



Seismic Sequence Stratigraphy and Hydrocarbon Potential of the Permo-
Triassic Karoo Group, Southwestern Ogaden Basin, Ethiopia

Mebatseyon Shawel

A Thesis Submitted to

The School of Earth Sciences

Presented in Fulfilment of the Requirements for the Degree of

Doctor of Philosophy (Applied Geophysics)

Addis Ababa University

Addis Ababa, Ethiopia

March, 2021

Addis Ababa University

School of Earth Sciences

This is to certify that the thesis prepared by Mebatseyon Shawel, entitled: Seismic Sequence Stratigraphy and Hydrocarbon Potential of the Permo- Triassic Karoo Group, Southwestern Ogaden Basin, Ethiopia and submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy (Applied geophysics) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining Committee:

Examiner: _____ Signature: _____ Date: _____

Examiner: _____ Signature: _____ Date: _____

Advisor: _____ Signature: _____ Date: _____

Chair of School or Graduate Program Coordinator

ABSTRACT

Ogaden Basin is the largest sedimentary basin in Ethiopia covering an area of approximately 350,000 sq. km and having an estimated sediment thickness of over 7 km in the deepest part. The Karoo sequence which lies at the base of the sedimentary section is a Permian - Triassic terrigenous clastics deposited in a tensional to trans-tensional tectonic setting. The sequence thickness reaches 3000 m and contains proven gas reserve in excess of 6 TCF. Previous studies of the Karoo sequence focused primarily on the sedimentology and lithostratigraphy of the section. This study presents the first integrated sequence stratigraphic analysis of the Karoo section using seismic and well data and in addition investigates the hydrocarbon potential of the sequence.

The first phase of the work involved seismic data reprocessing. Seismic data quality in the study area is generally inadequate for sequence stratigraphic analysis. Hence, in the current study, seismic lines with a total length 296 kms were reprocessed to improve reflectivity and continuity, especially in the Karoo section. Analysis of shot gathers showed that proper removal of source related groundroll and amplitude burst noises was imperative to recover reflections. The trace edit and spike and burst edit tools were used to effectively remove noise bursts and the groundroll noise was attenuated using linear Radon transform. Surface consistent amplitude correction, predictive deconvolution and velocity analysis looped with residual statics are among the other processing steps applied to the data. Stacking was done using the second pass velocity field which was also used in post stack migration of lines. The result of reprocessing, compared with the

previous processing, showed improvements mainly in recovering reflectivity in the Karoo section as well as in continuity of reflections.

The reprocessed seismic lines, two additional seismic sections and well data were used to define four second order sequences and at least four higher order sequences in the uppermost sequence. The transgressive systems tract and the overlying highstand systems tract separated by a maximum flooding surface constitute the bulk of these sequences. The dominant depositional systems in systems tracts include shallow and deep lacustrine, fluvio-deltaic and possibly sublacustrine fans and turbidites. Our study suggests that the major control in creation of accommodation space is related to wrench tectonics which gave rise to narrow pull apart sub-basins and their surrounding steep flanks. These structures are oriented NE-SW to E-W. The study also suggests a number of potential hydrocarbon plays associated with the identified systems tracts.

At the last phase of the work, 1D and 2D basin and petroleum system modeling was carried out to analyze the hydrocarbon potential of the Karoo sequence based on well data and the new sequence stratigraphic interpretation. The modeling process simulates the basin's thermal, hydrocarbon generation and accumulation history. The models, calibrated with Vitrinite reflectance (R_o) and temperature data, show that heat flow trends are similar throughout the study area with the exception of the western basin margin area which has consistently higher values. 2D modeling result shows peak transformation in sequence two, three and bottom of sequence four source rocks was reached during upper Permian, middle Triassic and middle Jurassic respectively and that

at present all potential source rocks have reached complete transformation. Simulation results also show potential reservoir targets are dominantly gas charged in the deeper parts whereas shallower targets are filled with high GOR oil.

Acknowledgments

First and foremost, I would like to express my deepest gratitude to GOD for giving me the opportunity to study for a Ph.D. degree and for His all-round support throughout my PhD journey.

I would like to thank Professor Tilahun Mammo for all the help, guidance, mentorship and remarkable classes. This research would not have been possible without his advisorship and for this reason I am very grateful.

I also would like to acknowledge the contribution of Professor Vikram Unnithan for co-working on my research and so much more. His comments and the several discussions we had have significantly improved my research.

I would also like to thank the PhD supervisory committee for all their constructive comments and the school graduate program coordinator Dr. Bayisa Regassa for his remarkable facilitation of our study in the short time since he started working in the position. I would also like to thank the staff of the School of Earth Sciences for all the help extended throughout the years of my study.

I would like to thank the Ministry of Mines and Petroleum, Dr Ketsela Tadesse and his team for providing data required to carry out this research. I would also like to thank Li Jianjun for the technical support and advice given in carrying out this work.

I also thank my student colleagues for all the good time we had together, the discussions, the struggles we faced and the brilliant ideas that we were throwing on one another.

Lastly, none of this would have been possible without the support of my family and I am grateful for all the help I have received.

Contents

ABSTRACT.....	ii
Acknowledgments.....	v
List of Figures	ix
List of Tables	xiii
Chapter 1 : Introduction	1
1.1 Problem statement	4
1.2 Aims of this study.....	5
1.3 Geological setting.....	5
1.4 Thesis outline	9
Chapter 2 : Theoretical Background on Reflection Seismic and Well Log Data Analysis.....	11
2.1 Seismic Data Processing.....	11
2.1.1 Deconvolution.....	12
2.1.2 CMP stacking.....	14
2.1.3 Migration.....	18
2.2 Seismic and Well Data Interpretation.....	19
2.2.1 Sequence Stratigraphy	19
2.2.2 Sequence stratigraphic interpretation technique	25
Chapter 3 : Seismic Data Reprocessing.....	60
3.1 Introduction	60
3.2 Seismic data processing sequence.....	62
3.2.1 Data preparation.....	63
3.2.2 Data correction	67
3.2.3 Data reduction and enhancement	81
3.3 Discussion and conclusion	84
3.3.1 Comparison with previous stack.....	88
Chapter 4 : Sequence Stratigraphic Interpretation	90
4.1 Data and Methodology	90
4.1.1 Seismic to well tie	94
4.2 The Permian – Triassic Karoo Sequences.....	95
4.2.1 Sequence 1.....	95
4.2.2 Sequence 2.....	99
4.2.3 Sequence 3.....	105

4.2.4 Sequence 4.....	107
4.3 Correlation with Well Log Interpretation	109
4.3.1 Sequence 1: 2763m – 2865m (Basement)	109
4.3.2 Sequence 2: 2763 - 2650m	111
4.3.3 Sequence 3: 2650 – 2400m.....	113
4.3.4 Sequence 4: 2400 – 2006m.....	119
4.4 Discussion.....	131
4.4.1 Tectonics controlling sequence development	131
4.4.2 Regional sequence stratigraphic correlation	132
4.4.3 Sequences, systems tracts and their implication for hydrocarbon exploration	134
4.5 Conclusion.....	138
Chapter 5 : Basin and Petroleum System Modeling of the Karoo Sequence.....	140
5.1 Introduction	140
5.2 Karoo Group sequence stratigraphic model and related petroleum systems.....	143
5.3 Basin and petroleum system modeling	144
5.3.1 Source rock properties.....	145
5.3.2 Boundary Conditions.....	147
5.4 BPSM results and discussion.....	149
5.4.1 1D Modeling.....	149
5.4.2 2D Modeling.....	154
5.5 Conclusions	167
Chapter 6 : General Conclusions and Recommendations	169
6.1 General Conclusions.....	169
6.1.1 Seismic data reprocessing.....	169
6.1.2 Sequence stratigraphic interpretation of the Karoo sequence	171
6.1.3 Basin and petroleum system modeling	173
6.2 Recommendations for future research.....	174
References	176

List of Figures

Figure 1-1. Location map of the Ogaden Basin, also showing basement top map, well and seismic lines used in this study (modified after Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia (2005)).	2
Figure 1-2. Stratigraphic column of the Ogaden Basin.	3
Figure 2-1 Different types of stratal stacking patterns related to forced regression, normal regression and transgression. After Cateneau (2006).	22
Figure 2-2 Stratal stacking pattern in lowstand and highstand normal regressions. After Cateneau (2006).	22
Figure 2-3 Different types of terminations observed in seismic sections. After Emery and Myers, (2009).	30
Figure 2-4 Different types of reflection configurations. After Veeken (2007).	32
Figure 2-5 Gamma ray energy spectra and measurement windows. After M. H. Rider (1986).	41
Figure 2-6 Photoelectric Factor (PEF) log. The log is less sensitive to porosity and hence a good indicator of lithology. After M. H. Rider (1986).	43
Figure 2-7 Density log measuring bulk density of formations. After M. H. Rider (1986).	44
Figure 2-8 Typical example of a neutron- density overlay plot, its interpretation and correlation with other logs (after M. H. Rider (1986)).	46
Figure 2-9 Wireline log trends representing different depositional facies (after M. H. Rider (1986)).	48
Figure 2-10 Schematic operation of microimage log also showing path of focused current (left). Pad and sensor detail of microimage log- an example from Schlumberger FMI tool (right) (after Serra and Serra (2003)).	51
Figure 2-11 Inclinator tool integrated with borehole image tool to determine orientation and for speed corrections (after Serra and Serra (2003)).	51
Figure 2-12 Illustration of borehole deviation and azimuth of a borehole that are required to plot image logs in proper orientation (after Serra and Serra (2003)).	52
Figure 2-13 Illustration of image log plots. Dipping layers plot as sinusoids (after Serra and Serra (2003)).	54
Figure 2-14 Static and dynamic normalization of image logs (after Serra and Serra (2003)).	55
Figure 2-15 Sedimentary structures from high resolution borehole image logs (Amer, Glascock, Schwalbach, Khan, and others, 2011).	57
Figure 3-1 Location map of reprocessed seismic lines, elevation along lines ranges from 225 to 475m.	61
Figure 3-2 A summary chart of seismic processing workflow applied to data.	64
Figure 3-3 Raw shot gathers showing strong shot generated noise, ground roll noise and random noise (Above). Frequency spectrum of respective shot gathers (below).	65
Figure 3-4 Shot gathers from two different locations after trace editing and application of spike and noise burst edit.	66
Figure 3-5 Shot gathers after spherical spreading and datum static corrections at two different locations.	69
Figure 3-6 Schematic diagram of forward and inverse Tau-p transform. After Russell, Hampson, and Chun (1990).	71

Figure 3-7 Shot gathers after linear noise attenuation.	72
Figure 3-8 Shot gathers after deconvolution.	75
Figure 3-9 Shot gathers after surface consistent amplitude compensation.	76
Figure 3-10 Typical velocity analysis procedure showing semblance plot, corrected gathers panel, dynamic stack and stack functions panel.....	79
Figure 3-11 CDP gathers before (a) and after (b) residual statics.....	80
Figure 3-12 Seismic section OG- A before (top) and after (bottom) residual statics applied to the data.	82
Figure 3-13 Final post stack time migrated seismic section, Line OG-A.	85
Figure 3-14 Smoothed interval velocity field derived from stacking velocity of seismic line OG-A.	86
Figure 3-15 Comparison of original (above) and reprocessed (below) seismic Line OG-A.	89
Figure 4-1 An example of a pad misalignment correction with the panel on the left showing borehole image before correction and the right panel showing image after correction (ellipse with red outline highlights the correction).	94
Figure 4-2 Seismic well tie using a synthetic seismogram.	96
Figure 4-3 Seismic dip line OG-A in the southwestern margin showing interpreted Karoo sequences, see Figure 1-1 for location. Sequence boundaries (SB) are unconformity and correlative conformity surfaces bounding sequences; they are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; MFS – maximum flooding surface; FL-D – fluvial deltaic units; LAC – shallow to deep lacustrine; BT- basement top. Arrows indicate onlaps. Also showing Well-A gamma ray log in red.	97
Figure 4-4 Seismic dip line OG-B interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. Sequence boundaries (SB) are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; FL-D – fluvial deltaic units; RD – regressive delta; LAC – shallow to deep lacustrine; BTS – bottom of transgressive surface; BT- basement top. Arrows indicate onlaps; double arrows in bottom of sequence 3 indicate hummocky type reflections.	98
Figure 4-5 Seismic dip line OG-B (phase attribute) interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. The phase attribute has a potential to reveal geometric relationships. SB - sequence boundaries; SQ- sequences; FL-D – fluvial deltaic units; RD – regressive delta; BTS – bottom of transgressive surface; LAC – shallow to deep lacustrine; BT- basement top. Arrows indicate onlaps.....	98
Figure 4-6 Seismic line S-A across Bodle Deep showing interpreted Karoo sequences, see Figure 1-1 for location. Sequence boundaries (SB) are unconformity and correlative conformity surfaces bounding sequences. BTS- bottom of transgressive surface; BT- basement top; SQ- sequences. Arrows indicate onlaps.	100
Figure 4-7 Seismic line S-B along the axis of Bodle Deep showing interpreted Karoo sequences, see Figure 1-1 for location. SB - sequence boundaries; BTS- bottom of transgressive surface; BT- basement top; SQ- sequences; FL-D – fluvial deltaic units. Arrows indicate onlaps.	100
Figure 4-8 Seismic strike line OG-C interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. Sequence boundaries (SB) are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; BT- basement top. Arrows indicate onlaps.	102

Figure 4-9 Seismic strike line OG-C (phase attribute) interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. SB - sequence boundaries; SQ- sequences; BT- basement top. Arrows indicate onlaps.	102
Figure 4-10 Seismic dip line OG-D interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. Sequence boundaries (SB) are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; BT- basement top. Arrows indicate onlaps.	104
Figure 4-11 Gamma ray, neutron-density overlay (higher percentage of mud indicated by wider separation filled by red color and sand indicated by red filled minimum separation to yellow filled separations) and an interpretation log of sequence 1 (sand indicated by yellow and mud by green color).....	111
Figure 4-12 Gamma ray, neutron-density overlay (higher percentage of mud indicated by wider separation filled by red color and sand indicated by red filled minimum separation to yellow filled separations) and an interpretation log of sequence 2 (sand indicated by yellow and mud by green color).....	113
Figure 4-13 Well A wireline logs from sequence 3 with facies interpretation using gamma ray, neutron-density overlay, static and dynamic image logs as well as a dip tadpole plot and a stereonet plot of dips.	119
Figure 4-14 Well A wireline logs from sequence 4 with facies interpretation using gamma ray, neutron-density overlay, static and dynamic image logs as well as a dip tadpole plot and a stereonet plot of dips.	126
Figure 4-15 Cross bedded sandstone, refer to Table 4-2 and text for detailed description of facies.	128
Figure 4-16 Laminated Mudstone, refer to Table 4-2 and text for detailed description of facies.	128
Figure 4-17 Hetrolithic, refer to Table 4-2 and text for detailed description of facies.	129
Figure 4-18 Structureless Mudstone, refer to Table 4-2 and text for detailed description of facies.	129
Figure 4-19 Horizontally bedded sandstone, refer to Table 4-2 and text for detailed description of facies.....	130
Figure 4-20 Structureless sandstone, refer to Table 4-2 and text for detailed description of facies.	130
Figure 4-21 A simplified model showing sequence stratigraphic framework of the Karoo Group in southern Ogaden Basin made up of four sequences and their constituent depositional systems. SB - sequence boundaries; BT- basement top; SQ- sequences.	137
Figure 5-1 A summary diagram of model building and forward modeling stages in basin and petroleum system modeling workflow. After Al-Hajeri et al. (2009).	142
Figure 5-2 Basement top map of the Ogaden Basin with dark brown color representing the deep part and yellow color representing shallow part of the basin, modified after Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia, 2005. .BD- Bodle Deep; ST- Shilabo Trough. Also showing BPSM profile line and well locations referred in text.....	145
Figure 5-3 (a) Hydrogen index (HI) versus oxygen index (OI) showing kerogen types of Adigrat, Gumburo and Bokh formation source rocks. (b) Plot of hydrogen index versus Tmax also	

showing kerogen types and maturity levels. Tmax values between 430 and 470 deg C indicate oil window.	148
Figure 5-4 Vitrinite reflectance, present day temperature and burial history plots shown from left to right in each raw for five wells modeled in the study area. Lines represent models, dark dots represent measured vitrinite reflectance values and black plus signs represent measured temperature. (a) WL-B well; (b) WL-C well; (c) WL-D well; (d) WL-E well; and (e) WL-F well.	153
Figure 5-5 Calibrated heat flow trends used in 1-D models for all wells. Trends show very small scatter at any geological time with the exception of WL-B, shown in blue, with a vertical offset from the other wells.	154
Figure 5-6 2D Geological cross section showing defined sequences and depositional systems, sequence boundaries are shown by dark dotted lines (above) and modeled cross section from Petromod (below).	156
Figure 5-7 Calculated temperature history of source rocks at the basin margin (a) and at the basin center (b). Red lines represent vitrinite reflectance isolines.	159
Figure 5-8 Calculated vitrinite reflectance maturity evolution along the model line from upper Permian (bottom) to present day (top) using Sweeny and Burnham (1990) Kinetic model.	160
Figure 5-9 Calculated transformation ratio history of source rocks at the basin margin (a) and at the basin center (b). Thick dark lines represent vitrinite reflectance isolines.	163
Figure 5-10 Migration and accumulation simulation of Karoo petroleum system showing oil flowpaths (green arrow) and gas flowpaths (red arrows). Also showing oil accumulations (green filled polygons) and gas accumulations (red filled polygons). (a) present day; (b) 184Ma; (c) 191Ma; (d) 255Ma; and (e) 270Ma.	166

List of Tables

Table 2-1 Definition of some post-stack attributes and their applications after Subrahmanyam and Rao (2008).....	27
Table 2-2 Table showing well logs, properties measured by each log, and their geological applications, After Octavian Catuneanu, (2006).....	37
<i>Table 4-1 Acquisition Parameters of Two-Dimensional Seismic Data in Southern Ogaden Basin.</i>	93
Table 4-2 Summary table of description and interpretation of electrofacies identified in well.	127

Chapter 1 : Introduction

The Ogaden Basin is the largest sedimentary basin in Ethiopia covering an area of approximately 350,000 sq. km, located in southeastern part of the country. The basin has an estimated sediment thickness in excess of 7 km at the deepest part (Figure 1-1). Ogaden Basin, according to Beicip-Franlab (1998) started to develop as a tri-radial rift system known as Karoo rift in the Permian and evolved as a passive margin starting from Jurassic, intermittently affected by regional tectonics. The stratigraphy of the basin can be broadly divided into two main intervals (Figure 1-2): a bottom sequence primarily composed of terrigenous clastics of Permian to Triassic age, also known as the Karoo sequence, and an overlying mega-sequence of Jurassic to Tertiary age composed of predominantly carbonates and evaporites (Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia, 2005).

The Karoo section in Ogaden Basin, with the exception of the top Adigrat formation, is completely subsurface and previous studies of the section are based on hydrocarbon exploration wells drilled in the basin. Around 65 wells are drilled to date with four gas field discoveries of an estimated 6.3 TCF reserve and numerous other shows from the Karoo section (K. Tadesse, personal communication, July, 2021). Various geophysical surveys leading up to drilling in most cases have also been conducted in the basin including over 20,000 line km 2D seismic and more than 200,000 line km gravity and magnetics surveys. Numerous geological and geochemical studies are also part of the basins geo-database.

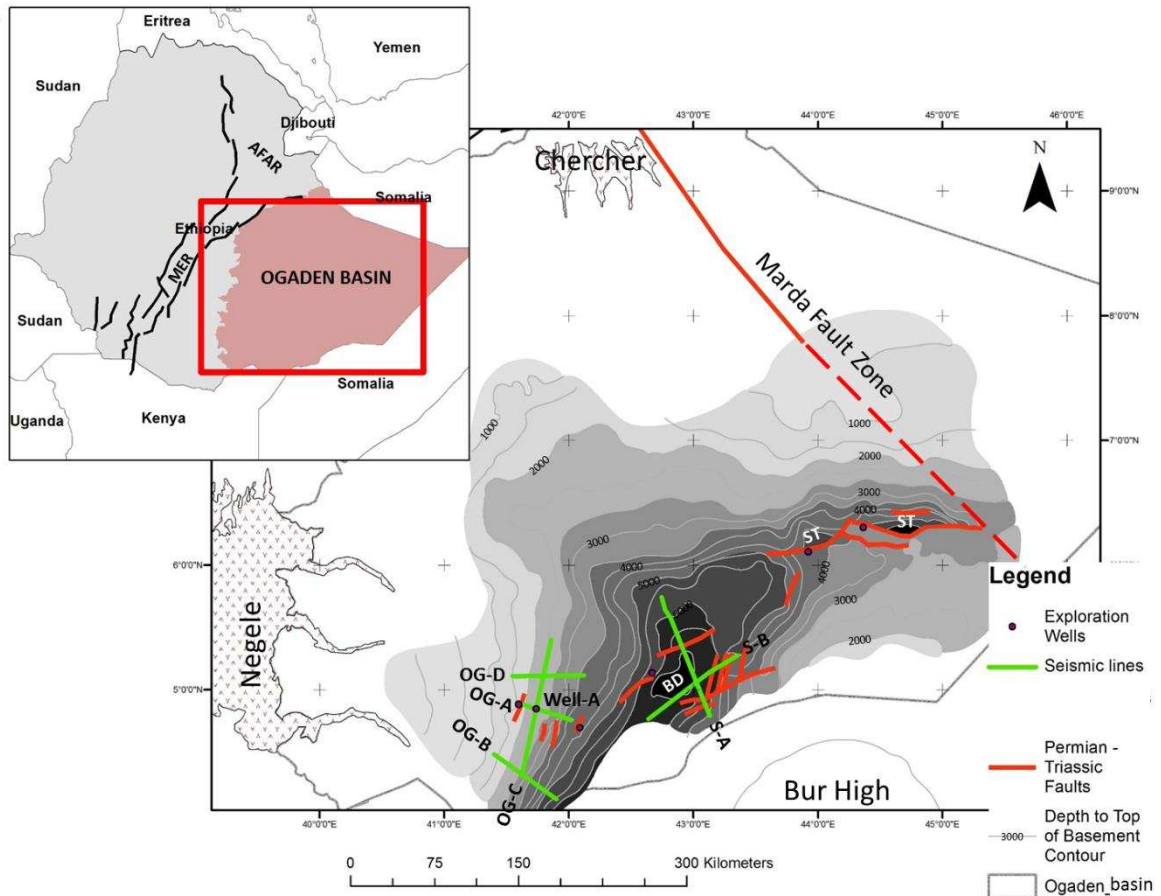


Figure 1-1. Location map of the Ogaden Basin, also showing basement top map, well and seismic lines used in this study (modified after Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia (2005)).

The first systematic study of the Karoo section in the Ogaden Basin was done by Worku and Astin (1992). Their study characterized the group using data from four wells drilled in the basin using mostly lithostratigraphic principles. This was followed up by a number of unpublished reports by Beicip-Franlab (1998), Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia (2005) and many others. These works have contributed greatly to our understanding of the sedimentology and stratigraphy of the group. However, a sequence

stratigraphic analysis of the Karoo section which allows a better understanding of the evolution and fill of the basin during the Permian – early Jurassic is still lacking.

ERA	PERIOD	EPOCH	FORMATION	DEPOSITIONAL ENVIRONMENT
CENOZOIC	TERTIARY	LATE	Margin Axial Zone	
		MIDDLE		
		EARLY	TALEH Auradu JESSOMA	Outer to inner shelf Fluvial to shallow marine
MESOZOIC	CRETACEOUS	LATE	FAF BELET UEN	Inner shelf
		EARLY	FERFER	Supratidal to lagoon
			MUSTAHIL	Outer to inner shelf
			GORRAHEI	Supratidal to inner shelf
		LATE	GABREDARRE UARANDAB	Inner shelf Basinal
	JURASSIC	MIDDLE	HAMANLEI	Supratidal to inner-outer shelf
		EARLY		
	TRIASSIC	LATE	ADIGRAT	Marine to fluvial
		MIDDLE	GUMBURO	Fluvial
		EARLY	BOKH	Lacustrine
PALEOZOIC	PERMIAN	LATE	CALUB	Fluvial to glacial
		EARLY		

Figure 1-2. Stratigraphic column of the Ogaden Basin (modified after Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia (2005)).

Sequence stratigraphic study is a revolutionary approach in stratigraphic studies. It has been used in different scales from regional studies to mapping stratigraphic targets and prediction of depositional facies in hydrocarbon exploration (eg. Flint et al., 2011;

Galloway, 1989; Khalifa and Mills, 2014; Sattar et al., 2017; Zeffa et al., 2003). The approach has enabled better understanding of temporal and spatial stratigraphic relationships of depositional facies (Posamentier and Allen, 1999) and sequence stratigraphic framework is commonly used for correlation of sequence stratigraphic units. The study is instrumental in frontier basins with limited data to establish plausible geologic models by effective integration of all available data.

1.1 Problem statement

An integrated sequence stratigraphic study of the Karoo sequence, involving seismic stratigraphic study and well log analysis, has not been conducted in Ogaden Basin previously. This study is needed for a robust understanding of the development and evolution of the Ogaden Basin during the Permian – Triassic. It is also an essential tool to analyze the stratigraphic architecture of the Karoo sequence and its petroleum potential. However, the quality of currently available seismic data is generally inadequate for seismic sequence stratigraphic study and this is one of the reasons the study of Karoo sequences has not been possible in Ogaden Basin. The poor quality of seismic data in Ogaden Basin related to factors such as low fold of coverage, random noise, pervasive multiple problems, penetration problems as well as poor ground conditions (Beicip-Franlab, 1998). Hence, an optimized reprocessing of existing seismic data to improve resolution and continuity is a required before sequence stratigraphic interpretation. In addition, the use of only amplitude data for interpretation limits the potential information that can be gained from the seismic data. Thus tests to see if the use of other attributes

contribute to our understanding of the basin are also required. Finally, well log interpretation using all conventional logs, advanced logging tools like the borehole imager and independent information such as cuttings samples is needed to achieve the least equivocal interpretation and is required for ground truthing seismic stratigraphic interpretations.

1.2 Aims of this study

The aim of this work is:

- 1- To present a sequence stratigraphic framework of the Karoo group in the southwestern Ogaden Basin using seismic and well data.
- 2- Analyze subsidence episodes, depositional systems and their distribution within defined Karoo sequences.
- 3- Evaluate hydrocarbon potential of the Karoo group based on a geological model established in the previous steps.
- 4- Improve seismic data quality for interpretation through reprocessing.
- 5- Analyze utility of seismic attributes for enhanced resolution and continuity, to incorporate in the sequence stratigraphic interpretation workflow.
- 6- Correlate seismic sequences with well log Interpretation carried out using wireline logs, cutting sample and other geologic data.

1.3 Geological setting

The early history of the Ogaden Basin is related to a Permian tectonic deformation that led to the deposition of Karoo group between the Permian – early Jurassic. The major

structural elements that controlled deposition of the group include the SW- NE trending Bodle Deep, a northern extension of the Mendera- Lugh basin and the ENE trending Shilabo trough and its extension east of the Marda Fault Zone (Purcell, 1976; Wood, 1979) (Figure 1-1). During this time the surrounding basement highs including the Bur Acaba in the south, Negele in the southwest and Chercher to the north supplied most of the sediments deposited in the Bodle deep and the Shilabo trough areas. The basin is thought to have formed under tensional and transtensional stresses that affected a large part of eastern Africa related to the southwards development of the Neo- Tethys (Beicup-Franlab, 1998).

However, only a few major bounding faults are mapped to date in the basin, including the Shilabo trough bounding faults with more than 3000m throw at the Karoo level. In the Bodle Deep steep flanks bound the sub-basin containing Karoo sediments comparable in thickness to Shilabo trough.

The Karoo group in Ogaden Basin has a thickness of over 3000 m in the deepest part of the basin. The Precambrian to Ordovician age basement is made up of both low and high grade metamorphic rocks and partly belong to the Mozambique Belt. Gneiss, migmatites, amphibole, quartzite of Archaean age represent the high grade metamorphic rocks and low grade types include phyllite, schist and stromatolitic limestone with slight or no metamorphism and intruded by granite and granodiorite. The overlying Karoo comprises of four formations namely: Calub, Bokh, Gumburo and Adigrat from bottom up. Calub Formation is of Permian age and is deposited in a pre- to early tectonic stage

unconformably overlying the basement complex. It is composed of mainly fine to medium grained arkosic sandstone with conglomerates and minor fine clastics, having a maximum thickness of 260m. The environment of deposition is interpreted variably as a river dominated alluvial fan (Worku and Astin, 1992) and as debris flow or glacial environment in the bottom part and fluvial in the upper part (Beicip-Franlab, 1998).

At the tectonic climax in late Permian to early Triassic, the overlying Bohk Formation composed of mostly carbonaceous, pyritic, red to brown shales, was deposited in a shallow to deep lacustrine environment. It has a variable thickness between 0 and 360m. The overlying Gumburo Formation was deposited in the mid to late Triassic in a late to post-tectonic stage. It has a maximum thickness of 750m and consists of grey to yellow, fine to medium to locally coarse grained sandstone, quartzitic and commonly feldspathic in composition, occasionally interbedded with shale units. Gumburo is interpreted as fluvial and possibly deltaic in the middle part. Adigrat Formation constitutes the top of the Karoo group. It is extensively deposited in the Ogaden Basin during the late Triassic but generally has diachronous age. Lithologically, fine to medium grained sandstone dominates the section with minor carbonaceous shales deposited in fluvial to tidal flat environment. It has an average thickness of ~140m.

The post Karoo period in Ogaden Basin mainly represents a tectonically quiescent setting as the basin evolved into a passive margin with the drifting away of Madagascar, India and Australia from the African plate (Petronas Carigali Sdn. Bhd. and Ministry of Mines of

Ethiopia, 2005). During the Early Jurassic, a transition zone made up of interbedded clastic and carbonate rocks and the overlying Hamanlie Formation were deposited as a result of a first transgression. Hamanlie is predominantly a thick limestone subdivided into lower, Middle and Upper units. Lithologies consist of limestone with intercalated shales in the lower section, anhydrite, dolomite and limestones with local oolitic and stromatolitic beds in the middle section and bioclastic/ oolitic limestones in the uppermost section. At the maximum flooding stage (Callovian - Oxfordian), Uarandab Formation composed of dark laminated marls and limestones containing a pelagic marine fauna was deposited. The overlying Gabredarre Formation (Upper Jurassic) comprises of bioclastic, locally oolitic and reefal limestones deposited as offshore bars and small reefal build-ups. In the Lower Cretaceous, a broad sabkha environment prevailed over vast areas of the basin. The lower Cretaceous Gorrahei Formation comprising of a basal shallow marine sequence of carbonates and shale, and an upper part containing thick evaporites and minor salt in the basin axis is observed from wells. The basin edge is marked by the continental Amba Aradam sandstones. The regional Aptian- Albian transgression marks still another cycle of sea level rise and led to the deposition of carbonates and shales of the Mustahil Formation. Later, a late Albian regression led to an evaporitic environment over the eastern Ogaden Basin, and the Ferfer gypsum was deposited. Widespread uplift and erosion took place in middle Cretaceous, its effect is pronounced in the Ogaden Basin and all coastal basins of East Africa and has eroded significant thickness of sediments varying from place to place. In the Upper Cretaceous, the Cenomanian Belete-Uen Formation and overlying Turonian to Maastrichtian Faf

Formations mainly restricted to the area east of MFZ were deposited. The overlying Tertiary sediments are similarly limited to the eastern Ogaden Basin, excluding continental sandstones that formed locally in many areas. The Jessoma sandstone, a non-marine, fluvial, deltaic sequence that spans Cretaceous/ Tertiary boundary is a coarse to fine grained quartzose sandstone with very little age defining fauna. Eocene sediments are mainly marine deposited during the last transgression. Auradu limestone was deposited during this time and it is generally characterized as dense mudstone to packstone, locally dolomitic, that grades to a gray shale deposited in an outer shelf environment.

1.4 Thesis outline

This thesis is structured in the following way: Chapter 1 deals with the general introduction and geological setting of the Ogaden Basin. Chapter 2 deals with theoretical aspects related to seismic data processing, sequence stratigraphy and interpretation techniques including seismic stratigraphy and well data analysis. Chapter 3 discusses the seismic data used in this study and the different processing steps applied to data to produce the final migrated stack that is ready for interpretation. Chapter 4 is devoted to detailed sequence stratigraphic interpretation of the Karoo group using seismic lines. The result of the seismic interpretation are correlated to a detailed well log interpretation carried out using all available information at the well. The new sequence stratigraphic framework and geologic model are also discussed, in this chapter, in relation to the regional geotectonic context and its implication to hydrocarbon exploration. Chapter 5

deals with basin and petroleum system modeling where the newly constructed 2D geologic model is simulated for its hydrocarbon potential. Chapter 6 discusses the important conclusions drawn from the research and outlines directions for further research in the future.

Chapter 2 : Theoretical Background on Reflection Seismic and Well Log

Data Analysis

2.1 Seismic Data Processing

The seismic reflection method employs seismic waves, primarily P- or compressional waves. These waves are generated using an artificial source at or close to the surface of the Earth and travel through the interior of the Earth to eventually return to surface after reflection at layer boundaries. Reflections are the result of contrast in physical properties (velocity and density) of the subsurface layers. On the surface geophones are laid out to detect these upcoming waves. The seismic reflection method can be divided into three branches: acquisition, processing and interpretation. The widely used acquisition technique is the common mid-point (CMP) method which involves redundant measurement of points known as midpoints along a survey line using different source-receiver pairs. The redundancy in measurement improves signal to noise ratio and has other benefits in multiple suppression and velocity model building.

Seismic processing is the production of an interpretable image of the subsurface from raw data acquired in the field. This involves a number of steps applied in sequence which includes amplification of signal and noise removal, achieving a better vertical and horizontal resolution and constructing a correct geometry of reflectors to the final product which is a more accurate seismic image of the subsurface. Seismic processing sequences are drawn after analyzing acquired data which strongly depends on data acquisition parameters and conditions. These factors include the type of survey such as

onshore/ offshore, type of source used, in case of onshore surveys the ground condition (loose, competent or hard ground) and many other factors dictate the type of processing performed on a seismic dataset.

Once all processing is performed to the data, it is ready for the next phase i.e. seismic interpretation. Seismic interpretation can be qualitative which includes stratigraphic and structural interpretations and if available by integrating with borehole logs and other geological data. Quantitative interpretation deals with inferring physical properties such as lithology, velocity and fluid content from pre- and post-stack data using methods like Amplitude Versus Offset (AVO), Impedance inversion and spectral decomposition.

In this section, a brief discussion of the three main processing steps which are deconvolution, stacking and migration follows. The application of processing steps to data used in this study is the subject of chapter three.

2.1.1 Deconvolution

A seismic trace is modeled as a convolution of Earth's impulse response $e[n]$ with a seismic wavelet $w[n]$. The seismic wavelet is a source signature modified by the immediate surrounding of the source point and other factors such as recording filter, receiver array response and so on (Mousa, 2019). Deconvolution is a process of compressing this wavelet to produce a trace that would have been recorded if the Earth's impulse response was convolved with a spike, thus achieving a higher temporal resolution.

Deconvolution can be effected by an inverse filter that when convolved with a seismic trace outputs a reflectivity series. This is called a deterministic spiking deconvolution and for a seismic trace $s[n]$ given by:

$$S[n] = e[n] * w[n] \quad (2.1)$$

An inverse filter $f[n]$ when convolved with seismic trace $s[n]$ will yield the Earth's impulse response $e[n]$ as:

$$e[n] = s[n] * f[n], \quad (2.2)$$

which implies

$$s[n] = s[n] * f[n] * w[n] \quad (2.3)$$

and hence

$$f[n] = \delta[n] * \frac{1}{w[n]} \quad (2.4)$$

$f[n]$ can be obtained by using Z-transform. This approach is deterministic because it assumes the wavelet $w[n]$ is known and works well with minimum phase wavelets.

The other approach for spiking deconvolution is using the Wiener filter which does not necessarily require the wavelet to be known. It is given by the matrix form equation (2.5):

$$\begin{pmatrix} R_{xx}[0] & R_{xx}[1] & & R_{xx}[N-1] \\ R_{xx}[1] & R_{xx}[0] & & R_{xx}[N-2] \\ & & & \\ R_{xx}[N-1] & R_{xx}[N-2] & & R_{xx}[0] \end{pmatrix} \begin{pmatrix} f[0] \\ f[1] \\ \\ f[N-1] \end{pmatrix} = \begin{pmatrix} g[0] \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

In this matrix form $R_{xx}[n]$ are auto-correlation lags of the input wavelet, while the column matrix elements $g[n]$ in the right side are lags of the cross-correlation of the zero lag spike with the input wavelet and $f[n]$ - are filter coefficients of length N . The Wiener filter is also used in shaping the wavelet to a desired form such as a delayed spike, a zero- phase wavelet or a time advanced form of the input wavelet by defining the desired output accordingly. This filter similarly works with a minimum phase wavelet and for numerical stability a white noise is usually added to the amplitude spectrum of the input known as pre-whitening (Mousa, 2019).

2.1.2 CMP stacking

Seismic data is usually acquired with a CMP method that results from multiple source-receiver pairs at successive mid-points with increasing offset from zero to the farthest offset which is equal to the cable length. This method of acquisition is required for velocity estimation where non-zero offsets provided by common mid point recording successively show reflection moveout that is analyzed to determine velocity. With estimated velocities we can correct for non-zero offset and compress the recorded data volume (in midpoint-offset-time coordinates) to a stacked section.

For a single constant- velocity horizontal layer, the traveltime curve as a function of offset is a hyperbola. The hyperbola is a good fit to small offsets and far offsets tend to move away from the curve. A normal moveout (NMO) refers to time difference between traveltime at a given offset and at zero offset and the velocity used to correct for normal moveout is called the normal moveout velocity.

The traveltimes equation in a horizontally stratified Earth with each medium composed of horizontal isovelocity layers, by making the small spread approximation, is given by:

$$t^2(x) = t^2(0) + x^2/v_{rms}^2 \quad (2.6)$$

Where x is the distance between source and receiver, v_{rms} is Root Mean Squared (RMS) velocity of the media above the reflecting surface, and $t(0)$ is twice the traveltimes along the vertical path. This equation can also be used to approximate several layers with arbitrary dips as long as the dips are gentle and the spread is small. Once the NMO velocity is estimated, the traveltimes can be corrected to remove the influence of offset. The NMO corrected gather then are summed to obtain a stack trace at a particular CMP location.

Conventional velocity analysis is based on the hyperbolic assumption. Velocity estimation is commonly done using constant velocity stacks (CVS) where different NMO corrections are applied to CMP gathers using a range of constant velocity values then displayed side by side. The velocity that best flattens each event as a function of offset is picked as its NMO velocity. Alternatively, velocity spectrum (semblance plots) are used; the idea is to display some measure of signal coherency on a graph of velocity versus two-way zero-offset time. The underlying principle is to compute the signal coherency on the CMP gather in small time gates that follow a hyperbolic trajectory. Stacking velocities are interpreted from velocity spectra by choosing the velocity function that produces the highest coherency at times with significant event amplitudes.

When the S/N ratio of the input data is poor, then the stacked amplitude may not be the best display quantity and different coherency measures such as normalized stacked

amplitude, normalized crosscorrelation sum and semblance can be used as attributes in computing velocity spectra. Semblance which is the normalized output to input energy is one example given by:

$$NE = \frac{1}{M} \frac{\sum_t S_t^2}{\sum_t \sum_{i=1}^M f_{i,t(i)}^2} \quad (2.7)$$

Where $f_{i,t(i)}$ is the amplitude value on the i^{th} trace at two way time $t(i)$ lies along the trial stacking hyperbola, M is number of traces and S_t is given by:

$$S_t = \sum_{i=1}^M f_{i,t(i)} \quad (2.8)$$

The presence of static time shifts due to near surface velocity variations cause an imperfect hyperbolic moveout. Statics can also severely distort the reflection hyperbola when there are large surface elevation changes. Residual statics variations refer to statics that remain in the data after initial corrections for estimated weathering layer variations and elevation changes have been done using refraction statics. The corrections for these residual statics normally must be estimated and applied to CMP gathers before stacking, and If not corrected, residual statics may cause false structures. After correction, traveltimes deviations show better alignment of reflections.

Estimation of residual statics is done after preliminary NMO correction using either a regional velocity function or information from a series of preliminary velocity analyses along the line. To estimate the time shifts from the time of perfect alignment, the

traveltime t_{ijh} that corresponds to the j^{th} source station, the i^{th} receiver station and the k^{th} midpoint along the h^{th} horizon can be approximately modeled as:

$$t_{ijh} = s_j + r_i + G_{kh} + M_{kh} X_{ij}^2, \quad (2.9)$$

where s_j is the residual static time shift associated with the j^{th} source station, r_i is the residual static time shift associated with the i^{th} receiver station, and G_{kh} is the difference in two way time at a reference CMP location i and the traveltime at the k^{th} CMP location along the h^{th} horizon. This term refers to structural variation along the horizon, $M_{kh} X_{ij}^2$ is the residual moveout that accounts for the imperfect moveout correction.

This is an over determined problem and is solved by minimizing the sum of the least squares error energy between the observed picks t'_{ijh} and the modeled times t_{ijh} :

$$E = \sum_{ijh} (t_{ijh} - t'_{ijh})^2 \quad (2.10)$$

In general, residual statics corrections involve three phases which are picking time values t'_{ijh} , decomposition of t'_{ijh} into its components and application of derived source and receiver terms to pre- NMO corrected CMP gathers.

Refraction based statics, on the other hand, are used to correct for long period statics components, by using first breaks, to account for weathered top layer and elevation variations. Different methods of refraction statics to estimate velocity and thickness of weathered layer and velocity of the bed rock include plus-minus, GRM and refraction tomography.

2.1.3 Migration

Migration is an imaging technique that moves dipping reflectors into their true subsurface positions and collapses diffractions, thereby delineating detailed subsurface features such as fault planes, synclines, anticlines and so on. It is also called lateral deconvolution because it improves lateral resolution (Schneider, 1978). Migration can be done in time or depth domain as well as in post stack sections and pre- stack gathers depending on the structural complexity in a survey area. The most common types of migration are F-K, finite difference, reverse time and Kirchhoff.

Kirchhoff migration is based on the scalar wave equation and can be applied in time and depth domains. It uses RMS velocity field that varies temporally as well as spatially. Kirchhoff integral represents the wave field $p(x_1, y_1, z_1, t)$ at any point in image space in terms of observations of the wave field $p(x, y, z=0, t)$ on the surface as:

$$p(x_1, y_1, z_1, t = 0) = \iint \frac{\cos \theta}{2\pi r c} \frac{\partial p}{\partial t}(x, y, z = 0, t = r/c) dx dy \quad (2.11)$$

Where

$$r = [(x_1 - x)^2 + (y_1 - y)^2 + z_1^2]^{1/2} \quad (2.12)$$

$C=v/2$ is the half velocity for a two way travel time t and θ is the angle between the z axis and the line joining (x_1, y_1, z_1) and $(x, y, z=0)$ (Gazdag and Sguazzero, 1984).

Equation (2.11) is used to compute the wave field at any depth z , the migrated section is obtained by performing the integration and setting $t=0$ for each output location. The

imaging principle is applied by mapping amplitudes of the resulting wave field at $t=0$ onto the migrated section at a corresponding output time.

The time derivative of the measured wave field modifies the wavefield phase and amplitude spectrum whereas the cosine of the angle θ of propagation corrects for the angle dependence of amplitude called directivity term or the obliquity factor. The $1/rc$ factor is the same as v^2t and corrects for amplitude decay and is known as the spherical spreading factor.

2.2 Seismic and Well Data Interpretation

2.2.1 Sequence Stratigraphy

Sequence stratigraphy is a sub discipline of stratigraphy that divides a sedimentary section into genetic packages bounded by unconformities and their correlative conformities (Emery and Myers, 2009). Sequence stratigraphic units are bodies of sedimentary rocks that are defined based on stratal stacking patterns and stratigraphic relations. The bounding surfaces that mark changes in stacking pattern are called stratigraphic surfaces and together with the sequence stratigraphic unit are used for a genetic, process-based stratigraphic correlation and mapping (Catuneanu et al., 2005). This approach sets sequence stratigraphic correlation apart from other types of stratigraphic correlations.

Sloss (1963) was among the pioneers to define sequences by dividing the North American Phanerozoic sedimentary section into six unconformity bound sequences, even though the use of unconformity surfaces to divide sedimentary successions was applicable before

that time (eg. Barrell, 1917; L L Sloss, 1949; Wheeler and Murray, 1957). Wheeler (1964) introduced the concept of a correlative conformity which led to definition of sequences that are bounded by unconformities of smaller magnitude and areal extent compared to Sloss (1963), where unconformity surfaces were interregional; this led to higher resolution in stratigraphic analysis. Then in the seventies, the developments in seismic data acquisition and processing led to higher resolution images of the subsurface and to the recognition of seismic scale sequences (R M Mitchum Jr et al., 1977). The trend of increasing resolution then integrated well data analysis and was termed high resolution sequence stratigraphy (Van Wagoner et al., 1990).

The fundamental unit of sequence stratigraphy is the stratigraphic sequence. A full stratigraphic cycle which starts and ends with the same type of sequence stratigraphic surface such as an unconformity delineates a 'sequence'. Sequences typically consist of two or more systems tracts which are defined as a linkage of contemporaneous depositional systems (Catuneanu, 2006). Systems tracts may consist of bedsets, parasequence sets, or sets of higher-frequency sequences (Brown Jr and Fisher, 1977) and may succeed each other in different orders depending on the conditions of accommodation and sediment supply at the time of deposition (Csato and Catuneanu, 2012).

The development of sequences and constituent systems tracts is controlled by the interplay of two fundamental variables which are accommodation and sediment supply. Accommodation refers to the space available for deposition of sediments that is created

by the interplay of tectonics, climate and sea level changes. Changes in accommodation are described as changes in relative sea/ lake level or base level. Sediment supply, on the other hand, refers to available sediment for transport and deposition into basins which can be terrigenous sediments sourced from surrounding areas or chemical and biochemical sediments. The interplay between sedimentation rate and change in accommodation creation rate leads to transgression - regression cycles which lead to different types of stratal stacking patterns such as aggradation, progradation and retrogradation. It is these stacking patterns that provide the basis for definition of different bounding surfaces and systems tracts.

2.2.1.1 Base level change and systems tracts

When sediment supply outpaces the amount of accommodation generated by relative sea-level rise at the shoreline, a normal regression occurs and results in a stratal stacking pattern defined by a combination of forestepping and upstepping (Catuneanu, 2006). A normal regression that comes after forced regression is called a 'lowstand' normal regression (Figure 2-1). Lowstand normal regressive shorelines typically indicate a concave-up trajectory (*Figure 2-2*), in response to the increase in the rate of accommodation creation during lowstand normal regressions. A lowstand systems tract is defined by a normal regressive stacking pattern (Figure 2-1) that is bounded at the base by the subaerial unconformity and the correlative conformity and at the top by the maximum regressive surface. Lowstand systems tracts typically include a continental topset and a marine foreset and bottomset.

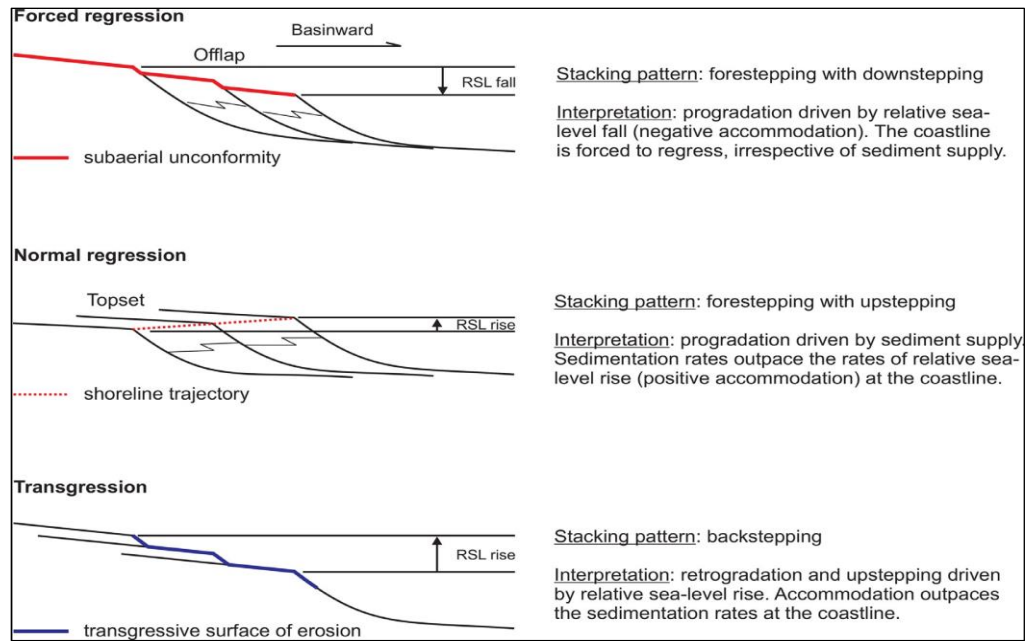


Figure 2-1 Different types of stratal stacking patterns related to forced regression, normal regression and transgression (after Cateneau (2006)).

