

Structural interpretation using seismic attributes:
A case study from the offshore Orange Basin, South Africa

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By

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Declaration

I declare that this thesis (*Structural interpretation using seismic attributes: a case study from offshore Orange Basin, South Africa*) is my own, unaided work. It is being submitted for the Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

A handwritten signature in black ink, reading "B J Donga". The letters are cursive and fluid, with the first name "Buhlebenkosi" abbreviated to "B J".

Buhlebenkosi Joylene Donga

30th day of August 2019 at the University of the Witwatersrand

Abstract

The Orange Basin is located offshore, west coast of South Africa. The basin is known for its proven main hydrocarbon reserves and potential for further discoveries. Previous studies suggest that the basin is characterized by several gas chimneys; which can create pathways for gas migration from the source rock to the surface. It therefore is of critical importance to map and understand these structural features in the Orange Basin. In this study, high-resolution, post-stack migrated 3D reflection seismic data, covering an area of $\sim 308 \text{ km}^2$, have been interpreted using conventional methods and state-of-the-art seismic attributes. The main objectives are to illuminate the large scale and sub-seismic geological structures that crosscut the hydrocarbon source rocks and act as conduits for gas migration to the surface. Horizon- and volume-based seismic attributes have been applied to improve visualization of structural relationships and to enhance the detection of Direct Hydrocarbon Indicators (DHIs). Seismic attributes are also used to map the relationship between structures, thus constraining their timing of activity.

The results suggest that the study is characterised by NW-SE trending major normal faults, NW-SE and NE-SW trending subtle normal faults. Some of these faults fall below the seismic resolution limit (a quarter of the dominant wavelength) and cannot be mapped using conventional seismic interpretation techniques. However, their detection was enhanced through the use of seismic attributes. The complex trace attributes identify the general locations of major faults; the dip attribute provides the orientations of major faults in the study area; the dip-azimuth, edge detection and ant-tracking attributes examine the connectivity between major faults and linear faults mapped as minor fault segments which is not otherwise clear on conventional seismic amplitude data; the variance and ant-tracking attributes have mapped the major faults. The edge detection attributes also reveal the presence of pockmarks and gas chimneys characterized by low-amplitude reflections. This study is one of the first attempts to study the structural setting, timing of fault activity and the tectonic history of the offshore Orange Basin through the interpretation of high resolution 3D seismic data. This study proposes that the state-of-the-art seismic attributes should be recognised as fundamental seismic interpretation tools in studying the tectonic history of the region and to map structures that have major controls on hydrocarbon migration and storage.

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Chapter 1: Introduction

1.1. Background and Motivation

“Seismic attributes should have clear and useful meanings. If you don’t know what an attribute means, don’t use it. If you know what it means but it isn’t useful, discard it. Prefer attributes with geological or geophysical meaning; avoid attributes with purely mathematical meaning” (Barnes, 2006, 2016).

Seismic data interpretation is the fundamental procedure for making sense of seismic data, thus, in principle, providing information about subsurface geology. Seismic data are generally interpreted on seismic sections using amplitude displays. However, the amplitude display, like any interpretation technique, has its specific limitations. For example, faults that are below the seismic resolution limit (i.e., a quarter of a dominant wavelength) and structural complexities (e.g., faults’ cross-cutting relationships, connectivity and continuity) cannot be easily interpreted using the amplitude display on seismic sections. However, seismic attribute analysis can be used to reveal characteristics of seismic data that are not readily seen in amplitude data. Seismic attributes enhance and quantify subsurface stratigraphic and structural features of interest (Chopra and Marfurt, 2007a).

In this study, the subsurface structural and stratigraphic setting of Block 2A in the offshore Orange Basin is investigated using post-stack migrated 3D reflection seismic data. Block 2A is located on a passive margin, which is characterised by geological structures such as faults (including small-scale or sub-seismic faults), folds, fractures and fluid-escape features. These structures are of critical importance for hydrocarbon exploration; therefore their delineation and characterization is essential.

Block 2A is underlain by the: 1. Upper Jurassic to Lower Cretaceous lacustrine source rocks, Barremian to Aptian (117.5 Ma – 112 Ma) marine source rocks; 2. Cenomanian to Turonian (100 Ma – 93 Ma) marine source rocks that contributed to the petroleum generation in the system; and 3. Upper Jurassic, Cretaceous and Cenozoic clastic rocks, which are regarded as potential reservoirs (< 150 Ma) (Muntingh, 1993; Muntingh and Brown, 1993; Jungslager, 1999; Hartwig et al., 2010; Brownfield, 2016).

Many studies (e.g., [Brown, 2004](#); [Barnes, 2006](#); [Chopra and Marfurt, 2007a](#); [Manzi et al., 2013](#)) have demonstrated that it is difficult to identify subtle faults and consistently track thin stratigraphic layers on conventional amplitude displays due to severe destructive interference resulting from overlapping wavelets, and because the thickness of the layers (or beds) is below the vertical seismic resolution limit (tuning thickness). Thin beds, in particular, generate complex seismic reflection patterns as a result of wavelet interference and can produce a tuning effect between closely-spaced events. The problem of resolving the top and bottom of thin reservoirs or beds and detecting subtle faults is well known in oil and gas industry ([Widess, 1973](#); [Chopra and Marfurt, 2007a](#)). Several seismic methods including broadband seismic processing and seismic inversion have been developed to try and address the problem. Unfortunately, on a fully processed seismic data, not much can be done to sharpen the wavelet and minimize the destructive interference. However, state-of-the art post-stack and migration seismic interpretation techniques, such as seismic attributes, can be used to improve the quality of the data and bring out subtle geological features from the processed data.

The aim of this study is to apply 3D seismic horizon-based and complex-trace-based seismic attributes to the migrated post-stack 3D reflection seismic data, acquired for hydrocarbon exploration in the offshore Orange Basin, to enhance the detection of structures and resolve beds that fall below the tuning thickness.

1.2. Previous Work

Several 2D and 3D dimensional reflection seismic data analyses have been conducted in the offshore Orange Basin. The presence of fluid and gas leakage features such as pockmarks, seafloor mounds, mud diapirs, gas chimneys and other seismic anomalies have been documented extensively in Blocks 2, 3 and 4 ([Ben-Avraham et al., 2002](#); [Viola et al., 2005](#); [Paton et al., 2007](#); [Boyd et al., 2009, 2011](#); [Hartwig et al., 2010](#); [Kuhlmann et al., 2011](#)). [Ben-Avraham et al. \(2002\)](#) and [Viola et al. \(2005\)](#) reported mud volcanoes in the northern Orange Basin, north-west from the current study area. The mud volcanoes strike N/NNW and align with the regional greatest horizontal stress as they are related to the onshore and offshore extensional faulting in both Namibia and South Africa ([Ben-Avraham et al., 2002](#); [Viola et al., 2005](#)).

Several researchers ([Boyd et al., 2009, 2011](#); [Hartwig et al., 2010](#); [Kuhlmann et al., 2011](#)) used 2D seismic data to investigate seismic anomalies in the Orange Basin from Blocks 1 to 4. The 113 gas chimneys identified were classified as either stratigraphically- or structurally-controlled. The stratigraphically-controlled gas chimneys are found on the pinch-outs and onlaps of Aptian successions, whilst structurally-controlled gas chimneys are located in the extensional domain, west of the shelf, and above normal faults. [Kuhlmann et al. \(2011\)](#) constructed a 3D model from 2D seismic profiles to explore the generation, migration and leakage of gas in Blocks 3 and 4, south of the current study area.

[Isiaka et al. \(2016\)](#) used 3D reflection seismic data to identify a possible ‘crater’ with a diameter of 5-7 km from the same study area. However, unlike other circular structures (pockmarks and mud volcanoes) that occur in Block 2A, the ‘crater’ is reportedly devoid of any gas. In this study area, [Berge et al. \(2002\)](#) used seismic inversion and neural networks to improve the prediction of reservoir properties across the area traversed by the AK 99 3D seismic survey. Their study also identified a fault termed ‘AK-fault’ zone, which cuts across the survey in a north west – south east (NW-SE) direction. This fault’s dimensions and its relation to the regional neotectonics of the study area has been studied by [Isiaka et al. \(2017\)](#).

1.3. Research Objectives

The subsurface of the Earth is a challenging environment since we are unable to physically behold it. The goal of this proposed research is to analyse and interpret the 3D reflection seismic data from Block 2A in the offshore Orange Basin to map the structural architecture of the area. 3D horizon-based and volume-based seismic attributes will be used to illuminate structures that cannot be mapped using conventional methods. By using 3D seismic attributes, this study aims:

1. To determine which attributes can best map the structural features in Block 2A. Software packages have numerous seismic attributes and the variety of seismic attributes described in existing literature is astounding.
2. To characterize the seismic properties of thin beds in the study area by evaluating the seismic resolution limit.
3. To enhance the geological interpretations of the structural complexities in Block 2A.
4. To identify and map the distribution of fluid-migration pathways and establish their connections to a potential hydrocarbon source horizon.
5. To confirm if there is a connection between the zone of structural and amplitude anomalies located between 2500 ms and 3000 ms, and map the potential fluid-escape features in the study area.

1.4. Study Area

The study area is located in the offshore Orange Basin, west coast of South Africa in the exploration license Block 2A. From $\sim 28^{\circ}\text{S}$ to 33°S , the shelf is 170 km – 230 km wide. The study location is 90 km from the shoreline, therefore it is assumed that it is located on the continental shelf (Ben-Avraham et al., 2002).

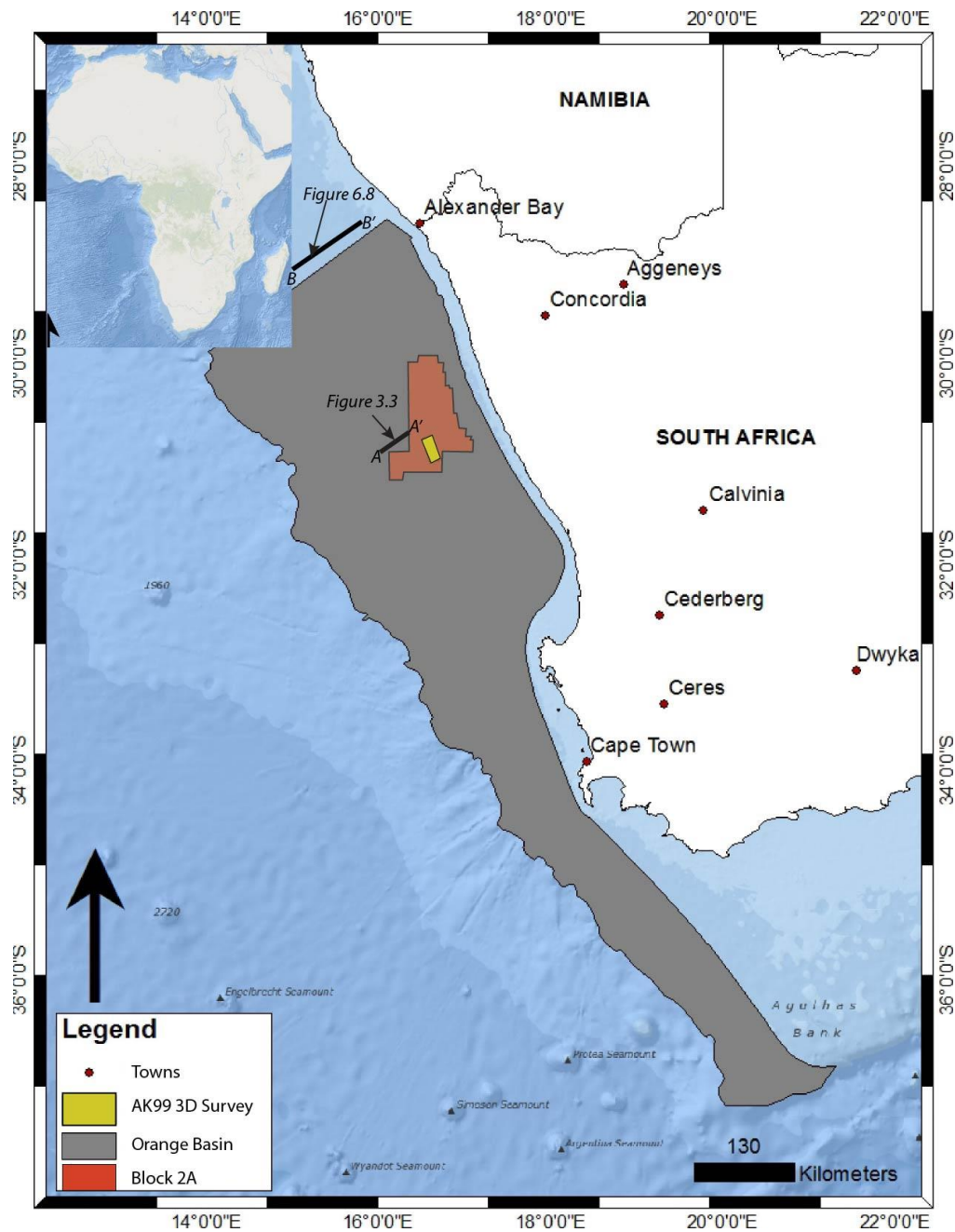


Figure 1.1: Location of the AK99 3D seismic survey in the offshore, west coast of South Africa (Esri et al., 2017). The study area is indicated by the yellow rectangle.

Block 2A covers an area of 1 500 km², while the Orange Basin covers an area of 130 000 km² down to the 2 000 m isobath. This area is under-explored since only 47 exploration wells have been drilled in the whole basin ([Petroleum Agency of SA, 2017](#)). Some of these wells led to the discovery of the Kudu gas field to the north of the Orange Basin and the Ibhubesi gas field in our study location. The Ibhubesi gas field hosts a major petroleum system located in the Cretaceous rocks of upper Barremian/lower Aptian (~125 Ma) to upper Albian/Cenomanian (~100.5 Ma) age ([de Vera et al., 2010](#)). The presence of gas in the study area was confirmed by the A-K1 well ([Jungslager, 1999; Broad et al., 2006](#)). The A-K1 well is an Albian stratigraphic-structural gas play that tested 53 million standard cubic feet per day (mmscfd) of gas and 342 barrels per day (bpd) of condensate. However, this was abandoned in 1986 after being designated a non-commercial stratigraphic trap ([Berge et al., 2002](#)).

1.5. Thesis Outline

The contents of chapters 2-7 are given below:

- Chapter 2 provides a literature review on the seismic reflection method and seismic attributes.
- Chapter 3 provides a literature review on the geology of the study area.
- Chapter 4 outlines the dataset from which this project is based and presents the methodology. Chapter 5 presents the results from: a) horizon and fault interpretation, b) structural and tectono-stratigraphic interpretation of the subsurface geology in the study area, and c) application of seismic attributes to improve the mapping of small scale geological features in the study area.
- Chapter 6 is the discussion of the results generated from this research.
- Chapter 7 presents the conclusions from the study and recommendations on future studies.

Chapter 2: Seismic Reflection and Seismic Attributes

2.1. Introduction

The main tool used in this study is the seismic reflection method, which has been used in the oil and gas industries since the 1930s. The application of the 3D seismic technique, in particular, has been advantageous to deep hydrocarbon exploration due to its high-resolution imaging of the geometry of the basin and complex geological features. The seismic reflection method is a geophysical technique which utilizes the reflection of seismic waves in order to image the Earth's interior (Yilmaz, 2001). A seismic wave is a perturbation that is dispersed through a medium, such as the Earth (Sheriff, 2002). Seismic waves can be classified as body waves (compressional (P) and shear (S) waves), boundary waves or surface waves (Rayleigh waves, ground roll, Love waves, Scholte waves, tube waves and Stonely waves), channel waves, standing waves and air waves. This study is primarily concerned with compressional (P) and shear (S) body waves (Sheriff, 2002). The reflection and refraction of the wave are determined by the physical properties of the medium of propagation. This method is discussed in detail in the following subsections.

2.2. Reflection Seismic Survey

2.2.1. Acquisition

Seismic data are acquired using acoustic source and receivers (Simm and Bacon, 2014). In marine or land settings, the method for acquiring seismic data involves generating an acoustic signal via a controlled seismic source. In marine environments, the source creates energy which propagates through the water column and into the subsurface. At geological boundaries, the seismic rays obey Snell's Law where the angle of reflection is equal to the angle of incidence and the angle of refraction or transmission is related to the angle of incidence by the velocity ratio (Herron, 2011).

The geological boundaries or interfaces may be sedimentary bedding planes, faults, conformities and unconformities, which can be marked by differences in pore fill characteristics (Veeken, 2006; Manzi et al., 2013).

The strength of the seismic reflection is dependent on the acoustic impedance (Z), which is the product of the seismic wave velocity (V), either P-wave or S-wave velocity, and the bulk density (ρ) (Simm and Bacon, 2014).

$$Z = V\rho \quad (1)$$

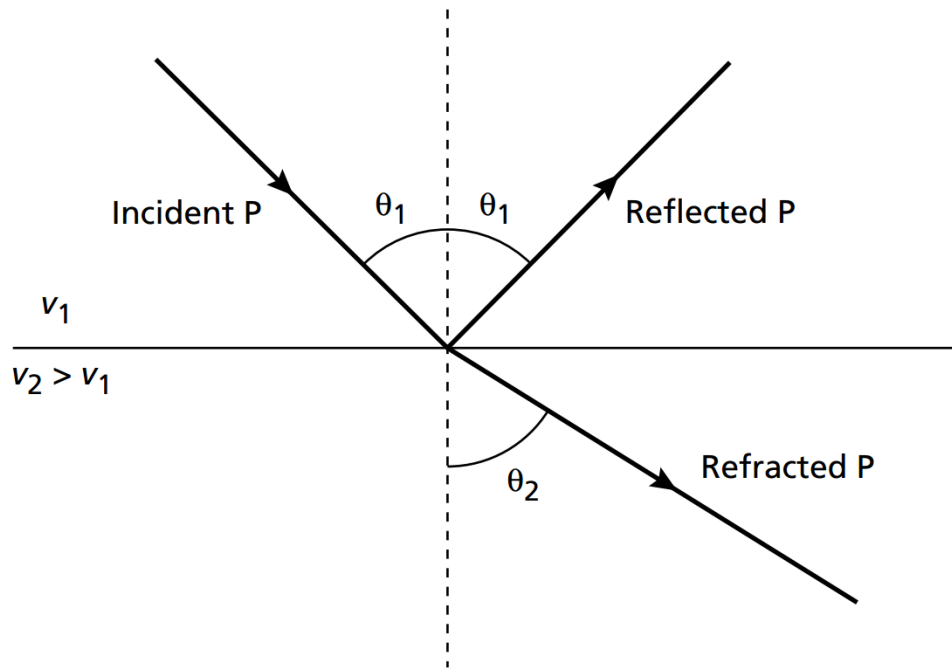


Figure 2.1: A seismic reflection arises from varying acoustic impedances across geologic boundaries. The acoustic impedance is defined as the product of the compressional wave velocity (P-wave velocity), V and the bulk density, ρ (modified after Kearey et al., 2002).

The contrast in acoustic impedance (Figure 2.1) across geological layers has an effect on the reflection coefficient, R , which determines the amplitude or strength of the seismic reflection (Sheriff, 2002; Lines and Newrick, 2004; Simm and Bacon, 2014). For normal incidence, the reflection coefficient (RC) across an interface that separates two media of densities ρ_1 and ρ_2 and velocities V_1 and V_2 is given by:

$$RC = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \quad (2)$$

Z_1 is the acoustic impedance, ρ_1 is the density and V_1 is the compressional wave velocity in medium 1; Z_2 is the acoustic impedance, ρ_2 is the density and V_2 is the compressional wave velocity in medium 2.

The reflection coefficient for seismically-mapped geological interfaces is usually between 0.2 and 0.5. Sea beds usually cause the strongest reflections in seismic sections. Reflection coefficients can be both positive and negative (Kearey et al., 2002).

In marine settings, a boat generally tows several streamers. An acoustic source such as an array of air guns may be located at the stern of the boat (Figure 2.2). Each streamer includes hydrophones attached to it, located at regular intervals (Biondi, 2006).

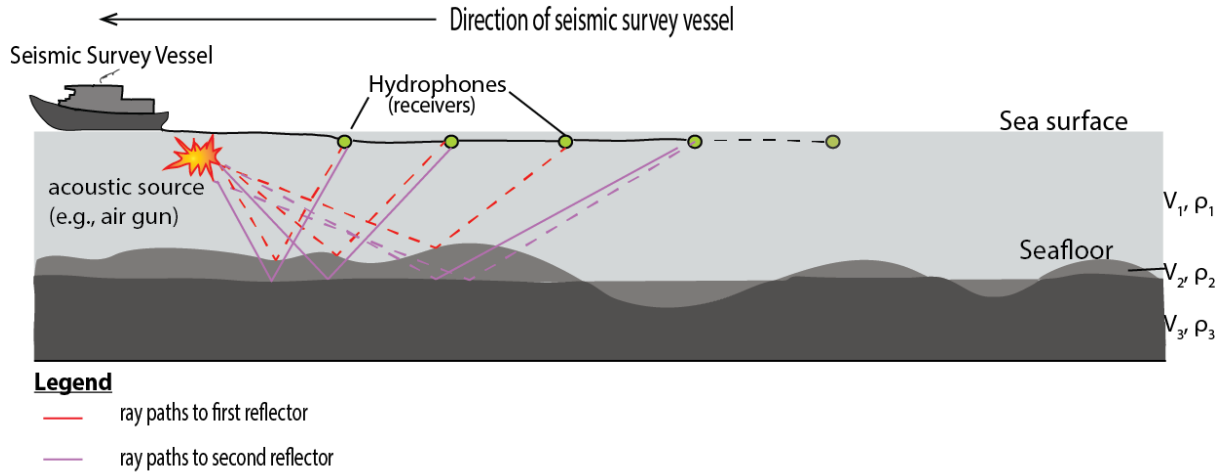


Figure 2.2: Schematic illustration of a seismic survey vessel towing hydrophones. The ray paths (in red and pink) originate via a shot from the air gun into a streamer of equally-spaced acoustic receivers (modified after Simm and Bacon, 2014).

The acoustic source (e.g., air gun) sends a wave of acoustic energy into the subsurface and the acoustic receivers (e.g., hydrophones) record response of reflected energy generated from contrasts in acoustic impedance associated with geologic boundaries (Sheriff and Geldart, 1995). The hydrophones record the subsurface response from the reflected waves at the surface via a seismogram and the outputs for each point on the subsurface are seismic traces (Sheriff, 2002; Simm and Bacon, 2014). The time that the signal takes from the acoustic source to the geologic boundary (reflector) and then back to the surface is known as the two-way-traveltime (TWT).

In March 1999, Petroleum Geo-Services Exploration (PGS) formerly known as Forest International (now Sabine Oil and Gas Corporation) shot the AK99 3D seismic survey covering the Block 2A, offshore Orange Basin. The seismic survey covers a surface area of about 380 km². The seismic acquisition parameters are summarized in [Table 2.1 \(Shaughnessy, 2003\)](#). The 3D seismic survey was acquired in an approximate northwest by southeast orientation. Map projection is UTM Zone 33S, central meridian 16°.

Seismic survey acquisition consists of 8 streamers and a dual source configuration with the sources running in flip-flop mode. The streamers are 4050 m in length and separated from each other by 100 m with 324 channels per streamer at 12.5 m spacing. The two sources were air gun arrays, buried at 6 m depth and separated by 50 m. The data have a recording length of ~ 6 s. Sample recording length is 7168 ms at a sample rate of 2 ms, yielding a Nyquist frequency of 250 Hz.

Acquisition parameters such as bin size, nominal fold, source and receiver geometry, source depths and streamer depths have an impact on seismic resolution ([Manzi et al., 2013](#); [Lee et al., 2014](#); [Table 2.1](#)). For instance, the horizontal resolution ([see section 2.3](#)) of the seismic data cannot be less than the bin size ([Cartwright and Huuse, 2005](#)).

Table 2.1: Acquisition parameters for the AK99 3D seismic survey of Block 2A (Shaughnessy, 2003).

Acquisition Parameters	
Seismic vessel	Ramform Viking
Survey area	380 km ²
<i>Source parameters</i>	
Number of source arrays	2
Array separation	50 m
Energy source	Air gun (3090 cubic inch operating at 2000 psi)
<i>Recording instrument details</i>	
Recording time length	7168 ms
Sample rate	2 ms
Recording filters	Low cut filter (3 Hz , 12 dB/octave)
	High cut filter (206 Hz, 276 dB/octave)
Digital tape format	SEGD-8036
<i>Spread geometry</i>	
Bin size	12.5 m x 12.5 m
Streamer length	4050 m
Streamer separation	100 m
Streamer depth	7.5 (±1.0) m
Number of groups/streamer	324 channels per streamer
Group interval	12.5 m

2.2.2. Processing

The aim of seismic data processing is to improve signal-to-noise ratio (S/N) and to improve the resolution of each seismic trace (Sheriff and Geldart, 1995). The data were processed by Core Laboratories Reservoir Technologies Division (Shaughnessy, 2003). The details about the acquisition parameters and processing sequence of the data are reported by Isiaka et al. (2017). Figure 2.3 presents the main steps of the processing workflow. There are many key steps that control seismic resolution in the processing of the seismic dataset. However, only deconvolution and migration are discussed in detail in this study.

2.2.1.1. Deconvolution

Deconvolution is an essential process with regard to optimizing vertical seismic resolution. In marine seismic processing, the far-field signature of the source array is recorded and then removed by deterministic deconvolution followed by predictive deconvolution (Yilmaz, 2001). Convolution is a mathematical operation that changes the shape of a wave by passing a signal through a filter (Sheriff, 2002). In one dimension, the convolution of two functions $f(t)$ and $g(t)$ is defined as by the integral:

$$g(t) * f(t) = \int_{-\infty}^{\infty} f(t) g(t - \tau) d\tau \quad (3a)$$

In two dimensions, the convolution of $f(x,y)$ and $g(x,y)$ becomes:

$$g(x,y) * f(x,y) = \int_{\alpha} \int_{\beta} g(\alpha,\beta) f(x - \alpha, y - \beta) d\alpha d\beta \quad (3b)$$

where both $g(t)$ and $g(x,y)$ are the input signal, both $f(t)$ and $f(x,y)$ are the impulse response and the asterisk,*, denotes convolution.

Deconvolution eliminates the effect of the source wavelet from the seismic trace, therefore increasing seismic resolution of the data (Yilmaz, 2001; Liner, 2016). Deconvolution in the frequency domain is represented as:

$$R(\omega) = \frac{S(\omega)}{W(\omega)} \quad (4)$$

where $W(\omega)$ is the source wavelet, $S(\omega)$ is the seismic trace, $R(\omega)$ is the Earth's reflectivity.

High frequencies and short wavelengths are essential for both vertical and lateral resolution of the data. However these high frequencies are not usually preserved at great depths because the Earth acts as a low-pass filter by selectively removing high frequencies and leaving low frequencies (Yilmaz, 2001; Sheriff, 2002; Bjørlykke, 2010; Liner, 2016). Deconvolution can improve the vertical resolution by generating a wide bandwidth of high frequencies, removing multiples and producing a compressed wavelet with a zero-phase spike (Bjørlykke, 2010).

2.2.1.2. Migration

Before migration, the lateral resolution is equal to the radius of the Fresnel zone and, in this state, the lateral variations in structures are not clear (Liner, 2016). 3D migration improves the lateral resolution by collapsing the dimensions of the radius of the Fresnel zone to one half of the wavelength ($\frac{1}{2} \lambda$), therefore making the Fresnel zone smaller (Yilmaz, 2001; Liner, 2016). On migrated seismic sections, the lateral resolution may be affected by the errors from migration aperture and velocities.

After correcting for dip move-out (DMO) and normal move-out (NMO) (Shaughnessy, 2003), as shown in Figure 2.3, the AK99 3D seismic data were then migrated using the Omega-x (f-x) algorithm (Equation 5) allowing the steep dips up to 60° with the migration frequencies set between 6 Hz and 70 Hz (Shaughnessy, 2003). When compared to other migration algorithms in the frequency domain, such as the Phase Shift Plus Interpolation (PSPI) and explicit algorithms, the Omega-x algorithm is the fastest for large 3D post-stack seismic data and can handle complex structure and large range of velocities (Farmer, 1992; Notfors, 1999). Researchers differ on its accuracy, with Notfors (1999) stating that the

Omega-x algorithm is least accurate for dips greater than 40° , while [Yilmaz \(2001\)](#) states that the Omega-x algorithm is accurate for dips equal and less than 60° . In these data, the algorithm was used for finite difference migration to image steeply dipping reflections associated with faults and fluid escape structures in the seismic data.

The Omega-x (f-x) algorithm can be defined as follows:

$$i \frac{1}{2w} \frac{\partial^3 Q}{\partial \tau \partial x^2} - \frac{\partial^2 Q}{\partial x^2} + i \frac{8w}{v^2} \frac{\partial Q}{\partial \tau} = 0 \quad (5)$$

Where τ is the time component of migration data, w is the angular temporal velocity, Q is the wavefield in the f-x domain, x and z are space variables and v is the seismic wave velocity.

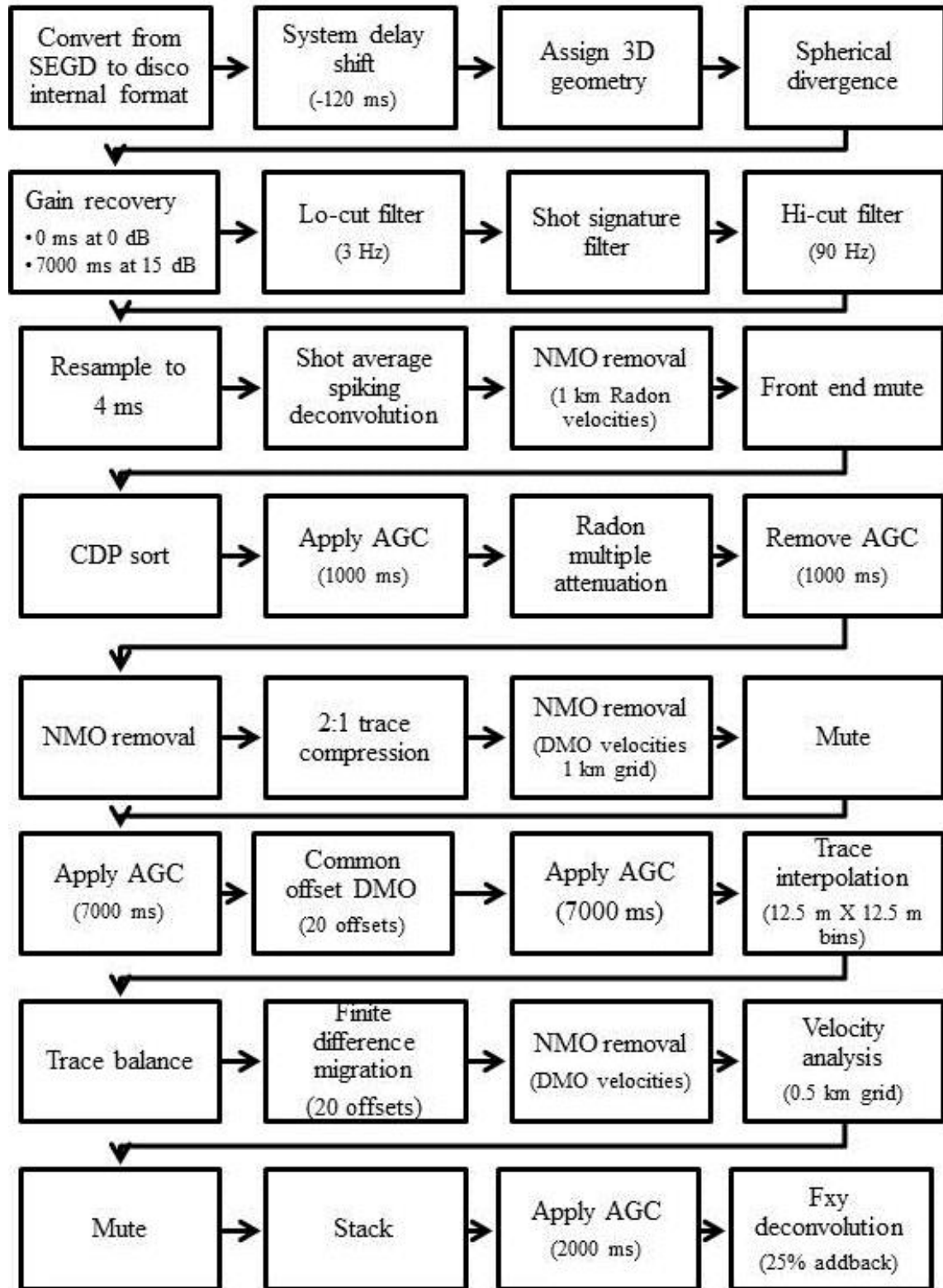


Figure 2.3: Processing flowchart for the AK99 3D seismic data (Shaughnessy, 2003).

2.2.3. Interpretation

The interpretation of seismic reflection data is based on the recognition and mapping of seismic horizons ([Dentith and Mudge, 2014](#)). The main approaches to seismic data interpretation are structural and stratigraphic analyses. ‘Structural analysis involves the study of reflector geometry based on reflection times, while stratigraphic analysis is the study of reflection sequences as the seismic expression of depositional sequences’ ([Kearey et al., 2002](#)). The current work is focused on using seismic attributes to enhance seismic resolution and enable structural interpretation of the AK99 3D seismic dataset. For structural interpretation, it is essential that the interpreter tracks horizons and faults on seismic sections and time slice displays ([Bjørlykke, 2010](#)). The method of tracking horizons is discussed in Chapter 3.

2.3. Seismic Resolution

Seismic resolution is the ability to separate two features that are very close together in seismic data (Sheriff, 2002). It comprises both vertical and horizontal seismic resolution. The definition of vertical resolution makes it possible for the ‘reflections from the top and bottom of a thin bed to be seen as separate events or wavelet lobes’. Therefore the shape of the seismic wavelet determines the vertical resolution of the seismic data (Yilmaz, 2001; Brown, 2011). The dominant wavelength is defined by the following mathematical relationship (Sheriff and Geldart, 1995; Yilmaz, 2001):

$$\lambda = \frac{v}{f} \quad (6)$$

where λ is the dominant wavelength, v is the average seismic velocity and f is the dominant frequency.

At shallow depths, the seismic response has a higher frequency, therefore a higher resolution. With depth, frequencies tend to be attenuated, therefore resolution becomes poorer (Brown, 2004). Seismic interpretation of the thin beds (i.e., layers below tuning thickness) from the seismic data is dependent on the limits of the vertical seismic resolution, which is defined by the quarter of the dominant wavelength, $\frac{1}{4}\lambda$ or tuning thickness (Widess, 1973; Kallweit and Wood, 1982). Below the tuning thickness individual beds are not resolved, and a seismic reflection is not generated from the top and base of a bed (Yilmaz, 2001). Vertical resolution is also essential in the imaging and interpretation of structural features (faults, pockmarks, gas chimneys, etc.).

The AK99 3D seismic data are characterized by a seismic wavelet with the dominant peak frequency of 100 Hz (Isiaka et al., 2017). The mean P-wave velocity of 3040 m/s has been determined from the data processing (Shaughnessy, 2003). Using the parameters above, the dominant wavelength and the vertical resolution limit are ~30 m and ~8 m, respectively. This means that maximum constructive interference (the tuning effect) occurs at $\frac{1}{4}\lambda$, 8 m, which is defined as the tuning thickness.

Horizontal resolution is the ability to distinguish one feature from another horizontally (Sheriff, 2002). Horizontal resolution is determined by the size of the first Fresnel zone, which is the subsurface area where constructive interference occurs at a reflection point (Sheriff, 2002). Migration improves horizontal resolution by collapsing the Fresnel zone, thus the Fresnel zone becomes narrower (Yilmaz, 2001; Sheriff and Geldart, 1995; Brown, 2004). As stated earlier, the data from the Orange Basin were migrated using finite difference Omega-x (f-x) algorithm (Shaughnessy, 2003). Post migration, the mathematical relation for calculating the radius of the Fresnel zone (r) is determined by Equation 7:

$$r = \left(\frac{v}{2}\right)\left(\sqrt{\frac{t}{f}}\right) \quad (7)$$

where r is the Fresnel zone radius, t is the two-way-traveltime (TWT), v is the average velocity and f is the dominant frequency (Yilmaz, 2001).

The Fresnel zone depends on the position of the source and receiver, depth, dip and curvature of the reflector, frequency and seismic velocity (Yilmaz, 2001). The Fresnel zone increases with depth as lateral resolution decreases. Two points within the Fresnel zone are not resolvable. At higher frequencies, the area of Fresnel zone is narrower and it is easier to differentiate between two reflecting zones than at lower frequencies, where the area of the Fresnel zone is wider. Therefore, the width of a shallow fault zone is easily resolved compared to the width of a deeper fault zone.

On 3D migrated seismic data, the horizontal resolution is approximately the dominant wavelength, which is 30 m for this study. Therefore, features with spacing much less than the Fresnel zone cannot be resolved.

2.4. Seismic Attributes: An Introduction

The algorithms emerging for seismic data processing and interpretation are suitable for enhancing the resolution of seismic data. Seismic attributes enable a comprehensive analysis of structural and stratigraphic characteristics of seismic data. Therefore, it is fitting that seismic attributes are used to aid the interpretation of structures and stratigraphic complexities.

The Cambridge Dictionary defines an attribute as ‘a quantity or characteristic that someone or something has’ (Good, 2008). Therefore, attributes are sub-classes of the entire information found in the original data set (Barnes, 2006). To relate this definition to seismic attributes, a seismic attribute can be viewed as that quantity or characteristic which can be extracted from the seismic data. As further defined by Brown (1996) and Sheriff (2002), a seismic attribute is ‘a measurement derived from seismic data, usually based on measurements of time, amplitude, frequency, and/or attenuation.’

Seismic attributes enhance and quantify stratigraphic and structural geological features of interest (Chopra and Marfurt, 2007a), which is the focus of this research. There are numerous seismic attributes that have been described in the literature, which have been sorted by several authors into various categories (Chopra and Marfurt, 2005). One such classification is that of Brown (1996) who organizes attributes into classes of time, amplitude and frequency (Figure 2.4). The measurements of time relate to structure; while amplitude and frequency-based measurements relate to stratigraphy and reservoir characterization (Sheriff, 2002).

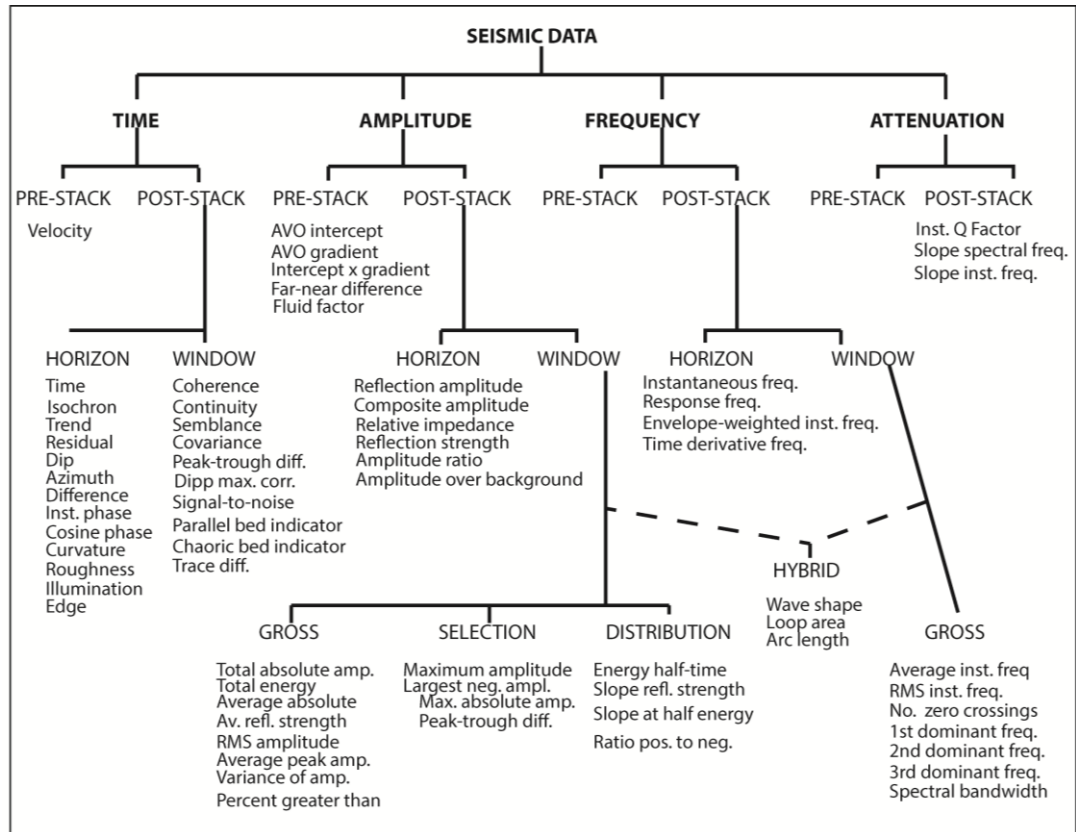


Figure 2.4: Classification of seismic attributes into categories of time, amplitude, frequency and attenuation (Brown, 2004).

