UNIVERSITY OF HAMBURG

MASTER THESIS

Subsalt Imaging with Prestack Data Enhancement Methods

Author:

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Supervisor:

Prof. Dr. Dirk GAJEWSKI

Examiner:

Prof. Dr. Christian HÜBSCHER

*A thesis submitted in fulfilment of the requirements
for the degree of Master of Science Geophysics*

in the

Applied Geophysics Group - WIT Consortium
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April 22, 2015

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Declaration of Authorship

I, Jesper Sören DRAMSCH, declare that this thesis titled, 'Subsalt Imaging with Prestack Data Enhancement Methods' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

*"In whatever you choose to do,
do it because it's hard, not because it's easy.*

Math and physics and astrophysics are hard. For every hard thing you accomplish, fewer other people are out there doing the same thing as you. That's what doing something hard means.

And in the limit of this, everyone beats a path to your door because you're the only one around who understands the impossible concept or who solves the unsolvable problem."

Neil deGrasse Tyson

UNIVERSITY OF HAMBURG

Abstract

Faculty of Mathematics, Informatics and Natural Sciences
Department of Geophysics

Master of Science Geophysics

Subsalt Imaging with Prestack Data Enhancement Methods

by Jesper Sören DRAMSCH

The Levantine basin is a world class site to study the onsets of salt tectonics. A commercial data set will be processed in a conventional processing flow, as well as, several prestack data enhancement methods. These methods include (partial) Common Reflection Surface processing, Partial Time Migration and the application of a Differential Evolution CRS global search.

The dataset is masked by noise and multiples, which will be attenuated. The Kirchhoff migration from the conventional processing flow shows the best results and is compared to the commercial TGS time migration. Prestack data enhancement improves the Partial Time Migration in the presence of multiples. The shallow subsalt has been imaged. The deeper sections did not provide enough seismic energy to gain any improvement from prestack data enhancement.

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Abbreviations

AGC	Automatic Gain Control
AVO	Amplitude Variation with Offset
AVA	Amplitude Variation with Azimuth
BMIG	Gaussian Beam MIGration
CDP	Common Depth Point
CMP	Common MidPoint
CIG	Common Image Gather
CO	Common Offset
CRS	Common Reflection Surface
CRP	Common Reflection Point
CSP	Common Scatter Point
CMRE	Common Migrated Reflector Element
DE	Differential Evolution
DMO	Dip MoveOut
EBCDIC	Extended Binary Coded Decimal Interchange Code
ESM	Eratosthenes SeaMount
FFT	Fast Fourier Transform
FZ	Fresnel Zone
FWI	Full Waveform Inversion
G&G	Geology and Geophysics
GPS	Global Positioning System
HTI	Horizontally Transverse Isotropy
iCRS	implicit Common Reflection Surface
IIP	Image Incident Point
KMIG	Kirchhoff MIGration

KTM	Kirchhoff Time Migration
LB	Levantine Basin
MES	Messinian Erosional Surface
MF	Multi Focusing
NMO	Normal MoveOut
NDSF	Nile Deep Sea Fan
OPF	Ordered Parameter File
PFZ	Projected Fresnel Zone
PreSDM	Pre-Stack Depth Migration
PreSTM	Pre-Stack Time Migration
PTM	Partial Time Migration
QC	Quality Control
RTM	Reverse Time Migration
SNR	Signal to Noise Ratio
S/N	Signal to Noise ratio
SRMA	Surface Related Multiple Attenuation
SRME	Surface Related Multiple Elimination
SRWEMR	Surface Related Wave Equation Multiple Reduction
TTI	Tilted Transverse Isotropy
TWT	Two-Way Traveltime
VTI	Vertically Transverse Isotropy
WEM	One-Way Wavefield Extrapolation Migration
ZO	Zero Offset

Chapter 1

Introduction

Evaporitic layers become more important in modern geophysical, geological and geotechnical applications. They are good hydrocarbon seals to form reservoirs. As the population density grows the analysis of salt diapirs in populated areas becomes more important to properly assess the risk of sinkholes due to washout.

Seismic data has been one of the most important remote sensing methods in geophysical settings within the last decades. Due to high impedance contrasts and seismic beam defocusing, subsalt imaging, however has been one of the more challenging areas on both the acquisition and processing side. Diffractions have been regarded as noise in seismic reflection data for a long time. Lately, scattered energy has been analyzed more closely and diffraction imaging is gaining ground.

One of the workhorses in the seismic industry has been Kirchhoff migration which collapses diffractions to its point source [Yilmaz, 2001]. However, other prestack processing techniques have been on the rise. Yilmaz and Claerbout [1980] introduced 'partly' time migrated gathers, which can be utilized to improve diffraction images. These have been implemented by Dell [2012] into a Common Scatter Point mapping algorithm that produces partial time migration.

Additionally, partial CRS stacks can be utilized to improve seismic data in the prestack domain [Baykulov, 2007]. This can serve useful to gain information in the subsalt regimes.

Additionally, it can be used as input to other prestack processes.

A new implementation of 2D zero offset Common Reflection Surface parameter search using a global search routine is tested and the influence of different apertures on the parameter search and the stacked image will be assessed [Walda and Gajewski, 2015].

The dataset for this thesis was acquired in the eastern Mediterranean Sea by TGS, in the Levantine basin. Recent hydrocarbon discoveries in the Isreali Slump Complex have drawn attention to the potential hydrocarbon play of the Levantine basin. An evaporite layer with a thickness of up to 3 km was precipitated in the Messinian. The salt sheet is in its early stages of deformation and therefore, presenting a world class site to study salt tectonics [Bertoni and Cartwright, 2006].

This thesis aims to study the application of prestack data enhancement methods in complex salt environments. A conventional processing flow will be applied to benchmark the enhancements. A commercial migrated section courtesy of TGS is available to benchmark the results against as well.

Chapter 2

Theoretical Background

2.1 The Seismic Experiment

Seismic data has constantly grown in importance when it comes to remote sensing of the earth's interior. The seismic experiment can be designed for specific purposes that may include different fields such as hydrocarbon exploration, geological research or structural analysis in both marine and land environments.

Two very common setups for the seismic experiment include an impulsive source or a time-variant (chirp) signal [Yilmaz, 2001]. This thesis will concentrate on a setup with an impulsive marine source, such as an airgun. This is due to the superiority of CRS-based approaches in marine environments [Mann, 2002] as well as the availability of marine data sets that include subsalt seismic data [Hudec and Jackson, 2007].

The marine seismic experiment is towed behind a seismic vessel. The impulsive source is an array of airguns with different volumes of compressed air to specifically shape the source signal. This signal is an acoustic wave packet with carefully shaped frequency content, in order to broaden the frequency spectrum of the data and reduce noise [Yilmaz, 2001].

The seismic signal is recorded by several single pressure probes that are usually grouped to filter specific noise [Yilmaz, 2001]. These receivers are fitted into a solid foam that is buoyancy neutral and steered to a common level below the sea surface by electronic fins without added weights [King, 1969]. A single solid state streamer can be towed to record 2D seismic data or several streamers can be towed in parallel to acquire 3D seismic data with multiple streamers. The theoretical limit for the farthest offset to the source to stay within the reflection seismic constraints is the depth of the target, considering a hyperbolic traveltime [Gajewski, 2010].

In the seismic industry this constraint is usually pushed, i.e. experiments with extremely long offset acquisition with up to 12km offset and beyond, have been conducted [Long et al., 2013]. Most recent advances in receiver technology have pushed the boundaries of seismic data acquisition even further. These new devices can record a three component particle velocity field [Tenghamn, Vaage, and Borresen, 2008; Vassallo et al., 2013], which can be utilized to eliminate the seismic ghost as well as other coherent noise [Vassallo et al., 2013]. Additionally, the velocity field can provide information that supports the reconstruction of the seismic time series from digitized samples beyond the Nyquist theorem [Vassallo et al., 2013].

The seismic signal used for data acquisition is a wave packet that can be transported by different media, depending on polarization. Two kinds of body waves are observed, namely longitudinally and transversally polarized waves. Longitudinal waves (P or compressional waves) are polarized in the direction of propagation, whereas transversal waves (S or shear waves) are polarized lateral to the direction of propagation. P waves can travel through gaseous, fluid and solid phases of media [Gajewski, 2010]. In marine environments the transport through fluid phases is of major importance as both the source and the receiver setup are towed in water [Yilmaz, 2001]. S waves are not transported by gaseous and fluid phases, as the shear modulus of these media approaches zero [Gajewski, 2010]. However, shear wave imaging is becoming more prominent as ocean bottom seismometers are developed further [Operto et al., 2006]. Both of these kinds of waves can be transported by solid phases. The resolution of the wave packet depends on the frequency content [Müller, 2007a], the wave will be partially reflected at an impedance contrast in the subsurface. Major impedance contrasts include the seafloor as well as the sea surface, where a large part of the wave energy is reflected and only a minor part is transmitted. Impedance contrasts can be reduced to changes in wave velocity or density of the material in the subsurface [Müller, 2007b]. The propagation of seismic energy in the subsurface can be further explained in the context of wave propagation or its approximation, ray theory.

2.2 Wave Propagation and Ray Theory

The propagation of the wave can be described by the following isotropic wave equation:

$$\nabla^2 \vec{u} = \frac{1}{V^2} \frac{\partial^2 \vec{u}}{\partial t^2} \quad (2.1)$$

This equation can be simplified under certain assumptions. These assumptions and concepts will be further explained in the following sections. We can use the following substitution

$$\vec{u} = u(x, y, z) \exp i(kz\omega t) \quad (2.2)$$

Then we can assume that we have a narrow bandwidth, as the earth is a natural low-pass filter [Gajewski, 2010]. This limits our seismic resolution (cf. Section 2.2.2), however, this lets us use the slowly varying envelope approximation (SVEA) [Butcher and Cotter, 1990]. The SVEA is better known as paraxial (ray) approximation in seismic imaging and implies that the longitudinal variation in the derivative of the modulation function of a wave is small in distance compared to the nominal wavelength [Jones, 2002].

$$\left| \frac{\partial^2 \vec{u}}{\partial z^2} \right| \ll \left| \frac{1}{\lambda} \frac{\partial \vec{u}}{\partial z} \right| \quad (2.3)$$

When we consider propagation in z-direction this gives the (parabolical) paraxial wave equation

$$\Delta_{\perp} \vec{u} + 2i \frac{\omega}{V^2} \frac{\partial \vec{u}}{\partial z} = 0, \quad \text{where} \quad \Delta_{\perp} \vec{u} = \frac{\partial^2 \vec{u}}{\partial x^2} + \frac{\partial^2 \vec{u}}{\partial y^2} \quad (2.4)$$

This can now be evaluated further, one solution is using the Gaussian Beam (GB) solution, carrying this out would go beyond the scope of this thesis. For the development of GB in seismic theory please refer to Cervený [1985] and Cervený, Popov, and Psencik [1982]. The evaluation of the GB solution to the paraxial approximation can be done in terms of radius of the curvature $R(z)$ of the spherical wave with a width of $w(z)$ in the depth z [Jones, 2002]. This evaluation is especially interesting for Section 2.2.1.

$$\frac{1}{q(z)} = \frac{1}{R(z)} + \frac{-i2}{kw^2(z)} \quad (2.5)$$

The wavefront of the GB, therefore, defines a surface, on which paraxial rays of the central ray can be evaluated [Vanelle and Gajewski, 1999]. These paraxial rays obviously have to be complex rays with complex traveltimes. In contrast to the central ray, they are not normal

to the wavefront. The GB can be regarded as a bundle of complex rays [Cerveny, Popov, and Psencik, 1982; Deschamps, 1972]. This has the benefit that adjacent points on a wave front can be evaluated, while the wavefield does not change. Paraxial ray theory is directly linked to the WKB approximation, point sources, gaussian beams and also perturbation theory [Cerveny and Psencik, 1983; Deschamps, 1972; Farra and Madariaga, 1987]. The paraxial ray itself is a ray that illuminates a point close to the central ray, while having the same source and receiver coordinates. The shift from wave theory to ray theory in seismic research is obvious as wave theory can give an exact but localized description of phenomena, while rays manage to give an approximate but global description [Bortfeld, 1989]. Paraxial rays can be evaluated within the scope of their real parts [Cerveny, Popov, and Psencik, 1982], they are essential in the evaluation of the Fresnel zone.

2.2.1 Fresnel Zones

The Fresnel zone (FZ) is an important concept in seismic signal theory. This section will give a short introduction to the FZ in terms of the wave equation as well as the conventional stationary wave approach.