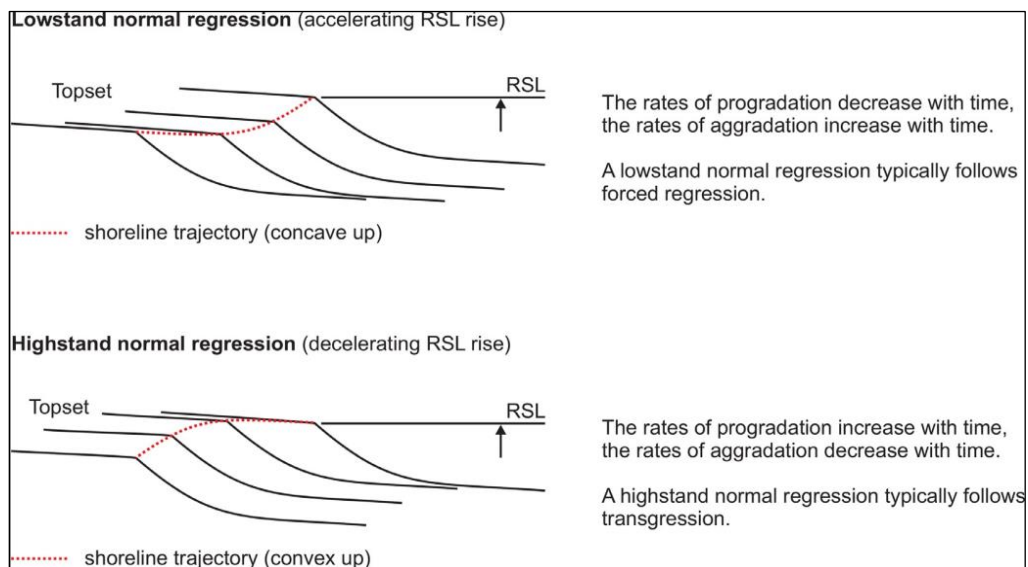


Figure 2-2 Stratal stacking pattern in lowstand and highstand normal regressions (after Cateneau (2006)).

A normal regression that follows transgression is designated as a 'highstand' normal regression where shorelines typically describe a convex-up trajectory (*Figure 2-2*). The highstand systems tract shows normal regressive stacking pattern (*Figure 2-1*) with the maximum flooding surface as the bottom boundary and the top boundary of a subaerial unconformity and the basal surface of forced regression (i.e., where followed by forced regression). Highstand systems tracts are characterized by a continental topset whereas the foreset and bottomset are marine in nature.

Forced regression results from relative sea-level fall and shows a stratal stacking pattern defined by a combination of forestepping and downstepping (*Figure 2-1*). The rate of forced regression increases as the rates of relative fall and sediment supply increases and is also a function of seafloor gradients. The falling-stage systems tract is defined by a forced regressive stratal stacking pattern (*Figure 2-1*). The systems tract is bounded at the base by the basal surface of forced regression and at the top by the subaerial unconformity and the correlative conformity. The downstream continental setting is subject to erosion or sediment bypass during relative sea-level fall excepting some fluvial deposits due to lateral accretion. Hence the falling-stage systems tract is the only systems tract that consists only of marine deposits.

Transgression is characterized by a stratal stacking pattern of a combination of backstepping and upstepping (Catuneanu, 2006; *Figure 2-1*). Transgressions occur when sediment supply is outpaced by the amount of accommodation generated by relative sea-level rise at the shoreline. Fluvial aggradation is typically high during transgressions.

Consequently, sediment starvation of the marine seafloors takes place since most sediment is trapped within fluvial and backstepping coastal systems. The transgressive systems tract is defined by a retrogradational stratal stacking pattern. It is bounded at the base by the maximum regressive surface and at the top by the maximum flooding surface.

2.2.1.2 Hierarchy of Sequences

The classification of sequence stratigraphic units and bounding surfaces based on their relative scale and stratigraphic significance defines the concept of sequence stratigraphic hierarchy (Catuneanu, 2015). Stratigraphic cyclicity can be observed at different scales and is in general basin-specific. Hence the definition of a hierarchy system is best approached on a basin-specific basis, rather than using any global standards or reference cycle charts. Hierarchical orders in a sedimentary basin may be assigned starting with the basin fill as a reference. A first-order sequence is defined as the entire sedimentary-basin fill that accumulated within a specific tectonic setting; in the case of 'polyphase' basins, first-order sequence boundaries mark changes in the tectonic setting. Within a first-order sequence, lower-rank sequences may be defined as a function of the relative magnitude of facies shifts that are associated with their formation. In this approach, sequences of different hierarchical orders have no time or thickness connotations, but only a relative stratigraphic significance in relation to each other.

The possibility that stratigraphic frameworks may correlate from one basin to another in response to global controls on accommodation may not be excluded, particularly in the case of tectonically 'passive' settings, but also it cannot be generalized. The importance

of local controls on accommodation, particularly in the case of tectonically active basins, cannot be underestimated and should be considered as a safe norm. For this reason, hierarchical orders are only meaningful within the context of the sedimentary basin in which they are defined, and their meaning may change from one basin to another.

2.2.2 Sequence stratigraphic interpretation technique

2.2.2.1 Seismic Stratigraphy

Seismic stratigraphy is a technique of using seismic data for the interpretation of stratigraphic information (Emery and Myers, 2009). The method was first introduced in the seventies and is described in a series of papers (Vail et al., 1977). The key concept in the method was that seismic reflections follow time lines which meant that correlative impedance contrasts come from bedding interfaces and not from lateral facies changes. Reflections can therefore be considered as time lines or time surfaces in three dimensions that separate strata in terms of age. Hence, seismic sections provide both chronostratigraphic information using time surfaces and lithostratigraphic information from internal reflection characteristics.

Seismic data resolution

Vertical resolution in seismic refers to the minimum vertical thickness between layer interfaces that is resolved by seismic data. This is a function of the wavelength of the seismic wavelet where shorter wavelengths give rise to higher resolution compared to long wavelengths. In general, interference between top and bottom interfaces begins

when the separation between the interfaces is less than a quarter of the wavelength; this is known as the thin bed effect or tuning. The other factors that affect resolution are related to attenuation of high frequencies as travel path of seismic waves increase and the effect of increasing velocity with depth that results in increasing the wavelength of the seismic wavelet.

Lateral resolution depends on the Fresnel zone which is a function of frequency in unmigrated sections. The Fresnel zone refers to the portion of the reflecting surface from which the energy returns to a geophone within a half-cycle after the onset which implies an area a quarter of the wavelength later the onset of reflection (Sheriff, 2012). The wavelength dependence means that the shorter the wavelength the smaller the Fresnel zone and the longer the wavelength the larger will be the Fresnel zone. Migration improves horizontal resolution by removing the Fresnel zone smearing. However, migration noise and incorrect migration, resulting from out of plane reflections, are introduced as a result of migrating data.

Seismic attributes

Seismic attributes are defined as any measure of data that help in visually enhancing or quantifying features of interest (Chopra and Marfurt, 2005). A good seismic attribute is either directly sensitive to the desired geologic feature or physical property of interest or allows to define the structural or depositional environments.

Taner et al., (1994) divided attributes into two general categories: geometrical and physical. The objective of geometrical attributes is to enhance the visibility of the

geometrical characteristics of seismic data. Physical attributes, on the other hand, deal with the physical parameters of the subsurface and so relate to lithology and pore fluid. The classification may be further divided into post-stack and pre-stack attributes. Pre-stack attributes are computed from pre-stack data and reflect variation of different attributes such as amplitude and instantaneous frequency with offset. Post-stack attributes are most commonly used attributes and are computed on stacked sections based on the complex trace concept which is defined as:

$$F(t)=f(t)+jf^*(t) \quad (2.13)$$

Where $F(t)$ represents the complex trace, $f(t)$ is the seismic trace and $f^*(t)$ is the imaginary component determined uniquely from the real part using Hilbert transform (Taner et al., 1979). Attributes defined using complex trace include envelope, derivatives, instantaneous phase and frequency. The expressions for some of the common attributes and their applications are shown in Table 2-1. These attributes play an important role in seismic stratigraphic interpretation by enhancing visibility of geometric features of seismic events such as event terminations, continuity and curvature of events, unconformities etc.

Table 2-1 Definition of some post-stack attributes and their applications after Subrahmanyam and Rao (2008)

Attributes	Expressions	Applications
Signal Envelope (E) or Reflection Strength	$E(t)=SQRT\{f^2(t)+f^{*2}(t)\}$	For identifying bright spots, gas accumulation, sequence boundaries, major changes or depositional environments, thin-bed tuning effects, major changes of lithology etc

Envelope Derivative (RE)	$RE(t)=dE(t)/dt$	To highlight change in reflectivity, sharp interfaces, discontinuities
Instantaneous Phase	$\phi(t)=\arctan f^*(t)/f(t) $	Best indicator of lateral continuity, can be used to compute the phase velocity, shows discontinuities (but may not be the best tool), sequence boundaries, detailed visualization of bedding configurations
Instantaneous Frequency	$F(t)=d(\phi(t))/dt$	Instantaneous frequency can indicate bed thickness and also lithology parameters. Chaotic reflection zone indicator, bed thickness indicator. Higher frequencies indicate sharp interfaces or thin shale bedding, lower frequencies indicate sand rich bedding. Sand/Shale ratio indicator.
Instantaneous Acceleration AC(t)	$AC(t)=d(F(t))/dt$	Highlights change in instantaneous frequency which may be indicative of thin bedding or absorption, accentuates bedding differences, higher resolution, may have somewhat higher noise level due to differentiation.

Seismic sequence analysis

Seismic sections can be subdivided into depositional sequences using unconformity surfaces. Unconformities and other sequence stratigraphic surfaces are delineated by mapping reflection terminations. Reflection terminations are characterized by geometric relationships between the reflection and the seismic surface against which it terminates. Terms such as lapout, truncation, baselap, toplap, onlap and downlap are used to describe reflection termination types. These are briefly described below and shown in Figure 2-3.

Lapout: refers to lateral termination of a reflector at its depositional limit.

Baselap: refers to termination of reflectors against an underlying seismic surface. A baselap can be a downlap when the dip of the underlying reflector is less than dip of the terminating reflectors. Whereas an onlap is where overlying reflectors terminate against a steeper underlying surface.

Toplap: refers to termination of inclined reflections against an overlying lower slope surface. An apparent toplap surface occurs when the topset are too thin to resolve in seismic or when erosion removes the topsets.

Erosional truncation: refers to termination of strata against an overlying erosional surface. Truncations are usually more extreme than toplaps. Apparent truncations is when low angle reflections terminate beneath a dipping seismic surface which represents marine condensation and it occur at the distal deposition limit.

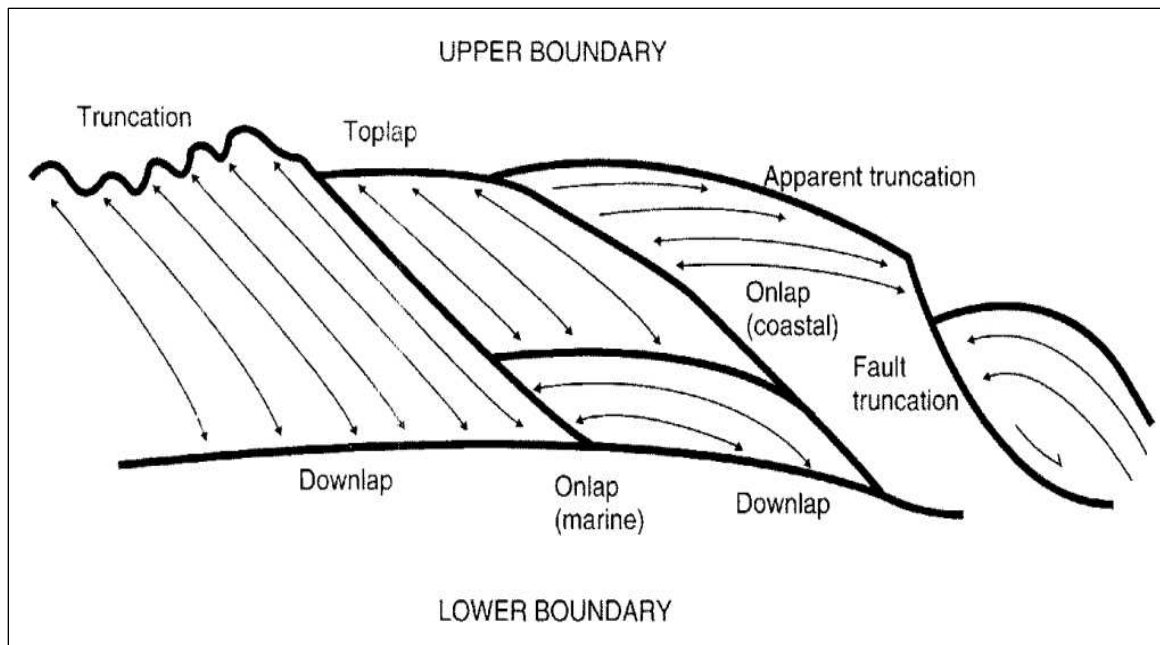


Figure 2-3 Different types of terminations observed in seismic sections (after Emery and Myers, (2009)).

Seismic facies analysis

This step is described as the interpretation of depositional facies from seismic reflections (Sangree and Widmier, 1979). It involves definition of seismic facies based on reflection characteristics such as reflection configuration, continuity, amplitude, frequency content and seismic velocities. Reflection configuration plays a major role in identifying different depositional facies and includes several principal types described below and illustrated in Figure 2-4.

Parallel to wavy reflection: this pattern indicates uniform sedimentation conditions in both shallow and deep waters and can be found in clastic and carbonate depositional environments. Subdivisions can be further made using continuity, amplitude and

frequency of events. High amplitude reflections are generally related to contrasting lithologies such as sand and shale whereas low amplitude indicates small changes in lithology across the reflector such as sand and silty shale (Veeken, 2007). Frequency can give some information on bed thicknesses. Continuity of reflections suggests the level of energy of the deposits where high continuity suggests similar sedimentation conditions in low energy environments whereas discontinuous reflections indicate high energy environments.

Divergent reflections: indicate geometries with wedge shape in asymmetric sediment thickness distribution. These can be due to variable sedimentation rates across the section or it can be related to syn-depositional differential tectonic movements.

Clinofoms/ foresets: are the result of progradation and can be further classified into different types based on shape and angle of repose which are a function of factors such as composition, sedimentation rate, water depth and others. Oblique shapes indicate topsets are absent implying an area of sediment bypass and little developed bottomsets imply a sediment starved distal part of the basin floor. A sigmoidal shape is when the topset and bottom sets exist, it is usually related to relative rise in sea level and a reasonable rate of sediment supply and it is usually related with low energy environments. Shingled shapes have smaller foreset heights and low angle of foresetting. They are formed due to progradation in high energy shallow marine environments but can also be found in deeper marine conditions resulting from massflow processes.

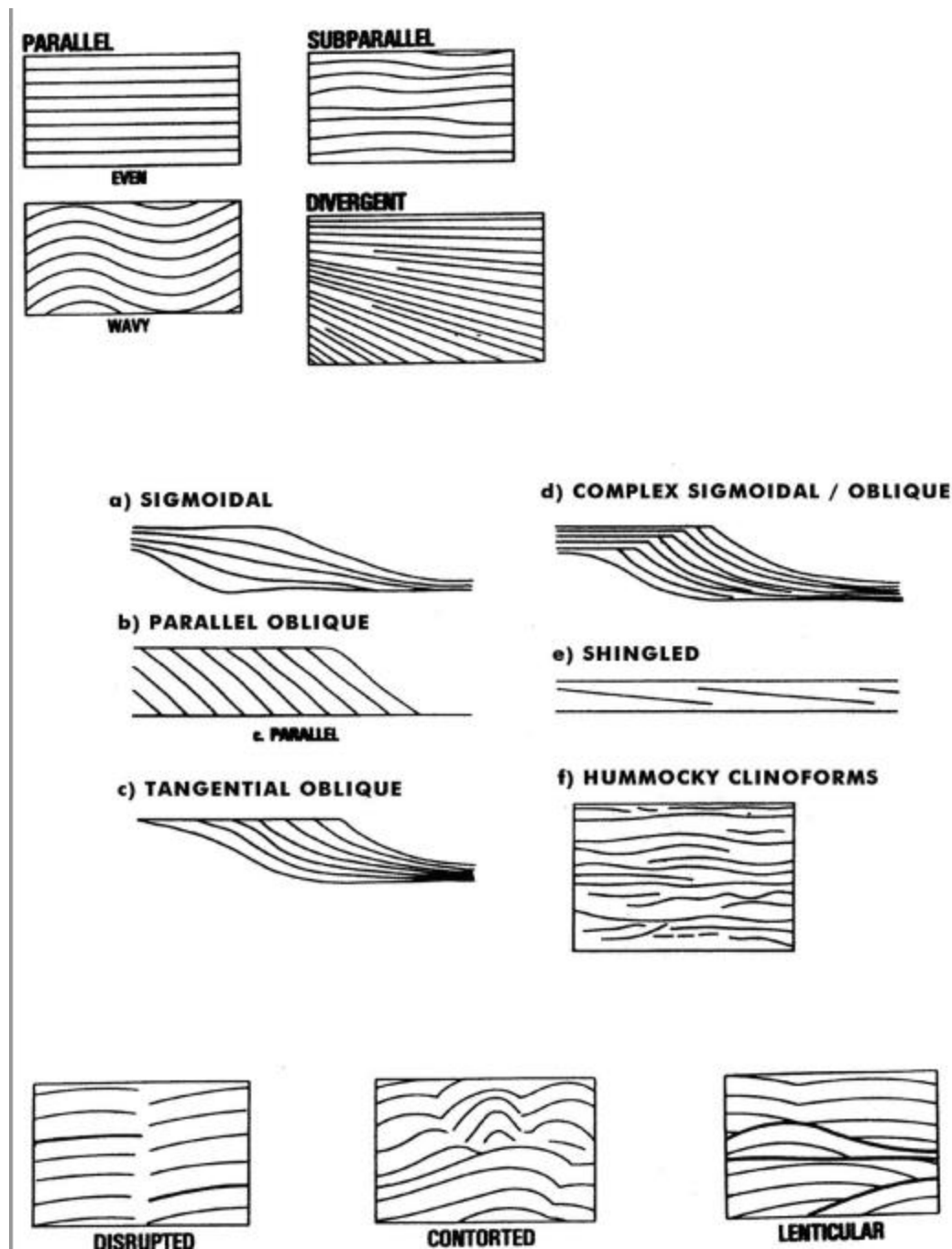


Figure 2-4 Different types of reflection configurations (after Veeken (2007)).

It is possible to use clinoforms as a measure of water depth in which they were formed. By taking the difference between the top set and bottomset reflection times and then

using appropriate interval velocity, after decompaction effects are estimated, the thickness of clinoforms can be determined which roughly estimates water depth.

Hummocky reflections: refer to irregular and discontinuous reflection types with variable amplitudes. These type of reflections show little systematic reflection terminations and are related to cut and fill geometries and contorted beddings.

Chaotic reflections: refer to highly disordered internal organization of reflections due to channel fills, slumped deposits, overpressured shales, volcanic rocks, mobile salts and similar deposits.

Reflection free zones: are due to weak acoustic impedance contrasts in homogenous gross lithology. Geologic units that show no or weak reflections include thick shales, limestones, massive reefal buildups and igneous bodies.

In addition to delineating geometries in 2D seismic sections, the three dimensional shape of these seismic facies or their external morphological shape is another tool used in identifying depositional environments. Different types of external shapes can be observed in seismic sections. Sheets or sheet drapes are one type of external shape which result from uniform sedimentation conditions generally related to fine grained sediments. Wedge is another type which indicates a lateral change in sedimentation rate whereas Banks and monoclines have an elongated shape and indicate a major differentiation in sedimentation pattern. Mounds represent another type of external shape which have 3D depositional buildups and which can be due to carbonate build ups, submarine fan complexes, contourites or volcanic cones. Slope front fills, erosive fills and non- erosive

fills represent still other types of morphologies with implications on depositional environment interpretation.

Recognition of systems tracts from seismic sections

Systems tracts are defined by the nature of their boundaries and their internal stacking patterns. The recognition of systems tracts from seismic applies the same principles. The key surfaces that divide sequences into systems tracts are the sequence boundary, transgressive surfaces, maximum flooding surface and marine onlap/ downlap surfaces between the lowstand fans and lowstand wedge. Sequence boundaries usually develop a high relief truncation surface and a basinward shift of coastal onlap above the boundary. A lowstand systems tract is bounded by a sequence boundary from below and a transgressive surface from above. A transgressive surface marks the end of lowstand progradation and a start of a transgression. It is identified as the boundary between a topset- clinoform interval and an overlying topset only interval. A transgressive systems tract is bounded at the bottom by transgressive surface and a maximum flooding surface upper boundary. It shows backstepping topsets and is usually thin. The maximum flooding surface is recognized by clinoforms downlapping underlying transgressive topsets. However not all downlapping boundaries represent maximum flooding surfaces because a downlap surface also exist at the base of a lowstand prograding wedge. A highstand systems tract overlying the maximum flooding surface showing progradation at the basin margin and is bounded at the top by a sequence boundary.

2.2.2.2 Well log sequence analysis

Sequence stratigraphy using outcrop and well data was developed to test seismic stratigraphic techniques during the early 1980s (Emery and Myers, 2009). The work of Van Wagoner, J.C., Mitchum R.M., and Rahmanian (1990) is among the early works on the subject that introduced the concept of high resolution sequence stratigraphy by integrating outcrop and well data to seismic sequence stratigraphy. Well-log data is generally used for analysis of vertical stacking patterns, grading trends, depositional elements and systems as well as to infer lateral facies trends and calibrate seismic data (Catuneanu, 2015). Sequence analysis using well logs involves interpretation of depositional lithofacies from wireline logs which are used for paleogeographic and depositional environment reconstructions. The interpretation of sequence stratigraphic surfaces and systems tracts is accomplished by analyzing the spatial and temporal relationships of depositional systems, which are the products of sedimentation in particular depositional environments, including their shift directions through time.

Analysis of depositional environments in the subsurface, in the absence of core data, is usually done using wireline logs (for example, M. H. Rider, 1986; Serra, 1985). The approach involves the study of electrofacies associations, the equivalent of facies associations in sedimentology, where we examine the context in which an electrofacies or a specific log pattern exists. Hence individual log patterns may be found in different environments however when considered together with the overlying and underlying patterns, it is possible to narrow down the possible depositional environments for a given log signature. However, the interpretations using only well logs are usually non-unique

and so constraining it with independent data set such as cores, cutting samples, seismic and other data is essential; to a minimum, well cuttings routinely collected to provide information on lithology, fluid contents, and biostratigraphy can be incorporated in the analysis.

Well logs used in sequence analysis

Well logs have a number of applications in the study of the subsurface geology from identification of lithology and stratigraphic correlations to determination of reservoir properties such as porosity and permeability and imaging fractures and assessing stress fields (See

Table 2-2 for details). In sequence analysis, the focus is on determining lithologies, sedimentary structures and other attributes of rock bodies that can be used to characterize sedimentary successions and decipher the evolution of sedimentary basins. In this regard, lithologs (gamma-ray, density, neutron, sonic and similar logs) play an important role.

There are a number of log types that are measurements of either an induced or spontaneous phenomena; the most common types are listed in

Table 2-2 below. Most logs are labeled conventional for being used over time while other are advanced log types such as NMR and borehole imaging (BHI) logs which were recently introduced. The micro-resistivity logs combine the methods of conventional resistivity and dipmeter measurements to produce high-resolution images that simulate the sedimentological details of an actual core. Such 'virtual' cores allow visualization of details

at a millimeter scale, including sediment lamination, cross-stratification, bioturbation, etc., in three dimensions (Catuneanu, 2015). In this section I will introduce some of the wireline logs that were also used in this research in more detail in the following table.

Table 2-2 Table showing well logs, properties measured by each log, and their geological applications, After Octavian Catuneanu, (2006).

Log	Property measured	Units	Geological interpretation
Spontaneous potential	Natural electric potential (relative to drilling mud)	Millivolts	Lithology, correlation, curve shape analysis, porosity
Conventional resistivity	Resistance to electric current flow (1D)	Ohm-metres	Identification of coal, bentonites, fluid types
Micro resistivity	Resistance to electric current flow (3D)	Ohm-metres and degrees	Borehole imaging, virtual core
Gamma ray	Natural radioactivity (e.g., related to K, Th, U)	API units	Lithology (including bentonites, coal), correlation, shape analysis
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, tightly cemented zones, coal
Neutron	Hydrogen concentration in pores (water, hydrocarbons)	Per cent porosity	Porous zones, cross plots with sonic and density for lithology
Density	Bulk density (electron density) (includes pore fluid in)	Kilograms per cubic metre (g/cm ³)	Lithologies such as evaporites and compact

	measurement)		carbonates
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (azimuth and inclination)	Paleoflow (in oriented core), stratigraphic, structural analyses
Caliper	Borehole diameter	Centimetres	Borehole state, reliability of logs

Gamma ray (GR) log

Gamma rays are packets of electromagnetic radiation also known as photons. Radioactive decay is spontaneous transition from one nuclear energy state to another and is the process that leads to emission of gamma rays (Ellis and Singer, 2007). The use of GR measurement in well logging is associated to radioactive isotope concentrations in formations. Radioactivity in sedimentary rocks mainly comes from uranium, thorium and potassium. The largest source of formation radioactivity is potassium, a fairly common element in the Earth's crust. The minerals containing potassium in sedimentary formations include sylvite, Feldspars, which, after quartz, are the most abundant minerals found in sandstones. The energy emitted by the three elements show a discrete spectrum between 0 – 3MeV and it is possible to differentiate each element by its spectral signature. Peak frequencies for uranium are recorded at 1.76MeV, for thorium at 2.62MeV and for potassium at 1.46MeV. As the gamma rays interact with surrounding formation, however, their energy is lost by Compton scattering and the final spectral

signature recorded at boreholes is a complex continuous spectrum that still retains the characteristics of the discrete spectrum.

The tool used to record gamma rays consists of a scintillation counter which is a sodium iodide crystal that flashes when interacting with gamma rays (Rider, 1986). These are collected by a photo-multiplier for a fixed period of time and are taken as a reading for a given depth point. Tools can be conventional or spectral type which measure the total emitted radiation and the radiation emitted by uranium, thorium and potassium respectively. The unit of a gamma log is API, it is defined with reference to a specially constructed well in University of Houston, Texas that is used as a standard of measurements and for calibration of instruments.

Gamma ray measurements are affected to some degree by borehole environment. The drilling mud and borehole irregularities such as cavings are two main factors that need to be compensated for by using various correction charts. Another factor is the type of mud used in drilling, additives such as barite which absorbs gamma rays and KCl which adds unwanted energy to measurements. These factors are similarly accounted for using correction charts.

Gamma logs are one of the most commonly used logs in sequence stratigraphy and are run in most wells. In general, they are considered as a measure of clay content in formations which has implications on depositional energy (Emery and Myers, 2009). Increase in gamma ray readings is correlated with decreasing depositional energy. However, interpretations are not always unique; there are examples of nonradioactive

clays and highly radioactive dolomites. The precipitation of uranium rich shales in sandstones, arkosic sandstones and concentration of heavy minerals in channel lag are still other alternatives that need to be considered in interpretation. The use of spectral gamma ray devices in this regard can discriminate anomalies such as a “hot” dolomite or other formations with some unusual excess of U, K, or Th.

Density and Photoelectric logs

The density log is a measure of formation bulk density using an active source of gamma rays. Compton Scattering and Photo-Electric Absorption are two important phenomena associated with density logs. Gamma rays emitted from a source interact with surrounding rocks and through this interaction lose their energies by Compton scattering. A gamma ray with an initial single peak energy spectrum will gradually show a widening spectrum to lower energies as the gamma rays travel longer distances into the formation and depending on number of collisions each ray undergoes.

As some of the most scattered gamma rays energies approach 0.2 MeV, the gamma ray can be completely absorbed by the atoms in the rock. This is called photo-electric absorption, and is a different process from Compton scattering. Different materials have different abilities to photo-absorb gamma rays such as a low, medium or high absorption indices as shown in Figure 2-5 for gamma rays that have travelled through the media to a detector. The count rates measured in the higher energy shaded window (for hard gamma rays) measure Compton scattering and hence the electron density which is the same as density of the formation. Whereas the count rate of the soft gamma rays in the lower

energy shaded window in Figure 2-5 is a measure of the effective electron density of the rock.

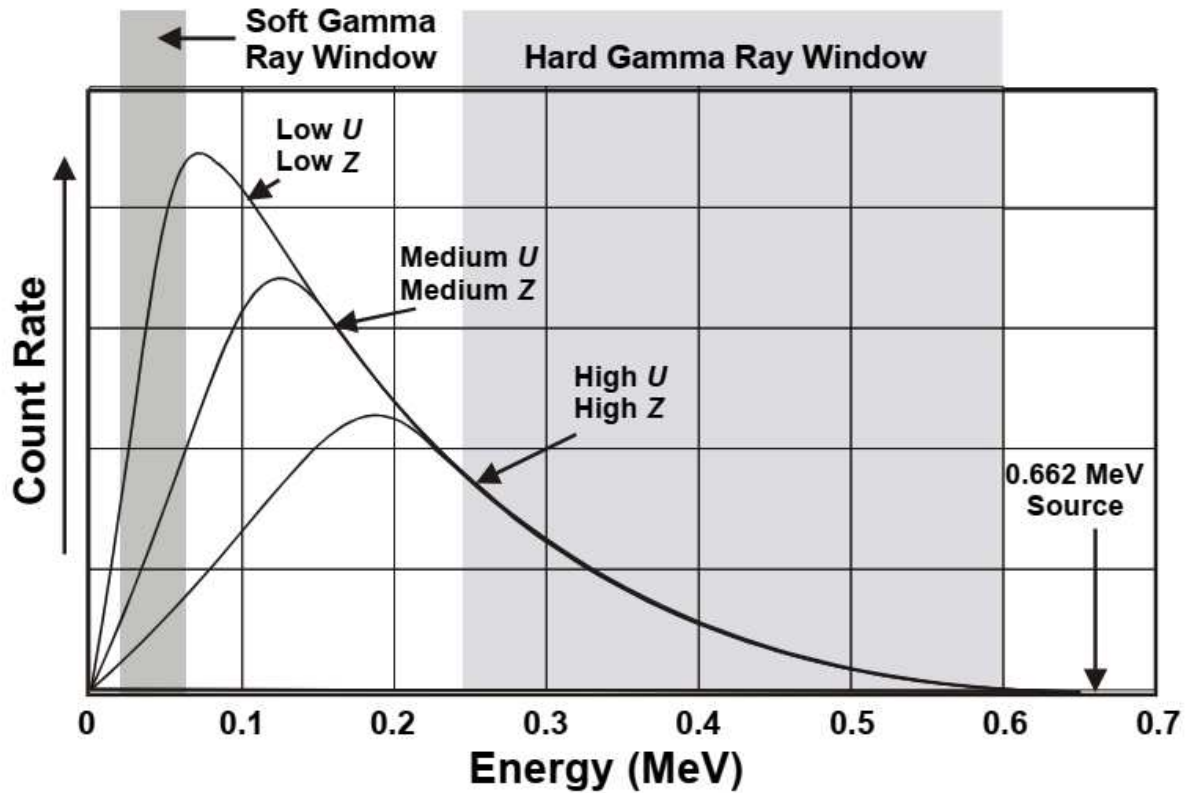


Figure 2-5 Gamma ray energy spectra and measurement windows (after M. H. Rider (1986)).

The tool used for density and PE measurements has a focused gamma ray source and a far and near scintillation detectors; two detectors are used for the purpose of compensating borehole effects. Recent tools use more efficient detectors which measure both density and photoelectric factor. Depth of investigation is usually very shallow and therefore the tool is likely much affected by hole conditions.

In dense formations Compton scattering is extreme and few detectable gamma rays reach tool's detectors and vice versa. Detector counts are then converted to electron density

and although electron density and density are almost identical, there are differences when water (hydrogen) is involved. For this reason, the actual values presented on the density log are transformed to give actual values of calcite (2.71g/cc) and pure water (Rider, 1986).

Density log is usually accompanied by a curve that shows borehole and mud cake corrections which have been automatically applied. Tool is typically run as a density-neutron combination along with gamma tool. The caliper is an essential accompaniment for QC reasons. Its shallow depth of investigation means that in porous rocks, it will measure in the invaded zone.

The Photoelectric factor log (PEF) is strongly dependent on the average atomic number, Z of the constituents of the formation and so the lithology. The effect of porosity is minimum, that is, the difference between PE values of two matrix types is more significant than the variations within each individual matrix type caused by porosity changes. Hence, principal use of PE is as matrix indicator, either alone or especially when cross-multiplied with density log to produce the value U. The method is generally useful in complex carbonate evaporite lithologies, where porosity is lithology dependent, especially in the presence of gas which does not affect the PE value. In sand shale sequence the effect is less evident. PE is ineffective when barite is used in the drilling mud.

Density logs are used for mineral identification and therefore they are very useful in sequence stratigraphic interpretations. However, they only detect changes in lithology if the adjacent lithologies have different densities, so they have to be used in conjunction with other logs. On the other hand, the neutron-density log combination is probably the best indicator of general lithology especially in the presence of a valid PEF curve. Density log can also be used to identify high TOC values.

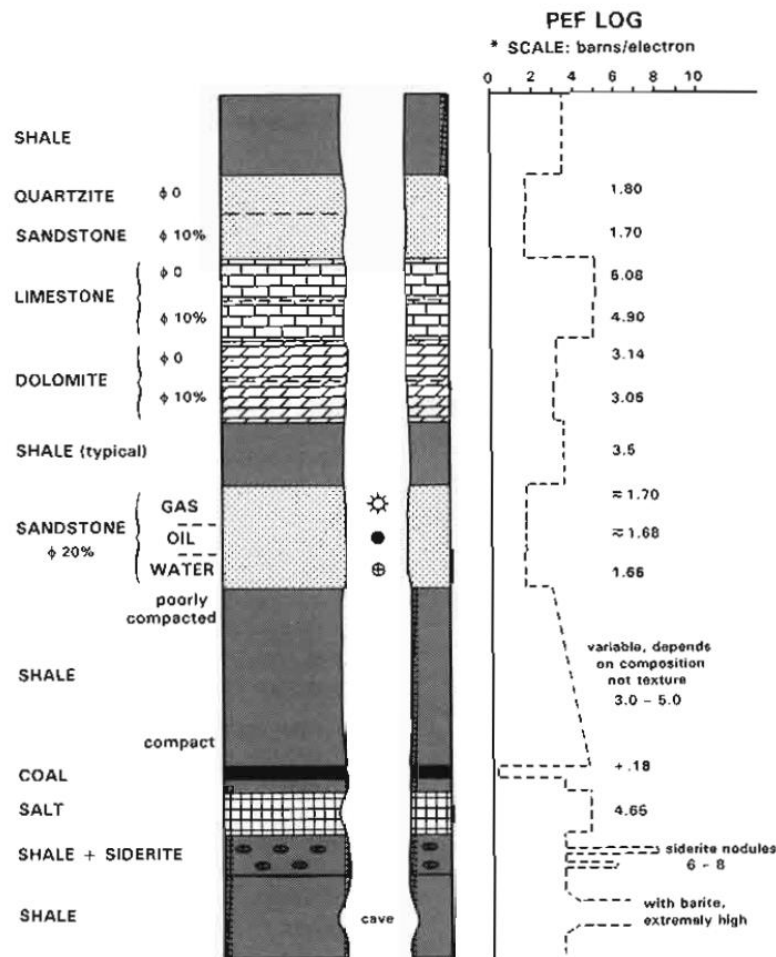


Figure 2-6 Photoelectric Factor (PEF) log. The log is less sensitive to porosity and hence a good indicator of lithology (after M. H. Rider (1986)).

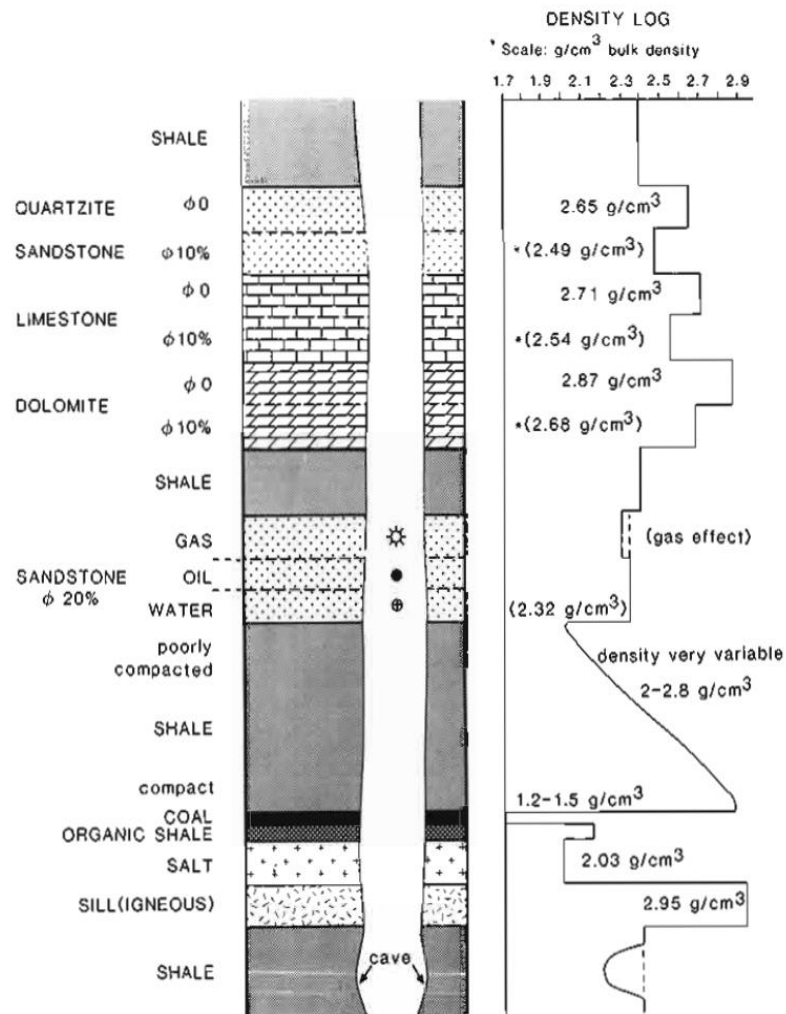


Figure 2-7 Density log measuring bulk density of formations (after M. H. Rider (1986)).

Neutron logs

Neutron logs measure porosity of formations by using neutrons emitted from a tool that also has detectors to measure returning neutrons after interaction with formations. Neutrons interact with matter in two ways, by collision and absorption (Rider, 1986). Collisions take place at higher energy state whereas absorption takes place at lower energy. A free neutron in the early stage of its release has an energy state namely fast that degrades with time to epithermic and finally to a thermic state. The energy loss also

results in velocity loss through elastic scattering. Collision with hydrogen nuclei reduces the energy of neutrons much more than collision with heavier elements, such as silicon. As collisions continue the thermal energy state is reached, at which point neutrons start to diffuse through formations to finally be absorbed by nuclei of formations.

The neutron tool consists of fast neutron source and two detectors which measure energy loss. Tools commonly detect both thermal and epithermal neutrons. The near detector measures borehole effects whereas the far detector measures both the effect of the borehole and formation. Therefore taking the ratio between the far and near detectors borehole effects are removed. The measurement unit is given directly in neutron porosity units. Neutron porosity is real porosity in clean limestones, but other lithologies require conversion factor. Tools usually have depth of investigation between 15 – 25cms and a good bed resolution.

There are three factors that lead to perturbation of neutron logs (Ellis and Singer, 2007). The first one is related to calibration where neutron porosities are usually calibrated using limestone or sandstone. It is important to know to which matrix type the log is calibrated. This is because in a limestone calibrated log a sandstone formation with the same water filled porosity as a limestone equivalent will read a lower porosity than the true porosity. The other factor is related to high values of porosity in shales. This is because of the hydroxyls associated with the clay mineral structure. Therefore large apparent porosity values are recorded primarily because of the hydrogen concentration associated with the shale matrix. The third factor is related to gas filled pore spaces. Gases have lower

hydrogen density compared to liquid which are used in calibration of neutron porosity. Hence the lower hydrogen density will result in a decreased apparent porosity. This error has been exploited for detection of gas in combination with density log.

The density- neutron overlay is the best indicator of lithology as shown in Fig. 2-8 and so can be used to study depositional trends. The logs are scaled to superimpose in clean carbonate lithologies but in clean sandstones there will be small separations which may be larger if feldspathic sand is present (Emery and Myers, 2009).

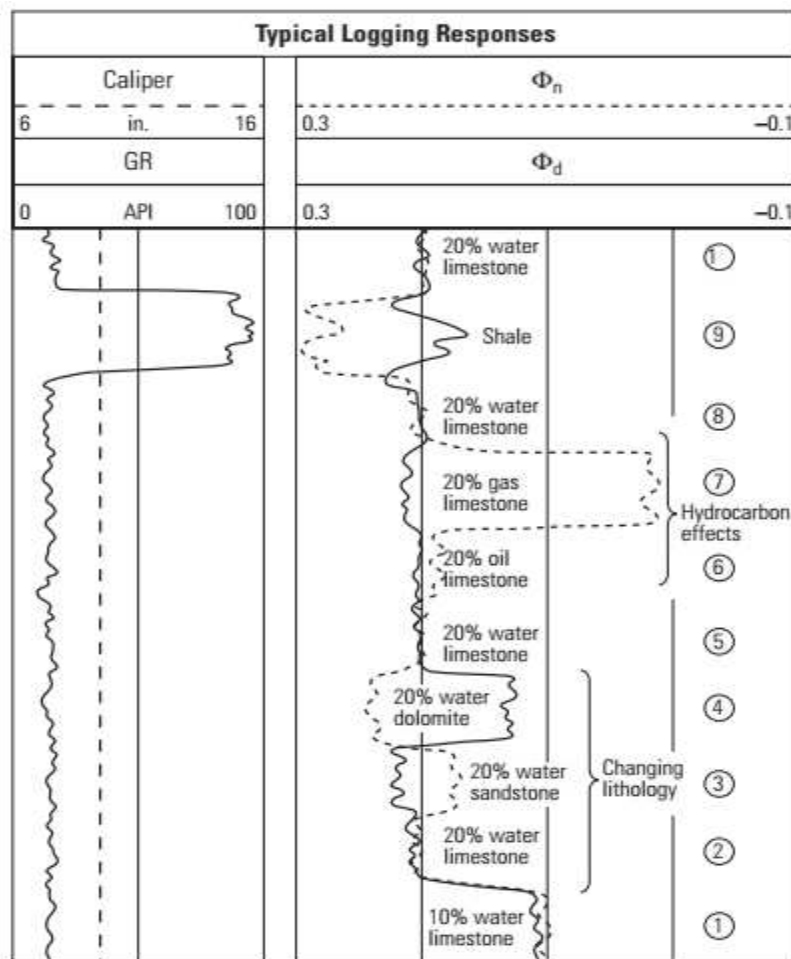


Figure 2-8 Typical example of a neutron- density overlay plot, its interpretation and correlation with other logs (after M. H. Rider (1986)).

Interpretation of log motifs

The most common types of log patterns include blocky or cylindrical, irregular or serrated, fining-upward or bell shaped and coarsening-upward or funnel-shaped patterns (Figure 2-9; Posamentier and Allen (1999)).

Blocky motif: generally implies a constant energy level, and constant sediment supply and sedimentation rates. It can be observed in a broad range of depositional environments, ranging from the nonmarine to the deep marine including fluvial-channel-fill sandstone, tidal-channel-fill sandstone, and nearshore-marine deposit.

Serrated motif: this pattern is indicative of a heterolithic lithofacies, implying deposition under rapidly alternating high and low energy. It can be observed in a broad variety of depositional environments, ranging from fluvial to deep marine. This alternation can occur in nonmarine floodplain environments, lower-shoreface to offshore transitional environments, shallow-water transgressive settings, and deep-water turbidite environments.

Fining-upward motif: this trend can be formed in almost every depositional environment, where there is a decline with time in energy levels. This kind of lithofacies element is indicative of deposits associated either with waning depositional events such as sediment gravity flows or progressive shifts of a depocenter away from the section in question (i.e., transgressive deposits), or due to a progressive decrease of available energy at the location of deposition (e.g., channel-fill deposits).

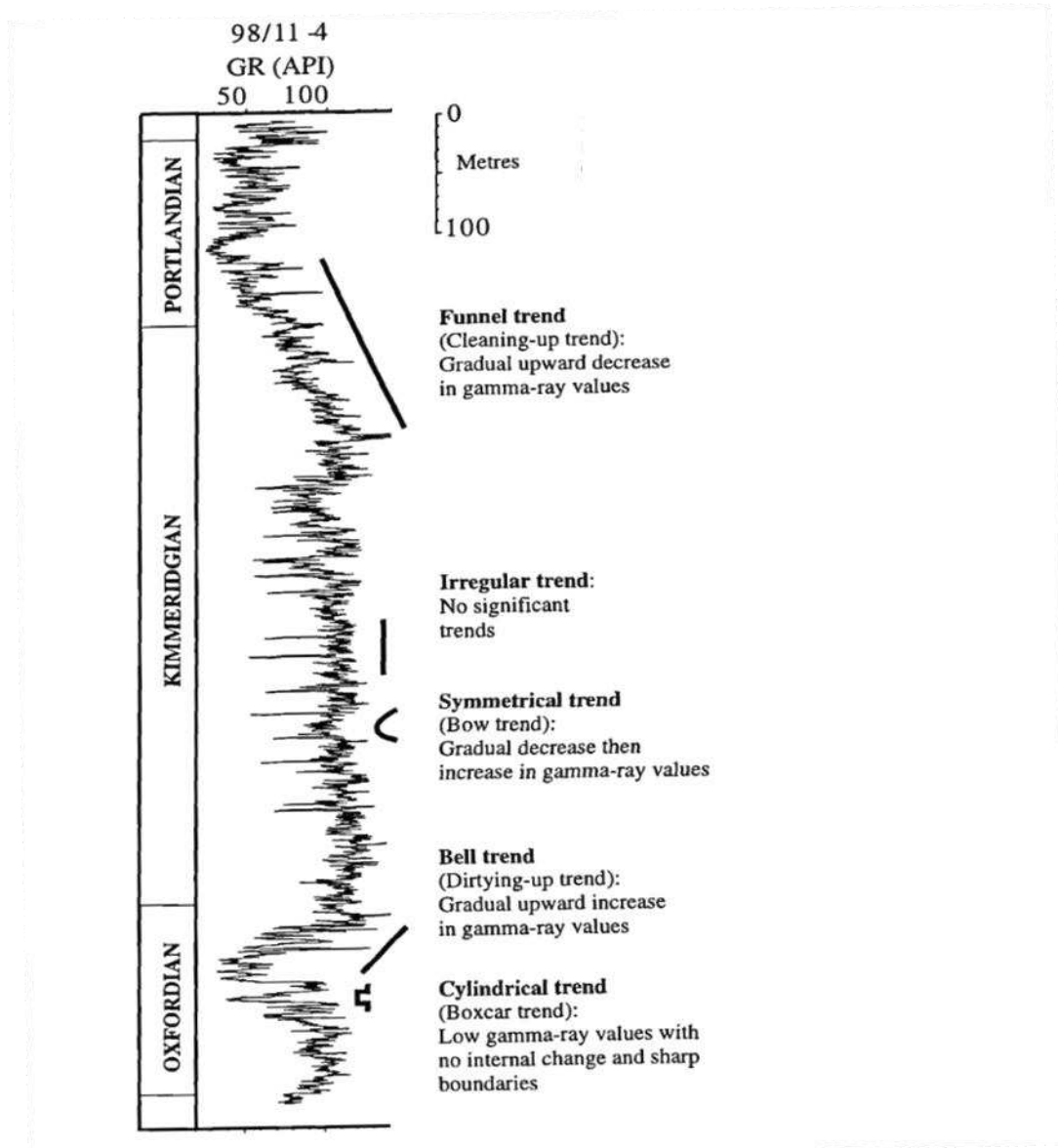


Figure 2-9 Wireline log trends representing different depositional facies (after M. H. Rider (1986)).

Coarsening-upward motif: indicates a gradual shift towards a progressively higher-energy depositional environment. This log motif is the least equivocal of all, especially for repeated sections 5–30 m thick (Posamentier and Allen, 1999). Typical examples of depositional elements that generate this log motif include prograding distributary mouth bars (deltaic settings) or prograding shoreface deposits (open shoreline settings).

However similar log pattern may also relate to crevasse splay deposits and gravity-flow systems in deep-water environments.

Borehole image log (BHI)

Borehole image logs are high resolution images of the borehole wall generated using mainly electrical resistivity and acoustic imaging tools. They are used for different purposes including sedimentological studies, structural analysis and reservoir parameter determination. Lithology, texture, dip and azimuth of bedding plane, faults and fractures are some of the sedimentary features interpreted from image logs. Borehole images have resolution that is much higher than seismic data and lower than a core sample.

From the two main types of borehole imaging tools, electrical resistivity tool is widely used because it is particularly effective at better imaging geological features due to inherent high-resolution capability and the wide dynamic range of the measured formation property (Serra and Serra, 2003). The borehole coverage of resistivity image tools vary (e.g., 30% to 80%) depending upon the number of pads and borehole size. Ultrasonic imaging, on the other hand, delivers a high-resolution acoustic image of the 360 degree borehole wall because the tool sends an ultrasonic wave out into the wellbore and the reflection of the wave from the entire borehole wall is recorded in the receiver. Use of this type of log, however, is limited to low solids in drilling mud and mud densities less than 11 lb/gal, because of attenuation of the sonic waves. Ultrasonic imaging logs are slower than conventional electric logs and when compared to a resistivity image, a

resistivity image log has about 10 times the spatial resolution and 500 times the amplitude resolution.