2.5. History of Seismic Attributes

Seismic attribute use is directly related to the advancement in technology (Chopra and Marfurt, 2005). In the 1930s, geophysicists began using travel times in seismic reflection studies. The 1960s saw the dawn of digital recording, which led to the link between hydrocarbon bright spots and strong amplitudes in seismic data (Chopra and Marfurt, 2005). During the 1970s, there was a development in the hardware and software capabilities of computers. For example, in 1971 A.H Balch developed a computer-graphic-photographic system called the color sonogram and published the first paper to appear in color in the Geophysics journal (Chopra and Marfurt, 2005).

The first personal computer with color graphics was released by Apple in 1977, thereby enabling color displays of seismic data (Ceruzzi, 2003; O'Regan, 2008). Thereafter other models from IBM followed suit and adopted color displays on monitors. The color displays made possible the identification of variations in characteristics such as frequency, phase, reflection strength and interval velocity (Chopra and Marfurt, 2005). By the mid-1980s, the 2D seismic attributes came into use to assist in stratigraphic interpretation. 3D seismic attributes came into use from the 1990s onwards, extending the applications of seismic attribute interpretation to exploitation and reservoir characterization (Chopra and Marfurt, 2005).

2.6. Complex Trace Attributes

Complex trace attributes are computed from the complex trace. The term ‘complex’ is used in the mathematical sense, meaning a number that contains both a real and an imaginary part. The seismic data are handled as analytic traces that contain the real seismic trace, $x(t)$, and the imaginary component, $y(t)$, which is the Hilbert transform of $x(t)$ (Taner et al., 1979). In Figure 2.5, the real and imaginary seismic traces are displayed in 3D space (x, y, t) where x is the real plane, y is the imaginary plane and t is the time. The real seismic trace, $x(t)$, is on the real plane, x , and the imaginary seismic trace, $y(t)$, is on the imaginary plane, y . A vector addition of $x(t)$ and $y(t)$ produces the complex seismic trace, $z(t)$, which is shown as a helix curled about the time axis, t (Taner et al., 1979):

$$z(t) = x(t) + iy(t) \quad (8)$$

$$z(t) = x(t) + (i/\pi) * \int (s(\tau)/t-\tau) dt$$

$$z(t) = a(t)e^{i2\pi\phi(t)}$$

where i is the square root of -1 .

The imaginary seismic trace, $y(t)$, is the Hilbert transform of the real seismic trace, $x(t)$:

$$y(t) = x(t) * 1/\pi t$$

$$y(t) = 1/\pi \int (x(\tau)/t-\tau) dt$$

By using the Hilbert transform, a value of amplitude, phase and frequency may be calculated instantaneously for each time sample of a seismic trace (Taner et al., 1979; Taner, 2001). The derivatives of instantaneous attributes are used for structural characterization in this study.

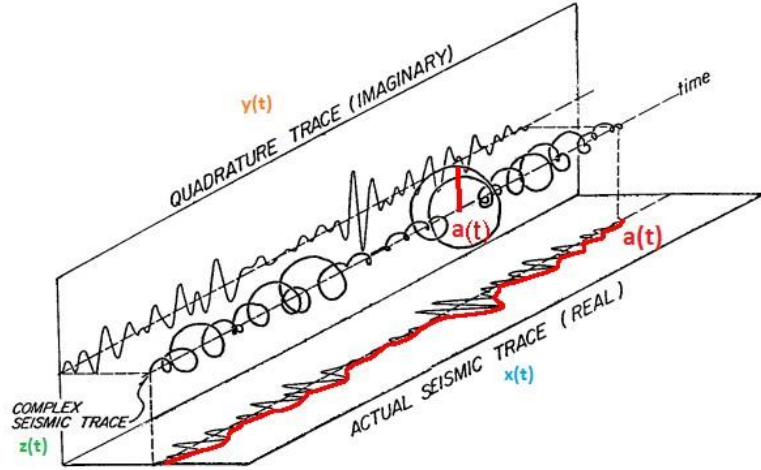


Figure 2.5: The complex seismic trace consists of the actual (real) trace ($x(t)$) and the quadrature (imaginary) trace ($y(t)$). The quadrature trace is calculated from the real trace by applying the Hilbert Transform (modified after Taner et al., 1979).

2.6.1. Instantaneous Amplitude

The instantaneous amplitude, $a(t)$, is the envelope of a seismic signal, which is calculated from the complex trace (Taner et al., 1979; Subrahmanyam and Rao, 2008). At any point on the time axis, t , a vector, $a(t)$, can be calculated in a plane perpendicular to the time (t) (Figure 2.6). The length of this vector is the amplitude of the complex trace and is known as the instantaneous amplitude, $a(t)$. The equation for the instantaneous amplitude is generated by taking then square root of the sum of the real seismic trace, $x(t)$, and the imaginary seismic trace, $y(t)$. This mathematical relationship is shown as:

$$a(t) = [x^2(t) + y^2(t)]^{\frac{1}{2}} \quad (9)$$

The instantaneous amplitude is sometimes referred to as the reflection strength or the (E) of the seismic signal (due to the instantaneous amplitude outlining the envelope of the seismic trace) (Taner et al., 1979; Subrahmanyam and Rao, 2008). The envelope is related to the changes in the energy of the seismic trace, revealing lateral changes in amplitude and hence acoustic impedance contrast. This sensitivity to interference makes the envelope an effective indicator of thin beds and illuminator of discontinuities in seismic data interpretation (Taner, 2001).

2.6.2. Instantaneous Phase

The instantaneous phase is the angle, $\varnothing(t)$, which defines where vector $a(t)$ is pointing at the seismic phase at time, t . This angle is between the actual seismic trace, $x(t)$, and the Hilbert transform, $y(t)$. The instantaneous phase section displays the phase of a waveform at a time corresponding to the peak, trough or zero-crossing (Nanda, 2016). The phase is calculated as the arctangent of the ratio of the imaginary seismic trace, $y(t)$, to the real seismic trace, $x(t)$. The equation is given by:

$$\varnothing(t) = \tan^{-1}(y(t)/x(t)) \quad (10)$$

The phase is independent of amplitude and relates to the propagation of the seismic wave front. Wave fronts are lines of constant phase; therefore the instantaneous phase is a physical attribute that is suitable for mapping lateral continuity or discontinuity of events in seismic data (Taner, 2001; Subrahmanyam and Rao, 2008).

2.6.3. Instantaneous Frequency

The instantaneous frequency is the rate of change of phase over time. It can be thought of as the frequency of the complex sinusoid that locally fits a seismic trace (Taner et al., 1979; Sheriff, 2002). The instantaneous frequency is the time derivative of the instantaneous phase (Taner et al., 1979).

Mathematically, the instantaneous frequency is defined as follows:

$$\omega(t) = d[\varnothing(t)]/dt \quad (11)$$

Instantaneous frequency is a physical attribute that is sensitive to the bed thickness. For example, instantaneous frequency values increase as the bed thickness decreases and they remain high even as the bed thickness falls below the quarter dominant wavelength limit, a phenomenon known as ‘frequency tuning’ (Robertson and Nogami, 1984). Low values for instantaneous frequencies indicate thicker beds.

2.7. Horizon Attributes

Dip and dip-azimuth are horizon-based attributes that highlight stratigraphic and structural features with offsets less than a seismic wavelet. The dip-magnitude and dip-azimuth are, respectively, the size and direction of the time vector, calculated sample by sample on picked horizons (Rijks and Jauffred, 1991; Manzi et al., 2013; Equations 12 and 13). The dip attribute is time derived and indicates variations in the dip on a seismic horizon or time slice (Brown, 2004). When calculating dip, a plane is fitted through neighboring data points and the calculated values are posted to the position of the central trace (Figure 2.6). The dip value can be expressed in degrees, radians, or milliseconds per meter (Rijks and Jauffred, 1991).

Mathematically, the dip and dip-azimuth are expressed by equations 13 and 14:

$$\text{Dip-magnitude} = \sqrt{\left(\frac{dt}{dx}\right)^2 + \left(\frac{dt}{dy}\right)^2} \quad (12)$$

$$\text{Dip-azimuth} = \tan^{-1} \left(\frac{dt}{dx} \right) / \left(\frac{dt}{dy} \right) \quad (13)$$

The dip and dip-azimuth, like many seismic attributes, have their detection limits. The dip can only detect a fault if its dip angle is considerably different from that of the horizon, while the dip-azimuth can only detect a fault whose fault plane direction is opposite to that of the horizon (Manzi et al., 2013).

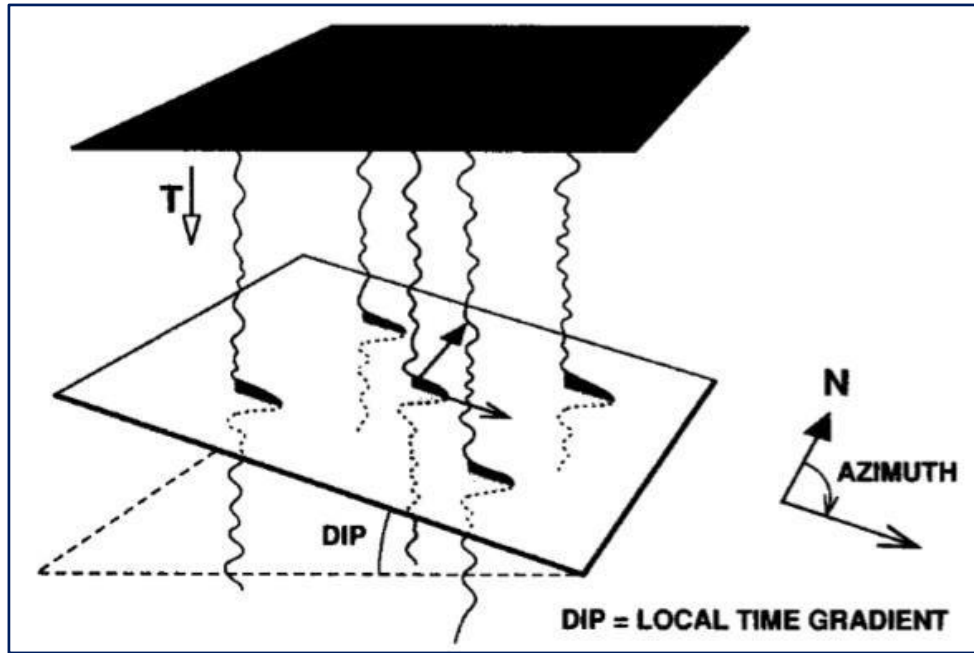


Figure 2.6: Calculation of the dip and-azimuth attributes. The dip and dip-azimuth are the size of the local time gradient vector at a grid-point on a picked horizon (Rijks and Jauffred, 1991).

2.8. Volumetric Attributes

Volumetric attributes are seismic attributes computed from the seismic volume. They include volumetric estimates of dip and azimuth, variance, chaos and ant-tracking (Pedersen et al., 2002; Chopra and Marfurt, 2007b). Variance, chaos and ant-tracking are computed as volumetric seismic attributes for this study.

2.8.1. Variance

Variance is an edge detection attribute that is opposite to the coherence attribute. Mathematically, variance is expressed as one minus the coherence value (Taner, 2001). Variance calculates the variability between traces while coherence measures the similarity between traces (Taner, 2001; Chopra and Marfurt, 2007b). Variance measures the changes in acoustic impedance. Discontinuities such as faults and fractures tend to have high changes in acoustic impedance, therefore variance attributes are useful in imaging these structures (Chopra and Marfurt, 2006).

2.8.2. Chaos

The chaos attribute enhances the detection of discontinuities in seismic data by estimating the lack of organisation in the estimation of dip or azimuth (Randen and Sonnenland, 2005). By computing the dip and azimuth via Principal Component Analysis (PCA), three eigenvectors $\vec{v}_1$ values exist for each C-matrix, which are all associated with an eigenvalue (λ_i). For a good estimation of chaos, the eigenvalue has to be large for the three eigenvectors to compute the dip and azimuth. The chaos is defined by:

$$J = \frac{2\lambda_2}{\lambda_1 + \lambda_3} - 1 \quad (14)$$

Where J is chaos, λ_1 , λ_2 and λ_3 are eigenvalues that are related to $\vec{v}_1$, $\vec{v}_2$ and $\vec{v}_3$ eigenvectors of the C-matrix (Randen and Sonnenland, 2005).

2.8.3. Ant-tracking

Ant-tracking is an attribute developed by Schlumberger Stavanger Research for fault and fracture interpretation. The algorithm uses swarm intelligence technology to emulate the behavior of ants (Pedersen et al., 2002, 2005). Swarm intelligence is a term describing the social behavior of ants (Pedersen et al., 2002). Ants use pheromones to find the shortest path from their nests to their source of food (Figure 2.7). The shortest path has more pheromones when compared to the longest path, therefore the ants will follow the shortest path, which is the easiest path to find food (Pedersen et al., 2002).

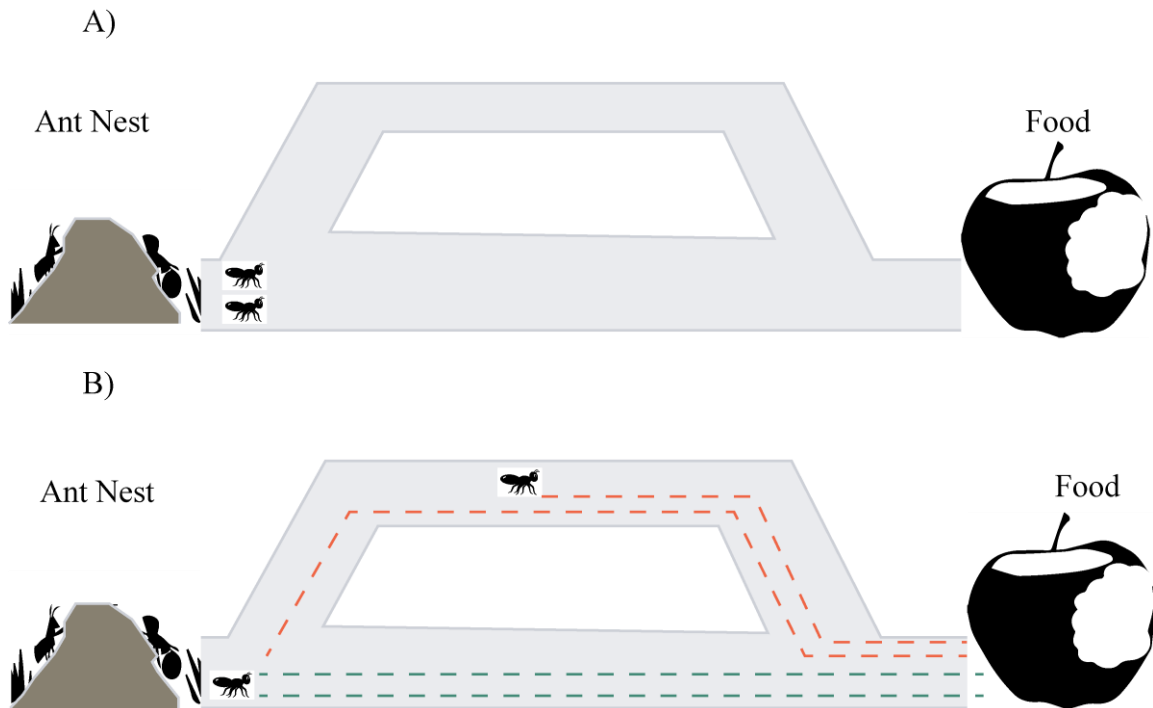


Figure 2.7: Schematic illustration showing the paths two ants may use to find food. A) Diagram shows the two ants at the starting point before they forage; B) The ant that chooses the shortest path (green dashed line) will have the shorter path to its food than the ant which chooses the longer path (orange dashed line) (modified after Pedersen et al., 2002).

Ant-tracking uses virtual ants which are deployed through a seismic volume to detect faults and fractures by using the following workflow:

1. Preparation of the seismic data via structural smoothing and filtering (to reduce the noise in the data);
2. Generation of an edge detection volume of variance or coherence;
3. Calculation of the ant-tracking volume using the variance or chaos volume as input.

The ant-tracking workflow is discussed in Chapter 4.

Chapter 3: Geology

3.1. Background

The Orange Basin is a volcanic-rifted passive margin, offshore south-western coast of South Africa. It covers an area of 145 000 km², from the coast to the 2 000 m isobath (Brown et al., 1995). The basin is bounded to the south by the Agulhas-Falkland Fracture Zone and to the north by the Walvis Ridge (Gerrard and Smith, 1982; Boyd et al., 2011).

3.2. Orange Basin Development

The Orange Basin is an extensional sedimentary sub-basin, the largest of the south-west African depocentres (Brown et al., 1995; Jungslager, 1999). The development of the Orange Basin is associated with lithospheric extension, Gondwana break-up (136 Ma-126 Ma), rifting of the American and African plates from the middle to the late Jurassic and subsequent drifting (Muntingh and Brown, 1993; Brown et al., 1995; Boyd et al., 2011). Coevally, the rifting formed a passive margin along the west coast of Africa in which the Orange Basin developed (Kuhlmann et al., 2011).

At the end of the Paleozoic era (~251 Ma), the current southern African subcontinent was bounded to the east by Antarctica, to the south by the Falkland Plateau and to the west by the South American continent (Figure 3.1). The break-up of the Gondwana supercontinent was initiated by the eruption of Karoo magmas occurring around 180 Ma for at least 5 Ma (Duncan et al., 1997). From 180 Ma to 175 Ma, the supercontinent experiencing rifting, however it did not split (Watkeys, 2006). From 175 Ma to 155 Ma, a north-south zone of rifting developed resulting in the trans-tensional rotation of the Falkland Islands (Marshall, 1994; Watkeys, 2006). This movement was made possible by extension along the Gastre Fault (GF) and the Agulhas-Falkland Fracture Zone (AFFZ) (Marshall, 1994; Watkeys, 2002, 2006).

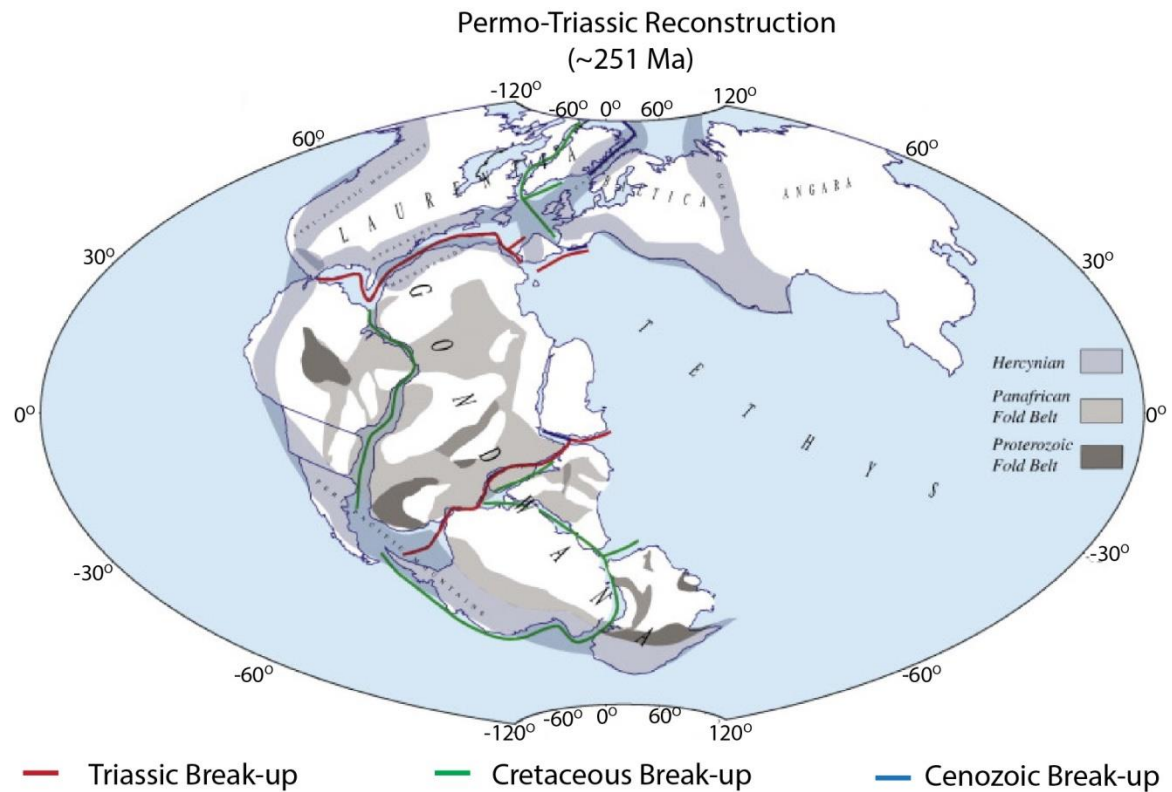


Figure 3.1: Plate reconstruction of the Gondwana supercontinent at the end of the Paleozoic (~251 Ma) modified from the reconstruction by [Moulin et al. \(2010\)](#).

From 155 Ma to 135 Ma, there was a dextral strike slip movement along the Davie Fracture Zone (DFZ), presently located to the north of Mozambique and offshore Tanzania ([Martin and Hartnady, 1986](#)). The DFZ is regional and was connected to the GF-AFFZ system and Gondwana via the Weddell Sea and the Mozambique Basin ([Watkeys, 2002, 2006](#)). The movement along the DFZ caused the parting of the Gondwana supercontinent along the GF-AFFZ into two subcontinents, East Gondwana (Antarctica, Australia, New Zealand, Madagascar and India) and West Gondwana (Africa, Arabia and South America), along with the development of the Orange and Walvis Basins ([Watkeys, 2002; Watkeys, 2006; Figure 3.2](#)). At 137 Ma, the Tristan da Cunha plume positioned itself under the Parana Basin in South America, forming the Parana Continental Flood Basalts (CFBs). Thereafter Gondwana moved westward over the plume, until it was positioned under an earlier rift, inducing sea floor spreading and forming the Etendeka CFBs ([Watkeys, 2002, 2006](#)). Between 115 Ma and 90 Ma, there was a triple junction jump to the southern Agulhas Plateau whose continental crust was intruded by basaltic magmas at ~93 Ma ([Tucholke et al., 1981](#)). The break between the African and South American crusts created full linkage of the Atlantic Ocean ([Fairhead, 1988](#)).

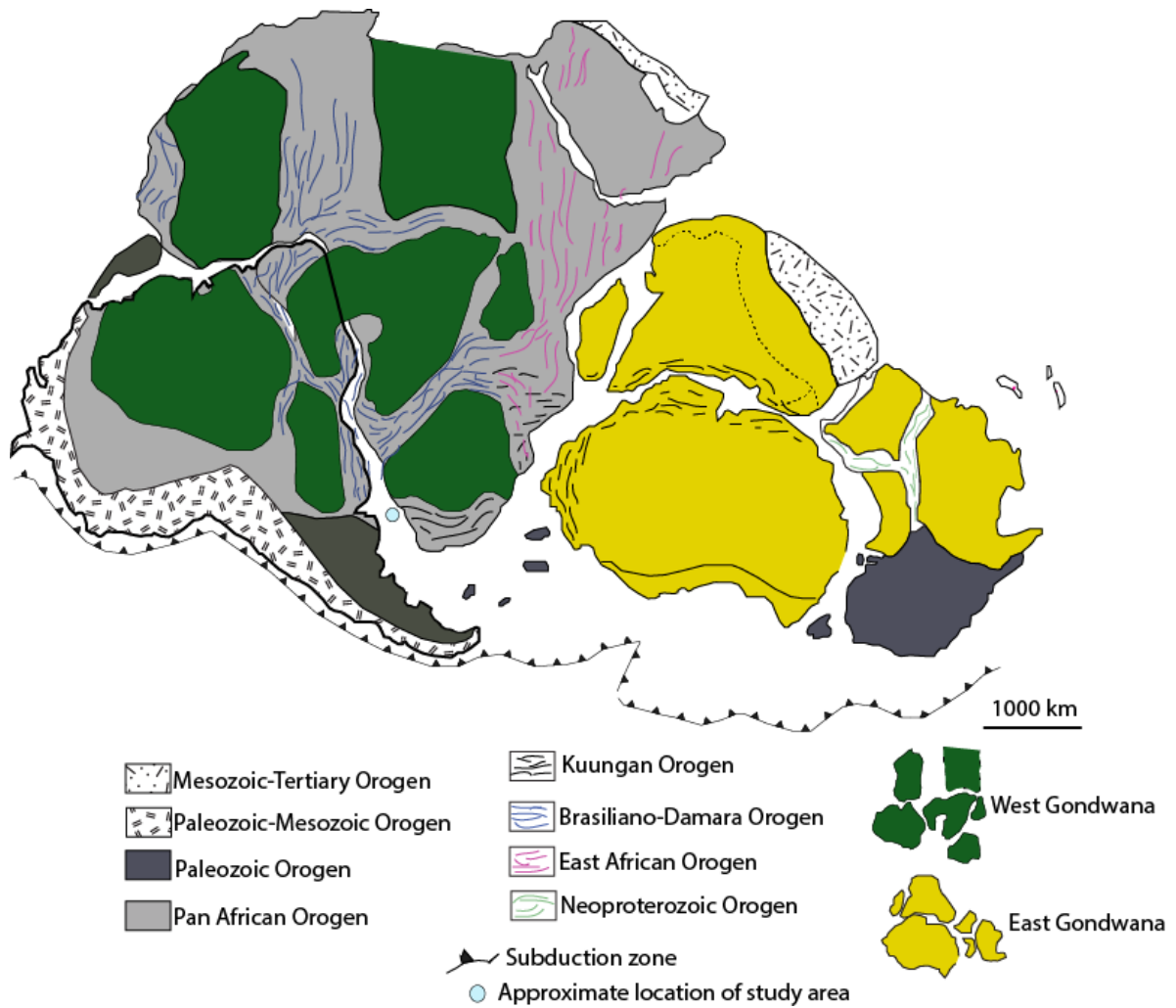


Figure 3.2: Plate reconstruction of West Gondwana (shaded green) and East Gondwana (shaded yellow) based on Gondwana reconstruction by [Gray et al. \(2008\)](#) and modified after [Meert and Lieberman \(2008\)](#). The approximate location of the current study is outlined by a light blue circle.

3.3. Tectono-stratigraphic and Structural Framework

Sediments in the Orange Basin have been transported by the Orange and Olifant River systems from the Mesozoic to present day (De Vera et al., 2010). Major deltaic depocenters are located at both river mouths signifying that they both were sediment providers to the Orange Basin (Dingle and Hendry, 1984). The sedimentary succession is a classic example of a rift-drift passive margin sequence recording the break-up of Gondwana and opening of the South Atlantic Ocean (Gerrard and Smith, 1982; Muntingh and Brown, 1993; Paton et al., 2007; Boyd et al., 2011). An 8 km thick succession of tectono-stratigraphic sequences preserves the phases of sedimentation in the basin, namely, the syn-rift, rift-drift, drift and post-drift phases (Jungslager, 1999; Boyd et al., 2011; Figures 3.3 and 3.4). Within these tectono-stratigraphic phases are super-sequences confined by second-order type 1 unconformities identified based on their acoustic impedances. The unconformities identified are: 6At1, 13At1, 14At1, 15At1, 17At1 and 22At1 (21At1+ 21Bt1+22At1) (Brown et al., 1995; Figures 3.3 and 3.4). Both super-sequences and unconformities will be referred to in the latter chapters of this study.

3.3.1. Syn-Rift

Horizon T is the rift onset unconformity which rests on basement rocks (Gerrard and Smith, 1982; Muntingh, 1993; Figure 3.4). Syn-rift deposits overlie horizon T. They comprise isolated rift grabens and half grabens trending parallel to the present shoreline and separated by major continental transcurrent faults, which correlate with oceanic fracture zones (Gerrard and Smith, 1982; Broad et al., 2006). The grabens and half grabens formed due to an extensional stress regime caused by lithospheric stretching from the Middle to the Late Jurassic (Gerrard and Smith, 1982). Muntingh (1993) divides the graben zone into an inner graben and a central syn-rift wedge.

The sedimentary fill of the inner graben consists of Late Jurassic and Lower Cretaceous coarse-grained continental clastics, fluvial or lacustrine sequences and volcanic deposits; while the central syn-rift wedge is filled with fluvial and lacustrine rocks deposited with alkaline and basic lavas (Muntingh, 1993; Jungslager, 1999). The central syn-rift wedge rests on seaward dipping reflectors (SDRs) that are interpreted to be subaerial basaltic lava flows related to rifting (Menzies, 2002; Séranne and Anka, 2005). The termination of active rifting is marked by the Hauterivian or drift onset unconformity (6At1, 117.5 Ma) (Muntingh, 1993; Jungslager, 1999; Figure 3.4).

3.3.2. Rift-Drift

The post-rift sequences comprise a rift-drift phase, characterised by continental fluvial red beds and marine deltaic deposits. The sediments were deposited in a transitional period between rifting continental conditions and drifting proto-oceanic conditions, thus the shift in sedimentation (Muntingh, 1993; Figure 3.4). The 6At1 unconformity seals the diverging syn-rift seismic reflectors from the overlying sub-parallel aggradational and slightly progradational reflectors (Brown et al., 1995; Séranne and Anka, 2005). The geometry of the seismic reflectors suggests that there was a low sea level rise accompanied by basin tectonic subsidence (Brown et al., 1995). The rift-drift phase occurs between the unconformities dated mid-Hauterivian (6At1, 117.5 Ma) and the mid-Aptian (13At1, 112 Ma), which correspond to Super-sequence 12 (Brown et al., 1995; Jungslager, 1999; Boyd et al., 2011; Figure 3.4).

3.3.3. Drift

The initiation of the drift phase occurred at 117.5 Ma and is marked by the mid-Aptian, 13At1 unconformity (Figure 3.4). The drift successions comprise a seaward and landward thinning sedimentary wedge of continental red beds to restricted marine sediments deposited under alternating fluvial and marine dominated environments responding to alternating regressive and transgressive cycles (Muntingh, 1993; Jungslager, 1999; Figure 3.4).

The drift successions, with a maximum thickness of 7700 m, comprise of different super-sequences: 13 (112-103Ma), 14 (103-93Ma), 15-16 (93-80Ma) and 17-20 (80-67Ma) (Muntingh, 1993; Brown et al., 1995; Figure 3.4).

Super-sequence 13 is confined by the 13At1 and 14At1 unconformities and is characterized by a period of initial uplift, sea level fall, transgression and subsequent sea floor spreading along the Atlantic Mid Oceanic Ridge. These processes caused regional drowning and rigorous subaerial and submarine erosion of the 13At1 unconformity on which the Lower Aptian source rock was deposited (Muntingh, 1993; Brown et al., 1995; Figure 3.4).

Super-sequence 14 is confined by unconformities 14At1, 15At1 and 16At1. Super-sequence 14 is characterized by a period of initial uplift, relative sea level fall, transgression, regional drowning and moderate erosion of the 14At1 unconformity. Progradational and aggradational sequences are found between 15At1 and 16At1 (Brown et al., 1995; Figure 3.4).

A period of sea level fall, transgression, regional flooding and moderate erosion of the 15At1 unconformity caused aggradational sequences to be deposited in Super-sequence 15-16, which is bound by 15At1 and 17At1 (Brown et al., 1995; Figure 3.4). Super-sequence 17-20 is characterized by gravity faulting, major uplift and regional drowning of the 22At1 unconformity where aggradational sequences were deposited mostly basinward between 17At1 and 22At1 (Brown et al., 1995; Figure 3.4). The 22At1 unconformity marks the end of Cretaceous deposition and is overlain by Cenozoic successions.

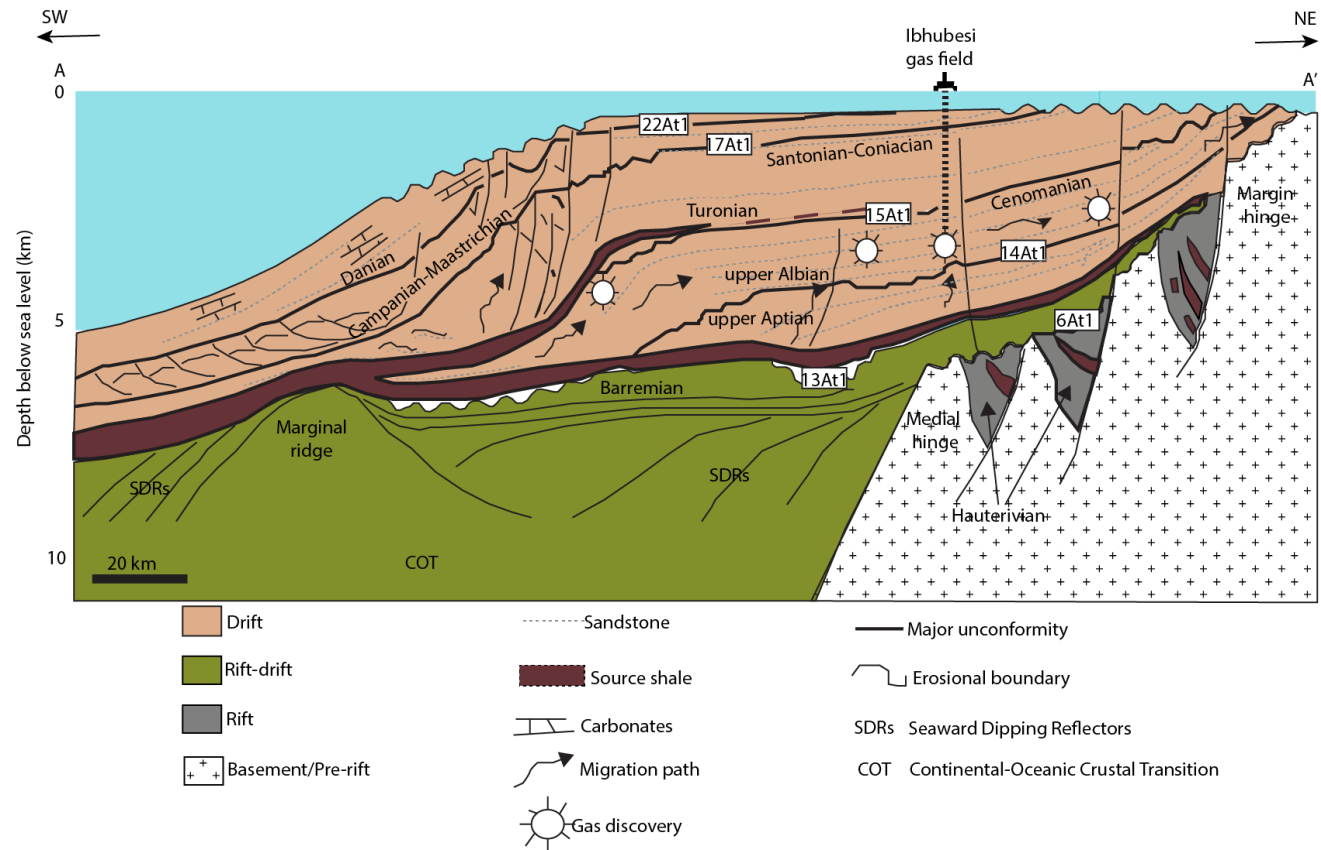


Figure 3.3: Generalized stratigraphic cross section through the Orange Basin, offshore South Africa. The cross-section shows the main hydrocarbon plays including the Ibhubesi gas field of Block 2A from which the 3D seismic data for this study have been obtained. Also indicated are the main tectono-stratigraphic phases, i.e., syn-rift, transitional (rift-drift) and the drift phases. The major unconformities indicated are the 6At1 (Hauterivian unconformity), 13At1 (Albian unconformity), 14At1 (Albian unconformity), 15At1 (Cenomanian unconformity), 17At1 (Maastrichtian unconformity) and the 22At1 (Paleogene unconformity) (Brown et al., 1995). See Figure 1.1 for approximate location of A-A' (modified after Jungslager, 1999; Van der Spuy, 2003).

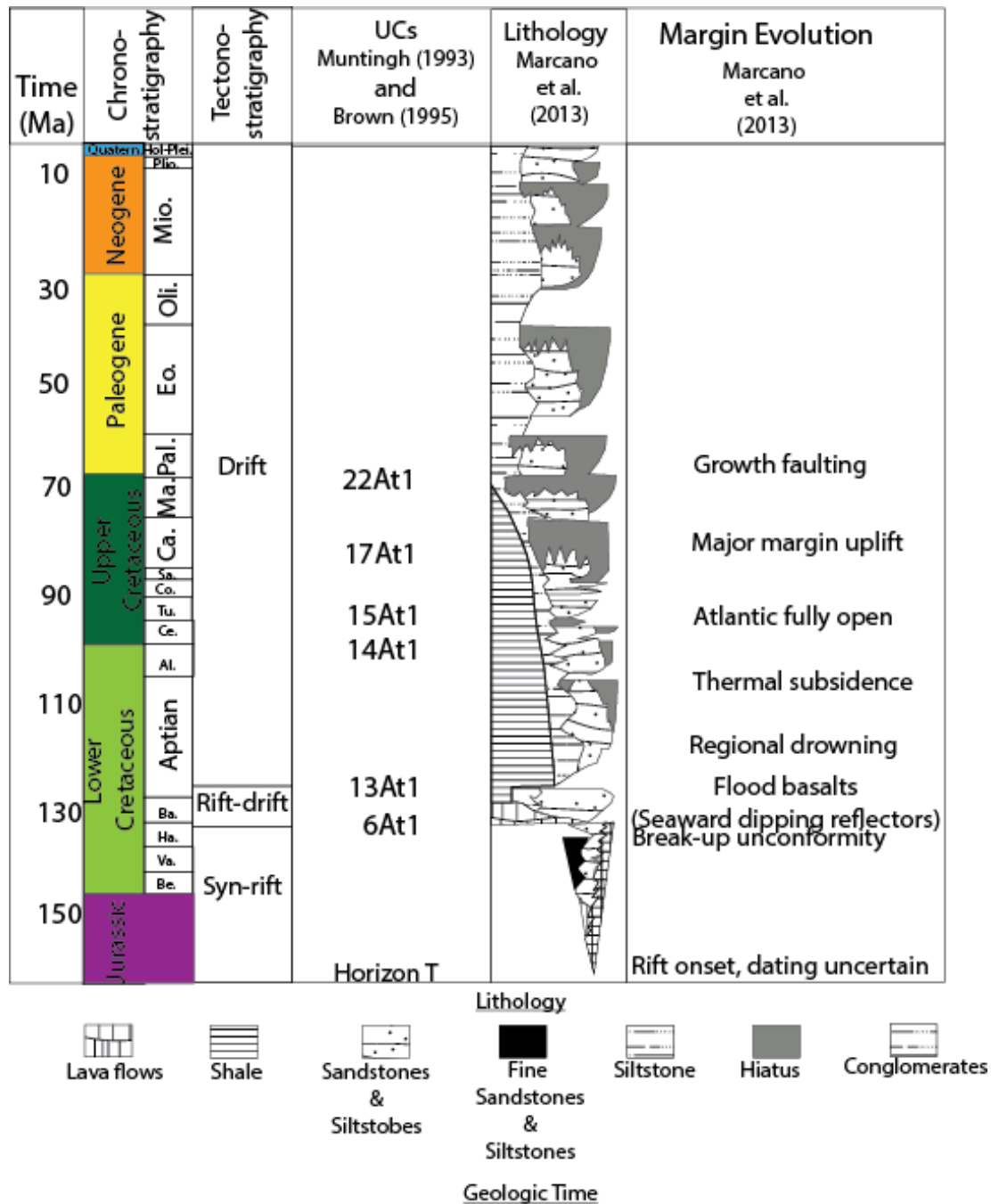


Figure 3.4: Orange Basin tectono-stratigraphy including unconformities (Muntingh, 1993; Brown et al., 1995), the timescale (Haq et al., 1987), lithology and basin tectonic evolution (Marcano et al., 2013). The Orange Basin tectono-stratigraphy is related to the phases of the margin tectonic evolution occurring within preserved major unconformities (UCs). Hol-Plei. = Holocene-Pleistocene, Plio. = Pliocene, Mio. = Miocene, Oli. = Oligocene, Eo. = Eocene, Pal. = Paleocene, Ma. = Maastrichtian, Ca. = Campanian, Sa. = Santonian, Co. = Coniacian, Tu. = Turonian, Ce. = Cenomanian, Al. = Albian, Ap. = Aptian, Ba. = Barremian, Ha. = Hauterivian, Va. = Valangian, Be. = Berriasian.