We can evaluate Equation 2.5 by assuming a perfectly flat reflector at arbitrary depth. This leaves us with a definition of the Fresnel length or confocal length.

$$\begin{aligned}
 \lim_{R(0) \rightarrow \infty} \quad & \frac{1}{R(0)} + \frac{-i2}{kw^2(0)} = \frac{1}{q_0} \\
 \Rightarrow \quad & 0 + \frac{-i2}{kw^2(0)} = \frac{1}{q_0} \\
 q_0 = \quad & i \frac{\pi w^2(0)}{\lambda} = iL_F \\
 \Rightarrow \quad & L_F = \frac{\pi w^2(0)}{\lambda}
 \end{aligned}$$

This is the area on a plane wavefront, where paraxial rays can be evaluated without reevaluating the wave field. This approach from a wavefield perspective is rather uncommon. Usually the FZ is evaluated from the ray perspective.

A transmitted signal between two stations will be subject to interference depending on the distance of the signal from the central ray. Usually, stationary waves are considered when it comes to the theory of FZ. Under this assumption, we can easily explain the concept of interference of waves. These stationary waves may interfere constructively or destructively,

depending on the phase shift of the signal. We can construct one of these waves from the superposition of two sinus waves of the form $y_{1,2}(x, t) = A \cdot \sin(kx - \omega t + \varphi)$, which gives the function $y(x, t) = 2A \cdot \sin(\frac{2\pi x}{\lambda}) \cos(\frac{2\pi t v}{\lambda} + \varphi)$. This characteristic equation shows that a phase shift of $\varphi = n \cdot \pi$ with $n = 1, 3, 5, \dots$ will cause a change in sign of the equation and hence, cause destructive interference. The period of a stationary wave is exactly λ and therefore, the maximum of destructive interference is characterized by a phase shift of $\frac{\lambda}{2}$. As we deal with reflections at an interface, we have to consider a loose end reflection, which implies no phase shift at the reflection point.

I consider a depth of the reflector at Zero Offset (ZO) of z_0 . This gives a length of $h_0 = 2 \cdot z_0$ for the stationary wave going down and up. Testing the limits of constructive interference in this setting will render the equation $h_1 = 2 \cdot (z_0 + \frac{\lambda}{4})$. This causes a phase shift of $\frac{\lambda}{2}$ of the signal. From basic geometry, we can see that a vertical reflector at the depth of z_0 will be illuminated in a circular area with a radius $r = \sqrt{(h\lambda + \frac{\lambda^2}{8})} \cdot \frac{1}{2}$. This is considered the First Interface Fresnel Zone. The ray path of this hypothetical setup causes a Projected FZ at the acquisition surface, where the constructive energy is collected [Schleicher2007]. The size of this Projected Fresnel Zone (PFZ) is $r_p = 2r$ in the case of a vertical reflector. The contribution of seismic energy from the first FZ is higher than the total amplitude of higher orders of the FZ, due to spherical divergence and directivity [Mehta, 2009].

FIGURE 2.1: Schematic of non-ZO FZ at horizontal reflector.

The central ray represents the specular reflection following Snell's law with a half-length s . The paraxial rays are non-specular theoretical rays that can be considered without reevaluating the wave-field for another central ray. The limit considering paraxial rays is the FZ, which, for stationary waves, is $s \pm \lambda/4$. The PFZ at the recording interface is limited by the specular reflections of the bordering rays of the FZ.

The assumption of stationary waves is a simplification as seismic waves are regarded to be transient waves. However, this simplification holds true for very-narrow-band-limited data, where f is the dominant frequency. Alternatively, the definition of the Fresnel Zone can be expanded to the use of transient waves, where T becomes the length of the signal [Cerveny1992; Knapp1991].

As mentioned beforehand, the first FZ defines an area on an interface where paraxial rays can be considered without reevaluation of the central ray or the according wave field. This relation makes the concept of the FZ very important for seismic resolution.

2.2.2 Seismic Resolution

The quality of seismic images is highly dependent on the resolution of a signal. According to the SLB Oilfield Glossary, seismic resolution can be defined as:

“The ability to distinguish between separate points or objects, such as sedimentary sequences in a seismic section. High frequency and short wavelengths provide better vertical and lateral resolution. Seismic processing can greatly affect resolution” Gillis, [n.d.](#)

This makes the concept of the FZ very important in the context of seismic resolution as it defines the threshold for the vertical resolution. In case of infinite bandwidth, the FZ collapses to the central ray [Cerveny, 2005]. In the case of a mathematical ray our seismic resolution is infinite as the ray can detect any small reflector in the subsurface. However, the subsurface naturally applies a frequency dependent attenuation to our signal, limiting the contribution of higher frequencies [Yilmaz, 2001]. The detection of arbitrarily low frequencies is also limited due to technical boundaries of geophones as well as the low frequency noise of the earth itself. Therefore, only limited bandwidth signals can be recorded, which decreases the seismic resolution and partially invalidates the ray assumption.

Vertical and horizontal resolution are very distinct from each other. Vertical or temporal resolution is defined as the ability to discern the top and bottom reflection of a layer in the subsurface [Yilmaz, 2001]. This ability is highly dependent on the frequency content of the data, as higher frequencies will provide a wavelet with the necessary properties to make a distinction of the two reflections. However, low frequency content in the data is equally important, so altogether the bandwidth of our data must be considered. The consensus on a mathematical approach on vertical resolution has been a $\frac{\lambda}{4}$, however, this should rather be regarded as a rough estimate [needed]. Different influences can render this estimate either too high, in case of low reflection coefficients, or too low in low noise datasets. Certain processes of deconvolution can increase the vertical resolution of a seismic image [Yilmaz, 2001].

Additionally, we have to take lateral or horizontal resolution into account. The limit can be defined as the first FZ (cf. Section 2.2.1). The limit of lateral resolution is closely tied to diffractions, because the bandwidth of a signal will determine if two diffractors are distinguishable in a seismic record. Seismic migration collapses diffractions and therefore, collapses the FZ, increasing the lateral resolution.

2.2.3 Diffractions

Any reflection event that is below the limit of vertical seismic resolution or sharp edges will serve as a diffractor of the seismic wave [Mehta, 2009; Vanelle, 2009; Yilmaz, 2001]. Diffractions have long been considered as noise in the data [Bolondi, Loinger, and Rocca, 1984]. While this might hold true in the context that it masks reflected data and introduces

conflicting events, high resolution imaging is impossible without the use of diffraction data. In fact diffractions can even serve to achieve superresolution, pushing on the boundaries of the Rayleigh limit [Asgedom, Tygel, and Gelius, 2011; Dell, 2012]. Geologic events such as rifts, faults and fractures as well as small-size objects and fronts of metamorphisms may be imaged reliably using diffraction data [Hubral, 1975; Kunz, 1960; Landa and Keydar, 1998]. Additionally, they may serve the purpose to identify hydrocarbon traps such as salt pinch-outs and the aforementioned fault systems [Krey, 1952; Moser and Howard, 2008]. However, NMO stacking velocities may not necessarily stack diffractions properly [Berryhill, 1977; Moser and Howard, 2008].

Diffractions have some very distinct features. The waves themselves can be separated into two groups. The first group of diffracted waves is invoked on edges, corners or vertexes at impedance contrasts. The second group is often referred to as scattered waves. These are invoked on velocity perturbations and objects about the size of the Fresnel zone of the dominant wavelength [Landa and Keydar, 1998]. The implication of objects of this size is generally referred to as small objects. The amplitudes of diffracted events show some very interesting behaviour apart from being generally weaker than classic reflection responses. The amplitudes are strongly frequency-dependent. High-Frequency content of a signal will excite less diffraction responses than low-frequency content. Additionally, frequency-dependent absorption of the subsurface will cause the waveform to change along the hyperbola [Dell, 2012]. At the edge of the hyperbola a phase change of 180° happens [Landa, Shtivelman, and Gelchinsky, 1987]. The amplitude itself decreases similar to the spherical divergence. In homogeneous media the diffraction response is a hyperboloid of revolution. However, considering heterogeneous anisotropic media the shape changes to a hyperboloid like complex and multivalued surface [Dell, 2012]. The pulse shape of diffraction is invariant [Berryhill, 1977] and the concept of Fresnel zones is not applicable. We can evaluate 2.5 again, with

$$\begin{aligned} \lim_{R(0) \rightarrow 0} \frac{1}{R(0)} + \frac{-i2}{kw^2(0)} &= \frac{1}{q_0} \\ \Rightarrow \quad \infty + \frac{-i2}{kw^2(0)} &= \frac{1}{q_0} \\ \infty &= iL_F \end{aligned}$$

which leads us to an infinitely large Fresnel zone for diffractions.

Diffracted waves may be utilized to approximate wave propagation. The Huygens-Fresnel theorem states that every point on an elementary wavefront serves as a source for another

wave therefore the envelope propagates as the traveltime surface [Huygens, 1690; Sheriff, 1996]. However, diffractions itself are more complicated [Moser and Howard, 2008]. A manifold of methods spanning mathematical and theoretical physics have been utilized to approach this problem. Gelchinsky [1982] has given a very good overview on this topic. I'd like to sum up the methods into the four categories of methods in conjunction with Dell [2012]. The first method uses the analytical scatter of known bodies to approximate that of the imaged body. The second set of solutions makes use of Greens-Kirchhoff integrals or field expansions, creating its namesake the integral methods. Method three uses perturbation theory, however these can only be used under the condition that the diffractors characteristics deviate from the characteristics of the medium by a small margin. The fourth method uses a very generalized asymptotic ray assumption in union with locality principles.

It has been attempted many times to separate diffraction images from reflection images [Fomel, Landa, and Taner, 2007; Kozlov et al., 2004]. This has often been done in the Common Offset domain or the dip-angle domain [Reshef and Landa, 2009]. Often a resort to accomplish this was partial time migration [Yilmaz and Claerbout, 1980], which is also referenced as offset continuation [Bolondi, Loinger, and Rocca, 1984]. This will be further developed in Section 2.3.3.

2.3 Seismic Data Processing

It is virtually impossible to read any reliable information from raw seismic data. Artifacts, noise and wave effects mask the image of the subsurface. However, it can be extracted through careful seismic processing. Generally, we can distinguish between pre- and post-stack processes. In subsalt imaging we have to use pre-stack data volumes Leveille et al., 2011, because the information density of pre-stack data is higher than that of post-stack data (cf. Section 2.4.2). The theory on seismic imaging is a vast field and Yilmaz [2001] has written two comprehensive books on the topic.

2.3.1 Fundamentals of Seismic Data Analysis

The acquisition of seismic data takes place in the Common Shot (CS) domain. This will create gathers with increasing offsets for every geophone [Drijkoningen, 2000]. Section 2.1 introduced the acquisition of seismic data. In processing however, there are many advantages to sort the data set into a different domain [Yilmaz, 2001]. The first and probably most important one is the Common

FIGURE 2.2: Schematic of geometry in Shot-Receiver Coordinates. Each circle shows a data traces and the marked frames show hypothetical gathers formed from data traces.
 Red - Common Midpoint (CMP)
 Blue - Common Shot (CS)
 Green - Common Offset (CO)

Midpoint (CMP) domain [Brown, 1969]. This sorts the data set into gathers of a theoretical common midpoint between shot and receiver. Another important data domain is the Common Offset (CO) gather [Drijkoningen, 2000; Gajewski, 2010]. This will sort the data into gathers according to their shot-receiver distance.

2.3.1.1 Velocity Analysis and Moveout Correction

Many operations on seismic data processing are based on the redundancy of data in every CMP. The recorded signals in the traces are shifted and stretched depending on the velocity of the subsurface $v_n mo$. In theory a CMP gather containing horizontal reflections would contain a hyperbolic moveout with increasing offset following the approximate relation of

$$t^2(x) = t_0^2 + \frac{x^2}{v_{NMO}^2} \quad (2.6)$$

. However, larger offsets cause the normal moveout (NMO) to be increasingly non-hyperbolic [Al-Chalabi, 1973]. When moving from horizontal reflectors to dipping reflectors dip-dependent moveout (DMO) has to be considered [Yilmaz, 2001].

FIGURE 2.3: Relation of v_{NMO} and v_{STK} modified from [Gajewski, 2010]

The DMO/NMO can be corrected by a non-linear dilation in the temporal direction. In the process of velocity analysis a velocity is estimated that it corrects the CMP gather ideally, by satisfying Equation 2.7. Figure 2.3 shows, however, that velocity analysis will reduce the total error of the moveout correction. This leads us to a modified equation for stacking

$$t_{STK}^2(x) = t_{STK}^2(0) + \frac{x^2}{v_{STK}^2} \quad (2.7)$$

The correction introduces an NMO stretch into the data, which can be dealt with by applying a mute to the data. The NMO stretch is especially strong in far offset traces [Yilmaz, 2001].

2.3.1.2 Raypaths

The data set contains the complete wavefield that was recorded at the surface. This includes the direct wave, primary reflections, multiples, scattered energy and noise. Commonly, the primary wave is considered to be the desirable part of the data set, therefore, primary reflections are enhanced while everything else will be attenuated.

FIGURE 2.4: Schematic primary and multiple raypaths in a marine seismics experiment.

Each reflection generating horizon reflects one primary ray. Any ray that consists of more than one upgoing or downgoing raypath, is considered a multiple. The image contains two generic multiples. The source and receiver ghost are a special kind of multiple. They generate an inverted image at the free surface of the subsurface with very short time lag.

