

**Deep-water channel-levee system: their geomorphic evolution, stratigraphic
architecture, and interaction with salt diapirs in the base of slope to basin
floor environment**

Thesis submitted for the degree of
Doctor of Philosophy and Diploma of Imperial College

By

Isaac Abraham Odeh

Department of Earth Science and Engineering
Imperial College London

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Isaac Abraham Odeh

Department of Earth Science and Engineering
Imperial College London

DECLARATION OF ORIGINALITY

The author of this thesis is responsible for all interpretations and conclusions submitted therein. No portion of this thesis has been submitted in support of any other degree or qualification. References and all other contributions to this research are fully acknowledged where applicable.

Isaac Abraham Odeh

Department of Earth Science and Engineering
Imperial College London

This thesis is dedicated to my grandmother of blessed memory – Rifkatu Hassana Odeh

ABSTRACT

This thesis combines an interpretation of 3D seismic and bore hole data (drill cuttings and cores) to analyse and describe the geomorphic evolution, and the stratigraphic architecture of deep-water depositional systems in (i) channel dominated Offshore Taranaki Basin, and (ii) a channel-lobe dominated Central North Sea Basin.

In the Taranaki basin, (Offshore New Zealand), two seismic units (SU1-2) were mapped, identifying three depositional elements: (channel and intra channel-fills, levees/overbank, and basin floor mudstones). Within SU1, several north-trending, channel-levee complexes, characterised by increasing sinuosity (SI 1.15 – 2.25), and having average width and depth of 346 m and 34 m, respectively, was identified. These channel-levee complexes were deposited in a basin-floor environment. In SU2, NW-trending channel-levee complexes, deposited in the base of slope were observed, however a decrease in sinuosity (1.01 – 1.40) and an increase in the width and depth (108 m – 104 m respectively) of the channels was noticed. Well data show that the channel fill facies are variable, comprising sandstone, muddy-sandstone, siltstone, and mudstone, with sandstone content decreasing upward. The levee/overbank facies are overall finer grained, and characterised by muddy, very fine-to-fine-grained sandstone interbedded with siltstone and mudstone. The slope/basin floor are mudstone dominated. Key differences between SU1 and SU2 channel complexes are: (i) palaeoflow direction was northwards during SU1 times and northwestwards during SU2 times; (ii) SU1 channel complex-fills are sandier (20-45% sand content), compared to those in SU2 (10-18% sand content); and (iii) SU1 channel complexes are relatively unconfined and characterised by lateral migration, whereas SU2 channel complexes are more commonly confined within valley systems.

In the Central North Sea Basin, the upper Palaeocene deep-water sandstone bodies are ca. 40-150 m thick and characterised by a high sandstone (i.e., 30 - 58%) content. Using core data, three facies associations; turbidite sandstone, heterolithics, and basin floor mudstones were identified. The turbidite sandstone represent the blocky or bell shape GR pattern, and in core are fine to very fine grained and are either structureless or are characterised by dewatering pipes, dish structures, mudstone clast, and oxidized quartz veins. The heterolithics facies represents the intervals characterised by high and low GR serrated GR well log patterns, and in core comprise interbedded units that display remobilisation features. The mudstone represents the intervals with low serrated GR patterns, and in core either appears massive or laminated.

The seismic characteristics of the interval of interest shows; (i) subparallel to parallel, high amplitude reflection (HAR) packages interpreted as sandstones, (ii) subparallel, interbedded HAR and low amplitude reflection packages interpreted as heterolithics and (iii) low amplitude reflection packages interpreted as basin floor mudstones. The top and base reflection characteristics of the interval of interest shows continuous, parallel to subparallel, HAR packages that are only truncated by salt diapirs. Internally, the seismic characteristics of the interval of interest show chaotic characteristics. Vclay analysis shows that these packages are characterised by high sand to clay contents.

Salt diapir was shown to control the pre-existing sea floor bathymetry during deposition. Analysis of cores facies and attribute map show (i) post depositional structures resulting from salt movement (ii) high amplitude reflection packages distributed around the diapirs flanks suggesting lobes deflection and diversion and (iii) Thickness variability suggesting local depocentres created by moving salt diapirs.

This study contributes significantly to the understanding of the stratigraphic evolution of basin floor fan system and provide insights into reservoir facies distribution in salt influenced basins.

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CHAPTER 1

INTRODUCTION

1.1 THESIS RATIONALE

Deep-water depositional systems (i.e. submarine channels and related fans, contourites, hemipelagites, pelagites and mass transport complexes) are some of the most intensively studied systems in sedimentary geology (e.g. Damuth et.al, 1988; Pirmez & Flood, 1995; Posamentier, 2003, 2006; Stow, 1982). They contain volumetrically important and globally significant hydrocarbon reservoirs, especially within sandstone-prone components (Mayall et.al, 2006; Posamentier, 2006). Constraining the spatial and temporal distribution of deep-water reservoirs, as well as their external morphology and physical properties (i.e., porosity, permeability), is however extremely challenging, especially in the subsurface. This is because, of accessibility, sparse wells, and limited high-resolution seismic data acquisition. A range of extrabasinal (i.e. provenance and tectonics) and intrabasinal factors (i.e. seafloor relief and accommodation, which can be controlled by growing faults, and salt and mud diapirs) control the geometry, scale and distribution of deep-water depositional systems (Doughty-Jones et.al, 2017; Jennette et al., 2003; Jolly, 2014; Mayall et al., 2010; Navarre, 2002).

In the Taranaki basin, offshore New Zealand previous work on deep-water systems were focused mainly on the development of the middle to upper Miocene deep-marine systems sourced from the uplifted hinterlands of NW North Island and the Northern South Island. The deposits of these systems are exposed along the Taranaki coast. These sediments are transported via submarine canyons and deposited in submarine fan systems on the slope and basin floor. Most of our understanding of the geometry, and the stratigraphic architecture of submarine channels and their depositional element comes from the study of outcrop exposures of the Upper Miocene Mt. Messenger Formation along the Taranaki coast (Browne et al., 2005; Rotzien et al., 2014). However, subsurface data, in the forms of cores, well-logs or 2D/3D seismic reflection data have also been used to study the offshore continuation of these systems (Bussell, 1994; De Bock, 1994; King, et al., 1995; Baur et al., 2010; Grahame, 2015). Despite the wealth of work done in deep-water submarine systems, Offshore Taranaki basin, our understanding of the planform evolution and the translation of this geomorphic features in the subsurface stratigraphic architecture is limited.

In the Central North Sea basin, UK North Sea, previous work have documented the tectonostratigraphic development of the Upper Palaeocene deep-water depositional systems (Davison, 2004; Davison et al., 2000; Knox & Harland, 1979; Vining, et al., 1993). However, the way in which salt tectonics controls deep-water depositional patterns, and the geometric and lithological character of related reservoirs, is only poorly understood. Despite the work done on the Central North Sea, understanding the implication of the spatial and temporal interaction of the evolving seafloor topography and deep-water depositional system on the internal architecture is not fully understood. This result in the poor understanding of the complexity related to the geometries and the stratigraphic architecture of deep-water depositional system.