4. 3D Seismic Data and Methodology

4.1. Data

In 1999, 3D reflection seismic data were acquired by PGS Exploration in the west coast, offshore of South Africa within Block 2A of the Ibhubesi gas field. The data were processed by Core Laboratories' Reservoir Technologies Division (RTD). The original 3D seismic data are 1500 km² in area with 12.5 m by 12.5 m bin size and 1019 inlines and 2350 crosslines. The fully processed 3D Seismic data were provided by Petroleum Agency SA. The polygon was created within the 3D seismic survey boundary to form the study area for this research (Figure 4.1). The seismic volume successfully imaged stratigraphic units from the seafloor to ~ 6000 ms (Figure 4.2) with an area of 308 km². The survey was designed to image the target of interest (gas reservoir) between 2500 and 3000 ms (TWT).

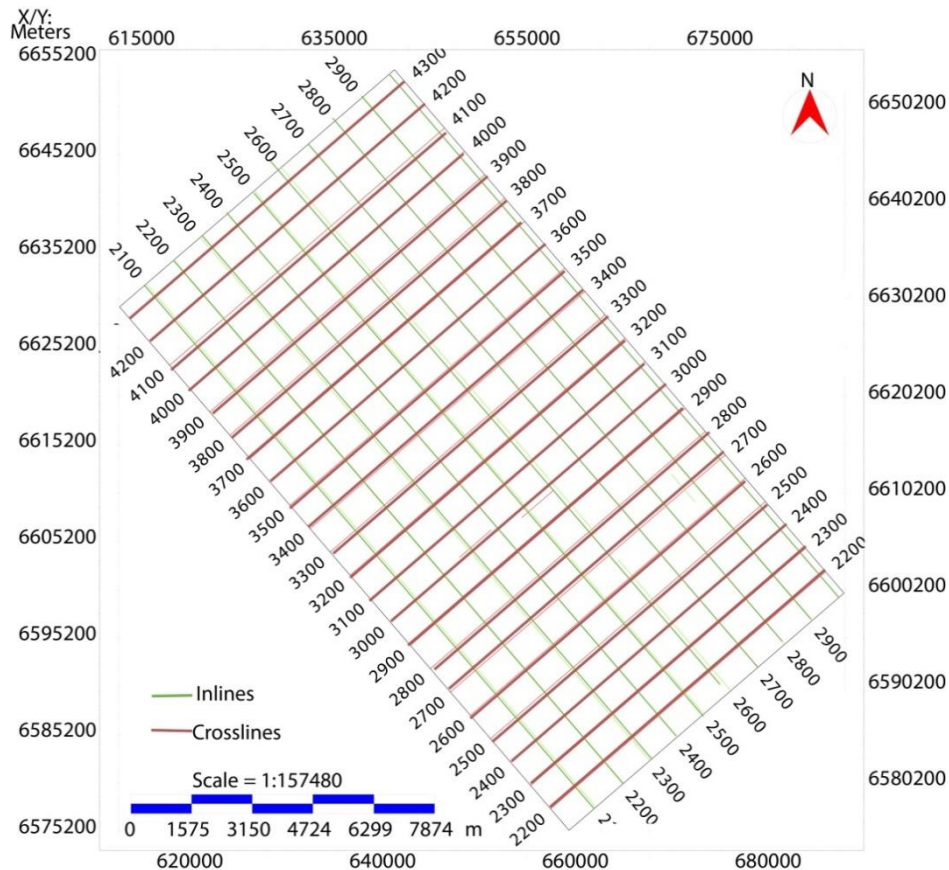


Figure 4.1: Extracted polygon of the 3D seismic survey with inlines outlined in red and crosslines in green. The polygon has an area of 308 km².

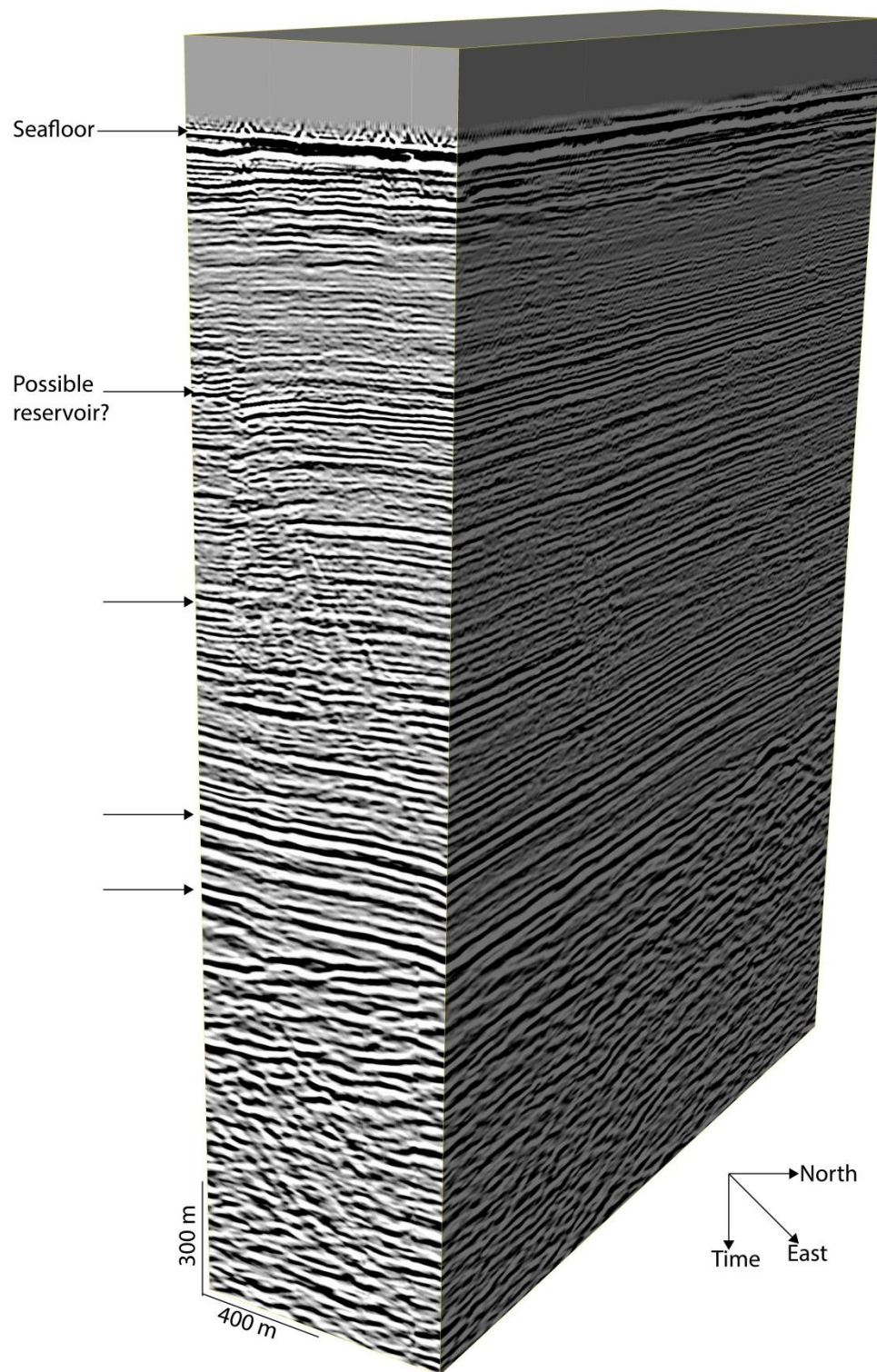


Figure 4.2: Extracted seismic volume from the full 3D seismic volume indicating some of the strong reflections (black arrows). The strong reflections include the seafloor and gas reservoir.

4.2. Methodology

Interpretation of the seismic data was done in IHS Kingdom suite (known as Kingdom) and Schlumberger's Petrel (known as Petrel). Firstly, a project was created in Kingdom with the specific coordinate reference system related to the study area. The 3D seismic data (in SEG-Y format) were then loaded into the Kingdom software and a polygon was created for the chosen working area. The horizons and faults were picked along the inlines, crosslines and time slices which were then imported into Petrel for further structural and seismic attribute analysis. The workflow for the project is summarized in [Figure 4.3](#).

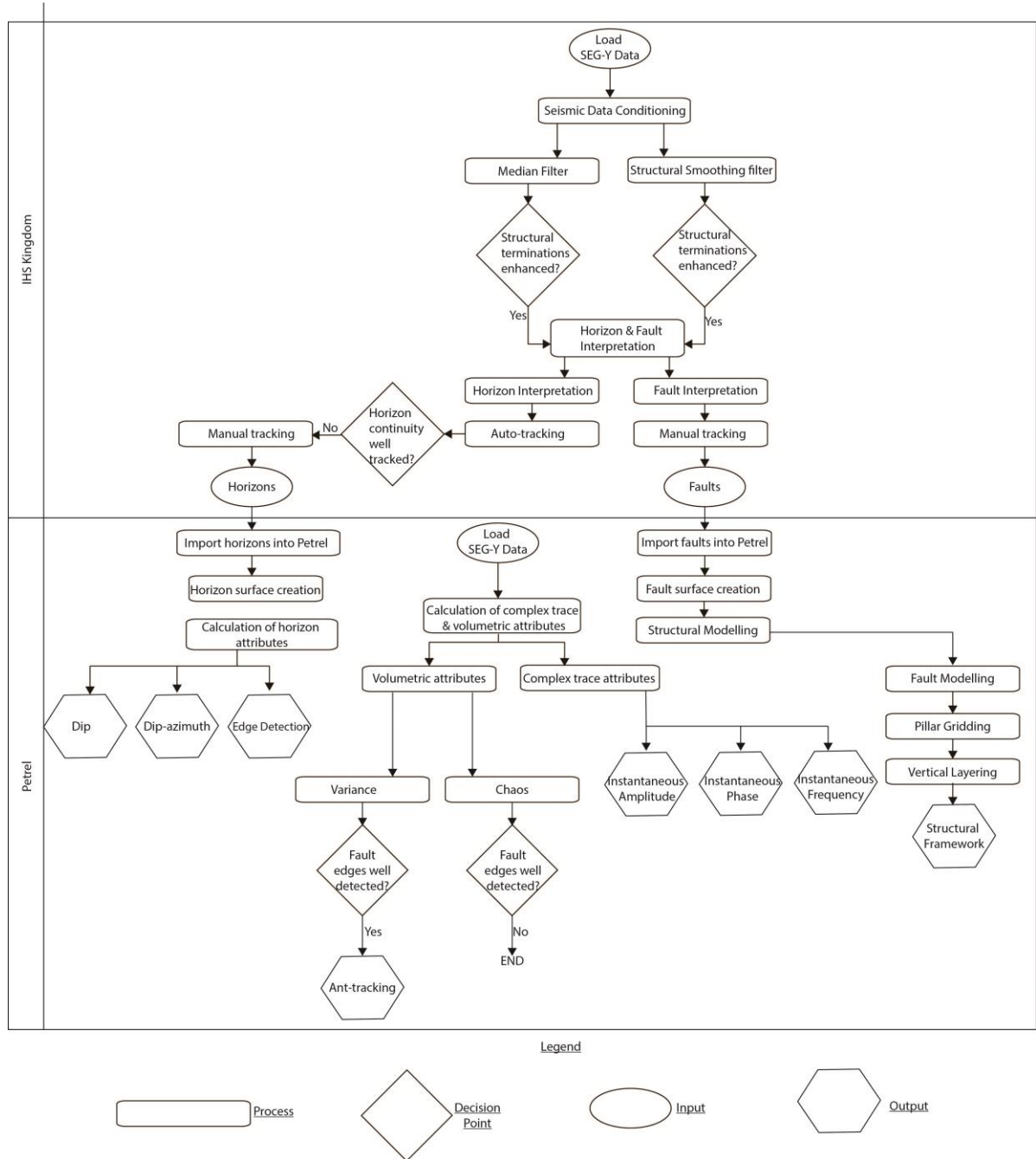


Figure 4.3: Seismic attribute and structural interpretation workflow.

4.3. Horizon and Fault Interpretation

Seismic horizon and fault tracking is an essential process for seismic interpretation. For the Block 2A 3D seismic data, five horizons were identified and interpreted using the IHS Kingdom. Manual tracking and auto-tracking were used in this study. Firstly, auto-tracking was performed to get a first pass regional interpretation of the horizon. Thereafter, manual tracking of horizons and faults was performed in areas with low signal-to-noise ratio (S/N) and complex structure. In seismic data, faults appear as discontinuities along which horizons may be displaced. The faults and horizons were picked for every single crossline and inline and later exported to Petrel software for seismic attributes analyses and modeling.

The study area is characterized by sandstones, shales, siltstones, claystones and volcanic rocks (Hirsch et al., 2007). Assuming that the study area is characterised by layered lithologies, each layer being homogeneous and horizontal, the rock velocities determined from the published work of (Press, 1966) were assumed to be interval velocities. Subsequently, the depths of the picked horizons (Appendix: Time to depth conversion) and regional unconformities were calculated and corroborated by the work of (Brown et al., 1995). Tectono-stratigraphic units were used to delineate unconformities based on their seismic amplitude character. Six unconformities (6At1, 13At1, 14At1, 15At1, 17At1 and 22At1) were identified on seismic data in three tectono-stratigraphic units corresponding to the syn-rift, post-rift (rift-drift transitional phase) and the drift phase (Figure 4.5). The horizons picked on the 3D seismic data include the seafloor (H1), H2, H3, H4 and H5. The H2, H3, H4 and H5 horizons are located at the interfaces associated with 17At1, 14At1, 13At1 and 6At1 unconformities, respectively.

For the processed seismic data, the minimum phase wavelet starts with a ‘down-kick’; therefore it is a trough at zero time (Sheriff, 2002; Figure 4.4). According to SEG convention, negative standard polarity in data arises when there is an increase in impedance is represented by a trough, while a decrease in impedance is represented by a peak. For example, there is an increase in acoustic impedance from a relatively lower velocity, lower density of water ($V_p = 1550$ m/s, $\rho = 1030$ kg/m³) to a relatively higher velocity, higher density rocks on the seafloor

($V_p = 1800\text{m/s}$, $\rho = 1700\text{ kg/m}^3$) (Sheriff and Geldart, 1995; Press, 1966; Cox et al., 1999; Hirsch et al., 2007; Figure 4.5; Figure 4.6; Table 4.1).

Therefore, the seafloor in these data, located at 300 ms, is represented by a strong trough because of the negative standard polarity at this interface (Figure 4.4; Table 4.1). The negative standard polarity can also be referred to as European polarity (Brown, 2004, 2001, 2011). This type of polarity is commonly used in hydrocarbon provinces around the world such as the North Sea (Sheriff, 2002).

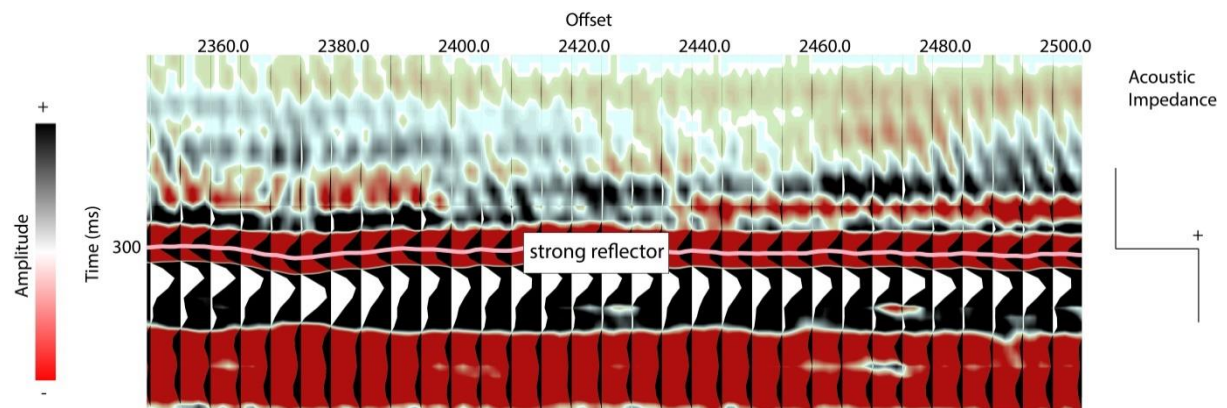


Figure 4.4: The SEG convention adopted for this dataset is negative standard polarity, which implies that an increase in acoustic impedance represents negative amplitude, the trough (red), while a decrease in acoustic impedance represents positive amplitude, the peak (black). The seafloor, H1, is therefore represented by trough. Color bar indicates seismic amplitude.

Table 4.1: Picked horizons and unconformities (UC) configured from Brown et al. (1995).

UC	Depth (m)	Corresponding Horizon	Lithology (V (m/s), ρ (kg/m ³))	RC
Seabed	225	H1	Water: V = 1500, ρ = 1030	0.31
			Unconsolidated sand: V = 1800, ρ = 1700	
17At1	1225	H2	Claystones: V = 2000, ρ = 1800	0.23
			Sandstone: V = 2500, ρ = 2300	
14At1	2655	H3	Silty sandstone: V = 2700, ρ = 2520	0.07
			Sandstone: V = 3000, ρ = 2600	
13At1	3955	H4	Sandstone: V = 3500, ρ = 2600	0.07
			Sandstone: V = 4000, ρ = 2610	
6At1	4555	H5	Sandstone: V = 4000, ρ = 2610	0.18
			Basalt: V = 5000, ρ = 3000	

The 17At1 unconformity (UC) is seismically defined by a distinct positive acoustic impedance contrast between interbedded claystones ($V_p = 2000$ m/s, $\rho = 1800$ kg/m³) and sandstones ($V_p = 2500$ m/s, $\rho = 2300$ kg/m³) of Campanian age (Press, 1966; Hirsch et al., 2007; Figures 4.5; Figure 4.6; Table 4.1).

The 14At1 unconformity is a relatively poor seismic reflector due to low impedance contrast between the Cenomanian silty sandstones ($V_p = 2700$ m/s, $\rho = 2520$ kg/m³) and Albian sandstones ($V_p = 3000$ m/s, $\rho = 2600$ kg/m³) (Press, 1966; Cox et al., 1999; Hirsch et al., 2007; Figure 4.5; Figure 4.6; Table 4.1). The mid-Aptian unconformity, 13At1, also occurs at the interface where there is low acoustic impedance contrast from the overlying sandstones ($V_p = 3500$ m/s, $\rho = 2600$ kg/m³) to the underlying sandstones of Aptian age ($V_p = 4000$ m/s, $\rho = 2610$ kg/m³) (Press, 1966; Cox et al., 1999; Hirsch et al., 2007; Figure 4.5; Figure 4.6; Table 4.1). The 6At1 unconformity is a relatively strong reflector because it occurs at the interface between the overlying sandstones ($V_p = 4000$ m/s, $\rho = 2610$ kg/m³) and the basalts ($V_p = 5000$ m/s, $\rho = 3000$ kg/m³) of the of the mid-Hauterivian (Press, 1966; Cox et al., 1999; Hirsch et al., 2007; Figure 4.5; Figure 4.6; Table 4.1). The velocities and densities used in the study were determined from laboratory measurements of various dry and saturated media.

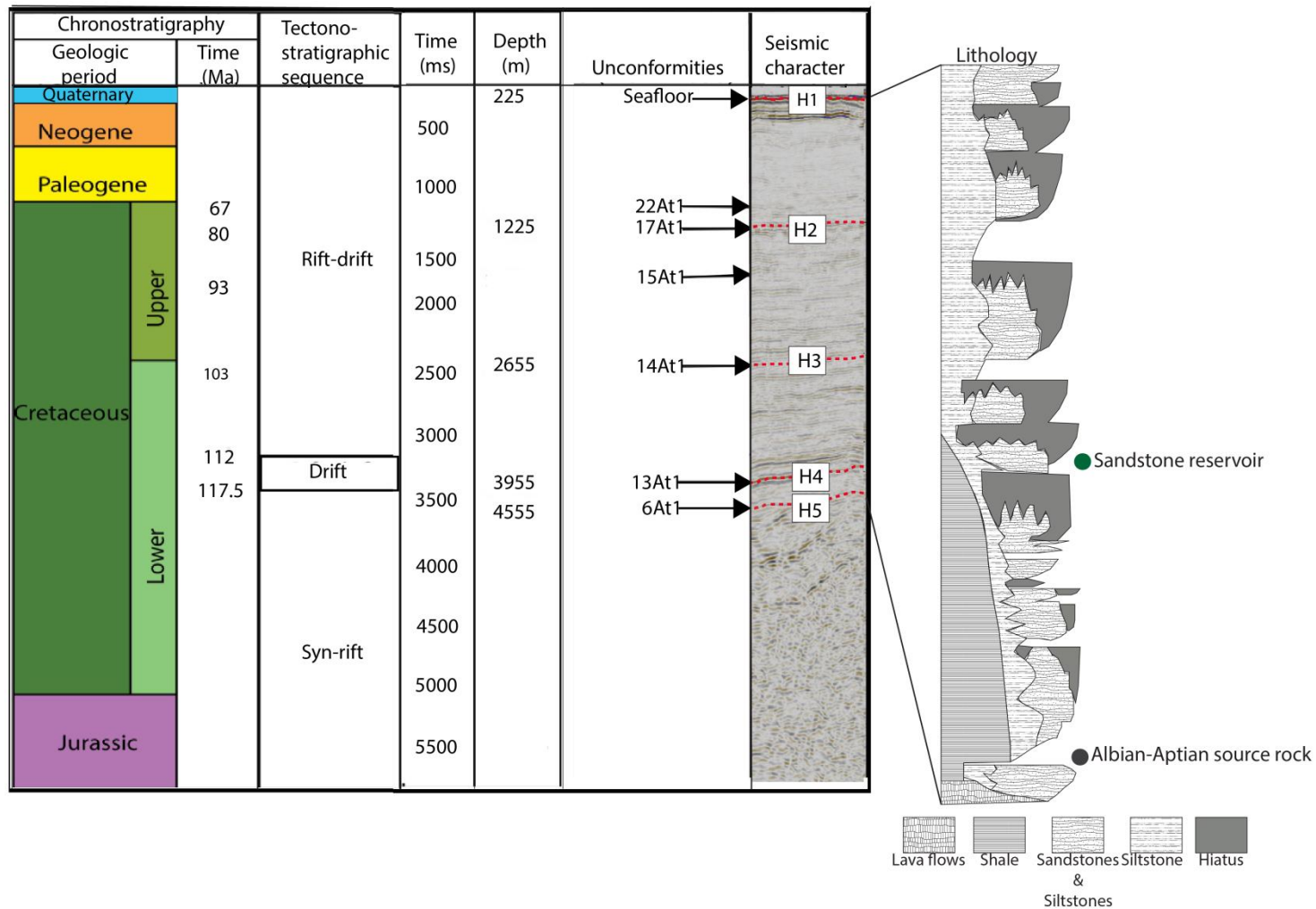


Figure 4.5: Chronostratigraphy (Haq et al., 1987), tectono-stratigraphy (Brown et al., 1995), unconformities (Muntingh, 1993; Brown et al., 1995), lithology (Brown et al., 1995), reflection seismic data and lithology (Marcano et al., 2013).

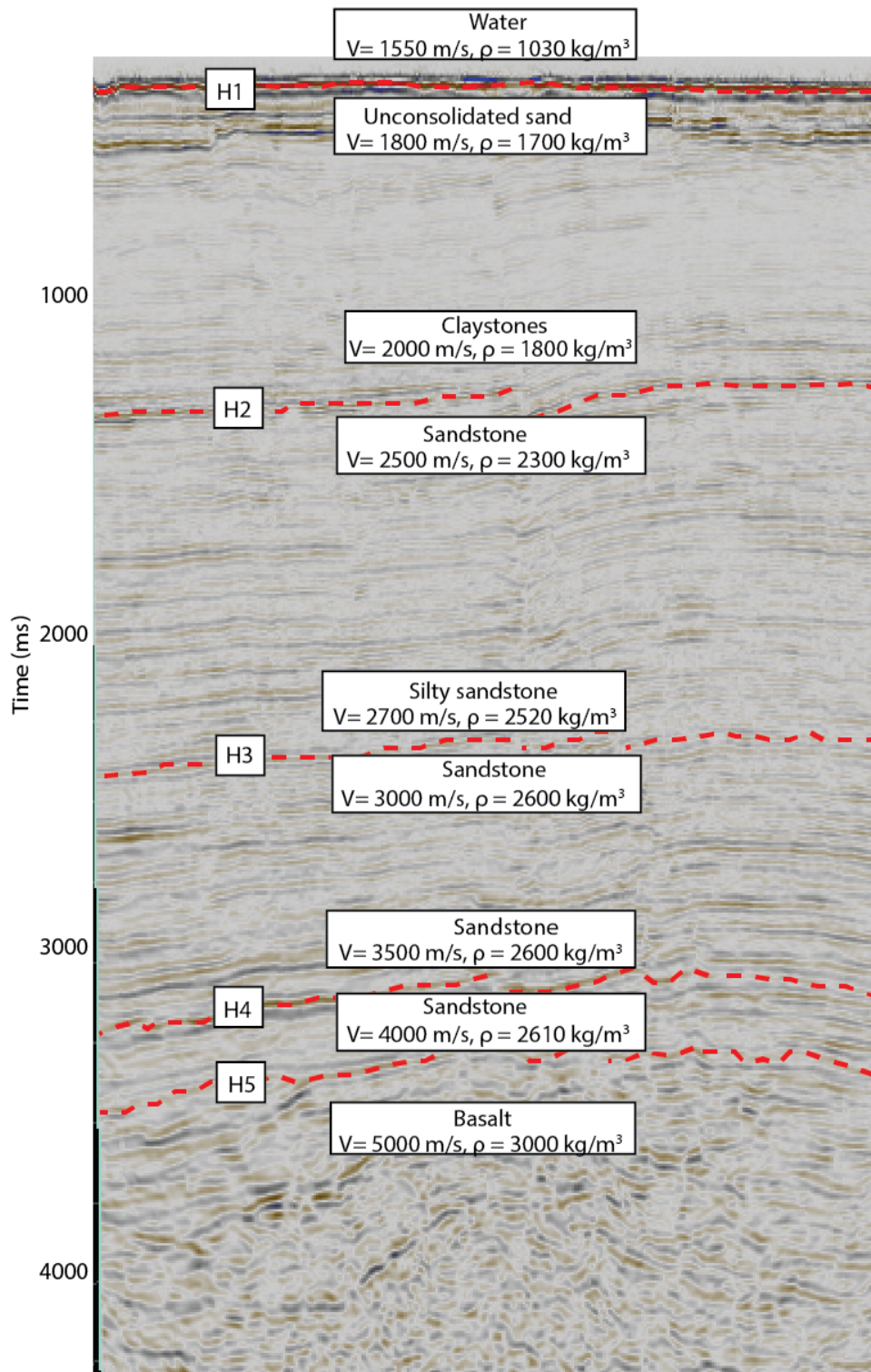


Figure 4.6: Unconformities (Brown et al., 1995) correlated to horizons (H1, H2, H3, H4, H5) and their respective velocities and densities. The unconformities are imaged as strong reflections by the seismic method if there is a significant acoustic impedance contrast between the overlying and underlying stratigraphic packages.

4.4. Seismic Conditioning

Seismic conditioning involves the application of filters to the data to reduce the noise related to both acquisition and processing of the data. Seismic conditioning therefore improves the signal-to-noise ratio (S/N). Examples of noise in the data are artefacts related to seismic acquisition imprint and processing errors. If the artefacts are not eliminated from the data, they could lead to misleading interpretation (Sheriff, 2002). Figure 4.7a shows an example of a horizon map, highlighting artefacts as a linear grid pattern parallel to the seismic acquisition direction.

The horizons were gridded using a flex gridding algorithm to remove the artefacts. Figure 4.7b is the gridded horizon, showing an improved quality of the data after gridding. Gridding parameters were fixed to a combination of minimum curvature of 0, midway smoothness of 6 and grid cell sizes of 12.5 by 12.5 m. Setting the grid cell size to the bin spacing eliminates the influence of cell averaging; therefore there exists only 1 datum per cell. Following the smoothing or gridding of the seismic horizons using mean and median filters, surfaces were created from each horizon.

The mean and median filters are structurally oriented filters which remove random noise and enhance lateral continuity (Chopra and Mafurt, 2007a). Figure 4.8a is an example of a surface before smoothing. Figure 4.8b is the smoothed surface after applying a combination of the mean and median filters, showing an improved quality of the data after surface smoothing.

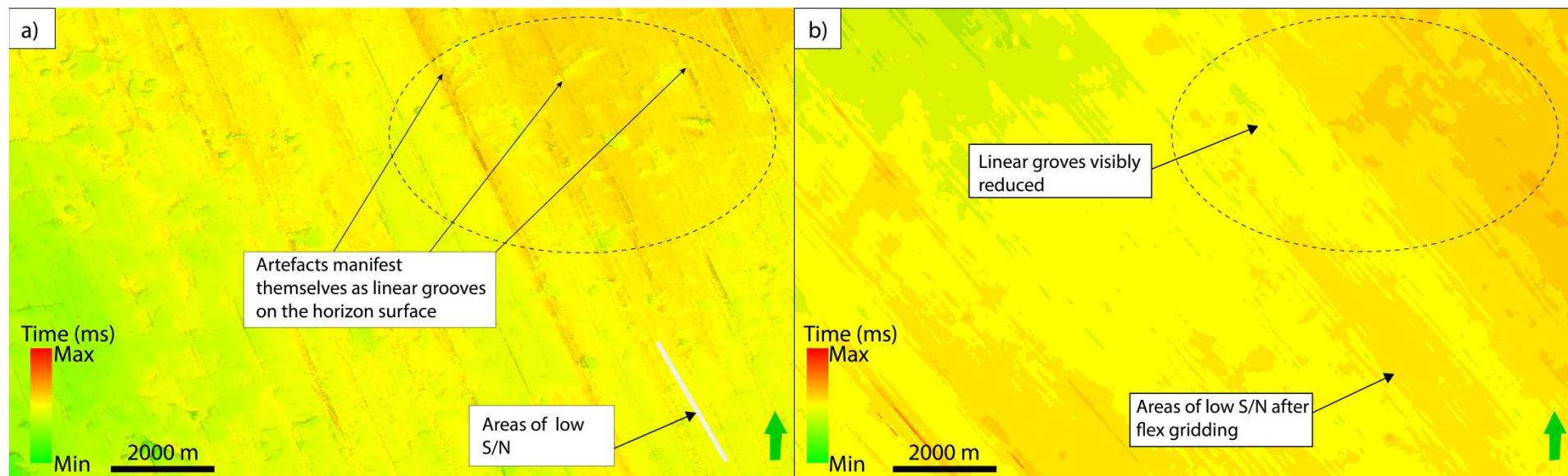


Figure 4.7: Horizons showing the application of a flex gridding algorithm to seismic data. a) Seismic acquisition or processing imprints (artefacts) contaminate the horizon surface. Artefacts can be seen as a series of linear grooves on the seabed parallel to the seismic data acquisition direction. The flex gridding algorithm increases S/N ratio by extrapolating across inlines and crosslines where horizon picking was skipped and reduces the visibility of artefacts in b). Color bar indicates two-way-traveltime (TWT).

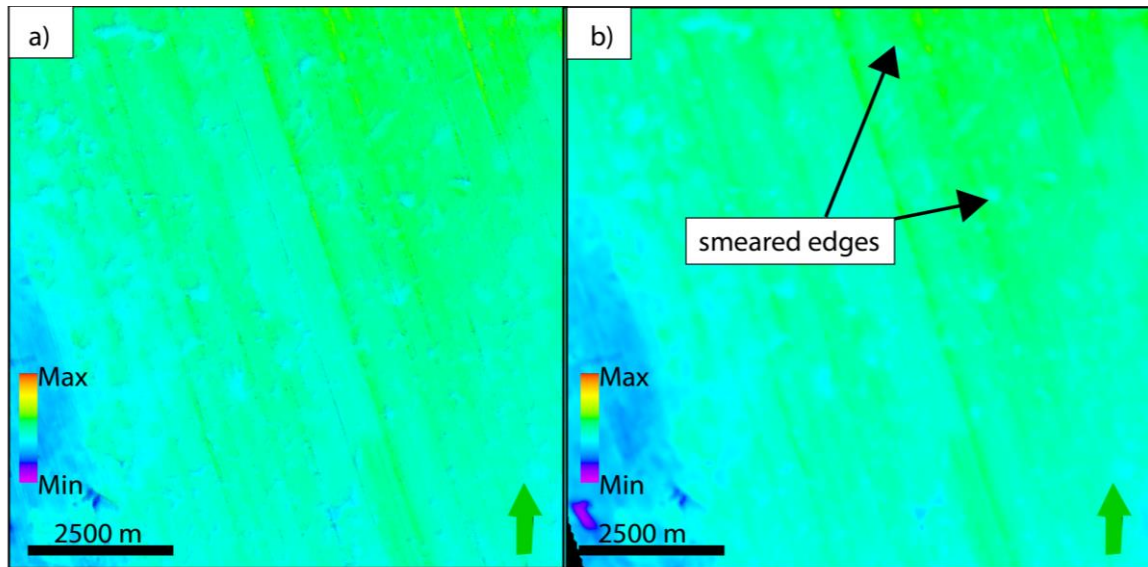


Figure 4.8: Horizon slice showing the a) horizon before surface smoothing versus b) the horizon after surface smoothing. Note that while the surface smoothing operation presents a more improved quality of the data, it tends to smear edges of some features. Color bar indicates two-way-traveltime (TWT).

4.4.1. Structural Smoothing Filter

The structural smoothing algorithm applies a 3D Gaussian filter to the seismic volume to reduce noise (Faraklioti and Petrou, 2005). This filter can be structurally oriented, calculating the local orientation of the bedding planes within the seismic data, to improve the seismic signal-to-noise ratio (S/N) without eliminating critical information associated to geological structures (Pedersen et al., 2002). In Petrel, a user has an option to change parameters for the filters to perform the structural smoothing operation.

The filter options available in the software are:

- a) Plain structural smoothing, which runs a routine structural smoothing filter on the seismic data without considering the estimated dip direction;
- b) Dip-guided structural smoothing, which runs a structural smoothing filter considering the estimated dip direction of the seismic data;
- c) Dip-guided with edge enhancement structural smoothing, which runs a structural smoothing filter in the dip direction of the data but runs two chaos attribute filters. The filter with less chaos is then filtered and its edges are enhanced.

In this study, the filter applied to the data was the dip guided structural smoothing with edge enhancement (Figure 4.9). The filter sizes available are Sigma X, Sigma Y and Sigma Z. The filter size used for the data is X,Y, Z = 1.5.

Figure 4.9a shows the seismic section before the application of the structural smoothing. The original section is characterized by noise that affects the continuity of the strong reflectors across the section. Figure 4.9b shows the seismic section after applying the structural smoothing filter. The filter enhanced the continuity of reflectors parallel to the orientation of the bedding planes and improved the visualization of the relationships between the seismic reflectors and their terminations.

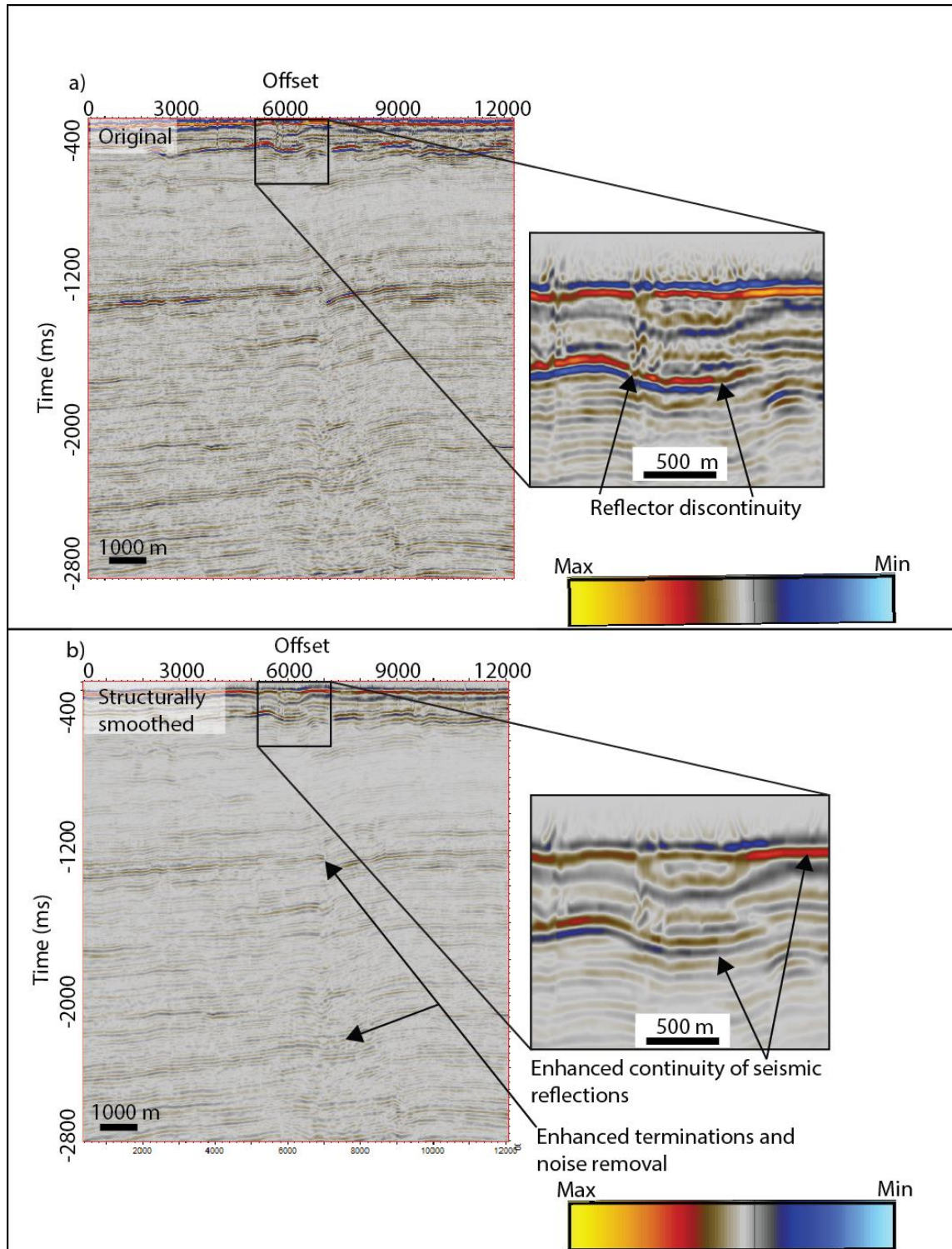


Figure 4.9: a) Data from the original seismic amplitude volume characterized by noise, b) Data from the dip-guided structurally smoothed volume (filter size: X, Y, Z =1.5) showing enhanced terminations and the enhanced continuity of seismic events. Faults are indicated by the arrows. Color bar indicates seismic amplitude.

4.4.2. Median Filter

If applied iteratively, the median filter is capable of reducing noise with high amplitudes at each successive iteration and yet not increasing the frequency of the geological structures on a surface (Chopra and Marfurt, 2008; Chopra et al., 2011). In Petrel, the median filter has three parameters: the crossline radius, inline radius and the depth radius. These input filters can be set according to the desired result. Figure 4.10a shows a seismic section before applying the median filter. Figures 4.10b-d demonstrate the effectiveness of the median filter in reducing noise by enhancing the reflector terminations and therefore mapping the faults across the seismic sections. It can also be noted that the median filter reduces frequencies associated with noise (e.g., 25 Hz to 17 Hz) and improves the S/N of the data. The filter size of 5x5x1 (crossline radius, inline radius and depth radius) was used.

When comparing the results after applying the structural smoothing (Figure 4.9b) and median filters (Figures 4.10b-d) to the original seismic data, the structural smoothing filter shows better structural terminations than the median filter. Generally, the enhancement of terminations such as faults and fractures is well detected by these filters compared to the original amplitude display of the data, and this is key to the aims of this study.