In contrast to primaries that have one downgoing path and one upgoing path, multiples have several upgoing and downgoing paths. There are special kinds of multiples such as the source and receiver ghosts. These multiples are reflected at the sea surface directly after the shot is fired (source ghost) or directly before recording (receiver ghost). These pose a problem on seismic data as they basically reproduce the data with a very short time lag, which results in a phase shift. This phase shift will cause interference with the primary image [Yilmaz, 2001]. Another important source of multiples are strong impedance contrasts, these are also called multiple-generating reflectors. These surface-related multiples will introduce additional apparent horizons in the data, which have reversed polarity and an increased dip, which is usually twice that of the primary horizon [Yilmaz, 2001]. The third type of multiples are interbed multiples, which will create a sort of ringing after stronger impedance contrasts or in shallow water regimes. There the seismic wave will bounce back and forth between two stronger horizons, resulting in several multiples that trail behind the primary reflection [Yilmaz, 2001]. In the past many approaches have been proposed to deal with multiples, these

will be discussed in Chapter 4.

2.3.1.3 Filtering Criteria

During processing it is important to satisfy several criteria. The Nyquist-Shannon sampling theorem is one of the most important sufficient criteria in filtering theory, stating that the highest frequency must be covered by at least two samples, to prevent aliasing. Aliasing introduces apparent frequencies, which would alter and damage our data irrevocably [Marks, 1991; Nyquist, 2002; Shannon, 1998]. Additionally, during frequency filtering we have to take the effect of sharp edges into account. The Fourier-transformation of a rectangular function is a sinc function. Therefore, a boxcar frequency filter results in the convolution of our signal with a sinc function, which results in ringing in the data [Yilmaz, 2001]. Additionally, filters applied to the data should be causal to avoid time or phase shifts in the data [Robinson and Treitel, 2000].

2.3.1.4 Data Domains

Oftentimes, the data set will be transformed into different domains because certain features appear more clearly. Seismic data is recorded in the time-space (TX) domain. The frequency-space (FX) domain is useful to analyze the main frequency content of the data. A deconvolution in the FX domain can be used as processing as well as imaging step and may increase the coherency of reflectors in prestack and poststack volumes. Closely related to the FX domain is the frequency-wavenumber (FK) domain, which results from a 2D Fourier transformation. This is especially useful for coherent noise, such as multiples or refracted energy in the data [Yilmaz, 2001]. A polygon can be picked to reject undesirable content in the data. Additionally, a fan-filter can be applied to image different velocity sections in the data. Using the FK domain is also very convenient to make frequency as well as spatial aliasing apparent as this causes the FK image to "wrap around" the edges, if aliasing was present [Sheriff and Geldart, 1995].

Another important data domain is the time-ray parameter (τ -p) domain. The radon transform sums the samples for every slope at a certain time sample τ . This transform is very useful to attenuate multiples and other coherent noise, using a velocity filter or muting sections in the τ -p section [Yilmaz, 2001].

2.3.1.5 Stack and Migration

The stack section is a simulated ZO section. Every time sample is a sum over the according NMO/DMO corrected trajectory. This step attenuates random noise, elevating the signal to noise ratio (SNR) by $\sqrt{n}$ where n is the number of contributing traces [Sheriff and Geldart, 1995].

Another deliverable of the seismic processing workflow can be a migrated section. The migrated section contains the true position of the reflectors, whereas the raw stack section portrays the reflection recorded at the surface [Sheriff and Geldart, 1995]. Seismic migration can be carried out pre- and poststack and results in a time- or depth-migrated section [Yilmaz, 2001]. Prestack migration includes a higher underlying information density than poststack migration, resulting in finer images but higher computational cost.

Time migration serves as a major improvement in seismic data quality. Diffractions and triplications are absent, while the high resolution content of scattered objects is still utilized in the imaging process [Dell, 2012; Dell, Gajewski, and Vanelle, 2010b]. Time migration routines use residual moveout analysis of Common Image Gathers (CIG), scanning or inverse NMO routes [Dell, 2012]. This has coined the term "The gathers are flat". Depth migration needs an accurate interval velocity model. Especially in regions where salt is present, the slightest velocity errors will cause artifacts in the data and these will be hard to discern from the already complex salt geometry [Beitz, 2008]. However, depth migration has the capability to resolve complex geological settings more reliably and provides a data volume or migrated section in cartesian coordinates.

2.3.2 Common Reflection Surface Imaging

The Common Reflection Surface (CRS) is a model-independent data-driven stacking routine that serves as a useful extension to the CMP workflow. The CMP workflow is limited to a single CMP location and the according offsets. However, the Common Reflection Surface spans several CMP locations as well as the according offset locations. This process is possible as the apertures for CRS (cf. Section 2.3.2.4) are closely tied to the Projected Fresnel-zone (cf. Section 2.2.1) [Mann, 2002; Wu et al., 2008]. This has several advantages in data processing as the fold increases significantly, therefore, enabling a stronger SNR improvement. In 2D ZO CRS three wavefield attributes are extracted from the data [Mann, 2002], namely:

- α : The emergence angle
- R_N : The curvature of the normal wave
- R_{NIP} : The curvature of the normal incidence point wave

2.3.2.1 Pragmatic Approach

The attributes can be estimated individually first in a pragmatic approach [Mann, 2002], afterwards a global optimization is possible. This is due to limited processing capabilities and the high complexity of a global optimization routine, which would render the CRS algorithm too computationally expensive. The pragmatic approach has shown to be a feasible approximation, may however, present a solution that is not optimal under certain circumstances, including complex structures and diffractions [Mann, 2002]. A global optimization with the local maxima as start values is highly recommended to obtain a good solution [Witte, 2014].

FIGURE 2.5: Schematic of α , R_N and R_{NIP} . α is the emergence angle at the surface, R_N is the radius of the wave normal to the reflector segment and R_{NIP} is the radius of the wave normal to an incident point on the reflector segment.

2.3.2.2 Differential Evolution

Another approach is a global search of the three wavefield attributes. Walda and Gajewski [2015] propose a Differential Evolution (DE) algorithm. This algorithm is congeneric to Genetic Algorithms [Holland1975].

The method was first proposed by Storn and Price [1997] and is classified as a evolutionary algorithm. Specifically DE is a meta-heuristic, utilizing lower-level heuristics, which is a experience based strategy for problem solving. A random population of initial solutions is tested for fitness. The initial population is constrained by three parameters CR, F and NP. The best constraints are given by Pedersen [2010], who used a meta-optimizer to determine the performance of different parameters.

```

Data: CR, F, NP
Random initialization of population;
while not reach abort criteria do
  for each individual i in population do
    choose 3 random different individuals
    Data: a, b and c
    for each dimension j do
       $y_{i,j} = a_j + F \cdot (b_j - c_j)$ ;
      if  $r_i \in [0, 1] < CR$  then
         $u_{i,j} = y_{i,j}$ 
      else
         $u_{i,j} = x_{i,j}$ 
      end
    end
  end
  evaluate fitness;
  if  $f(u_i) > f(x_i)$  then
     $x_i = u_i$ 
  else
     $x_i = x_i$ 
  end
end

```

Algorithm 1: Pseudo code for differential evolution (mod. Walda and Gajewski [2015])

Algorithm 1 describes a pseudo code of differential evolution. It shows how the mutation of an individual x_i will follow the following principle:

$$y_{i,j} = a_j + F \cdot (b_j - c_j), \quad (2.8)$$

where a, b and c are random individuals of the population. The index j is the dimension. The optimization parameters are $F \in [0, 2]$, differential weight, $CR \in [0, 1]$, crossover rate and NP denotes the number of the population. r_i is a random number in algorithm 1.

2.3.2.3 Traveltime Surface

Eventually, the attributes span the traveltime surface with the following equation, derived from a second-order Taylor expansion:

$$t_{CRS}(m, h, P) = \sqrt{\left(t_0 + \frac{2 \sin \alpha}{v_0} \cdot (x_m - x_0)\right)^2 + \frac{2 t_0 \cos^2 \alpha}{v_0} \cdot \left(\frac{(x_m - x_0)}{R_N} + \frac{h^2}{R_{NIP}}\right)}, \quad (2.9)$$

where t_0 is the ZO travel time, h is the half-offset, $(x_m - x_0)$ is the midpoint displacement and v_0 contains the surface velocity. P contains the kinematic wavefield attributes. (α, R_N, R_{NIP}) (cf. [Baykulov, 2009; Mann, 2002; Müller, 1999]). This travel time surface will have the shape given in Figure 2.6.

FIGURE 2.6: Traveltime surface of a curved reflector. The different apertures of the CRS algorithm are color-coded. Traveltime Surface, CRS surface, CRP-trajectory, partial CRS surface [Müller, 1999]

stacking aperture (cf. Section 2.3.2.4).

2.3.2.4 Apertures

In a CRS workflow a special emphasis has to be assigned to choosing good apertures. Any aperture will limit the contributing data. In CRS processing this is very important, so that contributions to the traveltime surface do not stem from traces exceeding the physical limitations of the process. Specifically, these physical limitations are within the first projected fresnel zone (PFZ) [Mann, 2002] (cf. Section 2.2.1). The PFZ provides an upper limit for the

In Figure 2.6, we can see the different apertures the CRS algorithm utilizes from the traveltime surface in blue. The green surface shows the CRS stacking surface, which limits the traveltime surface according to the stack apertures (cf. Section 2.3.2.4). The magenta line shows the CRP-trajectory [Müller, 1999], although it may be referred to as the CMP trajectory at times [Baykulov, 2009]. The red surface represents the partial CRS

aperture estimation [Mann, 2003]. In reality however, this area often creates a large smoothing effect and deteriorates the processing result. This behaviour derives its origin from several different circumstances. One reason is the effect of transient waves in terms of the fresnel wave, further outlined in Section 2.2.1. Another effect stems from the optimization nature of the process. Large apertures will deteriorate the validity of the second-order approximation, therefore changing the image of the objective function (J. Walda, personal communication, 2014-08-20). Large apertures have shown to sharpen the image of the objective function, which decreases the likelihood of the optimization algorithm to pick up the trace to a maximum [Witte, 2014]. This observation has already been made upon introduction of the algorithm by Mann [2002], but wasn't evaluated further.

In general the different uses of apertures can be divided into the following three applications:

- CRS Scan [Mann, 2003]
- CRS Stack [Mann, 2003]
- Partial CRS Stack [Baykulov, 2008]

In the pragmatic approach the number of apertures is increased even further, as the plane wave scan and the hyperbolic ZO scan need individual apertures [Mann, 2002]. With further development of the CRS algorithm and its applications the number of different apertures is also increased.

2.3.3 Partial Time Migration Imaging

The standard CMP and CRS method is generally seen as difficult or unsuitable in an area with diffractions and triplications. Additionally, the NMO correction inherent to CMP has a strong dip-filtering effect. Often this was improved by a process named DEVILISH: *prestack partial migration, and dip-moveout* [Hale, 1984]. The process of Partial Time Migration (PTM) was introduced by Yilmaz and Claerbout [1980]. This process applies a pre-stack data migration in Common Offset on the data while leaving the moveout intact. This provides the benefit of a high-fidelity CMP section, where the mute zone during stack is reduced and dipping events can be delineated more effectively [Yilmaz and Claerbout, 1980]. Several methods

for partial time migration have been introduced since [French, Perkins, and Zoll, 1984; Hale, 1984; Yilmaz and Claerbout, 1980].

The CSP-based Partial Time Migration by Dell [2012] is an approach to integrate diffraction imaging in the CRS workflow. Diffraction reflection separation can be done by means of a CRS-based approach. This is possible using the kinematic wavefield attributes to perform a separation of diffractions and reflections [Dell and Gajewski, 2011a,b; Dell, Gajewski, and Tygel, 2014].

Diffractions disturb the conventional reflection seismic image used to image the subsurface. However, diffractions are essential for the imaging of faults as well as other diffractors. These diffractors may consist of objects scaling around the size of the first Fresnel-zone (small-size scattering), pinch-outs, fracture corridors and karst structures. High-resolution images of these structures are essential in understand the diagenesis of the subsurface and diffraction imaging can enable imaging beyond the limits of the Rayleigh limit, leading the way to super-resolution images [Dell, 2012]. A velocity model solely based on reflection analysis may not stack diffractions properly. However, velocity analysis in the CSP domain directly provides time migration velocities. These can be generated through a focusing criterion [Sava, Biondi, and Etgen, 2005] rather than the usual gather comparison, which will evaluate if 'the gathers are flat' and is not well suited for automatic approaches [Dell, 2012; Dell and Gajewski, 2010].

PreStack Time Migration techniques account for the majority of served data in the industry sector. The speed and robustness of time migration in symbiosis with the information content of prestack data, in contrast to depth migration and poststack methods, combines many advantages [Vanelle, 2009]. A PreSTM gather contains pure focused reflected data. The diffractions were collapsed to a focused point and triplications are unfolded, therefore also reducing conflicting events.