While many previous work in deep-water systems have addressed submarine channel evolution, geometry, architecture and associated depositional facies example (Damuth et.al., 1988; Flood & Damuth, 1987; Kolla et.al., 2007; Mayall et al., 2006; Mutti & Ricci Lucchi, 1978; Mutti, 1977; Normark et.al, 2002; Posamentier, 2003, 2006), only a few studies have utilised 3D seismic reflection data, well data, drill cuttings and cores to explore (i) the translation of the geomorphic expression of deep-water

channels in the internal stratigraphic architecture example (Janocko, et.al., 2013; Jobe et al., 2017; Posamentier, 2003; Prather, et.al., 1998; Prather, 2003) and, (ii) the interactions between deepwater channels and seafloor bathymetry example (Doughty-Jones et al., 2017; Gee & Gawthorpe, 2006; Jolly 2014; Mayall et al., 2010b; Oluboyo et al., 2014; Rodriguez et.al, 2019). A better understanding of the relationship between the geomorphic expression of submarine channels and the internal architecture is important in constraining the stratigraphic evolution of deep-water channel systems. Similarly, understanding the interaction between submarine channel systems and basin floor bathymetry is important because channel pathways, geometries, internal architecture, and stratigraphic evolution are controlled by active geological structures (e.g., faults, salt, and mud diapirs) at, or near, the seabed in deepwater settings.

1.2 THESIS AIMS AND OBJECTIVE

This study aims to contribute to the understanding of deep-water reservoir development through the combined analysis of seismic facies, seismic attribute, well log analysis and core description of deepwater systems. Seismic and well data beyond the present-day shelf edge down to the basin floor, was utilized to provides an integrated study of the combined base of slope and basin floor area of deep-water basin i.e., deepwater Taranaki basin and the Central North Sea respectively. A grid of seismic horizon interpretations together with a coherent lithostratigraphic borehole data is used to provide better constraints on the geomorphic evolution of deep-water channels systems (in the Taranaki basin) and how they interact with bathymetric features (i.e., salt diapirs in the CNS) and the resultant controls on the facies distribution and architecture. A particular focus of this study is the integration of seismic attributes from 3D seismic surveys, bore hole data and core data to characterise the evolution of deep-water depositional systems and the internal architectures. This thesis aims to develop approaches usable for studying regional seismic geomorphology in other basins elsewhere in the world.

A combination of dataset across two case studies; (a) 3D seismic, borehole, core and cuttings data from the Taranaki Basin, North Island, New Zealand and (b) 3D seismic, borehole and core data, from the Central North Sea Basin, UK North Sea is utilised in this study. By employing seismic as well borehole data and core interpretation techniques, this study addresses two main objectives which are to understand:

- I. The geomorphic evolution, stratigraphic architecture, and the controls on the stratigraphic architecture of constrained deep-water channel systems in offshore Taranaki Basin, New Zealand.
- II. The interaction between submarine lobes and basin floor bathymetry example salt diapirs, and the implication for stratigraphic architecture on deep-water submarine fans reservoirs in the Central North Sea Basin, offshore UK.

These two case studies present a valuable opportunity to contrast channel geomorphic style, distribution and architecture in channel dominated deepwater system with little or no structural control (for example the Taranaki Basin) and lobe dominated deepwater system with pronounced bathymetric control (for example the Central North Sea).

The Taranaki Basin represents a favourable laboratory for studying deepwater sedimentary processes because:

- The preserved sedimentary succession of deepwater systems in the Taranaki Basin holds vital information about the geologic evolution of channel complexes and the processes that forms them.
- A robust data base of open-source information makes easier accessibility of data utilised in this study. Over 400 drilled petroleum exploration and production wells and extensive high-quality seismic reflection data sets covering the shore to deep-water environments provide the basis for a comprehensive analysis of deepwater systems.
- An extensive exposure of deepwater system outcropping along the coast of the Taranaki Basin peninsula provide a popular destination for developing deepwater models that are utilised to understand deepwater system.

The Central North Basin on the other hand, provides a favourable laboratory for studying bathymetric features (i.e., salt stocks) and their interaction with deepwater sedimentary processes because:

- The distal part of the Central North Sea basin preserved sedimentary succession of deepwater fan systems deposited in a complex basin
- The numerous salt stock structures present in the North Sea provide as priceless opportunity to study the interaction between deepwater system and salt diapirs. This study can also be applied in other deepwater system where the structural control isn't halokinetically related.

The North Sea Basin is considered a mature hydrocarbon province implying the availability of robust exploration and production dataset available for research purposes. Also, huge database of industry as well as research peer-reviewed journals on sedimentary systems makes the Central North Sea a good case study for this thesis.

1.3 RESEARCH GAPS ARISING FROM THE LITERATURE AND RESEARCH OBJECTIVES

Several research gaps have emerged from the overview of existing literature on the investigation of deepwater channels. The geomorphic evolution, the stratigraphic architecture and the interaction of submarine channels and actively growing salt structures (i.e., salt diapirs) in deep water settings are addressed in this thesis:

1. A number of studies using 3D seismic data have addressed submarine channel evolution, their geometries and internal architectures (Abreu et al., 2003; Babonneau et al., 2002; Deptuck et al., 2003, 2007; Fongnesu, 2003; Janocko et al., 2013; Mayall et al., 2006) but only few studies have utilised an integrated approach by integrating seismic, well and drill cuttings to systematically document the spatial and temporal geomorphic evolution of submarine channels, and investigates the translation of geomorphic expression in the stratigraphic architecture of submarine channels example (Prather et al., 1998; Prather, 2003). The analysis in chapter 3 is aimed at addressing this challenge in the Taranaki Basin. The objective here is to constrain the seismic geomorphology of middle Miocene deep-water channels system and to investigate the translation of the geomorphic evolution in the stratigraphic architecture.

2. A number of studies have documented the growth and interaction of structures i.e. salt diapirs with submarine channels (Davison, 2004; Gee & Gawthorpe, 2006; Mayall et al., 2010b; Oluboyo et al., 2014; Rodriguez et al., 2019; Rowan & Vendeville, 2006); however, only few studies have investigated how this structures affects the pathways of submarine channels and submarine flow dynamics. This problem is addressed in chapter 4 where salt diapirs from the Central North Sea Basin was shown to interact with the Palaeocene deepwater depositional system. The objective here is to integrate Seismic, well and cores to understand sediment dispersal and facies distribution around salt diapirs.

3. A number of studies have described many sediments gravity flow deposits in deepwater settings for example MTD, and turbidite however, only a handful of studies have looked at deepwater deposit exhibiting linked debrite and turbidite association (Haughton et al., 2003; Davis et al., 2009; Fonnesu et al., 2016; Haughton, Hodgson, 2009; Kane & Pontén, 2012; Southern et al., 2017). An outstanding question here is how are these deposit form? This is attempted in chapter 5 by applying petrographic (core) analysis approach. The objective here is to describe the stratigraphic architecture and facies distribution of deepwater deposit around salt diapirs. We attempt to link flow evolution and transformation to salt diapirs and the stratigraphic complexity to the response of the submarine fans to pre-existing salt diapirs.