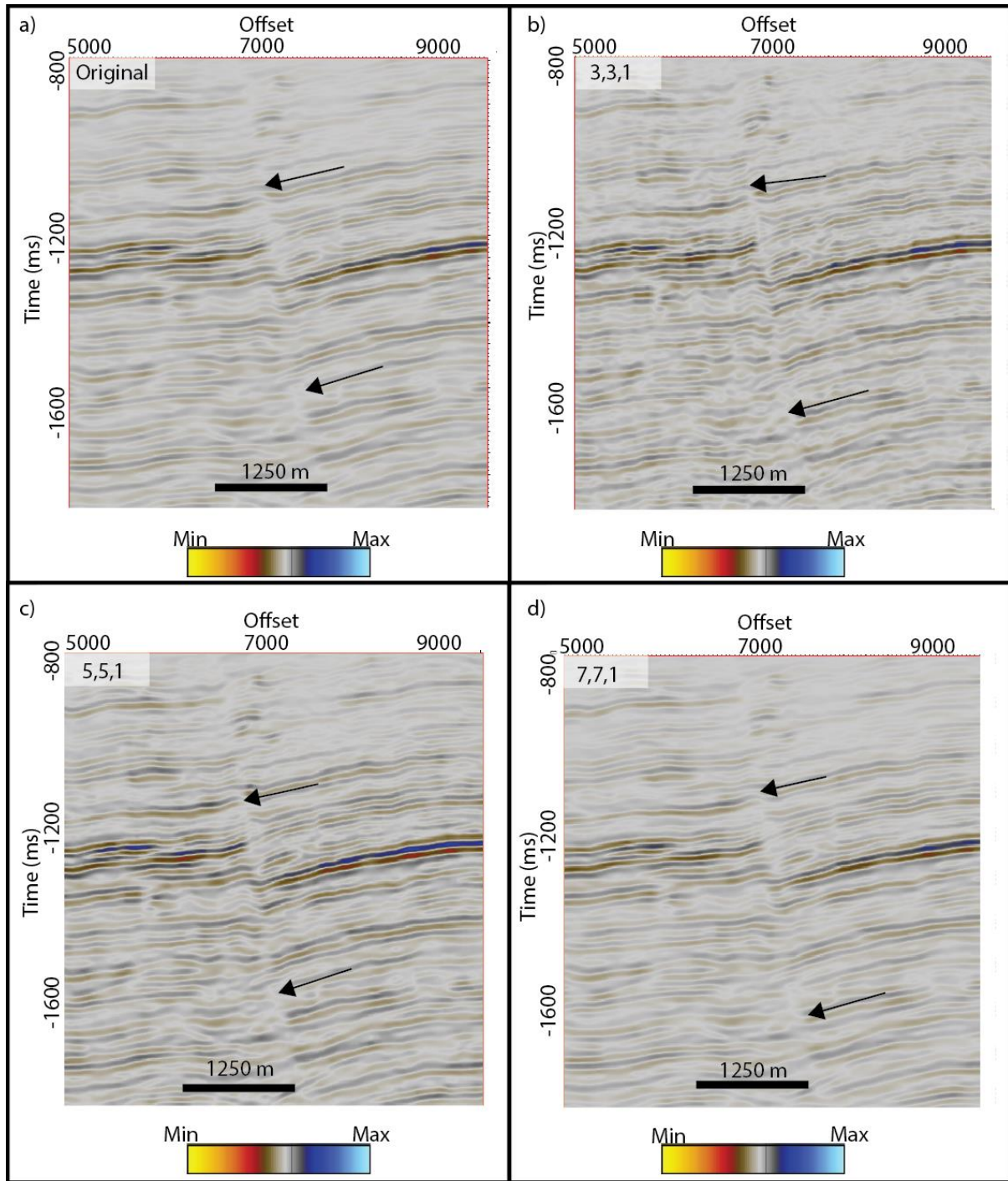


Figure 4.10: a) Seismic data are noisy and reflector continuity is diminished on the amplitude display of the seismic section. The median filter reduces noise and enhances reflector terminations using the following filter sizes (crossline radius, inline radius and depth radius) in b) 3,3,1, c) 5,5,1 and d) 7,7,1. The 5x5x1 median filter best enhances the seismic reflector terminations while attenuating the noise. Faults are indicated by the arrows. Color bar indicates seismic amplitude.

4.5. Volumetric Attributes

Volumetric attributes have been computed to enhance the detection of geological features in the data.

4.5.1. Variance

In Petrel, the parameters for calculating the variance attribute include the inline range, crossline range, vertical smoothing and the dip correction (Table 4.2). The inline and crossline range regulate the magnitude of the filter horizontally, while the vertical smoothing parameter controls the magnitude of the filter vertically. Dip correction computes the variance attribute in the direction of dip.

The variance attribute was applied for both the structurally smoothed and median filtered seismic volumes. Ten variance volumes were created and the filter sizes were kept constant for both inline and crossline directions. Var_1 and Var_7 were created using the default parameters for structural smoothing and median filtering volumes, respectively. Var_2, Var_3, Var_4, Var_5 and Var_6 were computed using the structurally smoothed volume as input; while Var_7, Var_8, Var_9 and Var_10 were calculated on the median filtered volume (Figures 4.11a, b, c, d; Table 4.2).

Figures 4.11a and c show the variance attribute applied to a dip-corrected structurally smoothed volume and a dip-corrected median filtered volume, respectively. Figures 4.11b and d show the variance attribute applied to a non-dip corrected structurally smoothed volume and a non-dip corrected median filtered volume, respectively.

The dip corrected volumes tend to show more detail in relation to the continuity of the major fault in the study area (Figures 4.11a, c), while the non-dip corrected volume appears ‘smeared’ (Figures 4.11b, d).

Seismic sections extracted from the dip corrected volumes after the application of short range filters (inline range; crossline range ≤ 5) exhibit a low signal-to-noise ratio. However, applications of these filters have preserved the edges in the data. Longer range filters (inline range; crossline range > 5) (Figure 4.12c; Figures 4.12e, f; Figures 4.13c and d) exhibit high signal-to-noise ratio, however these have the disadvantage of not preserving edges as compared to the short range filters (Figure 4.12a and b; Figure 4.12d; Figures 4.13a and b).

Furthermore, an application of the higher vertical smoothing (> 15) parameter produces a volume with increased vertical structural connectivity (Figures 4.12b-d; Figure 4.12f; Figures 4.13b and d) compared to a lower vertical smoothing (> 15) filter (Figures 4.12a and e; Figures 4.13a and c). The main objective was to isolate major structures as well as minor discontinuities from the background noise; therefore the parameters (inline range; crossline range; vertical smoothing) of 3x3x15 were used.

Table 4.2: Variance volumes calculated on structurally-smoothed and median-filtered volumes.

Input Volume	Variance Volume	Inline range	Crossline range	Vertical smoothing
Structural smoothing	Var_1	3	3	15
	Var_2	5	5	30
	Var_3	6	6	20
	Var_4	3	3	30
	Var_5	6	6	15
	Var_6	10	10	20
Median filtering	Var_7	3	3	15
	Var_8	3	3	30
	Var_9	6	6	15
	Var_10	6	6	30

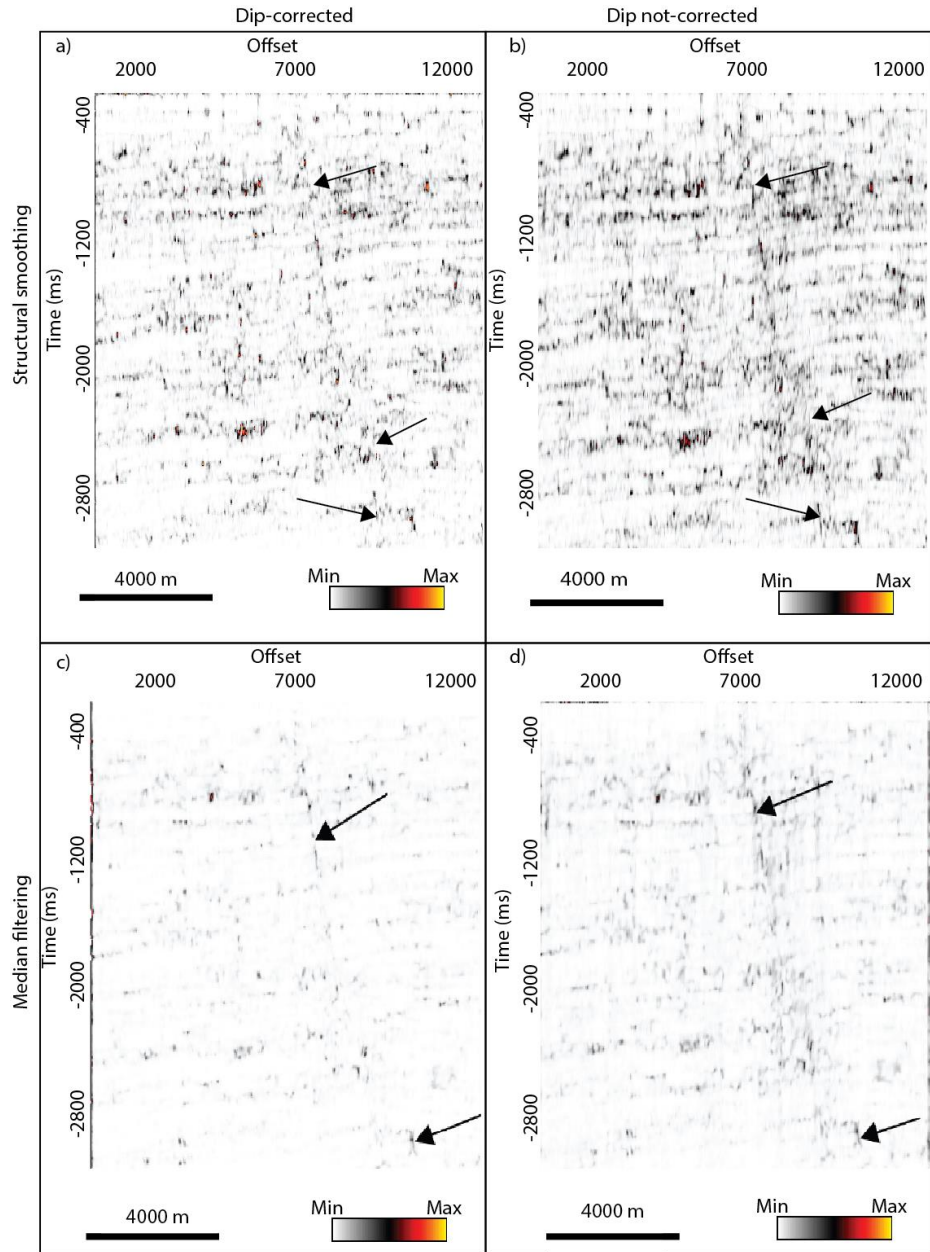


Figure 4.11: Tests of the seismic conditioning method on the calculation of variance on crossline 3237. Variance attribute with parameters (Var_1 = 3,3,15) applied on structurally smoothed volume on: a) a dip corrected volume vs. b) a non-dip corrected volume along crossline 3237. Variance attribute with parameters (Var_1 = 3,3,15) applied on median filtered volume: c) a dip-corrected volume vs. d) a non-dip corrected volume along crossline 3237. Faults are indicated by the arrows. Color bar indicates maximum variability between traces (black, red, yellow) versus minimum variability between traces (white). The structurally smoothed, dip-corrected volume was chosen because it enhanced the structural features of interest best while attenuating the noise. The non-dip corrected volumes appear smeared.

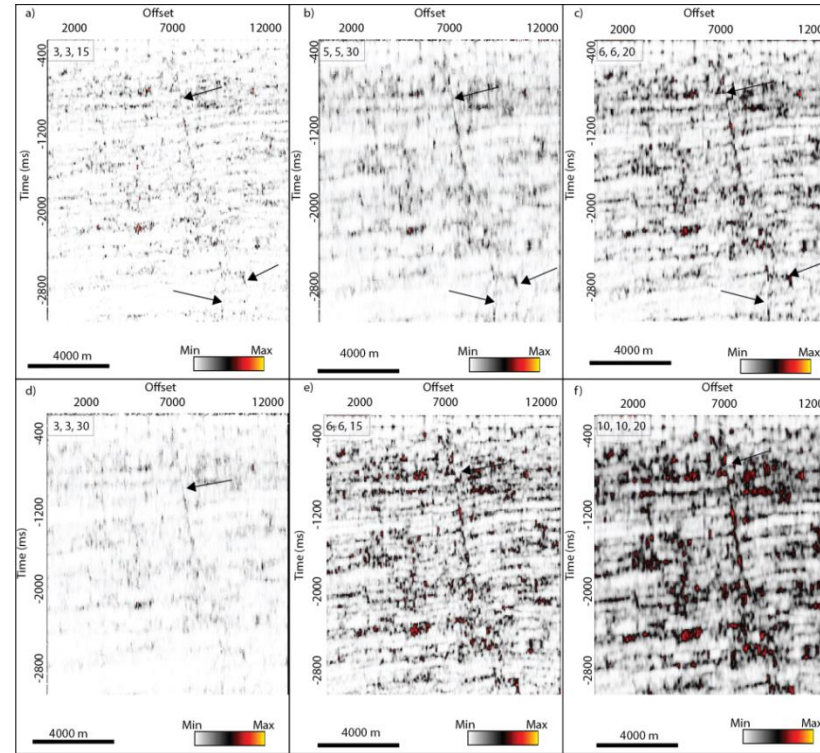


Figure 4.12: Tests of applying long range filters versus short range filters on a structurally-smoothed variance volume with parameters (inline range; crossline range; vertical smoothing): a) Var₁ = (3,3,15), b) Var₂ = (5,5,30), c) Var₃ = (6,6,20), d) Var₄ = (3,3,30), e) Var₅ = (6,6,15), and f) Var₆ = (10,10,20). Faults are indicated by the arrows. Short range filters (inline range; crossline range ≤ 5) exhibit a low signal-to-noise ratio; nevertheless they preserve the edges in the data. Longer range filters (inline range; crossline range > 5) exhibit high signal-to-noise ratio; however these have the disadvantage of not preserving edges as well as the short range filters. Color bar indicates maximum variability between traces (black, red, yellow) versus minimum variability between traces (white).

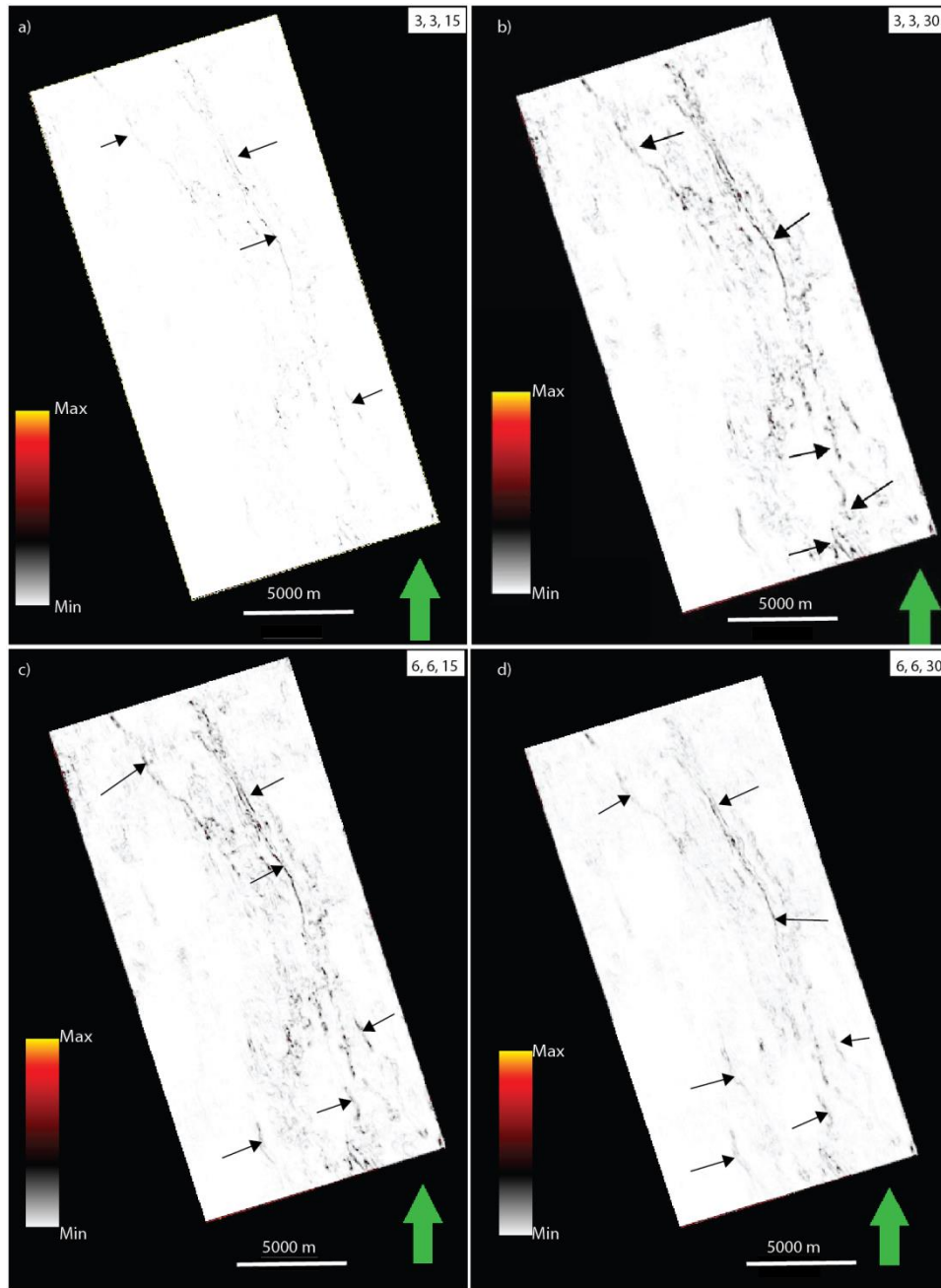


Figure 4.13: Tests of applying long range filters vs. short range filters on a median-filtered variance volume with parameters (inline range; crossline range; vertical smoothing): a) Var_7 = (3,3,15), b) Var_8 = (3,3,30), c) Var_9 = (6,6,15), and d) Var_10 = (6,6,30). Faults are indicated by the arrows. Short range filters (inline range; crossline range ≤ 5) exhibit a low signal-to-noise ratio; nevertheless they preserve the edges in the data. Longer range filters (inline range; crossline range > 5) exhibit higher signal-to-noise ratio, however these have the disadvantage of not preserving edges as compared to the short range filters. Color bar indicates maximum variability between traces (black) versus minimum variability between traces (white).

4.5.2. Chaos

In Petrel, the chaos attribute is an estimate of the degree of organisation of the seismic data and is scaled from 0 (minimum) to 1 (maximum), with 1 being the most chaotic (Randen and Sonnenland, 2005; Section 2.8.2; Equation 14). The parameters for the 3D window size can be set when computing a chaos attribute. For this study, the directional filter size, (σ), was set to the values summarised in Table 4.3.

Table 4.3: Chaos parameters.

	X	Y	Z
Filter size (σ)	1.0	1.0	1.0
	1.5	1.5	1.5
	2.0	2.0	2.0

Figures 4.14a, b, c and Figures 4.14d, e, f show the chaos attribute applied on both the structurally smoothed and median filtered seismic volumes, respectively. The median filtered volumes have a higher signal-to-noise ratio compared to the structurally filtered volumes; however, median filtered data show less detail about fault continuity compared to the structurally filtered volumes (Figures 4.14d, e, f). Higher values of σ (Figures 4.14c, d, f) yield a smoother result with a varied spectrum of chaos values than lower σ values (Figures 4.14a and d).

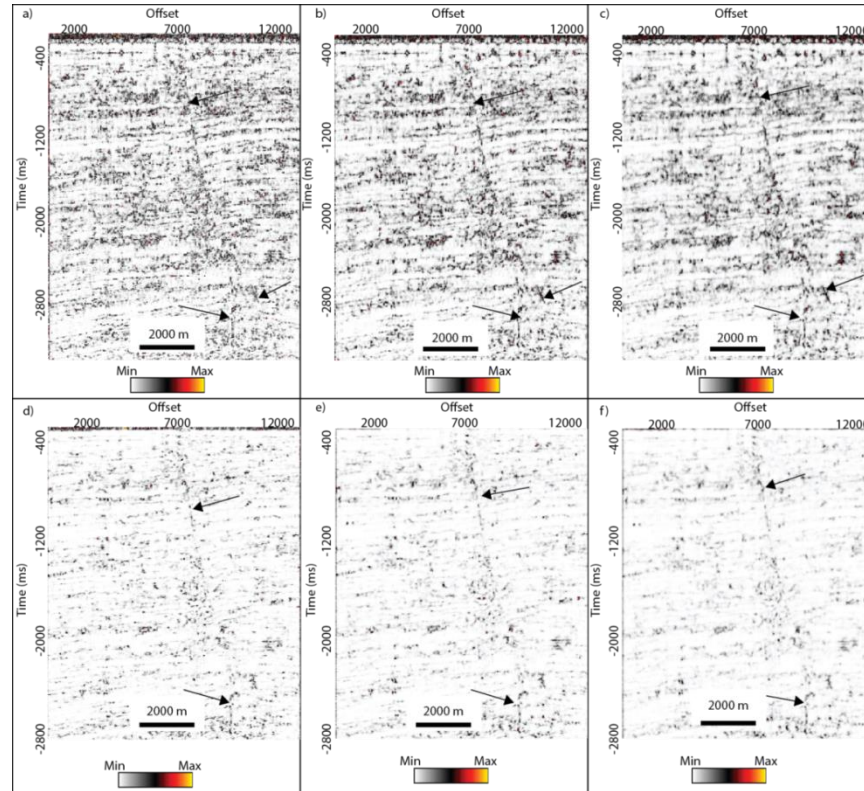


Figure 4.14: Assessment of the effect of the seismic conditioning method and filter size on the calculation of the chaos attribute. Chaos attribute with filter sizes (σ) of: a) 1.0; b) 1.5; c) 2.0 on a structurally smoothed volume vs the chaos attribute with filter sizes of: d) 1.0; e) 1.5; and f) 2.0 on a median filtered volume. The median filtered volumes have a higher signal-to-noise ratio compared to the structurally filtered volumes. Color bar indicates maximum variability between traces (black, red, yellow) versus minimum variability between traces (white).

4.5.3. Ant-tracking

The theory behind the ant-tracking algorithm has been discussed in [section 2.8.3](#). The ant-tracking workflow comprises: (1) seismic volume conditioning, (2) edge detection (variance and chaos), and (3) edge enhancement (ant-tracking) ([Figure 4.15](#)). To generate an ant-tracking volume, the original seismic volume is preconditioned by either structural smoothing or application of a median filter. Thereafter, edge detection algorithms are computed on the structurally smoothed or median filtered volume. The edge detection volumes are the input for the calculation of the ant-tracking.

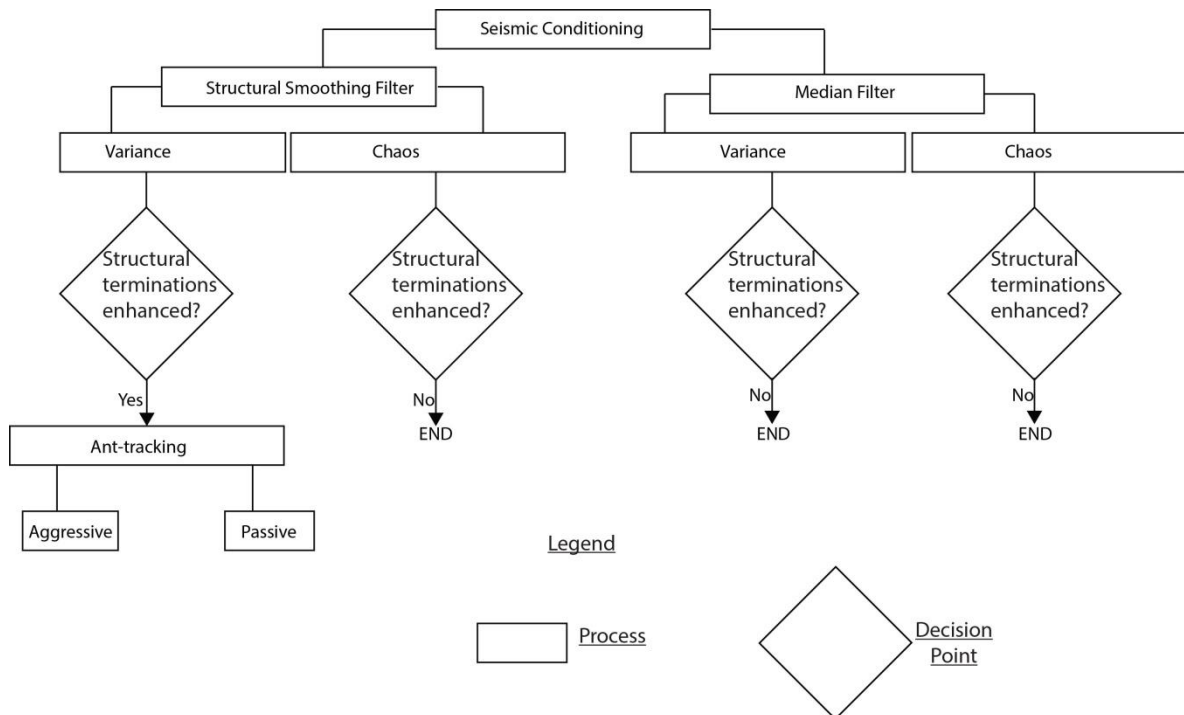


Figure 4.15: Ant-tracking workflow which contains the following steps: (1) seismic volume conditioning (structural smoothing or median filtering, (2) edge detection (variance or chaos attributes), (3) edge enhancement (ant-tracking) ([modified after Petrel, 2015](#)). Both the variance and chaos seismic volumes were computed for edge detection, however, the variance cube was chosen as it primarily contained the main structural features of interest.

4.6. Structural Enhancement using Ant-tracking

The ant-tracking algorithm can be run either in passive, aggressive or custom modes (Figure 4.15). The passive mode extracts major structural features such as regional faults; the aggressive mode tends to pick up subtle discontinuities such as minor faults and fractures; while the custom mode allows the user to set the ant-tracking parameters according to preferred result. The parameters whose values are set in both passive and aggressive modes or modified in custom mode are the: a) initial ant boundary (1-30), b) ant-track deviation (0-3), c) ant step size (2-10), d) illegal steps allowed (1-3), e) legal steps allowed (1-3), f) stop criteria (0-50%), and g) stereonet tab.

The initial ant boundary sets the limits for the spacing of the initial ants distributed through the seismic volume. To capture regional faults, a higher number of voxels is required than when capturing subtle discontinuities. The ant-track deviation controls the number of voxels an ant agent can move from its legal position to track for connections; therefore a higher number results in more connections as compared to a lower number. The ant step size controls the resolution of the ant's path as it determines how far the ant agent can go on a step to search for connections.

The illegal steps determine how many voxels an ant agent will move if no edge has been detected, while the legal steps determine the number of voxels an ant agent moves after detecting an edge. The stop criterion is a percentage that restricts the ant agent's illegal steps. The stereonet tab controls the orientations in which the ants may search for dips and azimuths of the faults (Figure 4.16). Table 4.4 presents the parameters for the ant-tracking volumes computed from the edge detection volumes of variance and chaos. The ant-tracking algorithm was iterated three times to get the desirable result (Figure 4.17).

Table 4.4: Ant-tracking parameters.

Input volume	Output volume	Parameters					
		Initial ant boundary	Ant-track deviation	Ant step size	Illegal steps allowed	Legal steps	Stop criteria
Parameters	Ant-track on Variance/Chaos (passive)	7	2	5	1	3	5
	Ant-track on Variance/Chaos (aggressive)	5	2	3	2	2	10

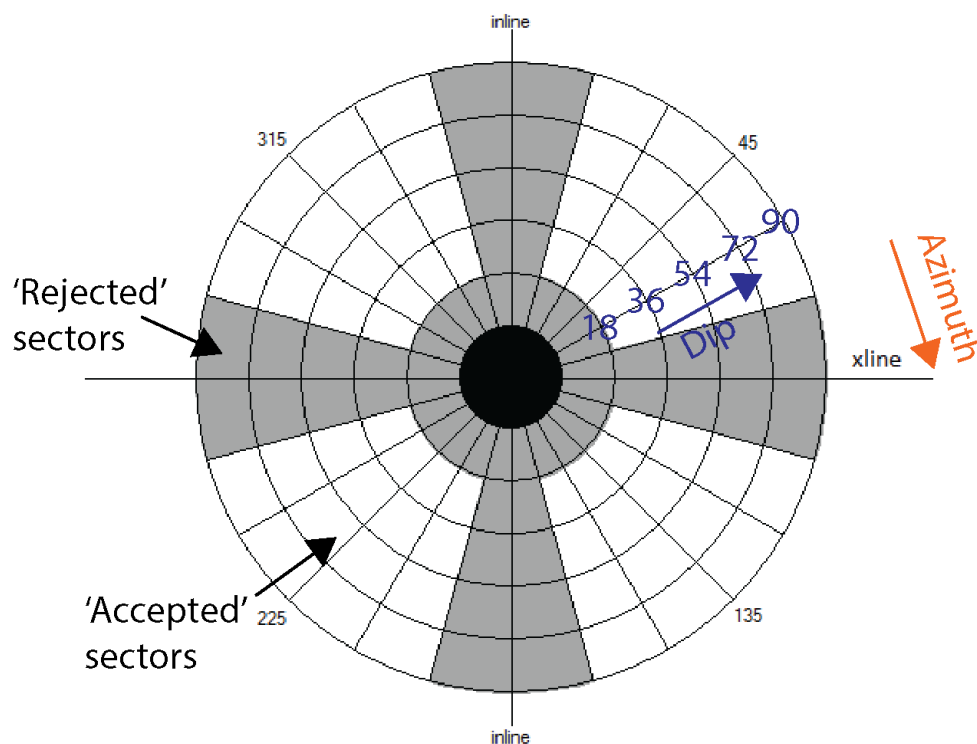


Figure 4.16: The stereonet is displayed with rejected (grey) and accepted (white) sectors for ant-tracking agents. The ant-track agents were set to search for dips above $\pm 20^\circ$ and azimuths of $\pm 15^\circ$.

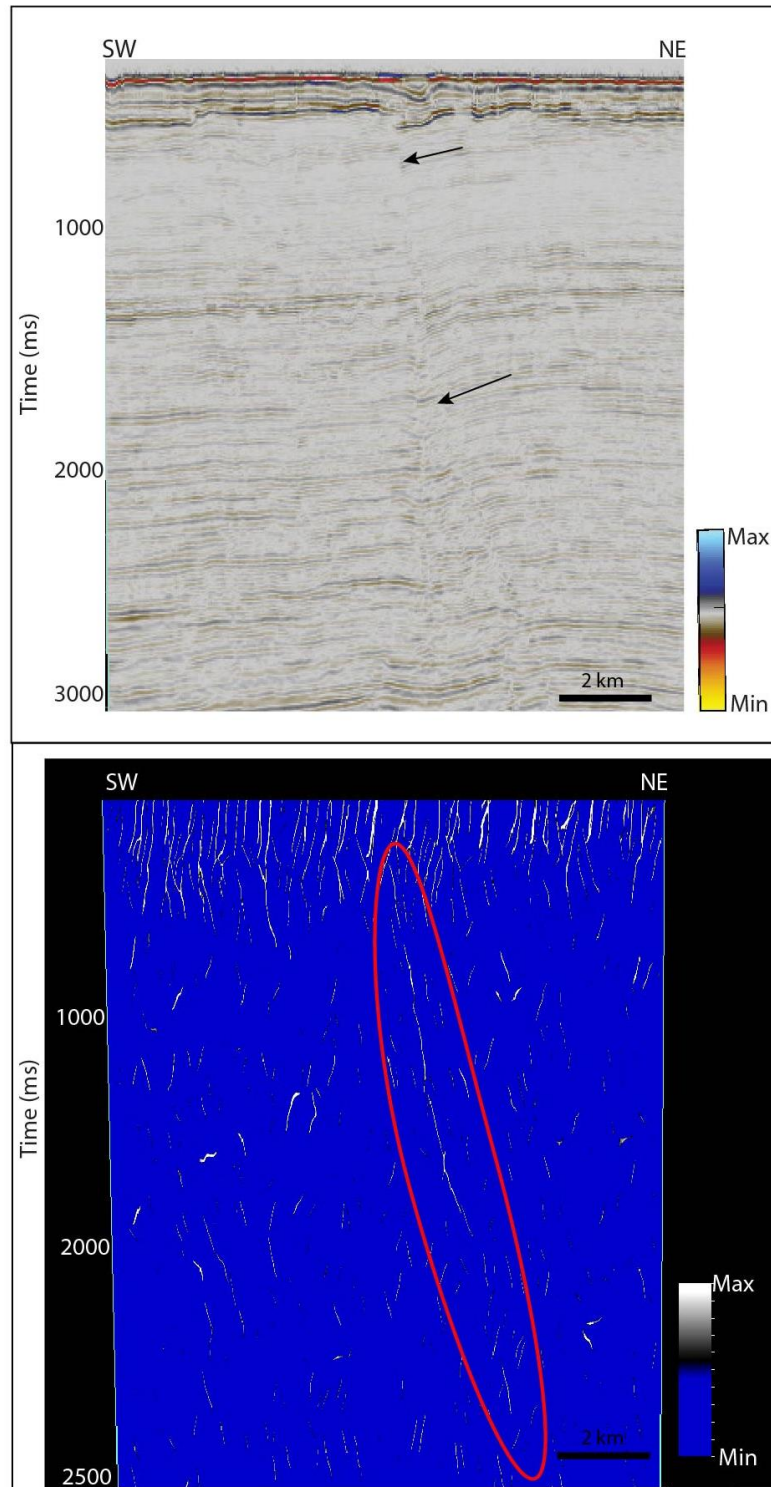


Figure 4.17: a) Fault trace visualized from conventional seismic data (black arrows). Colour bar indicates seismic amplitude. b) Fault trace visualized from the outputs of passive ant-tracking using the variance volume as the input (red oval). Structure discontinuity is better delineated by the ant-tracking attribute. Color bar indicates maximum variability between traces (white, black) versus minimum variability between traces (blue).

5. Results

5.1. Horizon Interpretation

5.1.1. Conventional Interpretation

5.1.1.1. *H1 horizon-seabed*

The horizons interpreted on the 3D seismic data include the seafloor (H1), H2, H3 and H4. [Table 5.1](#) provides the summary of the characteristics for the conventionally picked horizons (H1-H4). The time structure (or elevation) map of the H1 horizon, located at approximately 0.3 s in seismic sections, is a strong, laterally continuous seismic reflective interface that represents the seabed or seafloor ([Figures 5.1a, b; Table 5.1](#)). The seafloor surface across the study area is structurally stable (i.e., little or no faulting) when compared to the underlying rocks and seismic horizons (H2-H4). The surface has an average dip of 1° to the south due to its structural stability. The elevation map of the H1 horizon, as presented in [Figure 5.1a](#), exhibits a number of depressions elevated circular features with diameters ranging from 110 m to 620 m. The depressions on the seabed and are located mostly on the northern part of the study area ([Figure 5.2](#)).

The elevation map and seismic sections also show a successful mapping of a positive elevated seabed feature ([Figures 5.1a, b](#)). The positive elevated seabed feature is associated with upward hydrocarbon migration ([Hovland, 1994](#)). The position of the seabed feature in the elevation map coincides with that observed in the seismic section. The seabed feature is elongated in a NW-SE orientation, parallel to the crossline direction of the survey. A thorough smoothing of the data and analysis of the seismic section suggests that the feature is not an artefact, but represents a seafloor mound that is possibly related to some other subsurface features, especially the underlying fault ([Figure 5.1b](#)). The seafloor is also interpreted to constrain the age and timing of faulting of the fault relative to the deposition of the sedimentary sequences that under it ([Figure 5.1b](#)).

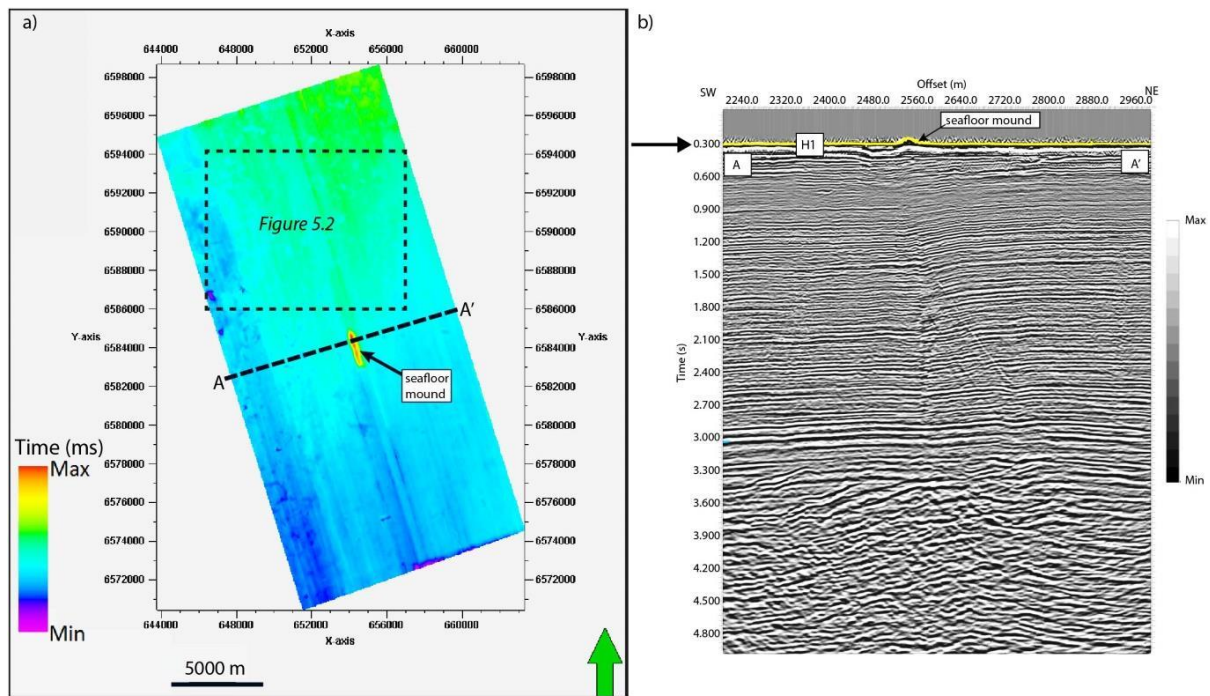


Figure 5.1: a) Time structure map for the H1 horizon. A seafloor mound and pockmarks have been identified on Horizon H1. Color bar represents two-way-traveltime (TWT). The seafloor is not faulted and is therefore structurally stable. b) The seafloor mound is a positively elevated, dome-shaped feature occurring on the seafloor. Color bar represents the seismic amplitude.

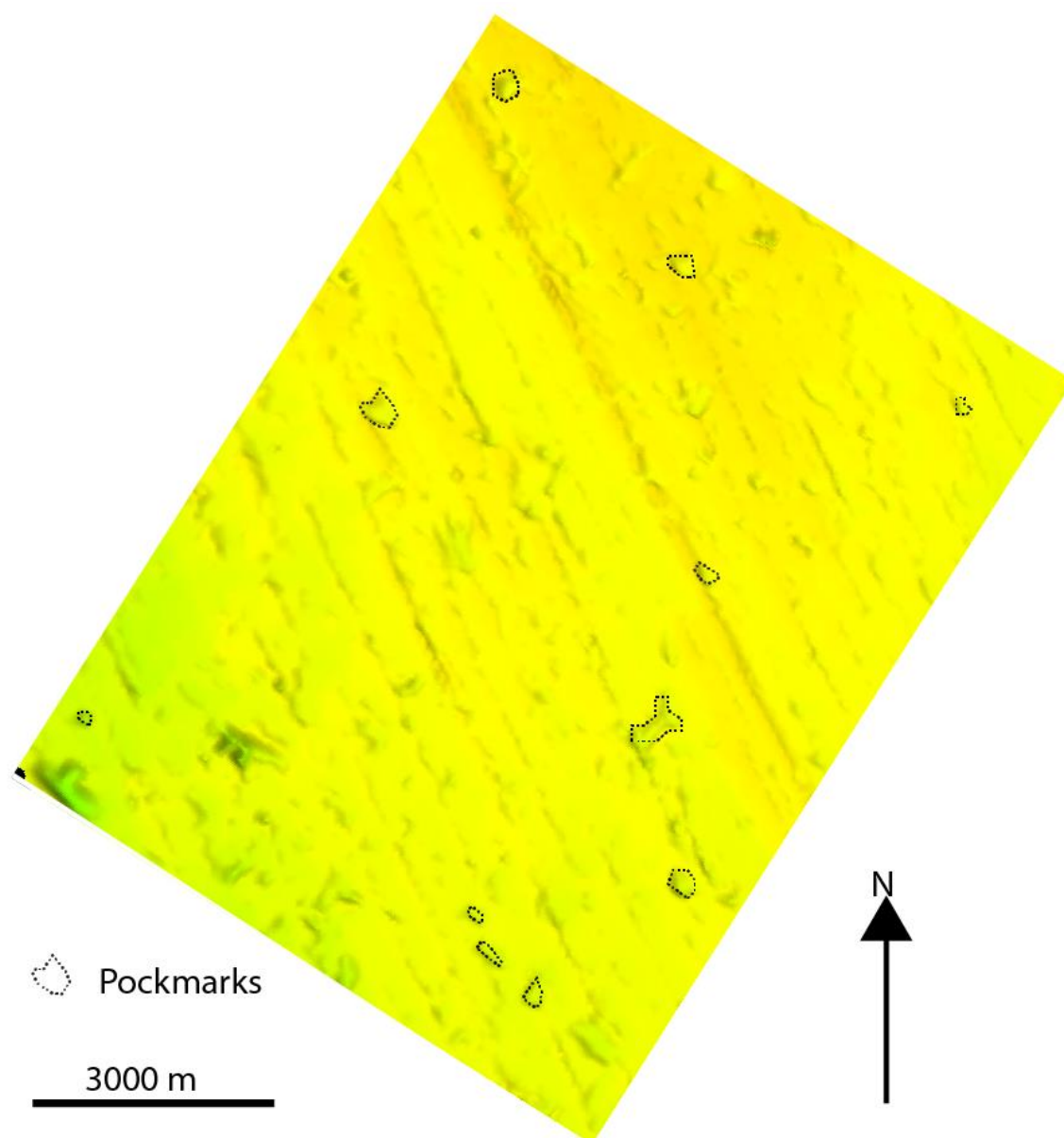


Figure 5.2: Negative depressions that are interpreted as pockmarks occur mostly in the northern part of the study area with sizes ranging from approximately 110 m to 620 m.