Common Scatter Point (CSP) gathers are 'partly' time-migrated data. This is a gather that contains the theoretical hyperbolic response of a mathematical

FIGURE 2.7: Comparison of conventional time migration and CSP mapping. [Dell, Gajewski, and Vanelle, 2010a]

The picture is comprised of four color coded components in three dimensions (t,m,h). The reflection response of a dipping reflector in a homogeneous model. The diffraction response or migration operator. The conventional ZO time migration operator in black and the CSP mapping result in the CO apex.

diffractor, based on the distance between the scatter-point and the collocated source and receiver. The contributions to these gathers are collected from neighbouring CMPs [Dell, 2012]. 'Partly' time migrated data has been generated by several methods from the industry. The standard approach is the application of a CO migration with a subsequent inverse NMO restoration. The velocity updates will be carried out iteratively with a residual moveout (RMO) analysis [Dell, 2012; Dell and Gajewski, 2010].

Resulting from comparison of the new CSP method by Dell with conventional time migration routines, a general enhancement of the image could be observed. Additionally, several important features have been pointed out that include improved illumination reconstruction [Wolf, 2013], better continuity [Wolf, 2013; Yang, Vanelle, and Gajewski, 2014] and clearer definition of faults [Dell, Gajewski, and Vanelle, 2012; Yang, Vanelle, and Gajewski, 2014] and salt structures [Dell, Gajewski, and Vanelle, 2010a]. The update of the time migration velocity model has been shown to be robust on 2D synthetic and field data, also resolution was enhanced [Dell, Gajewski, and Vanelle, 2012]. Nevertheless, the image quality, as with any Kirchhoff migration [Sun, 1998], depends largely on the proper selection of apertures [Dell, 2010; Wolf, 2013].

The method for automatic CSP data mapping for 'partly' time migrated gathers has two principal uses. The most important one is automatic time-migration velocity model building. The subsequent Common Migrated Reflection Element stack uses this data to perform reflection diffraction separation, which is also a very useful feature. In contrast to other methods for CSP gather building that may increase the trace count by several magnitudes, this method does not necessarily increase the trace number and may additionally be used for regularization. (This may increase the trace count if requested by user input.) [Dell, 2012; Dell and Gajewski, 2011b] Additionally, the CRME stack provides curvature information of the time-migrated reflector as this information can be extracted from the second-order derivative with respect to the scatter point displacement [Tygel et al., 2010].

2.3.3.1 Common Scatter Points

Bancroft, Geiger, and Margrave [1998] introduced the term of Common Scatterpoint (CSP) gathers. Specifically these are 'partly' time migrated gathers, where the hyperbolic moveout is still applied (or reapplied). Upon introduction of this data domain several methods have been introduced to create and use this data [Dell, 2012; Dell, Gajewski, and Vanelle, 2010a].

The CSP gather is not unlike a CMP. The moveout of a CMP gather depends on the source-receiver offset of a quasi-hyperbolic nature. The moveout of the CSP gather is based on the distance of the source and receiver to a scattering object or structure. This scattered energy is collected in a 3D data volume along the midpoint, offset and time (m, h, t) within suitable apertures and hence redistributed along a 2D hyperbolic path in the offset and time (h, t) domain. The method introduced by Dell, Gajewski, and Vanelle [2010b] generates CSP gathers directly by summation into the CO apex of a migration operator. The automatic search routine updates the velocity model to provide an optimal fit. These time migration velocities can be obtained directly by a velocity scan and evaluation according to the semblance norm [Dell, 2012; Dell and Gajewski, 2011a; Dell, Gajewski, and Vanelle, 2010b]. Another benefit of the time domain formulation is the aspect of forming CSP gathers at arbitrary locations and therefore achieving regularization similar to the partial CRS stack of Baykulov [2009] [Dell, 2012; Dell, Gajewski, and Vanelle, 2010b, 2012].

2.3.3.2 Multiparameter Stacks

Multiparameter stacking routines have improved processing in many areas of seismic imaging. These methods include but are not limited to the Common Reflection Surface (CRS) as well as its implicit formulation (i-CRS). Additionally, Multifocusing and shifted hyperbola methods can be used. The method presented by Dell is based on the 2D Zero Offset CRS and includes diffraction imaging in the CRS workflow [Dell and Gajewski, 2011b; Yang, Vanelle, and Gajewski, 2014].

The automatic stacking routine of 2D ZOCCRS contains a search routine in a three dimensional parameter space. These parameters contain the emergence angle, the curvature of a wave normal to the reflector element and the curvature of a point normal to the incidence point (cf. Section 2.3.2). These attributes can be used further in a CRS workflow with different purposes. Additionally the stacking velocity is extracted from the data [Dell and Gajewski, 2011b; Yang, Vanelle, and Gajewski, 2014].

The CRS multiparameter stack can be applied in a similar manner in the time-migrated domain. In the time-migrated domain the parameters are estimated model-based, whereas on conventional CRS they are estimated at the surface. The algorithm is formulated in space-time domain, this allows us to perform standard velocity analysis which will provide migration velocities. This multiparameter stack of 'partly' time-migrated data is named Common

Migrated Reflector Element (CMRE) stack. [Dell, 2012; Dell, Gajewski, and Vanelle, 2010a,b, 2012]. The imaging criterion will be further investigated in the Section 2.3.3.4. Compared to conventional time migration including the focusing criterion and model building, the CRME stack including the CSP gathers perform better [Yang, Vanelle, and Gajewski, 2014]. Although reevaluations have limited this improvement to the presence of noise (J. Walda, personal communication, 2014-11-15).

2.3.3.3 Diffraction Imaging

The Zero Offset Common Reflection Surface (CRS) provides three kinematic wavefield attributes as introduced in the previous section. The curvatures can be used to separate reflection from diffraction events. In theory for a diffractor the two curvatures would coincide. In reality however, the threshold is not as clearly defined. Dell suggests the following threshold function as a guide. The coincidence of the two curvatures also simplifies the process of estimating CRS attributes in 3D space [Dell, 2012; Dell and Gajewski, 2011a].

Due to the nature of seismic migration, diffractions are collapsed and triplications unfolded, which leave the image gather with pure reflected data. The migration process can even benefit from diffraction reflection separation as focusing of diffracted data can serve as an imaging criterion [Dell, 2012].

The CSP method is based on reflection diffraction separation. This, among others, serves the purpose to enable paraxial ray theory (Cerveny) in the vicinity of the central ray. Specular ray theory fails on diffractions while it's ideally suited for reflections [Asgedom, Tygel, and Gelius, 2011; Dell, 2012; Dell and Gajewski, 2010, 2011b].

2.3.3.4 Partly Migrated Sections

In contrast to conventional time migration imaging utilizes residual moveout analysis of CIGs, this method uses a focusing criterion to automatically update time migration velocities by conventional stacking velocity analysis [Dell, 2012; Dell, Gajewski, and Vanelle, 2010a]. Prestack time migration and the CRME stack can be regarded as kinematically equivalent [Yang, Vanelle, and Gajewski, 2014]. The multiparameter stacking nature of the latter method, however, increases the image quality by SNR improvement [Dell, 2012; Yang, Vanelle, and Gajewski, 2014].

'Partly' time migrated gathers are very well suited for further seismic processing. While conventional approaches to 'partly' time migration would perform a time migration on common-offset data (e.g. [Ferber, 1994]) and then apply inverse NMO analysis, the method by Dell, Gajewski, and Vanelle [2010a] can automatically build 'partly' time migrated data in so-called CSP gathers. These are based on the distance of a scatterpoint to a collocated source and receiver [Dell, 2012; Yang, Vanelle, and Gajewski, 2014]. The industry standard for 'partly' time migration is a CO migration followed by restoration of the NMO by inverse NMO analysis [Sava, Biondi, and Etgen, 2005]. The CO migration utilizes Kirchhoff diffraction stacking, where each point on a sufficiently dense grid in the target area is regarded as a scatter point location [Vanelle, 2009; Yilmaz, 2001]. The according traveltimes are given by a DSR [Yilmaz and Claerbout, 1980] along which the energy is stacked into the according sample. The sample lies in the ZO apex of the migration operator. Ferber [1994] and Bancroft, Geiger, and Margrave [1998] suggest to stack the resulting CSP gather along the (half) offset, while taking the moveout into account [Dell, 2012; Yang, Vanelle, and Gajewski, 2014].

Imaging Condition Partial Time Migration and the CMRE stack operate in the time migrated domain. Therefore, we have to consider hypothetical image rays instead of seismic rays. The image ray intersects the reflector at the Image-Incident-Point (IIP) [Tygel et al., 2009]. Nevertheless, in analogy to the NIP-wave experiment [Hubral and Krey, 1980], a IIP-wave experiment can be considered, where the hypothetical wavefront of a mathematical diffractor travels along a central image ray to the measurement surface [Dell, 2012]. The determination of the propagating image ray is conducted in terms of the second-order derivative of migrated traveltimes. These contain information regarding the wavefront curvature of the image ray [Dell, 2012]. Focusing can be conducted by migration velocity analysis rather than CIG flatness [Dell, 2012; Sava, Biondi, and Etgen, 2005].

Parametrization of the DSR Equation The Partial Time Migration uses a new approach to preserve the moveout in the data. This is achieved by a parametrization of the Kirchhoff Time Migration (KTM) DSR operator with the CO apex time. This diffraction traveltimes enables us to use the migration in a moveout-preserving fashion, while still obtaining the accuracy of the DSR traveltimes [Dell, 2012; Dell, Gajewski, and Vanelle, 2010a; Yang, Vanelle, and Gajewski, 2014].

The original DSR operator in shot-geophone coordinates $DSR(S, G) = [1 - S^2] \cdot 5 + [1 - G^2] \cdot 5$ is nicely separated. However, processing takes place in midpoint-offset coordinates, which renders us with $DSR(Y, H) = [1 - (Y + H)^2] \cdot 5 + [1 - (Y - H)^2] \cdot 5$ as the DSR operator [Yilmaz and Claerbout, 1980].

For layered media this operator has to be modified even further and leaves the KTM operator:

$$t_D = \sqrt{\frac{t_0^2}{4} + \frac{(m-h)^2}{v^2(t_0)}} + \sqrt{\frac{t_0^2}{4} + \frac{(m+h)^2}{v^2(t_0)}} \quad (2.10)$$

Dell, Gajewski, and Vanelle [2010a] have parameterized the DSR with the following CO apex time:

$$\sqrt{t_0^2 + \frac{4h^2}{v^2}} \quad (2.11)$$

Now he expands the binomial in the KTM DSR:

$$\begin{aligned} t_D &= \sqrt{\frac{t_0^2}{4} + \frac{m^2 - 2mh + h^2}{v^2(t_0)}} + \sqrt{\frac{t_0^2}{4} + \frac{m^2 + 2mh + h^2}{v^2(t_0)}} \\ &= \sqrt{\frac{t_0^2}{4} + \frac{h^2}{v^2(t_0)} + \frac{m^2 - 2mh}{v^2(t_0)}} + \sqrt{\frac{t_0^2}{4} + \frac{h^2}{v^2(t_0)} + \frac{m^2 + 2mh}{v^2(t_0)}} \end{aligned} \quad (2.12)$$

and substitutes the CO apex time:

$$t_D = \sqrt{\frac{t_{apex}^2}{4} + \frac{m(m-2h)}{v^2(t_0)}} + \sqrt{\frac{t_{apex}^2}{4} + \frac{m(m+2h)}{v^2(t_0)}} \quad (2.13)$$

Therefore, we can use this migration operator to directly map the migration result to the CO apex time.

2.3.3.5 Subsalt

Subsalt imaging has some very serious caveats. Weak amplitudes combined with micro- as well as macro undulations of displaced salt aggravates the processing flow. Many subsalt imaging specialists agree that Prestack time migration (PreSTM) is the best practice in subsalt regimes [Leveille et al., 2011]. Usually this is carried out in an iterative migration improvement [Epili et al., 2011]. The robustness of time migrations combined with the energy density of prestack volumes provides advantages in a riddled environment. Time migration in contrast to depth migration is very robust and less sensitive to velocity errors. The following method Partial

Time Migration uses CSPs to introduce automatic diffraction imaging in the prestack data domain [Yang, Vanelle, and Gajewski, 2014].

2.4 Rock Salt in Seismic Data

2.4.1 Salt Tectonics

Level layers of sediment in the subsurface are both rare and of minor relevance in geology as well as the hydrocarbon industry. Tectonics serve as a mechanism that will break up the level layering in all local, regional and global framesets. Rock salt deposits alter the tectonic behaviour of basins significantly.