1.4 THESIS OUTLINE

To achieve these aims and objectives, this thesis is organised into seven chapters. Chapters 1 and 2 describes the introduction and background to this study, whereas chapters 3-5 describe each specific aspect of this PhD research project in a journal paper format, which are in the process of being submitted to publication. Chapter 6 is the synthesis of the work presented in chapters 3-5. Chapter 7 is a summary of the conclusions based on the results of this research.

Chapter 2 presents an overview of the study focussing on: (i) deep-water sedimentology and stratigraphy; (ii) seismic imaging of deep-water depositional system; (iii) salt tectonics, with specific emphasis on diapirism and (iv) the interaction between deep-water depositional systems and seafloor topography (i.e., salt diapirs)

Chapter 3 utilizes 3D seismic, bore hole and cuttings data to describe the geomorphic evolution and the stratigraphic architecture of Middle Miocene submarine channel systems, offshore Taranaki Basin, New Zealand. This chapter documents the geomorphic expression, depositional thickness, facies distribution and the subsurface architecture of deep-water channel systems.

Chapter 4 uses 3D seismic, well log, and core data to investigate the interaction between upper Palaeocene deep-water depositional systems and salt diapirs. This chapter describes the influence of salt diapirs in controlling the pathways and the internal architecture of deep-water systems and related reservoirs.

Chapter 5 builds on the work presented in chapter 4 by using core data to characterise the sedimentology and the internal architecture of the Upper Palaeocene, salt-influenced deep-water depositional systems.

Chapter 6 provide a synthesis of key findings from chapters 3 - 5 and integrates these with previously published works on the sedimentology and stratigraphy of deep-water systems, including those controlled by syn-depositional, structurally induced seafloor.

Chapter 7 is a summary of the conclusions that relates to the aims of this study outlined in chapter 1

1.5 PUBLICATION STATUS AND CONTRIBUTUONS FROM CO-AURTHORS

The research chapters are presented as multi-authored manuscripts which at the time of writing this thesis have not been published or submitted yet. The author of this thesis is the first author in all the three chapters/manuscript and is responsible for the interpretation and the material submitted

herein. The co-authors form the supervisory team of the research, and their contribution is outlined below:

i. CHAPTER 3 - SEISMIC GEOMORPHOLOGICAL ANALYSIS AND STRATIGRAPHIC ARCHITECTURE OF SUBMARINE CHANNEL SYSTEMS, TARANAKI BASIN, NEW ZEALAND

Isaac A. Odeh¹, Christopher A-L. Jackson¹, Howard D. Johnson¹, David M. Hodgson² and Ian A. Kane³.

The first author was responsible for analysing and interpreting the seismic and borehole data. The co-authors provide supervision and critically reviewed and discussed interpretations and contributed to the outline and revision of the manuscript.

ii. CHAPTER 4 - CHARACTERISING THE INTERACTION OF THE UPPER PALAEOCENE DEEPWATER DEPOSITIONAL SYSTEM AND SALT-RELATED SEAFLOOR TOPOGRAPHY: FORTIES SANDSTONE MEMBER, SELE FORMATION, UK CENTRAL NORTH SEA

Isaac A. Odeh¹, Christopher A-L. Jackson¹, Howard D. Johnson¹, David A. Hodgson² and Ian A. Kane³

The first author was responsible for analysing and interpreting the seismic and borehole data and the sedimentological core descriptions. The co-authors provide supervision and critically reviewed and discussed interpretations and contributed to the outline and revision of the manuscript.

iii. CHAPTER 5 - INTERACTION OF SALT DIAPYRS WITH UPPER PALAEOCENE DEEP-WATER DEPOSITIONAL SYSTEM AND IMPLICATION FOR COMPLEX STRATIGRAPHIC ARCHITECTURE AND FACIES DISTRIBUTION: FORTIES SANDSTONE MEMBER, SELE FORMATION, CENTRAL NORTH SEA

Isaac A. Odeh¹, Christopher A-L. Jackson¹, Howard D. Johnson¹, David A. Hodgson² and Ian A. Kane³.

The first author was responsible for analysing and interpreting the sedimentological core descriptions. The co-authors critically reviewed and discussed interpretations and contributed to the outline and revision of the manuscript prior to submission.

CHAPTER 2

OVERVIEW OF DEEPWATER SEDIMENTOLOGY AND STRATIGRAPHY

Deep-marine depositional systems are sourced from the hinterland areas, with sediment transported via submarine canyons to the basin floor environment. These systems are commonly associated with major submarine fans, as such the Amazon Fan, Mississippi Fan, Bengal Fan and the Congo/Zaire fan that commonly develop in passive margin settings (Babonneau et.al., 2010a; Babonneau et.al., 2002; Damuth et.al., 1988; Damuth et.al., 1983). The deep-marine environment extends from the outer edge of the continental shelf, through the slope and into the basin floor environment (Figure 2.1). Siliciclastic deposits formed the largest volumes of sediments transported as sediment gravity flows into the deep water environment via submarine canyons as sediment gravity flows (Walker, 1978).

The Miocene to Recent period in the Taranaki Basin is characterised by extensive deepwater processes. From the shelf to the basin floor, channelisation and deposition of fans continues into the basin floor and extends into the New Caledonia Trough (Uruski & Wood, 1991). The middle Miocene lithofacies units (our interval of interest), are subdivided into basinal mud (Manganui Formation), lower slope to basin floor fans and channels of the Moki Formation (King & Thrasher, 1996). The earliest sand-dominated basin-floor fans that routed into the basin is the Moki Formation (Bussell, 1994). This was followed by a later phase of fan deposition around the central part of the basin which was named Moki B (Bussell, 1994) or SW sands based on its New Stage association (King & Thrasher, 1996). The entire middle Miocene succession occur as sheet sands and channel deposit with good reservoir quality especially in wells drilled around Kupe and Maui Fields towards the southern part of the basin (Baur, et.al., 2010; Bussell, 1994; Kamp et al., 2004; King & Thrasher, 1996). The Moki Formation and the SW Sand show a distinct wireline log signature of stacked tabular, sandstone packages with sharp upper and lower bed contacts with the marine basin floor mudstones of the Manganui Formation (Bussell, 1994; De Bock, 1994; King & Thrasher, 1996).

The Palaeocene stratigraphic framework of the North Sea has been extensively studied (Deegan & Scull, 1977; Knox & Holloway, 1992; Morton & Knox, 1990; Mudge & Bujak, 1994). In the Central North Sea, the Moray Group consists of the Sele Formation and the associated Forties Sandstone Member (the main hydrocarbon reservoir unit across the Central Graben). The Sele Formation and the associated Forties Sandstone Member is underlain and overlain by the Lista Formation and the tuffaceous Balder Formation respectively. Downdip (i.e., NW–SE) of the Central North Sea, the Forties Sandstone facies changes from (i) sand-rich stacked channels and lobes to stacked lobes showing high lateral facies variation and (ii) sand-poor lobes. Our understanding of the subregional facies variation of the turbidite sands within the NW-SE depositional trends, around salt diapirs is limited. It is unclear if the salt diapirs are the majors cause of the facies variation within the Forties Sandstone.