5.1.1.2. Horizons: H2, H3 and H4

The H2 horizon occurs within the Upper Cretaceous rocks. It is a strong seismic reflector across the study area and it represents the top of the sandstone reservoir. Interpretation of the H2 horizon was a priority target for this study for its potential for gas exploration. The elevation map computed for H2 horizon, as presented in Figure 5.3a, indicates that the H2 horizon is dissected by a major and prominent normal fault zone, which is mapped as two distinct normal faults (F1 and F2). In seismic section, presented in Figure 5.3b, the fault zone is listric in nature with a maximum displacement of 500 m. The full interpretation of the fault zone is described in the following sections. The H2 horizon exhibits variable strikes and dips across the study area as a result of some faulting (Figures 5.3a, b; Table 5.1).

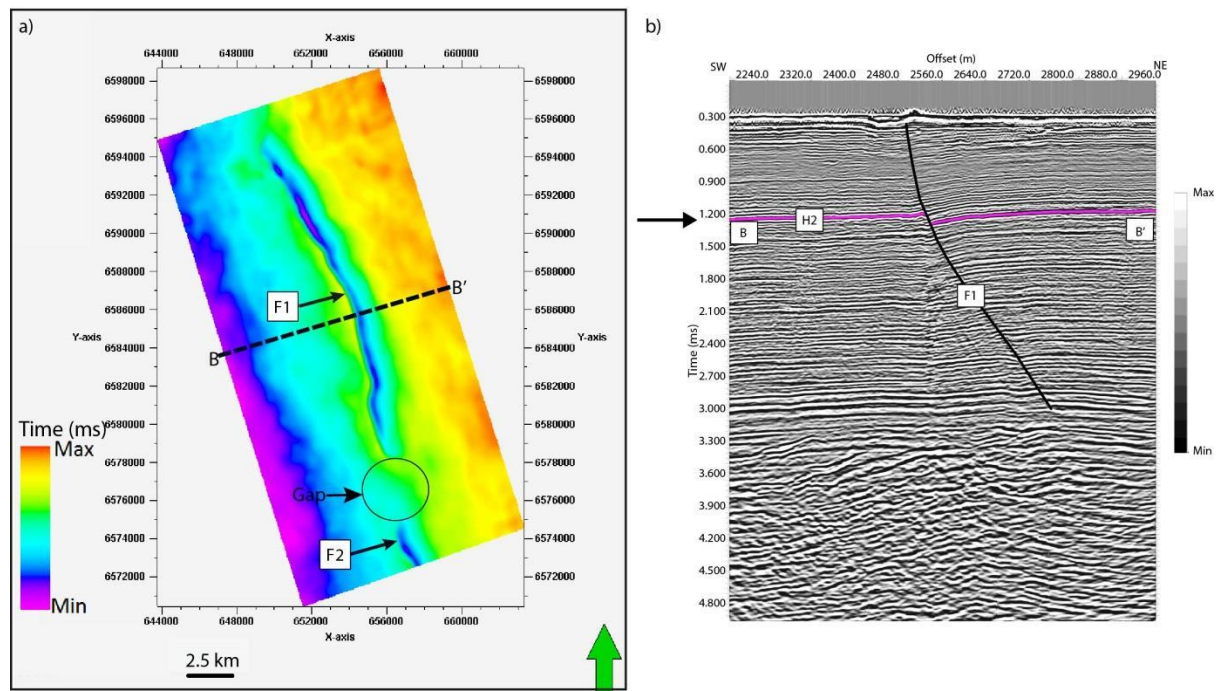


Figure 5.3: a) Time structure map for the H2 horizon. Two faults (F1 and F2) oriented in a NW-SE direction are the major regional structural elements interpreted in this study. Color bar represents the two-way-traveltime (TWT). b) In seismic section, the fault zone (F1) is listric with a maximum displacement of approximately 500 m. Color bar represents the seismic amplitude.

Similar to H1 and H2, the H3 and H4 horizons are mapped as strong, continuous and prominent reflectors across the seismic volume. These two horizons are located below H2 horizon at depths between 2.5 and 3.5 s, and they were interpreted to constrain the timing of faulting for the major north–northwest-trending fault zone (Figures 5.4-5.6) with a view to developing an understanding of the prevailing tectonic environment. H3 and H4 horizons have variable dips along strike due to faulting with an average horizon dip of 2° . H3 is dissected by north-northwest-trending faults F1 and F2 with F1 segmented into 2 parts in a zone where there is no appreciable or measurable displacement on seismic sections (Figures 5.4a, b; Table 5.1). On the other hand, H4 horizon is cross-cut by numerous north-northwest-trending faults (F1, F2, F3 and F5) (Figures 5.5a, b; Table 5.1).

Summarily, it is clear that these faults cross-cut and displace horizons H2, H3 and H4 but do not breach the base of the seafloor horizon. This type of information can be used to constrain the timing of these faults. It is also worth noting that wells and geophysical logs were not available in this study to calibrate, constrain and validate the seismic interpretation (e.g., positions of seismic horizons at depth). Therefore, seismic interpretation was constrained using the results published by (Haq et al., (1987); Muntingh, (1993); Brown et al., (1995) and Marcano et al., (2013).

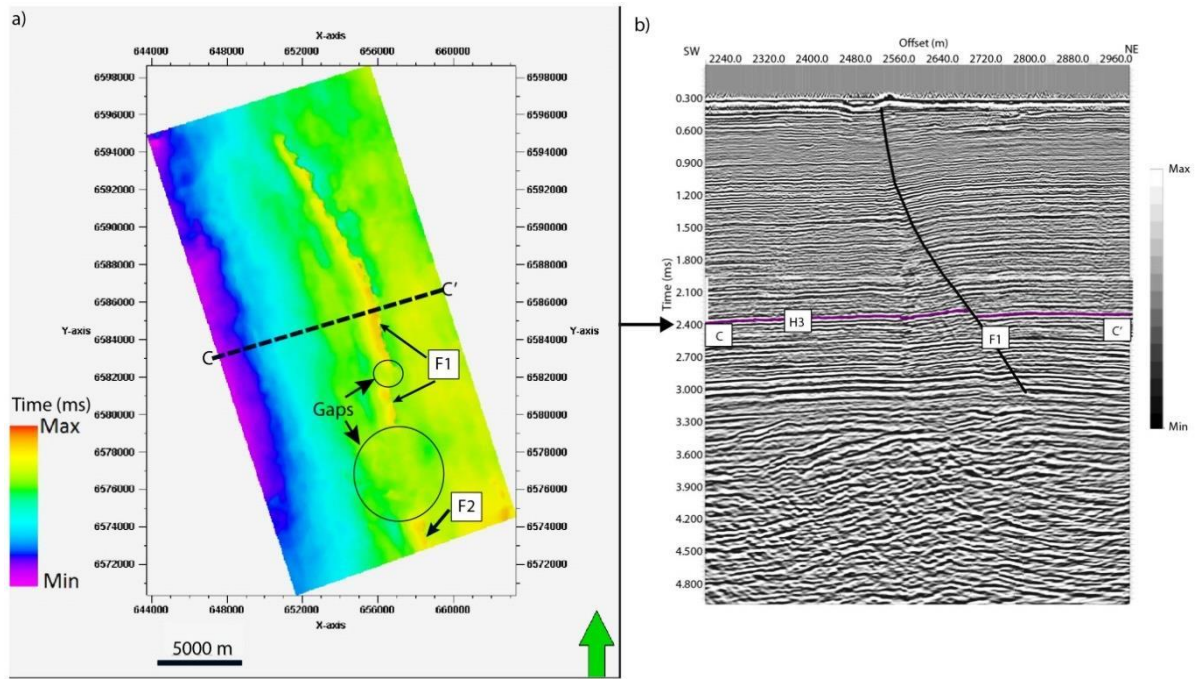


Figure 5.4: Time structure map for the H3 horizon. Two faults (F1 and F2) oriented in a NW-SE direction are the major regional structures that dissect the horizon. F1 is segmented into two parts in a zone (shown by a gap in the image) where there is no measurable displacement. Color bar represents two-way-traveltime (TWT). b) In the seismic section, the fault zone (F1) is listric with a maximum displacement of approximately 500 m. Color bar represents the seismic amplitude.

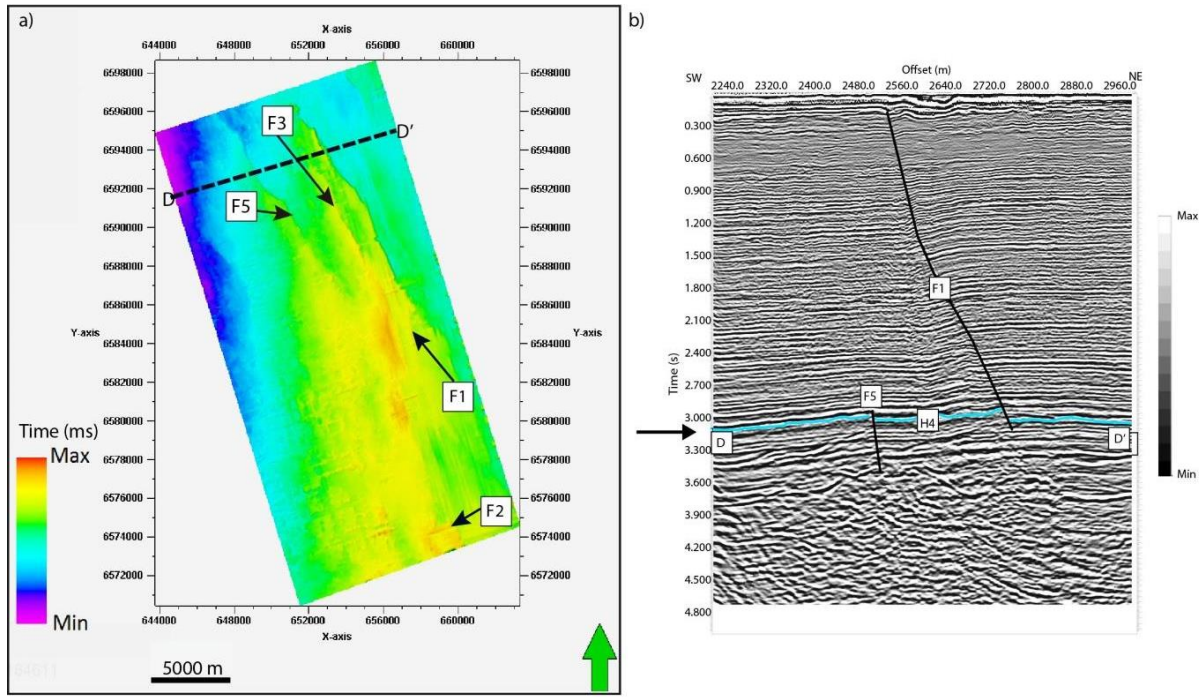


Figure 5.5: a) Time structure map for the H4 horizon showing north-northwest-trending faults (F1, F2, F3, and F5). Color bar represents two-way-traveltime (TWT). b) The seismic image shows that the H4 horizon is cross-cut by the listric F1 fault and the F5 fault across D-D'. Color bar represents the seismic amplitude.

Following the conventional picking of faults and horizons, these faults and horizons were used to build a first pass structural framework shown in [Figures 5.6-5.8](#). These structural relationships are difficult to see in seismic sections, and needed to be verified through the application of seismic attributes. To further enhance the detection and continuity of the faults in the horizons, horizon-based attributes were applied to the H2 and H3 horizons. These attributes were used to investigate the gaps between the tips of the faults: a) F1-F2 in H2, b) F1-F1 in H3 and F1-F2 in H3 ([Figures 5.3-5.4](#), [Figures 5.6-5.8](#)).

Table 5.1: Characteristics (polarity, time and depth) of picked horizons.

Horizon	Reflection Coefficient (RC)	Polarity	Time (ms)	Depth (m)
H1	0.31	Trough	-300	225
H2	0.23	Trough	-1300	1225
H3	0.07	Trough	-2400	2655
H4	0.07	Trough	-3200	3955

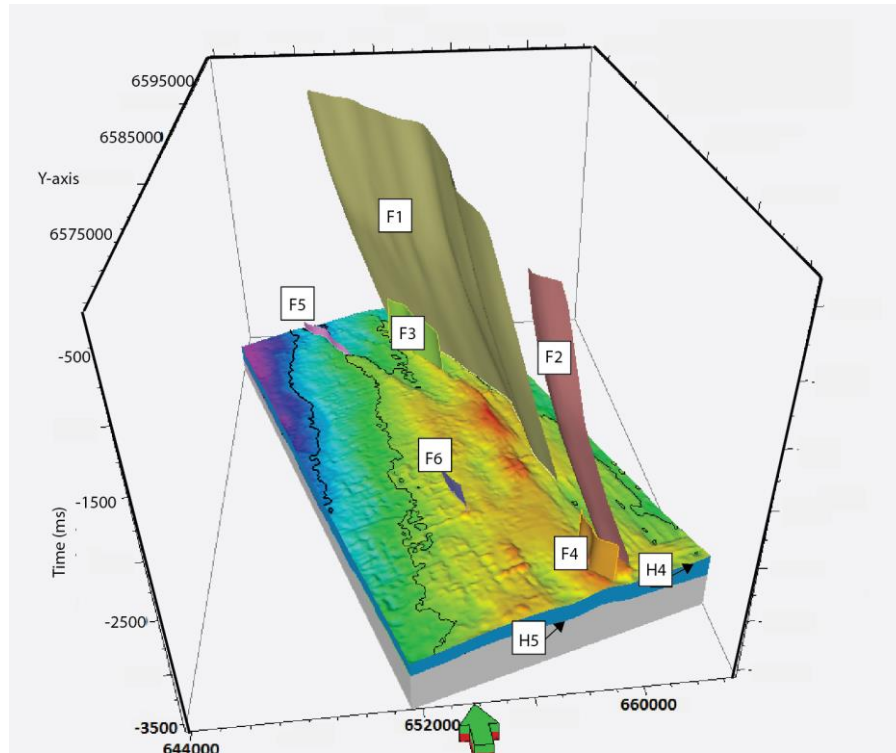


Figure 5.6: The H4 horizon and corresponding dissecting faults (F1, F2, F3, F4, F5 and F6) displayed in 3D view. Faults have a NNW-SSE trend.

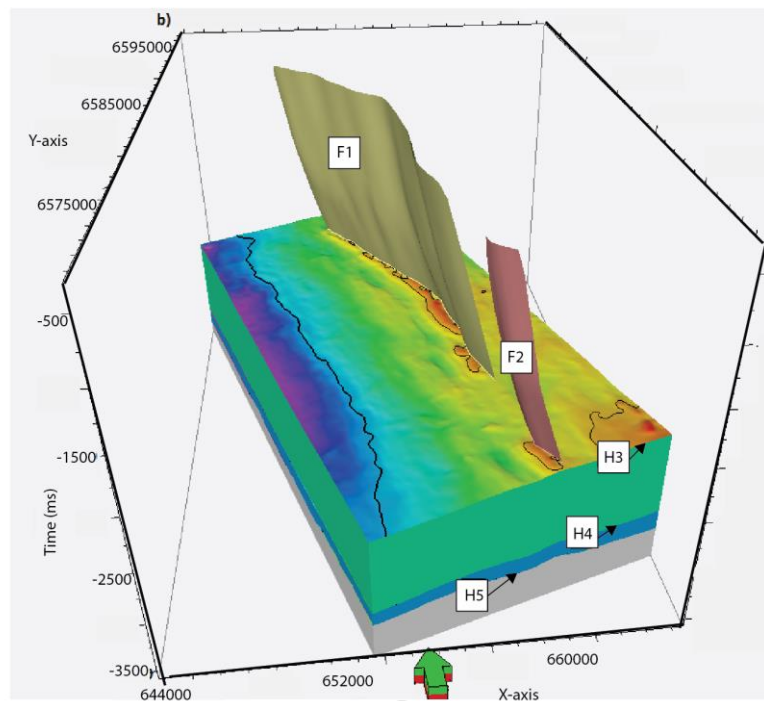


Figure 5.7: The H3 horizon and corresponding dissecting faults (F1 and F2) displayed in 3D view. Faults have a NNW-SSE trend.

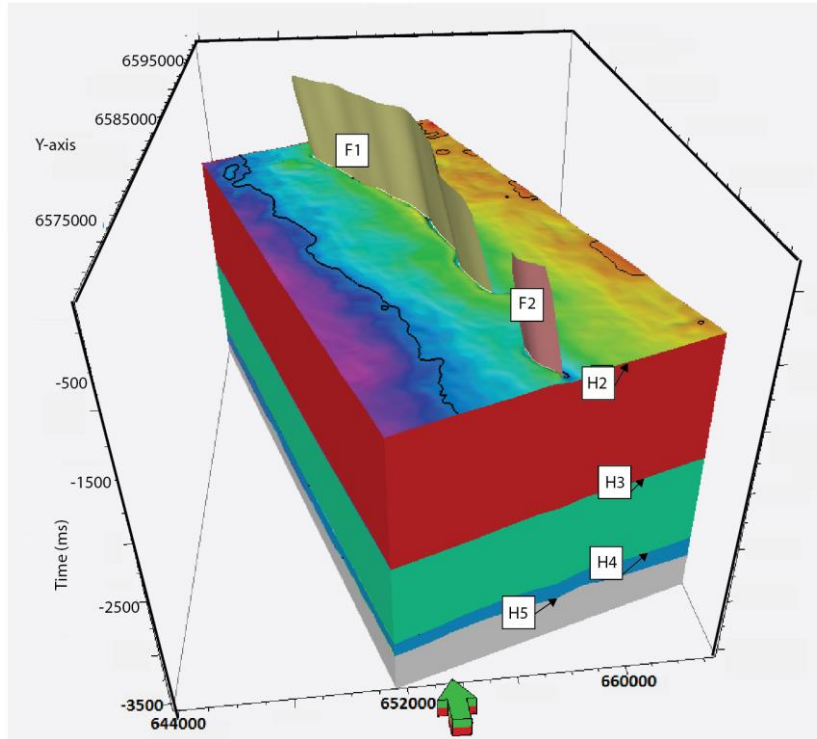


Figure 5.8: The H3 horizon and corresponding dissecting faults (F1 and F2) displayed in 3D view. Faults have a NNW-SSE trend.

5.1.2. Horizon Attributes

5.1.2.1. *Dip, Dip-azimuth and Edge detection*

The dip attribute map shows a higher resolution for structural mapping than conventional seismic interpretation (e.g., seismic sections and elevation maps). For example, the dip attribute map has managed to highlight major regional faults with dip angles above 25° . The dip attribute (Figure 5.9a) computed for the H2 horizon indicates that the horizon is mainly dipping $\sim 1^\circ$ from the horizontal. The question investigated further regards the possible relay ramp between: a) the two ends of faults F1 and F2 in the H2 horizon and b) the two ends of fault F1 in the H3 horizon. Relay ramps are sites of fault interaction where strain or displacement is transmitted or relayed from one fault to another (Fossen and Rotevatn, 2016). This is examined further by applying the dip-azimuth attribute to H2 horizon (Figure 5.9b; Figure 5.10) and edge detection attribute (Figure 5.11).

The dip-azimuth is measured in degrees clockwise from the geographic north. The dip-azimuth for all the horizons is between $225\text{--}275^\circ$, whereas the mapped faults have dip-azimuths between $0\text{--}75^\circ$ (Figure 5.9b; Figure 5.10). The regional faults (F1 and F2) dip NNE, opposite to the main SSW dipping horizon direction. Besides the dip direction, the dip-azimuth attribute has been used to investigate subtle features that are not detected by conventional seismic interpretation (i.e., normal and autopicking on seismic sections). These are predominantly NW-SE trending linear features or lineaments, which are consistent with the character (i.e., strike, dip angle and dip direction) of the major faults (F1 and F2) (Figure 5.9b; Figure 5.10; Figure 5.11). The dip-azimuth horizon-based attributes were also used to enhance the detection of fault connectivity and continuation in the H3 horizon (Figure 5.12b, Figure 5.13). The H3 dip attribute map exhibits dips of $\sim 1\text{--}5^\circ$ from the horizontal (Figure 5.11). The dip-azimuth map shows the connectivity between the two ends of fault F1 (Figure 5.12b; Figure 5.13). The two ends of fault F1 are a completely breached relay ramp (hard-linked) at 2.45 s and linked by a N-S striking segment which is the breaching fault. Again, the breached nature of the fault network was not previously observed from conventional seismic interpretation (see Figures 5.3 and 5.4).

The dip and dip-azimuth attributes both show successful imaging of the regional faults; however, the dip-azimuth attribute has the added advantage of imaging subtle linear features that are below the vertical seismic resolution limit of ~8 m. Furthermore, the edge detection attribute, which is a combination of the dip and dip-azimuth attributes, has been used to investigate the fault relationships such as continuity and connectivity. The results from the edge detection attribute are in agreement with dip-azimuth attribute results, in terms of imaging the structural architecture of these horizons. For example, they both show clear detection of the continuity of F1 (see Figures 5.11 and 5.14).

In general, the seismic attribute maps suggest that fault segments converge with depth as the two faults (F1 and F2) are not connected in horizon H2 (see Figure 5.3b). However, these faults show connectivity at the deeper horizon, H3, as indicated by dip-azimuth and edge detection attributes in Figures 5.12b, 5.13 and 5.14. The connectivity between the fault segments implies that F2 is in fact a continuation of F1, which was not observed from the conventional elevation map interpretations. The major fault is thus referred to as F1 due to growth by segment linkage.

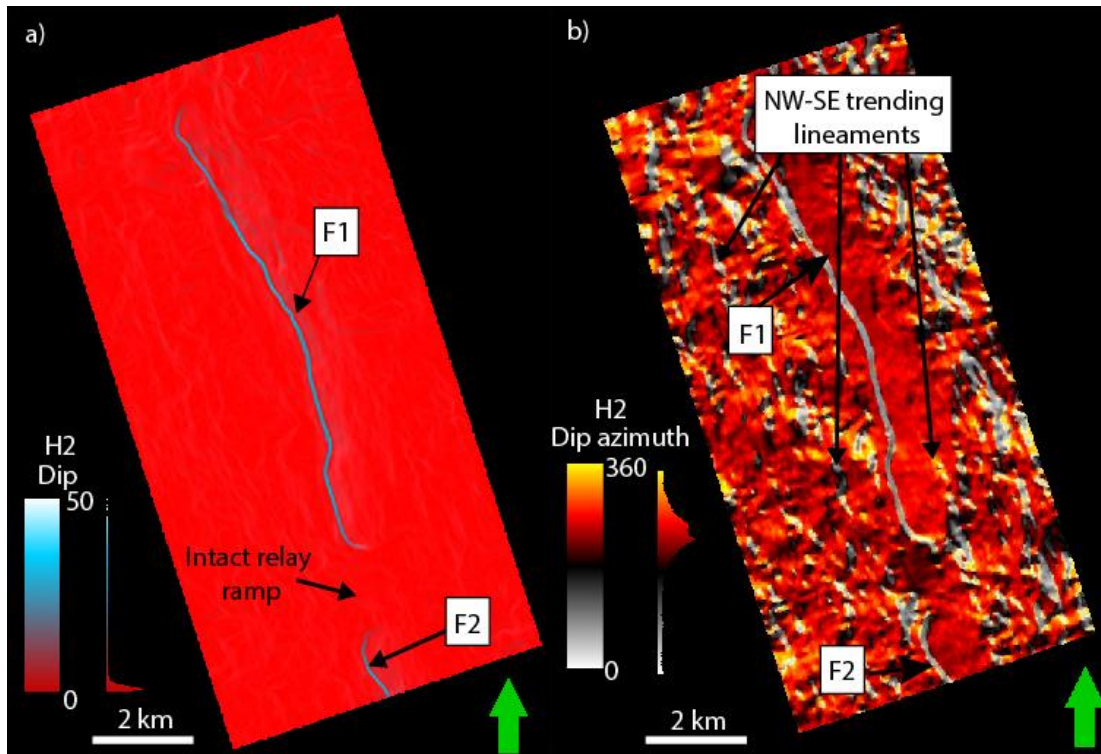


Figure 5.9: a) The dip attribute calculated for the H2 horizon highlighting NW-SE trending, major regional faults, F1 and F2. The color bar is given in degrees. The horizon is mainly dipping $\sim 1^\circ$ from the horizontal. b) The dip-azimuth horizon attribute calculated for the H2 horizon highlighting the non-connectivity between fault 1 (F1) and fault 2 (F2). The color bar is given in degrees. The dip-azimuth for the H2 horizon is between $225\text{--}275^\circ$ while the faults have an azimuth between $0\text{--}75^\circ$. The dip-azimuth attribute also clearly NW-SE trending lineaments straddling the major regional faults.

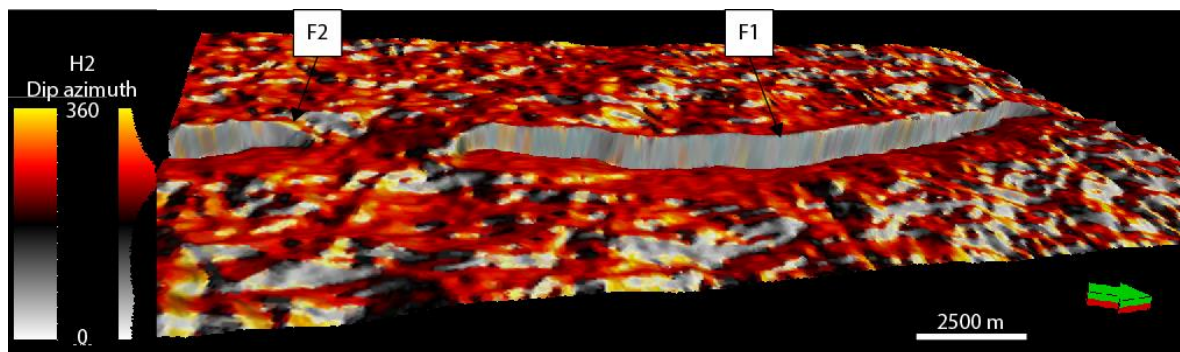


Figure 5.10: Perspective view of the H2 horizon after applying the dip-azimuth seismic attribute. Dip-azimuth horizon attribute for the H2 horizon showing the structural architecture of the faults (F1 and F2) bisecting the horizon. Color bar is given in degrees.

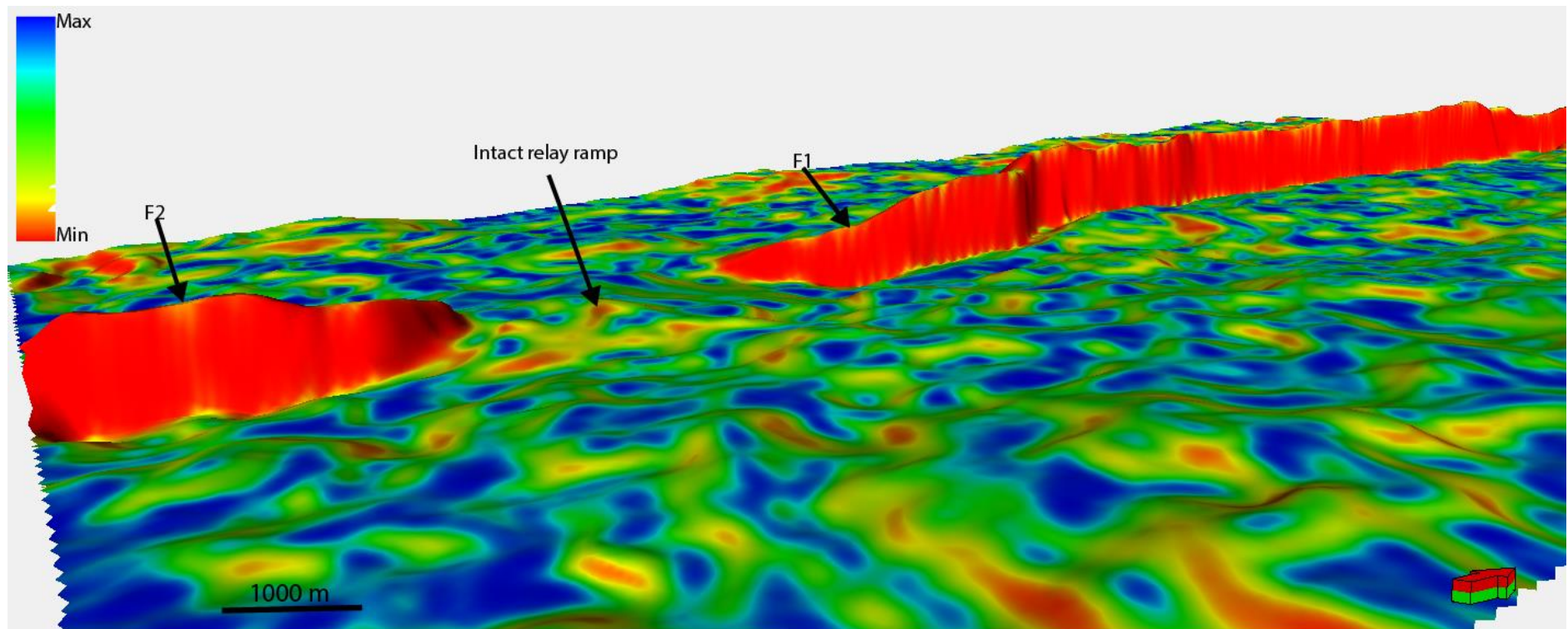


Figure 5.11: Edge detection attribute map calculated for the H2 horizon. The seismic attribute clearly mapped the intact relay ramp between faults F1 and F2, which was also mapped by the dip and dip-azimuth seismic attributes. Color bar varies from minimum to maximum percentages.

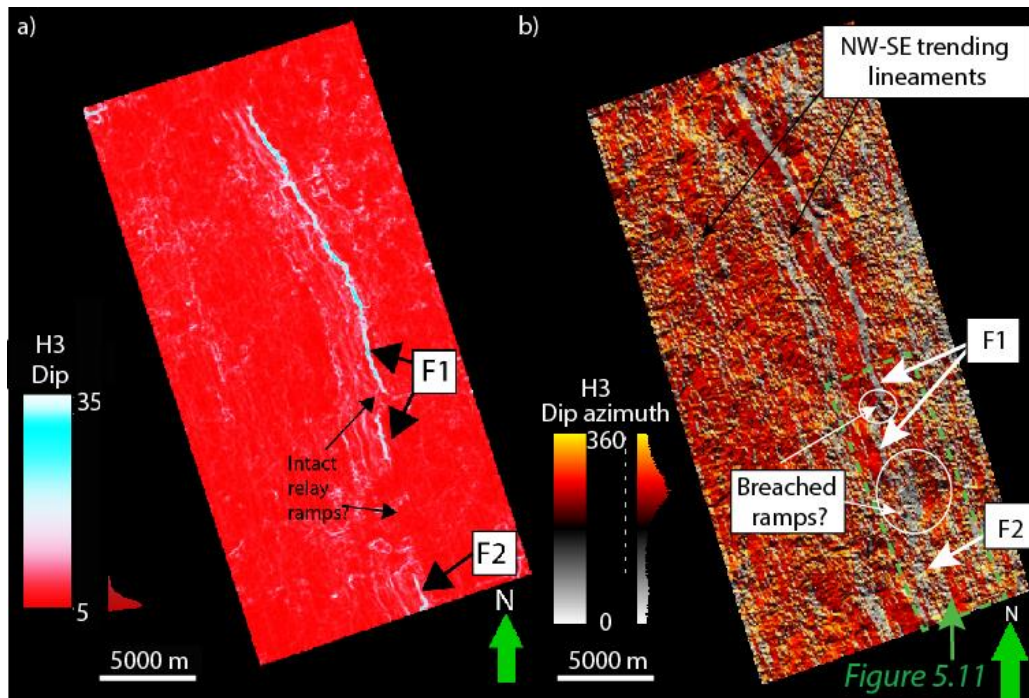


Figure 5.12: a) The dip attribute calculated for the H3 horizon highlighting NW-SE trending major regional faults, F1 and F2. The color bar is given in degrees. The horizon is mainly dipping ($\sim 1^\circ$ – 5°) from the horizontal. b) The dip-azimuth attribute calculated for the H3 horizon highlighting the connectivity between the two ends of fault F1 as well as fault F1 and fault F2 showing that the relay ramps become breached at depth. The color bar is given in degrees. The dip-azimuth for the H3 horizon is between 225° – 275° while the faults have an azimuth between 0° – 75° . The dip-azimuth attribute also clearly NW-SE trending lineaments straddling the major regional faults.

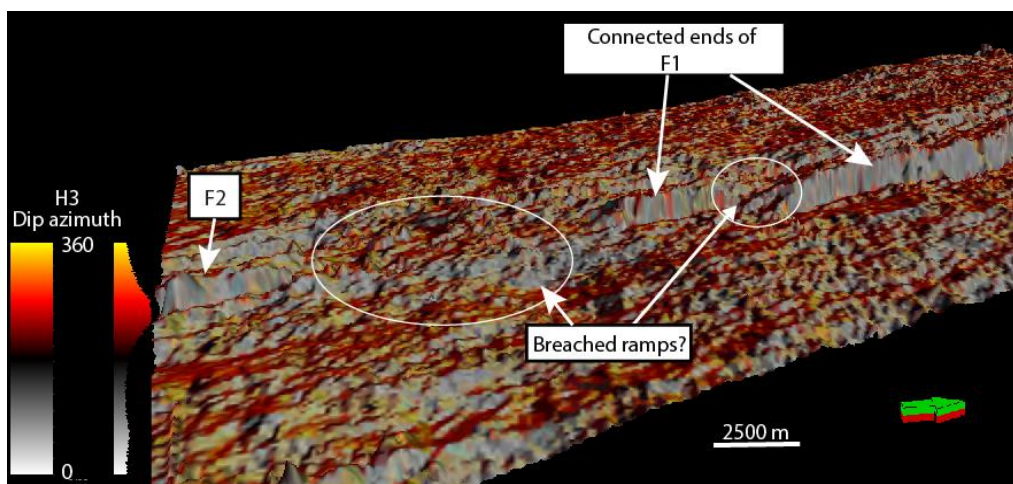


Figure 5.13: Perspective view of the H3 horizon after applying the dip-azimuth seismic attribute. The fault segments of F1 and F2 are linked along strike and are therefore one regional fault. Color bar is given in degrees.

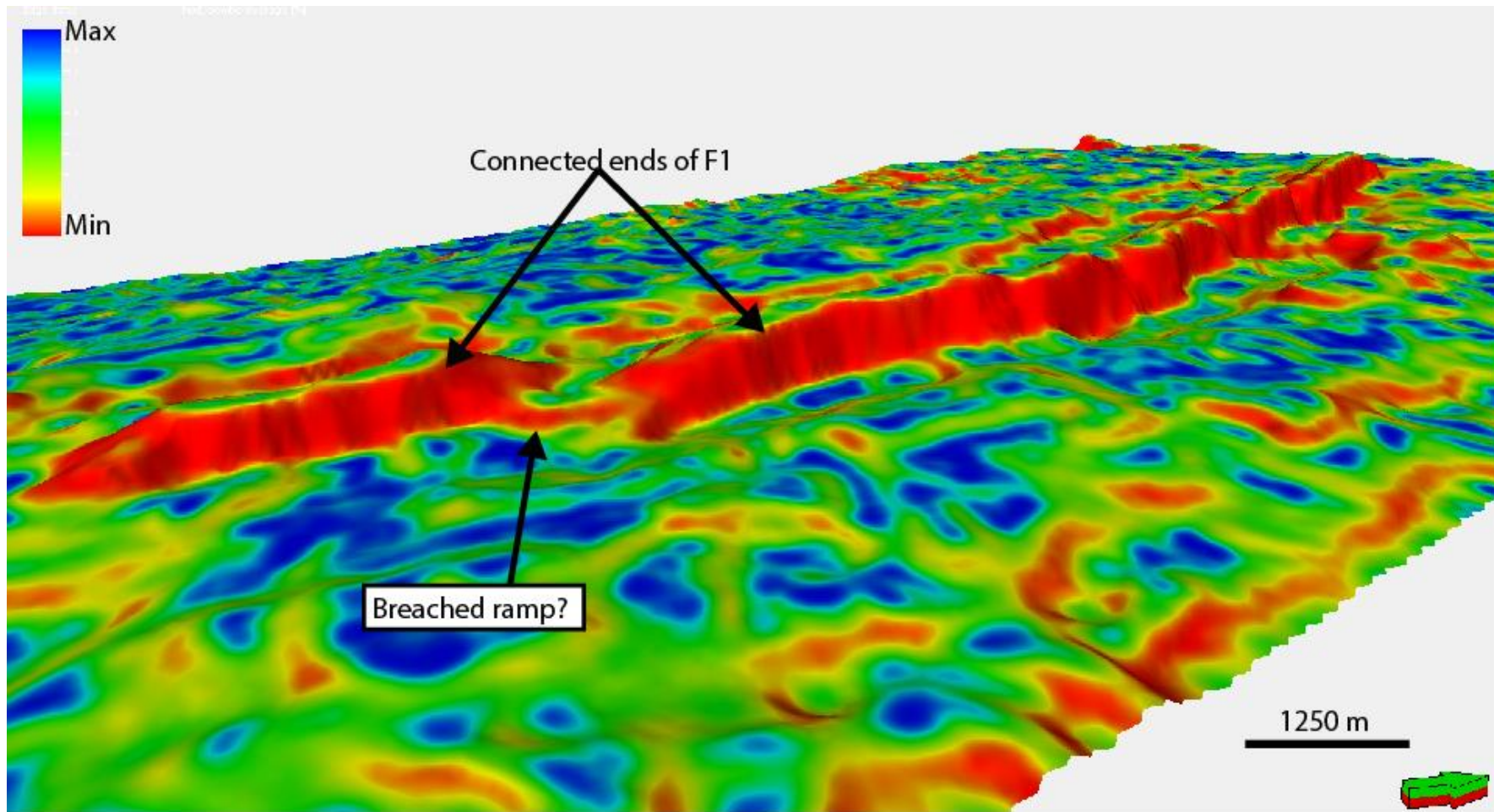


Figure 5.14: Edge detection attribute along horizon H3 showing the connected ends of fault F1. The edge detection attribute shows that the relay ramps become breached at depth. Color bar varies from minimum to maximum percentages.

5.1.2.2. *Complex Trace Attributes*

To further demonstrate the differences and similarities between attributes in fault mapping, the complex trace attributes, such as envelope, instantaneous phase and instantaneous frequency, were applied to the seismic horizons (Figure 5.15). In general these attributes have confirmed the general location of the major regional faults, F1 and F2, which are well detected by the elevation and edge detection maps as northwest-southeast trending features. Faults tend to have a consistent envelope, phase and frequency character that is distinct from non-faulted areas. For example, the envelope attribute shows the faulted zone with higher amplitude relative to its surroundings (Figure 5.15a). The instantaneous phase attribute characterizes the faulted zone as interchanged between negative and positive phase changes, therefore has not delineating the faulted zone explicitly as this attribute is highly sensitive to noise (Figure 5.15b). The instantaneous frequency attribute, on the other hand, highlights the faulted zone as a higher frequency zone (Figure 5.15c).