Throughout the last centuries the understanding of salt tectonics has been modified profoundly and continues to change as research progresses. Over the first 70 years of the last century the dominant theory reduces the evaporite layer and the overburden to two viscous layers that behave according to the Rayleigh-Taylor instability [Wilcock and Whitehead, 1991]. This entirely passive explanation has been discarded as initiator of salt diapirism. Nevertheless, in some rare cases it is still of importance. The three driving forces behind salt tectonics can be subsumed as differential loading, including gravitational loading, dislocation loading and thermal loading. Hudec and Jackson [2007] have summarized it as follows:

“Salt will move only if driving forces exceed the resistance to flow.” Hudec and Jackson, 2007
The evolution of salt tectonic theory from passive diapirism to modern theories of differential loading has some important cornerstones. A more comprehensive historical outline is given in Jackson [1997] and Jackson [1995].

Initial theories concentrate on passive vertical diapirism of evaporites [Trusheim, 1960; Trusheim, 1957]. Although thin-skinned tectonics and horizontal flow have been discussed they were never accepted as a major theory with regard to salt tectonics. The turning point can be placed roughly in 1980 when a large body of independent research found that prevalent salt rock structures could not be explained by buoyancy alone [Cobbold and Szatmari, 1991; Vendeville and Jackson, 1992a,b]. This was supported by the finding of Schultz-Ela, Jackson, and Vendeville [1993] that a sufficiently large overburden inhibits piercing of salt diapirs. This research replaced the ‘fluid era’ by the ‘brittle era’ of salt tectonics [Jackson, 1995].

Brittle diapirism theories postulate four mechanisms for rock salt displacement in brittle environments [Hudec and Jackson, 2007] and a fifth mechanism with a fluid overburden [Hudec

and Jackson, 2007; Nettleton, 1934; Talbot et al., 1991]. The first mechanism is a form of reactive diapirism that will intrude opening space in an extensional tectonic regime of the overburden. The second mechanism postulates active diapirism that forcibly breaks the overburden and interacts with the overburden by rotation and lifting. The third mechanism acts through erosion of the overburden and isostatic processes that force the salt to replace some of the eroded sediment. The fourth brittle mechanism occurs during thrust faulting of the overburden. These mechanisms are not mutually exclusive and may all influence a salt structure. The fifth mechanism is exclusive for fluid overburdens and formulates ductile thinning of the overburden. This mechanism however, is very rare and brittle deformations can be readily assumed in most cases [Hudec and Jackson, 2007].

2.4.2 Subsalt Imaging

The motivation to improve seismic imaging below salt layers or diapirs, lies within three distinct properties of salt bodies. One important reason is the decoupling of the sediment layer above the rock salt structure and the sedimentary layers situated subsalt. This behaviour can be particularly interesting in regard to the study of tectonic stress fields. Usually, local tectonic stress applies to rather shallow layers, whereas regional stress fields have a deeper impact. The decoupling of these layers thus provides the opportunity to study the regional tectonic regime with minimal local overprinting and vice versa. Subsalt imaging is also motivated by the impermeable properties of rock salt. This supplies prime seal layers for oil or gas traps therefore, providing an important constituent of reservoirs. The third motivation are geotechnical considerations as evaporites and groundwater can have a significant impact on civilization. These can either expand or cause sinkholes.

Nevertheless, rock salt poses difficulties using seismic methods. The reflection coefficient is dependent on the impedance contrast at a reflector. Typical values for halite for the seismic velocity fall within the range of $v_p = 5000 \pm 500 \frac{m}{s}$ and a density around $\rho = 2.1 \frac{g}{cm^3}$ [Mavko, 2005]. In comparison with granite ($v_p = 5250 \pm 750 \frac{m}{s}$ and $\rho = 2.6 \pm 0.1 \frac{g}{cm^3}$ [Mavko, 2005]) or saturated sandstone ($v_p = 2750 \pm 750 \frac{m}{s}$ and $\rho = 2.25 \pm 0.15 \frac{g}{cm^3}$ [Mavko, 2005]), we can see that either the p-wave velocity or the density differ significantly from the surrounding rock. This causes high reflection and relatively low transmission of seismic energy. It holds both true for the interface at the top and bottom of a salt body, as allochthonous salt bodies are

usually embedded in tertiary sediment basins. We can calculate a simple gedankenexperiment for vertical incidence with these typical compressional velocities and densities, to estimate the reflection and transmission coefficients at the top and bottom of a salt body. Therefore, we use the simplified equation for the reflection coefficients and assume conservation of energy at the interface:

$$R_{T,B} = \frac{v_2\rho_2 - v_1\rho_1}{v_1\rho_1 + v_2\rho_2} \quad (2.14)$$

$$T_{T,B} = 1 - R_{T,B} \quad (2.15)$$

For typical values in a tertiary basin, this yields a reflection coefficient of $R_T = 0.1 - 0.3$ and $T_T = 0.7 - 0.9$ at the top reflection and $R_B = 0.0 - 0.3$ and $T_B = 0.7 - 1.0$ (cf. [Leveille et al., 2011]). We can calculate the total reflectivity utilizing $R_{total} = (1 - R_T^2) \cdot (1 - R_B^2)$. Assuming the maximum of $R_{T,B} = 0.3$ at both interfaces, this yields $R_{total} = 0.91^2 \approx 82\%$ [Leveille et al., 2011]. Hence, the penetration of energy below a salt body is impaired and other effects add to the deterioration of the seismic image. One contributor is salt tectonics that force the body into unusual shapes. These shapes will often include unfavorable structures that further decrease the collected seismic energy of subsalt structures [Leveille et al., 2011]. Examples for these structures are hard to quantify in their effect, lense-like structures, however, have a defocusing effect on the seismic beam. The ductile behavior of allochthonous salt may cause rapid variations in the salt structure, which in turn defocus the seismic beam even when the overall salt geometry is simple [Leveille et al., 2011]. This was one of the driving forces for the development of wide- and full-azimuth data acquisition [Kapoor et al., 2007; Leveille et al., 2011; Moldoveanu and Kapoor, 2009; Moldoveanu, Kapoor, and Egan, 2008]. Additionally, an inverse correlation between salt deformation and anisotropy exists [Weiß, 2010].

In case this high-end data is not available, methods have to be developed that can reconstruct the wave field from the data provided. This implies the application of depth migration of prestack volumes. The recent increase in computing power has made four algorithms available, two of which are used commercially. These four algorithms are Kirchhoff Migration (KMIG), Gaussian Beam Migration (BMIG), One-Way Wavefield Extrapolation (WEM) and Reverse Time Migration (RTM). While RTM is the preferred method by subsalt imaging specialists, BMIG may give other insights into the data and shine due to its non-linear S/N improvement (cf. [Leveille et al., 2011]).

Chapter 3

Geology and Tectonic Setting

The Levantine basin (LB), which is the area surveyed in this study, is located in the eastern part of the Mediterranean Sea. It is a relatively small basin confined by the Levant margin to the East, the Eratosthenes Mount to the West, the Cyprus arc in the North and the Nile Deepsea Fan in the South [Ben-Avraham et al., 2002]. Additionally, it is underlain by continental crust [Netzeband, Hübscher, and Gajewski, 2006]. This area is characterized by the convergence of the Arabian, African and Anatolian plates [Robertson, 1998]. The basin can be described as a foreland basin on the African plate [Roberts and Peace, 2007].

The Northern boundary is defined by the Cyprus arc [Roberts and Peace, 2007]. Sediments of the LB terminate near vertically at the Hecataeus rise southeast of Cyprus [Reiche, Hübscher, and Erhardt, 2014; Vidal, Alvarez-Marrón, and Klaeschen, 2000]. The collision of the African and Anatolian plate is correlated at Cyprus and Hellenic arcs [Le Pichon and Kreemer, 2010; Robertson, 1998]. The eastern segment of the Cyprus arc separates the LB from the Tartus and Latakia basins in the North [Reiche, Hübscher, and Erhardt, 2014]. 2D gravity models suggest a downgoing slab underneath Cyprus [Ergün et al., 2005].

In the East the Arabian plate conducts a northward motion relative to the African plate and transcurrent motion is accommodated at the Dead Sea Transform. This is regarded as a 100km long left-lateral strike-slip fault [Eppelbaum, Lev, and Youri, 2011]. The border of the LB is characterized by the Syrian fold belt (Syrian Arc)[Bertoni and Cartwright, 2006; Eppelbaum,

Lev, and Youri, 2011]¹ as well as the libanese and israeli continental slope.

The Southern part of the LB is characterized by the Nile Deep Sea Fan (NDSF) [Roberts and Peace, 2007]. The Eastern NDSF differs significantly from the western parts. The presence of subsurface salt and a NNW-SSE-trending tectonic corridor visible on bathymetric maps imply a significant asymmetry compared to the western part of the NDSF [Loncke et al., 2006]. The Eratosthenes Seamount north of the NDSF furthers the asymmetric physiography of the NDSF [Loncke et al., 2006].

The Eratosthenes Seamount (ESM) also forms the western boundary of the Levantine basin [Roberts and Peace, 2007]. The ESM forms a prominent bathymetric feature that entered the collision zone in late Miocene [Reiche, Hübscher, and Erhardt, 2014; Robertson, 1998]. Being underlain by continental crust [Welford et al., 2015], ESM is therefore in the stage of continent-continent collision with Cyprus [Kempler, 1998; Reiche, Hübscher, and Erhardt, 2014; Robertson, 1998].

¹Eppelbaum, Lev, and Youri [2011] suggest a transition of oceanic to continental crust, which is based on data from Garfunkel [1998], however, this notion has been refuted by Netzeband, Hübscher, and Gajewski [2006].

3.1 History

3.1.1 Paleozoic Era

The LB has its origin in the mid Permian opening of the Neotethys ocean, shown in Figure 3.1 [Garfunkel, 1998, 2004; Robertson, 1998]. The breakup of Pangaea lasted until the Middle Jurassic and caused a thinning of the crust in the present-day Eastern Mediterranean basin [Garfunkel, 1998; Roberts and Peace, 2007]. The origin of the crust under the LB has been under debate for decades [Biju-Duval, Letouzey, and Montadert, 1978], however, Netzeband, Hübscher, and Gajewski [2006] were able to present conclusive arguments for a continental origin. Gardosh et al. [2008] additionally documents horst and graben structures that evolved in several pulses during the late Paleozoic, early Mesozoic era.

FIGURE 3.1: Global paleogeography (top) and major depositional settings in the southern margin of the Tethys (below) at the Permian-Triassic boundary (about 251Ma) (mod. Berra and Angiolini [2014])

3.1.2 Mesozoic Era

The rifting period was followed by a post-rift cooling period and subsidence [Gardosh et al., 2008; Garfunkel, 1998]. The basin was then filled by up to 10 km of sediments ranging from Mesozoic to recent times with very little deformation of the sediments away from the deformation front [Vidal, Alvarez-Marron, and Klaeschen, 2000]. Until the Middle Jurassic the basin was very narrow, during the Africa-Laurasia separation it doubled in size [Garfunkel, 1998].

FIGURE 3.2: Global paleogeography (top) and major depositional settings in the southern margin of the Tethys (below) during the Lower Cretaceous (about 120Ma) (mod. Berra and Angiolini [2014])

During the Lower Cretaceous the closure of the Neotethys initiated compressional deformation, as expressed by the Syrian arc and thrust belt [Ben-Avraham et al., 2002]. In the Upper Cretaceous - Eocene stages northward dipping subduction under present-day Cyprus was initiated as a consequence of the convergence between the Eurasian and Afro-Arabian plates. This also marks the end of shallow-marine carbonate deposition, which was superseded by hemipelagic and pelagic sedimentation regimes [Gardosh et al., 2008], which lasted until the Miocene [Bertoni, Cartwright, and Hermanrud, 2013].

3.1.3 Cenocoic Era

The early Miocene was marked by the onset of the formation of the Syrian Arc belt on the Levant margin [Buchbinder and Zilberman, 1997]. Overall clastic sediment supply increased and submarine canyons extended to the shelf regions [Bertoni and Cartwright, 2006]. The Middle to Late Miocene deposition regime was characterized by mud-rich debris flow and thin turbiditic sandstone deposits particularly in the aforementioned canyon systems [Bertoni, Cartwright, and Hermanrud, 2013; Steinberg et al., 2011]. The tectonic regime changed considerably during this time, i.e. a change from compressional to extensional faulting in the Cyprus region in late Miocene. Additionally, tectonically controlled subbasins were formed and filled with carbonates by the Miocene Pakhna formation

[Eaton and Robertson, 1993; Robertson et al., 1991].

