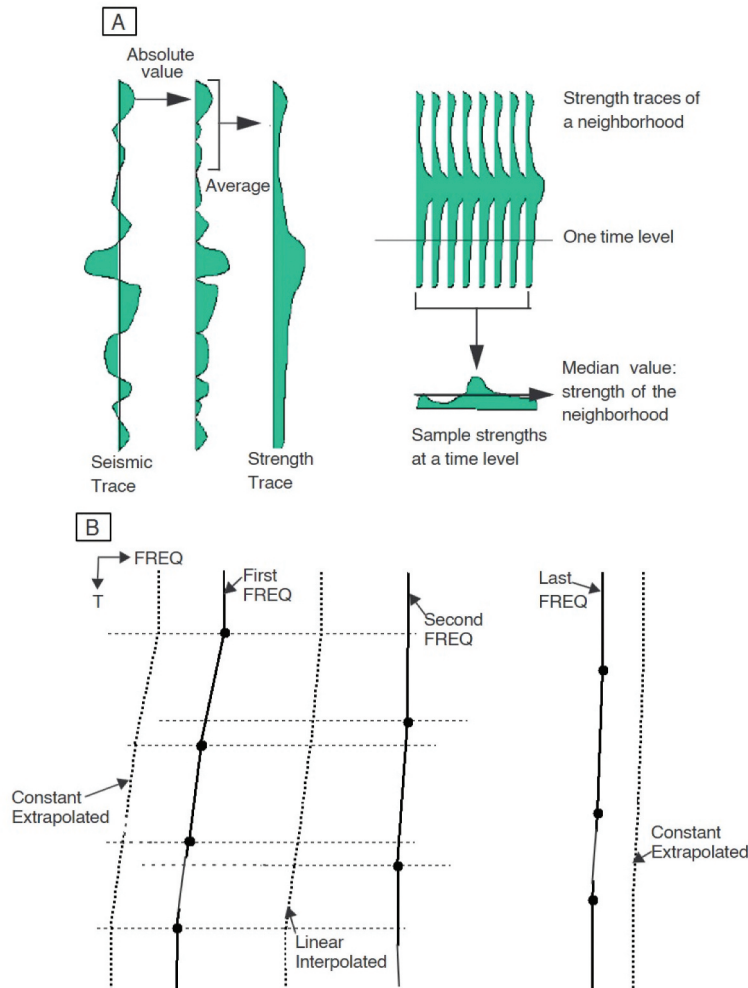

Figure 3. The definition of the strength of a trace sample (a); (b) shows the method used for interpolation of threshold (TH) values as a function of time and frequency (Geovation User's Manual 2010).

Table 1. FDNAT threshold Parameters.

Frequency (HZ)	Time(T)	Threshold value(TH)
10, 20,40,60	0	8
	1000	6
	2000	2
	5000	1

for the frequency panel containing events of 10 Hz, a threshold value (TH) of 8 is used at a time (T) zero, and when time increasing the (TH) decreased so and so as shown in (Table 1). Based on these values, we succeeded in preserving the seismic signal with negligible leakage and removing a significant amount of random noise. Figure 4 shows the shots data before, after, and difference applied frequency-dependent noise attenuation (FDNAT).

2.6. Adaptive groundroll attenuation

The effect of near-surface variations is the main reason for the modest quality of seismic data in the land seismic survey. Surface waves, such as groundroll or guided waves, are the main source of coherent noise in land seismic data (Le Meur et al. 2010). Ground roll is characterised by low velocity, low frequency, and high amplitude. It can be strongly dispersive, aliased, and have higher modes, i.e. for each frequency, there are different apparent velocities. Guided waves are characterised by high velocity and high amplitude. They are generally of higher frequency than ground roll but less dispersive. Groundroll suppression is the initial

problem that really must be adequately adopted throughout data processing steps. Groundroll can be effectively dispersive and aliased and behave as guided waves, meaning that there are different phase velocities for every frequency.

Over the past three decades, various solutions have been established to attempt to suppress or filter the groundroll in 2D and 3D seismic data involving the f-k method, Wiener-Levinson algorithm, wavelet transforms, empirical mode decomposition, S transform, high-resolution radon method, adaptive interferometry method, and modelling, etc (Treitel et al. 1967; Beresford-Smith and Rango 1989; Yuan et al. 2005, 2020; Yarham et al. 2006; Askari and Siahkoohi 2008; Wang et al. 2012; Li et al. 2016; Naghizadeh and Sacchi 2018; Liu et al. 2018). All of these techniques at the present-day applied sometimes alone and sometimes in cascaded applications. These techniques sometimes result in the absence of coherent artefacts and lead to low protection of primary amplitudes caused by severe or inadequate filtering (Le Meur and Traonmilin 2008; Le Meur et al. 2008b).

Adaptive ground roll attenuation (AGORA) is a data-driven method developed to perform adaptive filtering of aliased and dispersive surface waves at their true spatial coordinates for both 2D and 3D data. It handles rapid variations in near-surface character and adaptively subtracts coherent noise while preserving primary amplitudes. In short, it can handle the noise attenuation needs of a large number of processing scenarios in different domains, such as common
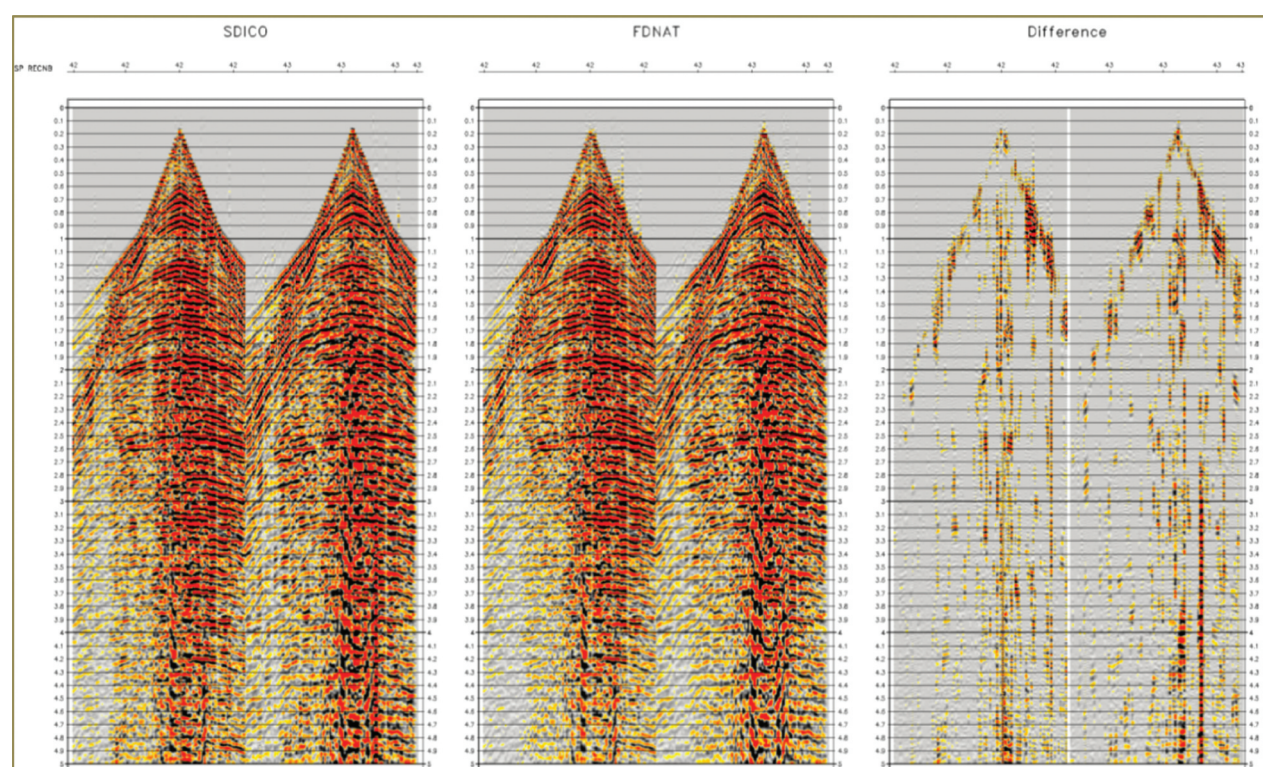
Figure 4. Shots gather before, after, and difference (FDNAT).

receiver gathers, shot gathers, or cross-spreads (Le Meur et al. 2010). The basis of the method is to extract characteristics contained in each gather to model "signal" and "noise" in the (*f-x*) domain. The signal is modelled as hyperbolic events, whose trajectories are described by stacking velocities. The ground roll and guided waves are modelled as a series of dispersive linear events, each distinguished by group and phase velocities. This modelling uses the true distance between source and receiver. A least-squares iterative approach is then used to adapt this model to the input data before subtraction of the noise (ground roll, guided waves). The principle of the modelling is described in more detail in Perkins and Zwaan (2000), Le Meur et al. (2008b), and Le Meur and Traonmilin (2008).

The principal AGORA module is modelling signal and noise in the f-x domain in each gather by separate characteristics contained them. The signal is modelled as hyperbolic events, whose trajectories are expressed by stacking velocities. The ground roll and guided waves are modelled as a series of dispersive linear events, each characterised by phase and group velocities. A least-squares iterative method is then used to adapt this model to the input data before subtraction of the surface noise. Note that this outline is efficient if the current frequency is reasonably close to a defined central frequency.

Before running AGORA, spikes, bursts, and noises must be removed because of their effects on the quality of the groundroll attenuation. This issue was handled by FDNAT before AGORA. The AGORA process can be described by the following main stages:

(1) Extractions of the ground roll characteristics via a frequency-velocity phase diagram.
(2) Wavelet domain. Wavelet filter banks allow a multi-resolution approach with a split of the input data in several frequency-wave number sub-panels using a "highly" reversible wavelet transform.
(3) Modelling in the (*f-x*) domain of aliased and dispersive surface waves is done for each sub-panel using the most adapted set of parameters derived from the data itself via the frequency-phase velocity panel. Adapt the groundroll model to fit data and subtract the Groundroll model from the data.