Resistivity Micro Image measurement

Borehole imaging tools usually have four pads attached to arms that extend and retract to maintain contact with borehole wall. Each pad contains a number of electrodes called buttons, 24 in case of FMI tool from Schlumberger, that are arranged in two or more rows (Figure 2-10). During measurement, high frequency current is emitted from each button (Figure 2-10). The pad face and buttons have the same potential and an equipotential surface is created parallel to the borehole wall and in these conditions the button current varies with the conductivity of the formation in front of it. The tool focuses the current a short distance into the formation and potential differences are measured between each button and the upper tool cartridge housing (tool upper electrode). The resulting raw data presentation would be a massive number of resistivity curves plotted in the log plot. In imaging tools such as the FMI tool, formation microresistivity values are measured at vertical resolution of 2.5 mm.

The tool also includes inclinometry tool which has a triaxial accelerometer and three single-axis magnetometers (Serra and Serra, 2003). The three-axis accelerometer is housed in a single unit and where A1, A2, and A3 axes correspond to pad 1, pad 2 and the tool axis direction, respectively (Figure 2-11). Accelerometer information is used to derive tool axis deviation and make speed corrections to the recorded curves.

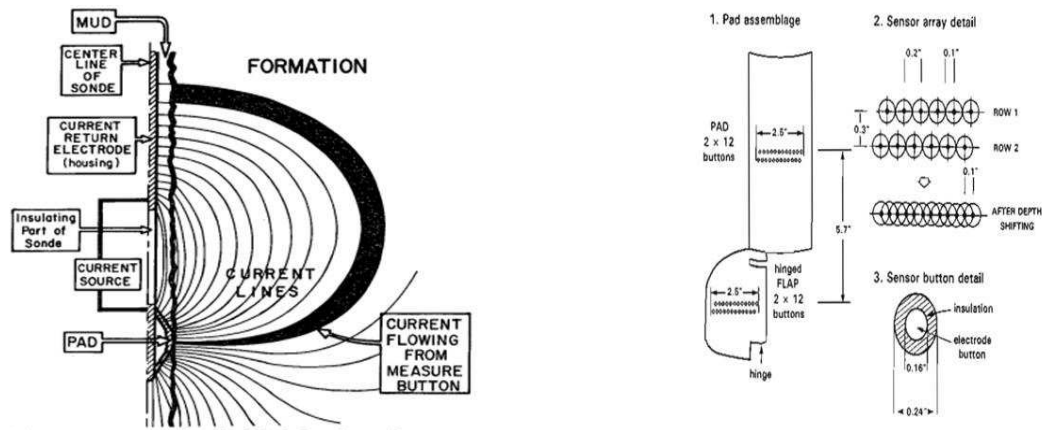


Figure 2-10 Schematic operation of microimage log also showing path of focused current (left). Pad and sensor detail of microimage log- an example from Schlumberger FMI tool (right) (after Serra and Serra (2003)).

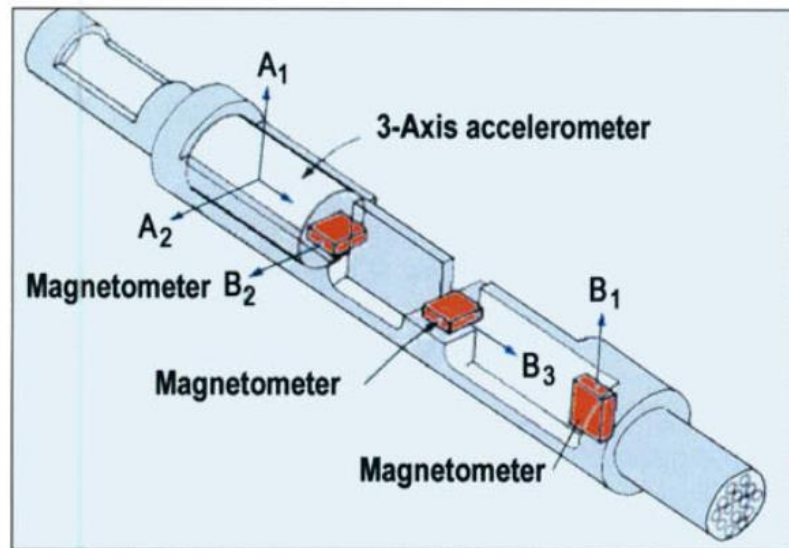


Figure 2-11 Inclinator tool integrated with borehole image tool to determine orientation and for speed corrections (after Serra and Serra (2003)).

Azimuth information is obtained by measuring the direction of the Earth's magnetic and gravity fields with respect to the tool axis. Because the tool is essentially a cylinder, its orientation is described by three angles namely: Deviation of the tool axis from the vertical (DEV), azimuth of the projection of the tool axis in the horizontal plane (HAZI) and a rotation angle of the tool about its own axis (Figure 2-12).

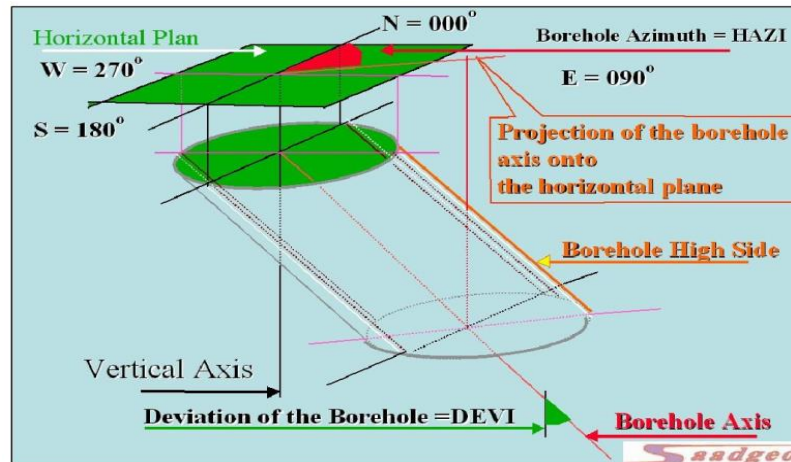


Figure 2-12 Illustration of borehole deviation and azimuth of a borehole that are required to plot image logs in proper orientation (after Serra and Serra (2003)).

Image log processing

A number of processing steps are taken before geological interpretation of the image logs can be performed. The main processing steps to generate the image logs from measurements recorded by electrode tool include speed correction, magnetic declination correction, and depth shifting offset.

Speed correction is applied to correct for irregular tool motion and to convert the time-based recorded data into a depth-based data. The acquisition system records data with reference to the cable depth. If the tool speed is greater than the cable speed, the data attributed to a given interval of curve need to be stretched out over a longer interval. The image has a compressed appearance in this case. Conversely, if the tool speed is too low, the curves or images appear stretched. The irregular motion of the tool during the logging due to sticking, variable tool friction, rig heave, and cable stretch is corrected by using accelerometer-based speed correction. This correction returns the miss-positioned data

to the correct depth point. Magnetic declination correction is applied to inclinometry measurements recorded by the tool relative to the magnetic North to convert them into geographic North. Depth shift offset correction is done to match the image log and the other logs in depth using the GR log correlation from these runs.

These corrections are partly done by the service companies and they deliver magnetic declination corrected and depth-based image data. However, a number of processing functions are applied to the image data by the interpreter to enhance the image accuracy and quality. Depth matching of the logs between image logs and the other wireline logs are sometimes not adjusted by the service companies and has to be done before interpretation. Usually The GR log from both runs is used for this correlation. Additional minor processing may be applied to the data to remove saw tooth artifacts, malfunctions of buttons, misalignment of pad/pads, filling small gaps on data, and removing dead buttons. In all these corrections, filters can be applied to enhance the log quality and increase the geological and structural features resolution.

Image Log Presentation

To display an image log of a cylindrical borehole, the well geometries and orientations have to be known besides the image data. The three important logs used for this purpose are borehole deviation (DEV or DEVI), borehole azimuth (AZI or HAZI) and Relative Bearing (RB). The first two logs are needed for well wellpath, iso-core and vertical depth calculations. The imaging tool rotation during logging is measured as the angle between the borehole azimuth and reference pad azimuth at every point and is known as Relative

bearing (RB). In general, these three logs are needed for accurate plotting of the image logs in correct depth position.

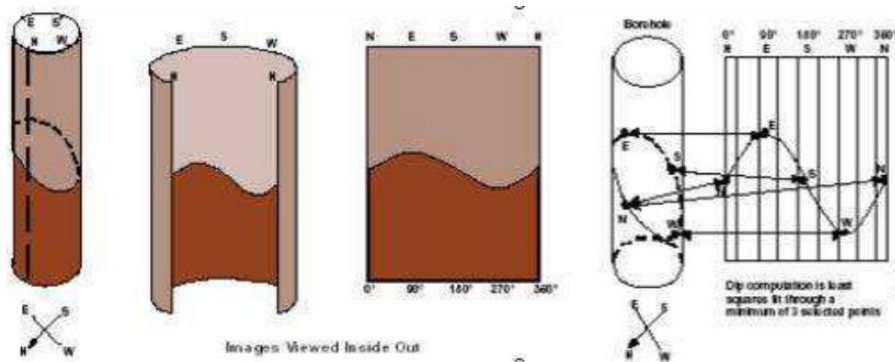


Figure 2-13 Illustration of image log plots. Dipping layers plot as sinusoids (after Serra and Serra (2003)).

The processed image which represents resistivity image of a borehole surface is then unwrapped at the north azimuth for display (Figure 2-13). The horizontal axis of the unrolled panel represents azimuthal directions and the vertical axis is depth. To visualize the image logs, two different types of color normalizations are done on the data; Static and Dynamic normalization (Figure 2-14). Static normalized images have the same color scaling over the entire logged interval and thus show large-scale resistivity variations

related to lithology changes and structural events (faults, fractures unconformities, etc.).

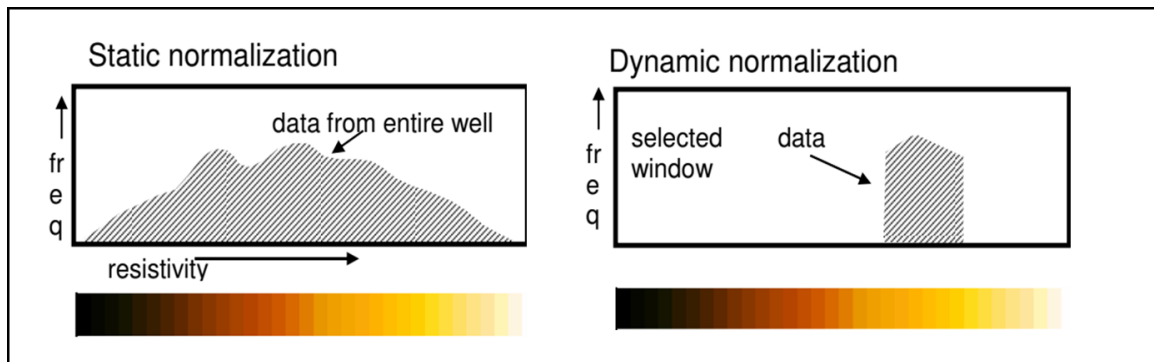


Figure 2-14 Static and dynamic normalization of image logs (after Serra and Serra (2003)).

Dynamic normalized images are color scaled on a 2-ft-sliding window, thus maximizing rock fabric detail (texture) and bedding information. In the static color normalization procedure, the resistivity values are color coded from highest resistivity values as white to the lowest resistivities as black in 32 color ranges. In dynamic normalization, a special range of resistivities are used to plot the data in a high resolution. Dynamic normalization allows a detailed resistivity image data visualization. Dips are observed on both image, but picked preferentially on dynamic images. On this display flatbed contacts plot as straight lines whereas dipping bedding planes plot as sinusoids whose lowest point defines dip direction and the difference between peak and trough is used in calculating dip amount. There are a number of other features that can be interpreted from image logs as shown in Figure 2-15.

Recognition of sequence stratigraphic surfaces and systems tracts from well logs

Subdivision of a stratigraphic section through the identification of different sequence stratigraphic surfaces from well logs is not an easy task. Surfaces are marked at different

locations have different characteristics and therefore it is always recommended to know the physiographic location of the well data before pursuing with delineating different surfaces that bound systems tracts. It is relatively easy to identify maximum flooding surfaces because it is usually associated with high gamma log response. Condensed sections at the climax of relative sea level rise result from sediment starvation giving rise to thin units of hemipelagic to pelagic sediments that cover a large part of the basin.

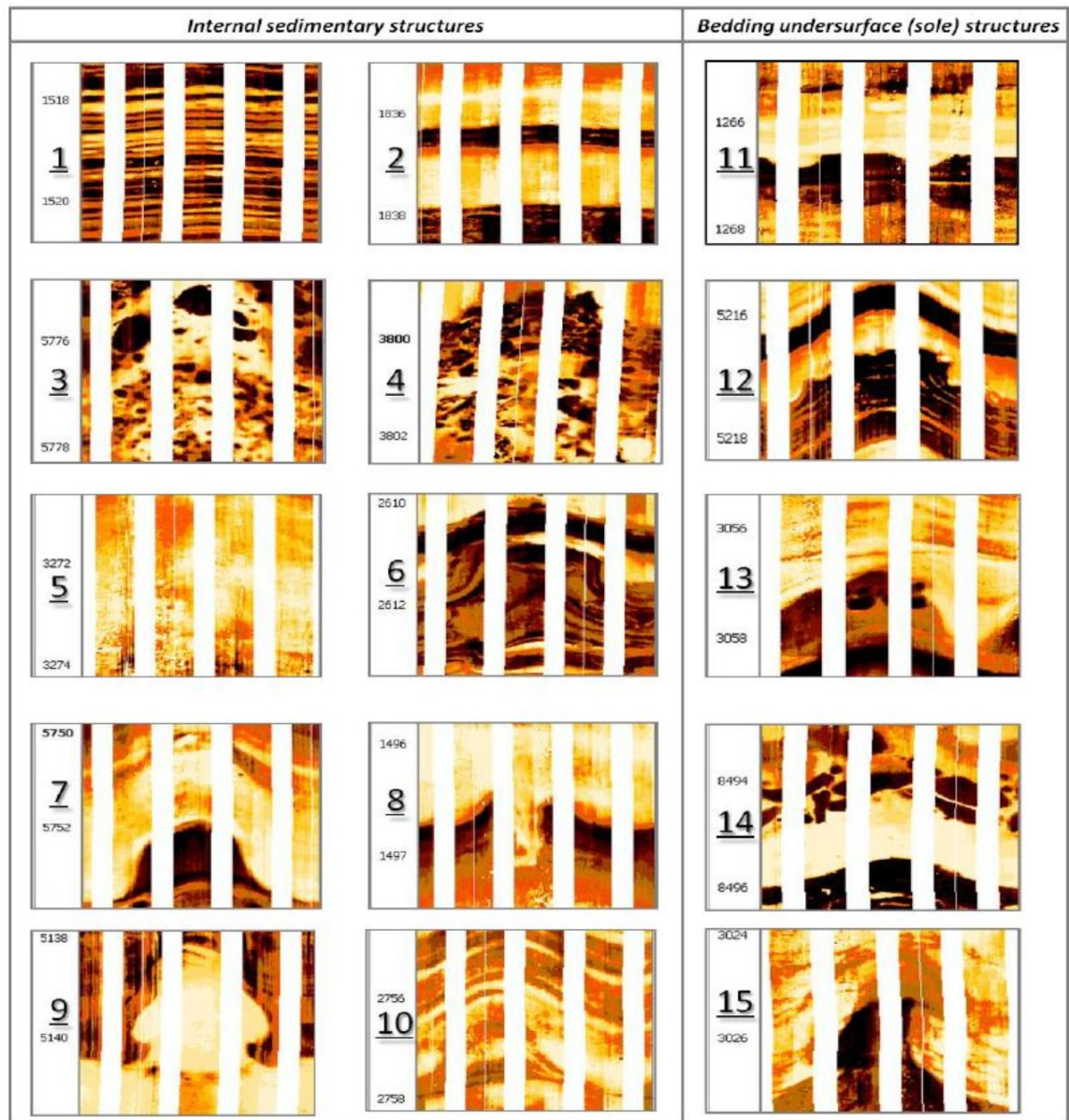


Figure 2-15 Sedimentary structures from high resolution borehole image logs (Amer et al., 2011).

1- lamination; 2- bedding; 3- inverse/ reverse grading; 4- conglomerate; 5- massive bed; 6- convolute bedding (slump); 7- sediment deformation; 8- water escape structure; 9- sand injection; 10- crossbedding; 11- groove cast; 12- load cast; 13- small- scale scour surface; 14- erosional channel base with lag; 15- flame structure.

The high GR log response of condensed sections can be easily correlated between different wells, however high GR log response is not always an indication of a maximum

flooding surface and a more appropriate way to define this surface is from convergence of time horizons at different well locations or from observations in seismic sections (Posamentier and Allen, 1999).

Sequence boundaries are more difficult to mark in well logs because of their varied expression in different parts of a basin. It is therefore preferable to pick sequence boundaries after maximum flooding surfaces have been identified. Because sequence boundaries are located between successive MFS we will search for candidate surfaces in the interval taking into consideration the depositional environment and the physiographic setting of the well location.

The overall log pattern is also a good indicator of sequence stratigraphic surfaces especially in shelf areas where it is easy to observe progradational, aggradational and retrogradational stacking patterns. In general, maximum flooding surfaces are located between retrogradational stacking pattern from below and progradational or aggradational stacking pattern above. Sequence boundaries, on the other hand, lie between a progradational trend below and retrogradational or aggradational stacking pattern above.

Identification of systems tracts that accommodate the space defined by bounding surfaces identified in the previously is based on interpretation of depositional environments and their stacking patterns. Highstand systems tracts lie over the maximum flooding surface and show progradational pattern especially on the shelf. However, the

overlying lowstand systems tract also shows the same character and defining the boundary between these systems tracts is not straightforward.

Transgressive systems tracts have a retrogressive stacking pattern and depending on physiographic locations in the basin it may overlie a highstand or lowstand systems tracts. Transgressive systems tract can vary in thickness between a thin condensed layer and thick retrogradationally stacked succession depending on the rate of accommodation creation and the rate of sediment influx and additional factors such as waves and currents. The lowstand systems tract has different expressions landward and seaward of the shoreline. On the side of the correlative conformity, upward coarsening and thickening progradational section is present. Whereas, over the subaerial unconformity fluvial deposits dominate which also can be confused with highstand fluvial systems. It is therefore advisable to integrate all available data to produce the least equivocal interpretation of systems tracts and stratigraphic surfaces.

Chapter 3 : Seismic Data Reprocessing

3.1 Introduction

The earliest seismic surveys in the Ogaden Basin date back to 1950s. These surveys were mostly regional with the exception of surveys in the area around WL-E 1 and Shilabo 1 wells where a dense grid of 2D lines were acquired. Over 20,000 line km 2D seismic data has been acquired up to the present and from these lines 30% were acquired pre-1970. These pre – 1970 seismic sections are generally outdated and are found in paper print outs with data ranging from single fold to 6 fold of coverages acquired mainly using dynamite sources (Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia, 2005). From the early 70s, 24 and 48 fold data were acquired using vibroseis and in the early 90s, 80 and 90 fold data were acquired in different parts of the basin. Majority of the seismic lines show fair to poor data quality and some of the problems related to data quality are low fold of coverage, random noise, pervasive multiples and penetration problems as well as poor ground conditions (Beicip-Franlab, 1998).

The data used in present study was acquired in 2006 in the western part of the Ogaden Basin. A total of four lines with 3 dip lines and 1 strike line connecting all dip lines were obtained from the Ministry of Mines, Ethiopia having a total length of 296 kms (Figure 3-1). Previous processing of the lines was done by CGGVeritas' data processing center in Kuala Lumpur and the result showed poor reflectivity and continuity especially in the Karoo section. The sections were of limited use for stratigraphic interpretation and hence seismic reprocessing was initiated to improve data quality in terms of reflectivity,

resolution and continuity. The objective of the current reprocessing is therefore to tackle problems related to random and coherent noise, improve stacking through detailed velocity analysis and enhance vertical resolution as well as lateral resolution. The zone of interest is the Karoo section found between 1.5 – 2.5 seconds.

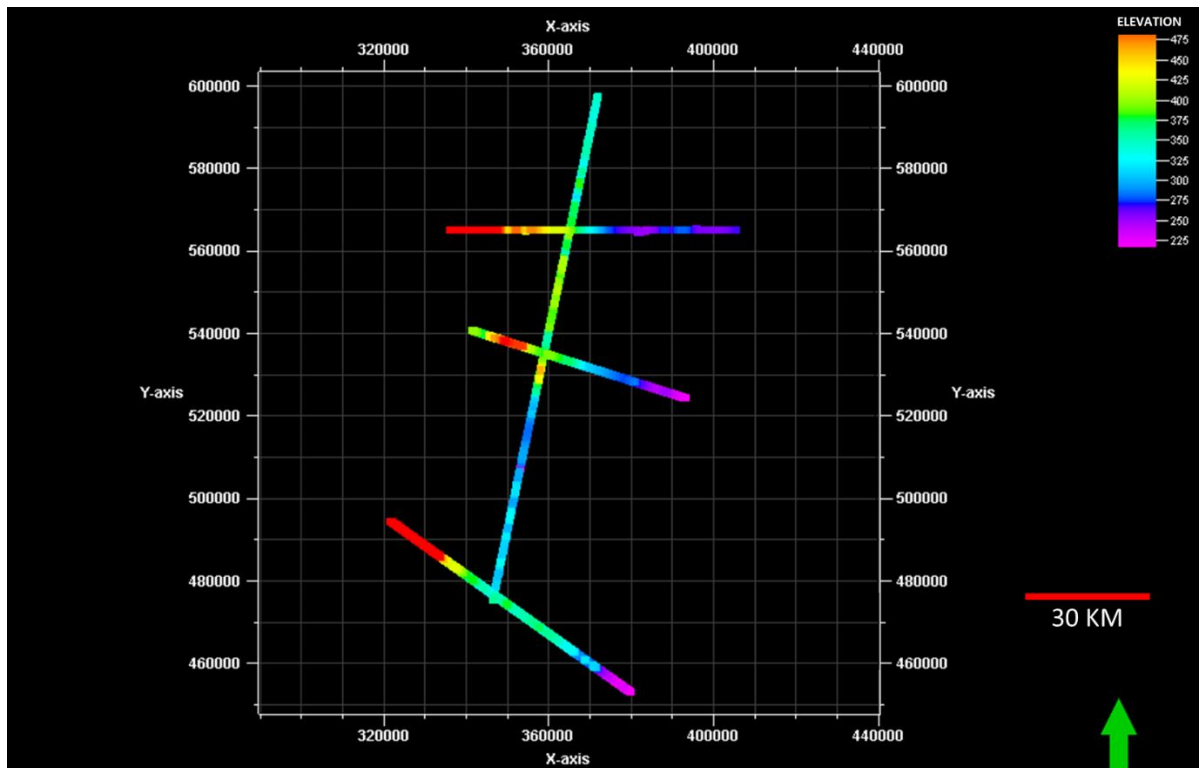


Figure 3-1 Location map of reprocessed seismic lines, elevation along lines ranges from 225 to 475m.

The seismic lines were acquired using an asymmetrical split-spread, with a 120 + 240 channel geometry and a 25m group interval. A vibroseis source was used with 50m vibration point interval, producing a 10 - 80Hz frequency bandwidth. The geophone array configuration was a linear type with 2.5m geophone spacing. Data was recorded using SERCEL 408 system; the seismic record has a total length of 6 seconds with 2ms sample

interval. During recording low cut filters were not used and high cut filters were set at 0.8 of Nyquist. The nominal fold of coverage of the data is 90 and CMP interval is 12.5m.

3.2 Seismic data processing sequence

Promax v. 5000.10.0.4, Landmark Graphics Corporation software was used for data processing. The processing steps applied to the dataset were first tested on a test line, a subset extracted from line OG-A. Numerous tests were carried out using different tools and parameters before the final workflow was established. The tests mainly focused on amplitude recovery, attenuating linear and random noise, demultiplying multiples, and deconvolution. In this section the final processing steps, summarized in Figure 3-2, are discussed from data import to the final migrated stack.

Seismic processing workflow can be grouped into four main tasks: data preparation, data correction, data reduction and data enhancement (Dondurur, 2018; Mari et al., 1999). The data preparation step includes importing and converting data into software data format, geometry assignment and trace editing. The data correction involves steps such as amplitude correction, noise attenuation, static corrections and velocity analysis. Reduction refers to mainly to CMP stacking step and multiple attenuation. Finally, enhancement relates to improving resolution and steps included in this class are deconvolution, migration and filtering and scaling. A processing flow may not follow a progression from one class to the next in the order presented especially between reduction and enhancement and occasionally looping between different steps is common.

3.2.1 Data preparation

Data import and geometry setup

Data import from SEG-D field records and reformatting to ProMAX inner format was the first step. Once in the system, the next step was geometry assignment. Trace headers were updated using SPS files which were supplied with the data. The geometry assigned traces were checked for accuracy using graphical tools. These tools apply linear moveout to shot gathers and splice multiple shots to check if there are problems with the geometry assignment which will show up as anomalies along the gathers. In addition, database tools were used to check different attributes such as live receivers per shot, CDP fold variations and others.

The geometry assigned shot gathers were then analyzed for frequency content, the change in energy in spatial and temporal domains and the types of noise present in the data. Accordingly, frequency spectrum of raw shot gathers show a narrow frequency range below 50Hz and peak frequency at ~20Hz (Figure 3-3). The amplitude of events rapidly falls in both spatial and temporal directions and the main types of noise identified are the source generated ground roll and random noises (Figure 3-3).

Trace editing

Trace editing was done to remove amplitude bursts and dead traces using information available from observer report and using database tools to select and remove “bad” traces. Random noise bursts and spikes that are not removed by these steps were removed using spike and noise burst edit tool.

Processing Flow Chart

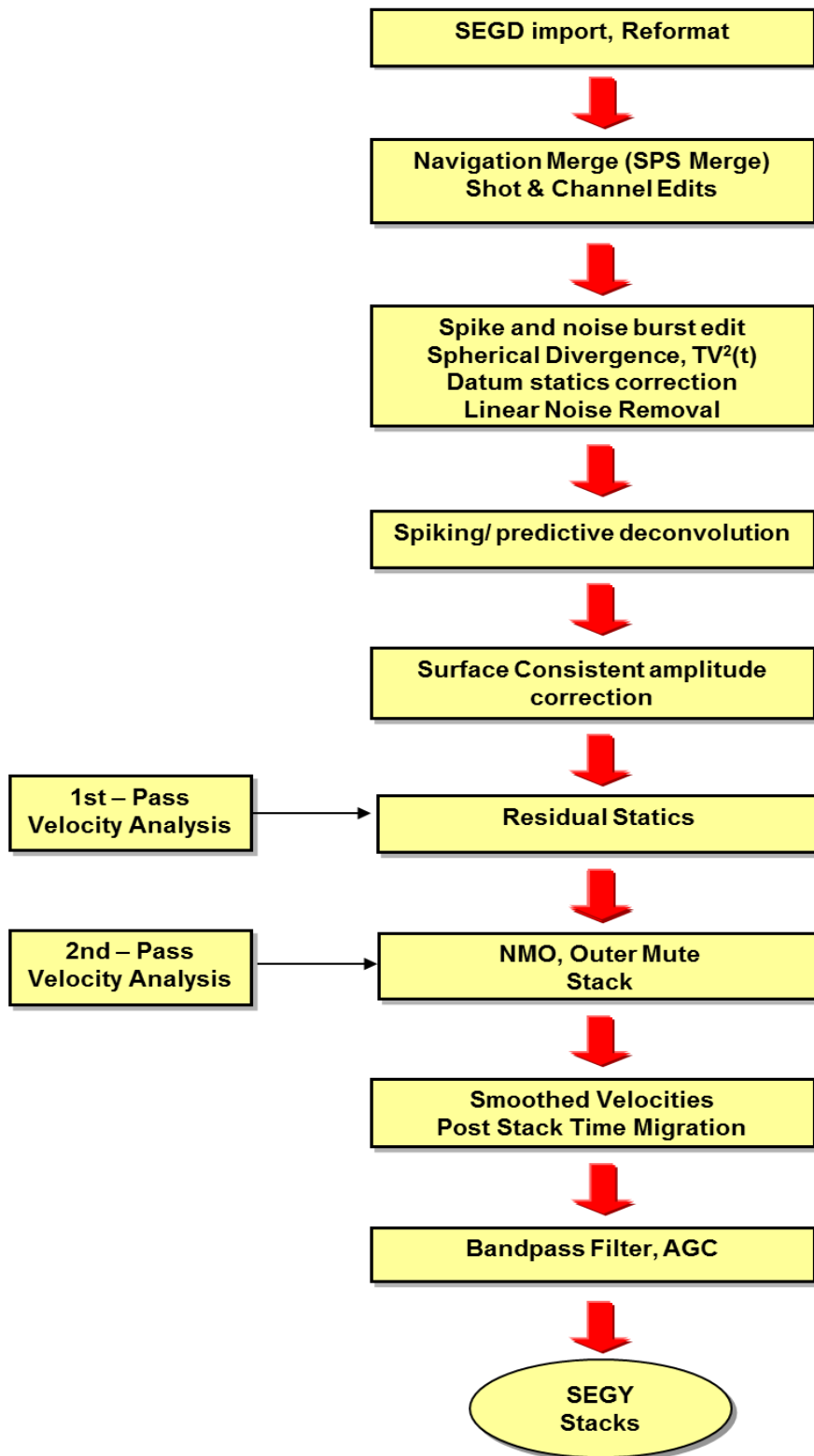


Figure 3-2 A summary chart of seismic processing workflow applied to data.

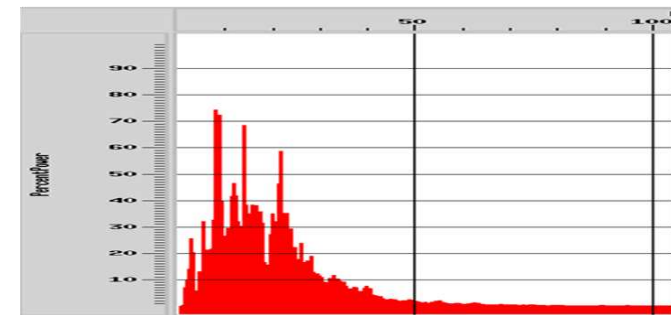
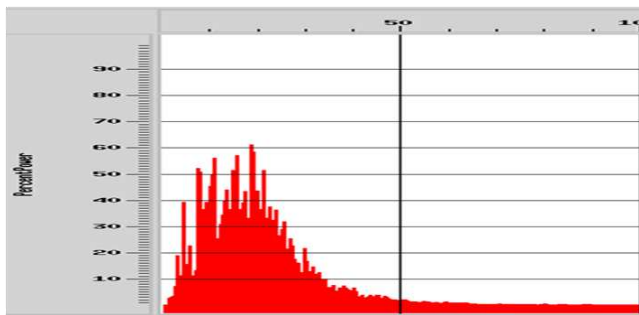
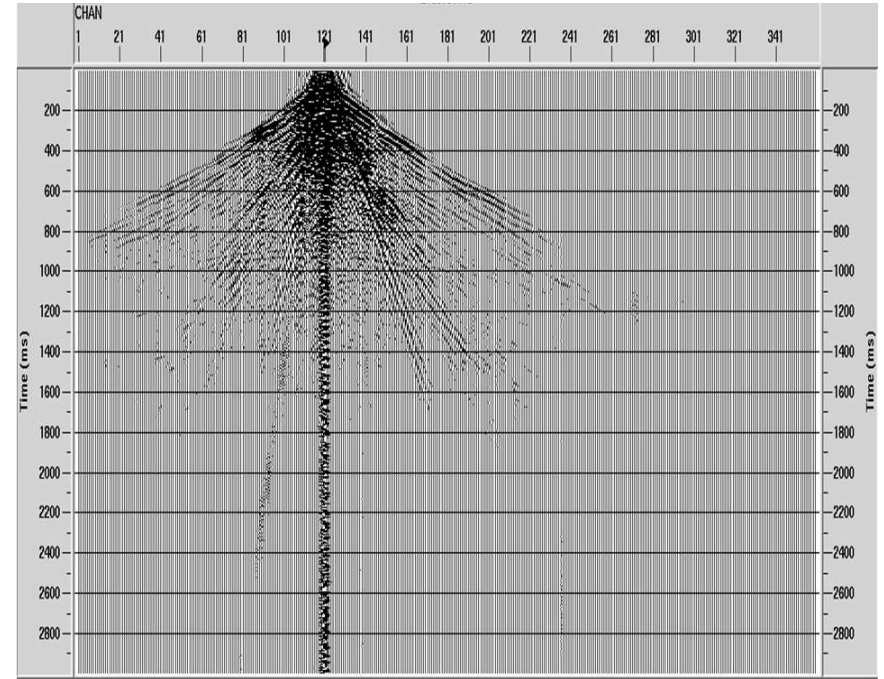
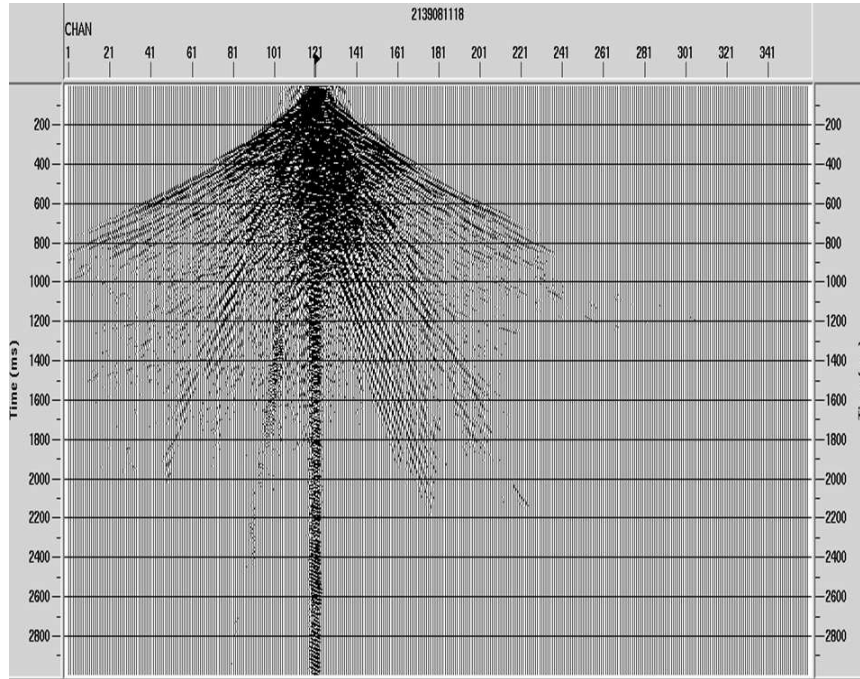


Figure 3-3 Raw shot gathers showing strong shot generated noise, ground roll noise and random noise (Above). Frequency spectrum of respective shot gathers (below).

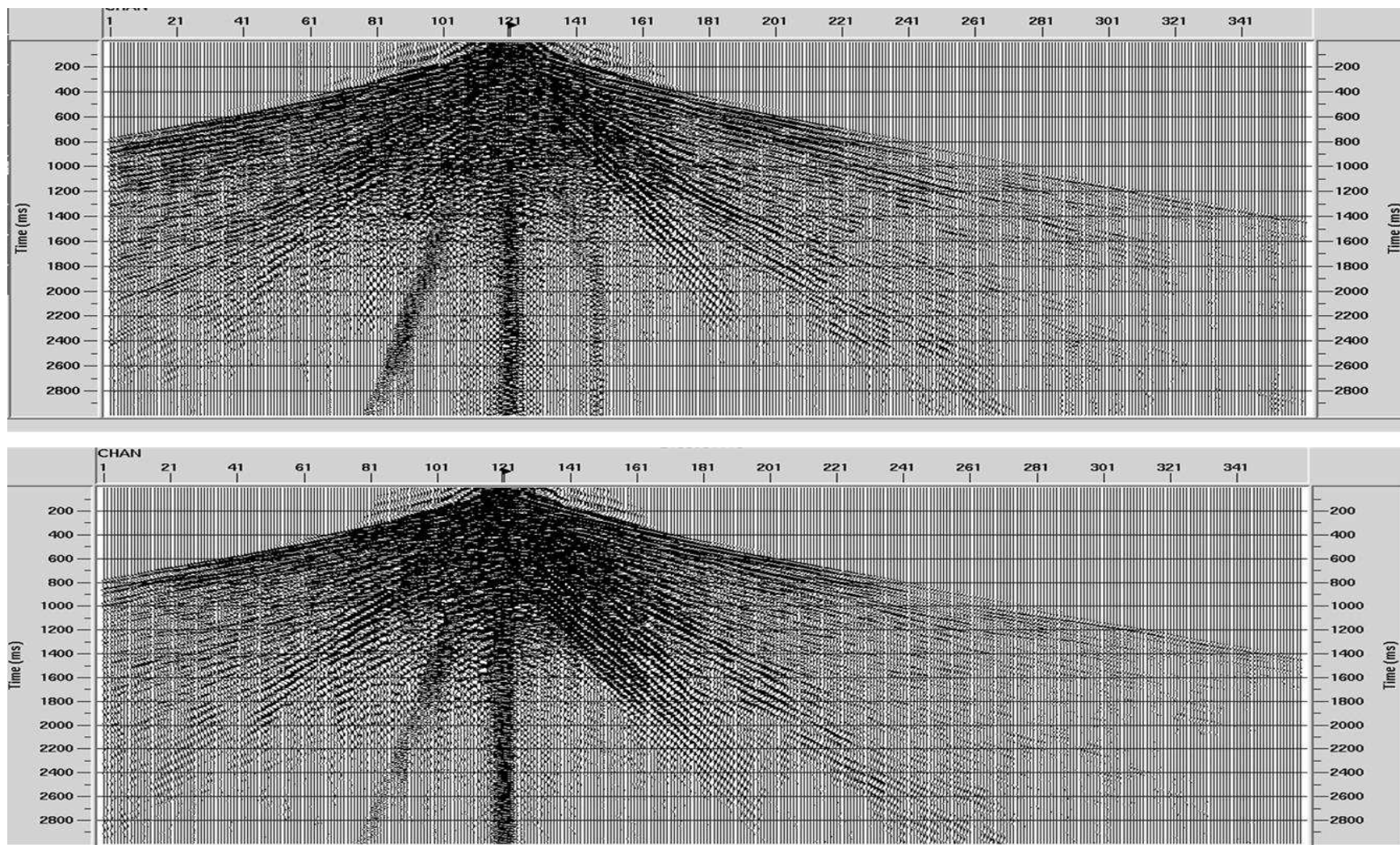


Figure 3-4 Shot gathers from two different locations after trace editing and application of spike and noise burst edit.

In the spike and noise burst edit module spikes are single samples identified by using a sliding window that measures average amplitude around each sample that excludes the sample itself. Then a ratio of the sample absolute amplitude to the average absolute amplitude is computed. If this ratio is larger than a specified threshold limit, the sample is classified as a spike, and is linearly interpolated from the samples above and below it. The gate is then moved down one sample, and the process is repeated.

Noise burst refers to multiple sample bursts of noise and are edited by determining a normal surrounding trace amplitude, and comparison of a three sample, running average of the absolute value of the differential amplitudes to this normal amplitude. A threshold is set to identify noisy samples and once they are identified the algorithm attempts to connect adjacent picked samples to make a more continuous noise samples blocks. These picked noise bursts must have a minimum noise burst length to be replaced and this is also set. The noise bursts samples are replaced with trace segments interpolated from adjacent traces. The noise burst samples can optionally be simply zeroed.

Trace editing using all tools mentioned above has been applied to shot gathers and the result shows improvements in noise level of data (Figure 3-4).

3.2.2 Data correction

Spherical divergence correction

A time variant gain function was applied in order to compensate for the loss of energy due to spherical spreading. A number of tests were conducted to compare which factor would produce the best result and the gain correction function $g(t)=t*v^2(t)$ was selected;

$v(t)$ is RMS velocity field which varies spatially and temporally. It was picked in a preliminary processing step and was subsequently used in spherical spreading correction (Figure 3-5).

Datum statics correction

Static correction is normally associated with land data and is essential for compensation of elevation variations along a profile and to compensate for the effect of weathered layers. It involves determination of corrections needed to bring all sources and receivers to a planar surface which is usually defined close to the surface of the topography. In this work both elevation and refraction statics were attempted. However, the refraction statics solution was unreliable due to poor first break picks and was not used in the final stack. The elevation statics was applied and a replacement velocity of 4500m/s was used similar to the value used in previous processing and a final datum of 400m was used.

Linear noise attenuation

Linear noise attenuation was done by transforming data from time – offset domain to tau - P domain using radon or slant stack transform (Figure 3-6). The data corresponding to linear noise was muted in this domain and an inverse transform was applied to data to time – offset domain.

The Radon transform has many applications; in seismic refraction it is used to produce velocity depth models and in seismic reflection processing, it is used to remove multiples and to eliminate spatial aliasing (Stoffa et al., 1981). Radon transform is a line integral that transforms series of curves in the X-

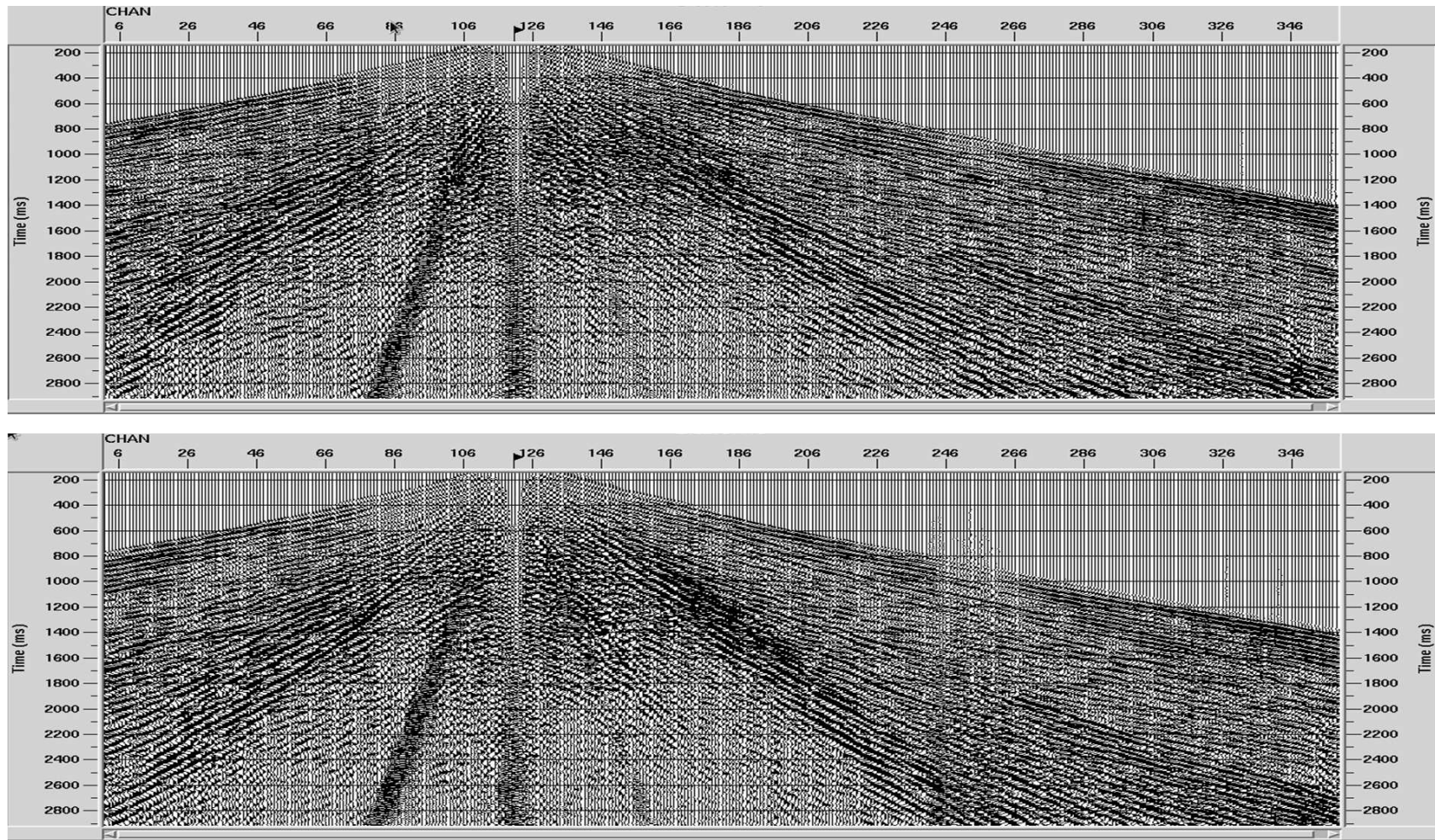


Figure 3-5 Shot gathers after spherical spreading and datum static corrections at two different locations.

T plane to tau-p plane. The curves can be linear, parabolic or hyperbolic. In case of a linear radon transform or slant stack, tau is defined as intercept time and p is slowness. The forward transform along linear paths in the X-T plane, defined by:

$$\tau = T - pX \quad (3.1)$$

is given by (Stoffa et al., 1981):

$$F(\tau, p) = \int f(\tau + pX, X) dx \quad (3.2)$$

Whereas the inverse transform is given by:

$$f(x, t) = \int F(p, t - pX) dp \quad (3.3)$$

For the present data shot gathers were forward transformed with a minimum slowness - 500ms/km and maximum slowness 500ms/Km and a time of interest used was between 0-3000ms. In the tau-p domain a time variant mute was manually picked and applied before transforming the data back to X-T plane. The result shows most of the linear noise has been attenuated by the process (Figure 3-7) and compared to other methods such as the F-K, these results were superior in quality.

Spiking/ Predictive deconvolution

Deconvolution corrects for undesirable effects such as reverberations, attenuation and multiples. These effects are modeled as linear filters and in deconvolution inverse filters are designed to remove them as highlighted in chapter 2. The wiener-Levinson least square algorithm is used to design and apply predictive deconvolution. The parameters

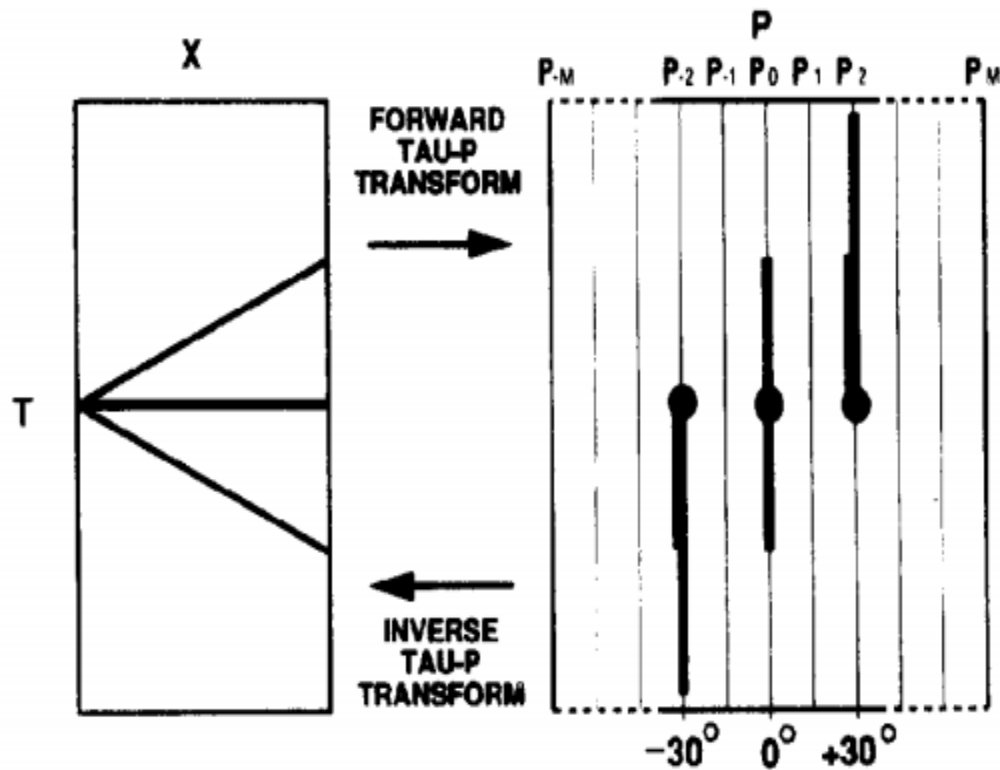


Figure 3-6 Schematic diagram of forward and inverse Tau-p transform. After Russell, Hampson, and Chun (1990).

that control the results of deconvolution are operator length, prediction lag and percent prewhitening. These are discussed briefly below in relation to the processed data.

Operator length- short operators yield spikes with small amplitudes and relatively high frequency tails, increasing operator length improves the spikiness and whiten the spectrum further. However increasing operator length does not indefinitely improve the results. On the contrary, more and more spurious spikes are introduced (Peacock and Treitel, 1969). For the current dataset a filter length of 200ms was used after testing a series of filter lengths.