3.1.3.1 Messinian Salinity Crisis

The Messinian Salinity Crisis (MSC) occurred in the late Miocene [Hsü et al., 1977; Krijgsman et al., 1999] and lasted from 5.96 Ma to 5.33 Ma [Lazar, Schattner, and Reshef, 2012]. During the MSC the Mediterranean was cut off from the world oceans and evaporites with a thickness of locally over 2km [Bertoni and Cartwright, 2006], but usually around 1.5km were deposited in varying depositional cycles in the easternmost Mediterranean Sea [Netzeband, Hübscher, and Gajewski, 2006]. Within the evaporites several layers can be detected. These intraevaporitic facies are interchanging between seismically transparent layers and halites [Hübscher et al., 2007]. Cartwright et al. [2012] suggested a basinal drawdown of approximately 800m, whereas Netzeband et al. [2006] favored a sea level drop in the order of 2km. This may have decreased the pore fluid pressure and released gas from the underlying Miocene clastic sediments [Bertoni, Cartwright, and Hermanrud, 2013]. Remobilization and syn-depositional deformation of the salt increased the available depositional environment [Gvirtzman et al., 2013]. Gvirtzman et al. [2013] also suggested that the entire evaporite body was deposited in a very short time span of approximately 50 kyr. The reflooding of the Mediterranean basin was also very fast in the range of 1000 to 2000 yrs [Hsü, Ryan, Cita, et al., 1973]. The post-Messinian deposition recommenced with a basin-floor turbiditic fan supplied from the Southern Levant hinterland [Bertoni and Cartwright, 2006; Frey-Martnez et al., 2007].

3.2 Stratigraphy

Seismic refraction data indicates the presence of a 10 - 14 km thick sediment layer in the LB [Ben-Avraham et al., 2002]. The oldest unit is composed of Cretaceous carbonates (see Section 3.1.2). Then a unit of hemipelagic and pelagic sediments follows. Pockmarks and mud volcanoes indicate fluid escape [Bertoni, Cartwright, and Hermanrud, 2013; Hübscher et al., 2009]. A prominent feature is the evaporite sequence deposited in the Messinian (see Section 3.1.3.1). Ben-Avraham et al. [2002] support a interval velocity of 4.2 km/s of this unit [Reiche, Hübscher, and Beitz, 2014]. The base salt is usually referred to as Horizon N

[Hsü et al., 1977] or Base Erosion Surface (BES) [Reiche, Hübscher, and Beitz, 2014]. The top salt is known as horizon M [Hsü et al., 1977], Messinian Erosion Surface (MES) [Bertoni and Cartwright, 2006] or Top Erosion Surface (TES)² [Reiche, Hübscher, and Beitz, 2014]. The evaporites reach a thickness of up to 2 km [Bertoni and Cartwright, 2006] but usually account for 1.5 km [Netzeband, Hübscher, and Gajewski, 2006]. The evaporites themselves can be subdivided into six intraevaporitic layers that are named ME-I through ME-VI [Hübscher et al., 2007]. The five subdividing reflections are named ME-20 through ME-60 [Reiche, Hübscher, and Beitz, 2014]. Reiche, Hübscher, and Beitz [2014] interpret these reflection to represent intra-salt gypsum/anhydrite layers. ME-I/II and ME-VI show seismic anisotropic behaviour in the form of Vertically Transversal Isotropy (VTI) [Weiß, 2010]. The Messinian evaporites are considered to be an excellent hydrocarbon seal [Lazar, Schattnner, and Reshef, 2012] (see Section 3.4) and form a wedge thinning out eastwards [Bertoni and Cartwright, 2006]. The uppermost unit are Plio-Quaternary sediments [Netzeband, Hübscher, and Gajewski, 2006].

3.3 Salt Tectonics

The evaporites, deposited in the Messinian are a world class site to study the initial stages of salt tectonics [Bertoni and Cartwright, 2006]. The autochthonous evaporites underwent local dissolution and significant deformation during and after deposition [Bertoni, Cartwright, and Hermanrud, 2013]. Recent 3D-seismic investigations support syn-depositional deformation phases [Gvirtzman et al., 2013]. The salt sheet is generally considered to have a decoupling effect of the sub- and suprasalt sediments and according tectonic regimes. Due to basin tilting and subsidence the main factors under investigation are gravity gliding and gravity spreading of the evaporites within the LB [Cartwright et al., 2012; Netzeband, Hübscher, and Gajewski, 2006]. Gravity spreading is a factor driving salt tectonics on passive margins due to differential sediment deposition [Loncke et al., 2010]. Gravity gliding is caused by a complex thin-skinned tectonic regime of extension in the part that experiences uplift and compression in the lower basinward area [Gradmann et al., 2005; Loncke et al., 2010], terminating against the ESM [Reiche, Hübscher, and Beitz, 2014]. This is facilitated by the nature of evaporites to easily deform [Hudec and Jackson, 2007]. Additionally, fluid migrating into the salt seem to play an important role in salt dynamics [Hübscher et al., 2009; Reiche, Hübscher, and Beitz,

²In this thesis TES will be used.

2014].

There is sparse evidence for deep-rooted tectonic faults extending through the evaporites [Gradmann et al., 2005]. Whereas thin-skinned tectonics, including salt welds and salt rollers, are very common in the LB. Additionally, Loncke and Mascle [2004] and Dupré et al. [2010] identified salt tectonic faults. Figure 3.3 summarizes the temporal and spatial variability of salt tectonics and its driving forces in the LB.

FIGURE 3.3: The conceptual map shows the temporal and spatial variability of salt tectonics and its driving forces. The green lines indicate the studies contributing to the map and consequently the research of Reiche, Hübscher, and Beitz [2014]. The red line shows the survey processed in this thesis.

(mod. Reiche, Hübscher, and Beitz [2014] with according sources:

Mechanisms driving salt deformation according to ¹Gvirtzman et al. [2013]; ²Netzeband et al. [2006]; ³Cartwright and Jackson [2008] and Gradmann et al. [2005]; ⁴Cartwright et al. [2012], Loncke et al. [2006, 2010], and Netzeband et al. [2006]. *The locations of extensional faults were drawn according to Kosi et al. [2012].)

3.4 Hydrocarbon Indicators

The first indications of hydrocarbons were found below the Israel Slump Complex (ISC) off the coast of Israel [Garfunkel, 1984; Netzeband, Hübscher, and Gajewski, 2006]. Eppelbaum, Lev, and Youri [2011] suggest that the convergence between Africa and Anatolia led to the formation of several potentially prospective hydrocarbon traps in the LB. Accordingly, the high-potential hydrocarbon plays in Tamar-1 and Leviathan may not be isolated features. The southern part with the NDSF hosts a world-class hydrocarbon province [Gardosh et al., 2008] substantiating the claim of wide-spread hydrocarbon presence in the LB. State of the art 3D seismic surveys of the LB show more evidence for gas reservoirs [Lazar, Schattner, and Reshef, 2012]. The USGS assesses the amount of technically recoverable gas resources to be 4 trillion m³ and 1.7 billion barrel recoverable oil [Eppelbaum, Lev, and Youri, 2011; USGS, 2010]. The discovery of large gas deposits has spawned more attention to the LB region.

Structures associated with gas escape, including pockmarks and mud volcanos, are observed at the seafloor and have been described in various publications (cf. [Bertoni, Cartwright, and Hermanrud, 2013; Dupré et al., 2010; Hübscher et al., 2009; Lazar, Schattner, and Reshef, 2012; Netzeband, Hübscher, and Gajewski, 2006; Reiche, Hübscher, and Beitz, 2014; Reiche, Hübscher, and Erhardt, 2014]). The mud volcanos have been correlated to feeder channels that only span a few meters in diameter [Dupré et al., 2010]. The gas conduits correlated to the pockmarks have been described as equally narrow in the NDSF [Dupré et al., 2010]. Seeps on the NDSF follow lineations on the seafloor that have been related to faults [Dupré et al., 2010]. Buried pockmarks in the LB at a depth of ~4 km span an area of 1000km² with diameters as wide as 2km [Bertoni, Cartwright, and Hermanrud, 2013]. The widespread undisturbed upper Pleistocene in the LB suggests that fluid escape has mainly ceased [Hübscher et al., 2009; Lazar, Schattner, and Reshef, 2012], therefore, inferring a trap structure with an intact seal. The absence of or faulted Messinian evaporites clearly show gas escape structures in the sediment column above [Gradmann et al., 2005; Lazar, Schattner, and Reshef, 2012; Loncke and Mascle, 2004]. Prior to the deposition of the evaporites vigorous gas escape occurred [Bertoni, Cartwright, and Hermanrud, 2013; Lazar, Schattner, and Reshef, 2012; Reiche, Hübscher, and Beitz, 2014].

The seismic data also contains some direct hydrocarbon indicators (DHI). Horst structures were correlated to acoustic blanking and bright spots on the flanks [Lazar, Schattner, and Reshef, 2012]. Roberts and Peace [2007] describe widespread occurrence of bright spots and gas chimneys. These claims were substantiated by 3D seismic analysis describing “volumes of acoustic blanking and bright spots, which were mapped by the analysis of various seismic attributes, such as variance and chaos (for detection of discontinuities such as faults and chimneys), envelope (bright spots, major lithological changes and sequence boundaries detection) and sweetness (changes in overall energy signal)” ([Lazar, Schattner, and Reshef, 2012]).

In the LB source rock from the Mesozoic age is the most profitable. Roberts and Peace [2007] identify source rock from the Upper Cretaceous as oil-prone and Triassic-Jurassic source rock as gas prone. The systems contain both biogenic and thermogenic gas [Bertoni, Cartwright, and Hermanrud, 2013; Gardosh et al., 2008; Roberts and Peace, 2007]. Additionally to the Messinian salt, shales and marls of the Paleogene, Neogene, Cretaceous and Jurassic as well as Triassic evaporites can be identified as potential hydrocarbon seals above mainly hemipelagic and pelagic reservoir rock [Roberts and Peace, 2007].

Chapter 4

Seismic Data Processing Workflow

Generally speaking, one can say that there is no true standard seismic processing. Every dataset has its own challenges and pitfalls. However, some processing steps are quite similar and will be summed up here, more thorough descriptions can be found in Hübscher and Grohl [2014] and Yilmaz [2001]. In general, the tools employed in this seismic data processing sequence include Seismic Unix by CWP, Promax 2D by Haliburton, Globe Claritas by GNS Science, Partial CRS by Baykhulov, Mann, Traub and Gerst, Differential Evolution CRS by Walda, Mann, Traub and Gerst, Partial Time Migration via CSP by Dell and Spinner.

4.1 Preprocessing

4.1.1 Preconditioning

In any seismic processing flow, at first bad traces should be identified and flagged or set to zero. Additionally, misfired shots must be identified and corrected. This will improve the overall data quality and reduce artifacts in the data. This step may be combined with picking a surgical topmute which can be utilized to mute any recorded seismic data before the primary. Picking a top mute can improve the overall quality of the seismic processing flow as it will reduce random energy content in the water column. However, one has to be careful in special cases the water column may introduce artifacts into the data which have to be accounted for [Hertweck and Elboth, 2012].

In smaller data sets these traces may be identified by hand, large industrial data sets should utilize statistic methods. Globe Claritas delivers a visual tool to load RMS or peak amplitude data for traces to identify bad traces, channels or shots (cf. Figure 4.1).

(A) RMS amplitudes with erroneous shots present, sur- (B) Muting erroneous shots (black) and re-gaining shows passing the other data by magnitudes. a better amplitude distribution.

FIGURE 4.1: RMS amplitudes of each channel (x-direction) in a shot (y-direction). Muting several erroneous shots in the display leads to an improved display. The dipping trends show reflection or diffraction, whereas a cross-dip would indicate swell noise or bad data (this image is generated after swell noise filtering).

4.1.2 Geometry and Data Domains

The realization of data domains takes the first and most important step in the preprocessing workflow. When the tapes with seismic data come from the vessel the geometry and the seismic data are separate. This data has to be merged into the header of the seismic data so that every shot and every receiver can be located [Halliburton, 2014]. Afterwards we start the process of calculating the CMP. However, in field data we have some variance in vessel

velocity and feathering of the streamer, which would leave exact CMP locations with just one shot receiver pair. Therefore, we need to do some binning on the data [Gajewski, 2010]. This essentially defines an area surrounding a CMP location to assign to shot-receiver pairs.

In Promax there are three essential modules to achieve this. Geometry Head Preparation will renumber the channel and write it into the trace header. Now we can load the 2D Marine Geometry Spreadsheet. This module will set up the Ordered Parameter File (OPF), which is necessary for Promax to start the binning process. The routine will take the user step by step through the binning process including a Quality Control (QC) at the end. Eventually, the data can be loaded into the headers of the traces using Inline Geom Header Load.

Promax 2D has some interoperability issues with other processing tools, so it is best to reset the geometry when working with some other tools. The setup of marine geometry in Globe Claritas needs the quick setup of a geometry file, which is subsequently loaded into the headers by the simple MGEOM module.

Additionally, the data was resampled to 4ms including an anti-alias filter using the Promax tool `Resample`.

4.2 Processing

In seismic data there is a distinction between a signal and noise. The signal is reflection data we can utilize to image the Earth, whereas the noise is undesirable. We can put noise into two categories, which are coherent and random noise. One of the first steps is reducing swell noise, which is a form of coherent noise. It is a low frequency noise generated by currents that will strike the streamer from the side and create turbulent flows that leave localized panels of strong coherent noise in the data [Elboth, Reif, and Andreassen, 2009]. A common approach is the utilization of low cut filters, however more sophisticated acquisition schemes such as BroadSeis[™] would need a more specialized approach for swell noise reduction [Lin et al., 2011]. Further linear noise can be traced to several sources i.e. powerlines or crosstalk. Powerlines have a limited spectrum and can be reduced by applying a notch-filter. Crosstalk is more complicated to come by and should be avoided on the acquisition side.