The basic is that the input data is a mixture of signals in addition to coherent and random noise. The signal (S) is modelled as hyperbolic events whose trajectories are described by RMS velocity using the equation (Le Meur et al. 2008b):

$$S^{j,k} = exp\left[if\left((t_j^2) + \sqrt{t_j^2 + \frac{xk^2}{V_{rmsj}^2}} \right) \right] \quad (4)$$

The coherent noise such as Groundroll is modelled as a series of dispersive linear events, each characterised via phase and group velocities using the following equation:

$$GR^{j,k} = \exp\left[i\left(\frac{f_\circ}{Vp_j} + \frac{f - f_\circ}{Vg_j} \right) xk \right] \quad (5)$$

For a j-th event: (t_o)zero offset travel time, (xk) true shot to receiver distance, (f_0) central frequency of the wave, (vpj) phase velocity, (vgj) group velocities. These events form the components of matrix A with column and row indices j and k.

In the frequency domain, the input data is represented by a matrix (D) which can be defined by a matrix (A) which presents the dispersive linear and hyperbolic events multiplied by a vector (W) which comprises an unknown wavelet corresponding to the signal and groundroll adding to a proportion of random noise (N) as explained by the equation:

$$D = A.W + N \quad (6)$$

rewriting equation (6) =

$$\begin{bmatrix} D(f, x1) \\ D(f, xn) \end{bmatrix} = \begin{bmatrix} exp\left[if\left(\sqrt{t_\circ^2 + \frac{x_1^2}{Vrms^2}} \right) \right] \\ exp\left[if\left(\sqrt{t_\circ^2 + \frac{x_n^2}{Vrms^2}} \right) \right] \\ \begin{matrix} \exp\left[i\left(\frac{f_\circ}{Vp} + \frac{f-f_\circ}{Vg} \right) \right] x1 \\ \exp\left[i\left(\frac{f_\circ}{Vp} + \frac{f-f_\circ}{Vg} \right) \right] xn \end{matrix} \end{bmatrix} \begin{bmatrix} w1(f) \\ wn(f) \end{bmatrix} + N \quad (7)$$

The least square iterative inversion approach is used to extract and subtract the groundroll from the input data. In the majority of the cases where the groundroll may have broadband of more than 30 Hz, however, it is resolved by splitting the data into multiple frequency bands that allow multiple different central frequencies to be used to optimise coherent noise modelling (Le

Table 2. AGORA parameters for shot gathers.

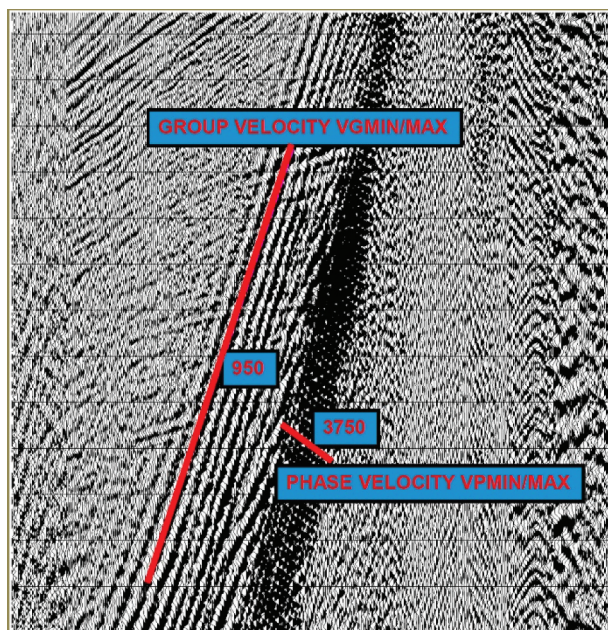| Parameter	Value	Parameter	Value
Min Frequency/ FMIN	2	Max Frequency (FMAX)	20
Min. GR velocity/ VGMIN	300	Max. GR velocity (VGMAX)	950
Min. phase velocity/VPN	500	Max. phase velocity (VPMAX)	3750
DBST(HISTA)	Static	% of Nyquist wave num. to preserve/KHCUT	100%
Num. of a linear event for noise/NUMMOD (parameter for *f-x* modelling)			4

Figure 5. Groundroll property over zoomed raw shot.

Meur and Traonmilin 2008). The applied AGORA Parameters summarised in Table 2. Figure 5 shows the groundroll property over raw shot. The results of AGORA are shown in (Figure 6) and (Figure 7).

2.7. Radial trace mix for noise attenuation

Henley (1999a, 1999b, 1999c) and Henley (2000) introduced radial trace domain (R-T) methods to attenuate coherent noise in seismic data, partly based on previous perform by Claerbout (1975) and Claerbout (1983) who presented radial trace transformation. (R-T) domain is a coherent noise suppression method that takes advantage of the fact that linear noise fragmented from reflection events can be accomplished in the (R-T) domain by aligning the transform coordinate trajectories with the coherent noise wavefronts in the (t-x) domain. As a result, linear noises projected across several constant offset traces of (t-x) gather are collapsed into relatively narrow groups of constant-velocity traces in the R-T domain. In addition, the apparent frequencies of these reflection events decay dramatically, often to the sub-seismic range (Henley 2003). In this domain, the noise is typically represented by a very low-frequency trend and is filtered out and transformed back to the x-t domain. Random noise bursts and spikes must also be addressed in processing seismic data at an early stage.

The Radial Trace Mix for Noise Attenuation (RADMX) module is designed for Random, coherent, and slanted noise attenuation in common offset sorting (offset-class). It stacks each trace of a gather with other neighbouring traces (depending on X and Y x-coordinates) falling within a specified radius to create a noise-reduced version of the same trace. Traces going into the stack are weighted according to their radial distances. The module provides different weighting schemes. RADMX has four available weighting schemes: Constant, Linear, Cosine-
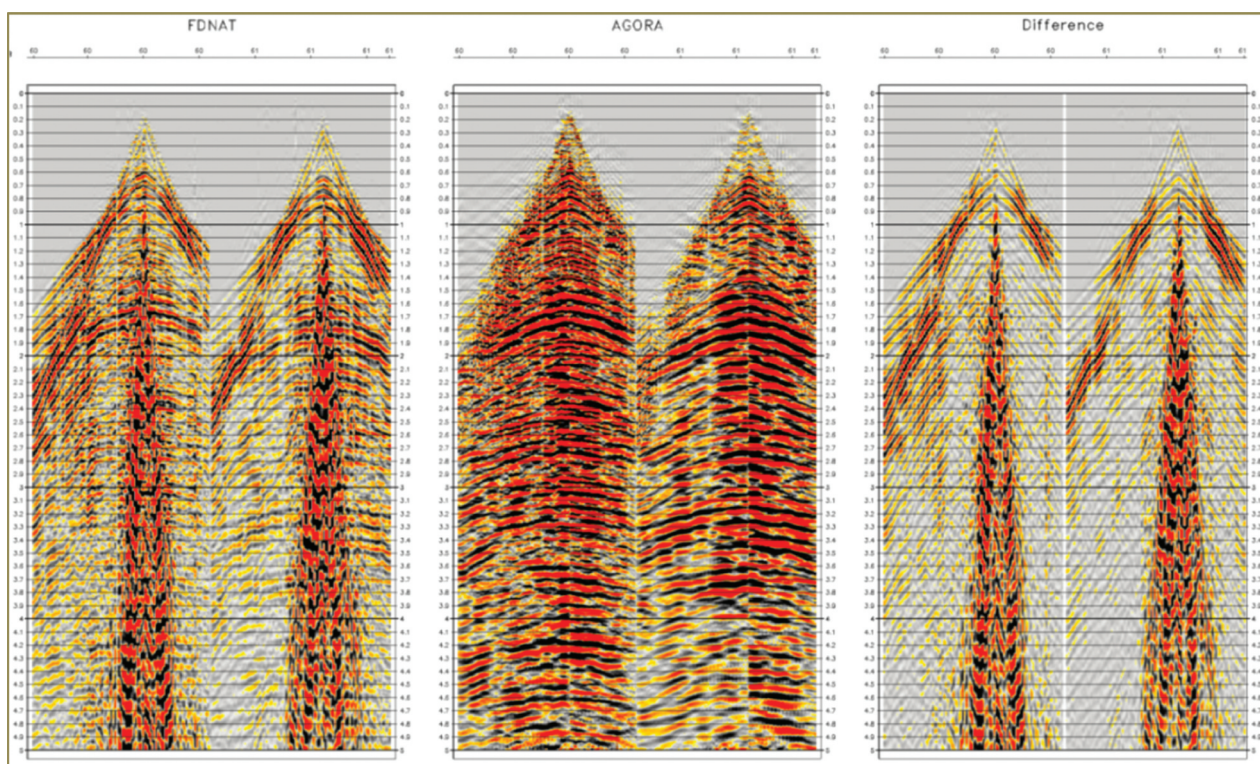