Hydrocarbon exploration in deepwater turbidite succession for example deepwater West Africa and within subtle stratigraphic traps in salt influence basins e.g., the Gulf of Mexico, Offshore Angola and Brazil has made the middle Miocene Moki Formation and the Palaeocene Forties Sandstone member good cases study for documenting the (i) deepwater channel evolution and (ii) salt-sediment interaction in salt influenced basins.

2.1 SEDIMENT TRANSPORT PROCESSES & SUBMARINE SEDIMENT GRAVITY FLOW EVOLUTION

Sediment gravity flows, including turbidity currents – both high and low density turbidity currents, debris flows, bottom ocean currents and hybrid flows are the main processes of transporting siliciclastic sediments down the slope and into deep-water settings (Bouma, 1962; Walker, 1978; Haughton, et.al, 2009; Lowe, 1982; Stow, et.al, 1999) (Figure 2.2). However, the mechanism of deep-water sandstones deposition is often argued, but widely attributed to either turbidity currents – both high and low density turbidity currents (Talling, et.al, 2005; Baas, 2004; Bouma, 1962; Hansen et al., 2015; Hansen, et.al, 2017; Stow et al., 1999; Stow, 1982; Stow & Johansson, 2000; Walker, 1976) or sandy and muddy debris flows (Shanmugam & Moiola, 1988; Stow & Johansson, 2000), and bottom ocean currents (Rebesco, et.al, 2014; Stanley, 1993; Stow & Smillie, 2020). More recently, it has been shown that flow transformation between the two flow types can generate hybrid gravity flow deposits (Haughton et.al, 2003; Haughton et.al., 2009; Mulder & Alexander, 2001; and Talling, 2013).

Sediment gravity flows are typically associated with slope failure and a subsequent downslope movement of sediment under the pull of gravity. These deposits are termed sediment gravity flow deposits (Covault et.al, 2011; Hampton, 1972; Maier et al., 2011; Stow & Johansson, 2000). The processes and triggers of shelf-edge sediment failures and downslope movement occur in various forms (Figure 2.2). The most common trigger factors include (i) storm wave when sea level is below storm wave base and (ii) seismically-induced failure as a result of catastrophic earthquake (Normark et.al., 2002; Shanmugam, 2009, 2017). Many types of sediment gravity flows have been described and they include; (i) slide - where a coherent mass of sediments bounded on all sides by distinct failure plane occurs without internal deformation (ii) slump - where the detached coherent rotational mass of sediments blocks show some internal deformation during transportation (iii) debris flows – a sediment flow showing plastic or laminar rheology and (iv) turbidity current – sediment flow showing Newtonian rheology and turbulent state and the sediment are supported by flow turbulence (Covault et al., 2011; Shanmugam, 2009, 2017) see (figure 2.2).

2.2 FACIES ANALYSIS

The concept of facies and facies analysis was devised by sedimentologist to aid in the classification and description of ancient sediments (Miall, 1985). The term facies originated from the Latin word *facia* or facies means external appearance or look of something. Sedimentary facies are one of the commonest yet debated term in sedimentology. Introduced by (Gressly, 1838) to describe the sum of lithological and palaeontological features of a stratigraphic unit, the subsequent interpretation and use of the term facies remains a point of argument among geologist particularly sedimentologist (Middleton, 1973). Sedimentary facies is the interpretation and description of the structures, fossils, and lithologic associations of sedimentary rocks on the scale of an outcrop, well section, or small segment of a basin (Anderton, 1985; Miall, 1990; Reading, 2001) (Figure 2.3). Despite the argument associated with the usage of the term facies, the last 3-4 decades saw the adoption of the term facies to encapsulate distinctive body of rocks formed under certain conditions, processes, or environment of deposition. Today, the term facies is widely used in both fluvial systems example (Miall, 1985, 1990) and deep-water sedimentology and stratigraphy example (Bouma, 1962; Mutti, 1977; Pickering, et.al, 1986; Walker, 1976).

Process sedimentology and environment of deposition has implications for predicting the facies classification and geometries of deep-water deposits, particularly in controlling large-scale sand body geometry and stratigraphic architectures (Pickering et.al., 1986; Pickering, Corregidor, & Clark, 2015). The term facies is now used in both descriptive and interpretive sense (Anderton, 1985; Miall, 1990). While the interpretive sedimentary facies summarizes a set of features such as processes and environment of deposition of certain rock units e.g. turbidite or debrite; descriptive sedimentary facies on the other hand, summarizes the grain size, geometry and structures e.g. fine grained

sandstone, cross bedded sandstone (Anderton, 1985; Walker, 1978; Middleton, 1973; Reading, 2001). Recently, there are clamour for facies analysis based solely on environment of deposition e.g. deltaic facies, fluvial facies, deepwater facies (Anderton, 1985; Miall, 1990; Reading, 2001; Stow, 1985; Walker, 1976).

Several works on facies analysis of deepwater systems has over the years improve our understanding of facies distribution in both ancient and modern deep-water system (Bouma, 1962; Mutti & Ricci Lucchi, 1978; Mutti, 1977; Pickering et al., 1986; Reading & Richards, 1994; Stow & Smillie, 2020; Stow, 1982). Deep-water facies are classified based on their processes i.e. turbidite, debrite, hemi pelagite, contourite, muddy and hybrid event bed facies (Stow & Smillie, 2020; Stow, 1982). Deep-water facies are also classified based on their bedding style and thickness, sedimentary structures, composition, and textures into (a) facies classes example gravels (or conglomerate) sandy, silty, and muddy, (b) facies group and (c) constituent facies. Seven facies classes are identified in deepwater systems (A – G i.e. gravel – oozes and marls) (Mutti & Lucchi, 1978). (Stow, 1985) reclassified these facies into facies classes (A – E i.e., gravel to mud), (F i.e., debrite and MTCs) and (G, i.e., comprises of purely biogenic oozes), based on their thickness, structures, and bedding type (Figure 2.4).

The key to interpreting process sedimentology is by defining individual facies in a community of facies association. When distinctive facies are related genetically and physically with each other, they form facies association (Figure 2.5) that are commonly repeated in the stratigraphic records (Stow, 1982). Example: facies association that defines fluvial channels, swamps and peat bogs commonly describe fluvial over-bank deposit. Similarly, facies association that defines deepwater channels, overbank and basin floor commonly describe deepwater deposit. A progressive change in space and time, of certain facies properties either vertically or laterally i.e. upward increase in clay or sandstone constitute facies succession or sequences (Walker, 1978). In deepwater systems, facies sequence or succession aid in clarifying the ambiguities associated with the processes, description, and environmental interpretations of deepwater facies example current lamination are unique to either fluvial or deepwater systems.

Architectural elements comprise of a combination of facies association and forms the building block of deepwater depositional system (Abreu, et.al, 2003; Janocko, et.al, 2013; McHargue et al., 2011; Posamentier & Kolla, 2003). Some channel fills are filled with low amplitude channels suggesting muddy channel fills. The levees/overbank are found banking the channels and they are formed by overspilling of sediment onto the channel bank when the channel is overfilled (Posamentier & Kolla, 2003). Seismic cross section shows the overbank to comprise of interbedded high and low amplitude reflection packages. This could suggest facies variability away from the channel fills. When the overbank is breach, channel splays and avulsion resulting in channel changing its cause of movement (Janocko et al., 2013; Posamentier, 2003). The basin floor mudstone elements are normally characterised by low amplitude reflection packages. They are normally cut across by the channel belts.