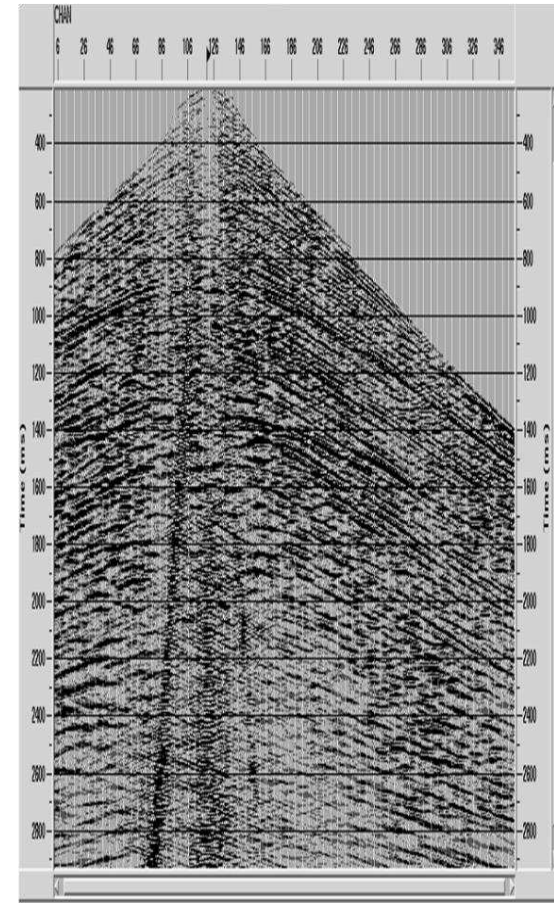
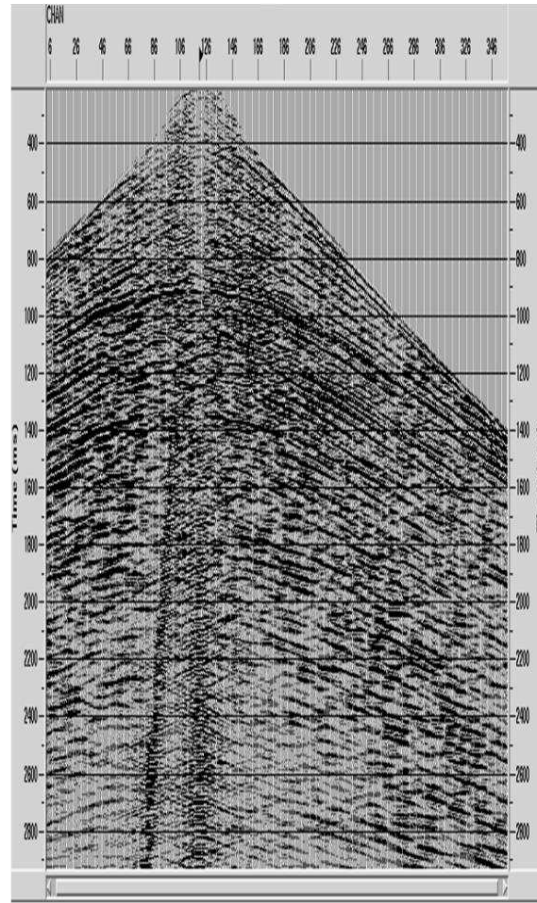
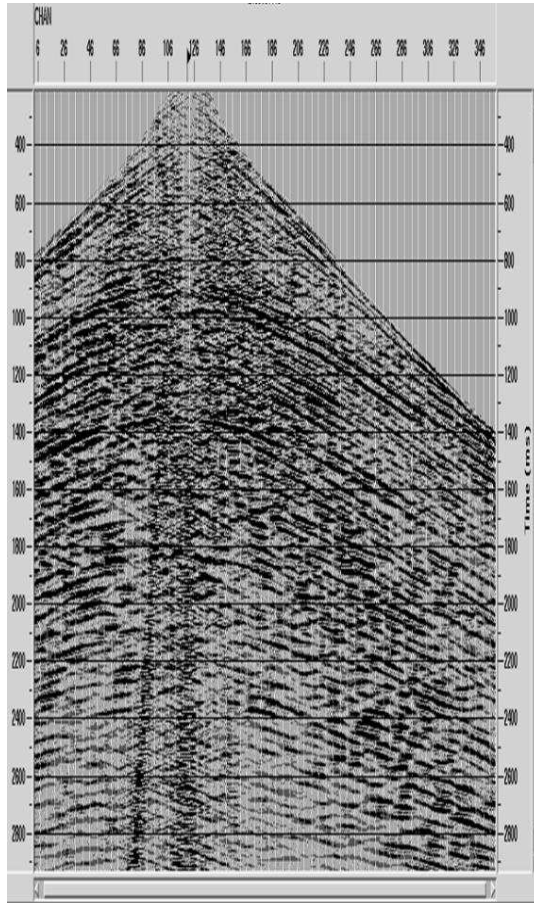


Figure 3-7 Shot gathers after linear noise attenuation.

Prediction lag- using a unit prediction lag is the same as performing a spiking deconvolution. When the lag is greater than 1, the deconvolution yields a wavelet which has some length instead of a spike (Peacock and Treitel, 1969). In ideal conditions with noise free data a spiking deconvolution can produce a high resolution however with real data spiking deconvolution will boost noise and it would be necessary to adjust the prediction lag so as to suppress high frequency noise. A greater than unity prediction lag will lead to a lesser bandwidth suppressing the high end of the spectrum and preserving a similar amplitude spectra to the input wavelet. Different prediction lags were tested in processing and the optimum lag was 32ms which was applied to all data.

Percent prewhitening- for the purpose of numerical stability it is always recommended to add some degree of noise before performing the deconvolution, usually a number between 0 – 1%. We used 0.1% to this end.

Surface consistent amplitude compensation

The amplitude of a trace is a function of different factors which include the shot strength, geophone coupling to the ground and its response to incoming vibration, the offset of the trace and the subsurface impedance contrast of the reflecting surface. It is possible to estimate these effects by using many traces which are available from the multiplicity of the CMP acquisition. The amplitude of a trace can be decomposed into different components (Taner and Koehler, 1981) as:

$$f_{nm} = s_n + r_m + c_k + d_l \quad (3.4)$$

where f_{nm} - natural logarithm of rms amplitude of trace with its source and receiver at surface positions n and m respectively, s_n - source performance factor at n th surface position, r_m - receiver performance factor at n th surface position, c_k - subsurface performance factor at k th surface position, with $k=1/2(m+n)$ and d_l - offset performance factor at offset $l=m-n$.

The performance factor is the natural logarithm of the average amplitude spectrum of the response function. We have one equation (the above equation) for each trace hence for most conventional CMP coverage there is a high order of redundancy. The desired solution can be obtained by the least squares technique. The Gauss-Seidel algorithm is used to iteratively determine amplitude estimates of each component.

During the application of surface consistent amplitude correction, amplitudes were decomposed into four components which are shot, receiver, offset and CMP. The order of decomposition was as in the previous statement and five iterations were used in amplitude partitioning and the result is shown in Figure 3-9.

Velocity Analysis and NMO Correction

Velocity analysis is a method used to determine accurate stacking velocities for NMO correction. Data sorted to CMP gathers are used for this purpose and traveltimes that follow hyperbolic trend (also discussed in chapter 2) are corrected based on the hyperbolic normal moveout equation (Equation 2.6). Stacking velocities are determined based on the acquisition geometry or source - receiver offset and recorded two way travel time of reflection events.

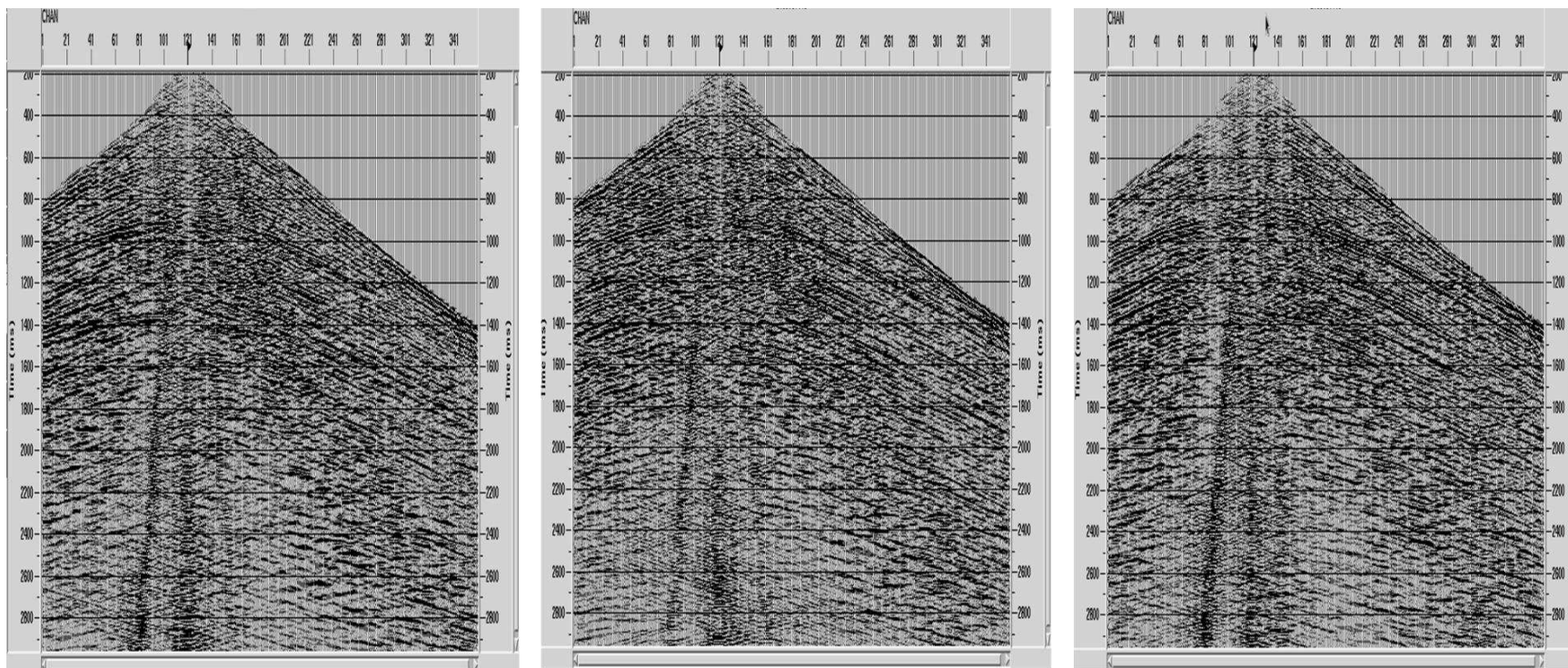


Figure 3-8 Shot gathers after deconvolution.

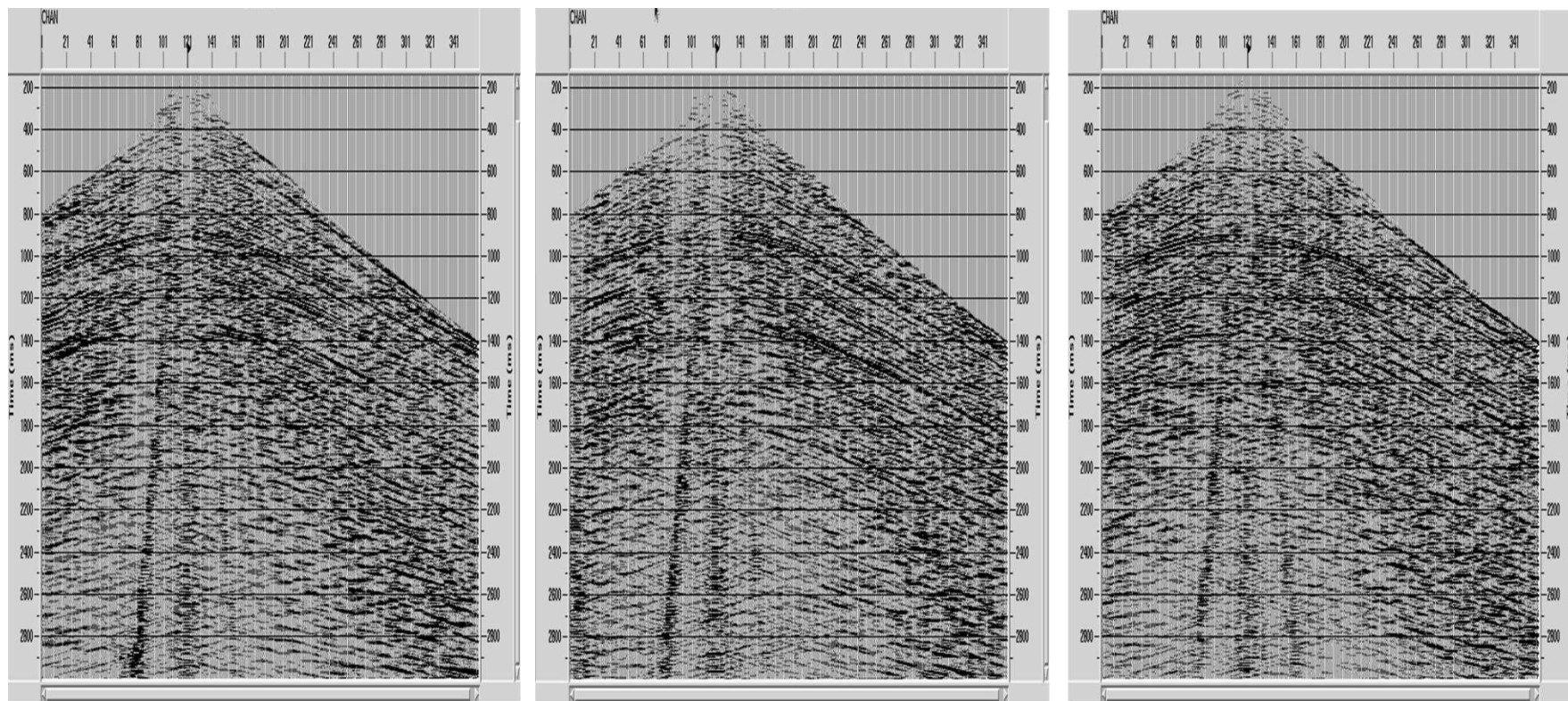


Figure 3-9 Shot gathers after surface consistent amplitude compensation.

Promax offers different techniques to analyze stacking velocity and usually these techniques involve comparing a display of a series of stacked traces that were corrected with a range of constant velocities (Figure 3-10). The analysis involves picking velocities in any one of the analysis windows that results in the optimum stacking amplitude.

One of the velocity analysis displays is a semblance panel which shows a stack response as a function of time and velocity in color coded plot. A minimum and maximum velocity as well as the interval between successive velocities are defined and similarity between traces along the hyperbolic trajectory is calculated for each velocity. The stack response is maximum at or close to the velocity which flattens reflections along the offset axis which is called the stacking velocity also called RMS velocity for a number of horizontal layers constituting the subsurface. Velocities are picked on maximum semblance. The gather panel is another analysis display which shows supergathers of a specified number of CDP points that are flattened as velocities are being picked. This panel aids in picking correct velocities and in picking top and/ or bottom mutes for interactive mute analysis. Velocity function stacks are another display types where a set of CDP points are stacked, displayed side by side with a series of constant velocities or a series of time variant velocity functions. Before the analysis, differential CDP mean statics are applied to ensure that dip of events match with data on stacked section. The panel can be used to pick velocities on the maximum stacked response. Velocities usually increase from left to right of display. A dynamic stack is still another display which shows an approximation of a stacked section with the picked set of velocities and is used for quality control purposes.

Velocity analysis was looped with residual statics and in the first pass velocities were picked every 1Km whereas in the second pass the velocity field was picked every 500m.

Surface consistent residual statics

Residual statics is applied in seismic processing to remove the effect of the weathered low velocity layer and the effect of elevation change within a spread which collectively cause time delays (Taner and Koehler, 1981). The correction improves quality of a seismic section as it removes the time or vertical misalignment of individual traces (Figure 3-11). A surface consistent approach is used in solving for time delays by using cross-correlations between traces to estimate relative time shifts. However time shifts derived from cross correlation are subject to threshold values which control unreliable correlations when poor signal to noise ratio data are cross correlated. Residual statics is usually applied after NMO correction to exclude dynamic effects related to velocity of layers.

A time shift determined from cross correlation for a given trace after NMO correction can be decomposed into its respective components as:

$$T_{ijk} = R_i + S_j + C_k + M_k(j-i)^2 \quad (3.5)$$

Where R_i – receiver static at i th receiver position, S_j – source static at j th source position, C_k – arbitrary time shift for the k th CMP gather (this is unknown), M_k – residual NMO component at k th CMP gather, and $(j-i)$ – source to receiver distance.

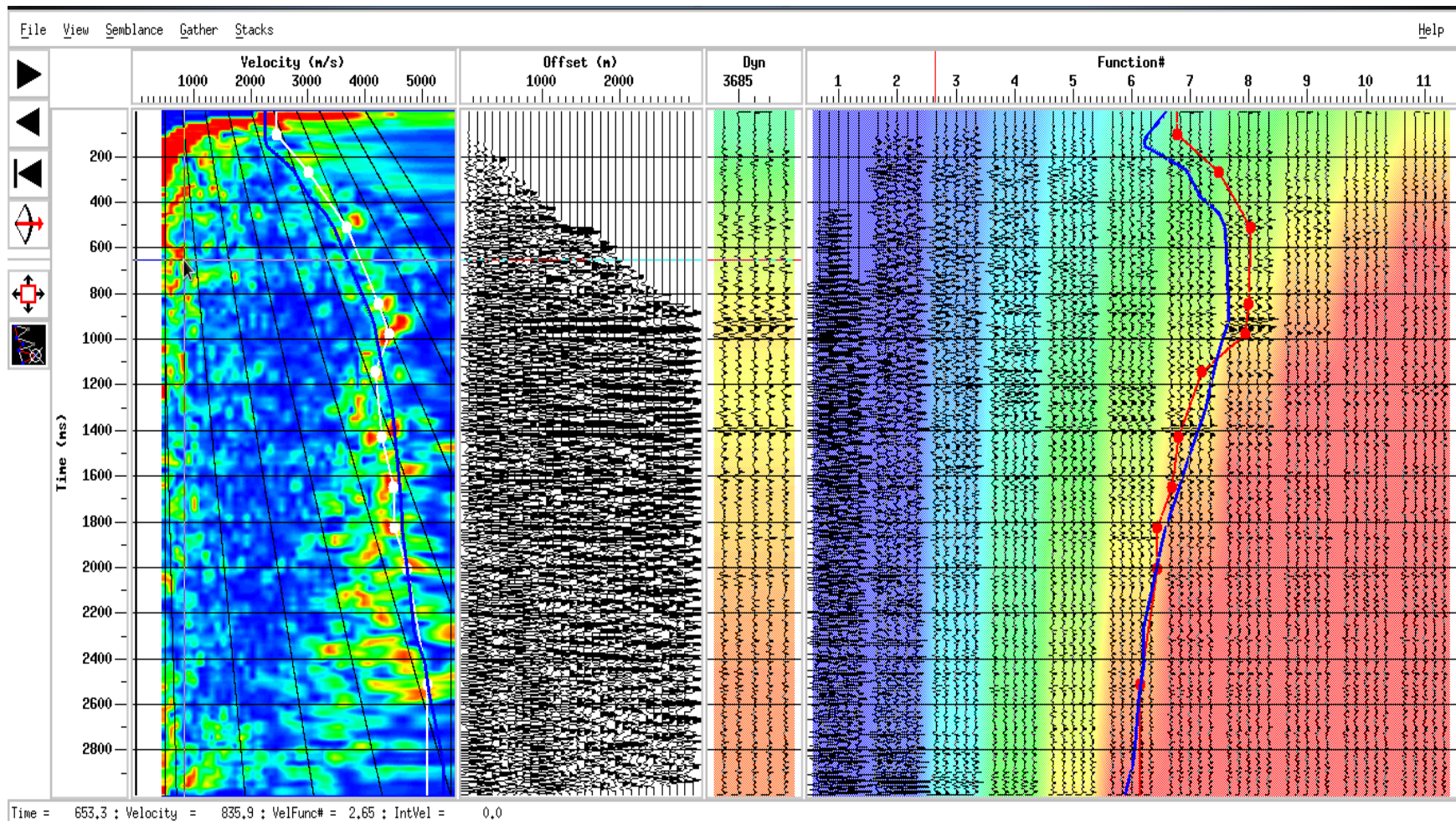


Figure 3-10 Typical velocity analysis procedure showing semblance plot, corrected gathers panel, dynamic stack and stack functions panel.

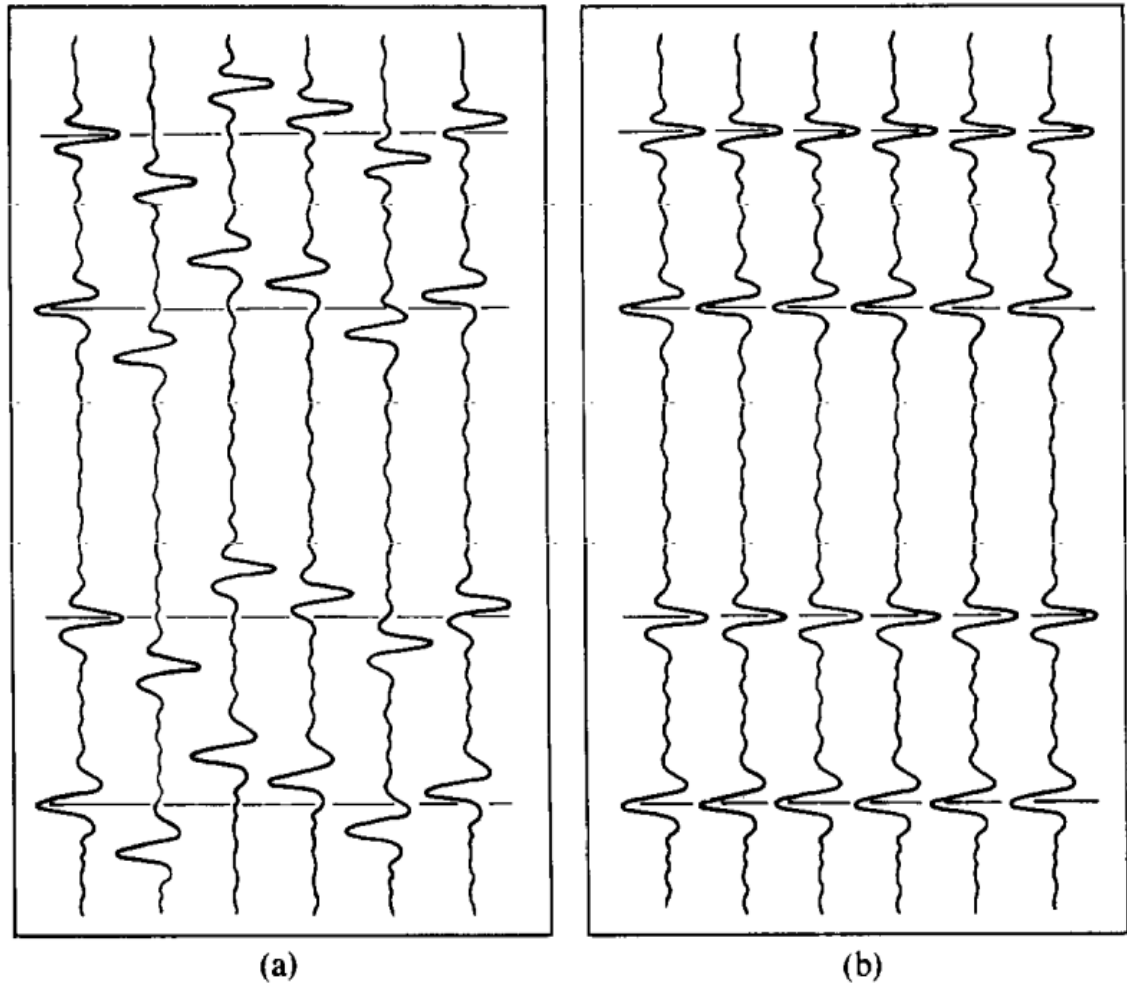


Figure 3-11 CDP gathers before (a) and after (b) residual statics.

The foregoing equation is applicable to all traces in the gather. The problem of determining these four unknown sets is an overdetermined type and solved using the least squares error minimization method.

In data processing, a Maximum power autostatics, which is effective in poor signal to noise ratio data, was used to compute time shift for each component. A manually picked horizon at a good SNR reflection event was used as a reference horizon in the calculations.

The number of iterations used was four and in each iteration threshold or maximum

allowable shifts were defined as 10, 15, 20 and 30ms from the first to last iteration respectively. The result shows a much improved continuity in reflections compared to a stack section without residual statics (Figure 3-12).

3.2.3 Data reduction and enhancement

F-X Deconvolution

F-X deconvolution is a spatial filter used to remove incoherent noise from a stack or NMO corrected gathers. It works by first transforming data into a frequency – offset domain by Fourier transforming each trace with respect to time and designing/ applying a unit lag complex wiener filter for each frequency component. Data is usually predictable by a unit lag predictive filter while the noise is not. Therefore by keeping only the predictable part the data, each frequency trace is transformed back to T – X domain.

The filter is designed in much the same way as a spiking deconvolution filter by minimizing the error energy between actual and desired complex output in the least squares sense. The details of filter derivation can be found in the works of (Canales, 1984; Gulunay, 1986). In the current dataset F-X deconvolution was applied to NMO corrected gathers prior to stacking. A Wiener Levinson filter was used with horizontal window length of 100 traces and a number of filter sample equal to 10. A frequency range between 1 – 250Hz was used and the filter was applied three times to each trace.

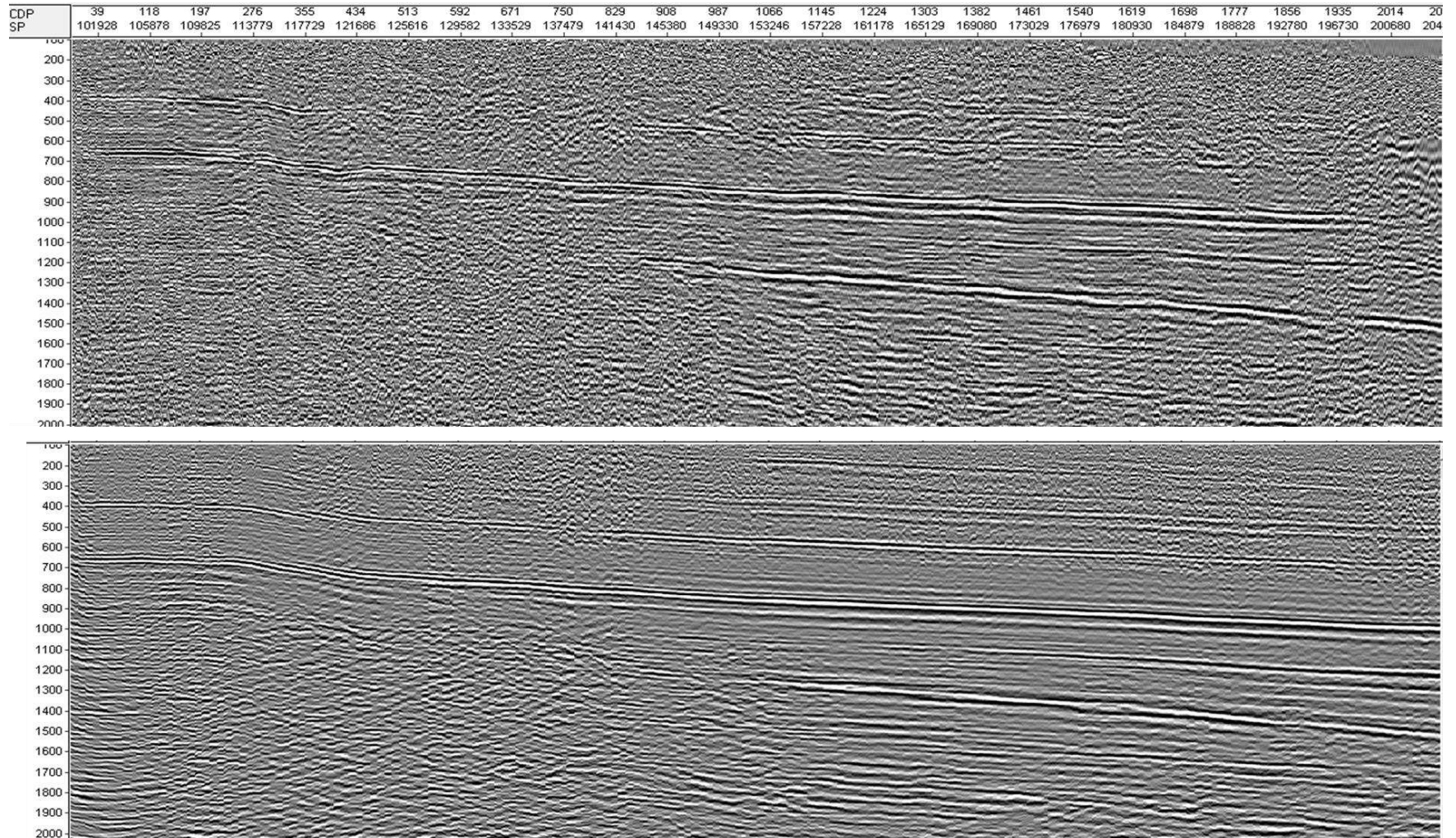


Figure 3-12 Seismic section OG- A before (top) and after (bottom) residual statics applied to the data.

Ensemble stack

The final stack is output to the final processing datum which was defined in previous processing to be 400m. A 50% stretch mute was applied prior to stacking and a mean stacking algorithm was used. This involves summing sample values of all traces and dividing by the number of samples summed raised to a given power which equals 0.5 for the present data.

Migration

Kirchhoff migration was used to migrate the post-stack time section. The method uses RMS velocity to calculate traveltimes and is generally good for handling steep dips. Aperture and dip are two important factors that control quality of migrated section when using Kirchhoff migration. Aperture is related to the lateral extent of the diffraction hyperbola, in distance unit, that is included in diffraction summation. A small aperture causes smearing in the output section whereas excessively large aperture widths will introduce noise into the data from the far and deeper part of the section and also result in long computational times. Dip has the same effect as aperture with smaller dips implying smaller aperture and hence steeply dipping reflections will not be migrated. Migration for the current processing was run using a smoothed RMS velocity picked every 500m. The migration was run using 7000m aperture and maximum dip migrated was set to 75 degree. The result of migration for line OG-A is shown in Figure 3-13.

Post stack processing

Migrated stack output from the previous processing was bandpass filtered using Ormsby band pass filter with corner frequencies 8 - 12.5 – 80 – 110. Similarly AGC with a long gate of 1000ms was applied to the migrated stack to amplify weak reflections.

3.3 Discussion and conclusion

Analysis of shot gathers shows that source related groundroll and amplitude burst noises are the main noise types recorded in data. Proper removal of these noises was imperative for recovering reflectivity especially from the near and mid offsets. Trace editing using database statistical tools and spike and burst edit tools were effective in removing source related amplitude bursts and random spikes. The removal of groundroll noise using linear Radon transform/ slant stack followed by muting the linear events in tau-p domain and inverse transform to T-X domain was more effective than the other tools tested including F-K and radial trace transform.

Static corrections were not complete due to poor first break picks which affected the refraction statics results, compromising the lateral continuity of reflection events. The source type and ground conditions are the main factors affecting the result. However, a more careful analysis of the low velocity layer would certainly improve the quality of sections and should be considered in any future reprocessing works.

Surface consistent amplitude corrections were invoked to correct amplitudes for disturbances/ anomalies generated in the near surface such as energy source variations, poor geophone coupling and the effect of the low velocity near surface layer. The correction enhanced amplitude anomalies due to changes in lithology and fluid content.

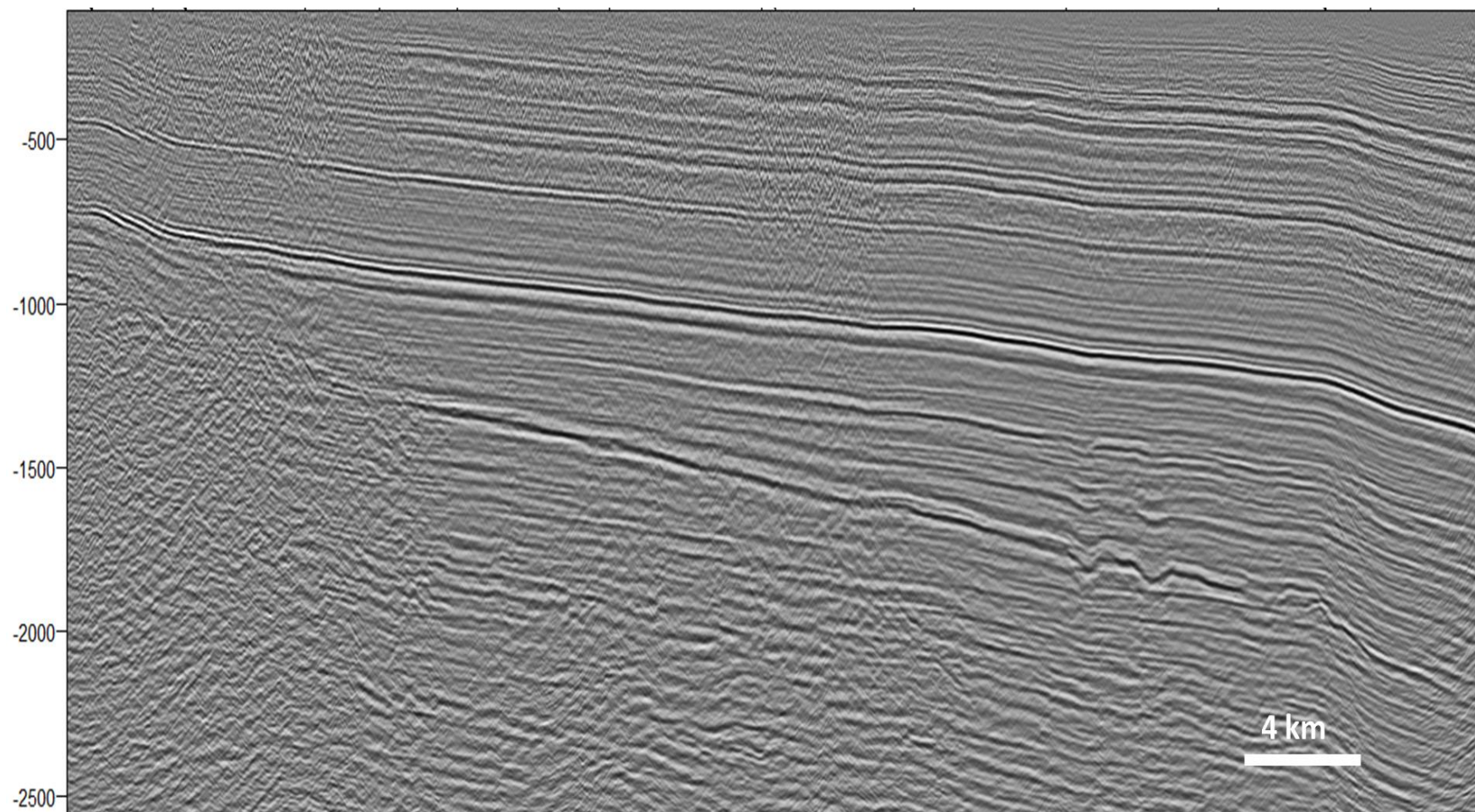


Figure 3-13 Final post stack time migrated seismic section, Line OG-A.

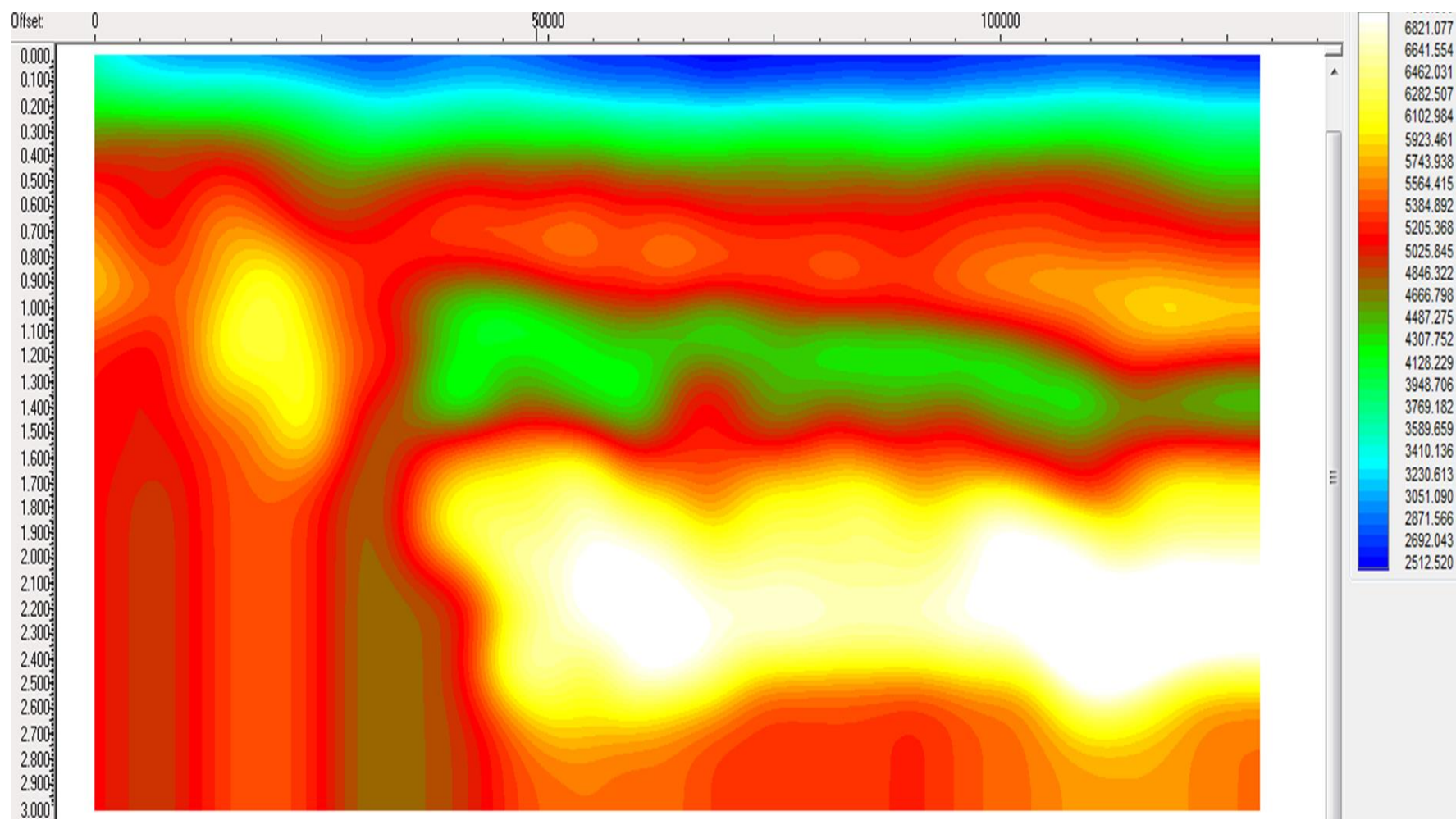


Figure 3-14 Smoothed interval velocity field derived from stacking velocity of seismic line OG-A.

Spiking deconvolution was not applied due to its high frequency noise amplification effect. The result of a 32ms lag gave the optimum result using a 200ms filter operator. Random noise attenuation using multiple passes of the F-X deconvolution has contributed to continuity of coherent reflections. Optimum results were observed with horizontal window length of 100 traces and 10 filter samples.

Velocity analysis was done in two passes before and after residual correction. The first pass was run every 500m and the NMO corrected gathers using this velocity field, with interpolation in between, were input to residual statics computations. The Maximum power surface consistent autostatics was used to compute residual statics using four iterations and maximum allowable shift of 10, 15, 20 and 30ms from the first to the last iteration respectively. The results of the maximum power autostatics were compared to correlation autostatics results and a much better reflectivity was achieved with the maximum power autostatics. The second pass velocity analysis was run after applying residual statics correction and was picked every 500m. A velocity analysis every 250m was also attempted on line OG-A to see if further improvements were possible but the changes were marginal and the 500m interval was used in all lines.

Stacking was done using a second pass velocity field and a 50% stretch mute. The mean stacking weighted with square root of number of samples gave a better stack response and was used to generate the final stacked sections. The smoothed, interpolated second pass velocity field was used in post stack migration of lines. The migration was run using 7000m aperture and maximum dip migrated was set to 75 degree.

3.3.1 Comparison with previous stack

Reprocessed Line OG-A was compared with the previous processing to highlight some of the improvements achieved in the present work. The main improvement is in recovering reflectivity in the Karoo section where poor signal to noise ratio and little coherency in the previous section, especially in the Karoo section, made it difficult to carryout seismic stratigraphic interpretation with confidence. The current dataset has shown noticeable improvements as can be seen in Figure 3-15. It is now possible to interpret unconformities, deltaic clinoforms and other seismic facies with ease and these were also correlated with well data to confirm/ support interpretations (see chapter four). Continuity of reflections has also improved and hence tracking different horizons mainly in the target zone is easily done. This is because of better attenuation of random and coherent noise that affected the data significantly. The improvement in vertical resolution from the original lines is not observed.

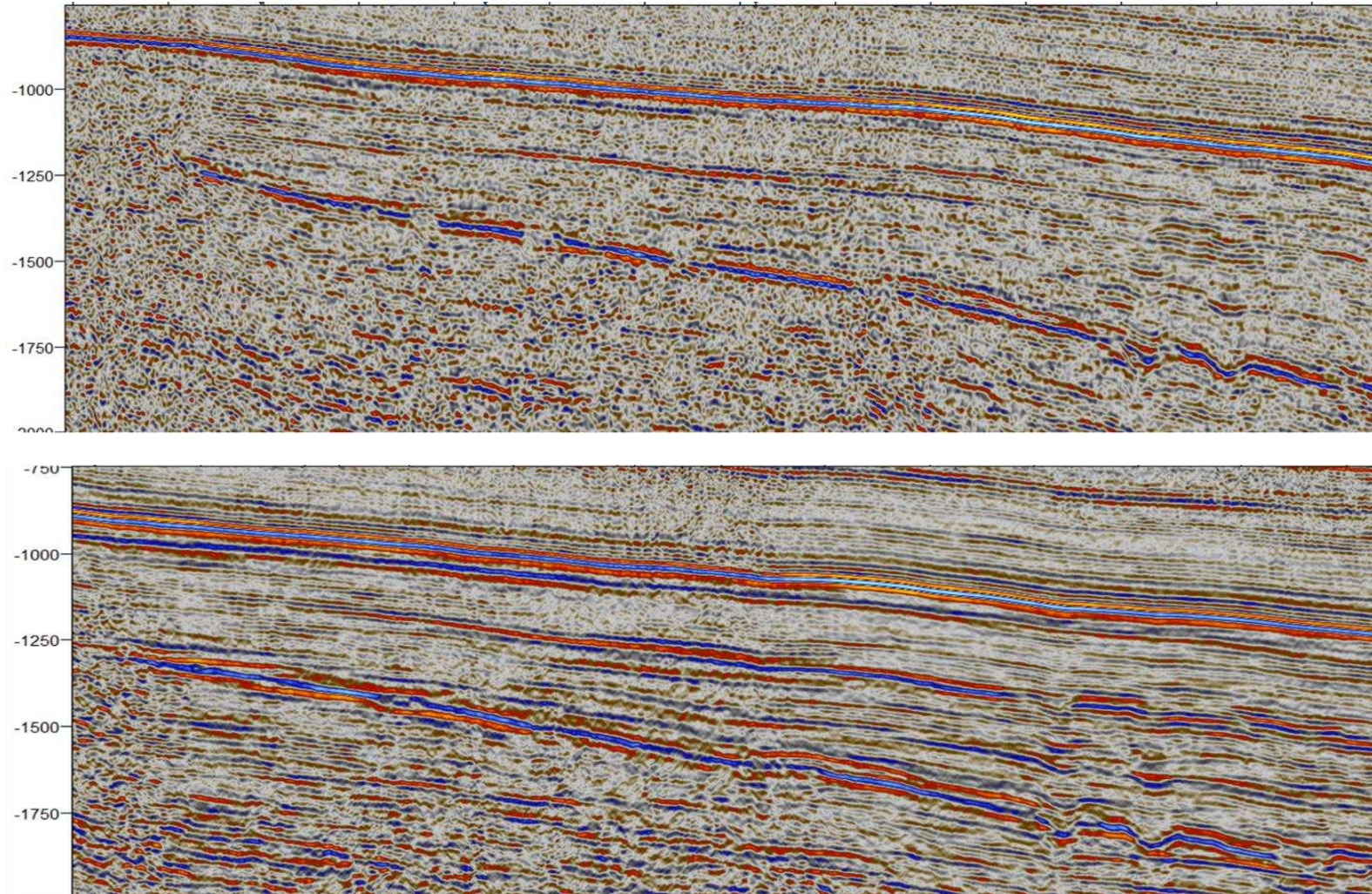


Figure 3-15 Comparison of original (above) and reprocessed (below) seismic Line OG-A.

Chapter 4 : Sequence Stratigraphic Interpretation

4.1 Data and Methodology

The data available for interpretation in this study are over 500 km of 2D migrated seismic reflection sections of different vintage and an exploration well drilled at the intersection between two seismic lines (Figure 1-1). The Seismic lines with “OG” prefix were acquired by PETRONAS Carigali Sdn Bhd in 2006 using vibroseis source and have 90 fold field coverage. The other two lines with an “S” prefix were acquired by Soviet Petroleum Exploration in 1990 using vibroseis source and have a field coverage of 24 fold (acquisition details in *Table 4-1*). The seismic lines are located in the steep southwestern flank of the basin and two lines lie over the Bodle Deep with the NW – SE line traversing both basement high and deep whereas the NE-SW line traversing the axial direction from shallow to the deep part of the basin Figure 1-1.

The data quality of seismic lines is generally good for the 90 fold data and good to poor for the 24 fold data. The vertical resolution of the lines is between 30 – 50 m at the Karoo level. Seismic attributes including median filter, structural filters and phase attribute were used to improve resolution and continuity prior to stratigraphic interpretation. The phase attribute in particular was used in aiding seismic facies interpretation and in defining sequence boundaries. Phase attribute is independent of the seismic amplitude and hence has the ability to enhance weak amplitude events, prograding clinoforms, onlap and offlap features (Taner et al., 1979).

Seismic interpretation was carried out using seismic sequence stratigraphic technique (R M Mitchum Jr et al., 1977; Vail et al., 1977). The Karoo section was divided into sequences by defining sequence boundaries based on geometric relationships such as onlap and truncation. Order of sequences was defined based on Embry (1995) criteria, in the context that deformation that led to deposition of the whole Karoo sequence is a major event giving rise to a first order sequence. Whereas subdivision of the Karoo sequence into second order sequences is based on the successive tilting that led to lake level fluctuations thus defining sequence boundaries. Higher order sequences show negligible evidence of the role of tectonics in their deposition.

Analysis of internal structure of sequences is the next step and is used to interpret seismic facies units, depositional systems and systems tracts boundaries. The main features used for this analysis are reflection configuration, continuity, amplitude and frequency of reflections (Hubbard et al., 1985; Rober M Mitchum Jr et al., 1977; Veeken, 2007). A strong, continuous reflection in the transition zone, at the top of the Karoo sequence, is used to flatten all seismic sections to remove the effect of later stage basin sag during the Jurassic and onwards. This has allowed a better visualization of earlier tectonic subsidence and depositional systems.

In order to construct a sequence stratigraphic framework which is consistent with well log interpretation wireline logs, cutting samples description, a borehole image log (BHI) and other well data were analyzed. The seismic interpretations were correlated with the well log interpretation and to this end seismic line OG-A was tied to well data using a

synthetic seismogram. The conventional wireline logs used are mainly gamma and neutron-density, in combination with BHI log and cuttings description; it was possible to identify lithology, shallowing and deepening upward trends and interpret depositional environments using these logs (Rider, 2002; Serra, 1984).

The BHI log used in this study was acquired using HMI tool of Weatherford. The tool measures electrical resistivity at a vertical resolution of approximately 1cm. It has a total of 150 electrodes in 6 pads giving a borehole coverage of 63% in 8.5" hole. The BHI was surveyed in the interval between 2075 – 2640 m which corresponds to defined sequences 3 and 4. Data processing among others included image enhancement steps such as removal of saw tooth artifacts, malfunctioning and dead buttons as well as image based pad misalignment corrections (Figure 4-1). Interpretation was done in both static and dynamic images and involves identifying and description of sedimentary structures and sedimentologic properties. Different surfaces related to crossbedding, faulting or erosional truncation appear as sinusoids in the image log and were manually picked and classified for interpretation of structural trend and paleocurrent directions. It was not possible to calibrate the image log to core data because no core samples were drilled in the well.

Location	OG Lines (Western flank)	S Lines (Bodle Deep)
Acquisition year	2006	1990
Recording geometry	Asymmetric split-spread	Asymmetrical split-spread
Number of channels	360	96
Geophones per group	12	24
Group interval	25m	50m
Source	Vibroseis	Vibroseis
Source interval	50m	100m
Sample interval	2ms	4ms
Record length	6 sec	5 sec
Fold	90	24
Frequency bandwidth	10-80Hz	14-64Hz
Replacement velocity	4500m/s	4000m/s

Table 4-1 Acquisition Parameters of Two-Dimensional Seismic Data in Southern Ogaden Basin.