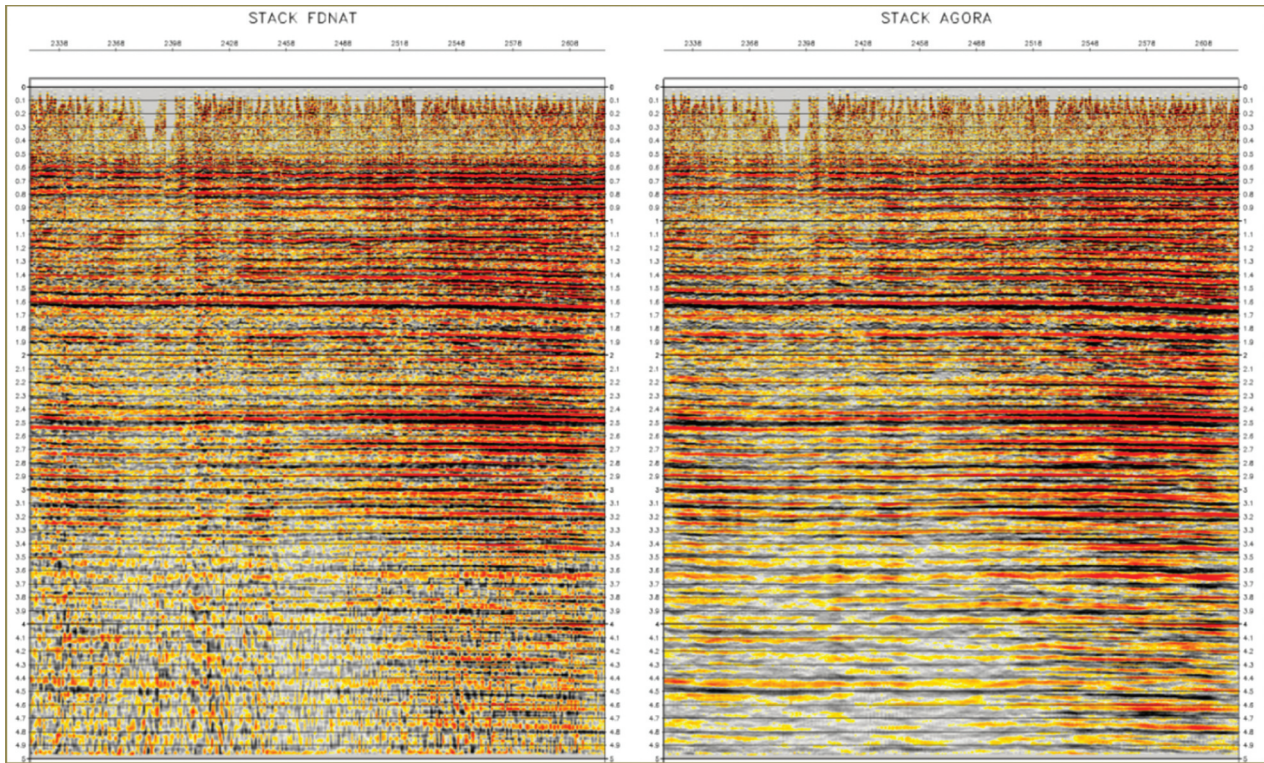**Figure 6.** Shots gather before, after, and difference (AGORA).

Figure 7. Stack before and after (AGORA).

Tapering, and Diversity-Stack types. Here we used a Constant weighting scheme.

Although this module has been designed to work on common receiver gathers (receiver domain), any type of gather domain can be used. RADMX is designed to perform noise attenuation by assuming traces have NMO applied, stacking traces locally (off-set domain) around each trace produces a noise suppressed version of the trace. RADMX has a built-in differential move-out application where the user defines velocity files so that the program can apply the differential move-out internally. Alternatively, NMO can be applied externally using any other NMO application module, in which case RADMX should be run without specifying a velocity file and then the NMO should be removed. Spatial sub-stacking based on 7 traces (module RADMX) was used for additional random and slanted noise attenuation by offset classes. We are using the flowing parameter in the RADMX module RADIUS (200 in distance units). The radial mixing process that yields these noise-reduced traces also seems to be an influential way of attenuating steeply dipping noise which otherwise leaks into stack volumes. The results of applied RADMX are shown in (Figure 8) and (Figure 9).

2.8. Structurally consistent filtering (f-x filter)

Attenuation of random noise and enhancement of structural continuity can significantly improve the quality of seismic interpretation (Guo et al. 2018). Structurally Consistent Filtering has generally proved an effective noise suppression tool for low dip geology. In this situation samples associated with geology or with parts of the seismic wavelet associated with similar geology are input to the filter. Structural requirements for seismic filters are that they should smooth in homogeneous areas while preserving trends, edges, and details. we would like to be able to vary the amount of filtering in homogeneous areas whilst retaining edges and details. The Popular random noise attenuation algorithms can suppress random noise but e.g. may smear fault boundaries. Hence, they are limited by their lack of protection of structural information (e.g. faults and folds). Structurally Consistent Filtering can suppress noise along with seismic reflectors while preserving major structural and stratigraphic discontinuities. This makes denoising and protecting structural information important (Hoeber et al. 2006). We used structurally consistent filtering to reduce random noise while protecting geological structures. This denoising method allows us to better control the balance between eliminating random noise and protecting structural information.

Structurally Consistent Filtering is random noise attenuation in the offset domain which is an effective solution to execute 2D dip filtering, driven by local, spatially varying dip fields. This algorithm uses differential filters from dip steered composite, and tolerates filtering over large distances even when dips are geometrically slightly changing over short distances. Conventional denoise processing is quite effective.
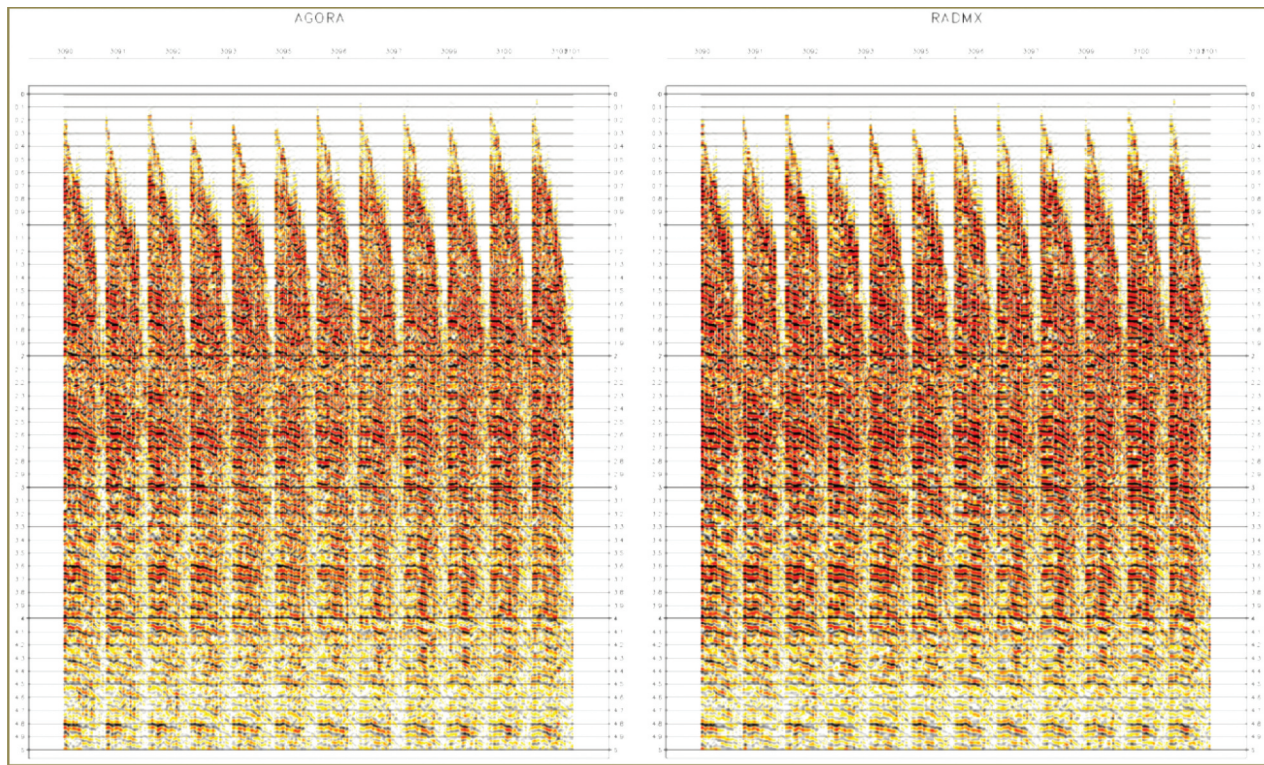
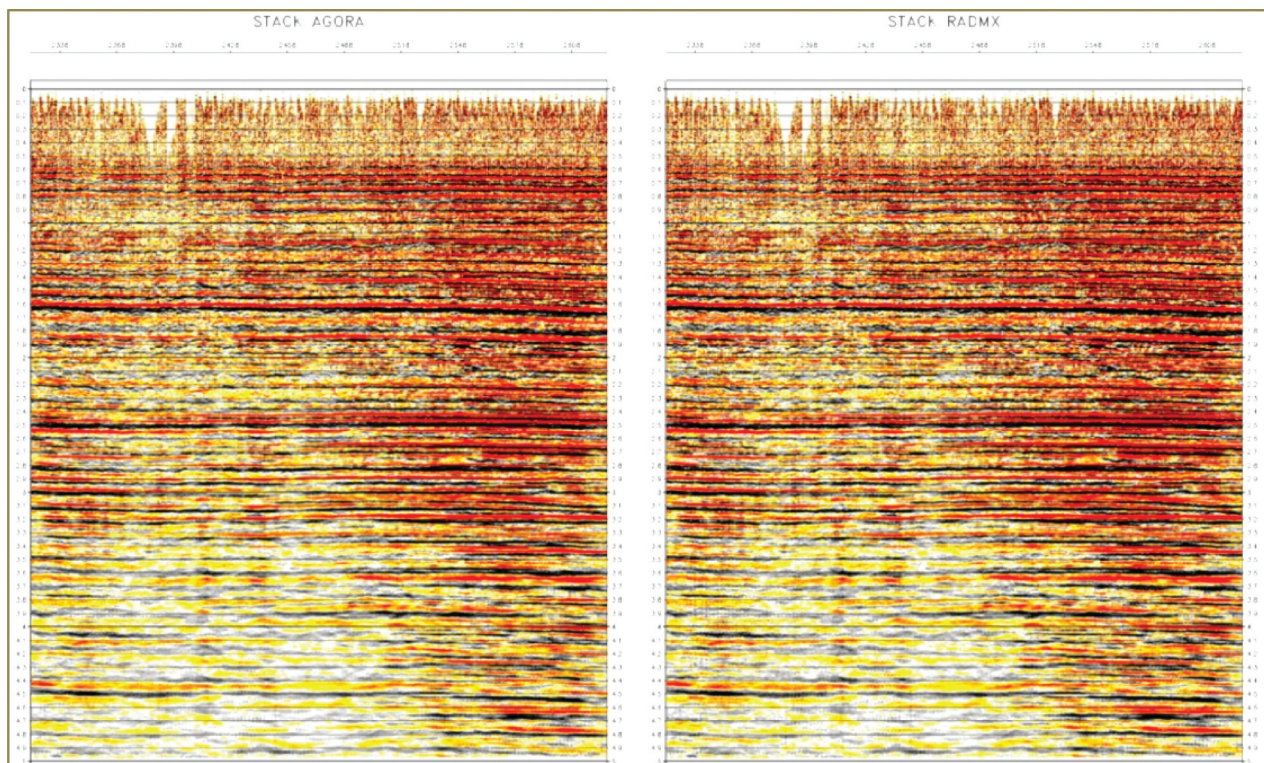**Figure 8.** CDP gathers data before and after (RADMX).