The main sedimentary structures observed in deepwater facies are either depositional or erosional. While the depositional sedimentary structures or primary sedimentary structures are produced by the processes of deposition e.g., plane bedding and crossbedding, the erosional or secondary sedimentary structures are produced by post depositional biogenic, chemical, or mechanical modification of sediments. Sedimentary structures are valuable tools in facies and process interpretation because they provide wealth of information on the mode and environment of deposition. In this thesis, post depositional sedimentary structures were observed in the Central North Sea. Also, there are documentation of primary sedimentary structures observed on outcrop exposures along the coast of North Island, Taranaki basin (Rotzien et al., 2014) (Figure 2.6).

Facies models have been a useful tool in putting into perspective, sedimentary processes and the resulting sedimentary facies (Walker, 1978). Facies models are based on inferred process by which sedimentary facies are formed and the information extracted from outcrop exposures are put into a 3D facies model for a better picture of depositional processes and the facies deposited (see Figure 2.3). Turbidite facies model has been the classic model used to describe and interpret ancient and modern deepwater depositional systems (Bouma, 1962; Reading, 2001) (Figure 2.3). The usage of this term is debatable and depend on individuals' observations.

In this thesis, we adopted the facies classification of (Walker, 1978; Walker, 1976) i.e. sandstone (i.e. fine to very fine) facies, silty facies, debrites (i.e. consisting of chaotic internal architecture) facies, basin floor mudstone facies and hybrid event bed facies. We also utilized the Markov chain facies analysis of facies succession of (Miall, 1990) particularly in chapter five to characterise core facies distribution in the Central North Sea. The sedimentary facies observed in this thesis are grouped into base of slope and basin floor facies association. These facies association show either a general upward finning or coarsening upward facies succession. The sandstone facies are often overlain or underlain by silty- mudstone facies e.g., in the Taranaki basin. In the Central North Sea, the sandstone facies are in most case overlain by linked debrite forming a hybrid event bed. The bed boundary is either sharp or gradational.

2.3 SEISMIC FACIES AND SEISMIC GEOMORPHOLOGY – OVERVIEW

Seismic facies have proven to be the fundamental stratigraphic approach in the observation of seismic reflection patterns from sedimentary strata hence it is commonly associated with seismic stratigraphy. This term comes to bear when interpreting and modelling sedimentary facies from seismic reflection data (Mitchum & Vail, 1977; Van Wagoner et.al., 1987;). Seismic reflections are shown to approximate to geologic timelines and represent certain genetically related depositional sequences, system tracts or depositional environment (Mitchum, et.al., 1977; Vail, 1977; & Van Wagoner et al., 1987;). Seismic facies are usually delineated based on reflection configurations, geometries, continuities, frequencies and termination (Table 2.1) and they may extend laterally across different depositional environments and incorporate a variety of lithofacies units (Mitchum & Vail, 1977a; Sangree & Widmier, 1979;). Within each depositional sequence lies a suite of seismic facies with a unique regional distribution, frequency, stratal geometry, reflection pattern, reflection continuities, thickness pattern, and geologic history. By integrating seismic facies with borehole data (i.e., well log data, core & cuttings data), important geologic features such as sedimentary facies or physical rock properties can be better understood.

Seismic stratigraphy i.e., a direct extraction of seismic information from seismic reflection data (vertical seismic profiling) and seismic geomorphology i.e., the plan-view investigation of seismic data was made possible owing to the rapid evolution of 3D reflection seismology (Kolla et al., 2007; Posamentier, et.al., 2007; Posamentier & Kolla, 2003). Seismic geomorphology and seismic stratigraphy have become one of the key steps in seismic interpretation (Burton & Wood, 2010; Hadler-Jacobsen et.al., 2007; Sarkar, et.al., 2010; Wood & Mize-Spansky, 2009; Zeng, 2007). Seismic geomorphology is the characterisation of seismic facies using seismic attributes. Seismic attributes represent a measure of specific constituents of the seismic signal such as reflection amplitude or continuity (Chopra & Marfurt, 2007; Haskell, et.al., 1995).

Effective and efficient seismic geomorphology workflow consists of three steps:

- Identification of seismic facies types within a depositional element and integrating it with geologic data e.g., well data, cores, and cuttings
- Seismic characterisation of seismic facies from seismic data using both volume and surface attributes to generate seismic attributes maps and,
- The display of the spatial distribution of these facies on a surface map that correlates to a time-slices, and mapped horizons.

2.4 THE EVOLUTION, GEOMETRY, AND INTERNAL ARCHITECTURE OF DEEP-WATER CHANNEL SYSTEMS

The evolution of deep-water depositional systems has been widely documented in many basins, such as in offshore West Africa, Angola, Brazil, Central North Sea, Gulf of Mexico (GoM) and offshore North Island, New Zealand (Burgreen & Graham, 2014; Den Hartog Jager, Giles, & Griffiths, 1993; Doughty-Jones, Mayall, & Loneragan, 2017; Gee & Gawthorpe, 2007; Hansen et al., 2017; Hartog Jager, Giles, & Griffiths, 1993; Morris, et al., 2014). The temporal and spatial evolution of deep-water systems has a significant impact on the scale, distribution, architecture and stratigraphic trapping of deep-water reservoirs (Mayall, et al., 2006; Prather, 2003). Deep-water systems were shown to have evolved by erosion, aggradation and deposition (Covault, et.al, 2016; Hodgson, et.al, 2011; Jobe et al., 2015; Maier et al., 2012; Rotzien et al., 2014).

The morphology, geometry, and the stratigraphic architecture of deep-water channel systems have been well studied in many sedimentary basins including offshore West Africa (Navarre, 2002; Adeogba, 2003; Deptuck et al., 2003, 2007; Adeogba et al., 2005; Babonneau et al., 2010; Jobe et al., 2017;), the Amazon channels (Damuth et al., 1983; Flood and Damuth, 1987; Damuth et.al, 1988; Pirmez and Flood, 1995;), offshore Angola (Gee & Gawthorpe, 2007; Oluboyo, et al., 2014), offshore Brazil (Rodriguez, et al., 2019) and in the Central North Sea (Den Hartog Jager et al., 1993; Hempton et al., 2005; Jones, et al., 2015).

The internal architecture of deep-water systems was shown to comprises of the following depositional elements: channels fills, levees/overbank and splays, lobes, and basin floor mudstones (see Figure 2.6) (Deptuck et al., 2003; Doughty-Jones et al., 2017; Janocko, et al., 2013; Mayall et al., 2006; Posamentier, 2003). A plethora of work has been done on channel depositional element e.g. channel-fills element (Posamentier and Kolla, 2003; Gamberi et al., 2013; Janocko et al., 2013; Hansen et al., 2017;), levees both internal and external (Posamentier, 2003; Kane et al., 2007a, 2007b, 2010; Kane and Hodgson, 2011; Janocko et al., 2013;), and channel bend mounds or nested mounds (Janocko et al., 2013; Posamentier, 2005). However, constraining the geometry, architectures, and lithology distribution of these depositional elements from planform morphology remains a challenge.