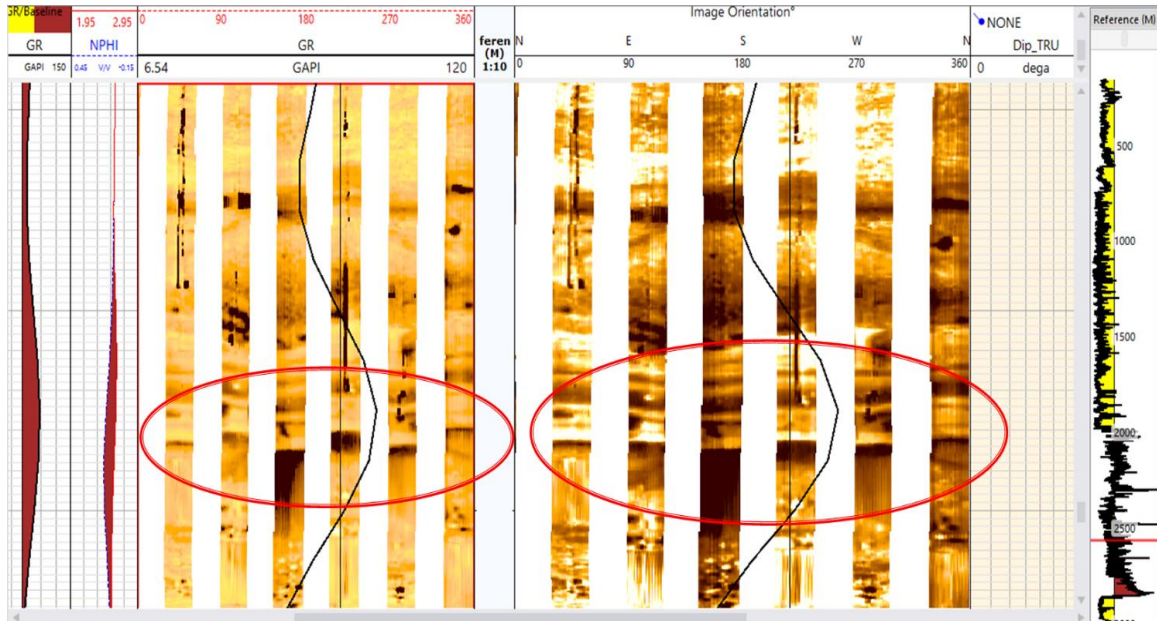


Figure 4-1 An example of a pad misalignment correction with the panel on the left showing borehole image before correction and the right panel showing image after correction (ellipse with red outline highlights the correction).

4.1.1 Seismic to well tie

Synthetic seismograms are used to tie depth domain well log data with time domain seismic sections. This allows to tie horizons picked from seismic to formation tops. A synthetic seismogram is produced by convolution of a wavelet with a reflection series R_i generated using density and sonic logs for a given well.

$$R_i = (\rho_{i+1}V_{i+1} - \rho_iV_i) / (\rho_{i+1}V_{i+1} + \rho_iV_i) \quad (4.1)$$

Where ρ_i and V_i represent density and velocity respectively at time index i . The wavelet used for computation of a synthetic seismic trace was extracted from seismic line S-A. The closest seismic trace to Well A was also extracted for comparison with synthetic trace. After reasonable synthetic seismogram was produced it was correlated with the extracted seismic trace and manual stretching and squeezing was used to improve the match

between the two types of traces. This will ensure well logs are displayed at the correct time depths (Figure 4-2).

4.2 The Permian – Triassic Karoo Sequences

In the Permian - Triassic Karoo group four second order sequences and constituting higher order sequences have been defined according to Embry (1995) criteria. The mega sequence is bounded at the base by the Precambrian basement and at the top by the transition zone to the Jurassic carbonate sequence. The sequence bounding surfaces are identified mainly using truncation and onlap features at basin margins with correlative conformable surfaces towards the basin center. We will discuss each sequence, analyzing individual seismic facies from internal reflection configuration, continuity, frequency characteristics and the range of thickness variations from interpreted seismic sections. Geological data from a well drilled close to the western edge of the basin will be integrated with seismic stratigraphic interpretation in the section that follows.

4.2.1 Sequence 1

Sequence 1 is bounded by the Precambrian basement below, marked by a strong reflection and an onlap surface above which is also characterized by strong continuous reflection. The top of this bottom sequence lies between 1.2 - over 3.2 S TWT (2400 – over 6500m) depth. In the southwestern basin margin, the sequence is generally thin and pinches out on to basement high. The thickness of the sequence is less than 150 ms TWT in this area but this thickness is seen to increase basin ward controlled by faulting (Figure 4-3 and Figure 4-4).

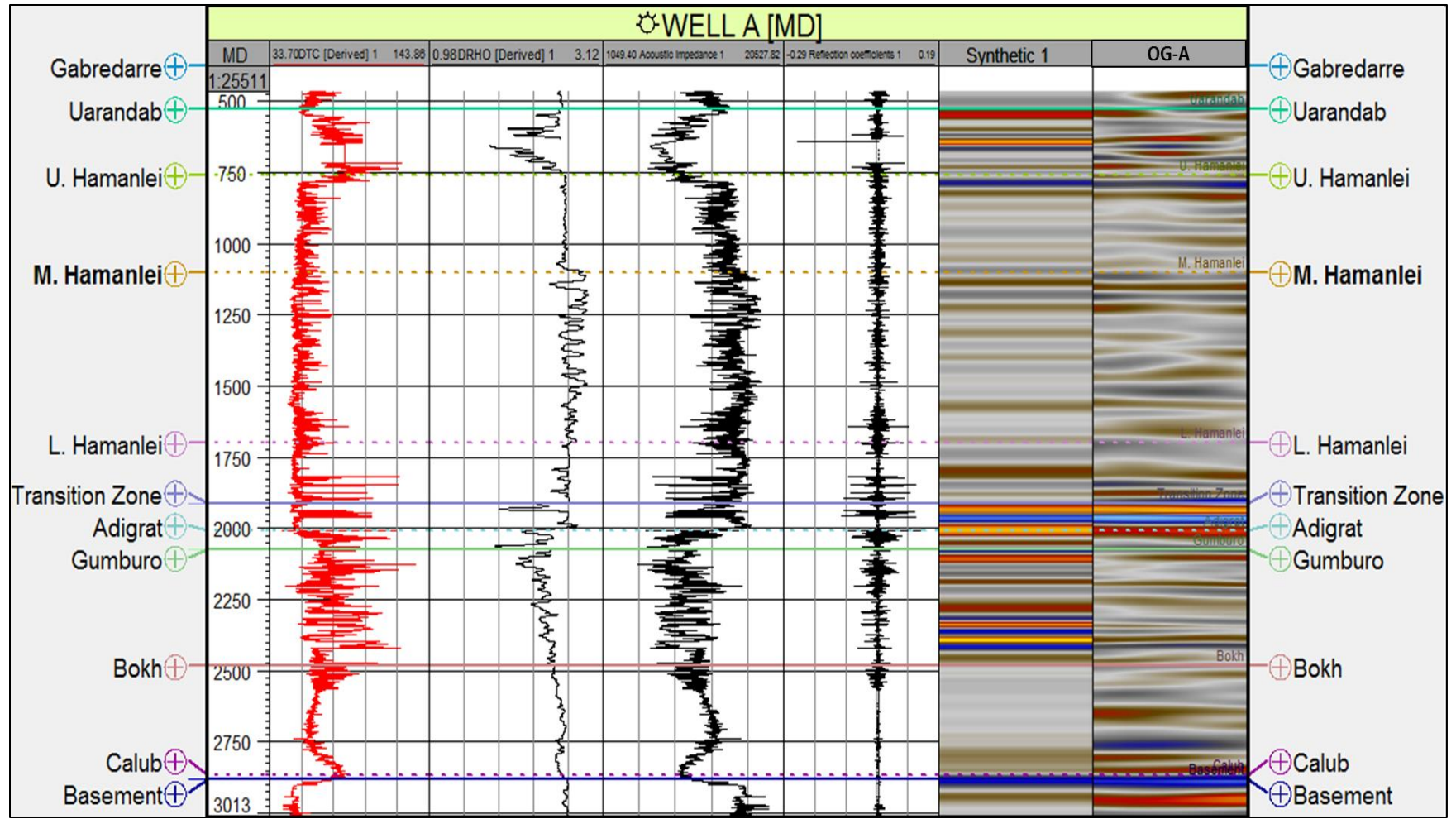


Figure 4-2 Seismic well tie using a synthetic seismogram.

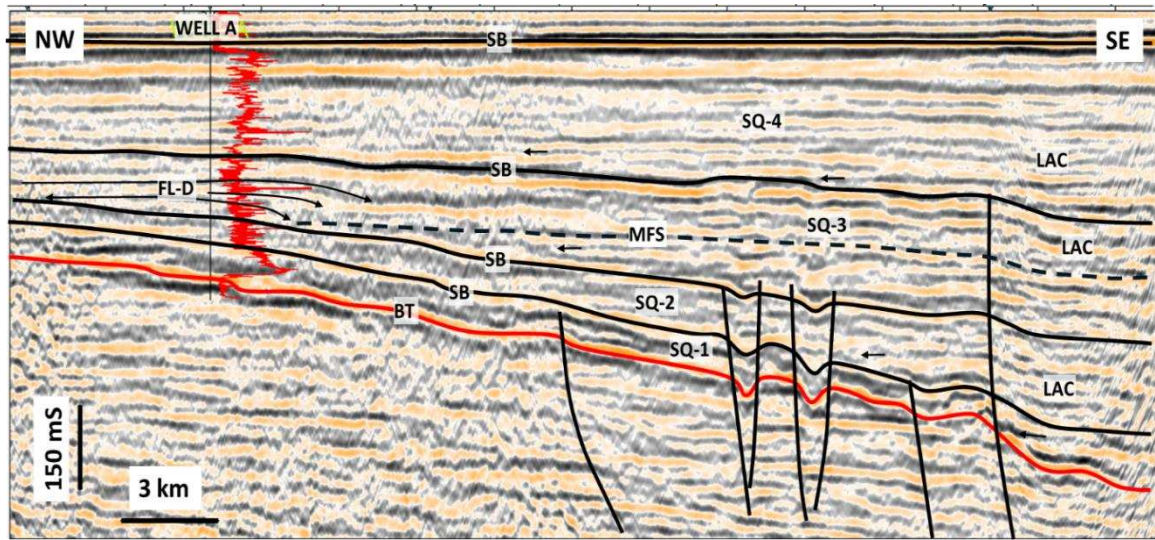


Figure 4-3 Seismic dip line OG-A in the southwestern margin showing interpreted Karoo sequences, see Figure 1-1 for location. Sequence boundaries (SB) are unconformity and correlative conformity surfaces bounding sequences; they are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; MFS – maximum flooding surface; FL-D – fluvial deltaic units; LAC – shallow to deep lacustrine; BT- basement top. Arrows indicate onlaps. Also showing Well-A gamma ray log in red.

The sequence also thins out towards north in line OG-C (Figure 4-8) and is absent in dip line OG-D (Figure 4-10). Internal reflection patterns are not resolved in seismic sections except towards the basin center where onlapping reflections exist.

The thickness of the sequence in Bodle Deep area varies between 130 - 340 ms TWT. In this area reflections are generally parallel to sub-parallel, variable amplitude, low to medium frequency and discontinuous to chaotic, probably due to overprinted effect of later stage tectonics. In line S-B reflections onlap on to the basement which slopes gently to the west and accordingly the sequence increases in thickness westward. In Line S- A, a probable SW-NE to E-W trending 25km wide zone of extensional deformation took place prior to deposition of sequence 1. Reflection events are confined to the structure low,

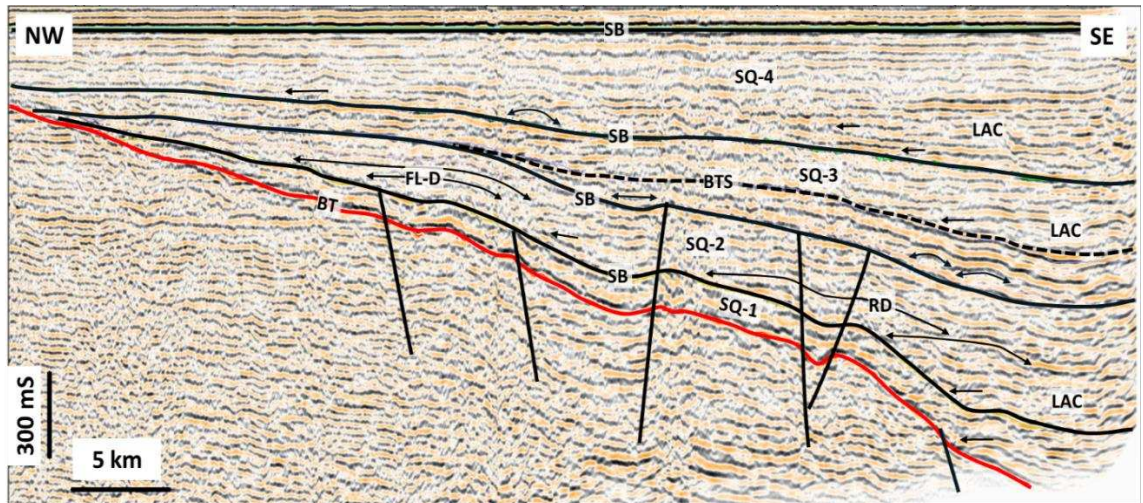


Figure 4-4 Seismic dip line OG-B interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. Sequence boundaries (SB) are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; FL-D – fluvial deltaic units; RD – regressive delta; LAC – shallow to deep lacustrine; BTS – bottom of transgressive surface; BT- basement top. Arrows indicate onlaps; double arrows in bottom of sequence 3 indicate hummocky type reflections.

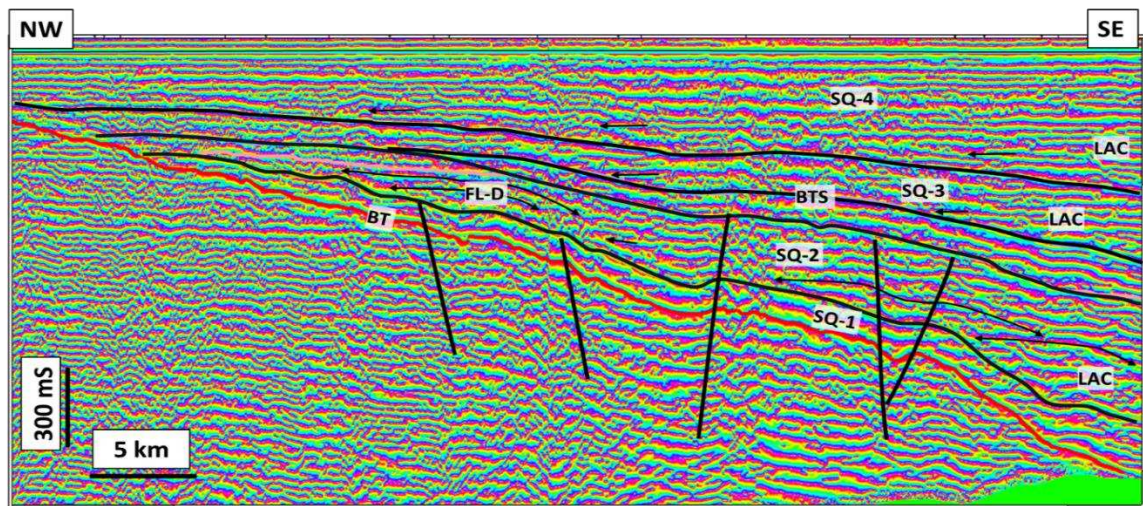


Figure 4-5 Seismic dip line OG-B (phase attribute) interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. The phase attribute has a potential to reveal geometric relationships. SB - sequence boundaries; SQ- sequences; FL-D – fluvial deltaic units; RD – regressive delta; BTS – bottom of transgressive surface; LAC – shallow to deep lacustrine; BT- basement top. Arrows indicate onlaps.

onlapping against the flanks of the structure at the bottom and progressively cover a wider area towards the top of the sequence. No clinoforms are visible in this sequence.

Interpretation: the bottom boundary is an unconformity surface whereas the top boundary is a composite surface of subaerial unconformity and a correlative conformity.

The variable amplitude, discontinuous seismic units in this sequence are probably related to alluvial/ fluvial environments (Sangree and Widmier, 1979; Veeken, 2007). These seismic units are more abundant in the sequence. However, laterally the units occasionally pass to moderately continuous, higher frequency events (Figure 4-7) which are probably deposited in a shallow lacustrine environment. At this stage, tectonics only affected a relatively small area compared to the overlying sequences with the depocenter located relatively close to the Bodle Deep area.

4.2.2 Sequence 2

The sequence is bounded by a bottom onlap surface which is a steep flank formed prior to deposition of the sequence both in the southwestern flank and the Bodle Deep areas. The upper boundary is also an onlap surface clearly defined in dip lines, and lies in a depth range of 1.2 – 2.87 S TWT (2400 - 6300m). In the southwestern flank, a significant thickness of sequence 2 is imaged in dip line OG-B (Figure 4-4), with a thickness of over 450ms in the deepest part. Whereas in Line OG-A to the north and at the study well location the thickness of sequence 2 is limited. In line OG-C, the sequence shows a wedge shape with a southward thickening. Despite the poor resolution and continuity of events in line OG-B, it is possible to identify depositional systems and stacking patterns that make

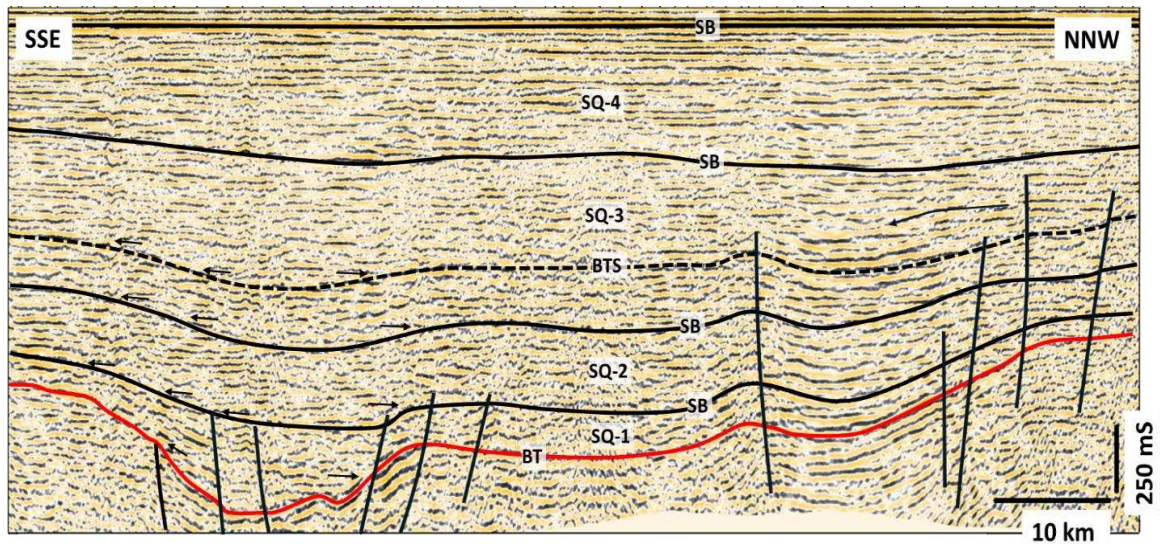


Figure 4-6 Seismic line S-A across Bodle Deep showing interpreted Karoo sequences, see Figure 1-1 for location. Sequence boundaries (SB) are unconformity and correlative conformity surfaces bounding sequences. BTS- bottom of transgressive surface; BT- basement top; SQ- sequences. Arrows indicate onlaps.

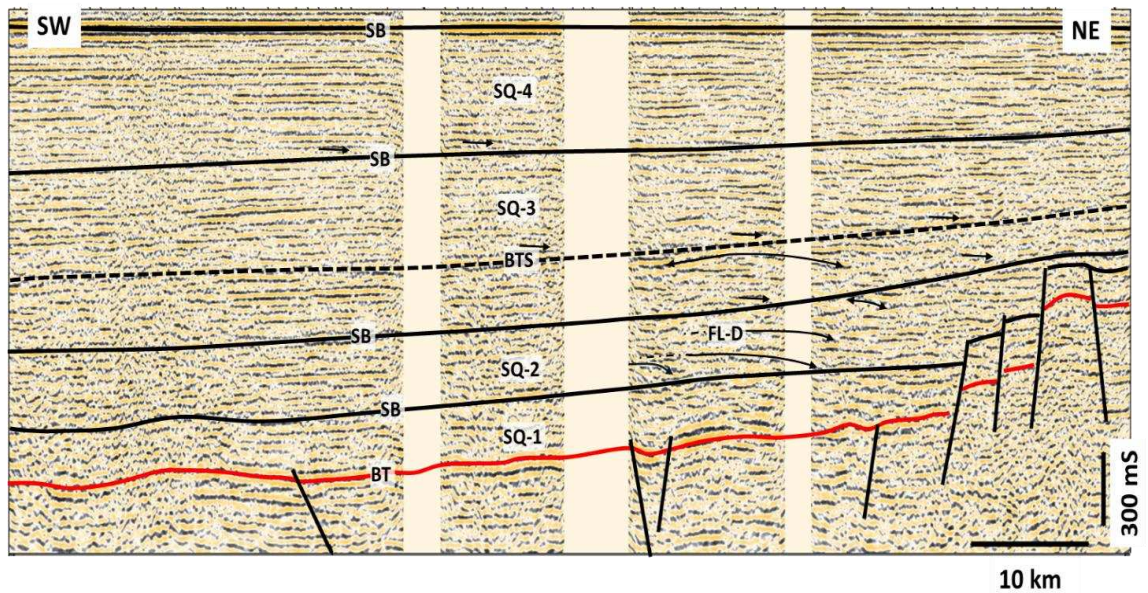


Figure 4-7 Seismic line S-B along the axis of Bodle Deep showing interpreted Karoo sequences, see Figure 1-1 for location. SB - sequence boundaries; BTS- bottom of transgressive surface; BT- basement top; SQ- sequences; FL-D – fluvial deltaic units. Arrows indicate onlaps.

up the sequence. The phase attribute further enhances the geometric features as well as continuity of events supporting interpretation.

The bottom reflections in line OG-B are generally parallel and onlap the sequence boundary. These events are close to 150ms thick and have relatively high amplitude and frequency. Higher up in the sequence, the margin is characterized by clinoforms onlapping the sequence boundary and downlapping basinal reflections. Laterally, the clinoforms are onlapped by younger basinal reflections that remain similar in character to bottom units. The clinoforms generally show oblique geometry and progressively back step onto higher ground of the western flank. These clinoforms have heights between 60-70ms (~130m). In the upper part of the sequence subtle clinoforms prograding southeast and downlapping underlying reflector are present. The height of these clinoforms is proportional to underlying clinoforms. Internally the clinoforms in this sequence show discontinuous, variable amplitude and subparallel events compared to their laterally equivalent more continuous reflections in the basin ward direction.

In the Bodle Deep area, a series of basement related faults are imaged at the eastern end of line S-B (Figure 4-7). The faults have a throw as much as 220ms with an N/NE – S/SW strike, oblique to axis of the basin and an along strike length of over 40 km (measured from previous mapping). In N-S Line S-A (Figure 4-6), steep sloped flanks similar to those imaged in the southwestern flank bound the sequence from below and the resulting trough has a width close to 80 km along the seismic section. The sequence increases in thickness basin ward in line S-A and also tends to increase along the axis of the basin

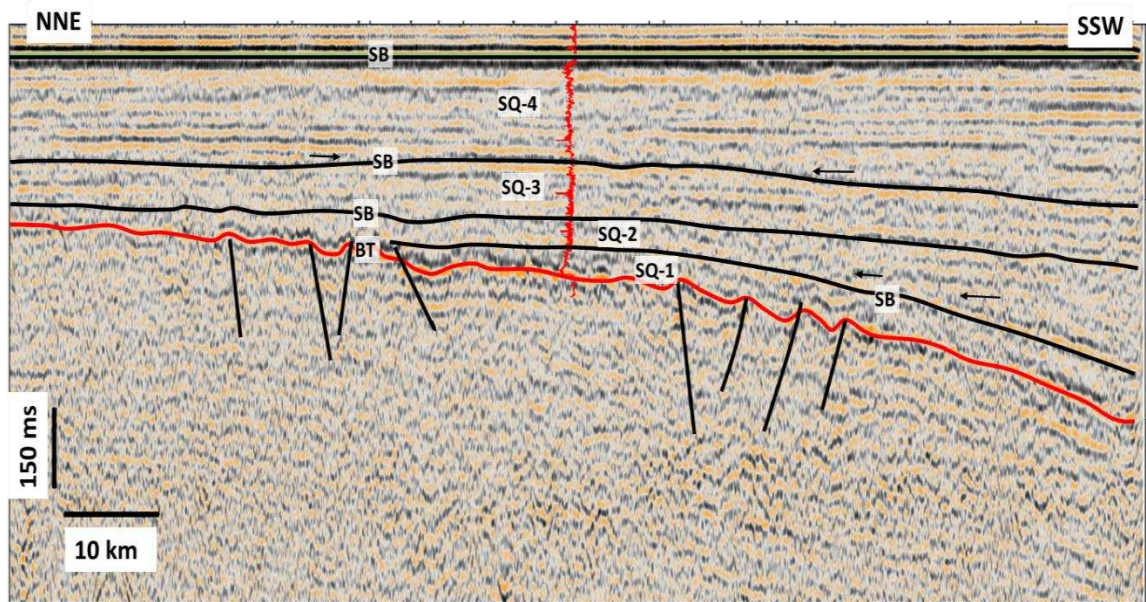


Figure 4-8 Seismic strike line OG-C interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. Sequence boundaries (SB) are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; BT- basement top. Arrows indicate onlaps.

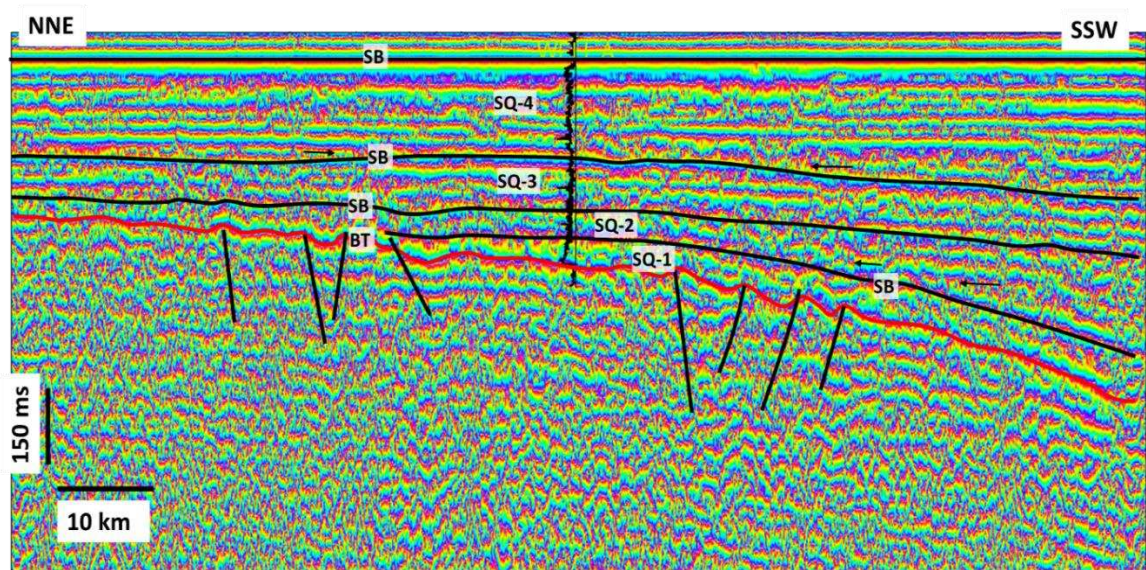


Figure 4-9 Seismic strike line OG-C (phase attribute) interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. SB - sequence boundaries; SQ- sequences; BT- basement top. Arrows indicate onlaps.

towards East - Northeast as seen in Line S-B. The sequence has an average thickness of 300 ms TWT from the two seismic lines.

The bottom part of the sequence in line S-A is confined to the deepest part of the newly formed trough where reflections are seen onlapping against the boundary. Higher up, reflections have an overall discontinuous and medium to high frequency character and are deposited in a wider area. There are also indications of marginal systems especially towards the southern part line S-A interfingering with onlapping horizontal reflections from low energy systems.

In Line S-B, sequence 2 reflections are parallel with variable degree of continuity and higher frequency in the southwest half of the section. In the right half, progressive northeastward stepping subtle clinoforms are observed prograding the hanging wall margin of the half graben. These oblique to sigmoidal type clinoforms overlie a rift fill which shows a hummocky type and parallel onlapping events. The boundary fault margin is mostly onlapped by rift fill from bottom to top.

Interpretation: the upper and lower boundaries of the sequence represent subaerial unconformity surfaces. Erosional unconformity at the top of the sequence in both the southwestern flank and Bodle Deep area probably followed a regional uplift. A much larger scale of erosion is noted at this boundary compared to other erosional events in the Karoo section. In the eastern Bodle area, the half graben created a local depocenter. The rifting episode resulted in sequence of depositional systems starting with a bottom shallow to deep lacustrine environment indicated by parallel onlapping reflections and

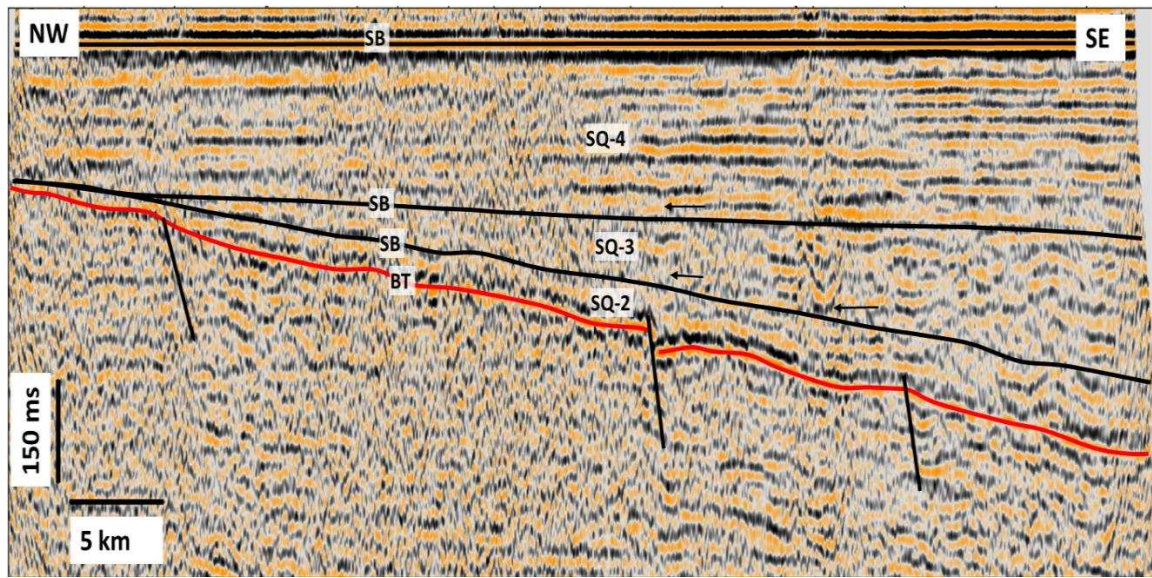


Figure 4-10 Seismic dip line OG-D interpretation of Karoo sequences in the southwestern margin, see Figure 1-1 for location. Sequence boundaries (SB) are mainly identified by the geometric relationships of reflections above and below the surface. SQ- sequences; BT- basement top. Arrows indicate onlaps.

prograding fluvio-deltaic systems in the margin that eventually filled the sub-basin. The sediments were routed dominantly along the axial direction and from the steeply dipping margins with sediments sourced from Bur high in the south and the northern Ogaden. It is not clear if the footwall source was significant at this stage.

In the southwestern flank, a low energy environment existed and deposition of shallow to deep lacustrine hemipelagic muds and silts took place with aggrading and retrograding marginal fluvio-deltaic systems. As the accommodation space filled up deltaic progradation took place and continued lake level fall was followed by an erosional unconformity. Water depth estimate using clinoform heights during this time is at least 130m using the method by Veeken (2007). Drainage basins in the northwest and western

flanks and possibly the southeastern Bur High supplied most of the sediments deposited in the subbasin at this stage.

4.2.3 Sequence 3

The bottom of sequence 3 in line OG-B consists of a subsequence bounded by a bottom erosional surface and an onlap surface at the top. The subsequence is 150ms TWT thick at the eastern, deeper part and gradually thins to 60ms towards the updip end of the line. The reflections are parallel, distinctly high amplitude and with a degree of continuity that improves down dip. This subsequence is however not recognized in the northern line OG-A which can be due to thinning of the subsequence below seismic resolution or non-deposition. In the Bodle area, the bottom of the sequence consists of at least two subsequences bounded by erosional unconformities and correlative conformities and a top onlap surface. In the southern half of line S-A, a deeper incision from the previous erosional event is filled by the subsequence. The lower subsequence tends to thin out in both the north and northeast directions while the upper is more extensive. These subsequences have similar thickness of just over 100ms. Internal reflection patterns are mostly flat, discontinuous and higher amplitude throughout the lines with a few hummocky type patterns. Distinctive features that can be linked to depositional systems are not evident because of the limited thickness of the subsequences as well as erosion of their tops.

The overlying subsequence represents a major clastic deposition following a regional tilt with its center between the southwestern margin and the Bodle Deep area. In the

southwestern flank the base of the subsequence is an onlap. The top surface is also an onlap surface with variable character along seismic sections and lies at a depth range of 0.9 – 2.24 S TWT (1735 - 4800m). The sequence has a general wedge shape increasing in thickness basin ward from 100ms to over 280 ms in a distance of 30 km in line OG-B. The thickness also decreases gradually northward in line OG-A.

The internal reflection patterns are parallel, relatively continuous and higher frequency in the deeper part. In the shallower marginal part reflections are discontinuous, subparallel and vary from weak to strong amplitude. At the top of this sequence, subtle oblique clinoforms prograde basin ward. These clinoforms are easier to identify in line OG-A where their height is around 50ms.

In the Bodle Deep area, a regional westward tilt led to deposition of the subsequence as observed in Line S-B. The bottom and upper boundaries are both onlap surfaces with the upper boundary even less steep than the bottom which adds to the uncertainty in defining the surface where data quality is poor. The thickness of the subsequence is over 450ms, it tends to decrease northward and probably towards the south where Bur high exists. There is also a small increase in thickness towards the west.

Internal reflection patterns seem to be different between the eastern and western half of line S-B as well as northern and southern half of line S-A. In the north and eastern parts of these lines the reflection events are generally discontinuous, parallel to subparallel, lower frequency and variably have weak to strong amplitude. The southern and western parts are relatively weak amplitude events with better continuity and higher frequency.

Occasional high amplitude and hummocky type reflections also exist in this weak amplitude dominated part.

In Line S-A subtle clinoforms prograde south or show aggradation patterns which is an indication of presence of higher order sequences. The thickness of these higher order sequences is under 100ms. The northern part of the line also shows tectonic deformation in a narrow zone which was active in the early stage of the sequence development controlling sedimentation locally. The bounding faults are near vertical and have a cumulative fault throw of around 60ms. The top of this sequence has not experienced a major erosion and is marked by a transgressive surface.

Interpretation: the top and bottom boundaries of the sequence are interpreted as subaerial unconformity surfaces with correlative conformity surfaces. The bottom subsequence is probably related to an early stage tectonic deformation before the main event that led to deposition of the overlying subsequence. The sequence is made up of lacustrine and fluvial-deltaic depositional systems similar to underlying sequences. Internal reflection patterns in the Bodle area suggest a lacustrine environment aerially restricted to southwest of Bodle Deep, surrounded by alluvial/ fluvial and deltaic environments. Sediment sources have remained probably the same as in previous episode since there was no major change in basin configuration.

4.2.4 Sequence 4

Sequence 4 followed another subsidence episode and is the last major clastic deposition before the Jurassic marine incursion. It is bounded by a bottom transgressive surface with

flat parallel reflectors onlapping against it. The top of this sequence is characterized by a flooding surface that bottomed the Jurassic marine setting. The sequence in southwestern margin has a thickness of 542ms in line OG-B which is almost twice that of the underlying sequence whereas in line OG-A the two sequences have nearly equal thicknesses. The sequence top lies at a depth range between 0.7 – 1.7 S TWT (1300 - 3600m).

Internal structure of the sequence is not clearly imaged, however, in general the lower part is wedge shaped and characterized by a strong amplitude, discontinuous to continuous events that are relatively lower frequency compared to the upper part. The upper part extends farther landward covering a wider area and shows lower amplitude, high frequency and more continuous events. In a closer look at the sections, it is possible to identify clinoforms which have retrogradational and progradational trends suggesting the presence of higher order sequences.

The lower boundary of the sequence is less certain in eastern Bodle area. However the top of gently dipping lower sequence and evidence of truncation in the eastern end of line S-B are used to interpret the surface. The upper boundary is defined by a strong reflector which is also used for flattening the seismic sections. The sequence thickens towards west in this area and has a thickness over 500ms. Internally, it generally displays a higher amplitude concordant reflections with variable degree of continuity and low to moderately high frequency. There are clinoforms identified in Line S-A that prograde south and possible truncation surface suggesting the presence of at least two higher order

sequences. The continuity of reflection improves in upper part of the sequence where events are higher frequency and variable amplitude.

Interpretation: the sequence is bounded by a bottom unconformity and a top transgressive surface. Depositional systems identified are similar in character to underlying sequences however the abundance of strong amplitude events may be related to relatively shallower high energy environments. The uppermost part represents an increasingly deeper environment that ended the sequence of continental sedimentation. The depocenter at this stage probably lies between the Bodle Deep and the southwestern flank.

4.3 Correlation with Well Log Interpretation

4.3.1 Sequence 1: 2763m – 2865m (Basement)

The sequence is close to 100m thick at the well location with a bottom boundary defined by a sharp increase in GR values as well as a large positive separation (where density is to the right of neutron log - corresponding to a shale) in neutron-density log (Figure 4-11). The top boundary is defined by sharp decrease in GR log and a corresponding minimum separation in neutron-density log. The sequence shows an upward coarsening GR log motif where the bottom approx. 20m thick interval has a high GR value that progresses upward into a 25m thick funnel shaped interval and an overlying 35m thick cylindrical and a second funnel shaped interval. At the upper most part, GR log shows a 20 m thick fining upward interval. The neutron-density log shows a positive polarity throughout the

sequence corresponding to shale. The separation between the two curves is moderate at the bottom and gradually closes up the sequence.

The bottom of the sequence is made up of shale according to the mud log and cutting samples are light to dark grey colored in the bottom part and dark grey to light green in the upper part of the sequence. The shale samples are laminated in part, silty in part, pyretic in part and slightly calcareous to non-calcareous. Sand increases in abundance up the sequence and is described as colorless, translucent, fine to medium grained, coarse in part, moderate to poorly sorted, glauconitic, argillaceous in part and contains traces of carbonaceous material.

Interpretation: Sequence 1 unconformably overlies basement and corresponds to Calub and the bottom of Bokh formations. Both the upper and lower boundaries of the sequence picked on seismic correlate with sharp changes in GR curve and neutron-density logs indicating a shift in depositional environment. The high GR blocky log motif at the base of the sequence is probably related to a shallow to deep lacustrine depositional environment. The dominance of shale cuttings from the bottom samples, dark to light gray color of samples and presence of pyrite also suggest the shale units were probably deposited in a low energy, occasionally reducing environment (Lewis, 1984). The coarsening upward to aggrading trend with a few fining up intervals in GR log in the upper part of the sequence as well as sandy nature of cutting samples can be interpreted as a result of deposition in a shallow lacustrine to fluvio- deltaic and flood plain environments. Glauconite in sand samples, if authigenic, may indicate a slightly reducing sublacustrine setting (McRae, 1972). Alluvial to fluvial environments interpreted from seismic to

represent the bulk of the sequence are probably the result of lake level fall where a short lived lacustrine environment covered a larger area in the initial stage. The subsequent lake level fall restricted the lake environment to the deepest part of the basin, exposing the rest of the area to erosion and alluvial/ fluvial sedimentation.

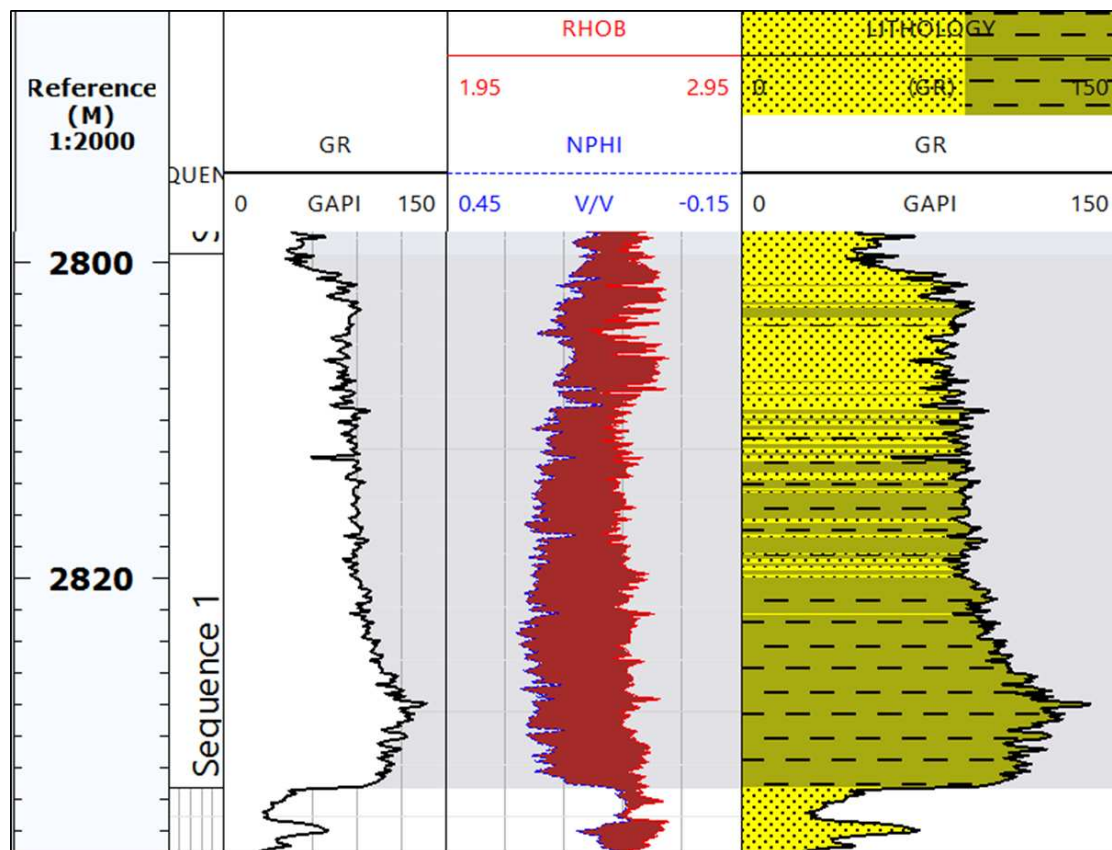


Figure 4-11 Gamma ray, neutron-density overlay (higher percentage of mud indicated by wider separation filled by red color and sand indicated by red filled minimum separation to yellow filled separations) and an interpretation log of sequence 1 (sand indicated by yellow and mud by green color).

4.3.2 Sequence 2: 2763 - 2650m

Sequence 2 has a thickness of 113m at the well location. The boundary with underlying sequence is characterized by a sharp change in GR whereas the upper boundary is less

obvious (Figure 4-12). Compared to underlying sequence, this sequence is dominantly sand prone with some clay rich intervals in the bottom and middle part as seen in both neutron-density and gamma logs. The GR log shows no obvious coarsening or fining upward trend, values are close to an average line which represents an aggrading sequence. No resistivity image logs exist for this sequence.

The mud log shows the sequence is dominated by sandstone and it is described as colourless to white, sub rounded to sub angular, moderate to poorly sorted, siliceous cement in part, glauconitic, pyretic in part, argillaceous in part with traces of carbonaceous material. Grain size tends to decrease upwards with some very coarse grained clasts in a medium to coarse grained lower part to medium to fine grained upper part. Shale is light green, reddish brown, light grey to dark grey, soft to moderately firm, sub blocky to sub flaky, silty in part, pyretic in part and slightly to non-calcareous.

Interpretation: Sequence 2 corresponds to lower part of Bokh formation. The irregular GR log pattern and sandy nature of sediments is probably related to deposition in a high energy environment, closer to sediment source such as in a fluvial and floodplain environments. The moderate to poor sorting of samples could also be related to lack of continuous reworking of deposits such as in a floodplain (Lewis, 1984). Glauconite and Pyrite in both sandstone and mudstone may indicate occasional flooding by lacustrine environments leading to chemically reducing conditions. Since the well was drilled in the shallow part of the basin, only a limited thickness of sequence 2 was intercepted and only

marginal systems were encountered. Hence it was not possible to confirm depositional systems interpreted from seismic.

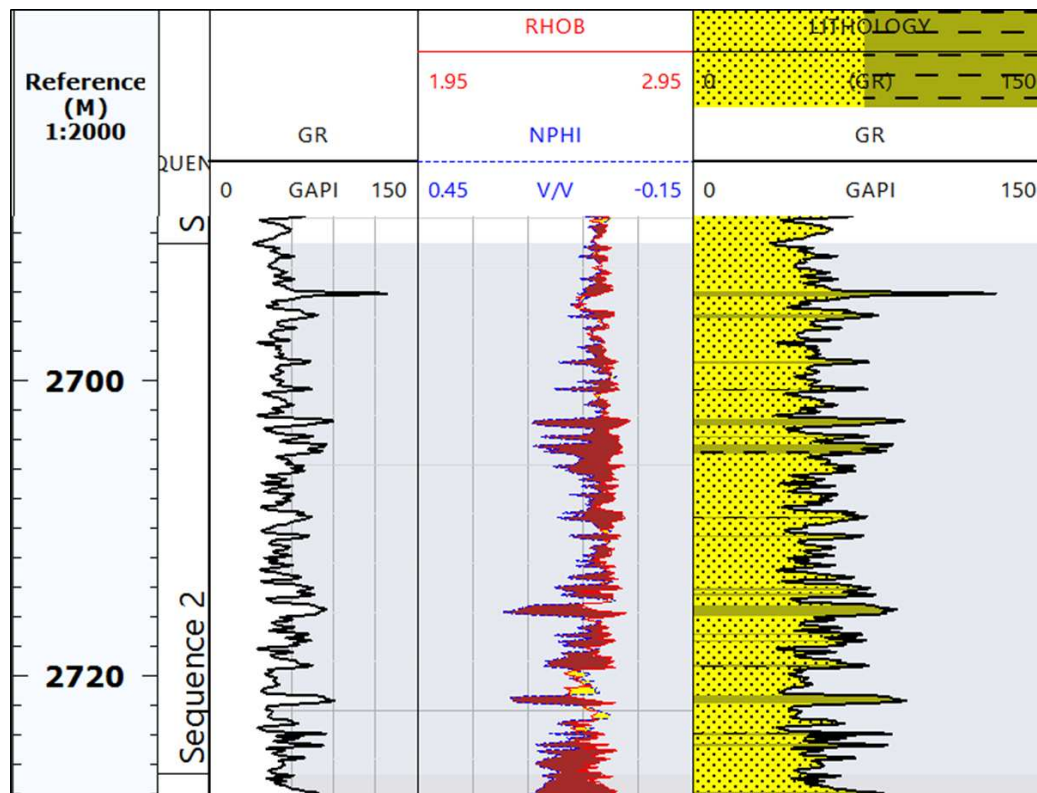


Figure 4-12 Gamma ray, neutron-density overlay (higher percentage of mud indicated by wider separation filled by red color and sand indicated by red filled minimum separation to yellow filled separations) and an interpretation log of sequence 2 (sand indicated by yellow and mud by green color).

4.3.3 Sequence 3: 2650 – 2400m

The lower boundary of sequence 3 is defined at the base of an increasing GR log trend and an upper boundary at the top of a shallowing up trend which is better defined in neutron-density overlay by an upward change from minimum to moderately high positive separation (Figure 4-13). The sequence can be broadly divided into a bottom half sand prone interval, excluding the very bottom interval, and an upper half shale prone interval.

Sequence 3 lower part: the lower half of the sequence consists of a bottom 30m thick unit showing high GR reading which alternates with or is punctuated with low GR units. The separation of the neutron and density curves is an alternating moderate positive and minimum correlating with GR log. In the BHI log, the interval is in orange to brown resistivity range with occasional dark brown thin layers giving rise to moderate to high resistivity contrast between individual beds. The beds are horizontal with individual units in a scale of cm to dm and are internally homogenous. This bottom unit overlies a possible scour/ erosive surface.

The basal units pass into a funnel shaped GR interval that is superimposed with spiky GR readings. This interval consists of crossbed sets and horizontal beds with faint to strong resistivity contrast between beds; individual beds are in a scale of cms to dms. Crossbedding sets have thicknesses up to 3m and show a scattered dip pattern but S - SE directions dominate with dip angle between 10 – 20 degrees. Lower GR readings correlate with cross bedded units whereas finely bedded horizontal units show higher readings.