Figure 9. Stacks of data before and after (RADMX).

Such techniques, however, adjust the original spatial organisation of the attributes along seismic horizons: a structurally consistent filtering method is therefore necessary. To avoid horizon picking, one can compute, from the seismic that the local dips are steered by the filtering along with the seismic layers (Traonmilin and Herrmann 2008). Such dip steered approaches have already been developed and

illustrated in the literature e.g. non-linear filters over planar surfaces, parallel to the dip (Hoeber et al. 2006) and Shaping regularisation filters (Fomel 2007)

SCFIL (structurally consistent filter) module performs non-stationary filtering which attenuates random noise in common offset sorting. The input data is organised by gathers. An auxiliary input is used to compute the parameters of the filtering. Traces must be at the same location (offset domain) as the main input. structurally consistent filtering (SC) filters along the local dips computed on the reference data. To filter along with the structure of the reference data used local dips.

The first step of applying structurally consistent filtering is to obtain the data's structural information. We compute the corresponding dip field [p (t, x)]. This field will drive the structurally consistent filtering. There are several methods for computing dip field, here a least-square strategy is used to ensure robust and stable dip estimation and then extract p from it. The second step is to filter once the dip field is calculated; then we have to build the filtering process. This solution can be considered as an adaptive convolutive f -x filtering. For each data point, a filter is calculated to select the known local dip (Traonmilin and Herrmann 2008). The Structural criteria for seismic filters are that they should be smoothing homogeneous areas while preserving trends, edges, and other details. Figure 10 shows how to filter along the structure of the reference data we use local dips. These dips are used to define local filters. The results of SCFIL are shown in (Figure 11) and (Figure 12).
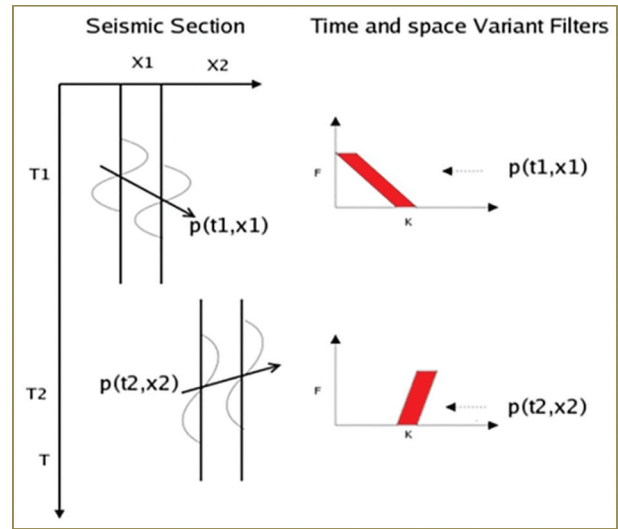

Figure 10. Shows how to filter along with the structure of the reference data. We use local dips and these dips are used to define local filters (Geovation User's Manual 2010).

2.9. Dip-dependent median filtering

There are two key geophysical assumptions used in dip-dependent median filtering: (1) that seismic data are coherent along a dominant local dip, and (2) the amplitude values vary slowly along this dip. The first assumption implies that one specific dip can be picked, along which events are continuous. The second assumption implies that, on a local scale, the median (or a spatially weighted trimmed mean) is a good estimate of the sample values. Given the above
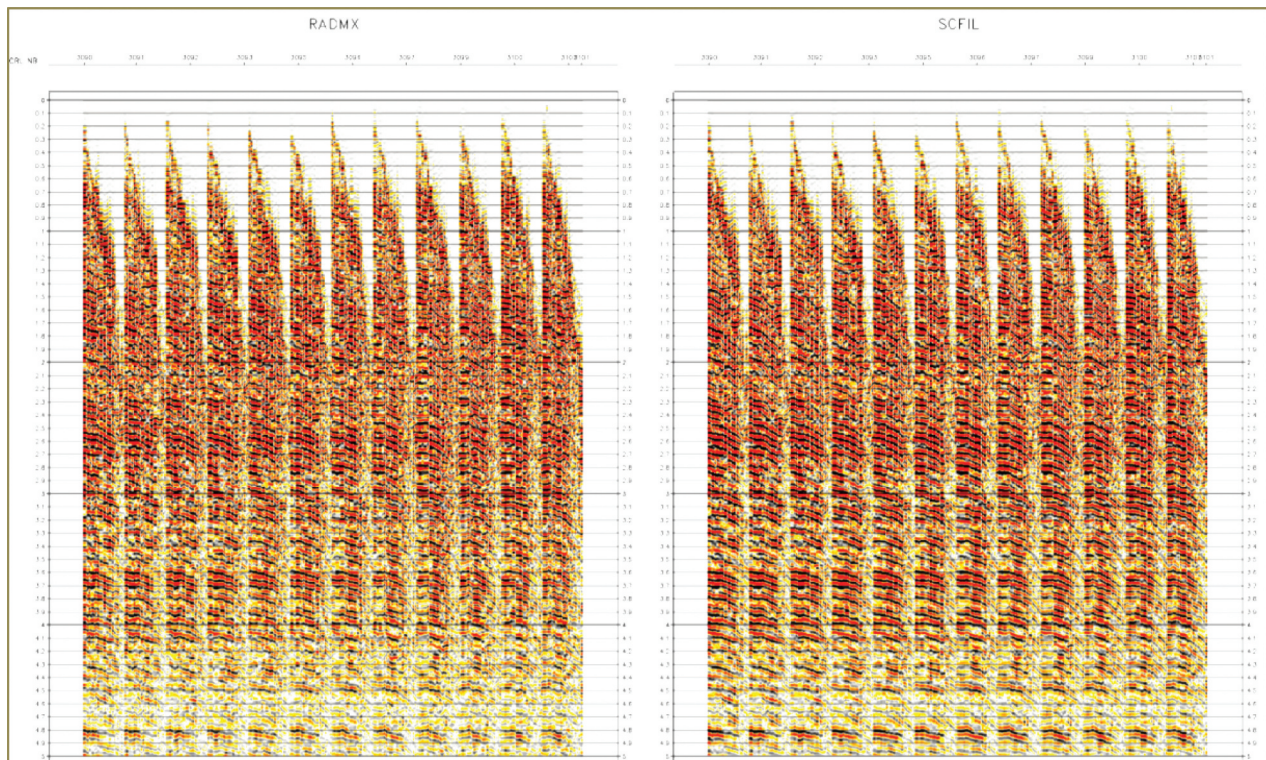

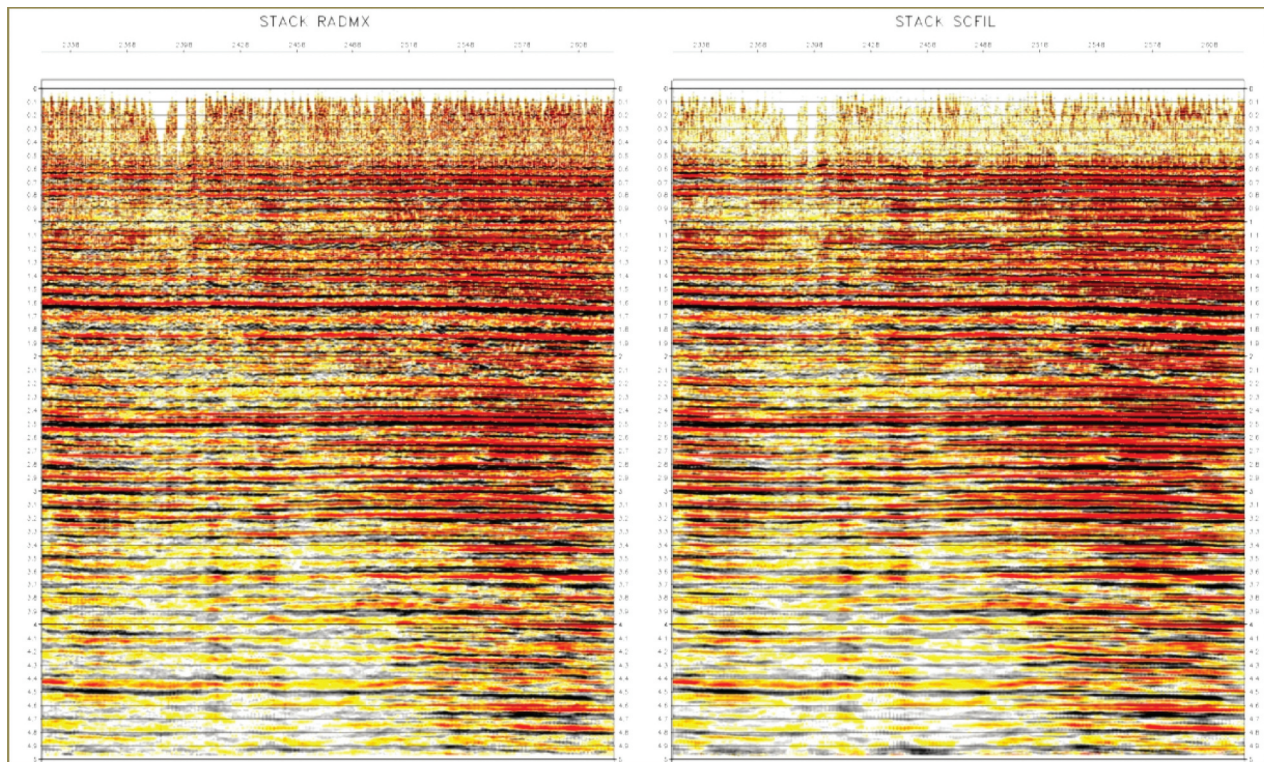**Figure 11.** CDP gathers data before and after (SCFIL).