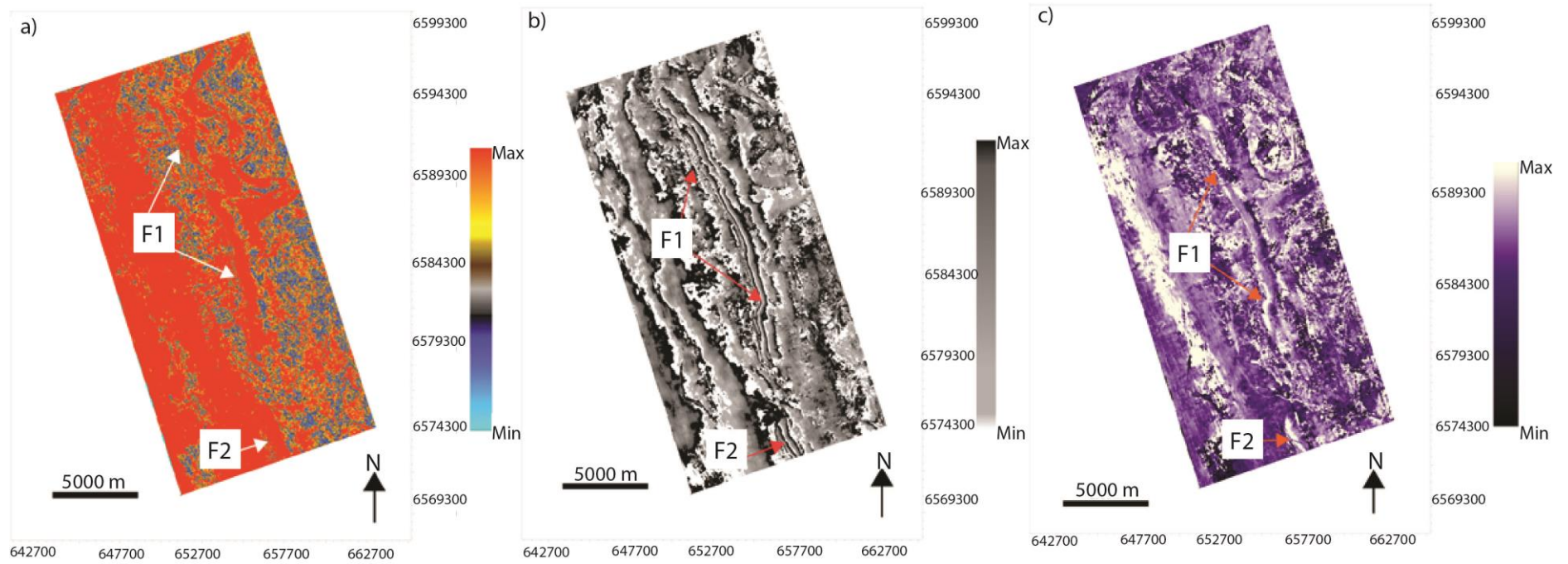


Figure 5.15: Stratal slices comparing: a) envelope, instantaneous phase and c) instantaneous frequency. Color bar indicates signal strength, phase change and frequency change, respectively. These complex trace attributes have been used in the identification of the major regional faults which are trending in a northwest-southeast direction.

5.2. Fault Interpretation

Structural analysis reveals normal faulting that can be associated with the major extensional episode in the Lower Cretaceous (103 Ma). F1, F2 and F6 strike NNW-SSE and have a NE dip direction, while F4, F5 and F7 strike NNE-SSW and have a SW dip direction as shown in the seismic sections and extracted fault surfaces (Figures 5.16) and stereonet maps (Figure 5.17). Table 5.2 provides the geometric characteristics of all the faults interpreted in this study.

Isopach thickness maps were computed between horizons; and these are shown in Figure 5.18. Isopach maps plot lines of equal thickness between rock types or formations (Sheriff, 2002). The thickness maps suggest an interesting relationship between the normal faults and sediment thickness. An immediate decrease in sediment thickness at the fault zone is observed between the H2 horizon and H3 horizon as well as the H3 horizon and H4 horizon (Figure 5.18). A decrease in sediment thickness close to the fault is shown by the localised zones of isopach thinning that straddles the normal faults (Figure 5.18). Extension is accommodated by concave-up NE dipping normal faults, F1 and F2, which have been active from the Lower Cretaceous to the Upper Paleogene (Figure 5.16a, c; Brown et al., 1995; De Vera et al., 2010; Isiaka et al., 2017).

The F3, F4, F5, F6 and F7 faults were only active in the Lower Cretaceous. Negative flower structures are observed between fault pairs (F1 - F4) and (F2 - F3) (Figure 5.16). The F3 fault splays off the F1 fault while the F4 fault converges at depth with the F2 fault.

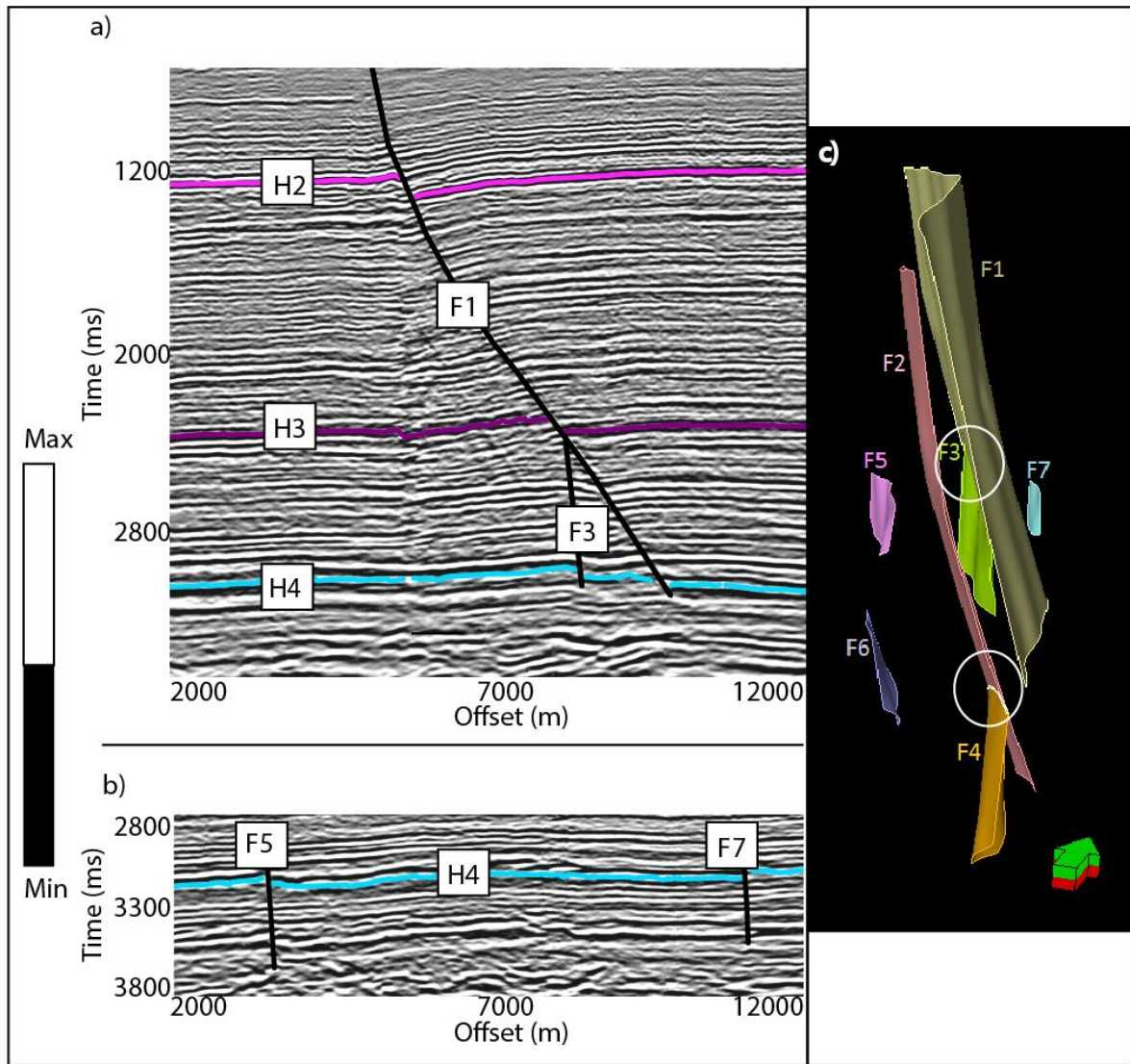


Figure 5.16: a) Seismic section (amplitude display) across the F1 and F3 faults and the horizons that the faults truncate. Color bar represents the seismic amplitude. b) Seismic section (amplitude display) across the F5 and F7 faults and the horizons that the faults truncate. Color bar represents the seismic amplitude. c) 3D fault plane geometry showing that negative flower structures (white circles) are observed between fault pairs (F1 – F3) and (F2 – F4).

Table 5.2: Strike, dip angle and geometry of picked faults

Fault Name	Strike (°)	Dip angle (°)	Dip direction	Nature of fault
F1	315	15 – 65	NE	Normal-listric
F2	315	20-50	NE	Normal-listric
F3	315	80	SW	Normal
F4	315	80	SW	Normal
F5	320	45	SW	Normal
F6	330	50	NE	Normal
F7	290	45	SW	Normal

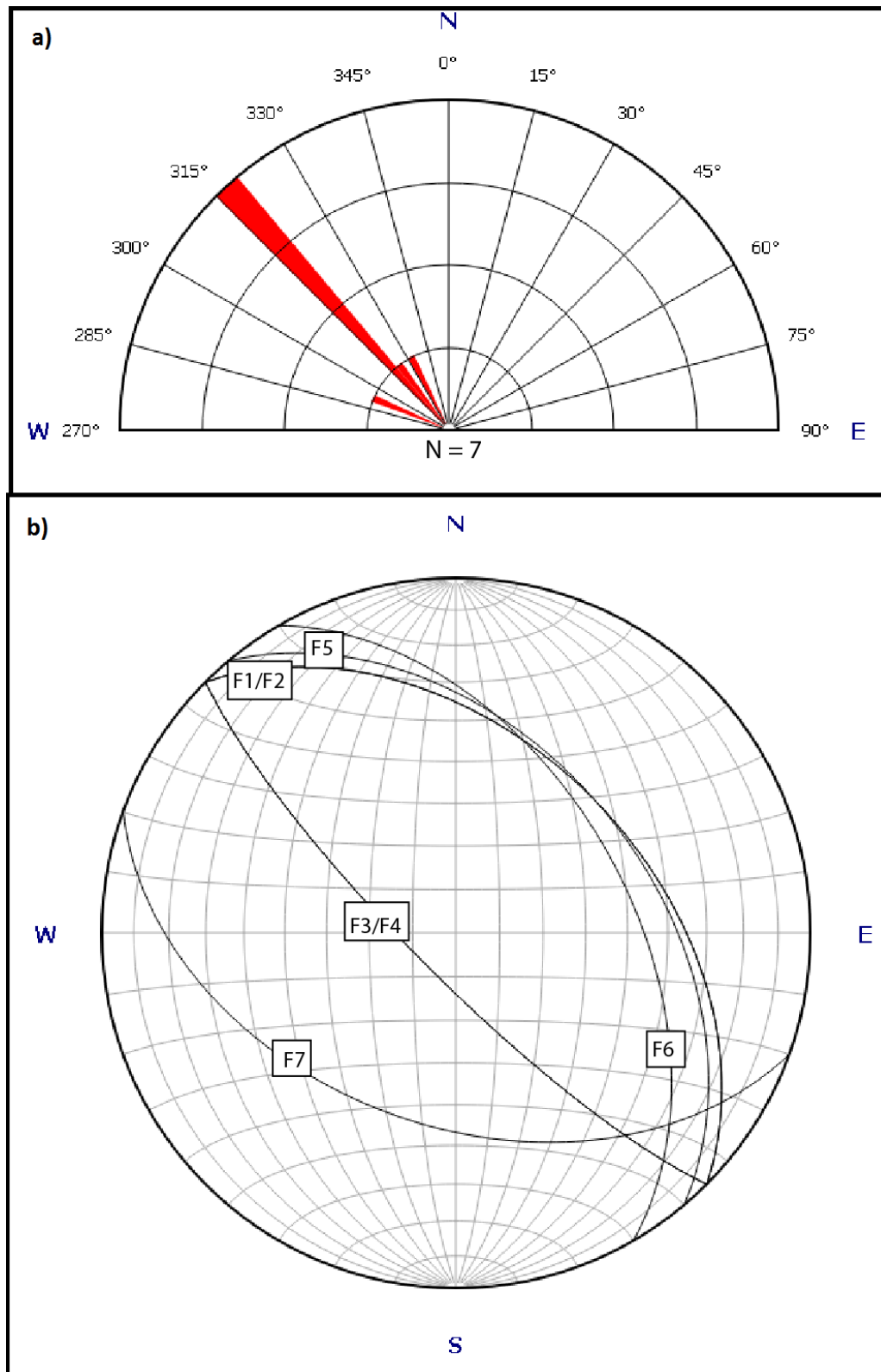


Figure 5.17 a) Equal area rose diagram half plot of fault plane orientations. $N = 7$ indicates the number of faults picked. There is a unimodal distribution in the strike of the faults; b) Stereonet of fault planes showing a bimodal distribution in the dip of faults. Faults dip NE or SW.

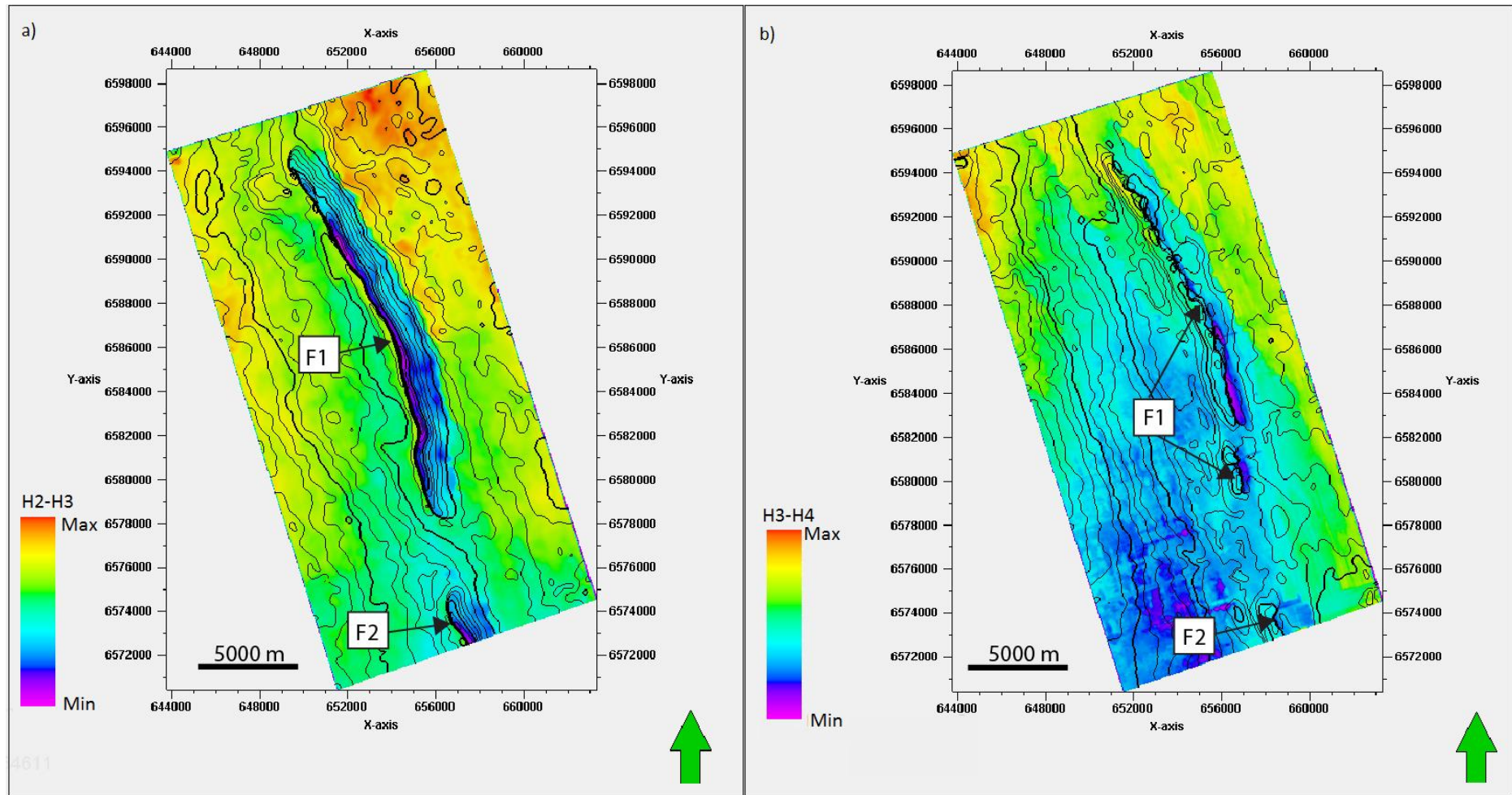


Figure 5.18: Isopach thickness maps between the a) H2-H3 horizons and b) H3-H4 horizons. Warmer colors indicate thicker rocks while thinner rocks are illustrated by the colder colors. The thickness of the rocks decreases at the fault zone for both the H2-H3 and H3-H4 isopachs due to faulting.

Throw versus depth (T-z) relationships were calculated to investigate the vertical variation in the throw of the main regional faults that have been interpreted. The throw was calculated from the time difference between the hanging wall and the foot wall cutoffs of a horizon (Figure 5.19; Figure 5.20) for four horizons: H2, H3, H4 and H5, using profiles orthogonal to fault strikes (Baudon and Cartwright, 2008). The relationship between the time difference of the hangingwall and foot wall cutoffs is directly proportional to the amount of fault throw (Figure 5.20). The time difference was then depth converted via the velocity model (Appendix I).

Consequently, the (T-z) plots were then plotted for faults F1 and F2. The average fault throw across all profiles is 37 m for fault F1 and 47 m for fault F2 (Figure 5.21). The maximum and minimum fault throw for fault 1 (F1) is 125 m and 34 m, respectively (Figure 5.21). The maximum and minimum fault throw for fault 2 (F2) is 91 m and 16 m, respectively (Figure 5.21). The T-z profiles for both faults F1 and F2 generally show a concave-up curve which tends to have the highest throws focused on the shallower regions of the profile and decreasing values with depth (Figure 5.21). There is a decrease in fault throws with depth for both faults F1 and F2; therefore the faults are listric in nature. The throw profiles show varying fault dips ranging from 15°-65° and 20°-50° for faults F1 and F2, respectively.

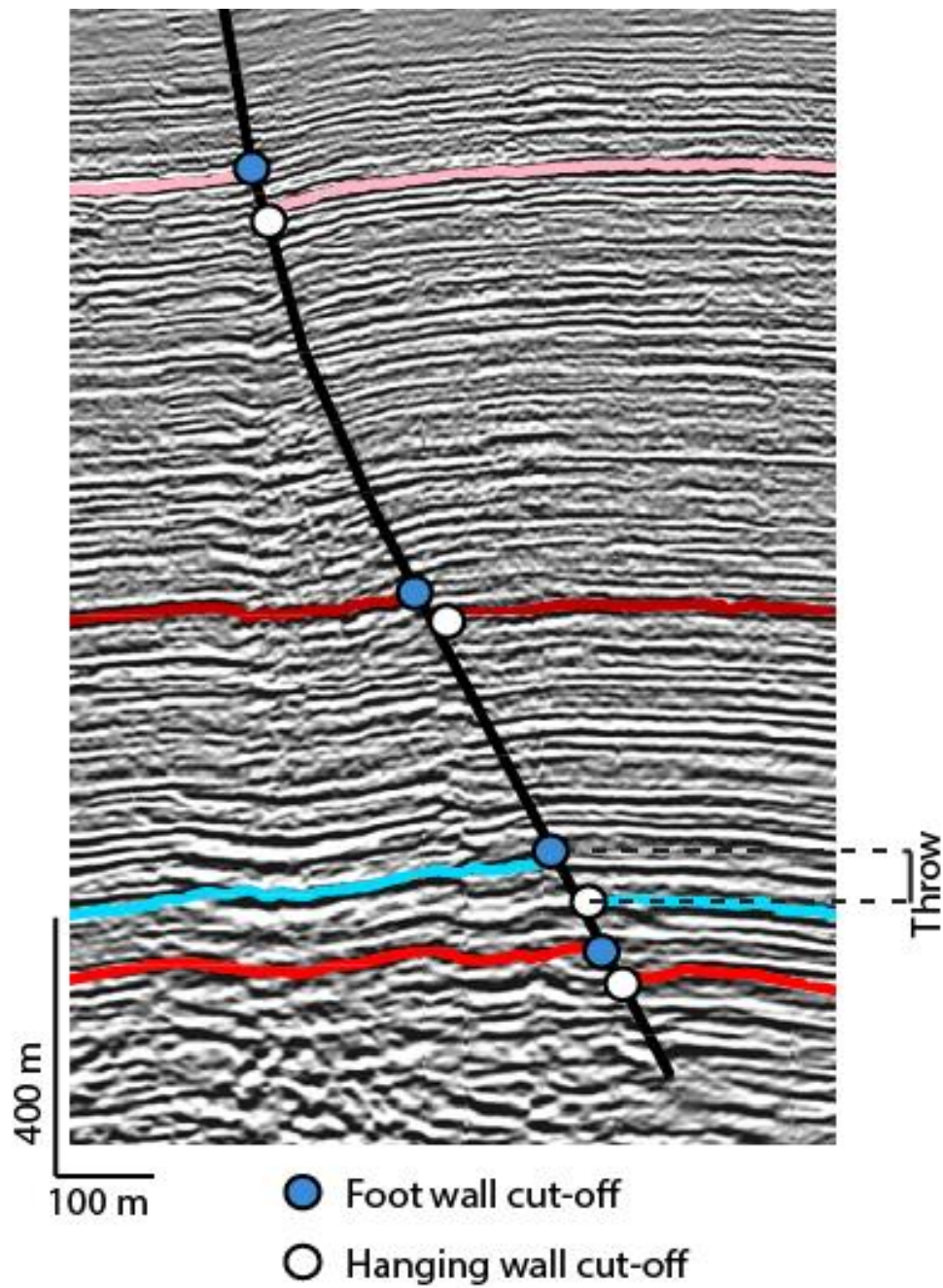


Figure 5.19: Representation of an interpreted fault from the study area in the Orange Basin to illustrate the technique used to estimate fault throws from the difference between the footwall cut-off (blue dots) and hanging wall cut-off (white dots).

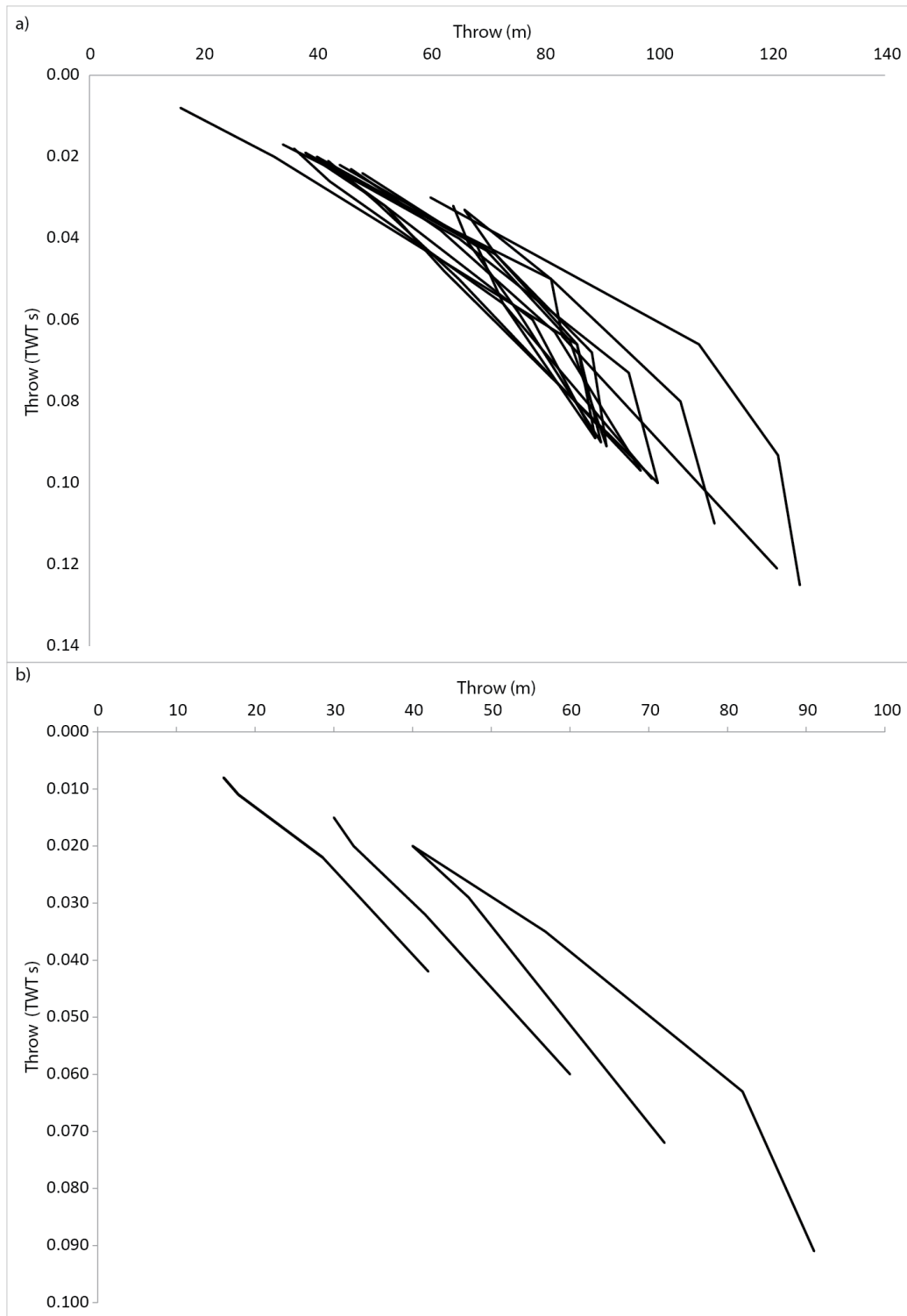


Figure 5.20: Vertical throw distribution plots for arbitrary crossline profiles with the throw in metres (m) on the horizontal axis versus the time difference between the hanging wall and foot wall of a fault given by the throw in two-way time (TWT) in seconds on the vertical axis. The time difference is directly proportional to the throw of a fault for both faults: a) F1 and b) F2.

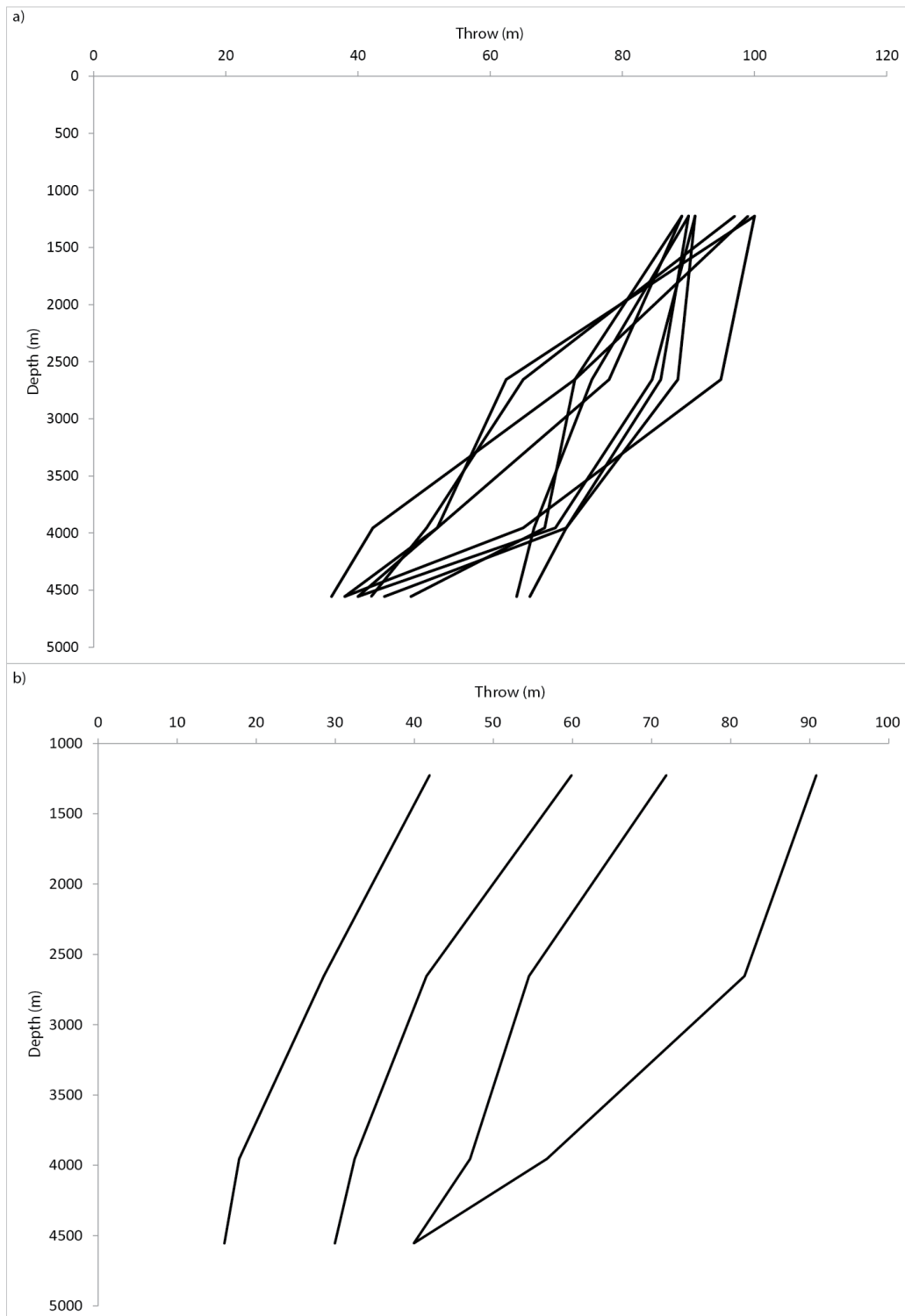


Figure 5.21: Throw versus depth (T-z) plots for arbitrary crossline profiles with the throw in metres (m) on the horizontal axis versus the depth in metres (m) on the vertical axis. There is a decrease in fault displacement with depth, concluding that the faults have a listric nature.
a) The maximum and minimum fault throw for fault 1 (F1) is 125 m and 34 m, respectively;
b) The maximum and minimum fault throw for fault 2 (F2) is 91m and 16m, respectively.

5.3. Fault Enhancement Through Volumetric Attributes

To further delineate and track the faults across the seismic volume (i.e., along inline, crossline and time slices), the volumetric attributes were computed to the entire volume covering the study area. The variance attribute was successful in mapping the faults. The attribute confirmed the existence of some of the faults (e.g., F1, F3, F5 and F6) that were mapped by conventional seismic interpretation and horizon-based seismic attributes (Figures 5.22; Figures 5.23). Furthermore, time slices extracted from the variance cube at 1300 ms (Figure 5.22a) and 2300 ms (Figures 5.23) show that the fault (F1) is composed of various segments. Also illuminated by the variance attribute is a possible meandering river system in the relay ramp between fault segments, F1 and F2 (Figure 5.22c). Additionally, several other NW-SE striking faults are identified by applying the variance attribute (Figure 5.24). Furthermore, the chaos attribute shows delineation of the major regional fault (F1) and also highlights the gas chimney on the seismic data (Figure 5.25b), which is not prominent on the conventional interpretation.

Following the application of the variance and chaos attribute, the ant-tracking was computed to enhance the detection of subtle faults and their crosscutting relationships (Figure 5.26b). The ant-tracking attribute provided some details on the degree of faulting that was not delineated by chaos, variance and normal amplitude displays. For example, the ant-tracking attribute has identified linear features that straddle the major regional faults (Figure 5.26b). These lineaments trend in both the NW-SE and NE-SW directions. The true vertical extent of the major regional fault is now observed at depths of 550 m to 3200 m, which was not known with the previous conventional interpretations.

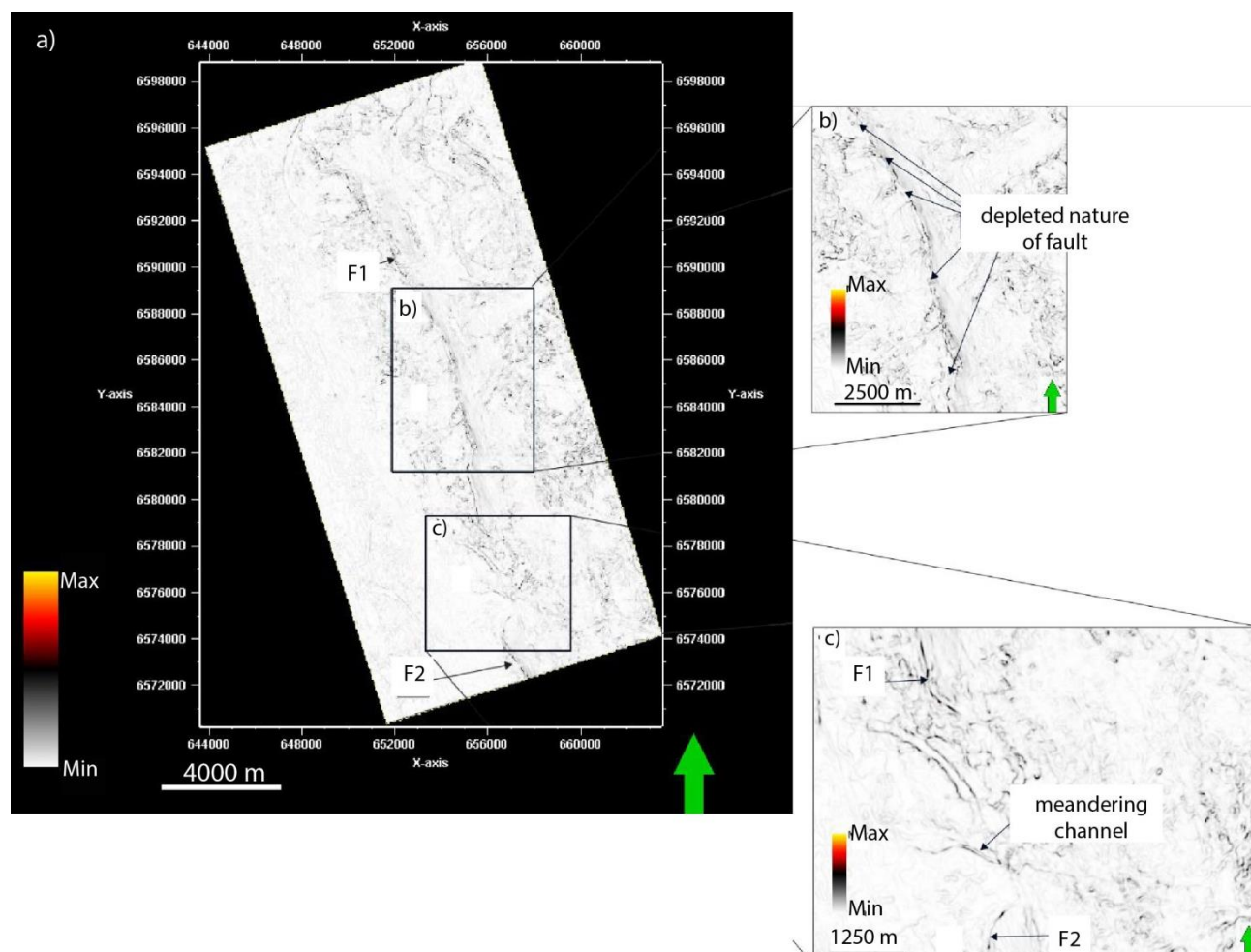


Figure 5.22: a) Variance time slice extracted at 1300 ms with the visible faults marked. b) Normal fault segments appear to make up the fault that has been interpreted as Fault F1. c) A meandering channel is observed between the main regional faults, F1 and F2. Color bar indicates maximum variability between traces (black) versus minimum variability between traces (white).

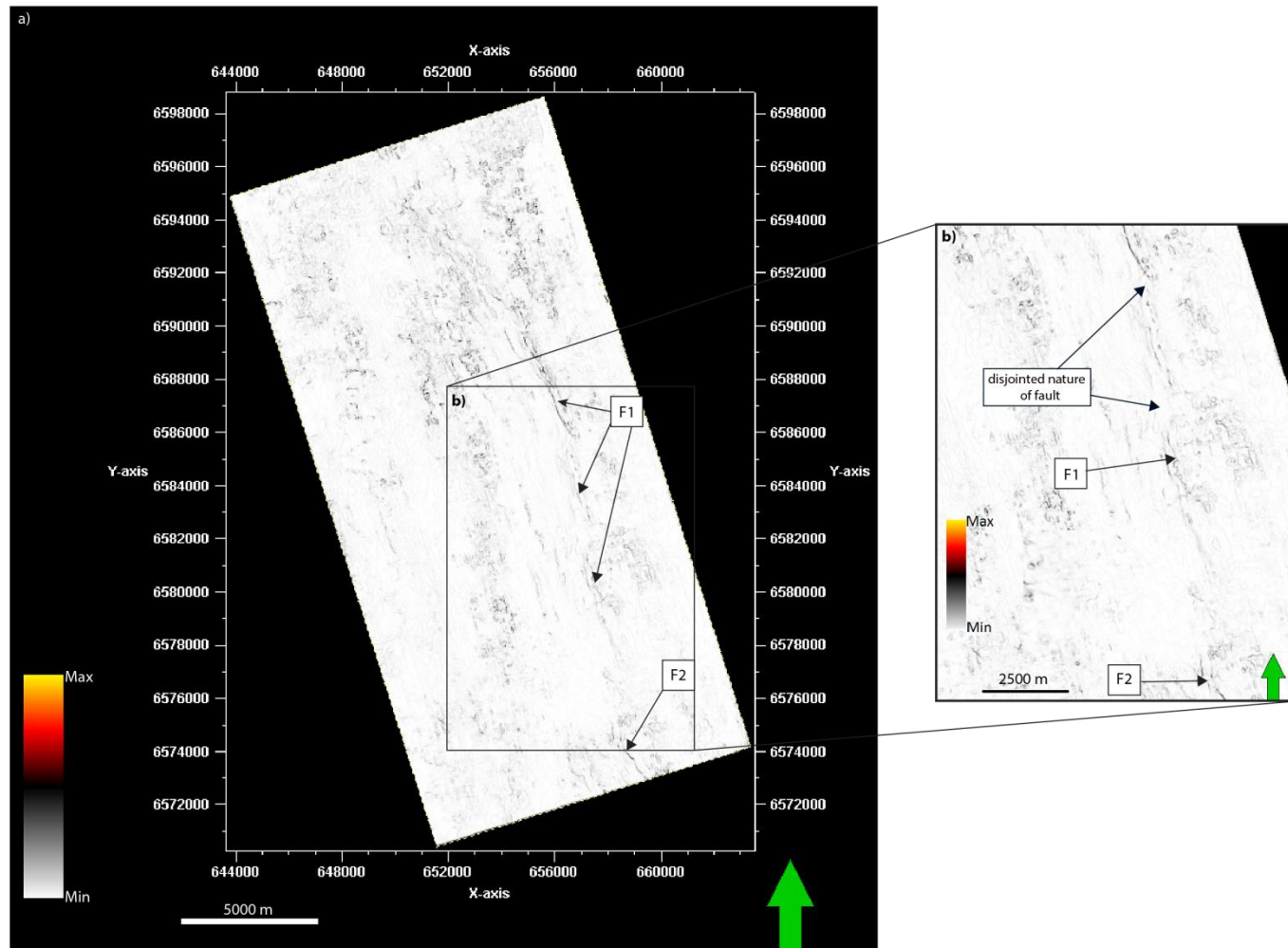


Figure 5.23: Variance time slice extracted at 2300 ms with the visible faults marked. b) Normal fault segments appear to make up the fault that has been interpreted as Fault F1. Color bar indicates maximum variability between traces (black) versus minimum variability between traces (white).