Many approaches have been adopted and utilized to understand the internal architecture of deep-water systems i.e., field-based and core/drill cutting analysis, 2D/3D seismic analysis and borehole or well log analysis. Field-based studies and core/drill cutting scale analysis provides reliable, high resolution information about the internal architecture of deep-water systems (Helle, 2003; Hodgson, et al., 2015; Kane & Hodgson, 2011; Masalimova, et al., 2016). In the last four decades, high resolution 3D seismic was also utilized in seismic geomorphology analysis of submarine systems to understand the morphology of deep-water systems (Deptuck et al., 2007; Kolla, et al., 2007; Posamentier & Kolla, 2003; Sawyer, et al., 2007; Zhu, et al., 2016). Seismic geomorphology is a powerful tool used to understand the long-term, long length-scale, temporal and spatial evolution of submarine systems, including prediction of large-scale stratigraphic architecture of thick sedimentary packages (Deptuck et al., 2007; Gee and Gawthorpe, 2007; Sawyer et al., 2007; Zeng, 2007; Wood and Mize-Spansky,

2009; Qin et al., 2016;). Borehole or well log analysis utilizes the electrical properties of rocks to characterise the internal architecture of deepwater systems.

When these three approaches are calibrated with each other i.e., calibrating seismic geomorphology with well logs, provides reliable information about subsurface stratigraphy (Prather, 2003;). Similarly, integrating 3D seismic and other petrographic techniques such as core/drill cuttings analysis, and field-based studies of outcrop exposures provides insights in constraining the facies distribution of deepwater depositional systems (Grain, 2008; Jobe et al., 2017; Mayall et al., 2006). The stratigraphic architecture of deepwater channel systems, display a variety of complexities. The channel axis is characterised by less facies variability which increases away from the channel axis, towards the levees and splays environment (i.e. predominance of heterolithics) (Brunt & McCaffrey, 2007; Deptuck et al., 2003, 2007; Doughty-Jones et al., 2017; Mayall et al., 2006). The basin floor mudstones are predominantly made of muds and clay grade materials.

2.5 CONTROLS ON THE EVOLUTION AND THE STRATIGRAPHIC ARCHITECTURE OF DEEPWATER DEPOSITIONAL SYSTEMS

The controls on the evolution and the stratigraphic architecture of deepwater depositional systems has been widely documented e.g. (Bernhardt, Jobe, & Lowe, 2011; Covault et al., 2016; Hansen et al., 2017; Kane et al., 2008; Oluboyo et al., 2014; Sawyer et al., 2007). These controls are either extra-or-intra basinal in nature. Extrabasinal controls (i.e. allocyclic controls) such as source area, shelf gradient and width, fall in relative sea level caused by either eustacy or tectonics, climate and, the characteristics of the drainage basin, influences (i) the type, forms and volume of sediment delivered to the shelf edge and ultimately, to the basin floor area, (ii) influences the timing, volume and type of the sediment deposited on the basin floor (Damuth et al., 1988; Flood & Damuth, 1987). Intrabasinal controls (i.e. autocyclic factors) such as those associated with individual channel and lobe systems, and bottom ocean currents reworking (Stow, 1982; Stow & Johansson, 2000; Wood & Mize-Spansky, 2009), influences the nature, size, and shape of channel and lobe deposit (Figure 2.7). Intra basinal structural highs may cause physical obstacles, for example related to older and younger fault fabrics/or salt or mud diapirs (Rodriguez et.al., 2019). Also, older stratigraphy create rugose exposure of pre-existing stratigraphy i.e. MTC example (Nwoko, Kane, & Huuse, 2020), contourites and in some cases turbidites.

Seafloor topography is widely recognized as the dominant intra basinal factors controlling the spatial and temporal distribution of deep-water deposits (Amy et al., 2005; Kneller, et al., 2016; Pickering, et al., 2015; Prather, et al., 1998; Prather, 2003; Vining, et al., 1993). Salt related structures, forms one of the key sea floor bathymetric features controlling deep-water depositional systems (Gee & Gawthorpe, 2006; Oluboyo et al., 2014; Rodriguez et al., 2019). Salt tectonics (halokinesis) deals with the processes of deformation of a thick layer of salt (i.e., evaporites) within a stratigraphic sequence of rocks and the geometries created as result of those processes. Salt structures are identified in many sedimentary basins partly because of the hydrocarbon resources associated with their occurrences (Hudec & Jackson, 2006, 2007).

Salt structures i.e. salt diapirs, salt welds, and salt walls are identified in the Central North Sea basins (Davison, et al., 2000; Hughes & Davison, 1993), Offshore West Africa (Dooley, Jackson, & Hudec, 2007; Gee & Gawthorpe, 2006; Hudec & Jackson, 2007; Morris et al., 2014; Oluboyo et al., 2014), Gulf of Mexico (Jackson & Rodriguez, 2014; Rodriguez et al., 2019; Talbot, 1993) and Offshore Brazil (Kang et al., 2018; Mohriak et al., 1995; Rodriguez et al., 2019). These salt structures could either be formed by passive processes (i.e. during continued sedimentary loading), active processes (i.e. during active tectonic processes) and reactive processes (due to salt layer flowing to areas of low pressure around

developing faults and folds)(Davison, 2005; Hudec & Jackson, 2007; Hughes & Davison, 1993; Jackson et al., 2014; Oluboyo et al., 2014) (Figure 2.8). Similarly, salt detached fault system (i.e. salt propagation fault i.e. radial and concentric faults), (Coleman, et al., 2017; Dooley et al., 2007), and salt welds (welding of supra-salt and subsalt stratigraphy resulting in the thinning of salt layer due to dissolution, detachment or removal) (Callot, et al., 2016; Rowan, et al., 2016) also occur in association with salt tectonics.

Similarly, other structural features such as faults, growing fold and thrust, detachment folds, and structural features created by older stratigraphy, are shown to have influenced submarine systems evolution. A number studies of many deep-water systems have shown, quantitatively that salt structures i.e. salt diapirs, growing folds and thrust faulting interacts with deep-water depositional systems, thus controlling their location, pathway, internal architecture and the reservoir distribution (see Figure 2.8) (Doughty-Jones et al., 2017; Gee & Gawthorpe, 2006; Jolly et al., 2017; Jolly et al., 2016; Mitchell et al., 2021). These studies example (Jolly et al., 2017; Jolly et al., 2016; Mitchell et al., 2021) have shown that active submarine channel responds to tectonic deformation by increasing their slope and depth of incision with little or no change to the planform width. For example, in the Niger Delta basin, Salt related seafloor topography results in confinement, diversion, deflection and ponding of deep-water systems (Clark & Cartwright, 2011; Kane, et al., 2012; Mayall et al., 2010; Oluboyo et al., 2014; Rodriguez et al., 2019; Stewart & Clark, 1999). Characterising the interaction of salt-sediment interaction is key to constraining reservoir facies distribution in deepwater system example (Lonergan et al., 1998; Mayall et al., 2010a).