Figure 12. Stacks before and after applied (SCFIL) module.

two properties, it is important to realise that any type of coherent noise along a specific dip (e.g. ground roll) will be enhanced. The process is a simple, sample-by-sample operation performed in the x-t domain as a roll-along process. First, the dominant local dip is determined, over a specified number of traces, immediately adjacent to the trace containing the sample in question. To remove performed on the samples along with the dominant dip. The data sample is then *replaced* with a normalised, spatially weighted stack of the remaining sample values (Holcombe and Wojslaw 1992; Reiter et al. 1993).

DDMED module applies a median or trimmed mean filter along the local dip of the data, thereby suppressing random noise and increasing trace-to-trace coherency. DDMID filtering is a non-linear seismic noise suppression process that can be applied to prestack or post-stack data. It is a robust, efficient, and relatively simple operation that, in general, improves the signal-to-noise ratio and increases the trace-to-trace coherency of the input data.

DDMED takes the input data and estimates the local (2D) dip at every sample point. A variable-width median filter (i.e. a trimmed mean) is then applied along with the dominant picked dip. At this point, the user can choose to apply a spatial weighting function as well. The filtered sample value then replaces the central sample value from the original local dip computation. Median filtering processes such as DDMED are generally better at removing
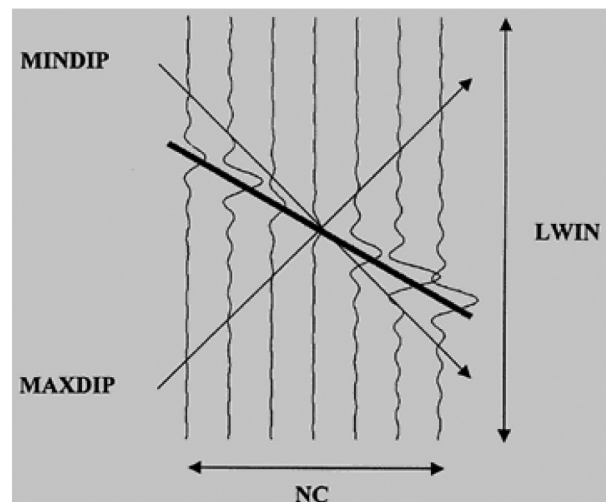

Figure 13. A range of dips is scanned about the central sample in the filter window. The dominant dip (denoted by the thick black line) is picked (NC) Size of the spatial window, (LWIN) the time window, MAXDIP &MINDIP (Geovation User's Manual 2010).

local high amplitude noise events than other techniques such as F-K and F-X filtering.

DDMED carries out the following steps:-

(1) For every time sample, a dip search estimates the dominant local dip as shown in (Figure 13).
(2) A fraction of the maximum and minimum local sample values along this picked dip are removed from the filtering process.
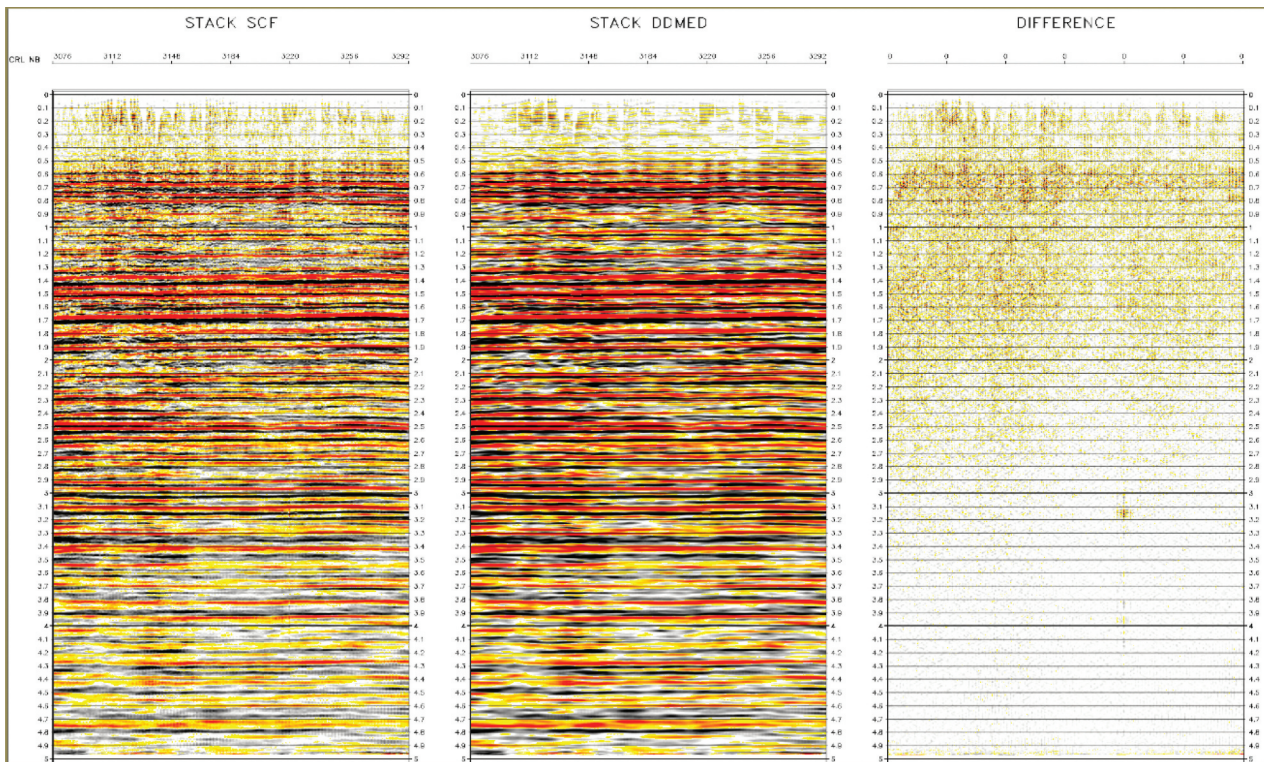
Figure 14. Stack before and after (DDMED).

(3) A weighted average is computed from the remaining samples. The weights are either unity or a user-defined spatial weight function.

(4) Finally, the original (central) time sample for the dip search is replaced by the filtered sample value.

In step (2), if all samples except the central amplitude value are removed, the process is equivalent to median filtering; and if no values are removed, the process is equivalent to taking the mean. While DDMED can be applied to data with variable trace spacing. Figure 14 shows the results of stacks before and after the applied (DDMED) filter. Table 3 summarises Applied Parameters for DDMED.

2.10. Time-variant filter (TVF)

The frequency content of the seismic signal decreases Versus depth increases, because the higher frequency bands of the seismic signal are absorbed as the signal propagates deeper in time (Yilmaz 2001;

Onajite 2013). Hence, the higher frequency of the signal is limited to the earlier part of the seismic section. Thus, the vertical resolution is decreased significantly in the deeper part of the seismic section. For this reason, the seismic data processor looks for the optimum filter at variable times down the section which provides a good SNR. Therefore, we need time-variant filtering (TVF). Also, because SNR and signal spectrum change with time and sometimes with space, it is more likely that one filter would not do for the entire section. Often a time-depended decay in SNR, thus, it is frequently necessary final processing step to utilise TVF to uncover the clearest possible image of stratigraphic boundaries (Scheuer and Oldenburg 1987).

TVF usually are applied to stacked data. The interpreter uses the frequency property of a sign horizon as a reference in the tracking process (Yilmaz 2001). A series of filters were tested in discrete 5 Hz bands, from 25 Hz to 70 Hz, then a series of low-cut filters were tested (8 Hz 10 Hz, 12 Hz, 14 Hz, 16 Hz, 18 Hz,), to select the best time-variant filter for the final stack. Then a series of time-variant filters took place, to choose the best one. Tables 4 summarise the Parameter of the TV Filter. Figure 15 shows stacks of data before and after application (TVF).

Table 3. DDMED Applied Parameters.

parameter	Value
Size of the spatial window used in (dip search and filtering routines) (NC)	3 (num. of traces in gather or stack)
Size of the time window (dip search) (LWIN)	300 (ms)
The start time of the processing (TI)	0 (ms)
MAXDIP &MINDIP (dip search)	6 & −6 (ms/trace)
Num. of dips scanned in the (dip search) ND	3
Spatial half-width of a Gaussian curve (SIGMA)	1

Table 4. Time variant filter parameter.