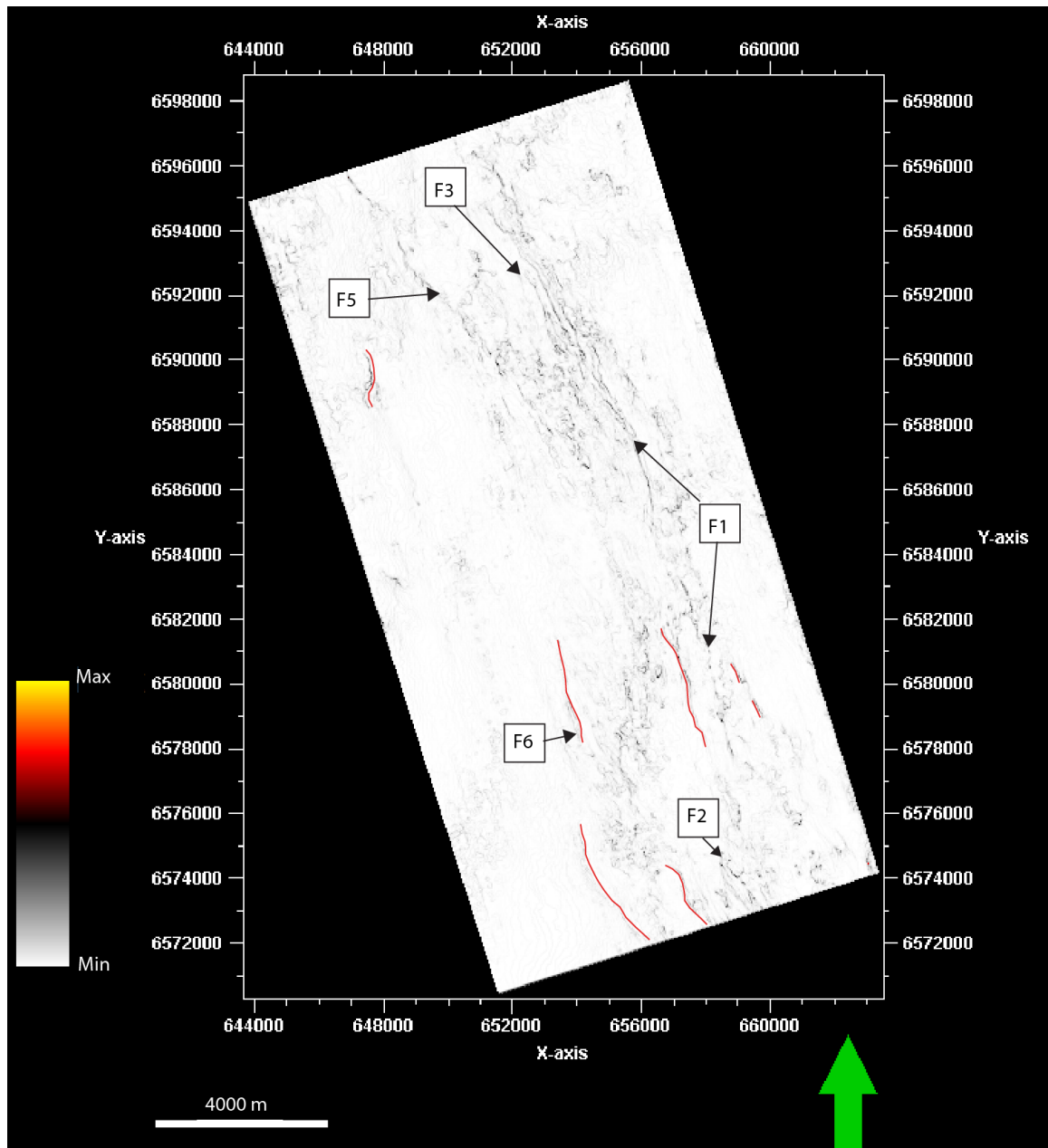


Figure 5.24: Variance time slice extracted at 3000 ms with the visible faults marked. NW-SE striking faults (in red) have been identified in addition to the conventionally picked faults from amplitude data (F1, F3, F5 and F6). Color bar indicates maximum variability between traces (black) versus minimum variability between traces (white).

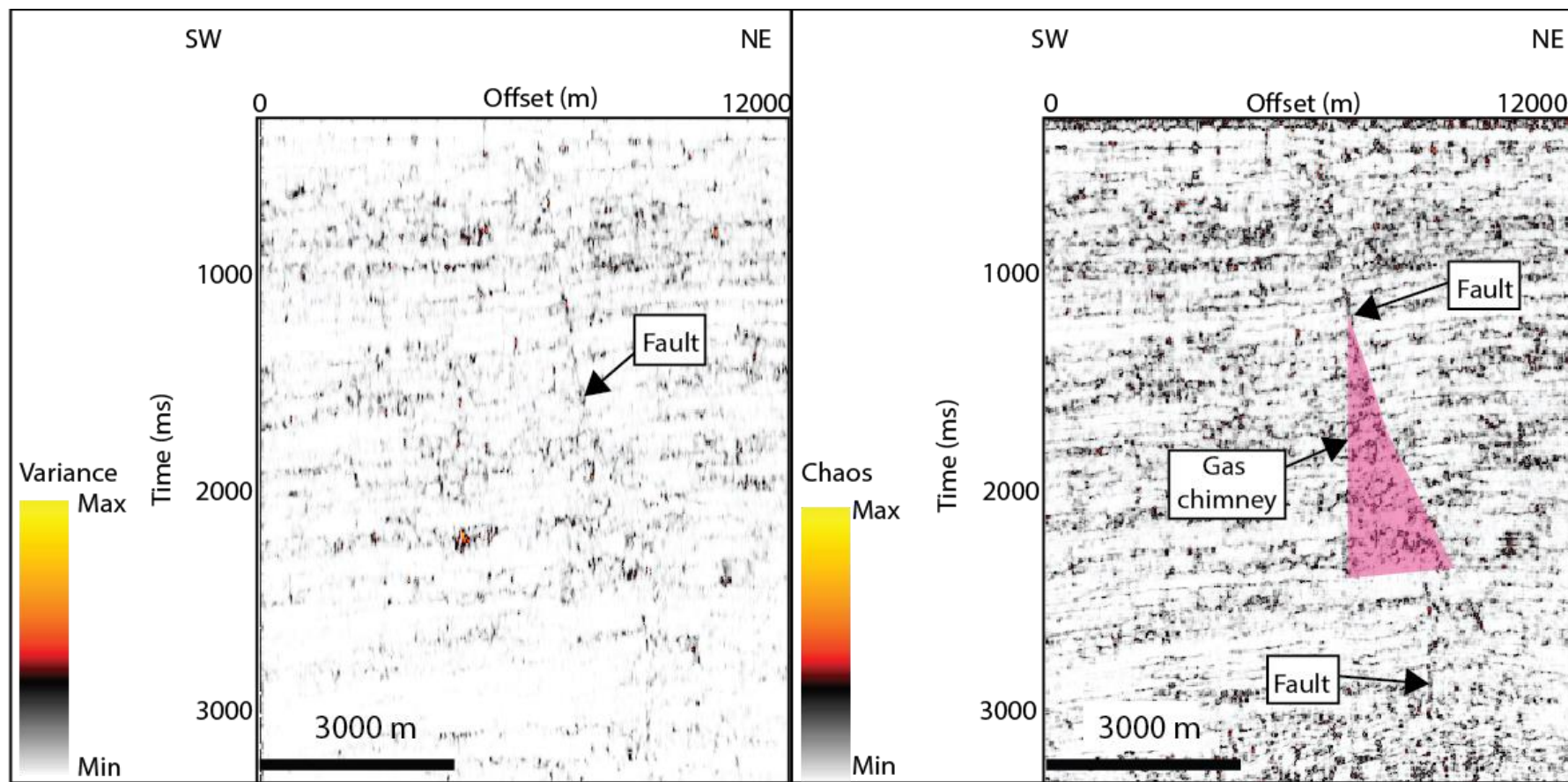


Figure 5.25: The variance attribute vs. chaos attribute. a) The variance attribute highlights faults. b) The chaos attribute highlights faults and a gas chimney. Color bar indicates maximum variability between traces (black) versus minimum variability between traces (white).

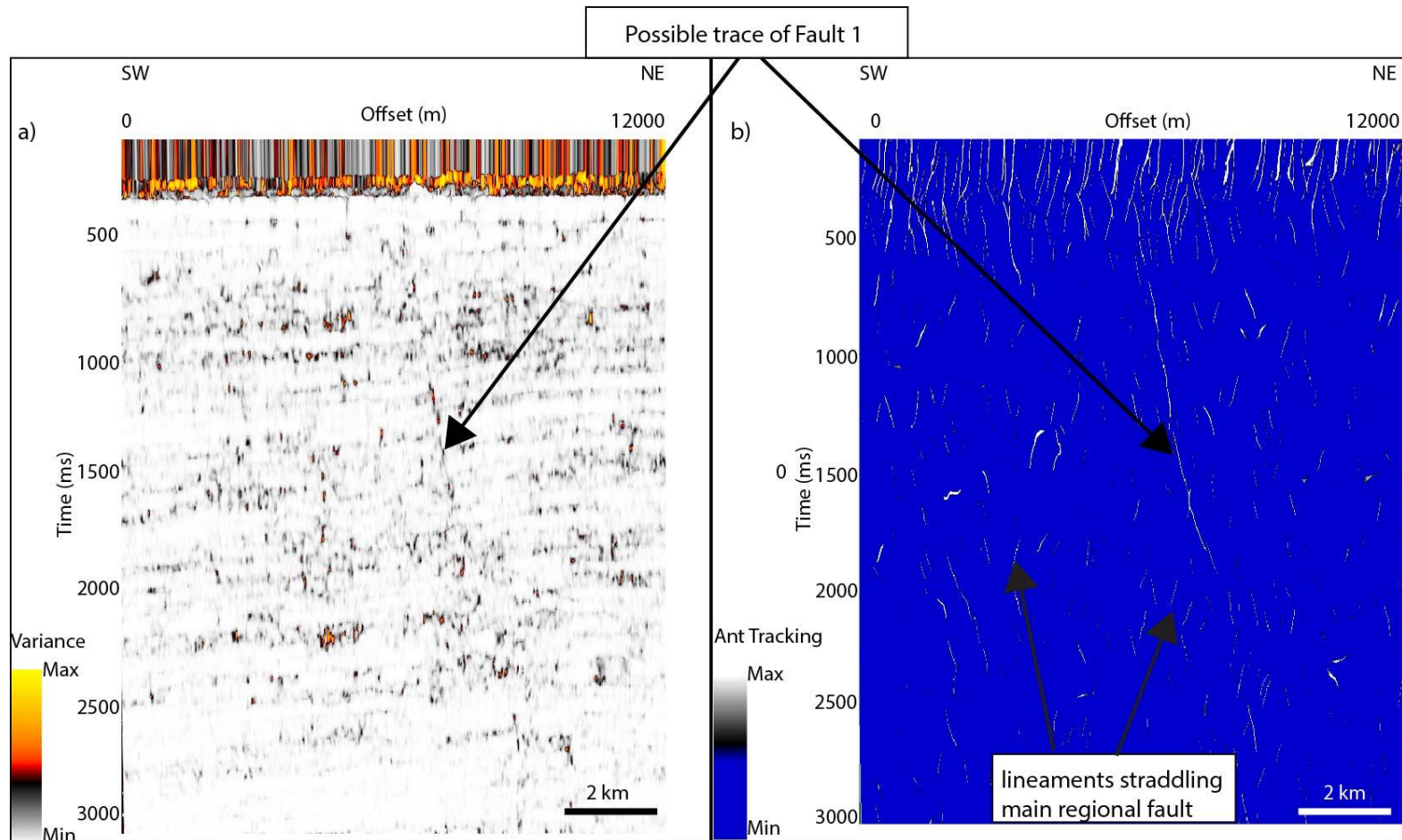


Figure 5.26.: The variance vs ant-tracking attribute. a) The variance attribute highlights major regional faults. Color bar indicates maximum variability between traces (black) versus minimum variability between traces (white). b) The ant-tracking attribute highlights the major regional faults and linear features that straddle the major regional faults. These lineaments trend in both the NW-SE and NE-SW directions. Color bar indicates maximum variability between traces (white, black) versus minimum variability between traces (blue).

5.4. Structural Modelling

The structural modelling process involves fault modelling, pillar gridding and vertical layering. The fault modelling process defines the fault surfaces that will form the basis of the 3D grid for structural modelling. The seven picked faults (Figure 5.27) have been modelled and incorporated into a structural framework (Figure 5.28).

5.4.1. Pillar Gridding

Pillar gridding creates a skeletal 2D grid of the top, mid and base skeletons (Figure 5.29). The grid is confined at its' top extent by the H1 horizon and at the bottom by the H4 horizon. Pillar gridding does not take into account the listric fault geometry; therefore all the seven faults have been gridded as linear surfaces. The cellular grid created has an average grid spacing of 100 increment in the I-direction and a 100 increment in the J-direction. The trend of faults was assigned automatically. Furthermore, the process of fault modelling is complex with the current data due to the negative flower structures which manifest themselves as conjugate (λ -type) faults. λ -type faults exist when a major fault is truncated by a minor fault. Where the λ -type intersection occurs, the fault planes have been eliminated prior to building the fault model. The pillar grid was constructed from the H2 to the H4 horizon.

5.4.2. Vertical Layering

Vertical layering involves making horizons, zones and layers (Figure 5.30). This is done by inserting the fault model into the pillar grid. The results from vertical layering were then used to construct a 3D structural model from the top of the H2 surface to the H5 surface (Figure 5.31). The 3D structural model is divided into zones.

The structural model provides a 3D volume in which the final geological model will be constructed with information obtained from the structural, tectono-stratigraphic and seismic attribute study conducted for the whole project.

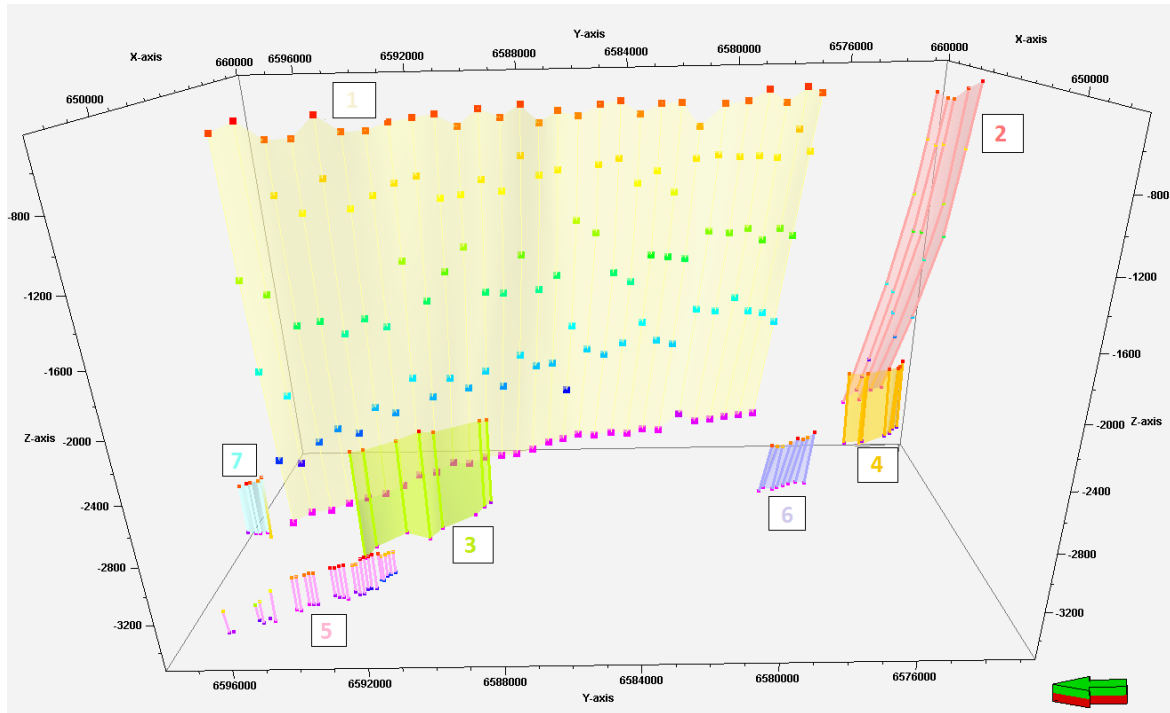


Figure 5.27: East-west cross-section of unmodelled faults for the AK99 3D seismic data. Each fault is marked by a number. Vertical exaggeration = 5.

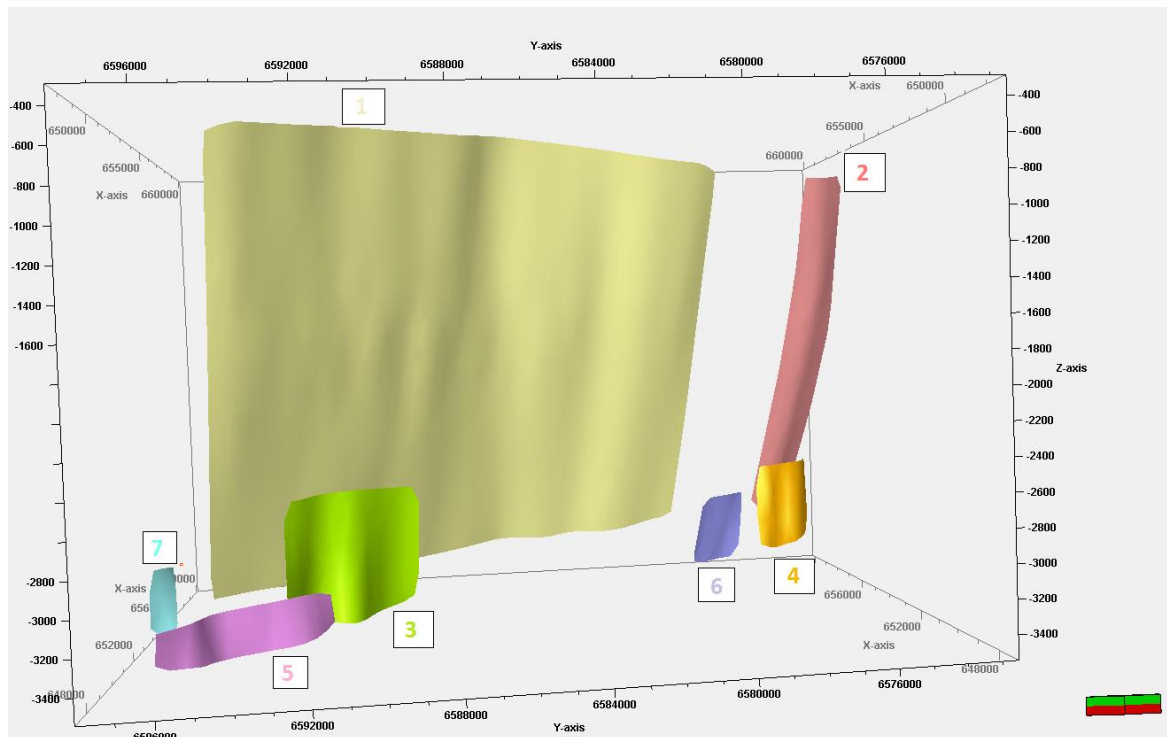


Figure 5.28: East-west cross-section of the fault framework for the AK99 3D seismic data. Each fault is marked by a number. Vertical exaggeration = 5.

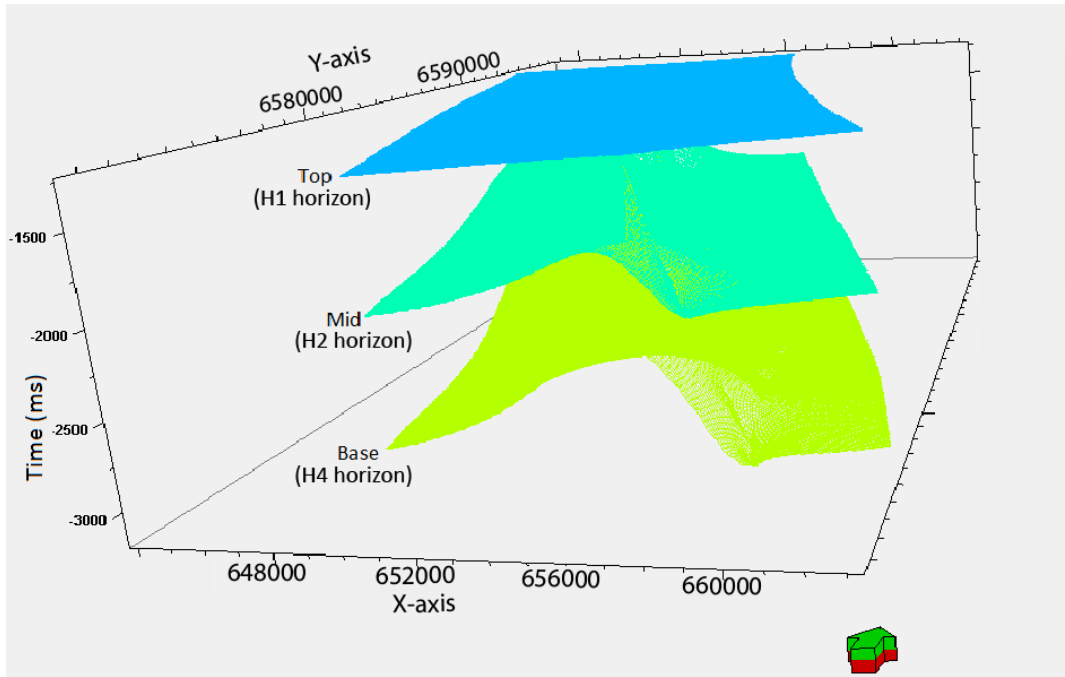


Figure 5.29: Skeletal framework generated from pillar gridding showing the top, mid and base skeleton grids. The pillar grid was constructed from the H2 to the H4 horizon. Vertical exaggeration = 5.

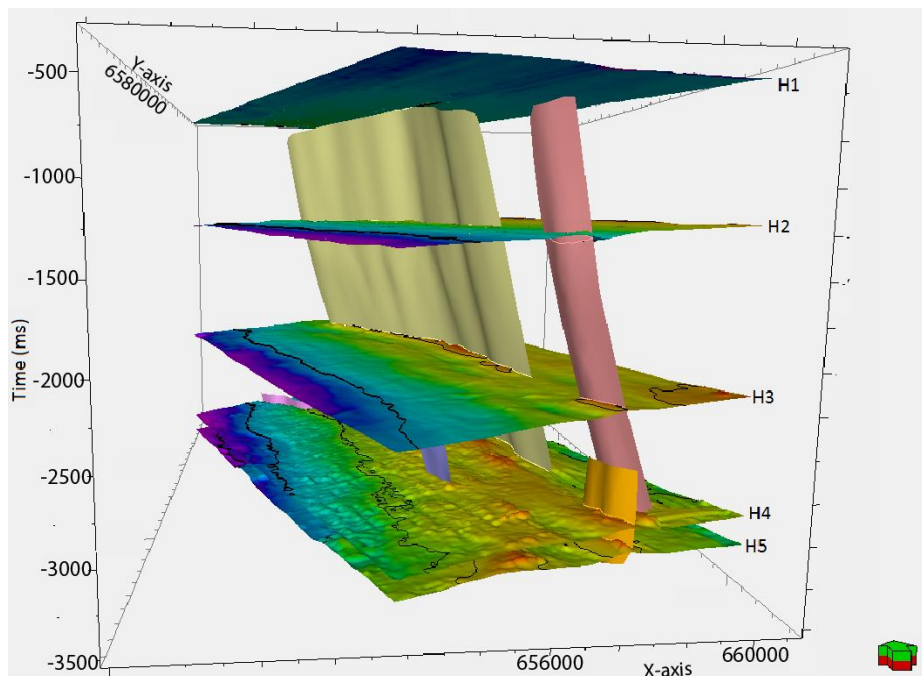


Figure 5.30: 3D model of horizons modelled onto the fault framework. The model was constructed from the top of the H2 surface to the H5 surface. Vertical exaggeration = 5.

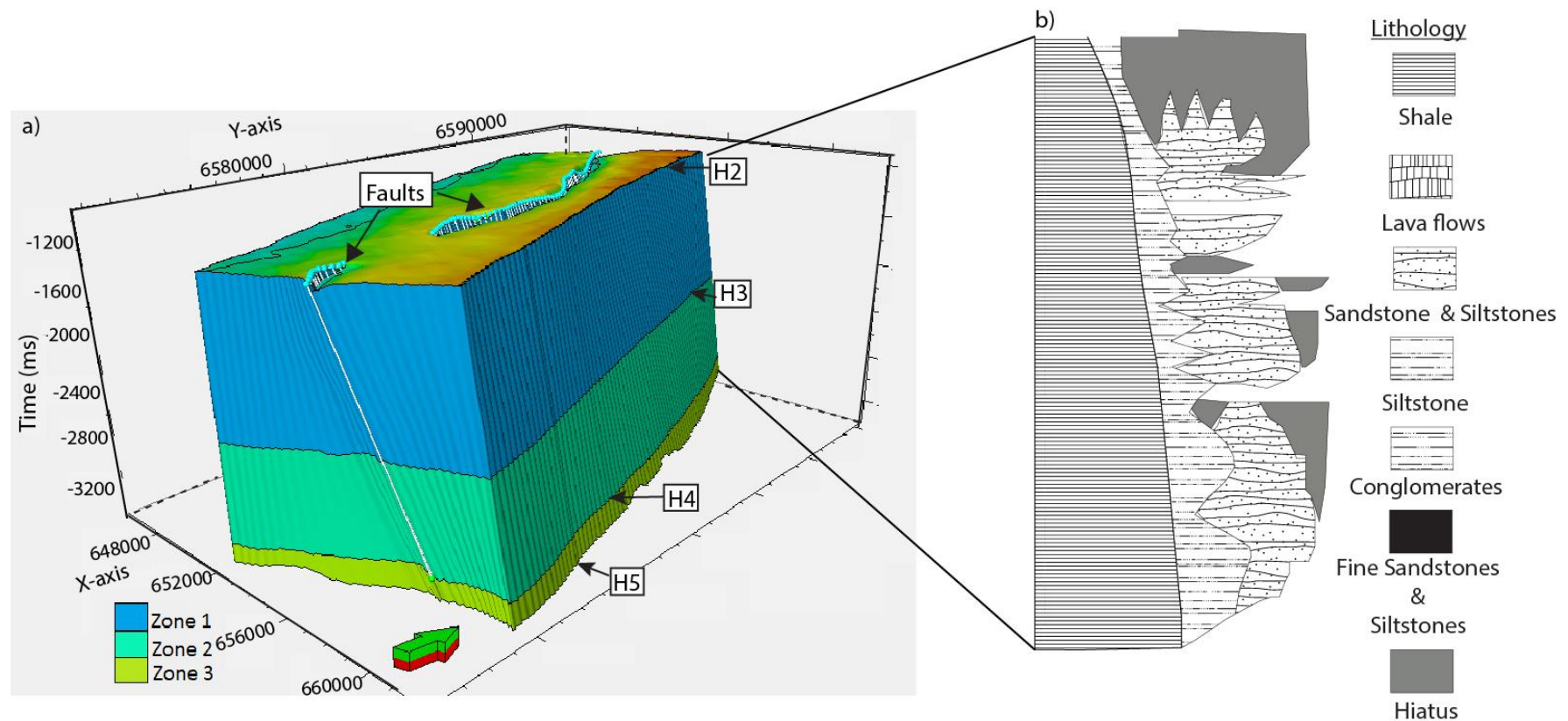


Figure 5.31: a) The 3D structural model from the top of the H2 surface to the H5 surface. The 3D model is divided into 3 zones and shows the major faults that cross-cut the zones. Vertical exaggeration = 5. The local stratigraphy is interpolated from previous studies ([Marcano et al., 2013](#)).

6. Discussion

6.1. Structural Enhancement Through Seismic Attributes

Seismic attributes have enhanced the detection of structures such as faults, lineaments, pockmarks and gas chimneys. The calculation of horizon-based seismic attributes successfully enhanced a number of faults below the conventional seismic resolution limit, therefore improving visualization of hydrocarbon migration pathways (see section 6.2). The dip attribute identified the major regional fault (F1) to have a dip above 25° (see section 5.1.2). The advantage of the dip-azimuth attribute over dip attribute is that it has identified NNW-SSE linear features trending in the same direction as the main regional faults (see section 5.1.2). These structures are interpreted as evidence that extension is the major tectonic regime in the Orange Basin (Muntingh and Brown, 1993; Brown et al., 1995; Jungslager 1999; Boyd et al., 2011). The application of edge detection attributes to the data provided a further confirmation of what has been observed from applying the dip-azimuth attribute (see section 5.1.2). However, it particularly enhanced the detection of the fault continuation and connectivity.

The concept of fault linkage is illustrated by the dip-azimuth, edge detection and variance attributes (see Figure 5.9b; Figure 5.10; Figure 5.11; Figure 5.12b; Figure 5.13; Figures 5.22a, b; Figure 5.23). Two end member models for hard linked fault systems have been proposed by Walsh et al. (2003): 1) the isolated fault growth system, and 2) the coherent fault growth system. The isolated fault growth model involves linkage across randomly distributed, isolated, minor faults due to a uniform accumulation of strain in each of them, therefore causing fault linkage (Fossen and Rotevatn, 2016). The coherent fault growth model involves a non-homogenous distribution of strain in the sedimentary cover above a reactivated fault, therefore causing linkage of segmented fault systems upwards from the reactivated fault (Childs et al., 2009; Fossen and Rotevatn, 2016). Normal faults form a relay ramp at 1.3 s (Figures 5.9a, b and Figure 5.10) and become breached at greater depth (2.45 s) (Figure 5.12a, b; Figure 5.13; Figure 5.14). The breaching fault, which is otherwise beneath the seismic resolution for conventional seismic interpretation, becomes visible via the application of horizon attributes.

The coherent model suits the current study because the major normal fault system (F1) is a growth fault, implying that rocks accumulate during the development of the fault. The growth nature of the fault is supported by the isopach maps between the horizons, which show thinning of rocks at the fault zone (Figure 5.18). Stress builds in the rocks during progressive fault growth causing linkage of segmented fault systems below the rocks (Walsh et al., 2003; Fossen and Rotevatn, 2016).

The chaos attribute is crucial in highlighting structural elements with a large variation in local dips and azimuth, such as the faults and gas chimney (Figure 5.25b). The chaos attribute highlights the gas chimney due to the chaotic nature of its seismic reflectors, while the fault is indicated by an abrupt change in the dip angle.

6.2. Structural Controls on Hydrocarbons

Hydrocarbon leakage dynamics have been assessed in the Orange Basin by various authors (Hartwig et al., 2010, 2011; Kuhlmann et al., 2011). This study takes the route of applying seismic attributes to the seismic data to clearly map the hydrocarbon pathways. The main structures identified for hydrocarbon migration are faults and the fractures, with the latter occurring ubiquitously throughout the gas field.

Figure 6.1 is a conceptual model showing the key elements in the structural evolution of the Orange Basin post-Cretaceous to the present. The model suggests a strong correlation between the major regional faults, fractures and hydrocarbon fluid dynamics. A gas chimney indicates that gas originates from the Albian-Aptian source rocks of late Lower Cretaceous age (Figure 6.1). From conventional seismic interpretation, the study has revealed two major regional faults (F1 and F2) (Figure 5.16a, c). The regional faults, active from the Lower Cretaceous until the recent Paleogene, have a strike orientation of NNW-SSE and dip in a NE direction (See section 5.2). These faults originate above the Albian-Aptian source rocks, therefore providing a conduit for hydrocarbon flow from the source (Figure 6.1).

When coupled with a rollover anticline, the faults form a structural trap for hydrocarbons, provided that the faults are non-communicative (Figures 6.2; 6.3a). Due to overpressure caused by the influx of fluids from the source to the reservoir and sediment overburden load, the trap could have failed (Heggland, 2005; Figure 6.1). Minor fault seal analysis reveals that there is possible leakage of hydrocarbons to the seafloor via vertical transmission from the main regional faults and laterally through the margins of the gas chimneys then through minor faults and fractures (Figure 6.3).

The elevation map and seismic sections show a successful mapping of a positive elevated seabed feature, which is interpreted in this study as a seafloor mound (Figures 5.1a, b). The seafloor mound located directly above the gas chimney could indicate fluid leakage (see Figure 6.3b). On the seafloor, there are pockmarks and a seafloor mound (Figure 6.3b,c), both which previously have been recognised by Aminzadeh and Berge (2013). Pockmarks are negative topographic features occurring on the seafloor formed via abrupt fluid flux (Judd and Hovland, 2009). The pockmarks have similar diameters when compared to other pockmarks elsewhere (Judd and Hovland, 2009; Hartwig et al., 2012; Ostanin et al., 2013).

According to [Heggland's \(2005\)](#) classification of traps and gas chimneys, the chimney is classified as a Class A Type 1 chimney where hydrocarbons migrate from a deeper source and leak through a fault at the crest of the trap ([Figure 6.4](#)). [Figure 6.5](#) presents a schematic illustration of soft-linked ([Figure 6.5 a](#)) and hard-linked ([Figure 6.5 b](#)) relay ramps, which have implications for fluid flow.

Whether breached or not, the structural complexities presented by faults and fractures present at relay ramps make them potential lateral and vertical migration pathways for fluids ([Fossen and Rotevatn, 2016; Figure 6.5](#)).

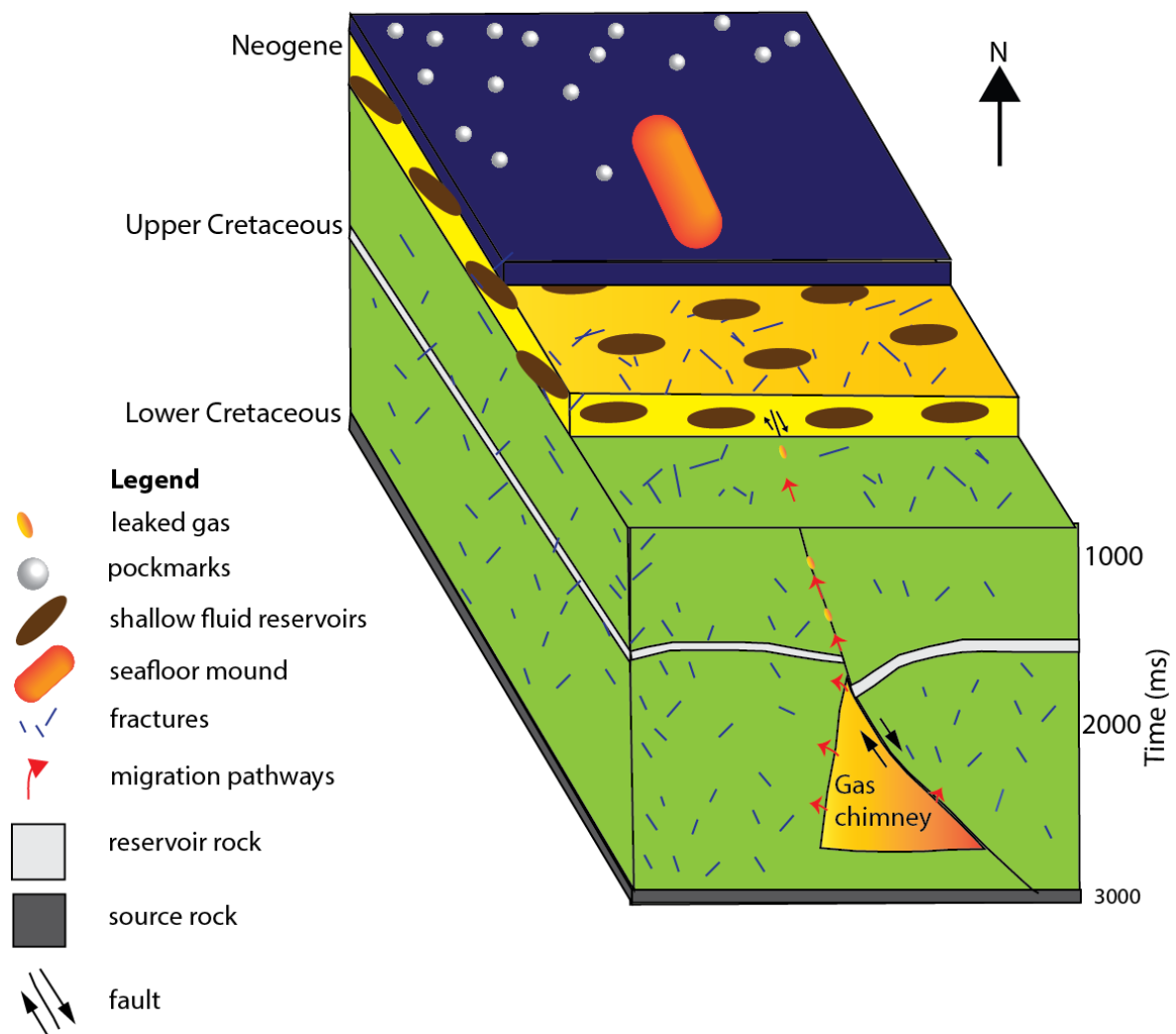


Figure 6.1: Conceptual diagram showing the key elements in the structural evolution of the Orange Basin post-Cretaceous to the present. There is a relationship between the major regional faults, fractures and hydrocarbon fluid dynamics. The hydrocarbons originate from source rocks and migrate upward in the form of a gas chimney. Hydrocarbons are dispersed via faults and fractures both laterally and vertically. The red arrow shows the migration pathway of the hydrocarbons from the gas chimney to the shallow reservoirs where they accumulate before they are expelled from pockmarks and the seafloor mound.

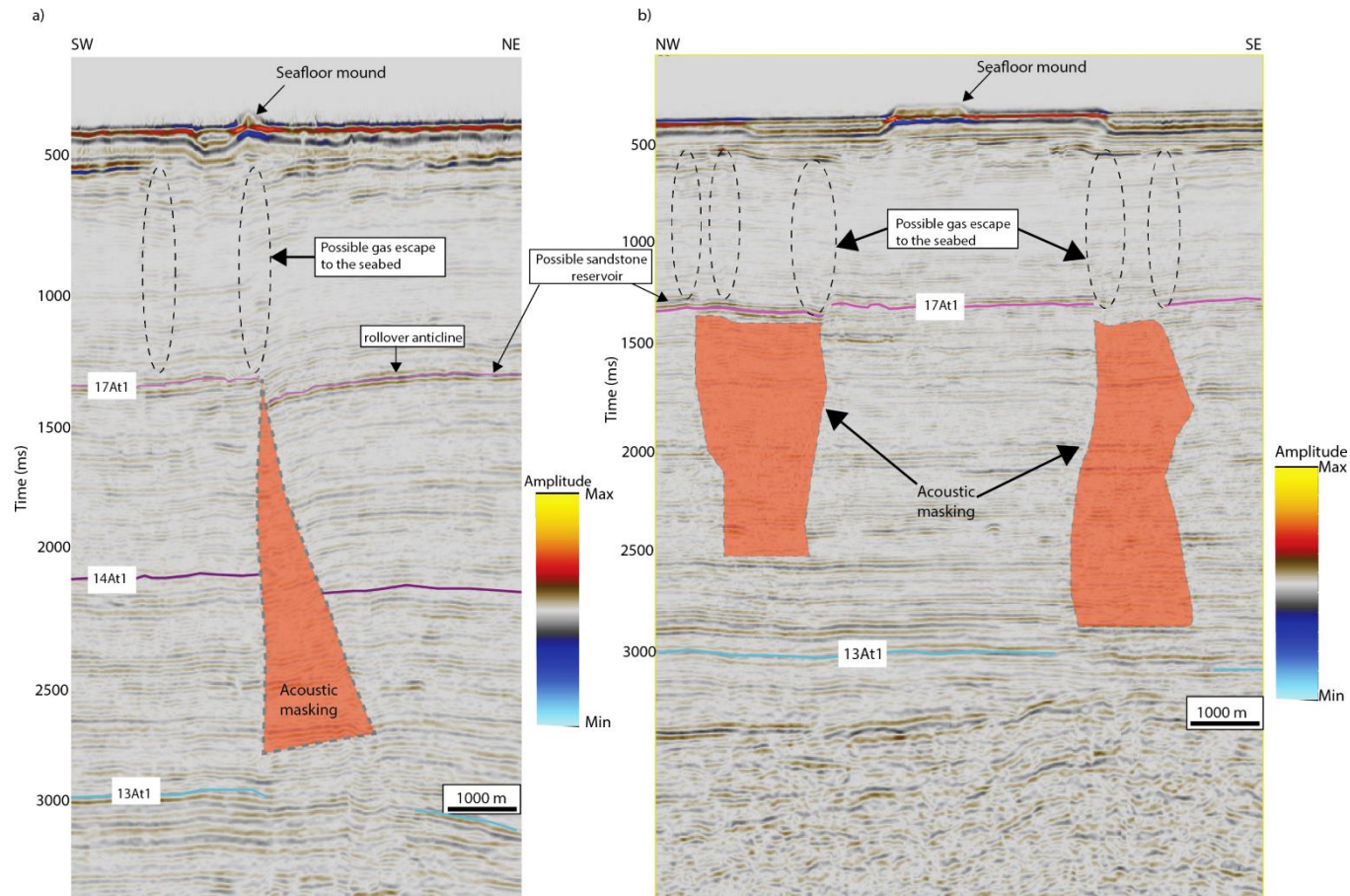


Figure 6.2: a) SW-NE section of seismic data with the gas chimney's morphology highlighted; b) NW-SE view of seismic data with the gas chimney's morphology highlighted. Due to the scattering of P-waves where gas is present, the gas chimney is indicated by acoustic masking in seismic data. Color bar represents the seismic amplitude.