2.6 METHODOLOGY – OVERVIEW

Available for this study are 3D seismic datasets each from the two case studies (i.e., the Taranaki Basin and the UK Central North Sea Basin), borehole data, cores and cuttings. Even though each chapter of this thesis has a dedicated section for methodology, this section intends to give an overview of the methodology adopted in this thesis. A Three-part methodology approach was adopted for the datasets available for this study. The first part of the methodology involves the typical seismic interpretation, seismic facies analysis and seismic geomorphology. Well-to-seismic-tie was utilised to map seismic horizons within the interval of interest for example the Taranaki Basin. In the UK Central North Sea, well-to-seismic-tie has given a rather bad tie due to the influence of the salt structures and hence wasn't completely relied upon for interpretation. Seismic interpretation in the CNS was however, based on seismic horizons mapped on published literatures (Charles & Ryzhikov, 2015;) (see Figure 2.9). Seismic facies analysis was employed to correlate seismic reflection patterns to tied borehole data. Seismic geomorphology however, allowed for the planform analysis of the geomorphic expression of deepwater systems. The general procedure involved in seismic geomorphology (i) direct calculations of seismic attributes (volume attributes) from seismic data, (ii) Horizon mapping and structure map generation to facilitate facies character investigations, (iii) Surface attribute extraction from mapped seismic horizon interpretation (horizon attributes) to display the seismic facies distribution in map view.

The second part of the methodology involves the petrophysical analysis of well data supported by limited drill cuttings (e.g., the Taranaki Basin). A combination of gamma ray (GR), density, neutron and sonic logs were used for lithological interpretation in both the case study. The consistent relationship between GR log response and lithologies described in drill cuttings allows for lithology estimation based on Vshale cut-off. Gamma ray (GR) log motif (facies) (e.g., bell-shaped, cylindrical and funnel shaped log profiles) were also used to infer smaller-scale depositional genetic units and architectural elements, in part based on their calibration with seismic-derived geometrical observations. These GR

log motifs were integrated with a well correlation panel to understand the sub-regional changes in the vertical and lateral arrangement of depositional elements.

The third part of the methodology involves core description using visual inference of lithologies from core samples and photos in both the Taranaki Basin and the UK CNS cases studies. Sedimentological investigation of lithologies from the interval of interest was examined using a graphic log and the lithologies are grouped into facies and facies association. We took the core analysis a step further by utilizing Markov chain analysis to have a good understanding of the lateral and vertical facies variability. Markov analysis is a process that consists of a finite number of states with the Markovian property and some transition probabilities p_{ij} , where p_{ij} is the probability of the process moving from state i to state j . When applied to stratigraphic sections, Markov chains, are suitable for the description of geological cycles which is provided by the eigenvalues of the Markov matrix. By applying the methods to a lithofacies of the Forties Sandstone Member, UK Central North Sea, a vertical as well lateral facies transition was established.

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Table 2. 2 Seismic facies character and geologic interpretation (modified from & Widmier, 1979). General attribute examples used in this study are shown on the right column.

Seismic facies parameters	Geologic interpretation	General seismic attribute examples	Example from this study
Reflection configuration	Depositional processes, erosion, and paleotopography	Coherency, Dip, lateral amplitude variations	Delineate channel geometry from amplitude variations on horizon attribute maps from 3D seismic
Reflection continuity	Bedding continuity, depositional processes	Coherency	Delineate channel orientation from variance attribute maps from 3D seismic data
Reflection amplitude	Velocity-density contrast, bed spacing, fluid content	RMS amplitude, Instantaneous amplitude	Map channel systems, and other deepwater facies using RMS attribute amplitude maps from 3D seismic data
Reflection frequency	Bed spacing, layer thickness, and fluid content	Instantaneous frequency, Dominant frequency	Useful in differentiating bedding character between channel and surrounding sheet deposits. This attribute was not utilised in this study
External form and areal association	Gross depositional environment, sediment source, geologic setting	Curvature, Dip	This attribute was not utilised in this study

FIGURE CAPTION

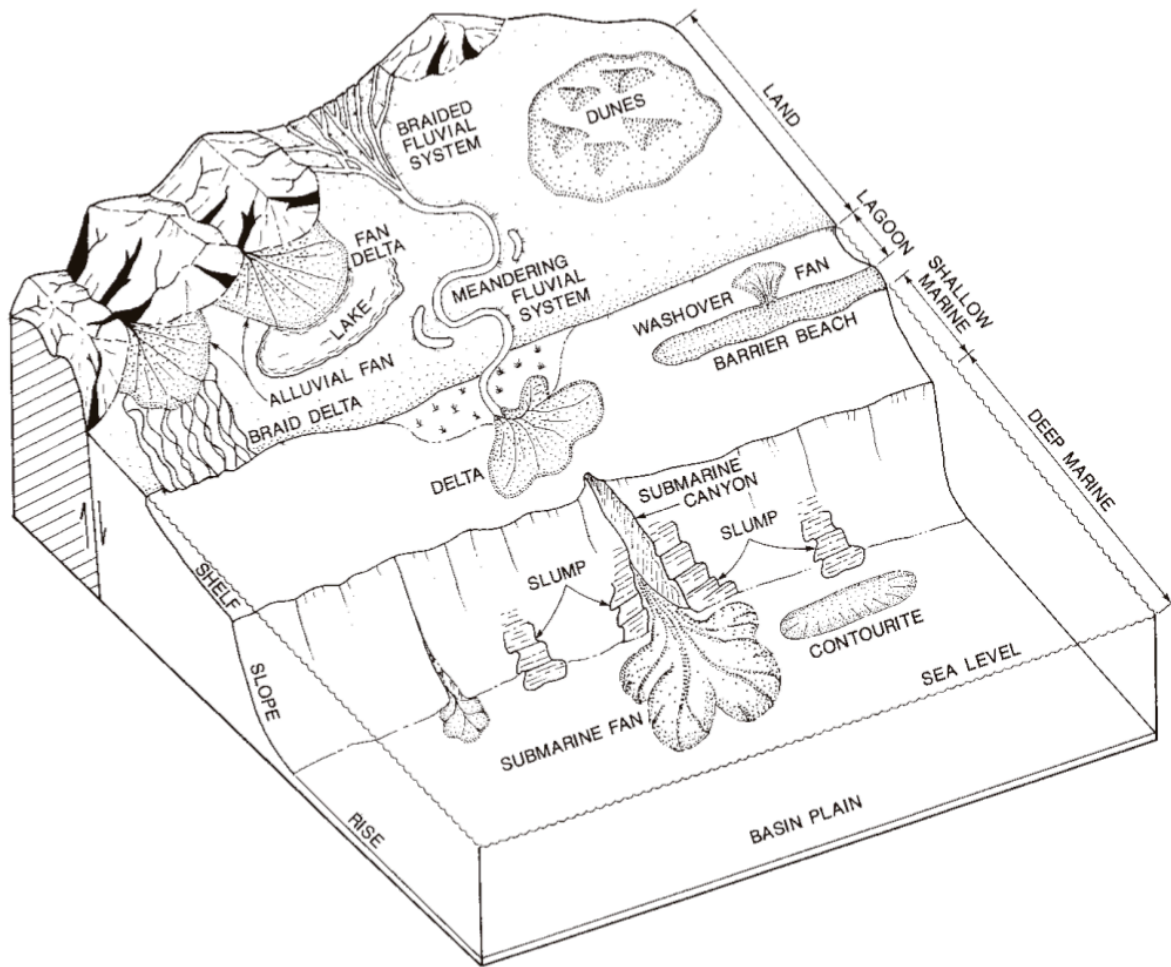


Figure 2. 1: Conventional block diagram of sedimentary depositional environment i.e., from fluvial, alluvial, delta down to deep-marine systems showing a submarine fan formed by turbidity current; Walker (1976)