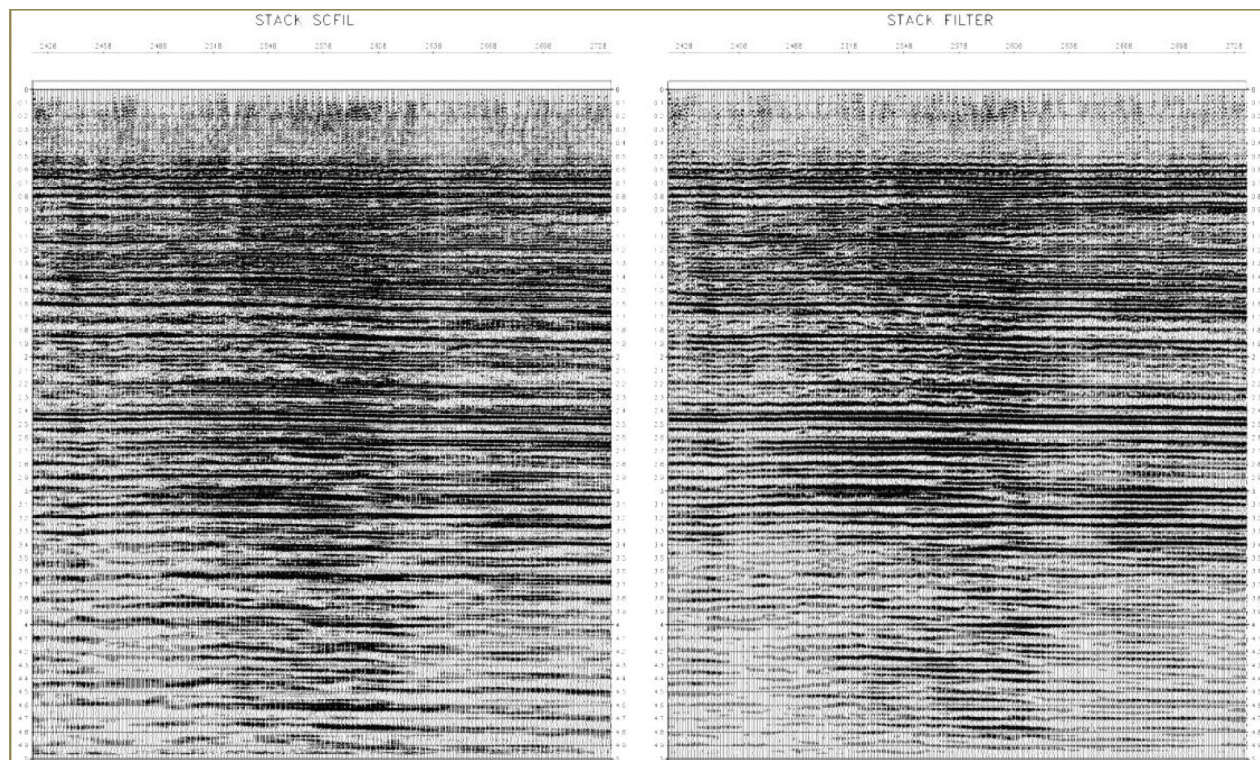| Time (in ms)	Filter Band (in Hz)
0–1100	14, 18–40, 50 Hz
1400–5000	12, 16–35, 45 Hz

Figure 15. Stack before and after (TVF) filter.

3. Results and discussions

In the final section, after applying the processing sequence for noise attenuation to current 2D seismic data as shown in (Table 5), we observed improved continuity of the reflection boundaries compared to the raw data. Figure 16 shows CDP gathers before, after, and difference full processing sequence of noise attenuation. Figure 17 shows stack before and after noise attenuation. We observed vertical resolution improvement, due to enhanced SNR after noise attenuation (Figure 18). Overall improvement in seismic resolution and the enhanced image will certainly help to understand the geology and reservoir properties better. FDNAT gives a good result for attenuating random noise (anomalous amplitude) after tested and applying threshold values

with the windows of times and frequencies. FDNAT determines the amplitude value in a specific time window and after that computes the suitable threshold corresponding to the properties of the time windows and signal frequencies for detecting high energy amplitudes. the results were effective in attenuation random noise in pre-stack data. Moreover, avoided signal data losses and increased SNR. AGORA filter confirmed the effectiveness of attenuating the coherent noise (ground-roll). The adaptive (AGORA) filter is applied to resolve the problem of coherent surface wave noise which offers advantages over conventional methods (modelling of surface and guided waves), so the data-driven estimate changes groundroll characteristics from the data, then the Adaptive modelling and estimate groundroll velocity, frequency, and aliasing. This filter is improving

Table 5. Summary of a noise attenuation processing sequence to current 2-D seismic data.

| Sequential Processing Flow	Parameters Applied
Reformatting (**SEGIN**)	Anti-aliasing High Cut filer 100 Hz/96 dB/Oct
Geometry Up-date (Onset App.) (**ETQXY**)	The input of XY Coordinates into the seismic traces
Spherical divergence correction (**SDICO**)	Using P. Newman's formulae.
Random Noise Attenuation (**FDNAT**) (Shot domain)	High-amplitude noise (frequency-dependent and time-variant amplitude (threshold).
Ground-Roll (GR) **AGORA**	group velocity 1000 m/s
Radial trace Mixing (**RADMX**)(offset domains)	Assuming traces have NMO applied, stacking traces locally (offset domain) around each trace produces a noise suppressed version of the trace.
Structural Consistent Filtering (**SCIFL**) (offset domain)	Structurally consistent (SC) filter. A spatial window of 7 traces, Filter length (500 ms). Frequency range – above 12 Hz).
Dip-Dependent Median/trimmed mean filtering (**DDMED**)	NC (3), LWIN (300 ms), TI (0 ms), MAXDIP &MINDIP(6&-6 ms/trace), ND(5).
Time Variant Filter (**TVF**)	time (in ms) /Filter Band (in Hz) 0–1100/ 14, 18–40, 50 Hz 1400–5000 /12, 16–35, 45 Hz
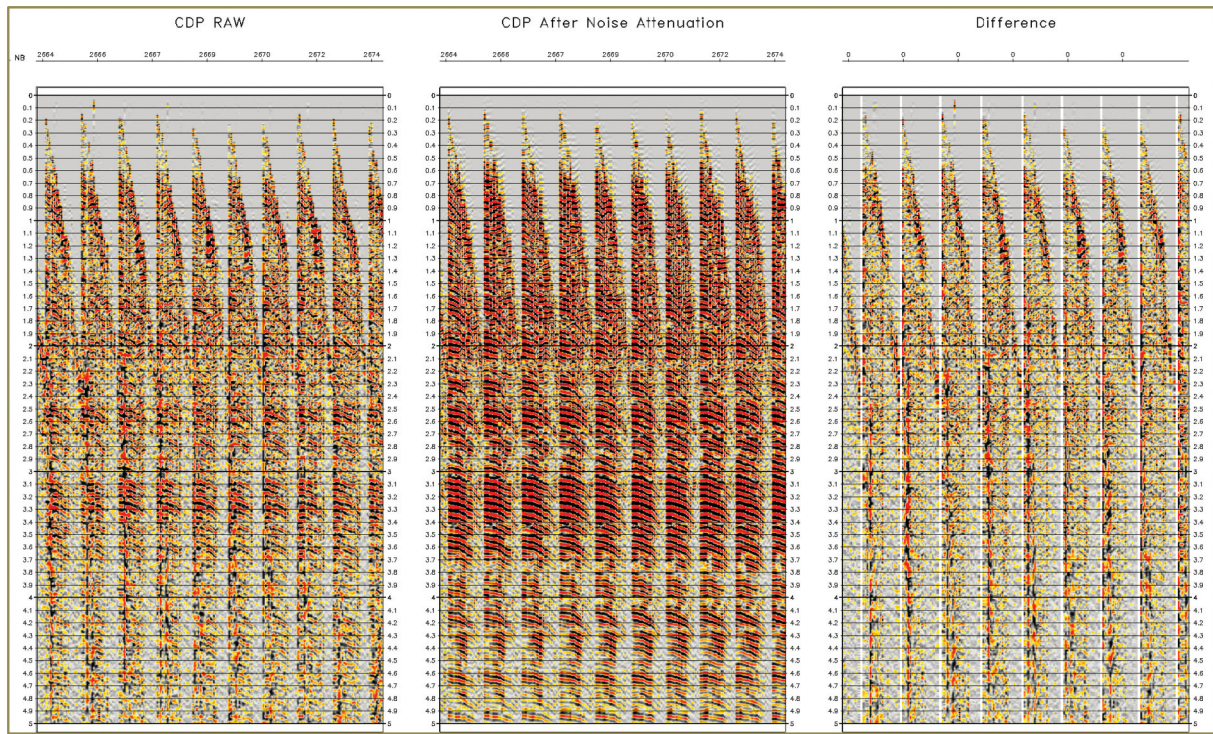
Figure 16. CDP gathers before and after noise attenuation with a difference.
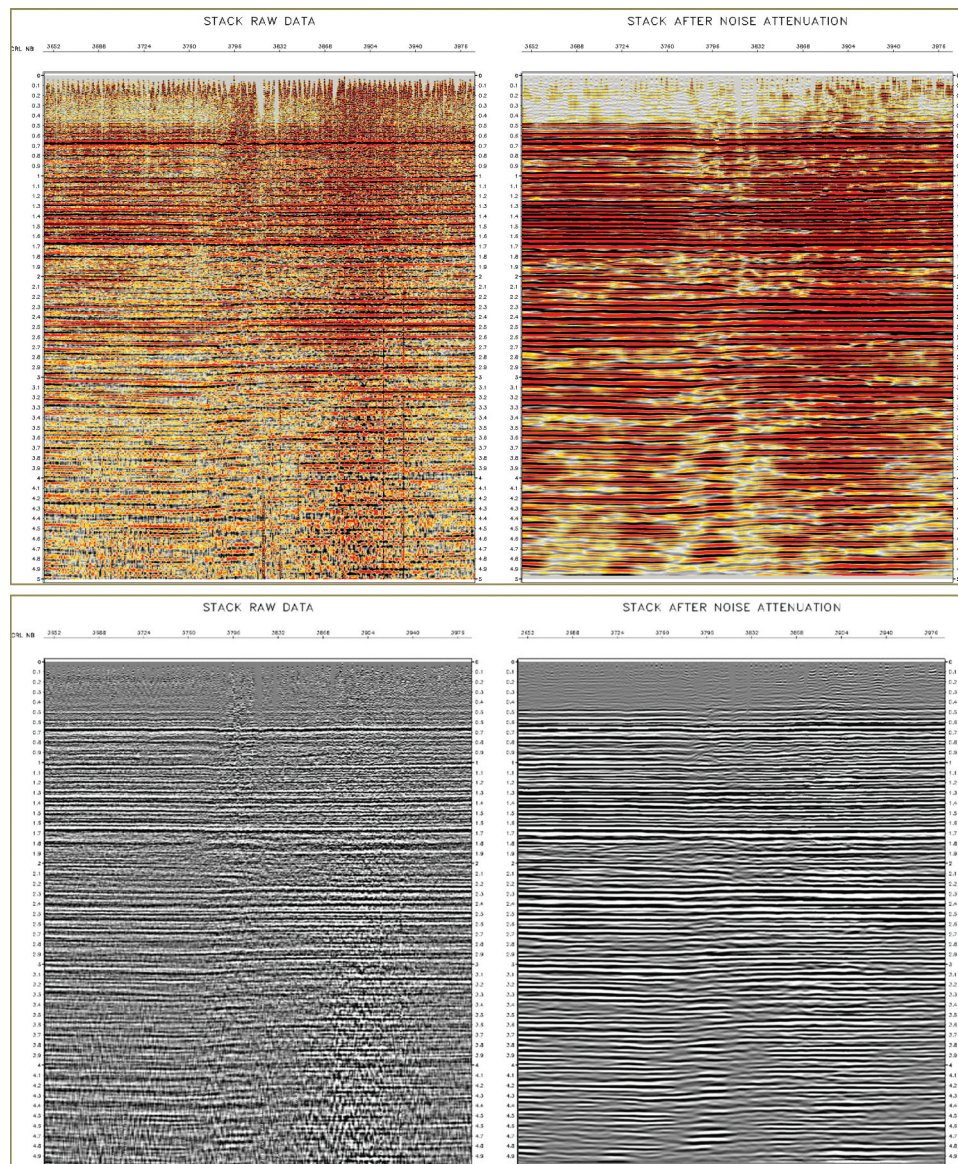
Figure 17. Stacks before(raw) and after noise attenuation visualised with colour and greyscale.
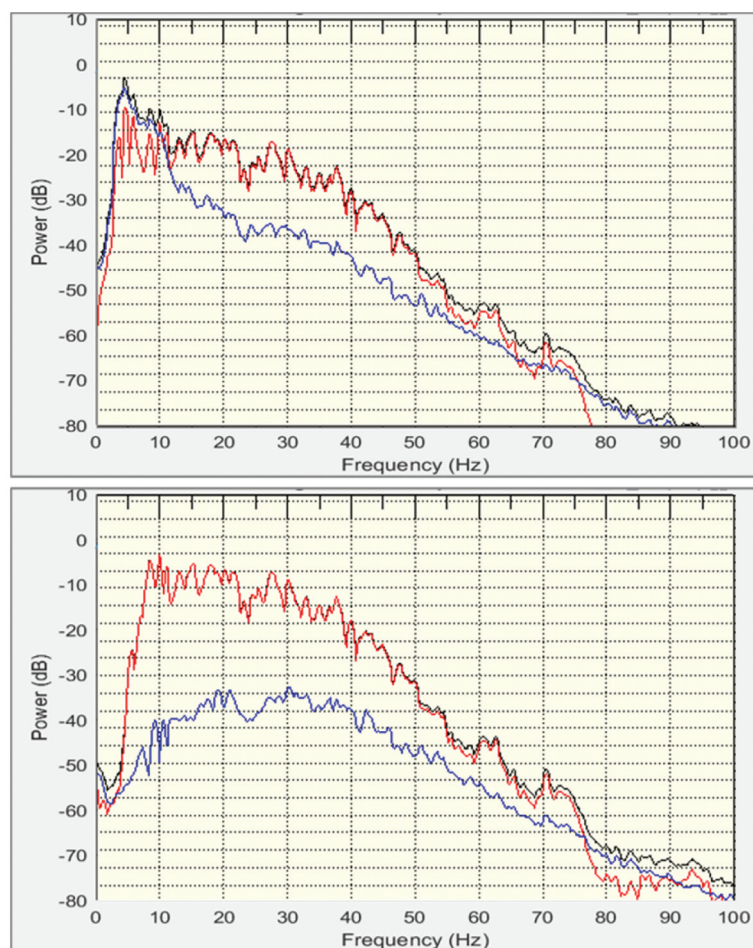
Figure 18. Frequency spectra before (top)and after noise attenuation: (black) signal+noise, (red) signal estimate, (blue) noise estimate. Spectra are calculated for window (500–3000)ms.