An irregular shaped GR log interval exists between 2585-2620m which shows minimum to moderate separation in neutron-density log. It is orange to brown colored in static BHI log with occasional thin dark brown layers. A closer look at the GR log from the interval however shows it consists of multiple fining upward cycles 2-10m thick. These cycles are bottomed by a possible erosional surface and occasionally shows clasts of measureable sizes above the surface. Overlying the basal lag is variably horizontal and crossbedded layers. Horizontal beds show faint to strong resistivity contrast in a scale of cms to dms

and are mainly found towards the upper part of the interval. Crossbedded units show moderate to strong resistivity contrast with sine waves better defined and dipping in a general southeast direction (14/ 150). The top of the cycles is a thin brownish faintly crossbedded unit and an overlying yellowish massive sand prone layer.

A ~55m thick sand prone interval tops the lower half of sequence 3. The separation in neutron-density remains minimum except in mudstone intervals where it shows a moderate positive polarity and correspondingly the gamma log shows spikes. In the BHI log a yellow to light brown resistivity color range is observed with thin dark brown layers dividing the interval into multiple cycles. Each cycle is characterized by a yellowish bottom progressively grading into dark brown at the top, having thicknesses 6 – 10 m. The low resistivity unit is characterized by a speckled appearance and dominantly faintly cross-bedded with some horizontal and massive bedded intervals. The orientation of crossbedded intervals indicate paleocurrent direction in the southeast to east direction, dip angles varying between 10 – 20 degrees. Occasionally, irregular large clast of low resistivity are also present as thin layers which give rise to high GR readings; these are probably due to intraclasts (e.g. at 2554.89m). Possible lag deposits at the bottom of each cycle are seen in some cycles. The thin mudstone layers found between the sandstone layers have thicknesses less than 2m. These units are dark orange to brown colored, horizontally bedded and internally homogeneous with only a few disturbed beddings. These layers tend to show a sharp upper boundary and a gradational lower boundary.

Sequence 3 upper part: the upper half of the sequence is ~135m thick and is dominated by a bow and blocky type GR log motifs and a funnel shape at the very top. Neutron-density log mostly shows moderate separation intervals alternating with minimum separation intervals. In BHI log, the interval is in the yellow to light brown static resistivity color range with occasional thin dark brown layers giving rise to a low to moderate resistivity contrast between units.

The lower ~50m thick interval is made up of interbedded massive to finely bedded sandstone and mudstone units which grade up into a structureless mudstone with a few crossbedded sandy intervals. The thickness and abundance of crossbedded sandstone units increases up the lower part and a massive sandstone unit with thin resistive layers is also observed. Higher up, multiple fining up cycles having thicknesses between 2-5m exist. GR log shows bell type motifs and a dominantly minimum separation in neutron-density log. Faint to well-defined crossbedded sandy bottom unit and an overlying interbedded sandstone and mudstone with individual units in a scale of cms constitute these cycles. In some cases the cycles are bottomed by irregular/ scour surfaces and dark or light spots indicating basal lag. The crossbedding layers show a south east dominant trend. Bedding planes are mostly well developed and only a few crude beddings are noted.

The upper part is characterized by a stacking of multiple block shaped GR log motif. Accordingly, alternating polarities in neutron-density log are observed resulting from interbedded sand rich and clay rich intervals. Individual GR high blocks have thicknesses

between 3-10m and the abundance of sandstone increases towards the top. In the BHI log the interval shows yellow to light brown beds giving rise to low to moderate contrast between individual units. Beds are in a scale of cms to dms separated by thin brown beds, internally homogeneous with few intervals displaying disturbed beddings. Bedding planes are mostly well developed and horizontal, crossbeddings are only observed near the top. Sand rich intervals tend to be yellowish and thicker individual beds than interbedded clay rich units.

Cutting samples from the sequence show the lower part is dominated by sandstone with minor shale compared to the upper part. The shale unit is described as light green to green, brown, greenish grey, sub flaky in part, silty in part, pyretic in part and non-calcareous. Sandstone is colourless, white, translucent, fine to medium grain, coarse in part, sub rounded to sub-angular, moderately sorted, siliceous cement in part, glauconitic, argillaceous in part and pyretic in part.

Interpretation: the sequence corresponds to the upper part of Bokh and lower part of Gumburo formations. The upper and lower boundaries of sequence three defined from seismic correspond to the top and base of GR log shallowing up trend respectively. The lower part exhibits a stacking pattern of increasingly shallower environments going up the section. Parallel finely bedded planar mudstones interbedded with sandy units in the bottom part are probably related to shallow lacustrine to prodelta environments which are deposited from suspension and interbedded with sandy units deposited by current and/or wave activity (James and Walker, 1992; Nichols, 2009; Selley, 1979). A gradual

shallowing up leading to deposition of small scale crossbedded sandstone, massive sand beds and scour surfaces overlain by coarse lag are possibly related to delta front to mouth bar and distributary channel environments.

The top of the lower part is dominantly crossbedded sandstone, where the difference with the underlying part is in scale of the fining upward cycles and the higher proportion of mud present in the underlying part. This top part is probably related to a stacked/ multi-storey sandy/ braided river type and floodplain depositional environments.

The interbedded sandstone and mudstone grading up into structureless mudstone in the upper part of the sequence suggests a shift to a low energy environment, such as a lacustrine, an interdistributary bay or floodplain environment. Farther up, fining upward cycles with evidences of erosional surfaces at their base overlain by crossbedded sandstone and interbedded mudstone and sandstone suggest a distributary channel or fluvial system. The uppermost part of the sequence with alternating sand and mud rich horizontal beds and clearly developed bedding can be due to a shallow lacustrine environment that is subsequently filled up clastic input from a fluvial deltaic system.

At the location of Well A only the upper subsequence of Sequence 3 is expected to be present. However, it is also possible that the lower part of sequence 3 at Well A may correspond to lower subsequence defined mainly in other seismic lines such as OG-B. The shallowing up trend, with the exception of the uppermost part, correlates with a delta interpreted in seismic line OG-A. This supports the seismic interpretation of a gradual shallowing up by delta progradation towards the top of sequence 3. A possible locally

restricted lacustrine deposition is indicated in seismic line OG-A at the uppermost part of sequence 3 which tends to increase in thickness towards west of the well location. This observation is in agreement with the well log interpretation.

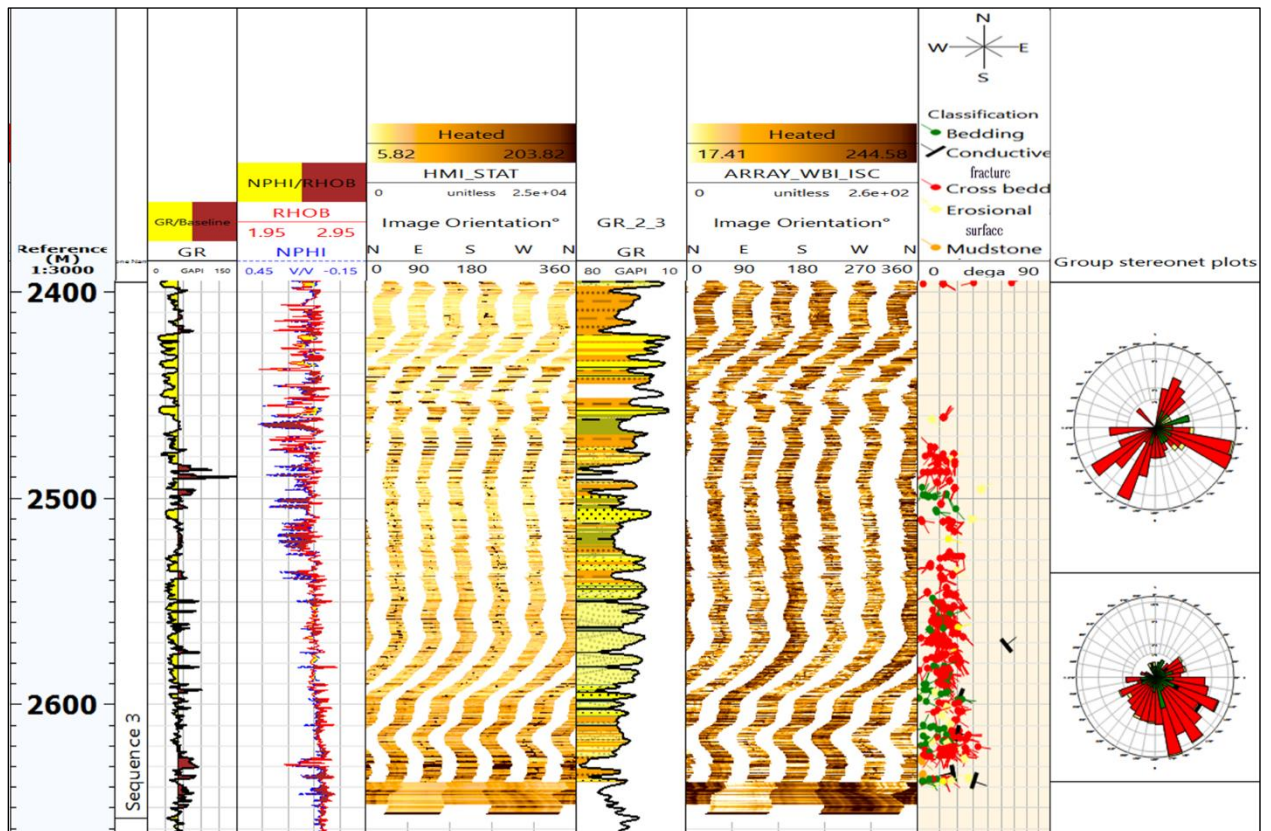


Figure 4-13 Well A wireline logs from sequence 3 with facies interpretation using gamma ray, neutron-density overlay, static and dynamic image logs as well as a dip tadpole plot and a stereonet plot of dips.

4.3.4 Sequence 4: 2400 – 2006m

Sequence 4 can be divided into four higher order sequences based on GR and neutron-density logs (Figure 4-14). The sequence is close 200m thick at the well location. The base of the sequence is defined at the bottom of a bow shaped GR motif which correlates with moderately high positive separation in neutron-density logs and transitions into a marine

environment near the top of the sequence where the GR log shifts to low readings. The sequence is dominated by shale at the well location with only a few sandy intervals.

Subsequence 4-1: 2355 – 2395m

This subsequence is 40 m thick at the well location. The base of the sub-sequence shows a gradual increase in GR log and a moderate to large positive separation in neutron-density log. The BHI log shows a sharp change in color from dark orange to yellow marking the lower boundary which is also an irregular surface possibly due to erosion. The lower part for the most part is made up of structureless mudstone with occasional crude beddings. Internally the mudstone shows dark spots having variable sizes and abundance throughout the lower part.

In the upper part the GR log shows a shallowing up trend reversing the bottom increasing GR trend. The neutron – density log shows a more sandy section as the separation of the two curves narrows up the section. The image log gradually changes from the massive lower part to poorly developed beds in the middle and to fine scale faint to clearly developed beddings in the upper part of the subsequence. In the upper most part of the sub-sequence small scale crossbedded units and a few horizontal beds with orientations showing a scatter between southwest and southeast exist. There also exists a thin coarser grained layer showing low resistivity spots and a possible erosional upper boundary.

Mudlog shows subsequence is dominantly shale and siltstone with minor sandstone. Shale is described as brick reddish brown, light grey to dark greenish grey, fissile to sub fissile and silty in part. Siltstone is off white, non-calcareous and sandstone shows clear,

translucent, off white, very fine to medium grain, rounded to sub rounded, moderately to well sorted, friable, siliceous cement in part and is argillaceous in part.

Interpretation: The subsequence corresponds to the lower part of Gumburo formation and its bow type GR trend suggests a rise in lake level followed by a fall. A structureless mudstone in the lower part of the subsequence, showing color that suggests deposition in an oxidizing environment, is probably related to a shallow lacustrine environment. This unit progresses to a possibly deltaic environment at the top of the subsequence which shows crossbedding structures and increasing abundance of sand.

Subsequence 4-2: 2260 – 2355m

This is another higher order sequence, 90m thick at the well location, defined by a possible bottom scour surface and a top surface with no clear evidence of a sequence boundary in the image log. However the top boundary is defined by increased abundance of sandy units in GR log as well as in neutron-density log.

The subsequence is characterized by deepening upward followed by a shallowing upward trend in GR log with superimposed blocky and spiky high GR readings. The neutron density log shows minimum separation at the bottom and upper boundaries and occasionally throughout the subsequence. The bottom section is made up of horizontal, low to moderate alternating resistivity beds grading up into homogeneous/ massive mudstone with a spotted appearance related to the presence of variable grain sized clasts. The upper half of the subsequence is similarly clay rich with sporadic horizontally interbedded sandstone and towards the top of the subsequence the massive claystone grades into

horizontal, massive to finely bedded yellowish units interbedded with thin orange units. Some of these intervals are under 1m thick and show a coarsening up gradation from brown at the bottom to yellow at the top. Both GR and neutron density show the interval is sandy.

A number of superimposed blocky to spiky high GR intervals exist on the bow type log motif. Higher GR blocky motifs are related to fine beddings, horizontal to low angle dipping, low resistivity contrast, having a general orientation 11/ 304 and internally homogeneous as well as speckled texture in some cases with units having thicknesses between 2 – 8m. These units are sand and silt rich embedded in a clay dominated section as is seen in neutron-density log by a narrow separation of the two curves. Cause of higher GR readings is the probably related to composition of sand and silt units.

Mudlog shows subsequence is dominantly shale and siltstone with minor sandstone. Shale is described as brick reddish brown, light grey to dark greenish grey, soft to firm, sub blocky to blocky, fissile to sub fissile, silty in part. Siltstone is off white, light grey, soft, blocky to sub blocky, non-calcareous and sandstone shows clear, translucent, off white, very fine to medium grain, rounded to sub rounded, moderately to well sorted, friable, siliceous cement in part, argillaceous in part.

Interpretation: The subsequence corresponds to the lower part of Gumburo formation. A dominantly mudstone section that progresses up hole into a sandier horizontally bedded top suggests a deep to shallow lacustrine depositional environment for this subsequence. The finely bedded, horizontal and gently dipping sandy units embedded in massive

mudstone are probably related to subaqueous turbidity currents (James and Walker, 1992).

Subsequence 4-3: 2140 – 2260m

The subsequence is ~120m thick and is similarly defined as underlying subsequence by a box type GR log motif with a number of superimposed high GR blocks. The exception is that frequency of occurrence of these blocky motifs is higher than in the underlying subsequence. The neutron density log shows moderate separation in the bottom half of the subsequence whereas in the upper half the proportion of moderate and minimum separation intervals is almost the equal. The upper and lower most units are also defined by minimum separation.

The bottom part of the subsequence is characterized by yellowish resistivity beds interbedded with orange to brown thin beds leading to low resistivity contrast between units. Beds are in a scale of cms to dms, poor to well developed, horizontal and with some beds showing grading. This unit grades up into a homogeneous mudstone with abundant dark spots in the image log.

The dominantly massive mudstone section is interrupted by multiple interbedded sandstone and mudstone intervals ranging in thickness between 3 and 15m. These intervals shows fine lamination, occasional disturbed bedding, moderate contrast between constituent units, graded bedding and a few crossbedded units. The GR log in these intervals shows a high reading in contrast to neutron-density log which shows a minimum separation.

The top of the subsequence is made up of massive sand beds in a scale of dms to mts interbedded with thin high resistivity beds. There also exists a small scale crossbedded sandy unit with dip direction to the West. A sharp increase in gamma reading marks the upper boundary of the sequence, the image log shows no evidence of scouring change to thinly bedded units.

Cutting samples show the subsequence is dominantly shale with minor sandstone. Shale cuttings are brick reddish brown, grey to dark greenish grey, soft to firm, sub blocky to blocky, fissile to sub fissile. Sandstone cuttings are clear, translucent, off white, fine grain, rounded to sub rounded, moderately to well sorted, friable, siliceous cement in part.

Interpretation: The subsequence corresponds to upper part of Gumburo formation. The depositional environment of this subsequence ranges from shallow to deep lacustrine with the embedded sandstone mudstone interbeds possibly related to subaqueous turbidity currents.

Subsequence 4-4: 2140 – 2006m

The bottom of the subsequence is defined by a sharp increase in GR reading whereas neutron-density log shows minimum separation with only a slight increase in clay content from underlying subsequence. The bottom 40 m thick section shows a stack of blocky GR log motif and an alternating minimum and moderate separation in neutron density log. In BHI log a dominantly structureless mudstone with a middle 10 m thick sandy interval. The contact between these two intervals is gradational with the bottom structureless mudstone grading up into a poorly bedded sandstone which in turn grades into a

horizontally bedded sandstone interbedded with mudstone. Similarly, the upper mudstone grades down into a poorly bedded sandstone.

The upper part show moderate GR reading and minimum to moderate separation in neutron - density log. Poor to clearly developed horizontal bedding, moderate resistivity contrast, beds in cm to dm scale. A sharp increase in GR log followed by a shallowing up trend is observed at the top of the subsequence which is only observed in GR log because images are not available in this part of the log.

The Mudlog shows the subsequence is dominantly shaly with occasional sand prone intervals. In cutting samples, shale is described as brick reddish brown, grey to dark greenish grey, fissile to sub fissile and calcareous in few samples. Sandstone is clear, translucent, off white, fine to medium grain, occasionally coarse grain, rounded to sub rounded, moderately to well sorted and siliceous cement in part. Calcareous cement is observed in part in the bottom part. Trace amounts Limestone and Dolomitic limestone are also found in in the top part of the subsequence.

Interpretation: The subsequence corresponds to the upper part of Gumburo formation and Adigrat formation. A possible environmental interpretation is a shallow lake environment deepening upward as the lake level increases with two shallowing up cycles/ possibly shallow lake to deltaic environment at the top of the sequence. There are possibly two additional subsequences included within subsequence 4 that are related to Adigrat formation. However detailed description is not possible because only a GR log exists in the interval.

Sequence 4 boundaries defined from seismic correlate with shifts in environment identified in wireline logs as discussed above. Moreover indications of the presence of higher order sequences in seismic sections are corroborated by the well data. The seismic facies interpretation of the sequence as dominantly shallow lacustrine is also in agreement with the well log interpretation exhibiting the overall conformity in interpretation between the two datasets.

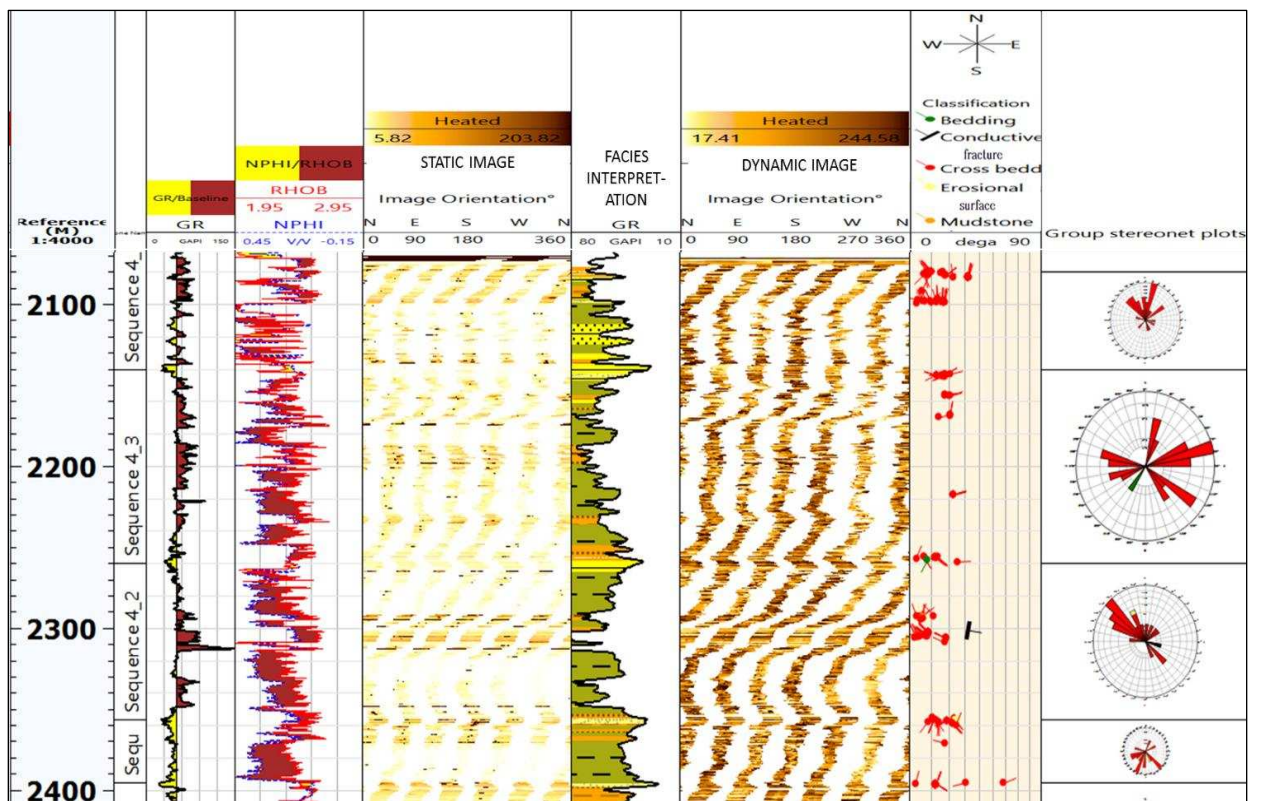


Figure 4-14 Well A wireline logs from sequence 4 with facies interpretation using gamma ray, neutron-density overlay, static and dynamic image logs as well as a dip tadpole plot and a stereonet plot of dips.

Electrofacies	Description	Interpretation
Crossbedded Sandstone (Figure 4-15)	Speckled to homogeneous appearance in BHI log, low to moderate resistivity contrast between beds, beds in cm to dm scale, dip angles commonly $<15^{\circ}$, low to moderate neut-rhob separation, low to medium GR reading	A flow indicator, related to fluvial, distributary channel or sublacustrine current deposits.
Laminated Mudstone (Figure 4-16)	Shows thin beddings, low to moderate resistivity contrast, commonly related with crossbedded sandstone, commonly shows abrupt upper boundaries, moderate to high separation in neu-rhob log, medium to high GR reading	Low energy environment deposits including lacustrine and floodplain deposits
Heterolithic (Figure 4-17)	Poor to clearly developed horizontal bedding, occasional small angle dipping, moderate to strong resistivity contrast, beds in cm to dm scale, minimum to moderate separation in neu-rhob log, moderate GR reading	Interbedded sandstone and mudstone typical of low energy environments such as shallow lacustrine, prodelta and flood plain
Structureless Mudstone (Figure 4-18)	Shows no obvious structure, dark spots observed with variable abundance, moderate to high separation in neu-rhob log, medium to high GR reading	Mudstone formed under low energy conditions such as lacustrine, lack of laminations could be related to very fine laminations or lamination destroyed by bioturbation.
Horizontally bedded Sandstone (Figure 4-19)	Homogeneous sandstone with thin mudstone beds, minimum to moderate resistivity contrast between beds, can grade up into heterolithic facies, shows negative polarity in neu-rhob plot and minimum GR reading	Deposition in a low energy environment where traction currents and suspension alternate, with higher proportion of traction sedimentation.
Structureless Sandstone (Figure 4-20)	Poorly bedded to massive sandstone, variably shows speckled and homogeneous appearance, grain sizes range from fine to coarse grained and includes larger gravel and cobble sized clasts that make up basal lag	Probably related to rapid deposition such as a distributary mouth bar

Table 4-2 Summary table of description and interpretation of electrofacies identified in well.

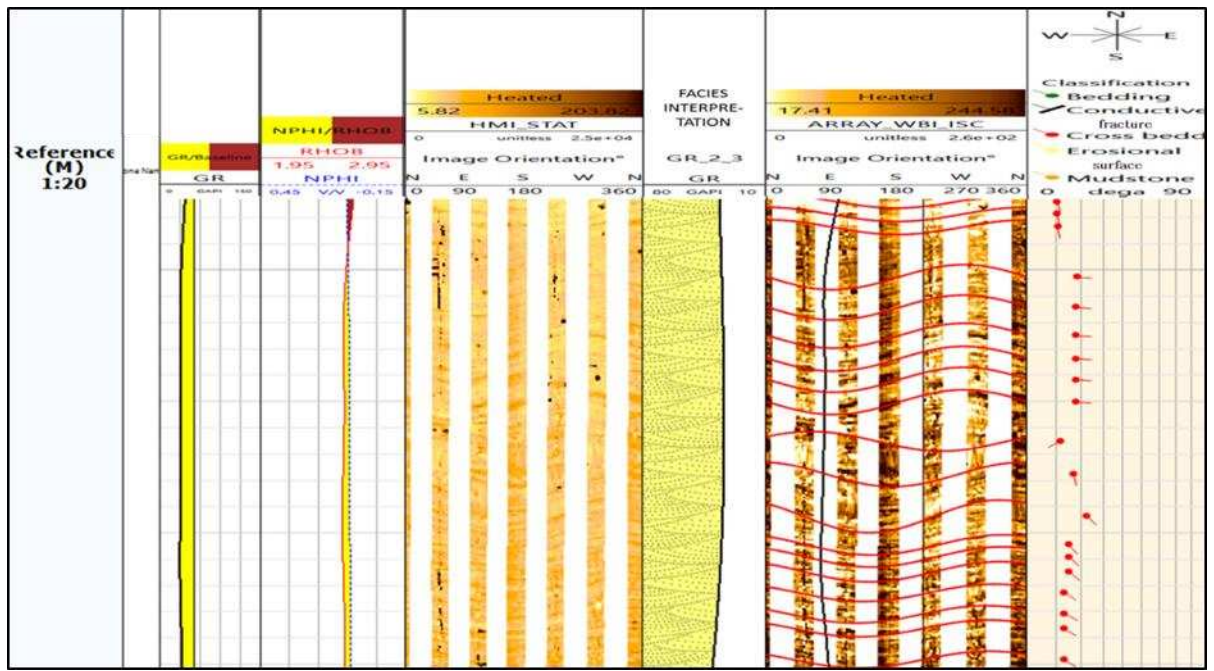


Figure 4-15 Cross bedded sandstone, refer to Table 4-2 and text for detailed description of facies.

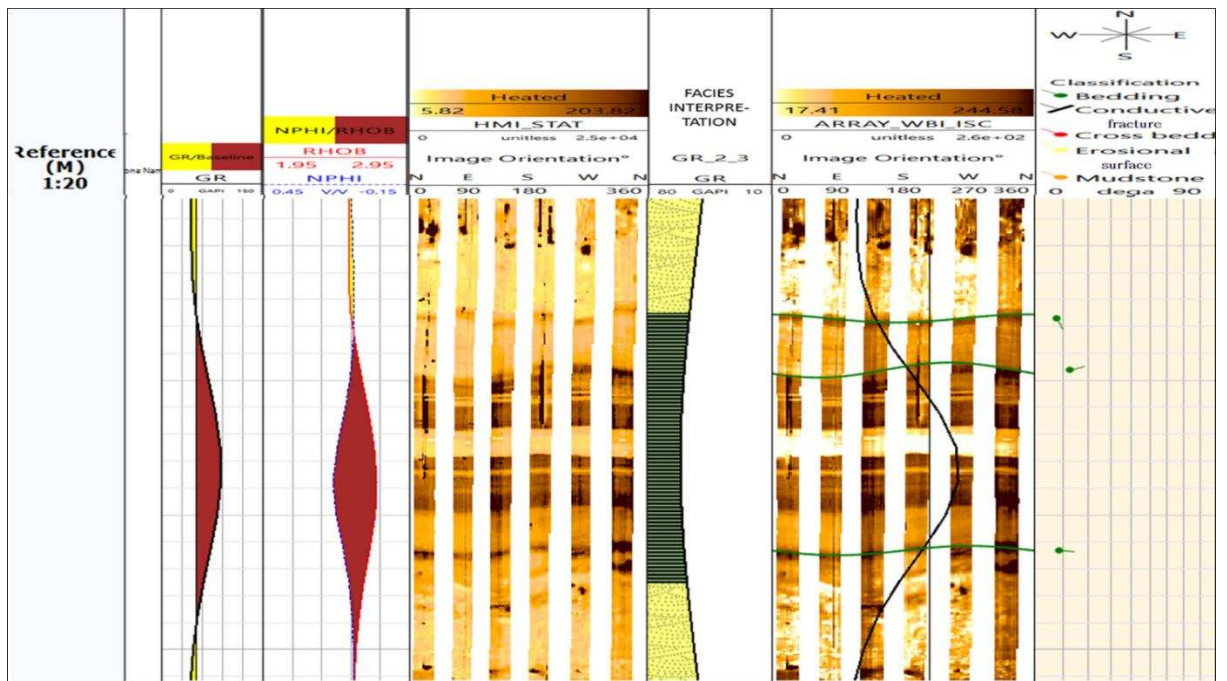


Figure 4-16 Laminated Mudstone, refer to Table 4-2 and text for detailed description of facies.

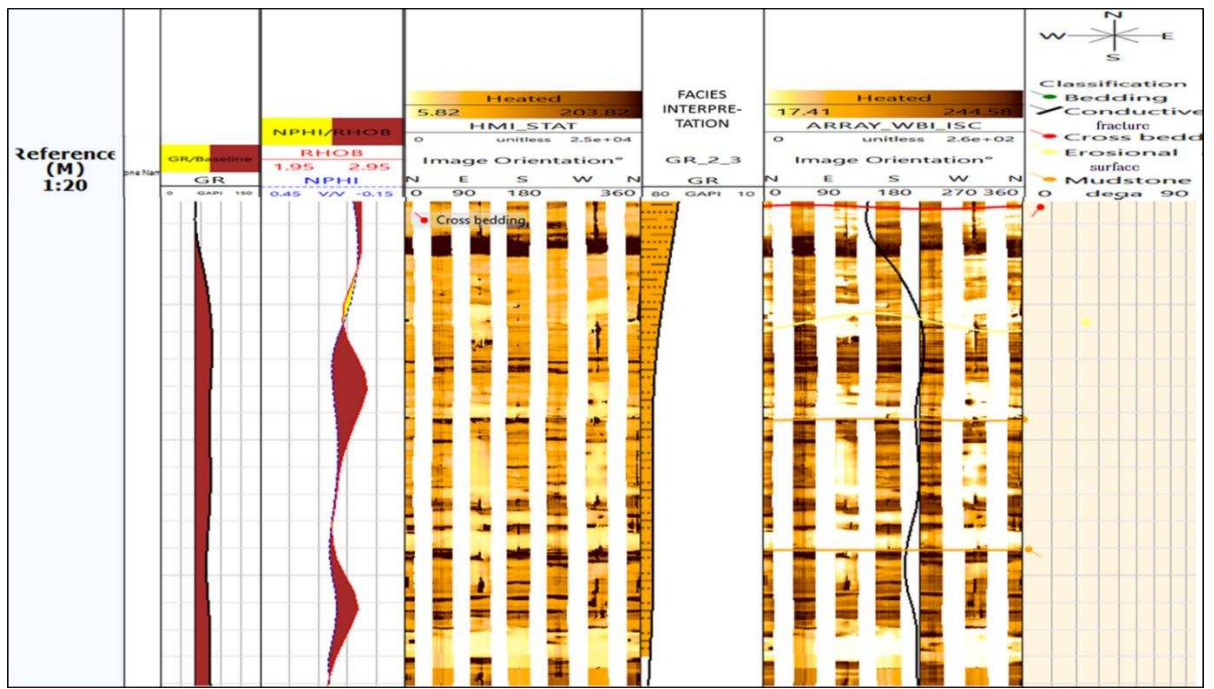


Figure 4-17 Hetrolithic, refer to Table 4-2 and text for detailed description of facies.

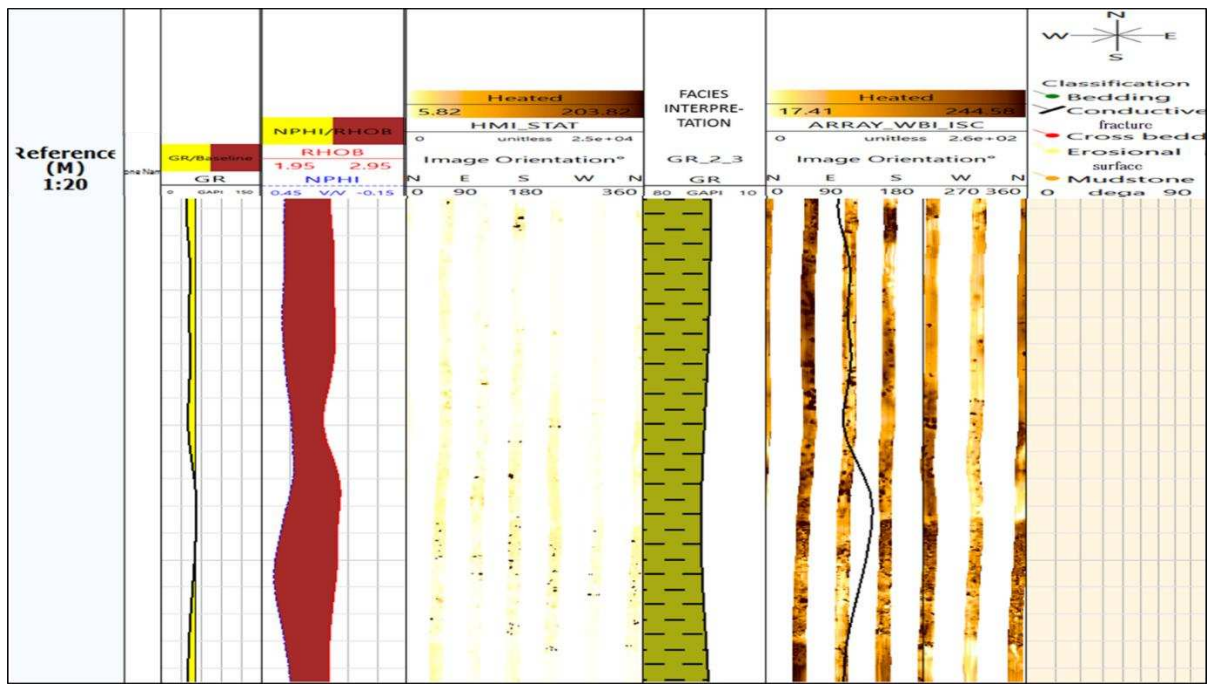


Figure 4-18 Structureless Mudstone, refer to Table 4-2 and text for detailed description of facies.

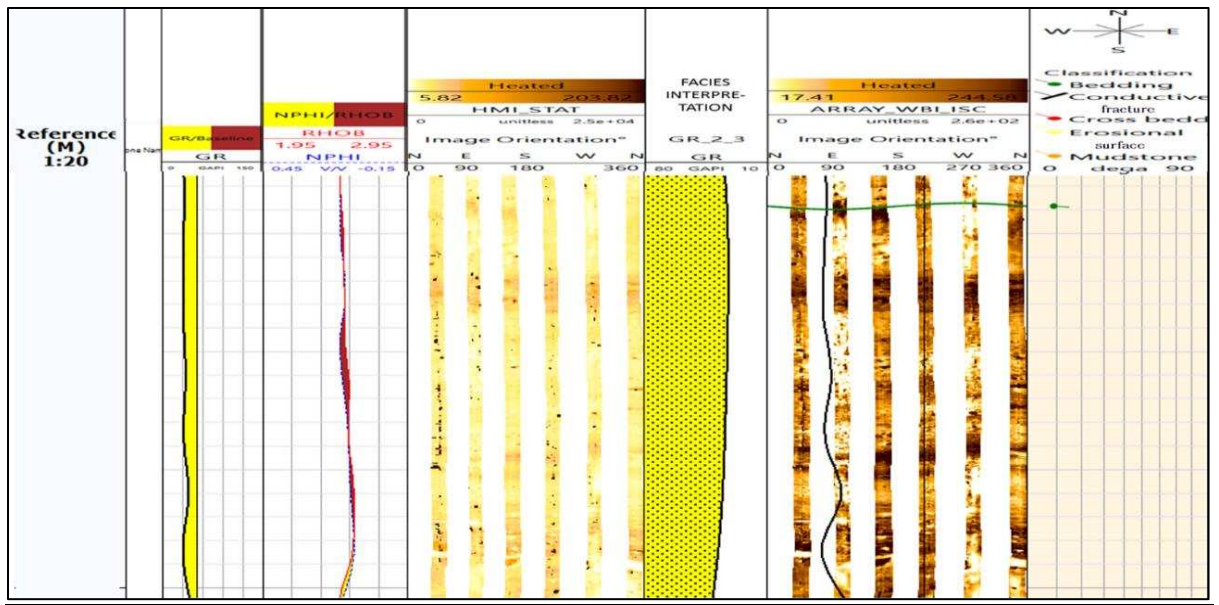


Figure 4-19 Horizontally bedded sandstone, refer to Table 4-2 and text for detailed description of facies.

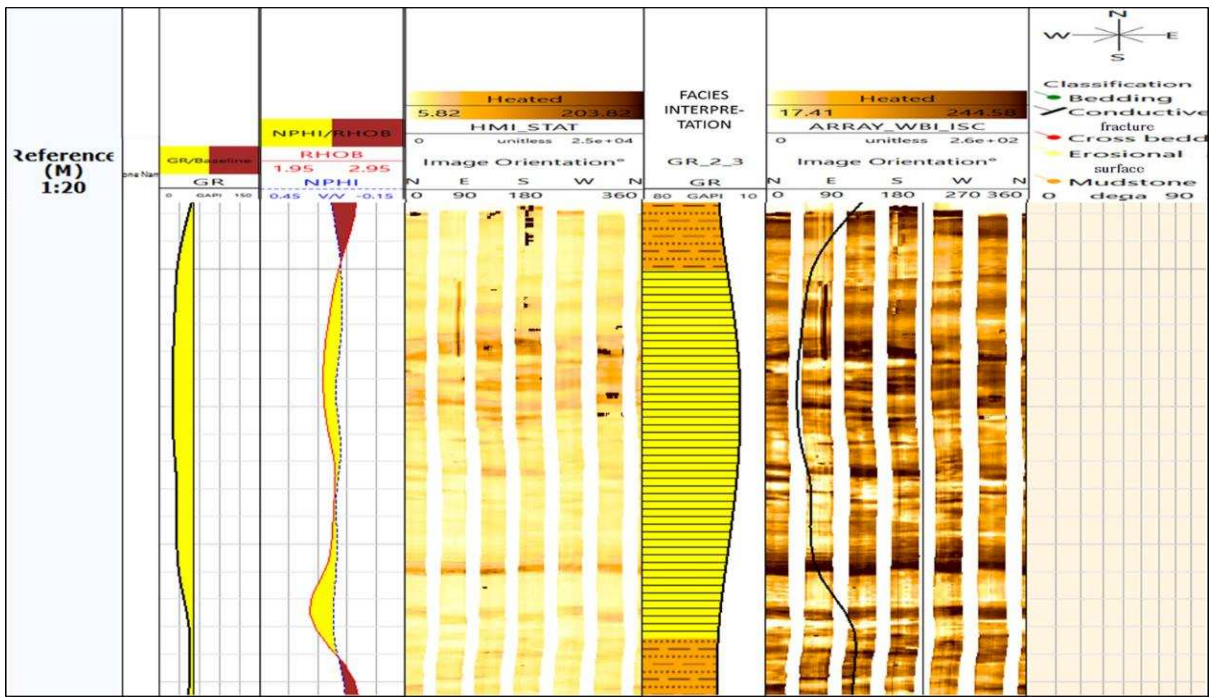


Figure 4-20 Structureless sandstone, refer to Table 4-2 and text for detailed description of facies.

4.4 Discussion

4.4.1 Tectonics controlling sequence development

In this study, four episodes of subsidence have been identified using seismic and well data in the Permian – Triassic Karoo section, in southwestern Ogaden Basin. However, no major bounding faults have been imaged, especially in Bodle Deep area. This led Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia (2005) to define the structural framework during deposition of Karoo sequence as a faulted sag. However, the different episodes of tectonic subsidence noted in seismic sections, for instance steep flanks formed prior to deposition of sequence 2, are not characteristic of intracontinental sag basins, where syn-sedimentary tectonic activity is minimum such as in the Michigan and Congo Basins (Busby and Pérez, 2011; Middleton, 1989; Sloss, 1988). On the other hand, the development of the basin as a proper rift basin is not consistent with models of extensional rift basin development and evolution (for example: Bott, 2006; Lambiase and Bosworth, 1995; Purser and Bosence, 1997).

The seismic sections that run along and across the axis of Bodle Deep (Lines S-B and S-A respectively) and previous mapping of the basement top (Figure 1-1) show that deformation is concentrated in narrow zones bounded by near vertical faults in the early stage of the basin development. This, in addition to the en-echelon type of fault arrangement in Bodle Deep with large throw (e.g. Line S-B, Figure 4-7) and relatively short strike length suggest a pull apart basin development related to left lateral movement on a series of fault segments trending NE-SW (Dooley and McClay, 1997; Mann et al., 1983).

The Shilabo Trough and the area north of Bodle Deep (as indicated by the northern part of Line S-A) are possibly other sub-basins formed by wrench tectonics. This argument is in line with Beicip (1998) who attributed the evolution of the basin to normal faulting and wrench tectonics.

The development of large basins related to strike-slip faults can be achieved through coalescing of pull apart sub-basins thereby increasing in width in proportion to length of the basin (Aydin and Nur, 1982). In the case of Ogaden Basin, it is possible that the basin developed as a number of isolated pull-apart basins with younger phases of subsidence affecting wider area of the basin.

4.4.2 Regional sequence stratigraphic correlation

There is a general correspondence between the Ogaden Basin Karoo sequence and the Permian – Middle Jurassic Karoo sequences in other East African basins. Karoo sequences in Kenya, Tanzania, Mozambique and Madagascar basins are mostly controlled by tectonics and are formed in tensional to transtensional tectonic settings (Hankel, 1994; Wopfner, 2002). The underpinning factor that led to the deposition of Karoo sequence in these basins is related to Gondwanaland fragmentation due to propagation of a deep chasm from the Tethyan margin (Helmut Wopfner, 1994).

The general equivalence between sequences defined in the study area and Karoo sequences in Ruhuhu Basin, Tanzania is one case in point. The earliest sequence that formed in the southern Ogaden Basin/ Bodle Deep corresponding to Calub and bottom of Bokh formations is dated as Early to early Late Permian which is equivalent to Ruhuhu,

Mhukuru and Mbuyura formations in Ruhuhu Basin (Hankel, 1994; Wopfner, 2002). These formations make up the third oldest sequence in the basin that is unconformity bounded similar to Sequence 1. The overlying sequence 2 has its top within the Bohk formation and is probably equivalent to the unconformable contact between Manda Kingori and Usili formations in Ruhuhu basin. Previously a correlation was made between an unconformable contact interpreted between Gumburo and Bohk formations in Ogaden Basin and the unconformable boundary at the top of Manda Kingori formations in the Ruhuhu basin (Hankel, 1994). This boundary was not identified in this study and the closest boundary is offset to a younger age, at the upper boundary of sequence 3 which is defined in the lower part of Gumburo formation.

There is also a common pattern that is observed in East African Karoo basins related to the areal expansion of the basins with age from the oldest basins which formed in localized areas to the later formed structures and resulting sequences that increasingly covered larger areas (Catuneanu et al., 2005). This phenomenon is also observed from the seismic lines analyzed in this study. The bottom sequence (Sequence 1) was formed in an early stage the basin development and only limited structurally controlled thickening is observed. Whereas, the younger sequences have increasingly overstepped onto basement with an expanding tectonic influence.

The depositional environments in the Ruhuhu basin during the Early - Mid Permian to Late Triassic period vary in a relatable way to environments in the study area. The earliest environments ranged from playas, braided rivers and alluvial fans deposited in hot arid to

semi-humid climate. The environments evolved into lacustrine in late Permian as the climate improved to warm humid and during the deposition of the overlying fluvial-deltaic to playa systems, the climate varied between warm semi-arid and hot semi-humid.

4.4.3 Sequences, systems tracts and their implication for hydrocarbon exploration

The discussion in this section focuses mainly on the spatial and temporal distribution of systems tracts and their general characteristics. A detailed analysis of systems tracts and depositional systems is not possible at this stage due to limited data.

There are a number of differences between marine and continental settings in the relative importance of factors that control the deposition and architecture of sequences. One of the differences is in the role of tectonics, where it plays a major role in creating accommodation space in continental basins compared to eustasy in marine settings. However, creation of accommodation space in continental basins may not be the immediate consequence of a tectonic subsidence, as opposed to in marine settings, because there only exists finite lake water which is redistributed as a result of the tectonic subsidence (Strecker et al., 1999). On the other hand, rapid lake level rise is also possible following tectonic subsidence that will result in flooding surfaces at the base of sequences (Martins-Neto and Catuneanu, 2010).

Based on our studies, multiple tectonically induced subsidence have led to lake level changes in the study area exposing the basin margin to subaerial erosion or resulting in

flooding surfaces, and hence defining sequence boundaries (Figure 4-21). The extent of erosion is more pronounced at the top of Sequence 2 compared to sequences 3 and 4 where bottom of flooding surfaces mark sequence boundaries. Subsequent lake level rise resulted in retrogradational or backstepping stacking pattern, typically in sequence 2 (Figure 4-21), which may indicate pulses of regressive events in an overall transgressive trend. In overlying sequence 3, only onlapping reflections are observed in the upper part probably due to a rapid lake level rise.

At the climax of the lake level rise, a maximum flooding surface (MFS) is defined by a downlap surface. The transgressive systems tract (TST) and possibly the lowstand systems tract (LST) are bounded by the MFS above and are made up of dominantly shallow to deep lacustrine sediments with a limited presence of marginal systems. The TST intervals intercepted in well A, at the bottom of sequence 3 and sequence 4 are similarly characterized by a low energy lacustrine deposits.

The investigated sequences may be bottomed by a thin layer of incised valley fills, sublacustrine fans and wedges of the LST. However, the LST was not identified from the current dataset which may be due to seismic data resolution limits or poor development of the systems tract as has been noted in similar tectonic settings (Martins-Neto and Catuneanu, 2010; Strecker et al., 1999). An exception, however, is the lower part of sequence 3 bounded by the upper boundary of sequence 2 from below and a flooding surface above. This interval is possibly related to an early tectonic episode and so can be

attributed to an LST. The distinctively high amplitude of the unit suggests it is most likely related to high energy alluvial to shallow lacustrine deposits.

The subsequent normal regression above the MFS represents the highstand systems tract (HST) and is marked by a delta progradation which laterally grades into shallow to deep lacustrine environments towards the depocenter. This systems tract is better preserved in sequence 3 compared to the underlying sequence where erosional truncation was more intense. The GR, BHI and other logs of Well A are similarly interpreted as shallowing up fluvio-deltaic deposits in the HST interval.

It is difficult to identify systems tracts in sequence 1 using seismic sections because of the limited thickness of the sequence and poor data quality. However, the GR log pattern shows a shallowing up trend from a bottom high reading suggesting similar development as in the overlying sequences. On the other hand, higher order sequences recognized in sequence 4 using well logs are characterized by an alternating HST and TST represented by shallow and deep lacustrine depositional systems respectively at the well location.

Implications for hydrocarbon exploration: the sequence stratigraphic framework allows a better understanding of existing petroleum plays in the study area as well as in defining new play concepts for the Karoo sequence. The petroleum system of the Karoo sequence is proven in the Ogaden Basin from exploration wells (Beicip-Franlab, 1998). The known Karoo plays involve hydrocarbon sourced from Bohk shale and charging reservoirs in Adigrat or Calub formations with sealing from the Transition zone at the top of the sequence and Bohk shales respectively. Targets are mainly structural traps and the

stratigraphic traps usually have lesser importance. The problems related to Karoo plays include poor reservoir quality, lack of effective seals and sizable structures among others (Hunegnaw et al., 1998).

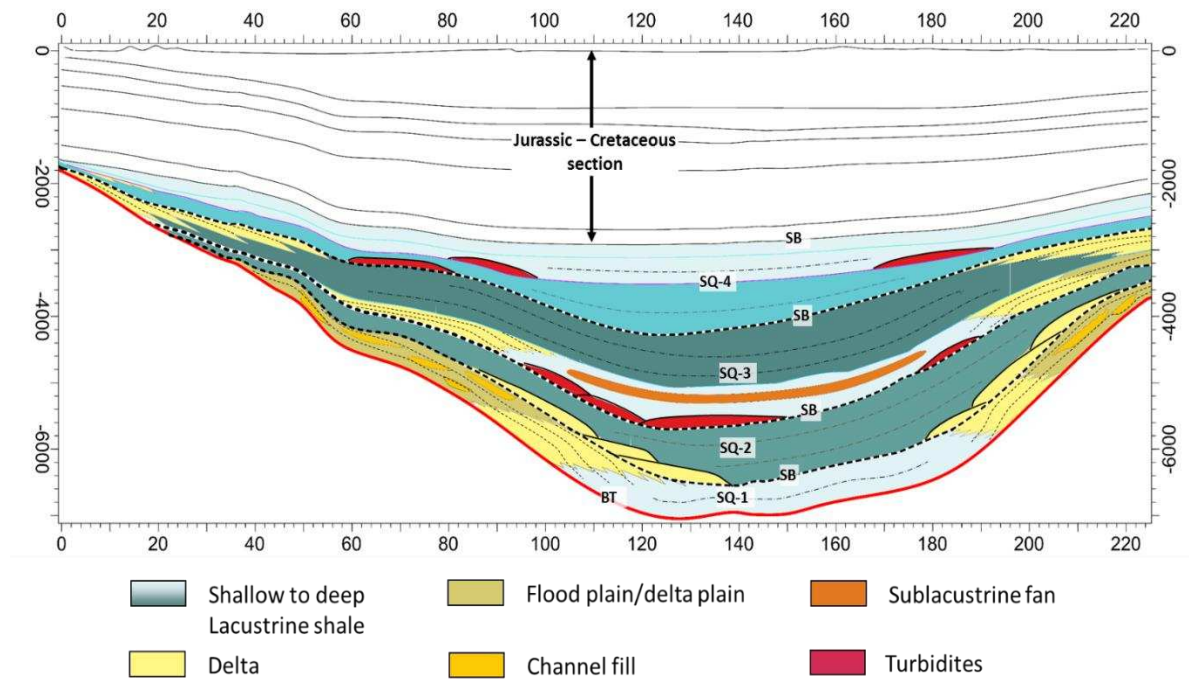


Figure 4-21 A simplified model showing sequence stratigraphic framework of the Karoo Group in southern Ogaden Basin made up of four sequences and their constituent depositional systems. SB - sequence boundaries; BT- basement top; SQ- sequences.