Incoherent noise is usually attenuated by using approaches that rely on the coherency of our signal. Sudden energy elevations such as spikes and noise bursts in traces can be eliminated

by median filters. This will not work on traces that have a total elevated noise level. These traces may have to be eliminated in the preconditioning of the data (cf. Section 4.1.1). Deconvolution methods can be used to further attenuate random noise. The F-X deconvolution has shown to be particularly effective in attenuating random noise as it will focus on coherency in the data. The last step for noise cancellation is stacking (cf. Section 2) the data as well as migration (cf. Section 4.3) [Yilmaz, 2001]. In case source signature information is present, a designature / minimum phase filter can be designed to comply with the minimum phase assumption for several subsequent processing steps. For this data this was not the case.

Amplitude gain is a step to account for spherical divergence and other effects that diminish the amplitudes of deep signals [Yilmaz, 2001]. This step is best applied after noise attenuation because a gain will also elevate noise levels present in the data.

In Promax the tools used to attenuate noise are **Bandpass Filter**, **Spike & Noise Burst Edit**, **Ensemble Balance** and **F-X Decon**. The **Bandpass Filter** module applies a frequency filter to every trace, a range from 2-5 Hz and 80-90Hz was chosen. The **Spike & Noise Burst Edit** module uses a sliding gate approach to find noise bursts and spikes, these are ideal to diminish swell noise. This allows the bandpass to contain very low frequencies. The deleted samples are interpolated from adjacent samples or traces depending on the size of the gap (cf. [Halliburton, 2014]). The **Ensemble Balance** module calculates the RMS of all traces and scales the trace accordingly. This may introduce spikes into the data so that the **Spike & Noise Burst Edit** should be applied again [Weiss2013]. The **F-X Decon** module calculated can be applied pre- or poststack, serving as a processing or imaging step [Halliburton, 2014]. Each trace is Fourier transformed into a frequency trace then a complex, Wiener, unit prediction filter is applied in the space domain [Halliburton, 2014].

4.2.1 Velocity Analysis

The NMO in offset direction can be corrected for by solving for v_s in Equation 4.1. This stacking velocity can be estimated during the velocity analysis.

$$t_s = \sqrt{t_{0s}^2 + \frac{x^2}{v_s^2}} \quad (4.1)$$

Velocity analysis calculates a coherency measure such as the semblance in Equation 4.2 that calculates the local energy divided by total energy.

$$S = \frac{\sum_{i=1}^M \left(\sum_{j=1}^N a_{ij} \right)^2}{N \sum_{i=1}^M \sum_{j=1}^N a_{ij}^2} \quad (4.2)$$

Modern velocity analysis tools implemented in Globe Claritas and Promax can also prepopulate velocity picks from previous CMP locations, show Constant Velocity Stacks (CVS), show iso-velocity images, as well as, long-offset extensions, i.e. [Al-Chalabi, 1973], and other useful utilities. GNS Science [2014] and Halliburton [2014] give further insight into these tools. In industry processing workflows the velocity file is usually refined/repicked along the processing flow in several passes.

4.2.2 Multiple Removal

Shallow water multiples and peg-legs in strong multiple generating horizons may cause "ringing" multiples in the data. These multiples can be attenuated using a gapped Wiener error filter for predictive deconvolution [Yilmaz, 2001]. In deep water an industry standard is considered to be the Surface Related Multiple Elimination (SRME), which uses a convolution of the source and receiver traces to predict multiples. This approach is very effective but computationally expensive. Several approaches are based on the wave equation. There are also approaches that use velocity filters, which utilize the fact that multiples have a slower apparent velocity. Especially the Radon velocity filter has gained traction in the elimination of coherent noise. The Radon transform however, does not have a clean inverse transformation. This may leave artifacts in the data that have to be reduced in further processing steps. The FK-Filter makes use of the 2D Fourier transform. It transforms standard *time-space* (TX) data into the *frequency-wavenumber* (FK) domain. This domain has a special emphasis on different dips of events in the data. Then a polygon can be picked to reject certain dips. This is especially useful for coherent noise, such as multiples or refracted energy. Using the FK domain is also very convenient to make temporal as well as spatial aliasing apparent as this causes the FK image to "wrap around" the edges, if aliasing was present.

Promax turns out to have some downsides in respect to multiple removal. The SRME modules only allow data below 2GB header size and require several modules to run. The wave-equation based module **Surface-Related Wave Equation Multiple Elimination** is only partially working, making it nearly impossible to subtract the generated multiple model from the data. The **Radon Velocity Filter** left the data set riddled with artifacts, even when using the TGS-provided velocity model. The modules **FK-Analysis** and **FK Filter**, however, worked very well to attenuate some surface related multiples and refracted energy. The **FK-Analysis** module opens a graphical user interface to manually pick polygons at user-provided intervals. Especially, refraction mutes have to be picked carefully not to cut reflections.

FIGURE 4.2: The FK domain shows the frequency content (y-direction) per wavenumber (x-direction) of the input shots. The center of the x-direction shows $k = 0$ and the frequency axis has 0Hz at the bottom to 125 Hz at the top. The applied bandpass filter from 2-5-80-90 Hz is visible. After application of the filter in Figure 4.2b, the attenuation of scattered frequency noise in the left half of the wavenumbers becomes apparent. Promax does not provide a colorbar.

Globe Claritas provides several modules for multiple attenuation. The **PRT Demult** module provides a fully integrated parabolic radon mute demultiple. The **SRME2_MPI** module is a parallelized stand-alone SRME implementation, especially suited for long offsets and industry-sized data sets [Maslen, 2013].

Previous to the application of an SRME the data has to be preconditioned. The shot:geophone spacing should be equal and ideally near-offsets up to the zero offset should be present and regularized. These prerequisites can be met using the **SHOTINT** module for shot interpolation and **OFFREG** module for offset regularization and interpolation.

4.3 Pre-Stack Time Migration

Promax offers the module `Prestack Kirchhoff 2D Time Mig.`. I was not able to test the `KPRET2D` module by Globe Claritas, as time ran out and concentrating on one prestack migration was a task big enough for this thesis.

The Promax module can be run in parallel mode. I used the RMS velocity file provided by TGS and utilized a velocity scan to account for possible timing errors by $\pm 10\%$. This processing step was limited to the CDPs 2000 to 2500 as the process is very time consuming.

4.4 Common Reflection Surface Processing

The common reflection surface stack is a standalone package written in C++. Compilation is laid out in Mann [2003].

4.4.1 Conventional CRS

The data has to contain shot and geophone coordinates and be CMP sorted.

The call can be made via Makefile or a parameter file. The parameter files for reproducibility are in Appendix A. It is very important to change the angle settings to accommodate for angles over 60° to enable diffraction imaging. The apertures should be chosen according to the imaging objective.

The code runs in sequential mode. Input is in seismic unix format, which is derivative of SEG-Y.

4.4.2 Differential Evolution

DE CRS can be run in parallel using MPI. The call can be done via Makefile or submission script, according to the local architecture. The DE parameters are:

- $CR = 0.7455$
- $F = 0.9362$
- $NP = 20$

Additionally, a parameter sets the number of dip panels to search. The dips will be allocated automatically. An uneven number of dips is recommended, this forces the "middle" dip panel to include 0° .

The parameters for DE CRS have been significantly reduced. The code is pre-release.

4.5 Partial Time Migration Processing

The Partial Time Migration velocity mapping routine by Dell [2012] is a standalone package. It can be executed in parallel using MPI. The call can be done via Makefile or submission script, according to the local architecture. The parameters have been documented in Appendix B.

The input includes the data and a time migration (stacking) velocity file. The shot and receiver coordinates have to be present in both files. Sampling does not have to coincide but the boundaries have to be adjusted accordingly.

Chapter 5

Results

The results presented in this thesis include the processing up to CMP 10000. Computation intensive processes were performed on a selected set of CMPs in the range of 2000 to 4500. This subset of the data is of special interest, as it contains different salt structures, including the salt rollers.

The raw data in Figure 5.1 reveals some important processing steps that need to be investigated along the processing flow. The image in general is riddled by random noise. There is also strong low frequency noise present in the data. Additionally, the seafloor generates three strong multiples in the data. The data is reverberating ('ringing'). The top of salt is another strong multiple generating surface, but these multiples are mainly masked by noise and stronger multiples from the seafloor.

One main objective in the course of this processing flow is to eliminate multiples as they strongly mask the subsalt area.

FIGURE 5.1: Raw seismic data. Strong noise, multiples (orange) and reverberations present.

5.1 Seismic Processing

5.1.1 Preprocessing

Line P2039 from TGS-NOPEC investigates the evaporite layer in the Levantine Basin. Additionally to the caveats subsalt imaging poses in a seismic processing workflow, this profile was recorded along the wrong direction. This introduces some problems in the setup of the geometry in the data.

Once the geometry is set up correctly, preprocessing can commence. The goal in this step was to eliminate low frequency noise. Figure 5.1 shows high noise levels especially below the shallow water area. This area is not be of primary interest in the steps of the processing flow. However, more sophisticated processes, especially in other data domains, may suffer in quality, if this noise was still present.

A bandpass filter may eliminates the frequency content of these noise bursts. Alternatively, a light bandpass filter with additional noise cancelling modules has proven to give better results while preserving more bandwidth of the data set, as described in Chapter 4

In Figure 5.2 three strong multiple-generating horizons become apparent, the seafloor, TES and BES. Additionally, the reverberations within the data set are now very obvious.

The stacked section includes four erroneous shots (2638, 2773, 3158, 6500). They produce artifacts in the vicinity of CDP 3250, 3550, 4400 and 5000 below 6s TWT. This is particularly visible in the close-up in Figure 5.3.

FIGURE 5.2: Denoised seismic data. Three strong multiple generating surface, namely seafloor (blue), TES (red) and BES (yellow).

FIGURE 5.3: Denoised seismic data. Seafloor multiple (orange) cuts through subsalt. TES generates diffraction multiples (red). Erroneous shots produce noise (blue)

Figure 5.3 focuses on CDP 2000 to 4500. The TES around 2.5 generates many diffractions that additionally generate multiples throughout the subsalt, clearly visible at 4s and 5s between CDP number 2500 and 3000. The seafloor around CMP 4000 at 1.5s TWT generates a very strong multiple that cuts directly through the upper subsalt. Erroneous shots introduce

linear noise below 6s, they're pictured in Figure 5.4.

FIGURE 5.4: Three erroneous shots. The direct wave is shifted to larger times, which can usually be attributed to an error during SEG-D $\rightarrow$ SEG-Y conversion.

5.1.2 Processing

The main processing sequence is focused on multiple reduction and the elimination of linear noise, while keeping the primary signal intact. The zoom on CDP 2000 to 4500 is especially interesting in this case for several reasons:

1. The dipping seafloor induces a strongly dipping multiple that cuts through other reflections and intersects part of the strongly diffracting TES.
2. Reverberating reflections especially in the flat region of the seafloor.
3. Diffractions from TES create multiples.
4. Preserving the weak amplitudes from strongly dipping flanks of salt rollers is difficult.

The first tool I used was FK analysis and a FK Filter, presented in Section 4.2.2. The picked polygon can be tested in "accept"- and "reject" mode. Using the opposite mode would show if any primary signal was picked to be filtered from the data and corrected accordingly. In

Figure 5.6 the resulting image is presented.

The FK Filter shows some clear improvements of the data. The first signs of internal structures in the evaporite layer become visible. Additionally, multiples in the lower parts have been attenuated.

However, the FK Filter did not manage to eliminate large parts of the seafloor multiple. The fk-dip of this linear noise was too close to primary data, so lossless attenuation would not have been possible.

Surface Related Multiple Elimination was attempted. The multiple model did not resolve the diffractions ideally. Additionally, the SRME algorithm is very susceptible to timing errors in the data. This may be the case for the data set as the timeshift in Figure 5.5a suggests.

FIGURE 5.5: Comparison of SRME model and FK analysis result. The SRME model was not able to account for the TES diffraction multiples and shows a strong time shift compared to the stacked data.

FIGURE 5.6: Fk filtered seismic data. Linear noise such as refractions and some multiples attenuated. Some multiples still present (orange). First intra-salt reflections visible (magenta).

FIGURE 5.7: Fk filtered data CMP 2000 to 4500. Good improvements, but sea floor multiple still present.

The next step is a predictive deconvolution of the data to attenuate ringing and reverberating signals. The result can be seen in Figure 5.8. This step was crucial to reduce artifacts in a Radon demultiple.

FIGURE 5.8: Gapped deconvolution reduces reverberations especially in shallow water environment (blue) and high amplitude columns. Seafloor multiple present (orange).