image quality without loss of data (reflection events). Also, the result was encouraging even if the seismic data set does not agree with the noise model and later it was very effective in increasing the SNR as we show in spectral analysis. RADMX suppressed coherent noise in the radial trace domain. This module is more valuable than some of the more traditional noise attenuation modules. Because efficiently suppresses linear noise almost parallel to the long offset limbs of reflections. Some very dispersive noises, such as a bit of the ground-roll are very difficult to handle in the *f-k* domain but yield further easily in the R-T domain. The radial mixing process seems to be an influential way of attenuating steeply dipping noise which otherwise leaks into the stack image. Nonstationary filtering (SCFIL) attenuates random noise (offset domain) which is an effective solution to execute 2-D dip filtering, steered by spatially, local varying dip fields. This module smoothing structural in homogeneous areas while preserving trends, edges, and details, so, it gives the best result in structural conformity. RADMX and SCFILL were efficient and can reveal features and geological structures that were masked by noise present in the current data. A median or trimmed mean (non-linear) filter DDMED suppressing random noise and increasing trace-to-trace

coherency, and increasing the signal/noise ratio and is generally better at removing local high amplitude noise events than other techniques such as *f-k* and *f-x* filtering. Overall, the final results show a comprehensive noise attenuation processing sequence for current 2D seismic data. It is shown that an improved resolution and signal-to-noise ratio.

4. Conclusions

The quality of seismic products and solutions being delivered today is, without doubt, a huge improvement compared to a few years ago. The rate of development, however, is very fast and it remains problematic for seismic data processing. In the south Iraq environment 2D seismic data was acquired, where structures are relatively flat and seismic data are contaminated by strong noises. The current data is convoluted by a considerable amount of coherent and random noise. We successfully applied advanced and a wide range of modules for noise attenuation processing technologies on low-fold data. We have tested the effectiveness of currently available modules and filters in our processing system for noise attenuation to

increase the signal-to-noise ratio (SNR), and improve and enhanced seismic image quality. The random and coherent noise attenuation shows superior denoising performance As a result, significantly improved frequency content, improved' resolution, and increased the signal-to-noise ratio (SNR) of the seismic data set and it showed a strong ability to remove random and coherent noise while preserving the useful seismic signal. We are optimistic that the improvement in seismic images will have a positive impact on the next step of processing and finally interpretation.

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No potential conflict of interest was reported by the author(s).

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References

Abdel Fattah TH, Diab A, Younes M, Ewida H. 2020. Improvement of Gulf of Suez subsurface image under the salt layers through re-processing of the seismic data-a case study. NRIAG J Astron Geophys. 9 (1):38–51. doi:10.1080/20909977.2020.1711575.

Abma R, Claerbout J. 1995. Lateral prediction for noise attenuation by tx and fx techniques. Geophysics. 60 (6):1887–1896. doi:10.1190/1.1443920.

Aminzadeh F, Shivaji ND. 2013. Fundamentals of Petroleum Geophysics. UK: Elsevier, p. 37–92, Vol. 60.

Askari R, Siahkoohi H. 2008. Ground roll attenuation using the S and x-f-k transforms. Geophys Prospect. 56:105–114. doi:10.1111/j.1365-2478.2007.00659.x

Bekara M, Van der Baan M. 2007. Local singular value decomposition for signal enhancement of seismic data. Geophysics. 72(2):V59–V65. doi:10.1190/1.2435967.

Beresford-Smith G, Rango R. 1989. Suppression of ground roll by windowing in two domains. First Break. 7 (2):55–63. doi:10.3997/1365-2397.1989004.

Canales LL, 1984, Random noise reduction: 54th Annual International Meeting, SEG, Expanded Abstracts, Atlanta, Georgia, 525–527, doi: 10.1190/1.1894168.

Carolyn D (2010) " seismic processing – noise attenuation techniques for relative amplitude processing" (technical articles), Petroleum Africa Magazine, Dec. 2010pp. 47–49.

Chen Y, Fomel S. 2015. Random noise attenuation using local signal-and-noise orthogonalization. Geophysics. 80 (6):WD1–WD9. doi:10.1190/geo2014-0227.1.

Chen W, Song H. 2018. Automatic noise attenuation based on clustering and empirical wavelet transform. J Appl Geophys. 159:649–665. doi:10.1016/j.jappgeo.2018.09.025

Claerbout JF, 1975, Slant-stacks, and radial traces, stanford exploration project report, SEP-5, pp. 1–12.

Claerbout JF, 1983, Ground roll and radial traces, stanford exploration project report, SEP-35, pp 43–53.

Dobrin MB, Savit CH. 1988. Introduction to geophysical prospecting. 4th. New York: McGraw-Hill Inc, p. 867.

Dondurur D. 2018. Acquisition and processing of marine seismic data. 1st ed. Elsevier, Amsterdam: Elsevier; p. 606.

Donoho DL, Johnstone IM, Kerkyacharian G, Picard D. 1996. Density estimation by wavelet thresholding. Ann Stat. 508–539.