This study indicates that vertically stacked plays are possible in the Karoo section depending on the spatial and temporal arrangement of systems tracts. In general, the TST is formed in a favorable environment for the deposition of good quality source rocks as well as potential seals, especially in the sediment starved deep lacustrine environment (Bohacs et al., 2000; Creaney and Passey, 1993; Posamentier and Allen, 1999). TST also has a reservoir potential in incised valley fills. The HST progradational delta, on the other hand, has a good reservoir potential and lake floor fans which also form in this systems tract are additional reservoir targets. The LST fluvio-deltaic reservoirs charged and sealed

by overlying TST can be excellent targets. We predict that the HST fluvio-deltaic deposits in the Karoo sequence have a good reservoir potential for hydrocarbon sourced from transgressive lacustrine shales of the TST and laterally grading HST prodelta and lacustrine sediments. The seal is provided from the flooding surface of the overlying sequence. Another potential lies in regressive pulses within the TST where the regressive deltas are laterally charged from the TST shales and sealed by a transgressive surface. Still other reservoir potential exists in LST incised valley fluvial, deltaic and sublacustrine fan units during the early stage of tectonic episode in Sequence 3.

4.5 Conclusion

The application of sequence stratigraphy to Karoo sequence in Ogaden Basin has led to the identification of four second order sequences bounded by unconformity surfaces that are traced in the southwestern flank and the Bodle Deep areas. These sequences are recognized in both seismic sections and well logs and the identification of at least four higher order sequences in sequence 4 was possible using well logs. With the acquisition of better quality seismic data, it should be possible to identify these higher order sequences from seismic sections.

The constituent systems tracts of sequences identified in this study are the transgressive and highstand systems tracts. Transgressive systems tracts represent the bulk of the sequences and are separated from the overlying highstand systems tract by a downlap or maximum flooding surface. The highstand systems tract have different degree of preservation due to ensuing erosional events but identification of the system has been

possible in sequences 2 and 3. The dominant depositional systems in these systems tracts are shallow to deep lacustrine, fluviodeltaic and possibly sublacustrine fans and turbidites.

The tectonic regime that led to deposition of Karoo sequences is proposed here to be related to wrench tectonics giving rise to a number of pull apart basins formed in NE-SW to E-W directions. These pull apart basins are narrow regions bounded by near vertical faults of large throw and with steep flanks forming in the larger surroundings of these narrow zones such as the southwestern flank, Shilabo trough and down slope Bur High. Tectonic tilts and uplift in these steep flanks are thought to be the cause of unconformities and climate is an additional factor.

Organic rich lacustrine shales commonly associated with transgressive systems tract and prodelta to lacustrine shales of highstand systems tract are potential source rocks in the Karoo sequences. The generated hydrocarbon from these source rocks are predicted to charge deltaic and fluvial sand reservoirs of the highstand systems tracts as well as potential targets such as turbidites, sublacustrine fans and possibly lowstand systems tracts. The seal for petroleum play is usually provided by transgressive systems tract. This study is one of the first detailed analysis of the Karoo sequence using sequence stratigraphic approach, integrating seismic and well data, to predict an enhanced hydrocarbon potential in the Ogaden Basin.

Chapter 5 : Basin and Petroleum System Modeling of the Karoo Sequence

5.1 Introduction

The Ogaden Basin is underexplored even though significant hydrocarbon discoveries have been made in the basin. From a total of close to 50 wells drilled to date, two gas fields with an estimated total of in excess of 4 TCF reserve and numerous other shows have been discovered. These discoveries are mainly from the Karoo play (Hunegnaw et al., 1998; Wolela, 2007); the main reservoir targets in this play are Adigrat and Calub sandstones with hydrocarbon sourced from the Bokh shales. Both stratigraphic and structural trap play types are present in the basin. The Calub pinch out at basin margins sealed from the top by Bokh shales and the bottom by basement is one example of a stratigraphic play type; reservoirs are charged from downdip and laterally lying Bokh shales. Faulted anticlinal structures at Adigrat and Calub level in the south central part of the basin represent an example of a structural play type.

Basin and petroleum system modeling (BPSM) is a simulation that tracks the evolution of a basin through time as it fills with sediments and fluid which may eventually generate hydrocarbon (Al-Hajeri et al., 2009). At each time step of the simulation, geological processes such as deposition, compaction, heat flow analysis, hydrocarbon generation and so forth are calculated and updated (Hantschel and Kauerauf, 2009). BPSM takes inputs such as stratigraphy, structure, geochemical data and boundary conditions to predict the generation, migration and entrapment of hydrocarbon. BPSM workflow involves a model building and forward modeling steps which are shown in Figure 5-1.

Models can be 1D also called maturity models carried out at a point such as a well or 2D

- modeling hydrocarbon generation, migration and entrapment on a cross section.

Whereas 3D models simulate petroleum systems using surfaces and are required for a full quantitative analysis of hydrocarbon volume. The theory and practice of BPSM can be found in Hantschel and Kauerauf (2009) for further reading.

Previous BPSM and geochemistry studies are few and limited to 1D maturity modeling including Beicip-Franlab (1985), Robertson Research (1986, 1988, 1989) and Alconsult (1996) all of which are compiled in Beicip-Franlab (1998). The geochemical results showed a good generative potential for gas in the three formations- Bokh, Gumburo and Adigrat. Furthermore calibrated maturity models at well locations showed all three source rocks are overmature in the deepest part of the basin. Beicip-Franlab (1998) carried out geochemical analysis and maturity modeling at 15 wells using Bokh as the main source rock and Gumburo and Adigrat intervals as additional potential source rocks in the Karoo sequence. The results showed Bokh shale intervals have low to fair source rock potential and maturation of organic matter is very high (R_o : 1 – 1.3%). The top of Bokh Formation reached the beginning of oil generation in early Jurassic time in Bodle area and that currently the interval is in the gas window. The objective of this chapter is to carry out a basin and petroleum system modeling using a structurally and stratigraphically representative two -dimensional model of the Karoo sequence from chapter four that also incorporates additional data for a better understanding the petroleum system and future exploration success in the Permo-Triassic Karoo play.

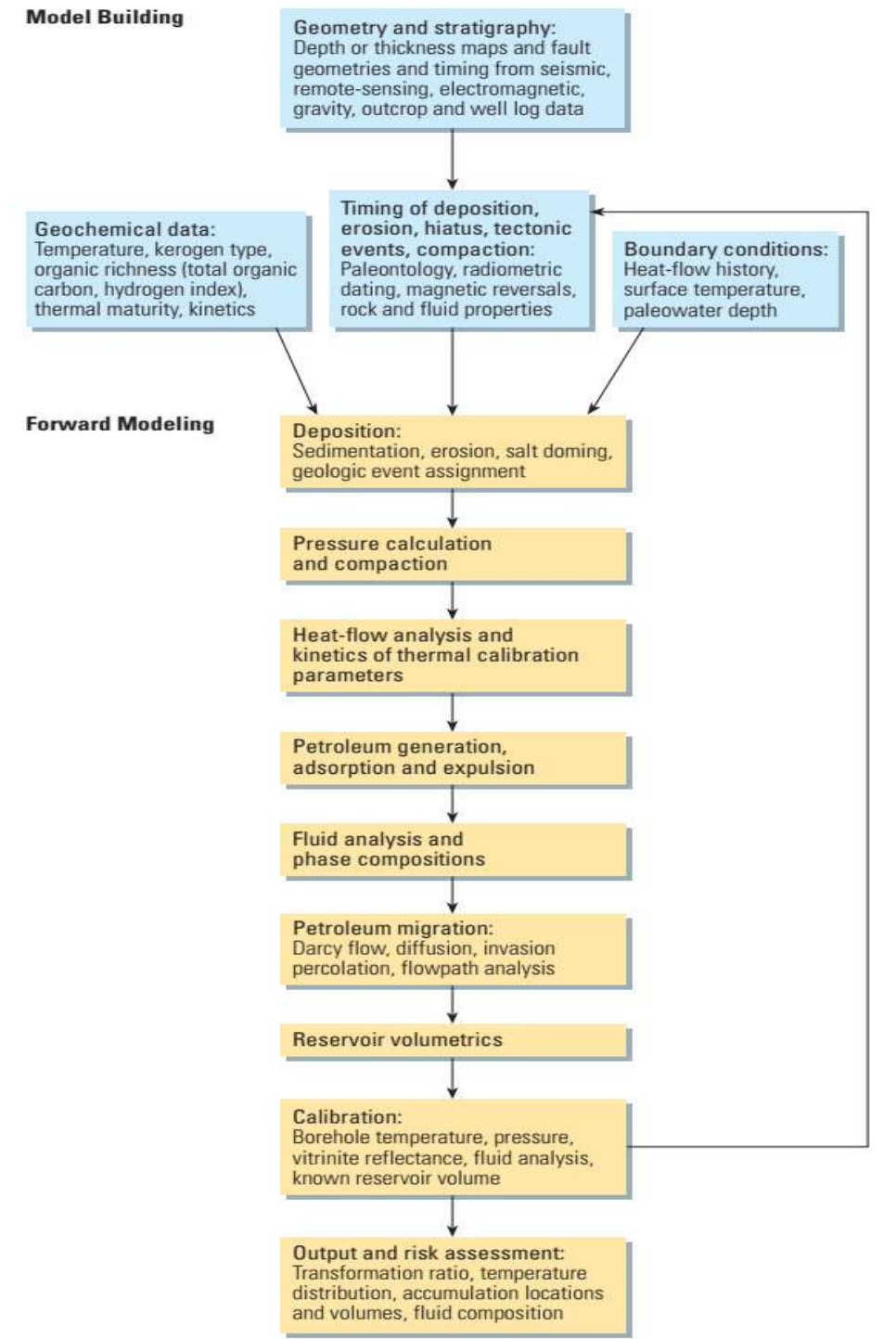


Figure 5-1 A summary diagram of model building and forward modeling stages in basin and petroleum system modeling workflow. After Al-Hajeri et al. (2009).

5.2 Karoo Group sequence stratigraphic model and related petroleum systems

The basis for 2D BPSM in this study is the sequence stratigraphic framework presented for Karoo group in chapter four. From the defined four sequences, the potential for development of organic rich source rocks is higher in sequence 2, sequence 3 and the bottom part of sequence 4. Sequence 2 was formed following a major tectonic subsidence creating a conducive environment for the deposition of deep lacustrine organic rich mudstones of the transgressive systems tract (TST) at the basin center. This system laterally grades into retrograding fluvio-deltaic systems at the basin margins creating a potential stratigraphic trap sealed by an overlying transgressive surface. The sequence corresponds to the lower part of Bokh formation.

The overlying sequence 3 is a result of renewed subsidence leading to the return of lacustrine environment with a potential for deep stratified lakes favorable for source rock development and marginal systems for reservoir development. The bottom of the sequence shows a layer of high amplitude, discontinuous events in seismic lines probably related to lowstand systems such as prograding delta, sublacustrine fans and wedges during an early stage of a tectonic subsidence. This lower part is restricted to the deeper part of the basin. As the rate of subsidence increased and accommodation space was increasing, the LST was replaced by mudstones of the TST in the deep lacustrine as well as prodelta environments. The sequence corresponds to the upper Bokh and Lower Gumburo formation. Upper Bokh is identified as the main source rock for the proven Karoo play in the basin. The existence of deep stratified lake during deposition of Bokh formation is supported by the work of Worku and Astin (1992).

Sequence 4 is made up of four higher order sequences where the bottom sequence was formed following a tectonic subsidence creating an accommodation space for a shallow to deep lacustrine environment. A better development of source rocks can be expected in the bottom part of the sequence from TST lacustrine shales. In the subsequent filling up of the basin the influence climate is thought to be the cause of the higher order sequences made up of alluvial- fluvial to shallow lacustrine sequences. The presence of potential source rocks is relatively low in these higher order sequences. The sequence corresponds to the upper part of Gumburo and Adigrat formation. On the other hand, the bottom sequence (sequence 1) is formed in the early stage of the basin development with little evidence for the development of a deep lacustrine environment. It corresponds to the Calub formation and bottom part of Bokh formation. It is not known to contain viable source rock intervals.

5.3 Basin and petroleum system modeling

BPSM was carried out in both 1D and 2D models using Petromod V. 15 software. 1D models were constructed on five selected wells spread out particularly over the Bodle Deep (Figure 5-2). A representative two dimensional geological cross-section was constructed using 2D seismic and well data and depth converted using T-D relations from a seismic - well tie. Petromod workflow was followed in model building and simulation which requires different inputs such as formation tops and lithology in addition to the inputs discussed in detail below. Geochemical data were After Beicip-Franlab (1998) who complied their laboratory results with all previous data to produce a complete set of all

existing data at the time. Calibration of models was done using Vitrinite reflectance (Ro) and temperature data at well locations to produce the final model results.

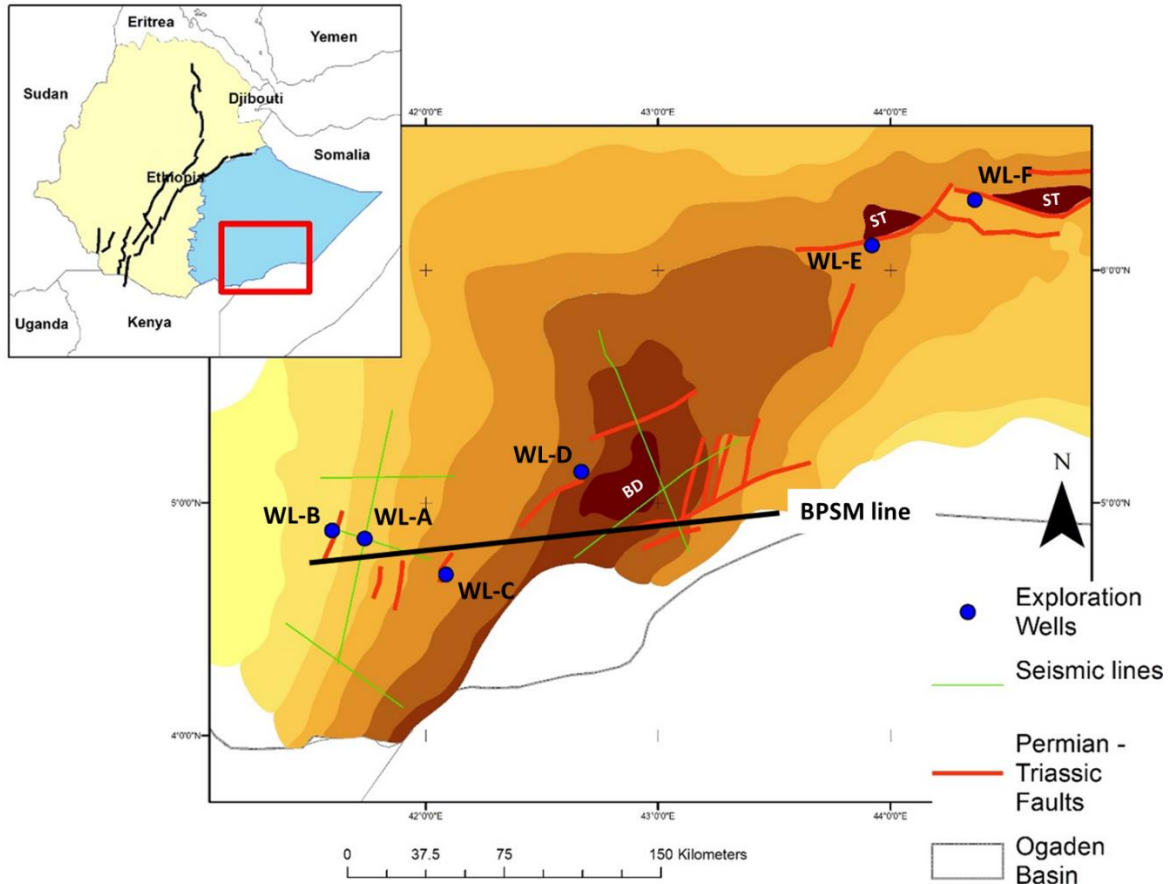


Figure 5-2 Basement top map of the Ogaden Basin with dark brown color representing the deep part and yellow color representing shallow part of the basin, modified after Petronas Carigali Sdn. Bhd. and Ministry of Mines of Ethiopia, 2005. .BD- Bodle Deep; ST- Shilabo Trough. Also showing BPSM profile line and well locations referred in text.

5.3.1 Source rock properties

There is limited geochemical data for the whole Karoo section in the basin. The data, however, shows there is a source potential in all formations with the exception of the bottom Calub Formation where almost no data is available. The wells in general are located in the margins and/or basement highs mostly sampling marginal systems and thus underestimating the generating potential of the Karoo group source rocks. In the Bodle

Deep area, there are only a few wells drilled and from the wells that were drilled only two (WL-A and WL-B) were drilled to top of basement. The other two (WL-C and WL-D) did not penetrate below the Gumburo formation where there exists a potential for good quality source rock development.

Adigrat source rock intervals: TOC values as high as 6% are measured in WL-C well for Adigrat and a number of intervals show values between 1 and 2 in WL-C and WL-E wells whereas WL-B, WL-F and WL-E contain intervals with TOC ranges between 0.5 and 1%. The average from samples above 0.5% is 1.1%. The data points of Adigrat plot mostly above the type 3 median line and below the type 2 line suggesting a mixed type 2(3) kerogen (Peters et al., 2005; Welte et al., 2012) (Figure 5-3). An HI value of 300 representing a type 2(3) is used in modeling.

Gumburo source intervals: a value of 3.71% is measured in Calub 1 well. Gumburo fm intervals in WL-E and Calub 1and2 show values > 1% and a number of intervals in WL-B, Calub 1 and Faf-1 show TOC values between 0.5 and 1. The average of samples with TOC >0.5% is 1.02. Gumburo is consistently shown to lie in type 3 trend and below indicating an inert kerogen. However the samples may not represent the depositional environment in Bodle deep as the wells are more concentrated in the marginal parts of the basin where they are interpreted as fluvial. HI values > 150 are only few and hence may not be representative of the lacustrine environments formed in the Bodle Deep. In the modeling, we used values 2 for TOC, and 350 for HI with a type 2/3 kerogen.

Bokh source intervals: samples from this formation are limited. Samples are mostly from Calub and Magan 2 wells which contain intervals >0.5 with the highest value of 1.04%. The average of samples >0.5 is 0.81. Kerogen type 2 and 3 are suggested to be present from the plots. HI/OI plot shows a type 3 kerogen dominates and Tmax/ HI plot suggests type 2 to type 2-3 is also present (Figure 5-3); Beicip-Franlab (1998) made similar suggestions. A TOC value 2 and an HI of 400 is used in modeling to represent better quality source rocks than the average 180 from samples considering a better development of source rocks in the Bodle Deep.

5.3.2 Boundary Conditions

Three boundary conditions are required before running simulation in Petromod which include heat flow (HF), paleowater depth (PWD) and sediment water interface temperature (SWIT). The starting point for estimation of heat flow history is the tectonic history of the basin. In the Ogaden Basin the Permian Karoo rifting and the recent East African rifting episodes are taken as the major controls of paleoheat flow history of the basin.

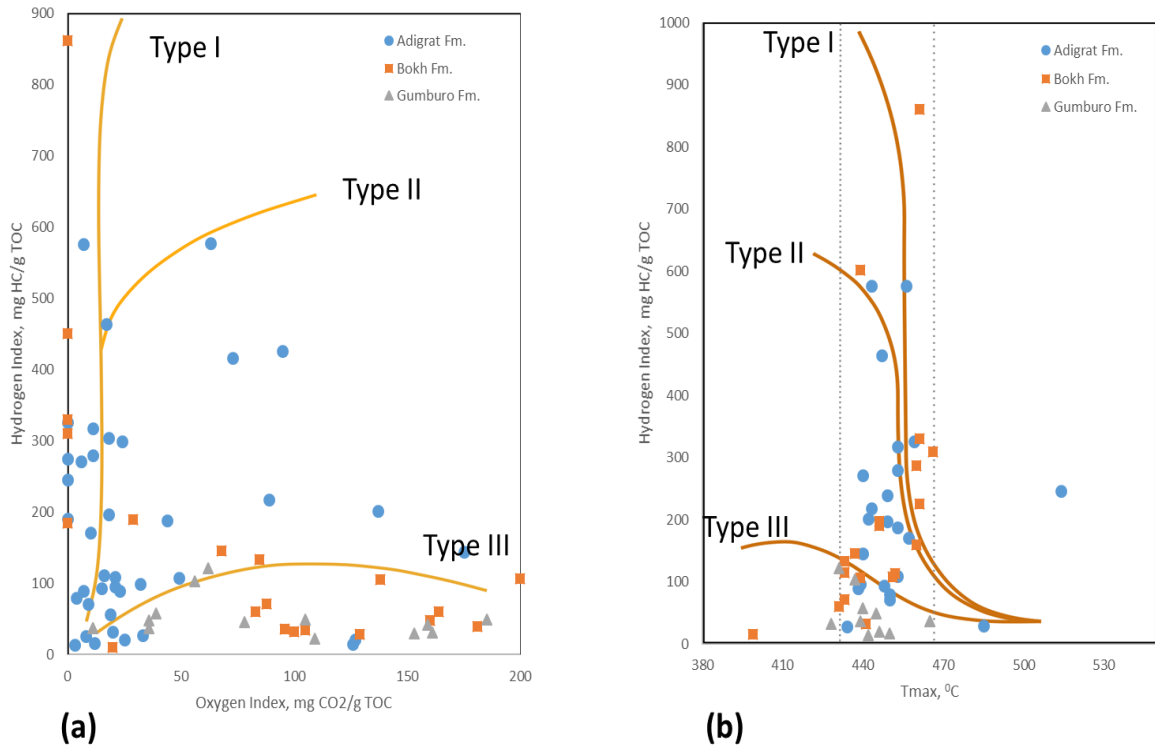


Figure 5-3 (a) Hydrogen index (HI) versus oxygen index (OI) showing kerogen types of Adigrat, Gumburo and Bokh formation source rocks. (b) Plot of hydrogen index versus T_{max} also showing kerogen types and maturity levels. T_{max} values between 430 and 470 deg C indicate oil window.

The paleoheat flow trends reflecting these two rifting episodes of elevated heat flow values were constructed using the lithospheric stretching model after (McKenzie, 1978) in Petromod. A pre-rift granitic crust and peridotite mantle with thicknesses of 30km and 95km were used respectively. In addition, different stretching factors were used for crust (Beta=3) and mantle (Beta=4) and a rift episode duration of around 60Ma followed by a period of thermal subsidence. Trends were later calibrated using bottom hole temperature (BHT) and vitrinite reflectance (R_o) data through trial and error before hydrocarbon generation modeling step.

PWDs were estimated from depositional environment interpretation of lithofacies (for example Jacobus P Le Roux et al., 2016; Jacobus Philippus Le Roux et al., 2005). Water depths were assigned for each lithofacies ranging from 0m for foreshore and fluvial environments to 170m for outer shelf environment. In addition, clinoform heights from seismic sections were used to estimate water depth of lacustrine deposits in the Karoo section. SWIT was calculated from the built in tool in Petromod based on Wygrala (1989). It uses a graph of global mean surface temperature estimate drawn to predict temperature for any location throughout the Phanerozoic. Water bottom temperatures are then calculated as a function of water depth where surface temperature equals SWIT for a 0m water depth, a 3 deg C decrease for a water depth of 200m, and an Arctic water temperature for a depth greater than 600 (Hantschel and Kauerauf, 2009). Intermediate water depth based corrections are interpolated linearly between these values.

5.4 BPSM results and discussion

5.4.1 1D Modeling

Before the 2D modeling exercise 1D models were constructed using 5 wells located in both margins and axes of the Bodle Deep and the Shilabo trough (Figure 5-2). This step was taken to analyze individual wells in detail in terms of burial history and heat flow trends which will be used in calibration of the 2D model. Formation tops, ages and lithologies were compiled from well reports and where available temperature data was also After the reports. Formations were divided into members when a reasonably thick unit with uniform lithology/ facies was encountered for a better characterization of

thermal conductivities. Lithologies were also mixed using harmonic averages to represent layered units within formations or members in the calculation of bulk vertical thermal conductivities (Hantschel and Kauerauf, 2009). Bulk thermal conductivities were calibrated at two wells against BHT data (Figure 5-4 d and e) by changing the proportion and properties of lithologies and the present day heat flow value is estimated to be 47 mW/m².

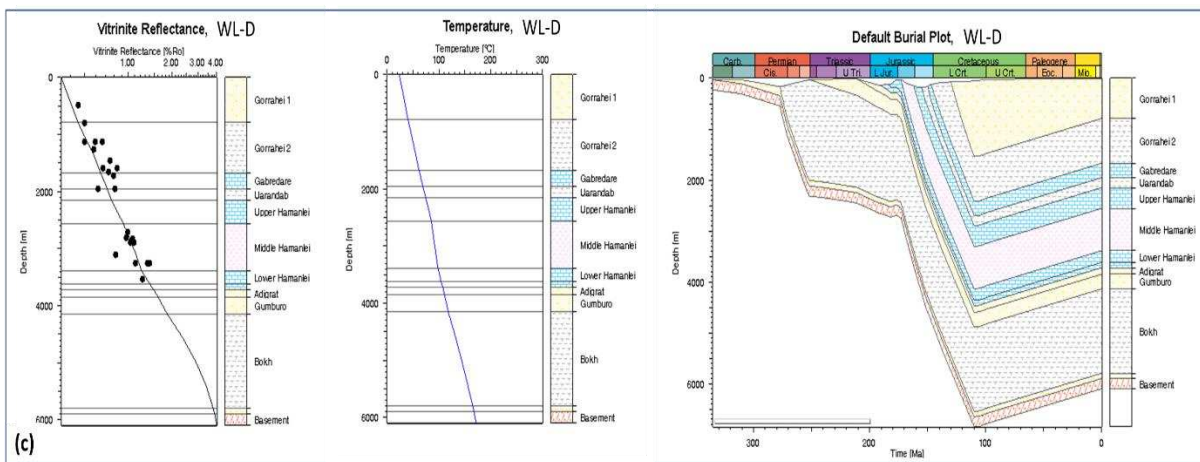
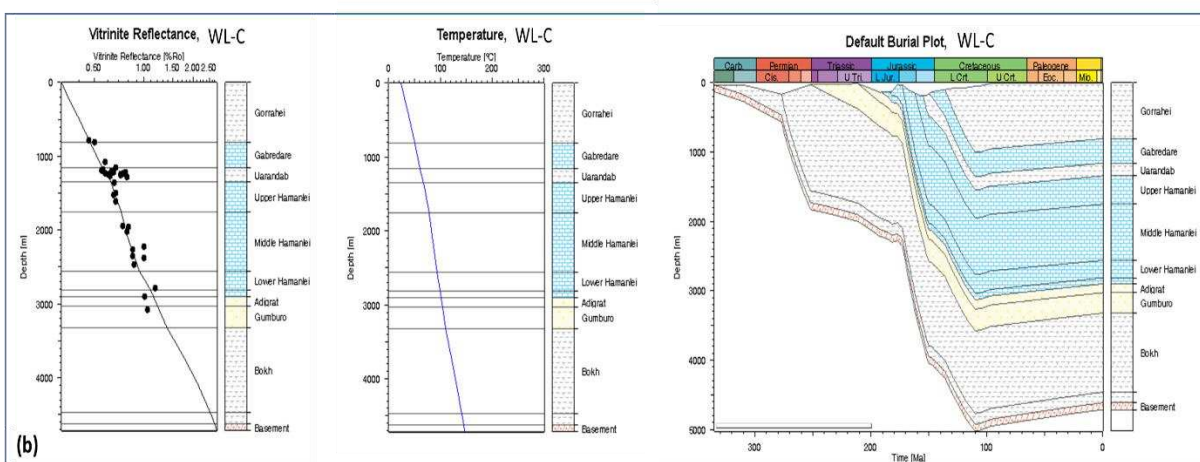
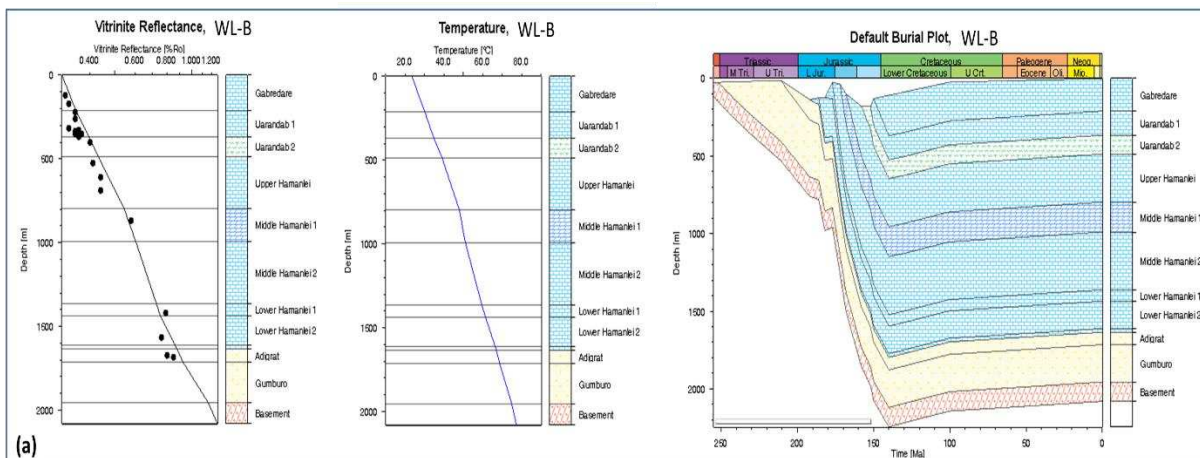
Burial History and Heat Flow

The burial history plots from the model wells show two main events of significant subsidence throughout the history of the basin (Figure 5-4 a - e). The first subsidence event related to Permian age Karoo rifting shows over 1000m of subsidence in WL-C and WL-D wells whereas in WL-B well, located on a basement high at western basin margin, the event does not exist. At the WL-E and WL-F well locations the event does exist but the subsidence is less pronounced. The other subsidence pattern common to all wells and with comparable magnitude is the early –Mid Jurassic episode. This event is related to deposition of thick marine sequence following a large scale down wrapping of the basin. The similarity of the subsidence curves during this time in all wells, spread out in the southern Ogaden Basin, is further evidence for the passive margin that existed during this time.

Following the deposition of marine successions which continued to early Cretaceous, a major uplift and erosion is took place starting from the middle Cretaceous. The magnitude of this event is suggested by calibration with vitrinite reflectance data, where

different thicknesses of erosion were needed for a plausible fit between calculated and observed Ro values. The maximum eroded thickness of 700m is in WL-D well, close to the center of the Bodle deep and the amount of eroded thicknesses decrease in the landward direction to 50m in WL-B well.

Heat flow trends calibrated by Ro data were key output from 1D modeling to constrain the subsequent 2D model. Heat flow values range between 85 – 110mW/m² in the Permian tectonic episode and gradually decline to 60 – 70mW/m² until the Paleogene-Neogene. A second event of elevated heat flow, attributed to the East African Rift system (Woldegabriel et al., 1990; Wolfenden et al., 2004), has a range between 65 – 80mW/m² and gradually decreases to present day 47mW/m². The basin can be classified as hotter than normal or hyperthermal which in the case of Ogaden Basin can be attributed to rifting and/or deep strike-slip movement involving lithosphere (Allen and Allen, 2005). The time gap between the two events lies in post rift or passive margin heat flow regime. Comparison of the calibrated trends from the five wells shows a minimum/ small spread between respective heatflow values for a given age (Figure 5-5). An exception in this regard is WL-B well which shows an offset to higher values relative to the rest of the wells. This is probably due to a relatively shallow basement at the location of the well.



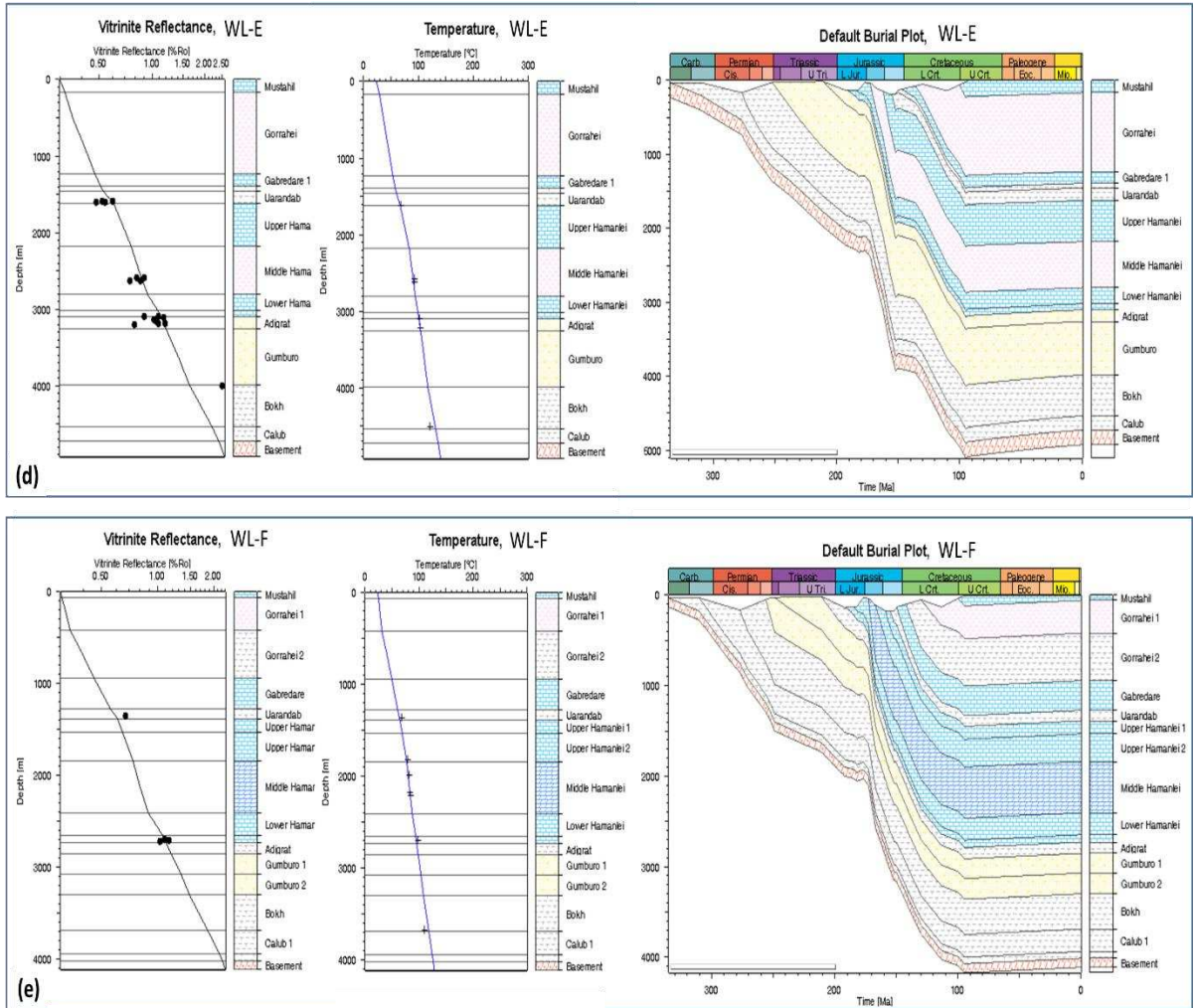


Figure 5-4 Vitrinite reflectance, present day temperature and burial history plots shown from left to right in each row for five wells modeled in the study area. Lines represent models, dark dots represent measured vitrinite reflectance values and black plus signs represent measured temperature. (a) WL-B well; (b) WL-C well; (c) WL-D well; (d) WL-E well; and (e) WL-F well.

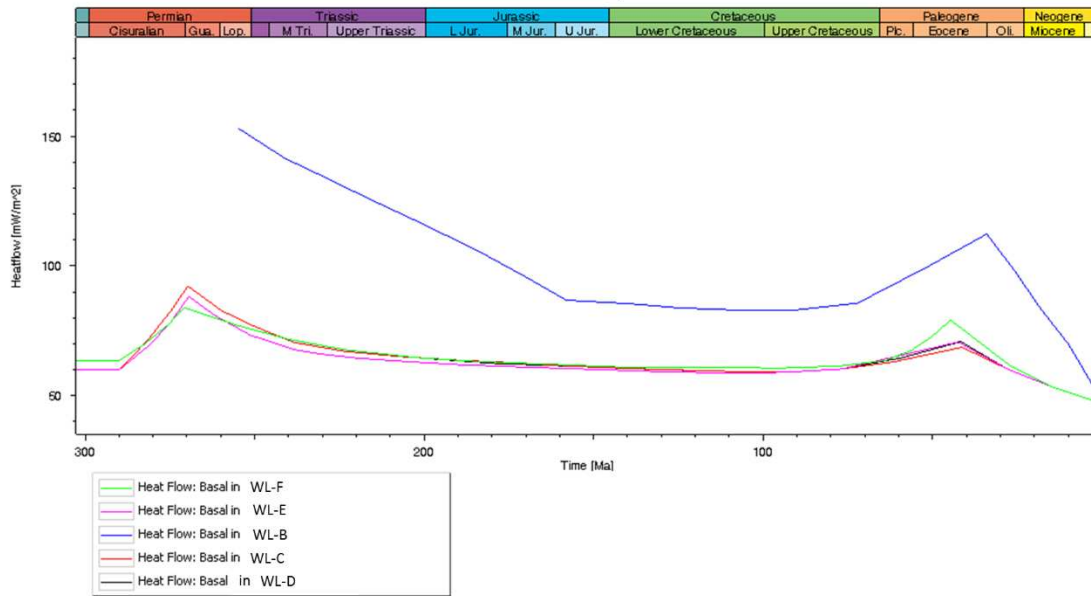


Figure 5-5 Calibrated heat flow trends used in 1-D models for all wells. Trends show very small scatter at any geological time with the exception of WL-B, shown in blue, with a vertical offset from the other wells.

5.4.2 2D Modeling

The model line is located in the southwestern part of Ogaden Basin over the Bodle Deep (Figure 5-2). The line is oriented roughly E-W and has a total length of 224 kms. It traverses the western flank, the basin center reaching depths of over 7000m and the rising part of Bur Acaba high, a major structural high to the south of Ogaden Basin. There are four nearby exploration wells and three were studied in the previous section.

The 2D model is constructed based on sequence stratigraphic interpretation of seismic sections and a simplified version was used in modeling (Figure 5-6). The model tested potential source rocks found in sequences two, three and the bottom part of sequence four. Lithologies were assigned based on sequence facies interpretations and also taking into account thermal conductivity calibration of lithologies in the previous section.

Similarly geochemical properties were assigned based on well data and seismic facies interpretation. The main reservoir targets tested in this study are stratigraphic traps including high stand deltas, sublacustrine fans and turbidites and fluvial channel sands in a depth range of 3000 and 6000m. Boundary conditions were based on 1D model results where heat flow, PWD and SWIT trends at well locations were projected into the cross section and respective maps were generated by interpolating between trends for the whole cross section. The erosional event included in the model is the middle Cretaceous unconformity as it represents a major event with significant thickness removal. Eroded thickness was suggested from calibration with Ro data at well locations and a smooth surface was generated that increased in thickness basin ward from 50m at the flank to 700m at the basin center. The lithology of the eroded section was taken to be similar to Gorrahei formation. A Burnham kinetic model (Burnham, 1989) for a type 2 kerogen type was chosen based on hydrogen index versus oxygen index plot which characterized Karoo source rock intervals as type 2 (3).

There are four different methods of modeling hydrocarbon migration from source to its destination (Hantschel and Kauerauf, 2009). In this study a hybrid method which combines Darcy and flowpath fluid flow models is used. The Darcy model is used in low permeability source rocks while flowpath is used in high permeability carrier and reservoir rocks.

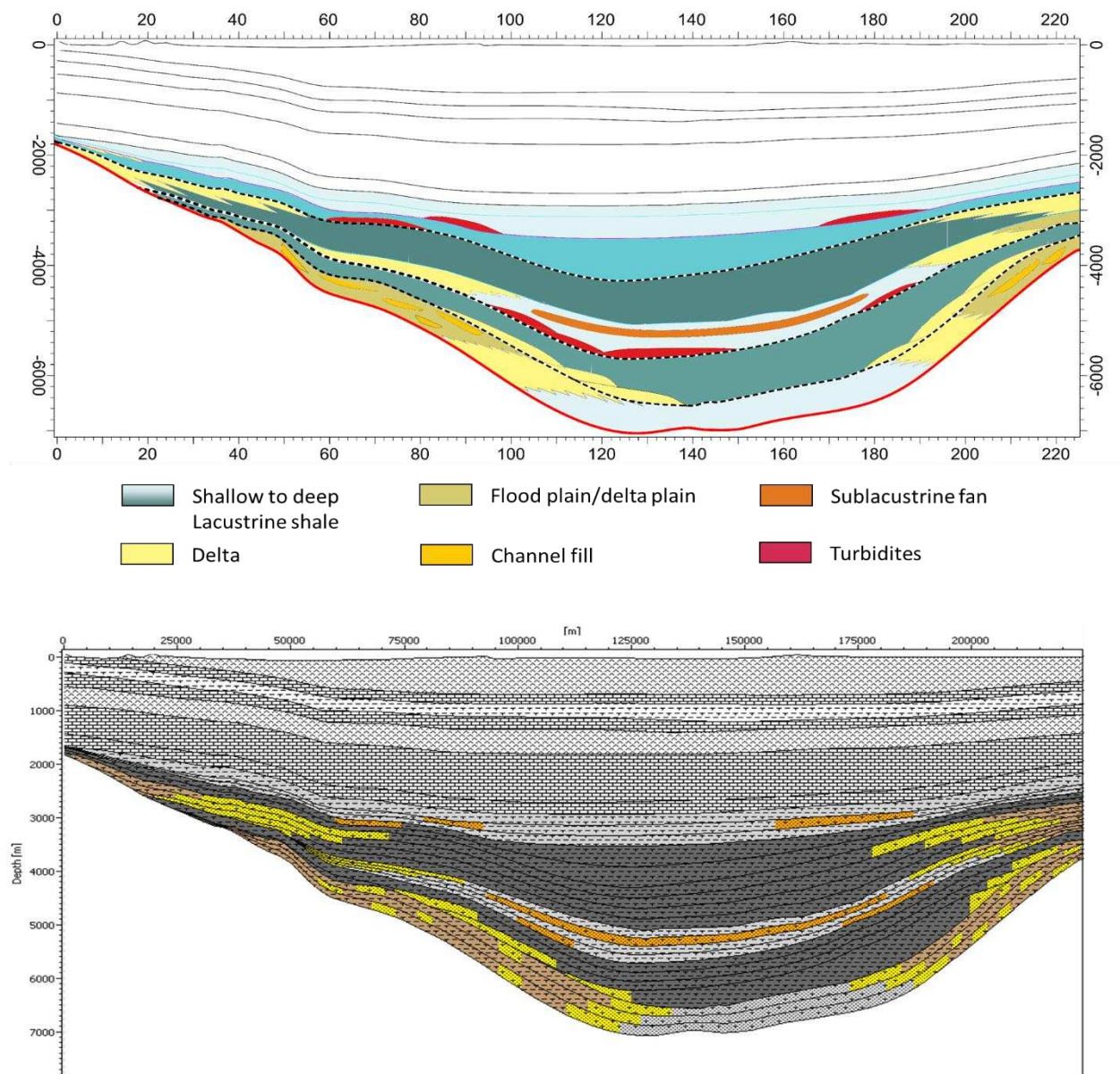


Figure 5-6 2D Geological cross section showing defined sequences and depositional systems, sequence boundaries are shown by dark dotted lines (above) and modeled cross section from Petromod (below).

Thermal history, maturity and hydrocarbon generation

Thermal history – modeled thermal history of Karoo source rocks is shown in Figure 5-7.

Source rocks of sequence two at the basin center have gone through a temperature change from c.a. 15 deg. C at surface to a 100 deg C in a time of less than 10Ma under the

influence of high heat flow and rapid burial. The continued burial progressively exposed sequence two to higher temperature with the maximum 252 deg C reached in lower Cretaceous. The middle Cretaceous inversion event led to uplift and erosion lowering temperature from the upper Cretaceous to present day temperature which is around 190 deg C. The top of source rocks in sequence three and bottom of sequence four reached maximum temperatures 200 and 170 deg C respectively during the lower cretaceous and at present it is 150 and 120 deg C. In the flanks the maximum temperature in lower Cretaceous is in the range of 190 deg C at sequence two and is 145 at the bottom of sequence four. At present day temperatures are between 130 – 100 from bottom to top of the sequences. Reservoir rocks being found interbedded with source rocks exist in similar temperature range.

Maturity history - vitrinite reflectance (%Ro) calculated using Sweeney and Burnham (1990) algorithm was used as a thermal maturity indicator for potential source rocks in sequence two, upper part of sequence three and bottom of sequence four. The model (Figure 5-8) shows that at present day all source rocks have exceeded 1.3% Ro which corresponds to wet gas window except in the flanks. The highest maturity is attained at the basin center where basinal source rocks in sequence two is overmature (>4.0% Ro). The maturity history of sequence two, a relatively thick sequence at the basin center, shows the bottom of the sequence entered early oil window (0.55 – 0.7% Ro) while deposition of the overlying lower part of sequence 3 was underway (280 Ma). Except for thin units in the marginal areas, large part of the sequence has already entered the main oil window in 270Ma. At this time the bottom the sequence has entered a wet gas window

(1.3 – 2.0% Ro). The whole sequence progressively entered the wet gas and dry gas windows in 162Ma which corresponds to time of deposition of Upper Hamanlei. At this time the flank units were in the main oil window. From 155Ma onwards a significant thickness of the sequence at the basin center progressively entered the overmature window with the highest temperature recorded before erosion of the middle Cretaceous.

A large portion of Sequence three with potential for source rocks mainly in the upper part of the sequence was in the oil window around 245Ma. At 155Ma the sequence was buried further deep to wet and dry gas window stage. At the present lower half of the sequence is in dry gas window with the remaining less than half portion is in wet gas window.

Sequence 4 bottom potential source rock entered an early oil window before the end of Karoo sequence deposition (230Ma). The interval remained in the oil window until the end of Upper Hamanlei deposition (approx. 162Ma) and with the exception of thin units in the margin the main pod remains in the wet to dry gas window at the present.

HC generation - at present all potential source rocks of sequences two, three and four have reached a complete kerogen transformation. At the basin center (Fig. 10b), generation at the top of sequence two started (0.01% TR) in the lower Permian (275Ma) and reached a peak transformation (50% TR) at a temperature of 125 deg C. This took place in a relatively short time in the upper Permian (268Ma) after deposition to a depth of approx. 1800m. A 95% TR was attained at a temperature of 145 degC, at a depth of 2130m, in the upper Permian (265Ma) much earlier than maximum burial depth and temperature were reached.