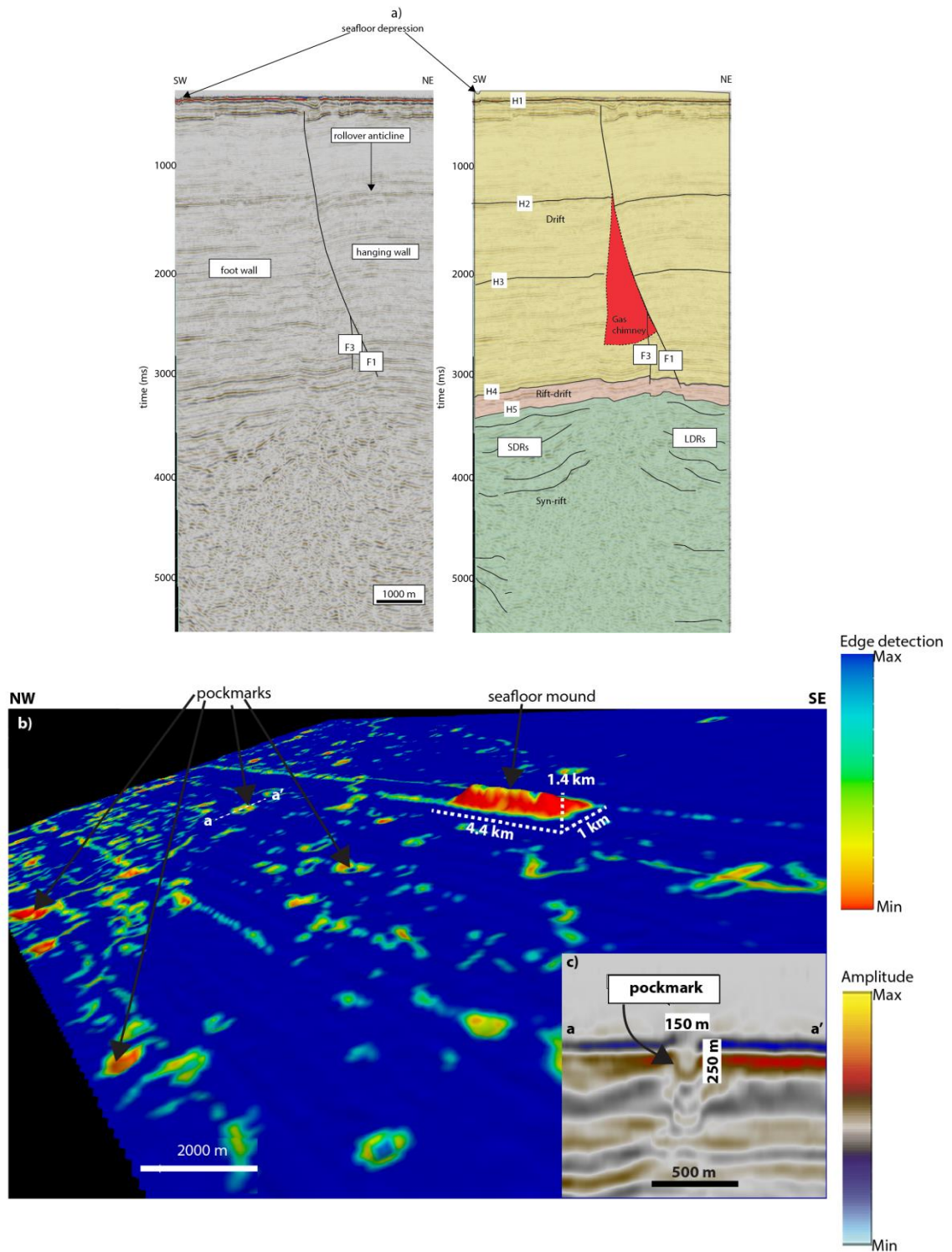


Figure 6.3: a) Gas chimney is possibly fault compartmentalized as gas migrates along the fault till it appears to be trapped by a rollover anticline; b) Edge detection attribute map showing seabed depressions and positive seabed expressions which are interpreted as pockmarks and a seafloor mound. The pockmarks appear to be randomly arranged; c) Morphology and typical dimensions of pockmarks.

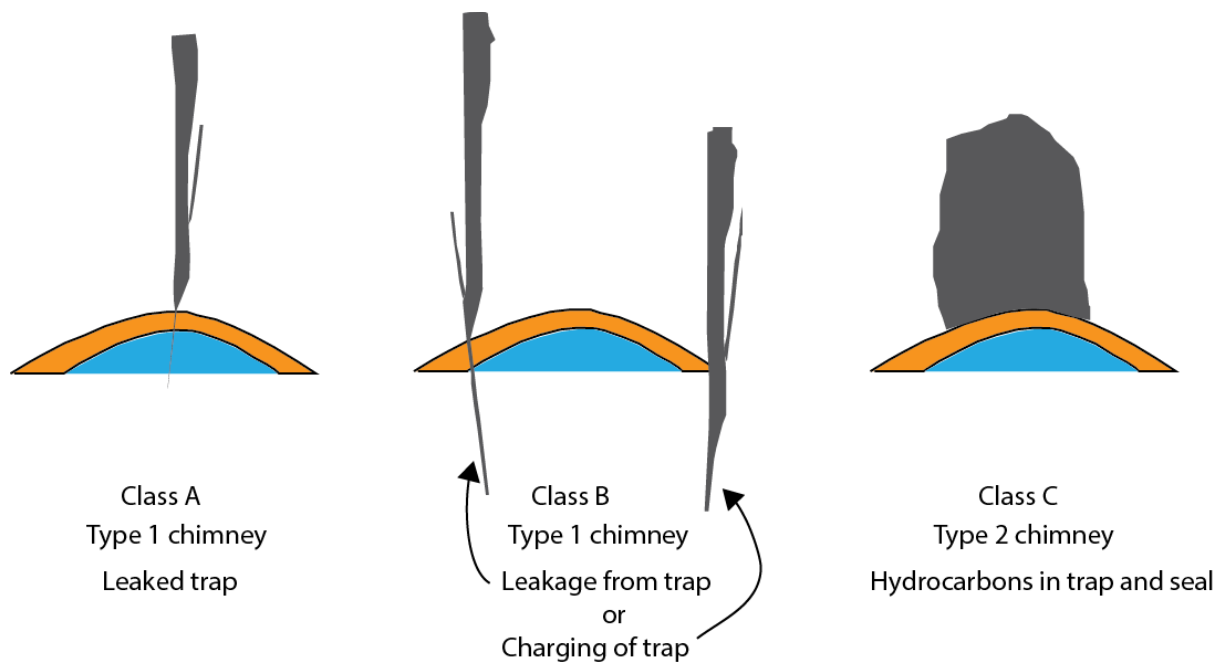


Figure 6.4: Classification of traps and corresponding gas chimneys (modified after (Heggland, 2005)). The gas chimney is classified as a Class A Type 1 chimney where hydrocarbons migrate from a deeper source and leak through a fault at the crest of the trap

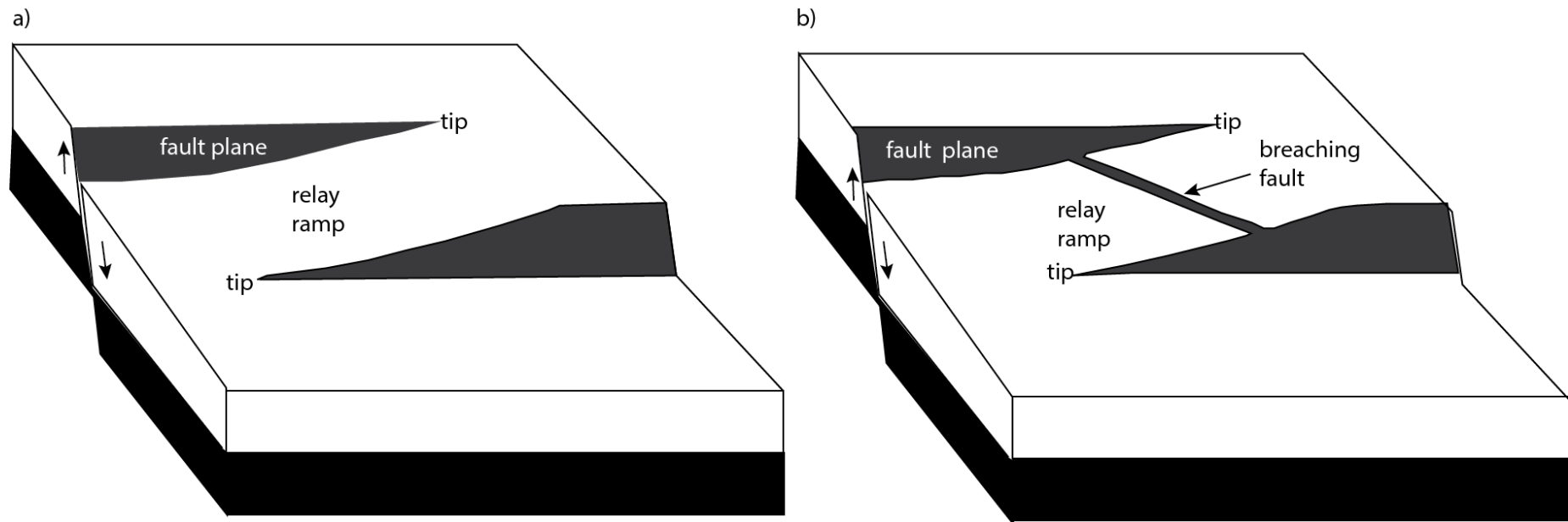


Figure 6.5: Schematic illustration of a) soft-linked and b) hard-linked relay ramps. Relay ramps have implications for fluid flow (See [section 6.2](#)). The hard-linked and soft-linked ramps have got implications for fluid flow across structures such as faults.

6.3. Tectono-stratigraphy

6.3.1. Tectonostratigraphy and Seismic Facies Classification

The tectono-stratigraphy is not covered in thorough detail, however, its analysis is closely linked to the structural evolution of the Orange Basin. Based on the seismic interpretation of the study area, the tectono-stratigraphic development of the Orange Basin may be described in three stages. These stages are:

Syn-rift

The syn-rift phase is the oldest tectono-stratigraphic unit covered by the seismic volume (Figure 6.7a). The syn-rift phase is characterised by high amplitude and shallowly-dipping Seaward Dipping Reflectors (SDRs) and Landward Dipping Reflectors (LDRs), which are inter-bedded with high amplitude, chaotic seismic events (Table 6.1; Figures 6.6, 6.7). To the author's knowledge, this is the first work that identifies the LDRs in the Orange Basin. Clinoforms of the SDRs and LDRs exhibit a wedge-shaped external form with simple, parallel stratified internal configurations, corresponding to seismic facies E (Figures 6.6, 6.7). The SDRs have been previously reported in the Orange Basin and interpreted as sub-aerially extruded basaltic lava flows typically found at volcanic rifted margins as a result of continental breakup (Clemson et al., 1997; Gladchenko et al., 1997). The LDRs could also represent landward flows of basaltic extrusion (Planke et al., 2000). In the current setting, the SDRs and LDRs could have developed during the breakup of the Gondwana supercontinent (Muntingh and Brown, 1993; Brown et al., 1995; De Vera et al., 2010; Boyd et al., 2011). LDRs are unexpected in this setting as they have only been previously identified at convergent plate margins where they are interpreted as tilted-bedding or thrust-fault surfaces (Cloos, 1984). The shallowly-dipping LDR and SDR clinoforms offlap onto a sequence boundary, 6At1 unconformity, which is the deepest strong seismic reflector in the study area (Figure 6.7).

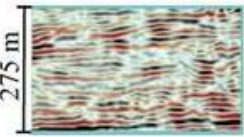
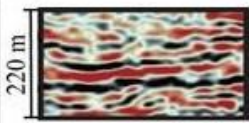
Rift-drift

The rift-drift tectono-stratigraphic sequences are bounded at the base by the 6At1 Hauterivian angular unconformity and at the top by the 13At1 mid Aptian unconformity (see Figure 3.4; Figure 6.7). In the study area, the transitional sequences have a thickness of approximately

165 m, while thicknesses of up to 2200 m have been reported in the northern Orange Basin (Muntingh, 1993; Kuhlmann, 2010).

Sediment thickness in the north coincides with the Cenozoic depocenters located at the mouth of the Orange and Olifants Rivers and thermal subsidence of the passive margin (Broad et al., 2006). The rift-drift successions have seismic reflectors that appear generally uniform (Figure 6.6; Table 6.1). This ‘ramp-like’ internal geometry of the seismic reflectors is typical of an aggradational seismic package deposited during conditions of basin tectonic subsidence and low sea level rise (facies A) (Table 6.1).

Table 6.1: Reflection configuration, amplitude characteristics and examples of seismic facies from seismic data.

Seismic facies	Reflection configuration	Amplitude trait	Tectono-stratigraphic temporal distribution	Seismic data e.g.
A	Parallel, continuous	High amplitude	Occurs during the rift-drift and drift phases	
B	Parallel, continuous	Low amplitude	Occurs mainly during the drift phase	
C	Chaotic, discontinuous	Low amplitude	Occurs mainly during the drift phase	
D	Sub-parallel, sub-continuous	Medium amplitude	Occurs mainly during the drift phase	
E	Sub-parallel, continuous	High amplitude	Confined to the syn-rift phase	
F	Chaotic, sub-continuous	High amplitude	Confined to the syn-rift phase	

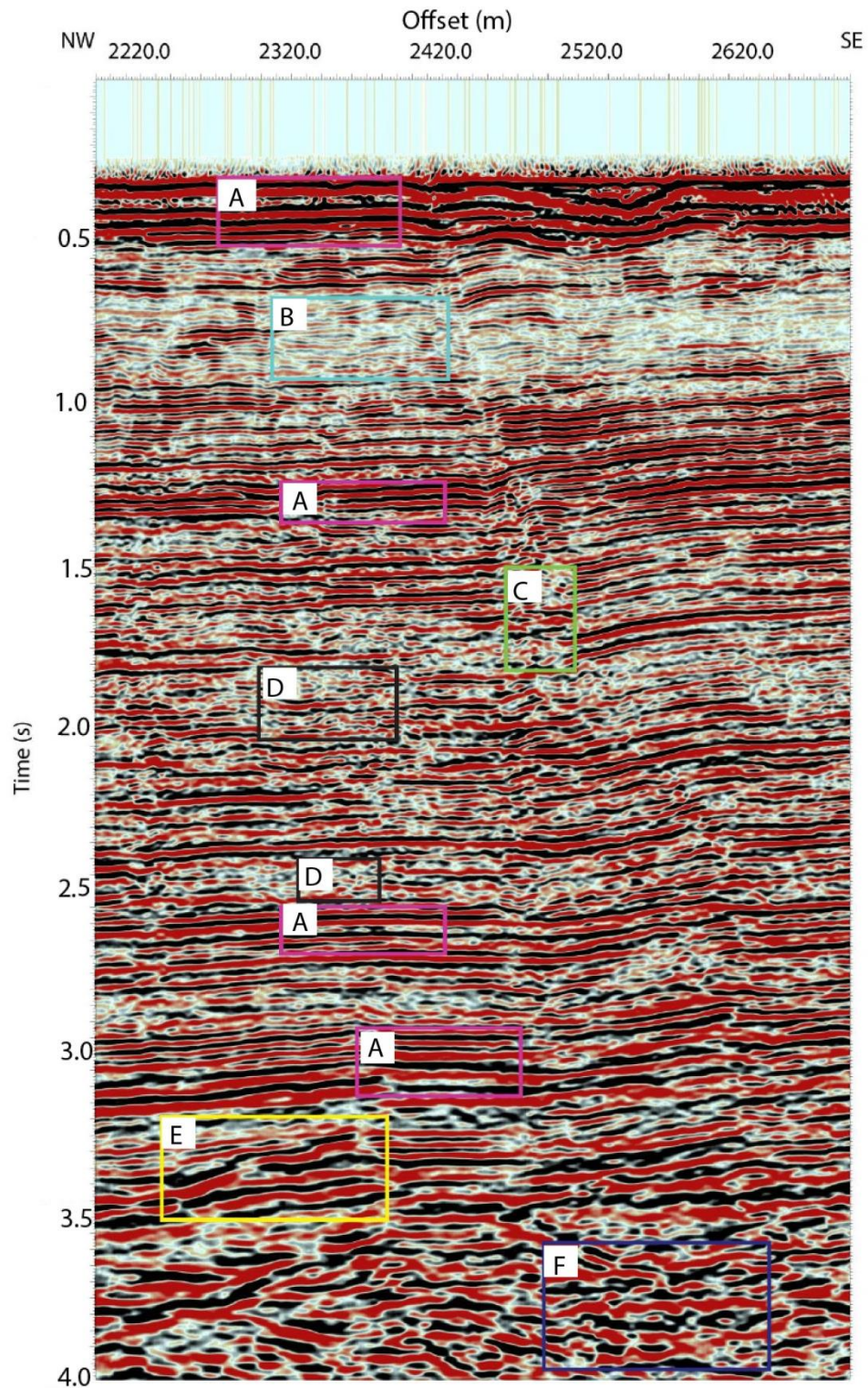


Figure 6.6: Seismic facies classification in the study area. Seismic facies interpretation is based on reflector configuration and reflector amplitude traits. The facies comprise of parallel and continuous high amplitudes (A), parallel and continuous low amplitudes (B), chaotic and discontinuous low amplitudes (C) , sub-parallel and sub-continuous medium amplitudes (D), sub-parallel and continuous amplitudes and continuous (E), sub-continuous high amplitudes (F).

Drift

The 13At1 unconformity marks the initiation of drift (Figure 6.7). The thickness of the drift successions in the study area is 3520 m; however this thickness has been reported to reach up to 7700 m in some parts of the Orange Basin (Muntingh, 1993; Brown et al., 1995). The drift successions comprise of seismic facies A-D which include alternate facies of high amplitude, parallel, continuous reflectors, low amplitude, parallel, continuous reflectors and medium amplitude, sub-parallel reflectors (facies A, B, D) as well as chaotic, seismic facies (facies C). Facies A, B and D are testament to the various cycles of sea level fluctuations prevailing from the end of the Lower Cretaceous to the recent past. (Table 6.1; Figure 6.6).

Amplitude and structural anomalies of chaotic, discordant seismic facies (facies C) are observed at approximately 3000 ms, above the Albian-Aptian source rock which is located at the transition from rift-drift to drift conditions (Table 6.1; Figure 4.5; Figure 6.4). From these anomalies, a gas chimney originates at ~2750 ms and migrates upward till ~1250 ms. The gas chimney is approximately 1500 m in height (Figure 6.6a,b), where it pools into what has been recognised as a sandstone reservoir by Isiaka et al. (2017). The presence of a gas chimney therefore implies a gas migration pathway. On seismic sections, gas chimneys appear as vertical wipe-out zones of acoustic masking in the seismic data due to scattering and an attenuation of the seismic amplitude where the gas is present (Anderson and Hampton, 1980; Figure 6.6a, b).

The gas chimney in the study area appears to be fault compartmentalized and possibly fracture related (Figure 6.7a). As the gas migrates upward along the up-thrown side of the listric faults on the footwall, there is rotation of the downthrown block on the hanging wall. The extension from the gas expansion is accommodated by a rollover anticline in the hanging wall (Figure 6.6a). Due to its physical configuration with the reservoir, the rollover anticline acts as a structural trap and becomes a barrier to the upward migration of gas.

A positively elevated feature is suspiciously elongated parallel to the inline direction (Figure 6.1; Figure 6.3a, b). This is peculiar because the inline direction is parallel to the seismic data acquisition direction (Shaughnessy, 2003). Upon further inspection, the feature is interpreted as a seafloor mound and is located at the top the gas chimney, implying that gas could have been leaked from the trap. Twenty-five depressions of varying sizes are located on the seafloor (Figure 6.3b, c).

These features have been interpreted to be pockmarks associated with upward fluid migration. Based on their morphological appearance, spatial distribution and reflector characteristics, the depressions in the study area have been classified as circular, randomly-arranged and symmetrical pockmarks (Hovland et al., 2002) .

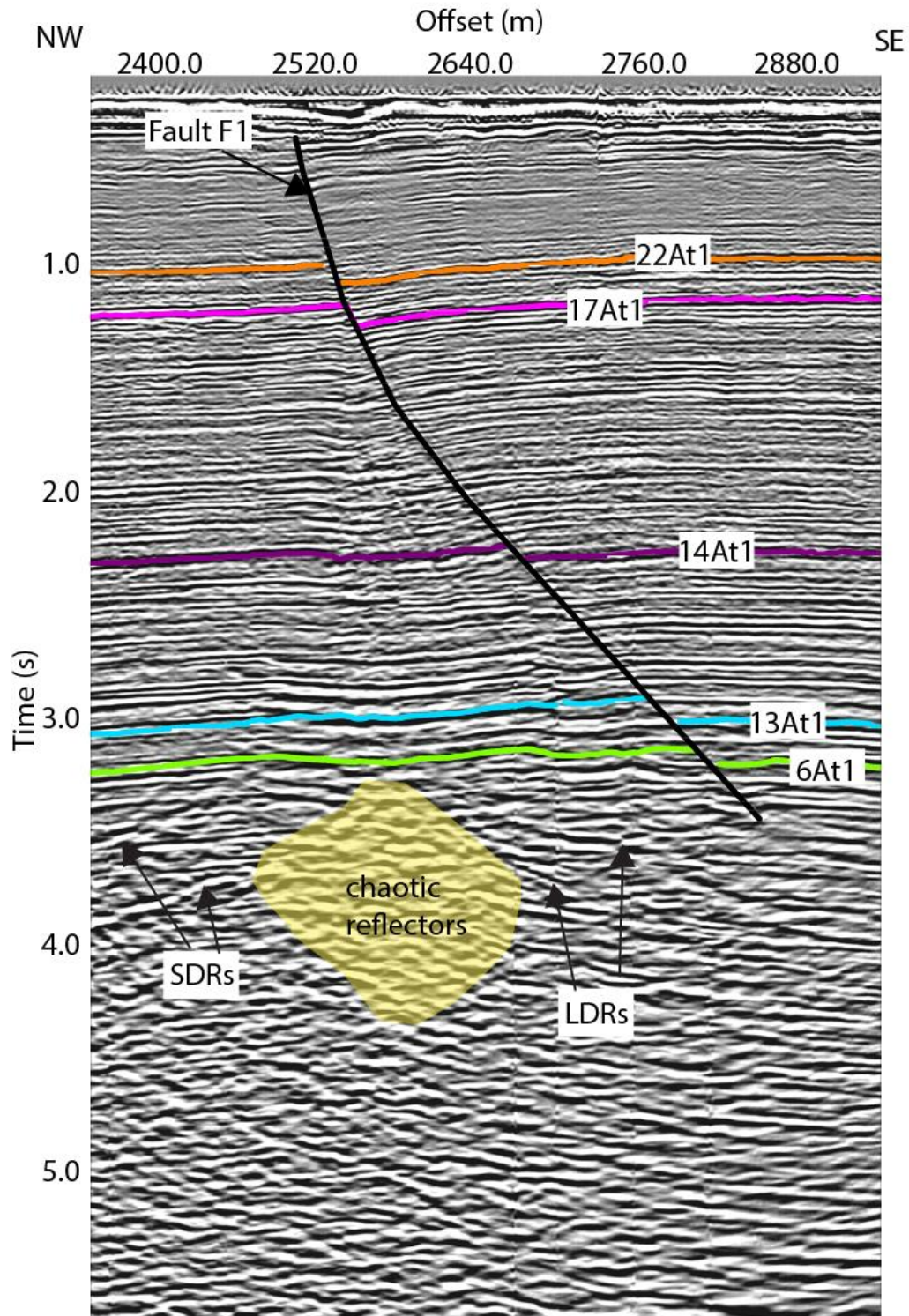


Figure 6.7: Seaward dipping reflectors (SDRs) and Landward dipping reflectors (LDRs) occur within the syn-rift seismic package. Both SDRs and LDRs represent landward flows of basaltic extrusion that developed during the breakup of the Gondwana supercontinent. The study area is divided into major unconformities which are noted as the: 6At1, 13At1, 14At1, 15At1, 17At1 and the 22At1 unconformity (Brown et al., 1995).

6.3.2. Tectono-stratigraphic Model Comparisons

When compared to the tectono-stratigraphic model of [De Vera et al. \(2010\)](#), there are certain similarities and differences ([Figures 6.8 - 6.9](#)). Both models identify SDRs during the syn-rift phase and interpret them as sub-aerially extruded lavas, however, this study also recognises LDRs which have not been previously identified in the Orange Basin. During the rift-drift phase, also known as Post-rift I ([De Vera et al., 2010](#)), the seismic data from both studies are characterized by horizontal seismic reflectors of high amplitudes. These seismic reflectors are characteristic of the basin fill of Albian-Aptian marine incursions deposited after tectonic subsidence. Unlike the seaward-dipping regional growth faults identified by [De Vera et al. \(2010\)](#), the current study has picked out landward-dipping regional growth faults ([Figure 6.9](#)). Growth faults are typical structures at extension-type margins ([Mauduit and Brun, 1998](#)).

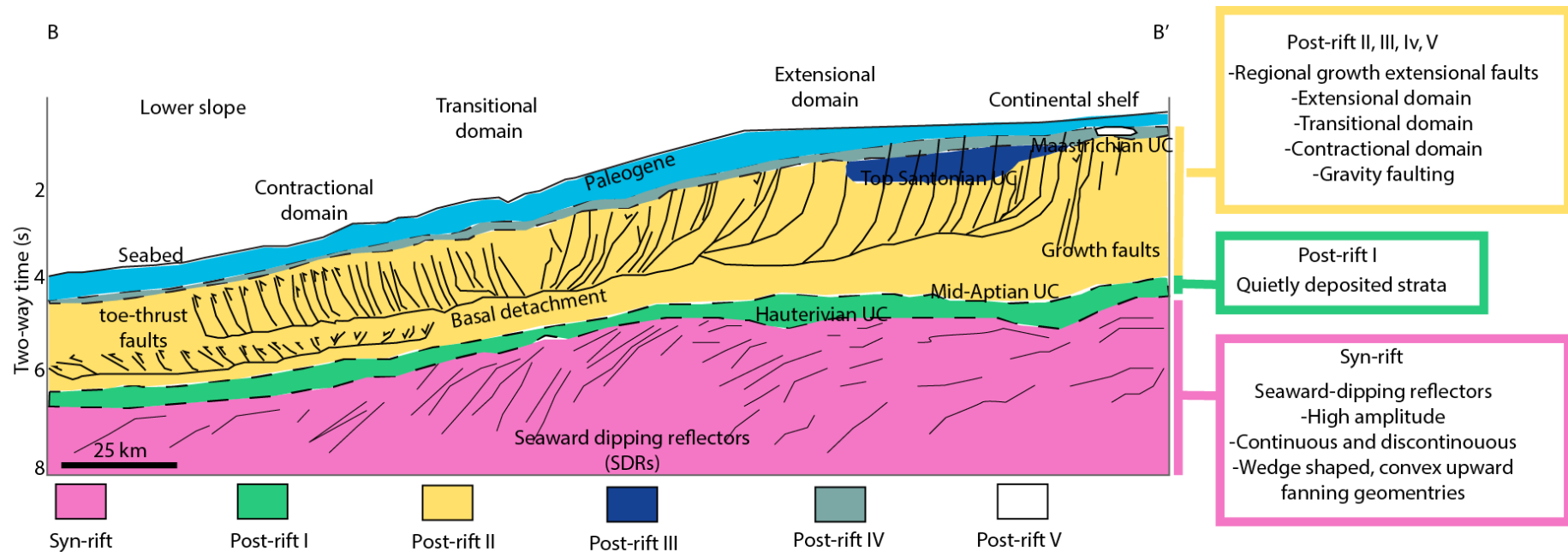


Figure 6.8: Geoseismic section showing the tectono-stratigraphic model of the Orange Basin (De Vera et al., 2010). See Figure 1.1 for location. The tectono-stratigraphic model categorizes the main phases of tectonic activity into the synrift and post-rift (I-V) megasequences. These have been correlated to the megasequences in the current study area. Within the synrift package, the seaward dipping reflectors have wedge-shaped, convex upward, fanning geometries. The post-rift (I-V) packages are characterized by quietly deposited strata indicating basin tectonic subsidence and faults in an extensional, transitional and contractional domain.

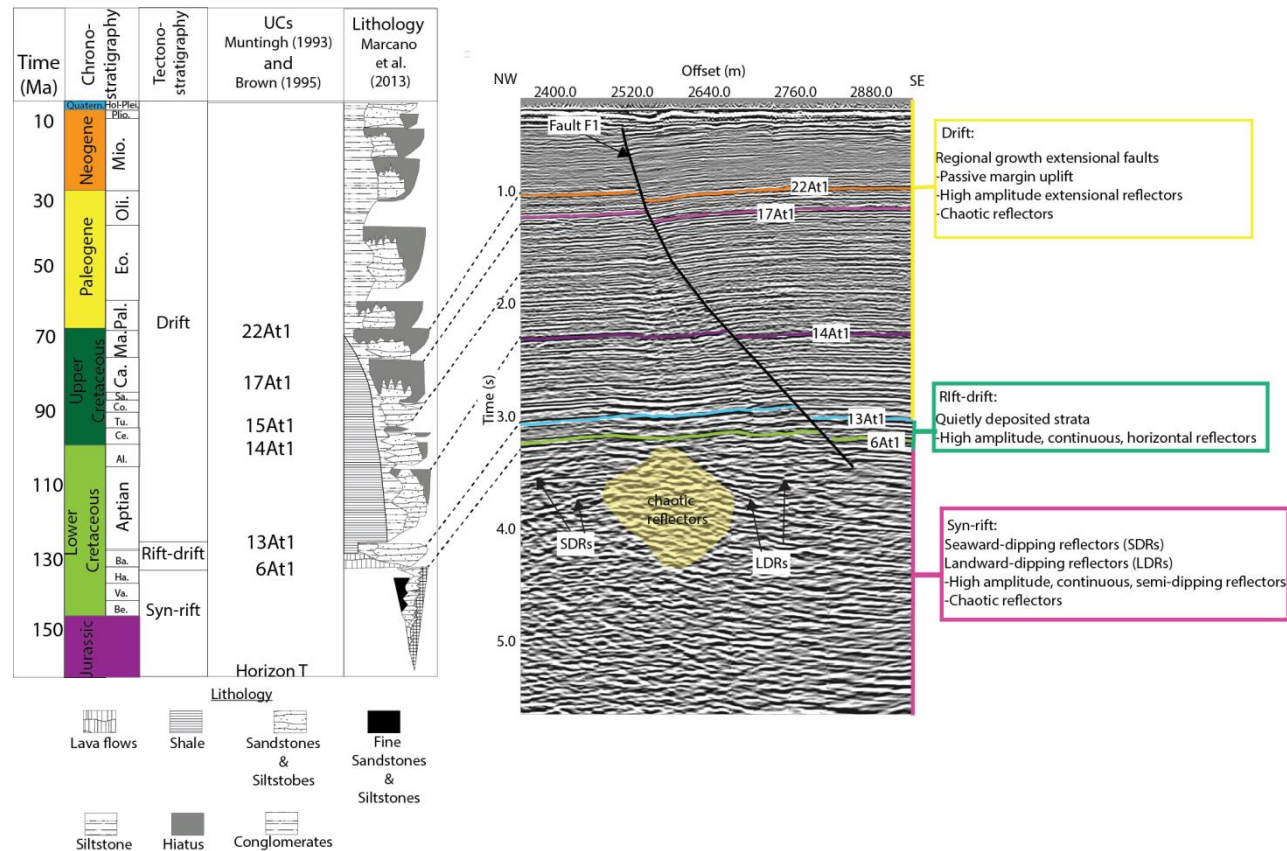


Figure 6.9: Tectono-stratigraphic model based on 3D reflection seismic data. Seaward dipping reflectors and Landward dipping reflectors were identified within the synrift package and interpreted as extruded basaltic lava. Within the transitional zone are continuous and horizontal reflectors indicating the tectonic subsidence of the Basin, The post-rift sequences consist of alternating facies indicating continuous transgressions and regressions from the Upper Cretaceous till present. The major unconformities indicated are the 6At1, 13At1, 14At1, 15At1, 17At1 and the 22At1 (Brown et al., 1995), lithologies (after Hartwig et al., 2012) and the time scale is that of Haq et al., (1987).

7. Conclusions and Recommendations

7.1. Conclusions

The main objectives of this study were to characterize and enhance the geological interpretations of the structures in the Orange Basin. The structural evolution of the Orange Basin is strongly influenced by NW-SE trending normal regional faults. Seismic attributes have enhanced the detection of geological structures in the study area. The conclusions drawn from applying seismic attributes are: (1) complex trace attributes identify the general locations of major faults; (2) the dip attribute provides the orientations of major faults in the study area; (3) the dip-azimuth, edge detection and ant-tracking attributes examine the connectivity between major faults and linear faults mapped as minor fault segments which is not otherwise clear on conventional seismic amplitude data; and (5) the variance and ant-tracking attributes have mapped the major faults while the chaos attribute has highlighted a funnel-shaped feature which was interpreted as a gas chimney originating in rocks of Albian-Aptian age.

The complex trace attributes confirm the geometry of the major regional faults as northwest-southeast trending features which are well detected by the elevation and edge detection maps. Application of the dip attribute to the seismic data confirms that the northwest-southeast trending faults have dip angles above 25° . The dip azimuth attribute illuminated subtle NNW-SSE features, which are consistent in geometry with the major regional faults and enhanced the interpretation of fault linkage between a major regional fault, F1, at ~2.45s. The two ends of fault F1 are breached by a N-S striking segment, which is a breaching fault below the vertical seismic resolution limit of 8 m. The application of edge detection attributes to the data provided a further confirmation of what has been observed from applying the dip-azimuth attribute. However, it particularly enhanced the detection of the fault continuation and connectivity. The variance and ant-tracking attributes have mapped the major regional faults and confirmed the existence of NW-SE trending linear features which straddle the faults.

This study has mapped the distribution of fluid migration pathways existing from a potential hydrocarbon source. The major faults have been reactivated via syn-sedimentation and fault linkage. A possible source has been identified in rocks of Albian-Aptian age. There is active

fluid migration from the source, located in rocks of Albian-Aptian age, to the reservoir and to the seabed where evidence of fluid expulsion exists in the form of pockmarks and a seafloor mound. The reservoir is coupled with a rollover anticline which provides an ideal trap for fluid, however due to the existence of gas escape features on the seafloor, the trap is thought to have failed. Fluid migration is mapped as an amplitude anomaly in the form of an acoustic disturbance originating at ~2750 ms.

The tectono-stratigraphic evolution of the Orange Basin is linked to the rift, rift-drift and drift stages. The tectono-stratigraphic model produced from examining the current study's seismic data were correlated to a previous model by [De Vera et al., \(2010\)](#). The characteristics of the faults and temporal seismic facies variations fit within the framework of extensional tectonics that occurred during the syn-rift, rift-drift and drift phases of the Orange Basin development.

7.2. Recommendations

Seismic data provide a good understanding of the subsurface, however seismic attributes have proved to be tools that further enhance that interpretation as they have revealed some interesting trends in the structural complexities of the major and minor faults from the study area. Additionally, the integration of more types of geophysical and geological information would be very useful in constraining multiple outputs from this project such as the 3D structural model and horizon picks.

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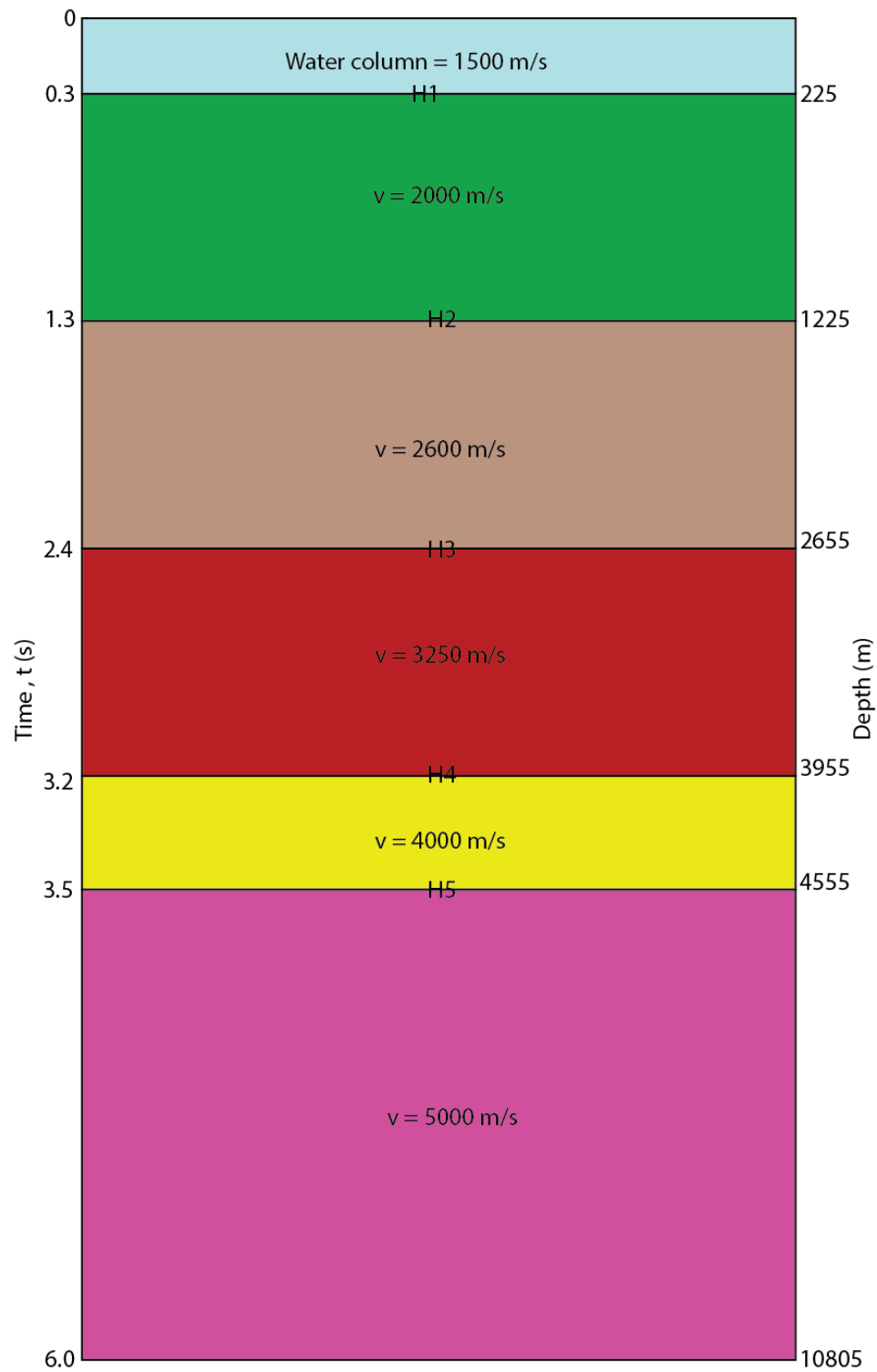
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Appendix: Time to depth conversion

Velocity Model



Depth Conversion Calculation

$$d = V \times (\Delta \frac{t}{2} - t_n) \quad (15)$$

(where d = depth to seismic reflector, V = interval velocity, t = two-way-time, $\frac{t}{2}$ = one-way-time, t_n = time at previous n^{th} reflector and Δt = time between the seabed and the reflector)

$$d_1 = 1500 \text{ m/s} \times 0.15 \text{ s} = 225 \text{ m}$$

$$d_2 = (2000 \text{ m/s} \times (0.65 \text{ s} - 0.15 \text{ s})) + d_1 = 1225 \text{ m}$$

$$d_3 = (2600 \text{ m/s} \times (1.2 \text{ s} - 0.5 \text{ s})) + d_2 = 2655 \text{ m}$$

$$d_4 = (3250 \text{ m/s} \times (1.6 \text{ s} - 0.7 \text{ s})) + d_3 = 3955 \text{ m}$$

$$d_5 = (4000 \text{ m/s} \times (1.75 \text{ s} - 0.9 \text{ s})) + d_4 = 4555 \text{ m}$$

t	t/2	V	d
0.3	0.15	1500	225
1.3	0.65	2000	1225
2.4	1.2	2600	2655
3.2	1.6	3250	3955
3.5	1.75	4000	4555