FIGURE 5.9: Gapped decon demultiple data CMP 2000 to 4500.

Following the deconvolution, a Parabolic Radon Mute has been applied. The radon demultiple was applied to supergathers to avoid spatial aliasing to further reduce artifacts.

FIGURE 5.10: Radon demultiple seismic data. Most surface related multiples have been eliminated from the data set. BES multiple still present.

FIGURE 5.11: Radon demultiple data CMP 2000 to 4500.

5.1.3 Pre-Stack Time Migration

FIGURE 5.12: Prestack Kirchhoff migrated data CMP 2000 to 4500.

5.2 CRS at different starting points

5.2.1 Preprocessing

FIGURE 5.13: CRS stack after initial denoise. Bottom ellipse shows bad shots. Top ellipses show good resolution of diffractions.

FIGURE 5.14: CRS stack after denoise without erroneous shots (ellipses).

5.2.2 Processing

FIGURE 5.15: CRS stack after FK demultiple. **Diffractions** good resolved, but **diffraction multiples** also present.

FIGURE 5.16: CRS stack on final Radon demultiple

5.3 CRS Aperture Variation Analysis

This section elaborates on the response of the CRS stack and the R_{NIP} section as exemplary search space on variation of the scan and stacking aperture.

The main task in the CRS processing flow is finding adequate CRS apertures. The different apertures were introduced in Section 2.3.2. Two of these apertures are the scan and stacking apertures. Scan apertures are used for limiting the search space for the contribution to the parameter set. Smaller apertures will decrease the computational cost. The stack aperture is used to limit the contributing data to the final stacked section.

First a medium aperture was used for the CRS scan. The estimated wavefield attributes were then used to stack the data with varying apertures. Figure 5.17a shows the stack with a medium aperture, in Figure 5.17b the according R_{NIP} section is displayed. Figure 5.18a shows the according stack with a small stacking aperture and Figure 5.18b shows the stack with a large stacking aperture.

stack aperture	CMP aperture [m]	ZO aperture [m]	R_{NIP} section
small	50 - 75	400 - 2000	Figure 5.17b
medium	100 - 200	400 - 3000	Figure 5.17b
large ¹	135 - 800	500 - 4000	Figure 5.17b

The next part evaluates different scan apertures.

FIGURE 5.17: CRS stack and Rnip section generated with medium aperture

FIGURE 5.18: Comparison of CRS stacks with small and large stacking apertures but wavefield attributes scanned with medium aperture (cf. Figure 5.17b)

The following part evaluate different scan apertures. R_{NIP} is taken as an exemplary wavefield attribute, as it is also important to diffraction imaging.

First the data is searched with a scan aperture and subsequently stacked with the same aperture.

Aperture size	CMP aperture [m]	ZO aperture [m]	Scan Aperture R_{NIP} section	Scan and Stack with equal aperture
small	50 - 75	400 - 2000	Figure 5.19b	Figure 5.19a
medium	100 - 200	400 - 3000	Figure 5.17b	Figure 5.17a
large	135 - 800	500 - 4000	Figure 5.20b	Figure 5.20a

Furthermore, in Figure 5.22a and Figure 5.22b are compared to see the improvement of a R_{NIP} section from the pragmatic approach after global optimization of the three parameters.

The large apertures were chosen and combined with an input V_{NMO} model to see the improvement of the stacked section in Figure 5.21a and the R_{NIP} section Figure 5.21b

Eventually, the result from the DE CRS is presented in the stacked section in Figure 5.23a and the R_{NIP} section in Figure 5.23b. The parameters are then used to CRS stack the data with a small aperture.

Aperture size	CMP aperture [m]	ZO aperture [m]	Global Search R_{NIP} section	Differential Evolution CRS Stack
small	50 - 75	400 - 2000	-	Figure 5.24a
enormous	300 - 500	1500 - 4000	Figure 5.23b	Figure 5.23a

FIGURE 5.19: CRS stack and Rnip section of small scan and stacking aperture

FIGURE 5.20: CRS stack and Rnip section of large scan and stacking aperture

FIGURE 5.21: CRS stack and Rnip section large scan and stacking aperture with provided velocity field

FIGURE 5.22: Comparison of Rnip sections from pragmatic approach and subsequent optimization.

FIGURE 5.23: CRS stack and Rnip section of global Differential Evolution parameter search

FIGURE 5.24: Comparison of CRS stack apertures on Differential Evolution parameter sections with small and large stacking apertures

The global parameter search shows some significant improvements in the stacked section and the R_{NIP} section. Concerning the choice of apertures, the scan improves with larger apertures, whereas the stack benefits from smaller apertures, when stable parameter sections are available.

Large stacking apertures introduce a smoothing or smearing effect on the data. This should be avoided. Additionally, artifacts may be introduced in unfortunate cases. This can be seen in Figure 5.24. Very good parameter sets were obtained from the global search routine, but the stacked section with a large aperture introduces some smearing of the data and the small aperture stack looks very clean.

5.4 Partial Time Migration

The results in this section contain three stacks from partially time migrated gathers (Figure 5.25, Figure 5.26 and Figure 5.27). In comparison the migration stack from the conventional processing flow is presented in Figure 5.28 and a commercial time migration courtesy of TGS as benchmark in Figure 5.29.

The data has been limited to 4.5s TWT to be comparable to the TGS data.

FIGURE 5.25: Initial PTM section. Multiples dominate the image.

The initial PTM section in Figure 5.25 shows that the quality suffers from the multiples present in the data.

FIGURE 5.26: The DE CRS parameter sections are used for Partial CRS processing to precondition subsalt.

Partial CRS supergathers using the DE CRS parameter sections as input into the PTM showed some improvement in the subsalt.

FIGURE 5.27: Radon demultiple attenuates multiples further.

Attenuating the multiples has shown to be the best improvement for the Partial Time Migration. The steep flank of the salt rollers has not been imaged correctly. This might be due to a velocity error, or other data interfering with the flank. The subsalt looks very clean.

FIGURE 5.28: Prestack Kirchhoff Migration.

The Prestack Time Migration shows a better image than the PTM, the subsalt, however, has been imaged well with both algorithms. The salt rollers have been imaged nicely and the subsalt is clean and well visible. The multiple generates some migration artifacts, as well as out-of-plane reflections and diffractions generated at the TES.

FIGURE 5.29: Time migrated section courtesy of TGS.

The final comparison of the commercial product shown in Figure 5.29 shows that TGS chose stronger multiple attenuation limits. The salt rollers have been imaged well in Figure 5.28. The subsalt has been improved significantly in all end products.

Chapter 6

Conclusion

One of the main objectives in this thesis was a final prestack migration. The final Kirchhoff migration in Figure 5.12 still has some multiples in the data. But generally, the resolution is very good and the subsalt is well resolved and minimally masked by the multiples. Comparing the commercial data in Figure 5.29 with the data shows that the salt rollers are well resolved.

The multiple reduction of the data was crucial to further processing of the seismic data. The subsalt was completely masked by multiple energy. Using different techniques to preserve as much primary energy as possible proved to be a good decision.

The final migration stack shows some migrations smileys. Especially the deeper parts are completely masked by migration artifacts. A large quantity of artifacts stems from boundary effects. Some energy however, can only be explained by out-of-plane energy. The salt rollers are especially prone for this scattering behaviour.

Analysis of different starting points in a seismic processing workflow has shown that multiples may be enhanced through CRS processing and a multiple free dataset improves the quality of the CRS stack significantly.

The analysis of CRS apertures has shown that three common misconceptions reside around CRS apertures. The first misconception stems from the understanding that better resolution and a sharper objective function are desirable. As was discussed in Section 2.3.2, large apertures would facilitate this. While better resolution is generally desirable in seismic data, the optimization of an overly focused objective function may become impossible at a certain point. Therefore, pushing on the physical boundaries, namely the first Fresnel zone, as an aperture is generally ill-advised (M. Baykulov, personal communication, 2011-04-26).

The second misconception is about the different apertures in CRS. The choice of apertures is dependent on the application. The different apertures were outlined in Section 2.3.2.

The third misconception overestimates the apertures. The choice of apertures is one of the most important steps in the CRS processing flow. However, the CRS algorithm works with many constraints to improve quality and processing speed of the algorithm [Baykulov, 2008; Mann, 2002; Mann, 2003]. Abiding by the default parameters can be contrary to the processing objective and a better choice of apertures may not improve the image. In general it is advisable not to limit the emergence angle to 60° .

The R_{NIP} section does not show many differences in the conventional CRS. The DE CRS output however, shows some strong improvements over the other sections.

Generally, it is advisable to use larger apertures to scan for the wavefield attributes, to stabilize the search. The stack, however, profits from smaller apertures.

Additionally, V_{NMO} reference model proves to be a very efficient way to stabilize the parameter search and improve the search remarkably, almost independent of aperture choice.

The global parameter search shows some major improvements over the pragmatic approach but comes at a high computational cost.

The quality of the Partial Time Migration suffers from multiples in the data. Supergather generation using partial CRS stacks with the wavefield set of the DE CRS algorithm has shown to be effective at countering this. Multiple attenuation, however, has proven to be a bigger factor in the outcome of the diffraction imaging.

Concluding, the shallow subsalt has been imaged by conventional processing techniques as well as CRS and PTM. The application of Prestack Time Migration has shown the best results, but improvements in the subsalt were visible in the prestack data enhancement methods.

Appendix A

Parameter File CRS

```
verbose=1
datapath=/scratch/local1/Master/CRS170
input=./170_cdp2000-4500.cdp
basename=170
logfile=170.log
survel=1510
vnmomin=1400
vnmomax=8000
autoCMPstack=1
Z0search=1
Inistack=1
Optimize=0
Supergathers=0
migmap=0
convop=0
jcdp=0
ndips=0
globcohthresh=0.65
relcohthresh=0.5
coherence=0
cohband=5
qdtfac=1
```

qiter=5
pwaperfac=.4
maxangle=90
minangle=-90
dangle=.75
angleiter=5
Rndtfac=1
Rniter=0
Rnipdtfac=1
Rnipiter=0
mincohthresh=.5
maxcohthresh=.1
optiter=10
opteps=.0001
transrad=100
varangle=10
varRnip=10
varRn=10
minoffsetap=400
maxoffsetap=3000
minxap=30
maxxap=70
shotint=25
avgvel=2500
wavefr=50
offsign=1
recint=12.5
offreg=1
offap=125

Appendix B

Batch Job Partial Time Migration

```
#!/bin/bash
#SBATCH --job-name=PartialTimeMig
#SBATCH --output=JobName-%j.ptm
#SBATCH --error=JobName-%j.err
#SBATCH --partition=geophysics
#SBATCH --nodes=4
#SBATCH --ntasks-per-node=16

# if you want to use the module system:
source /sw/share/Modules/init/bash
# after initialization you can load a module
# module load openmpi/default
module load gcc/4.8.2
module load openmpi/1.8.4-static-gcc48

# below your job commands:
mpirun /scratch/uni/u250/u250111/code/CSP/result/bin/vmapping \
prestack=/scratch/uni/u250/u250111/data/170_cdp2000-4500.cdp \
      out=/scratch/uni/u250/u250111/result/CSP/mapped_Nip.su \
      velmodel=/scratch/uni/u250/u250111/data/2039_Nip.vel \
      v0=1510 \
offset=0,7338 \
```

```
    binsize=12.5 \  
xtarget=138054,169303,12.5 \  
ttarget=0.,8.,0.004 \  
aptap=100,700 \  
    aprad=150,1000 \  
intap=100 \  
    inter1d=sinc \  
    netload=0 \  
    tap=lin
```


Appendix C

Batch Job Differential Evolution CRS

```
#!/bin/bash
#SBATCH --job-name=tgsDE2
#SBATCH --output=JobName-%j.crs
#SBATCH --error=JobName-%j.err
#SBATCH --partition=geophysics
#SBATCH --nodes=4
#SBATCH --ntasks-per-node=16

# if you want to use the module system:
source /sw/share/Modules/init/bash
# after initialization you can load a module
# module load openmpi/default
module load gcc/4.8.2
module load openmpi/1.8.4-static-gcc48

# below your job commands:
mpiexec ../crs_dm \
    verbose=0 \
    par=tgs_pickedmutes \
    datapath=/scratch/uni/u250/u250111/result \
    input=/scratch/uni/u250/u250111/data/164_2000-4500.cdp \
    logfile=tgs.DE.log \
```

```
    basename=tgs.DE \  
    surve1=1510 \  
    coherence=0 \  
    cohband=6 \  
    minxap=300 \  
    maxxap=500 \  
    minoffsetap=1500 \  
    maxoffsetap=4000 \  
    wavefr=50 \  
    maxangle=90 \  
    minoffset=150 \  
    maxoffset=7338 \  
ndips=11 \  
Optimization=1 \  
algorithm=1 \  
abortcrit=10 \  
    miniteration=30 \  
    maxiteration=100 \  
CRin=0.7455 \  
Fin=0.9362 \  
NP=20
```

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