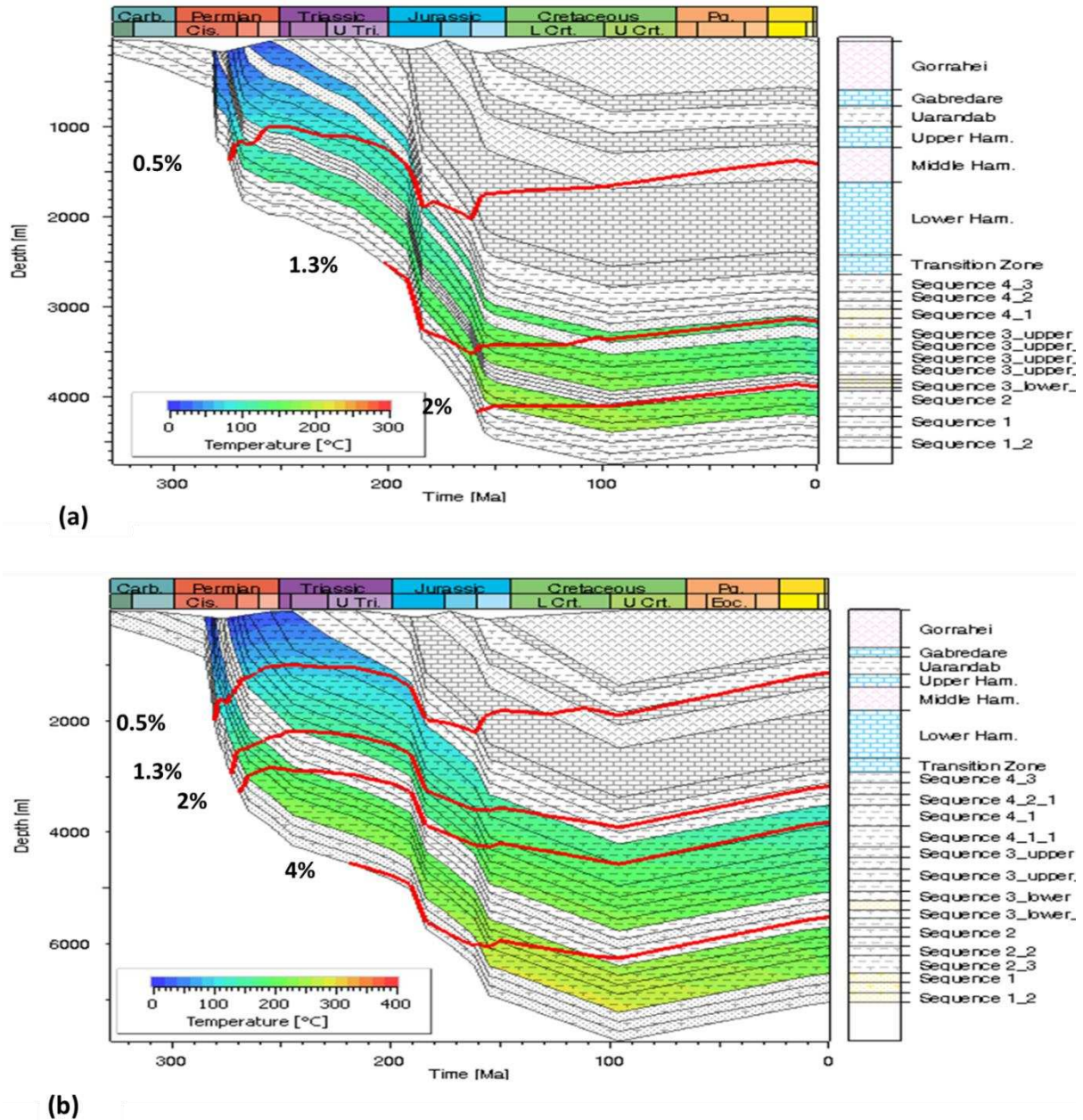


Figure 5-7 Calculated temperature history of source rocks at the basin margin (a) and at the basin center (b). Red lines represent vitrinite reflectance isolines.

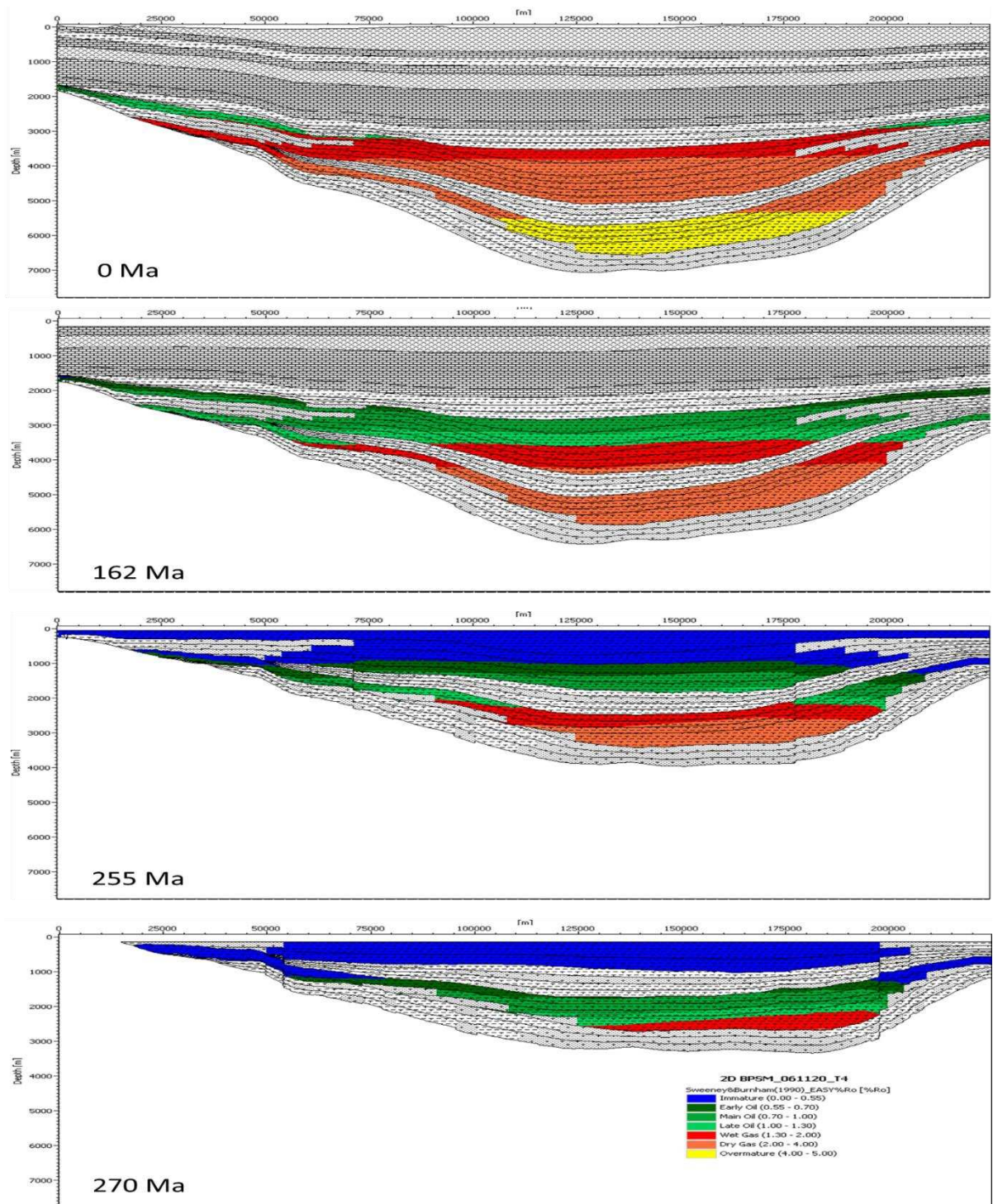


Figure 5-8 Calculated vitrinite reflectance maturity evolution along the model line from upper Permian (bottom) to present day (top) using Sweeny and Burnham (1990) Kinetic model.

Whereas in the western flank transformation took place at a shallower depth where 50% TR of sequence 2 took place at a depth of 1658m (Figure 5-9a), at 112 degC in upper Triassic (212 Ma). A complete transformation took place in lower Jurassic at a depth of 2855m.

The top of sequence three achieved 50% TR at even a shallower depth than sequence two (at less than 1500m and 115 deg C) in middle Triassic (230 Ma) and >95% TR at 1945m depth since early Jurassic (200 Ma) at the basin center. In the western flank the 50% TR was attained during the deposition of Upper Hamanlie in middle Jurassic (164Ma) at a depth of 2674m. Transformation in sequence 4 took a longer time and at a deeper depth compared to underlying sequences. The top of the sequence reached a 50% TR at a depth of 2620m in the middle Jurassic (166 Ma) and eventually reached 95% at a depth of 3254m in the upper Jurassic (155Ma). The top of sequence 4 at the western flank reached the 50% mark at 2660m depth in the upper Jurassic (159Ma) and a 95% transformation in upper Jurassic (154Ma).

The primary factor controlling transformation in sequence 2 and 3 source rocks is probably high heat flow related to tectonic subsidence in the Permian causing a rapid rate of transformation at shallow depth. The heatflow model peaks (reaching 80 - 90mW/m²) in the base of upper Permian and is followed by a gentle ramp until the Oligo-Miocene. This Permian HF peak coincides with deposition of syn-tectonic sequences two and three creating a thermal stress for rapid conversion into hydrocarbon. Sequence 4 was

deposited as the heatflow was gradually decreasing and hence took a relatively longer time to for transformation with burial depth playing a major role.

Hydrocarbon migration and accumulation history

The model constructed is a simplified regional model that does not include faults and hence the role of faults in migration and structural trapping is not simulated in the model; this requires further study using additional data. There is also limited knowledge on petrophysical and geochemical properties of modeled units due to limited well control. The results of the migration modeling, however, give insight into the working petroleum system and would be useful for guiding future more detailed works.

Hydrocarbon migration from source rocks to reservoirs in Karoo sequences is modeled using the hybrid method. The result shows oil and gas migration is mostly vertically upward while some vectors show migration in a lateral updip direction and still other vectors show vertically downward migration paths (Figure 5-10a - e).

Migration from sequence two started around 270Ma when deposition of sequence 3 was underway. During this time potential reservoir targets were backstepping deltas in sequence 2 in the basin margins and lowstand system targets including deltas, sublacustrine fans and turbidites of sequence 3 (Figure 5-10e). In addition fluvial - deltaic units in the underlying sequence 1, all of which are stratigraphic traps, were available for charging. The model shows oil column starting to build up mainly in sequence two backstepping deltas at the time. By 255Ma (Figure 5-10d) while sequence four deposition was going on, deeper targets in sequence 2 and fluvial targets in sequence 1 have gone

through secondary cracking and only a gas phase was present. Whereas the shallow targets of sequence 2 and LST targets of sequence 3 were charged with both oil and gas phases.

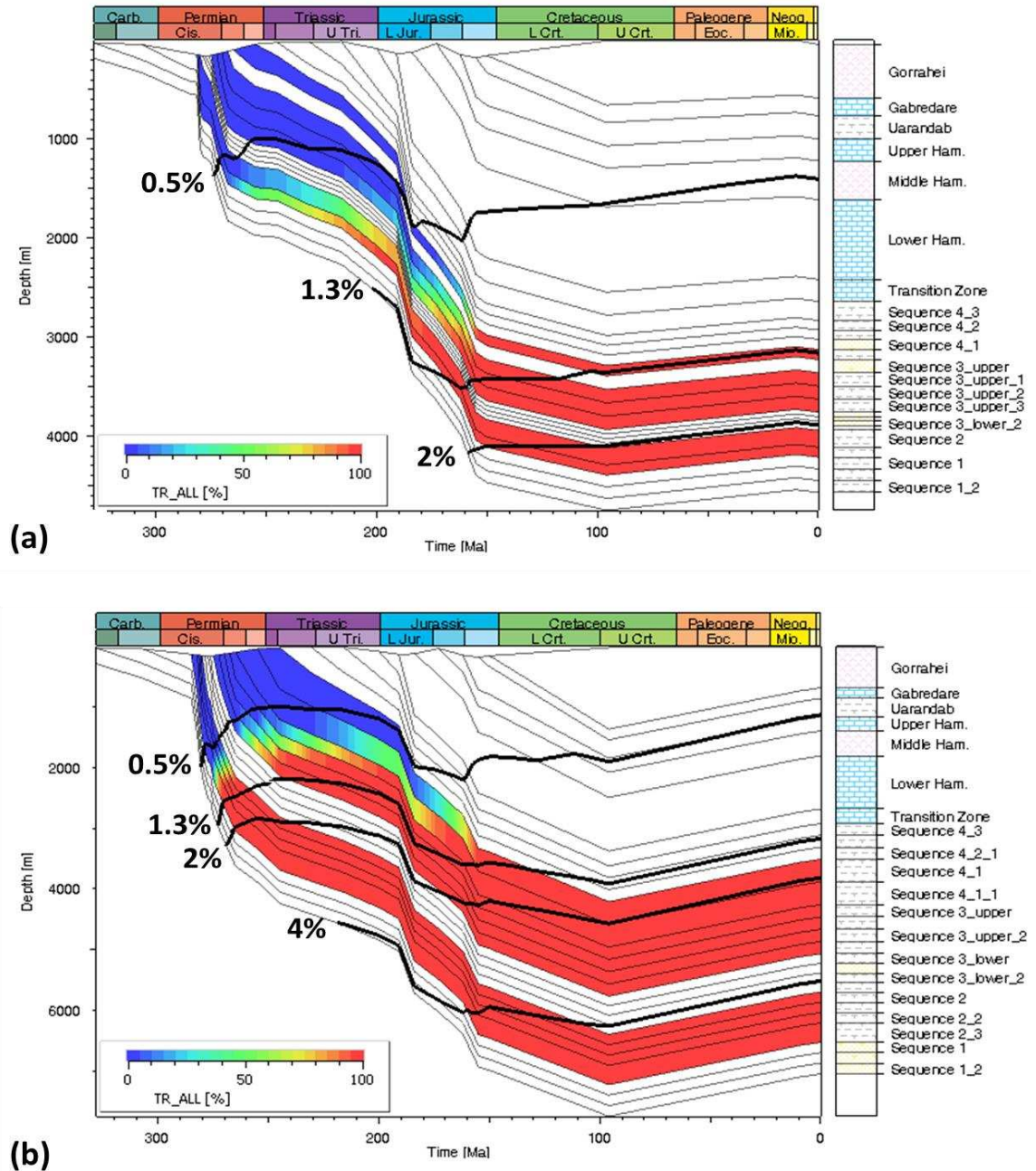
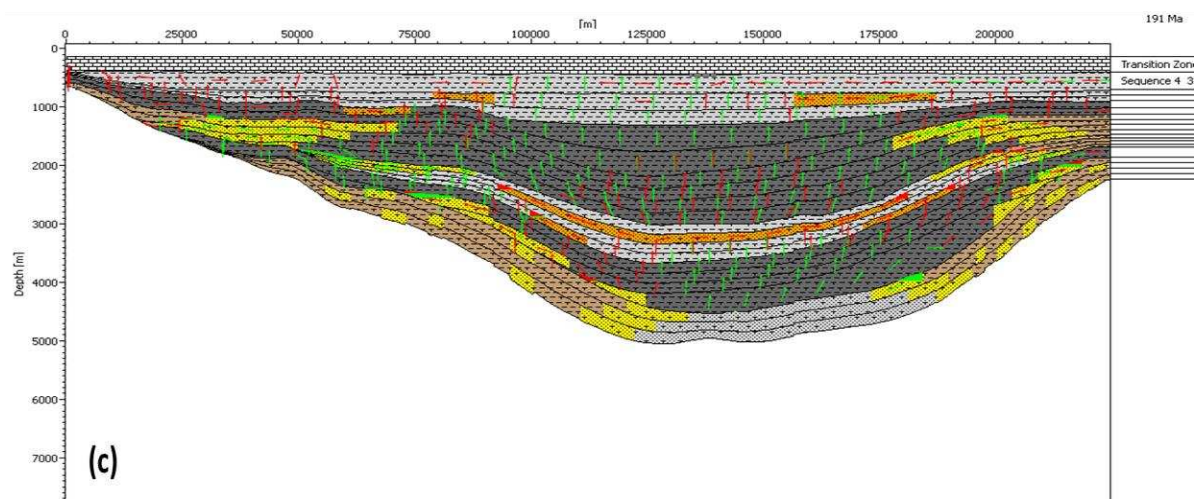
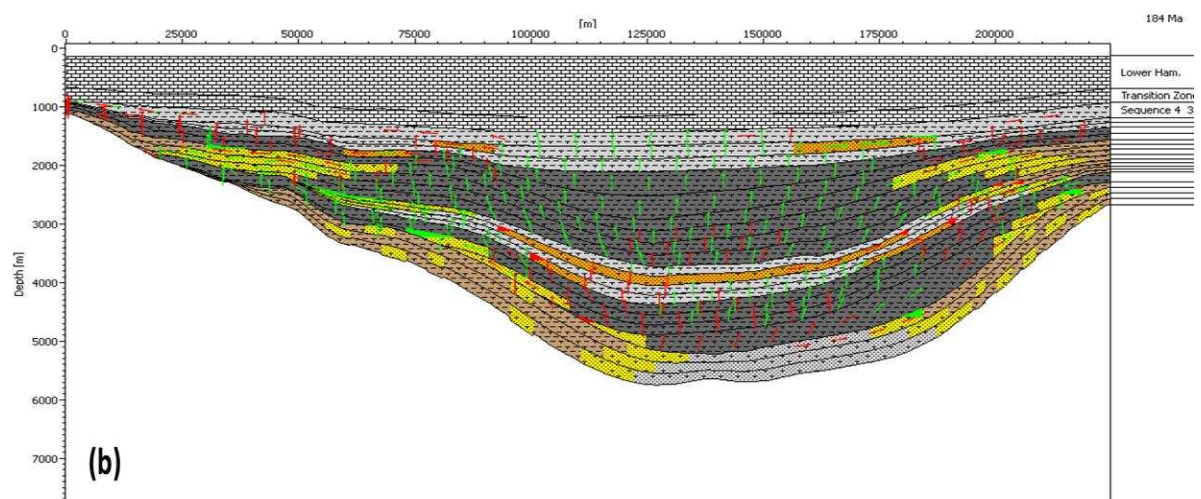
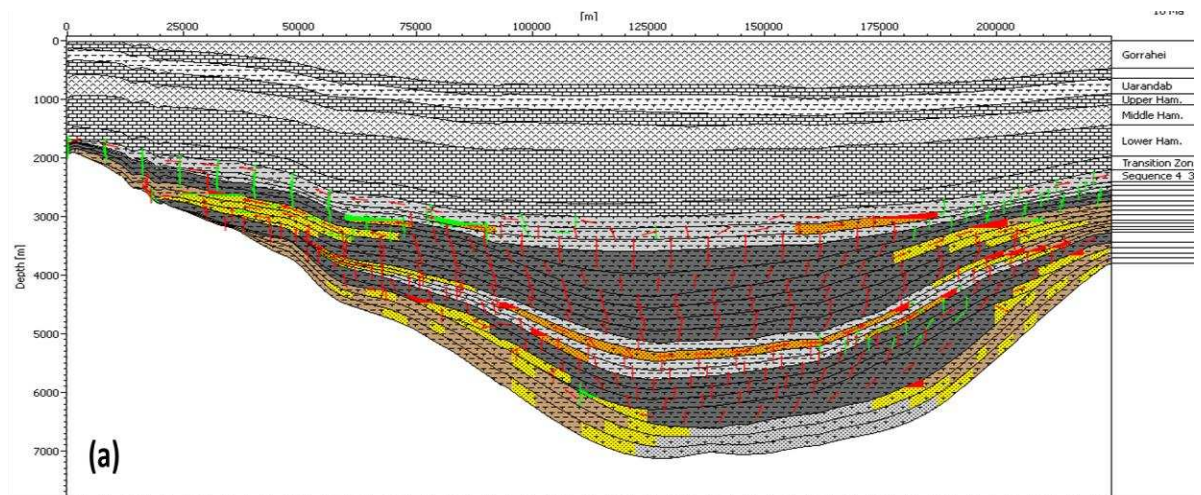


Figure 5-9 Calculated transformation ratio history of source rocks at the basin margin (a) and at the basin center (b). Thick dark lines represent vitrinite reflectance isolines.

By the end of Karoo deposition (191Ma) additional targets in sequence three highstand deltas were charged with oil and gas (Figure 5-10c). Source rocks with peak transformation during this time were sequence 3 basinal shales and shallow parts of sequence 2. LST sublacustrine fans and turbidites were increasingly forming synforms due to continued subsidence and oil columns in these targets were being cracked and replaced by a gas phase.

In sequence 4, turbidites are modeled as potential reservoirs and were subsequently charged starting from 184Ma (Figure 5-10b). At maximum burial depth in lower Cretaceous, reservoir targets in sequence 1, 2 and lower part of sequence 3 were all gas saturated with different proportions of associated oil. Whereas targets in the upper part of sequence 3 and sequence 4 were charged with oil which contained a significant amount of associated gas. This trend continued to present day (Figure 5-10a) where a large proportion of the Karoo hydrocarbon resource is gas with a good chance for finding oil residing in sequences 4 and shallow parts of sequence 3. The model also shows numerous vectors pointing to paths of hydrocarbon escaping the system in the flanks area at present. These thermogenic gases could be detected by a surface geochemical survey conducted along the flank areas. There is also a potential in reservoirs in the overlying marine sequence which could be charged from the Karoo source intervals.

Source rock tracking shows sequence two and three are possible source rocks charging the highstand delta reservoirs penetrated by Genale B2X well in sequence 3. Source rock



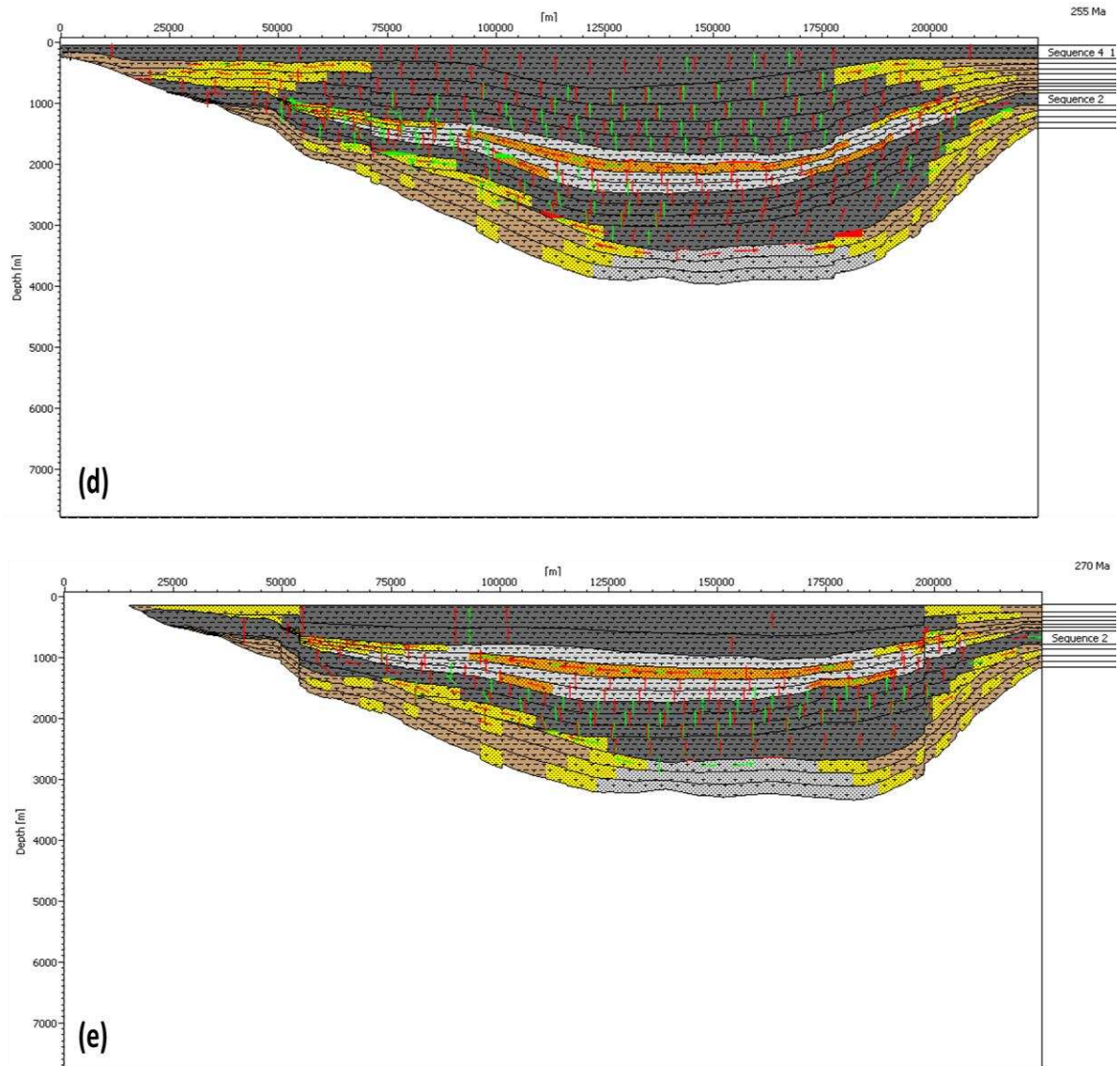


Figure 5-10 Migration and accumulation simulation of Karoo petroleum system showing oil flowpaths (green arrow) and gas flowpaths (red arrows). Also showing oil accumulations (green filled polygons) and gas accumulations (red filled polygons). (a) present day; (b) 184Ma; (c) 191Ma; (d) 255Ma; and (e) 270Ma.

tracking also shows reservoirs in sequence 2 and LST targets of sequence 3 were charged from sequence two source rocks.

There also exists a small percentage contribution from sequence 3 source rocks in the upper most part of the sequence 3 LST package. Sequence 4 targets were charged from

sequence three and four source rocks with the larger proportion from sequence three source rocks.

5.5 Conclusions

A model cross section constructed based on sequence stratigraphic interpretation of the Karoo sequence in the southern Ogaden Basin is used to analyze the basin's thermal, hydrocarbon generation and accumulation history. Three potential source rocks have been evaluated in this study including sequence 2, upper part of sequence 3 and the bottom part of sequence 4.

- Basin models calibrated with vitrinite reflectance data show heat flow trends are similar throughout the study area with the exception of WL-B well at the western edge of the basin which has consistently higher values. A present day heat flow of 47mW/m² is determined by calibration with borehole temperature data at two wells.
- 2D Model result shows all potential source rocks have reached complete transformation at present. Peak transformation in sequence two, three and bottom of sequence four source rocks was reached during upper Permian, middle Triassic and middle Jurassic respectively.
- The main controls in maturation of source rocks in sequence two are possibly related to high heat flow during Permian – Triassic tectonic activity whereas in the overlying sequences the thermal maturity is attributed to deep burial.

- Simulation results show potential reservoir targets in all sequences are hydrocarbon charged. Reservoir targets in sequence two and LST of sequence three are gas filled whereas potential targets in the shallow marginal parts of sequence three and sequence four are oil filled with high GOR ratios.

Chapter 6 : **General Conclusions and Recommendations**

6.1 General Conclusions

A sequence stratigraphic study of Karoo group in Ogaden Basin was undertaken with the objective of a better understanding of the development and evolution of the basin during the Permian – early Jurassic and its hydrocarbon potential. However, seismic sequence stratigraphy requires a good quality seismic data and for this reason reprocessing of existing seismic sections was required before interpretation. The interpretation step was done using reprocessed seismic data and post stack seismic attributes, mainly phase attribute, and well data was used to support/ confirm the seismic interpretation. A two dimensional geologic model was produced as a result of these steps and the model was simulated to assess the hydrocarbon potential of the Karoo sequence. In the following sections conclusions from each stage of the work are presented followed by a recommendations for future research.

6.1.1 Seismic data reprocessing

The reprocessing work showed that source related groundroll and amplitude burst noises are the main noise types recorded in data. Proper removal of these noises was imperative for recovering reflectivity especially from the near and mid offsets. Hence, trace editing using database statistical tools and spike and burst edit tools were used to effectively remove random noises. The removal of groundroll noise using linear Radon transform/ slant stack followed by muting the linear events in tau-p domain and inverse transform

to T-X domain was more effective than the other tools tested including F-K and radial trace transform.

Static corrections were not complete due to poor first break picks which affected the refraction statics results, compromising the lateral continuity of reflection events. The source type and ground conditions are the main factors affecting the result. However, a more careful analysis of the low velocity layer would certainly improve the quality of sections and should be considered in any future reprocessing works.

Surface consistent amplitude corrections were invoked to correct amplitudes for disturbances/ anomalies generated in the near surface such as energy source variations, poor geophone coupling and the effect of the low velocity near surface layer. The correction enhanced amplitude anomalies due to changes in lithology and fluid content.

Spiking deconvolution was not applied due to its high frequency noise amplification effect. The result of a 32ms lag gave the optimum result using a 200ms filter operator. Random noise attenuation using multiple passes of the F-X deconvolution has contributed to continuity of coherent reflections. Optimum results were observed with horizontal window length of 100 traces and 10 filter samples.

Velocity analysis was done in two passes before and after residual correction. The first pass was run every 500m and the NMO corrected gathers using this velocity field, with interpolation in between, were input to residual statics computations. The Maximum power surface consistent autostatics was used to compute residual statics using four iterations and maximum allowable shift of 10, 15, 20 and 30ms from the first to the last

iteration respectively. The results of the maximum power autostatics were compared to correlation autostatics results and a much better reflectivity was achieved with the maximum power autostatics. The second pass velocity analysis was run after applying residual statics correction and was picked every 500m. A velocity analysis every 250m was also attempted on line OG-A to see if further improvements were possible but the changes were marginal and the 500m interval was used in all lines.

Stacking was done using a second pass velocity field and a 50% stretch mute. The mean stacking weighted with square root of number of samples gave a better stack response and was used to generate the final stacked sections. The smoothed, interpolated second pass velocity field was used in post stack migration of lines. The migration was run using 7000m aperture and maximum dip migrated was set to 75 degree.

Reprocessed Line OG-A was compared with the previous processing and the main improvement is in recovering reflectivity in the Karoo section where poor signal to noise ratio and little coherency in the previous section made it difficult to carryout seismic stratigraphic interpretation with confidence. The current dataset has shown noticeable improvements and it is now possible to interpret unconformities, deltaic clinoforms and other seismic facies with ease. Continuity of reflections has also improved and hence tracking different horizons mainly in the target zone is easily done. This is because of better attenuation of random and coherent noise that affected the data significantly. The improvement in vertical resolution from the original lines is not observed.

6.1.2 Sequence stratigraphic interpretation of the Karoo sequence

The application of sequence stratigraphy to Karoo sequence in Ogaden Basin has led to the identification of four second order sequences bounded by unconformity surfaces that are traced in the southwestern flank and the Bodle Deep areas. These sequences are recognized in both seismic sections and well logs and the identification of at least four higher order sequences in sequence 4 was possible using well logs. With the acquisition of better quality seismic data, it should be possible to identify these higher order sequences from seismic sections.

The constituent systems tracts of sequences identified in this study are the transgressive and highstand systems tracts. Transgressive systems tracts represent the bulk of the sequences and are separated from the overlying highstand systems tract by a downlap or maximum flooding surface. The highstand systems tract have different degree of preservation due to ensuing erosional events but identification of the system has been possible in sequences 2 and 3. The dominant depositional systems in these systems tracts are shallow to deep lacustrine, fluviodeltaic and possibly sublacustrine fans and turbidites.

The tectonic regime that led to deposition of Karoo sequences is proposed here to be related to wrench tectonics giving rise to a number of pull apart basins formed in NE-SW to E-W directions. These pull apart basins are narrow regions bounded by near vertical faults of large throw and with steep flanks forming in the larger surroundings of these narrow zones such as the southwestern flank, Shilabo trough and down slope Bur High.

Tectonic tilts and uplift in these steep flanks are thought to be the cause of unconformities and climate is an additional factor.

Organic rich lacustrine shales commonly associated with transgressive systems tract and prodelta to lacustrine shales of highstand systems tract are potential source rocks in the Karoo sequences. The generated hydrocarbon from these source rocks are predicted to charge deltaic and fluvial sand reservoirs of the highstand systems tracts as well as potential targets such as turbidites, sublacustrine fans and possibly lowstand systems tracts. The seal for petroleum play is usually provided by transgressive systems tract.

6.1.3 Basin and petroleum system modeling

A model cross section constructed based on sequence stratigraphic interpretation of the Karoo sequence in the southern Ogaden Basin is used to analyze the basin's thermal, hydrocarbon generation and accumulation history. Three potential source rock intervals have been evaluated in this study including sequence 2, upper part of sequence 3 and the bottom part of sequence 4. The main findings from this work are that 1D basin models, calibrated with vitrinite reflectance data, show heat flow trends are similar throughout the study area with the exception of WL-B well at the western edge of the basin which has consistently higher values. Also from the model, calibrated with borehole temperature data at two wells, present day heat flow is determined to be 47mW/m².

2D Model result shows all potential source rocks have reached complete transformation at present. Peak transformation in sequence two, three and bottom of sequence four source rocks was reached during upper Permian, middle Triassic and middle Jurassic

respectively. The main controls in maturation of source rocks in sequence two are possibly related to high heat flow during Permian – Triassic tectonic activity whereas in the overlying sequences the thermal maturity is attributed to deep burial. Simulation results also show that potential reservoir targets in all sequences are hydrocarbon charged. Reservoir targets in sequence two and LST of sequence three are gas filled whereas potential targets in the shallow marginal parts of sequence three and sequence four are filled with high GOR oil.

6.2 Recommendations for future research

This research has shown that with the current geo-database of the Ogaden Basin, it is possible to extract far more information than we have to date used. The study also suggests additional data can prove, improve or supersede the model presented in this work. The different depositional systems interpreted with the limited data in this work can be checked/ verified with other lines from the basin and the framework can be extended to the eastern part of the basin. Paleogeographic maps in different sequences can also be drawn to represent the distribution of different depositional environments with geologic age. In addition, the BPSM using 3D models can offer a better understanding of the basins hydrocarbon potential from the Karoo sequence. It would also be possible to have a better understanding of the structural control in the development of the Ogaden Basin with acquisition of new seismic lines among other areas in the southwestern extension of Bodle Deep, across the axis of the basin and in the

northwestern part of the basin to see if a northwest third arm of the proposed tri-radial rift system exists and if so to study its evolution.

References

- Al-Hajeri, M.M., Al Saeed, M., Derks, J., Fuchs, T., Hantschel, T., Kauerauf, A., Neumaier, M., Schenk, O., Swientek, O., Tessen, N., others, 2009. Basin and petroleum system modeling. *Oilf. Rev.* 21, 14–29.
- Allen, P.A.P.A., Allen, J.R., 2005. Basin Analysis - Principles and Application. *Geology*. <https://doi.org/10.1017/CBO9781107415324.004>
- Amer, A., Glascock, M.R., Schwalbach, J.R., Khan, M., others, 2011. Applied Borehole Image Analysis in Complex Sedimentological and Structural Settings: A Single Well Case Study, California, USA, in: SPE Annual Technical Conference and Exhibition.
- Aydin, A., Nur, A., 1982. Evolution of pull-apart basins and their scale independence. *Tectonics* 1, 91–105.
- Barrell, J., 1917. Rhythms and the measurements of geologic time. *Bull. Geol. Soc. Am.* 28, 745–904.
- Beicip-Franlab, 1998. The petroleum potential of Ethiopia. Ministry of Mines and Energy, Petroleum Operations Department, Addis Ababa, Ethiopia. France.
- Bohacs, K.M., Carroll, A.R., Neal, J.E., Mankiewicz, P.J., others, 2000. Lake-basin type, source potential, and hydrocarbon character: an integrated sequence-stratigraphic-geochemical framework. *Lake basins through Sp. time AAPG Stud. Geol.* 46, 3–34.
- Bott, M.H.P., 2006. Mechanisms of rifting: Geodynamic modeling of continental rift systems. *Dev. Geotecton.* 25, 27–43. [https://doi.org/10.1016/S0419-0254\(06\)80006-6](https://doi.org/10.1016/S0419-0254(06)80006-6)
- Brown Jr, L.F., Fisher, W.L., 1977. Seismic-stratigraphic interpretation of depositional systems: examples from brazilian rift and pull-apart basins: section 2. Application of seismic reflection configuration to stratigraphic interpretation.
- Burnham, A.K., 1989. A simple kinetic model of petroleum formation and cracking.
- Busby, C., Pérez, A.A., 2011. Tectonics of sedimentary basins: Recent advances.
- Canales, L.L., 1984. Random noise reduction, in: SEG Technical Program

- Expanded Abstracts 1984. Society of Exploration Geophysicists, pp. 525–527.
- Catuneanu, O., 2015. Sequence Stratigraphy, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier.
<https://doi.org/10.1016/B978-0-12-409548-9.09536-1>
- Catuneanu, O., 2006. Principles of sequence stratigraphy. Elsevier.
- Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., Hancox, P.J., 2005. The Karoo basins of south-central Africa. *J. African Earth Sci.* 43, 211–253.
<https://doi.org/10.1016/j.jafrearsci.2005.07.007>
- Chopra, S., Marfurt, K.J., 2005. Seismic attributes—A historical perspective. *Geophysics* 70, 3S0--28S0.
- Creaney, S., Passey, Q.R., 1993. Recurring Patterns of Total Organic Carbon and Source Rock Quality within a Sequence Stratigraphic Framework. *Am. Assoc. Pet. Geol.* 77, 386–401.
- Csato, I., Catuneanu, O., 2012. Systems tract successions under variable climatic and tectonic regimes: a quantitative approach. *Stratigraphy* 9, 109–130.
- Dondurur, D., 2018. Acquisition and processing of marine seismic data. Elsevier.
- Dooley, T., McClay, K., 1997. Analog modeling of pull-apart basins. *Am. Assoc. Pet. Geol. Bull.* 81, 1804–1826.
- Ellis, D. V, Singer, J.M., 2007. Well logging for earth scientists. Springer.
- Embry, A.F., 1995. Sequence boundaries and sequence hierarchies: problems and proposals, in: Norwegian Petroleum Society Special Publications. Elsevier, pp. 1–11.
- Emery, D., Myers, K., 2009. Sequence stratigraphy. John Wiley & Sons.
- Flint, S.S., Hodgson, D.M., Sprague, A.R., Brunt, R.L., Van der Merwe, W.C., Figueiredo, J., Pr  lat, A., Box, D., Di Celma, C., Kavanagh, J.P., 2011. Depositional architecture and sequence stratigraphy of the Karoo basin floor to shelf edge succession, Laingsburg depocentre, South Africa. *Mar. Pet. Geol.* 28, 658–674.
<https://doi.org/10.1016/j.marpetgeo.2010.06.008>

- Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis II: application to northwest Gulf of Mexico Cenozoic basin. *Am. Assoc. Pet. Geol. Bull.* 73, 143–154. <https://doi.org/10.1306/703C9AFA-1707-11D7-8645000102C1865D>
- Gazdag, J., Sguazzero, P., 1984. Migration of seismic data. *Proc. IEEE* 72, 1302–1315.
- Gulunay, N., 1986. FXDECON and complex Wiener prediction filter, in: *SEG Technical Program Expanded Abstracts 1986*. Society of Exploration Geophysicists, pp. 279–281.
- Hankel, O., 1994. Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar. *Geol. Rundschau* 83, 703–710. <https://doi.org/10.1007/BF00251069>
- Hantschel, T., Kauerauf, A.I., 2009. Fundamentals of basin and petroleum systems modeling. Springer Science & Business Media.
- Hubbard, R.J., Pape, J., Roberts, D.G., 1985. Depositional sequence mapping as a technique to establish tectonic and stratigraphic framework and evaluate hydrocarbon potential on a passive continental margin.
- Hunegnaw, A., Sage, L., Gonnard, R., 1998. Hydrocarbon potential of the intracratonic Ogaden Basin, SE Ethiopia. *J. Pet. Geol.* 21, 401–425. <https://doi.org/10.1111/j.1747-5457.1998.tb00793.x>
- James, N.P., Walker, R.G., 1992. Facies Models: response to sea level changes. *Geol. Assoc. Canada* 407. <https://doi.org/10.1097/00000433-198206000-00020>
- Khalifa, M.K., Mills, K.J., 2014. Seismic stratigraphic analysis and structural development of an interpreted upper cambrian to middle ordovician sequence in the NW Blantyre sub-basin, darling basin (Western new South Wales, Australia). *J. Pet. Geol.* 37, 163–181. <https://doi.org/10.1111/jpg.12576>
- Lambiase, J.J., Bosworth, W., 1995. Structural controls on sedimentation in continental rifts. *Geol. Soc. London, Spec. Publ.* 80, 117–144. <https://doi.org/10.1144/GSL.SP.1995.080.01.06>
- Le Roux, J.P., Achurra, L., Henríquez, Á., Carreño, C., Rivera, H., Suárez, M.E., Ishman, S.E., Pyenson, N.D., Gutstein, C.S., 2016. Oroclinal bending of the Juan Fernández Ridge suggested by geohistory analysis

- of the Bah{\`i}a Inglesa Formation, north-central Chile. *Sediment. Geol.* 333, 32–49.
- Le Roux, J.P., Gómez, C., Venegas, C., Fenner, J., Middleton, H., Marchant, M., Buchbinder, B., Frassinetti, D., Marquardt, C., Gregory-Wodzicki, K.M., others, 2005. Neogene-Quaternary coastal and offshore sedimentation in north central Chile: Record of sea-level changes and implications for Andean tectonism. *J. South Am. Earth Sci.* 19, 83–98.
- Lewis, D.W., 1984. *Practical Sedimentology*: Stroudsburg. Pennsylvania, USA, Hutchinson Ross.
- Mann, P., Hempton, M.R., Bradley, D.C., Burke, K., 1983. Development of pull-apart basins. *J. Geol.* 91, 529–554.
- Mari, J.-L., Glangeaud, F., Coppens, F., 1999. *Signal processing for geologists & geophysicists*. Technip Paris.
- Martins-Neto, M.A., Catuneanu, O., 2010. Rift sequence stratigraphy. *Mar. Pet. Geol.* 27, 247–253.
<https://doi.org/10.1016/j.marpetgeo.2009.08.001>
- McKenzie, D., 1978. Some remarks on the development of sedimentary basins. *Earth Planet. Sci. Lett.* 40, 25–32.
- McRae, S.G., 1972. Glauconite. *Earth-Science Rev.* 8, 397–440.
- Middleton, M.F., 1989. A model for the formation of intracratonic sag basins. *Geophys. J. Int.* 99, 665–676.
- Mitchum Jr, Rober M, Vail, P.R., Sangree, J.B., 1977. Seismic stratigraphy and global changes of sea level: Part 6. Stratigraphic interpretation of seismic reflection patterns in depositional sequences: Section 2. Application of seismic reflection configuration to stratigraphic interpretation.
- Mitchum Jr, R M, Vail, P.R., Thompson III, S., 1977. Seismic stratigraphy and global changes of sea level: Part 2. The depositional sequence as a basic unit for stratigraphic analysis: Section 2. Application of seismic reflection configuration to stratigraphic interpretation.
- Mousa, W.A., 2019. *Advanced Digital Signal Processing of Seismic Data*. Cambridge University Press.
- Nichols, G., 2009. *Sedimentology and stratigraphy*. John Wiley & Sons.

- Peacock, K.L., Treitel, S., 1969. Predictive deconvolution: Theory and practice. *Geophysics* 34, 155–169.
- Peters, K.E., Peters, K.E., Walters, C.C., Moldowan, J.M., 2005. The biomarker guide. Cambridge University Press.
- Petronas Carigali Sdn. Bhd., Ministry of Mines of Ethiopia, 2005. Joint Ogaden Basin study project.
- Posamentier, H.W., Allen, G.P., 1999. SILICICLASTIC SEQUENCE STRATIGRAPHY-CONCEPTS AND APPLICATIONS, Society for Sedimentary Geology.
- Purcell, P.G., 1976. The Marda fault zone, Ethiopia. *Nature* 261, 569–571.
- Purser, B., Bosence, D., 1997. Sedimentation and Tectonics in Rift Basins.
- Rider, M., 2002. The Geological Interpretation of Well Logs. Rider-French Consult. Ltd.
- Rider, M.H., 1986. The geological interpretation of well logs.
- Russell, B., Hampson, D., Chun, J., 1990. Noise elimination and the Radon transform, part 1. *Lead. Edge* 9, 18–23.
- Sangree, J.B., Widmier, J.M., 1979. sangree1979.pdf. *Geophysics* 44, 131–160.
- Sattar, N., Juhlin, C., Koyi, H., Ahmad, N., 2017. Seismic stratigraphy and hydrocarbon prospectivity of the Lower Cretaceous Knurr Sandstone lobes along the southern margin of Loppa High, Hammerfest Basin, Barents Sea. *Mar. Pet. Geol.* 85, 54–69.
<https://doi.org/10.1016/j.marpetgeo.2017.04.008>
- Schneider, W.A., 1978. Integral formulation for migration in two and three dimensions. *Geophysics* 43, 49–76.
- Selley, R.C., 1979. Concepts and methods of subsurface facies analysis.
- Serra, O., 1985. Sedimentary environments from wireline logs. Schlumberger Limited.
- Serra, O., 1984. Fundamentals of Well-log interpretation, first volume.
- Serra, O., Serra, L., 2003. Well logging and geology.
- Sheriff, R.E., 2012. Seismic stratigraphy. Springer Science & Business Media.
- Sloss, L.L., 1988. Sedimentary Cover—North American Craton: US.

Geological Society of America.

- Sloss, L.L., 1963. Sequences in the cratonic interior of North America. *Geol. Soc. Am. Bull.* 74, 93–114.
- Sloss, L.L., 1949. INTEGRATED FACIES ANALYSIS, in: *Sedimentary Facies in Geologic History: Conference at Meeting of the Geological Society of America Held in New York, New York, November 11, 1948.* p. 91.
- Srivastava, R.P., Sen, M.K., 2009. Fractal-based stochastic inversion of poststack seismic data using very fast simulated annealing. *J. Geophys. Eng.* 6, 412–425. <https://doi.org/10.1088/1742-2132/6/4/009>
- Stoffa, P.L., Buhl, P., Diebold, J.B., Wenzel, F., 1981. Direct mapping of seismic data to the domain of intercept time and ray parameter—A plane-wave decomposition. *Geophysics* 46, 255–267.
- Strecker, U., Steidtmann, J.R., Smithson, S.B., 1999. A Conceptual Tectonostratigraphic Model for Seismic Facies Migrations in a Fluvio-Lacustrine Extensional Basin 1. *Am. Assoc. Pet. Geol. Bull.* 83, 43–61.
- Subrahmanyam, D., Rao, P.H., 2008. Seismic attributes-a review, in: *7th International Conference & Exposition on Petroleum Geophysics, Hyderabad.* pp. 398–404.
- Sweeney, J.J., Burnham, A.K., 1990. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *Am. Assoc. Pet. Geol. Bull.* 74, 1559–1570.
- Taner, M.T., Koehler, F., 1981. Surface consistent corrections. *Geophysics* 46, 17–22.
- Taner, M.T., Koehler, F., Sheriff, R.E., 1979. Complex seismic trace analysis. *Geophysics* 44, 1041–1063.
- Taner, M.T., Schuelke, J.S., O'Doherty, R., Baysal, E., 1994. Seismic attributes revisited, in: *SEG Technical Program Expanded Abstracts 1994.* Society of Exploration Geophysicists, pp. 1104–1106.
- Vail, P.R., Mitchum Jr, R.M., Thompson III, S., 1977. Seismic stratigraphy and global changes of sea level: Part 3. Relative changes of sea level from Coastal Onlap: section 2. Application of seismic reflection Configuration to Stratigraphic Interpretation.
- Van Wagoner, J.C., Mitchum R.M., and Rahmanian, V.D., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for

- High-Resolution Correlation of Time and Facies_Pt. 2. AAPG Methods Explor. Ser. 7 16–20. <https://doi.org/0-89181-657-7>
- Veeken, P., 2007. Seismic Stratigraphy, Basin Analysis and Reservoir Characterisation. Handb. Geophys. Explor. Seism. Explor. 37, 7–109. [https://doi.org/10.1016/S0950-1401\(07\)80033-4](https://doi.org/10.1016/S0950-1401(07)80033-4)
- Welte, D.H., Horsfield, B., Baker, D.R., 2012. Petroleum and basin evolution: insights from petroleum geochemistry, geology and basin modeling. Springer Science & Business Media.
- Wheeler, H.E., 1964. Baselevel, lithosphere surface, and time-stratigraphy. Geol. Soc. Am. Bull. 75, 599–610.
- Wheeler, H.E., Murray, H.H., 1957. Base-level control patterns in cyclothemic sedimentation. Am. Assoc. Pet. Geol. Bull. 41, 1985–2011.
- Woldegabriel, G., Aronson, J.L., Walter, R.C., 1990. Geology, geochronology, and rift basin development in the central sector of the Main Ethiopia Rift. Geol. Soc. Am. Bull. 102, 439–458.
- Wolela, A., 2007. Fossil fuel energy resources of Ethiopia: Coal deposits. Int. J. coal Geol. 72, 293–314.
- Wolfenden, E., Ebinger, C., Yirgu, G., Deino, A., Ayalew, D., 2004. Evolution of the northern Main Ethiopian rift: birth of a triple junction. Earth Planet. Sci. Lett. 224, 213–228.
- Wood, C.A., 1979. The Marda Fault Zone and the opening of the Red Sea. Apollo/Soyuz Test Proj. Summ. Sci. Proj. 2, 29–36.
- Wopfner, H., 2002. Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. J. African Earth Sci. 34, 167–177. [https://doi.org/10.1016/S0899-5362\(02\)00016-7](https://doi.org/10.1016/S0899-5362(02)00016-7)
- Wopfner, H., 1994. The Malagasy Rift, a chasm in the Tethyan margin of Gondwana. J. Southeast Asian Earth Sci. 9, 451–461. [https://doi.org/10.1016/0743-9547\(94\)90056-6](https://doi.org/10.1016/0743-9547(94)90056-6)
- Worku, T., Astin, T.R., 1992. The Karoo sediments (Late Palaeozoic to Early Jurassic) of the Ogaden Basin, Ethiopia. Sediment. Geol. 76, 7–21. [https://doi.org/10.1016/0037-0738\(92\)90136-F](https://doi.org/10.1016/0037-0738(92)90136-F)
- Wygrala, B., 1989. Integrated study of an oil field in the southern Po basin, northern Italy.

Zerfass, H., Lavina, E.L., Schultz, C.L., Garcia, A.J.V., Faccini, U.F., Chemale, F., 2003. Sequence stratigraphy of continental Triassic strata of Southernmost Brazil: A contribution to Southwestern Gondwana palaeogeography and palaeoclimate. *Sediment. Geol.* 161, 85–105. [https://doi.org/10.1016/S0037-0738\(02\)00397-4](https://doi.org/10.1016/S0037-0738(02)00397-4)