Elboth T, Geoteam F, Qaisrani HH, Hertweck T. 2008. Denoising seismic data in the time-frequency domain". SEG Tech Program Expand Abstr. 2622–2626. doi:10.1190/1.3063887

Fomel S. 2007. Shaping regularization in geophysical-estimation problems. Geophysics. 72(2): R29–R36. doi:10.1190/1.2433716.

Fomel S, Liu Y. 2010. Seislet transform and seislet frame. Geophysics. 75(3):V25–V38. doi:10.1190/1.3380591.

Gan S, Wang S, Chen Y, Chen X, Xiang K. 2016. Separation of simultaneous sources using a structural-oriented median filter in the flattened dimension. Comput Geosci. 86:46–54. doi:10.1016/j.cageo.2015.10.001

Geovation User's Manual. 2010. CGGVaritas company. France.

Guo L, Liu Y, Liu C, Zheng Z. 2018. Structure-oriented filtering for seismic images using nonlocal median filter. In: SEG technical program expanded abstracts 2018. Society of Exploration Geophysicists; p. 4623–4627. doi:10.1190/segam2018-2998154.1

Henley DC. 1999a. Coherent noise attenuation in the radial trace domain: introduction and demonstration. CREWES Rese Rep. 11.

Henley DC, 1999b, Demonstration of radial trace domain filtering on the Shaganappi 1998 geotechnical survey, CREWES Research Report 11.

Henley DC, 1999c, Radial trace computational algorithms at CREWES, CREWES Research Report 11.

Henley DC. 2000. More radial trace domain applications. CREWES Rese Rep. 12 14.

Henley DC. 2003. Coherent noise attenuation in the radial trace domain. Geophysics. 68(4):1408–1416. doi:10.1190/1.1598134.

Hoeber H, Brandwood S, Whitcombe D (2006), structurally consistent filtering: 68th EAGE Conference and Exhibition incorporating SPE EUROPEC, Expanded Abstracts. Vienna, Austria, 2006 Jun 12-15. 10.3997/2214-4609.201402373.

Holcombe HT, Wojslaw RS, 1992. Spatially weighted trim stacking: a Technique for Pre-Stacked noise suppression. Proceedings Society of Exploration Geophysicists- SEG, Annual Meeting, New Orleans,Louisiana, USA, pp.1157–1160. 10.1190/1.1821935.

Hosseini SA, Javaherian A, Hassani H, Torabi S, Sadri M. 2015. Adaptive attenuation of aliased ground roll using the shearlet transform. J Appl Geophys. 112:190–205. doi:10.1016/j.jappgeo.2014.11.018.

Ismail A, Ewida HF, Al-Ibiary MG, Nazeri S, Salama NS, Gammaldi S, Zollo A. 2021. The detection of deep seafloor pockmarks, gas chimneys, and associated features with seafloor seeps using seismic attributes in the West offshore Nile Delta. Egypt

Explor Geophys. 52(4):388–408. doi:10.1080/08123985.2020.1827229.

Kearey P, Brooks M, Hill I. 2002. An introduction to geophysical exploration. 3rd ed. UK: Blackwell Science; p. 272.

Kong XL, Chen H, Wang JL, Hu ZQ, Xu D, Li LM. 2017. An amplitude suppression method based on the decibel criterion. Appl Geophys. 14(3):387–398. doi:10.1007/s11770-017-0636-7.

Le Meur D, Benjamin N, Cole R, Al Harthy M (2008a, June). Adaptive groundroll filtering. In 70th EAGE Conference and Exhibition incorporating SPE EUROPEC 2008 (pp. cp–40). Rome, Italy: European Association of Geoscientists & Engineers. 10.3997/2214-4609.20147745

Le Meur D, Benjamin N, Cole R, Al-Harthy M (2008b) "Adaptive Groundroll filtering" 70th EAGE Conference and Exhibition incorporating SPE EUROPEC, Rome, Italy 10.3997/2214-4609.20147745

Le Meur D, Benjamin N, Twigger L, Garceran K, Delmas L, Poulain G. 2010. Adaptive attenuation of surface-wave noise. First Break. 28(9). doi:10.3997/1365-2397.28.9.41394.

Le Meur D, Traonmilin Y. 2008. Adaptive noise attenuation. SEG Tech Program Expand Abstr. 2008:3667–3670. doi:10.1190/1.3064093

Li Q, Feng H, Li Q. (2009). Method of seismic interactive velocity analysis. In Beijing International Geophysical Conference and Exposition: Beijing 2009 International Geophysical Conference and Exposition, Beijing, China, 2009 Apr 24–27 (pp. 68). Society of Exploration Geophysicists.

Liu G, Chen X. 2013. Noncausal f–x–y regularized nonstationary prediction filtering for random noise attenuation on 3D seismic data. J Appl Geophys. 93:60–66. doi:10.1016/j.jappgeo.2013.03.007

Liu G, Chen X, Du J, Wu K. 2012. Random noise attenuation using fx regularized nonstationary autoregression. Geophysics. 77(2):V61–V69. doi:10.1190/geo2011-0117.1.

Liu Z, Chen Y, Ma J. 2018. Ground roll attenuation by synchrosqueezed curvelet transform. J Appl Geophys. 151:246–262. doi:10.1016/j.jappgeo.2018.02.016

Li H, Yang G, Wang J, Jiao J, 2016, Ground roll suppression by EMD algorithm based on average value constraint: 6th Annual International Meeting, SEG, Expanded Abstracts, 4664–4668, doi: 10.1190/segam2016-13950568.1.

Miller RD. 1992. Normal moveout stretch mute on shallow-reflection data. Geophysics. 57(11):1502–1507. doi:10.1190/1.1443217.

Naghizadeh M, Sacchi MD. 2012. Multicomponent seismic random noise attenuation via vector autoregressive operators. Geophysics. 77(2):V91–V99. doi:10.1190/geo2011-0198.1.

Naghizadeh M, Sacchi M. 2018. Ground-roll attenuation using curvelet downscaling. Geophysics. 83(3):V185–V195. doi:10.1190/geo2017-0562.1.

Nanda NC. 2021. Seismic data interpretation and evaluation for hydrocarbon exploration and production. Springer Nature Switzerland AG: Springer International Publishing.

Nazari Siahsar MA, Gholtashi S, Kahoo AR, Chen W, Chen Y. 2017. Data-driven multitask sparse dictionary learning for noise attenuation of 3D seismic data. Geophysics. 82(6):V385–V396. doi:10.1190/geo2017-0084.1.

Neelamani R, Baumstein AI, Gillard DG, Hadidi MT, Soroka WL. 2008. attenuation using the curvelet transform. Lead Edge. 27(2):240–248. doi:10.1190/1.2840373.

Newman P. 1973. Divergence Effects in A Layered Earth. GEOPHYSICS. 38(3):481–488. doi:10.1190/1.1440353.

Onajite E. 2013. Seismic data analysis techniques in hydrocarbon exploration. : USA: Elsevier.

Perkins C, Zwaan M. 2000. Ground roll attenuation. 62nd EAGE Conference & Exhibition, Expanded abstract, session L0021, Glasgow, UK, pp. cp–28.

Reiter EC, Toksoz MN, Purdy GM. 1993. A Semblance-guided Median Filter. Geophys Prospect. 41(1):15–41. doi:10.1111/j.1365-2478.1993.tb00563.x.

Saad OM, Chen Y. 2020. Deep denoising autoencoder for seismic random noise attenuation. Geophysics. 85(4):V367–V376. doi:10.1190/geo2019-0468.1.

Scheuer T, Oldenburg D. 1987. Time-variant band-pass filtering. SEG Tech Program Expand Abstr. 1987:266–269. doi:10.1190/1.1892117

Sheriff RE, Geldart LP. 1995. Exploration seismology. New York, USA: Cambridge university press.

Starck JL, Candès EJ, Donoho DL. 2002. The curvelet transform for image denoising. IEEE Trans Image Process. 11(6):670–684. doi:10.1109/TIP.2002.1014998.

Traonmilin Y, Herrmann P. 2008. Structurally consistent f-x filtering. SEG Tech Program Expand Abstr. 2642–2646. doi:10.1190/1.3063891

Treitel S, Shanks J, Frasier C. 1967. Some aspects of fan filtering. Geophysics. 32(5):789–800. doi:10.1190/1.1439889.

Wang W, Gao J, Chen W, Xu J. 2012. Data adaptive ground-roll attenuation via sparsity promotion. J Appl Geophys. 83:19–28. doi:10.1016/j.jappgeo.2012.04.004

Wang J, Zhou XY, Yun CH. 2011. Under the restriction of surface consistent anomaly amplitude decay technology implementation. Geophys Prospect Pet. 50(5):493–498.

Yarham C, Boeniger U, Herrmann F, 2006, Curvelet-based ground roll removal: 76th Annual International Meeting, SEG, Expanded Abstracts, New Orleans, Louisiana, USA. pp. 2777–2782.

Yilmaz O, Edited by Stephen M. Doherty, (1987) "Seismic data processing", Society of Exploration Geophysicists (SEG) Investigations in Geophysics No. (2).

Yilmaz Ö. 2001. Seismic data analysis: processing, inversion, and interpretation of seismic data. Investigate Geophys Soc Explor Geophys (SEG). 2065. doi:10.1190/1.9781560801580.

Yuan Y, Si X, Zheng Y. 2020. Ground-roll attenuation using generative adversarial networks ground-roll attenuation using GANs. Geophysics. 85(4):WA255–WA267. doi:10.1190/geo2019-0414.1.

Yuan Y, Zhou Z, Niu B, Wang H, Xiang A. 2005. A method for improving the signal to noise ratio in seismic data. Oil Geophys Prospect. 40:168–171.

Zhang JH. 2011. The method of seismic data denoising. China: China University Of Petroleum Press House.