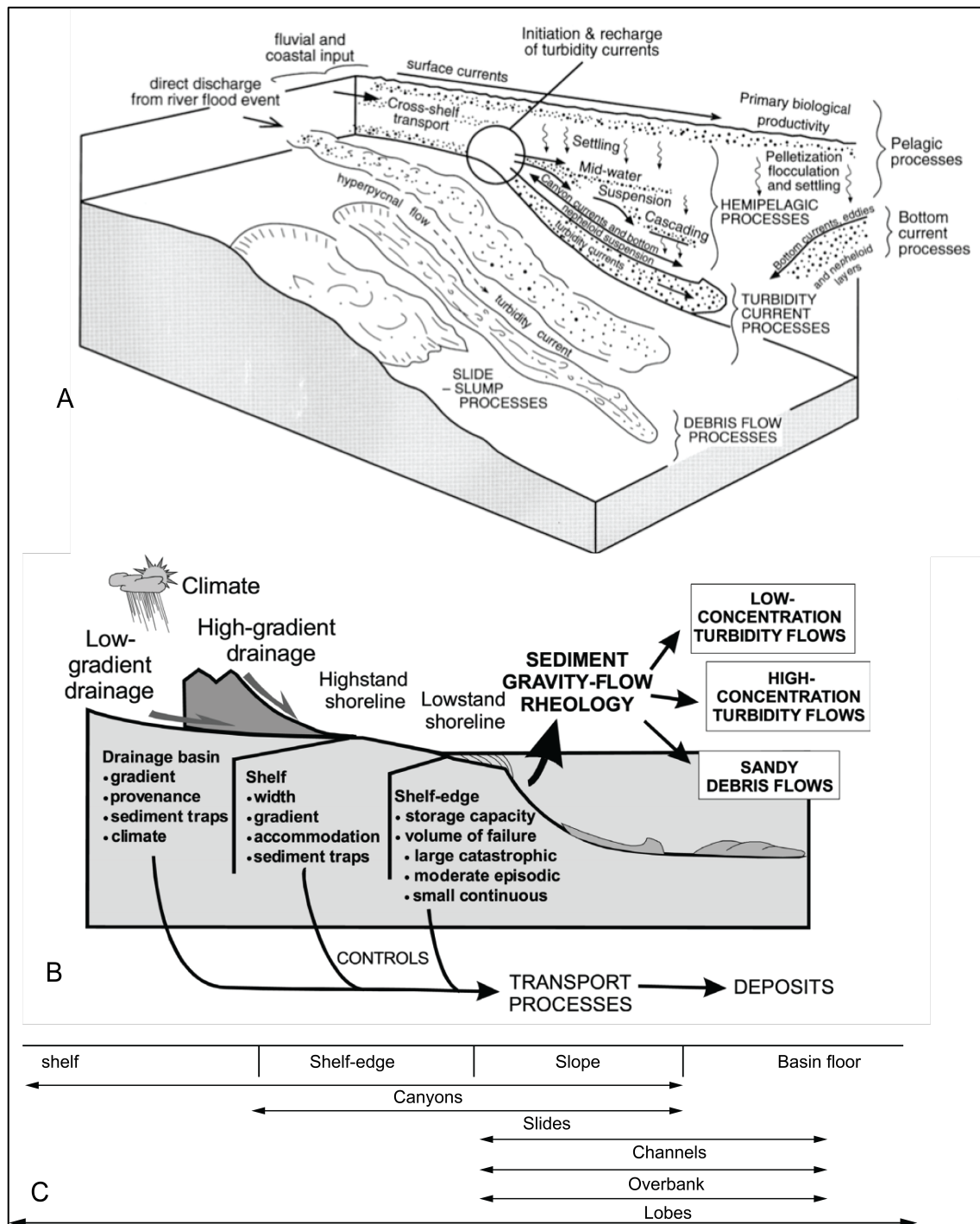


Figure 2. 2: (A) Schematic Block diagram depicting the range of processes that influence the transport of sediment gravity flows in deepwater settings (Stow and Mayall, 2000). (B) Schematic cross-section across a margin, illustrating the sediment delivery system and (C) Line drawing depicting a shelf-basin floor physiography and associated depositional system (Garfield et.al 2005)

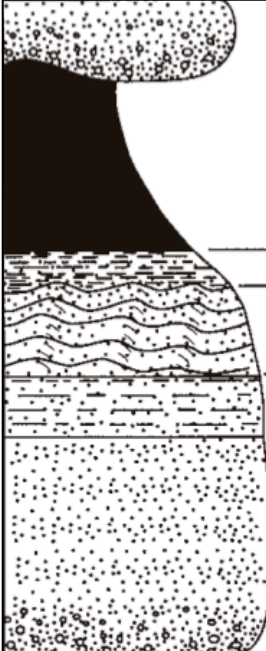
	Grain Size	Bouma (1962) Divisions		Middleton and Hampton (1973)	Lowe (1982)
	Mud	Te	Laminated to homogeneous	Pelagic and low - density turbidity current	Pelagic and hemipelagic
	Sand - Silt	Td	Upper parallel laminae	Turbidity current	Low-density turbidity current
		Tc	Ripples, wavy or convoluted laminae		
		Tb	Plane parallel laminae		High-density turbidity current
	Sand - (to granule at base)	Ta	Massive, graded		

Figure 2. 3: Turbidite facies model (Bouma sequence) showing the individual facies Ta, Tb, Tc, Td and Te divisions. The entire sequence is conventional interpreted as a product of a turbidity current (Bouma, 1962, Walker, 1965, Middleton, 1973). Lowe (1982) Reclassified the Bouma sequence into Ta, deposited by high density turbidity current and Tb – Td deposited by low density turbidity current

Class	Group	Facies				
		1	2	3	4	5
A Gravels + pebbly sands	A1 Disorganized grvl + p.sst					
	A2 Organized p.sst					
B Sands	B1 Disorganized					
	B2 Organized					
C Sand - mud units	C1 Disorganized					
	C2 Organized					
D Silts + silt-mud units	D1 Disorganized					
	D2 Organized					
E Muds	E1 Disorganized					
	E2 Organized					
F Chaotic mixed-grade units	F1 Isolated displaced clasts					
	F2 Contorted + disturbed beds					
	F3 Muddy gravel + pebbly mud					
G Oozes + 'Arls'	G1 Ooze					
	G2 Arl					

Figure 2. 4: The main classes of sediment facies recognized in deepwater systems. Over 50 distinct facies have been identified as illustrated (modified after Mutti & Ricci Lucci, 1978)

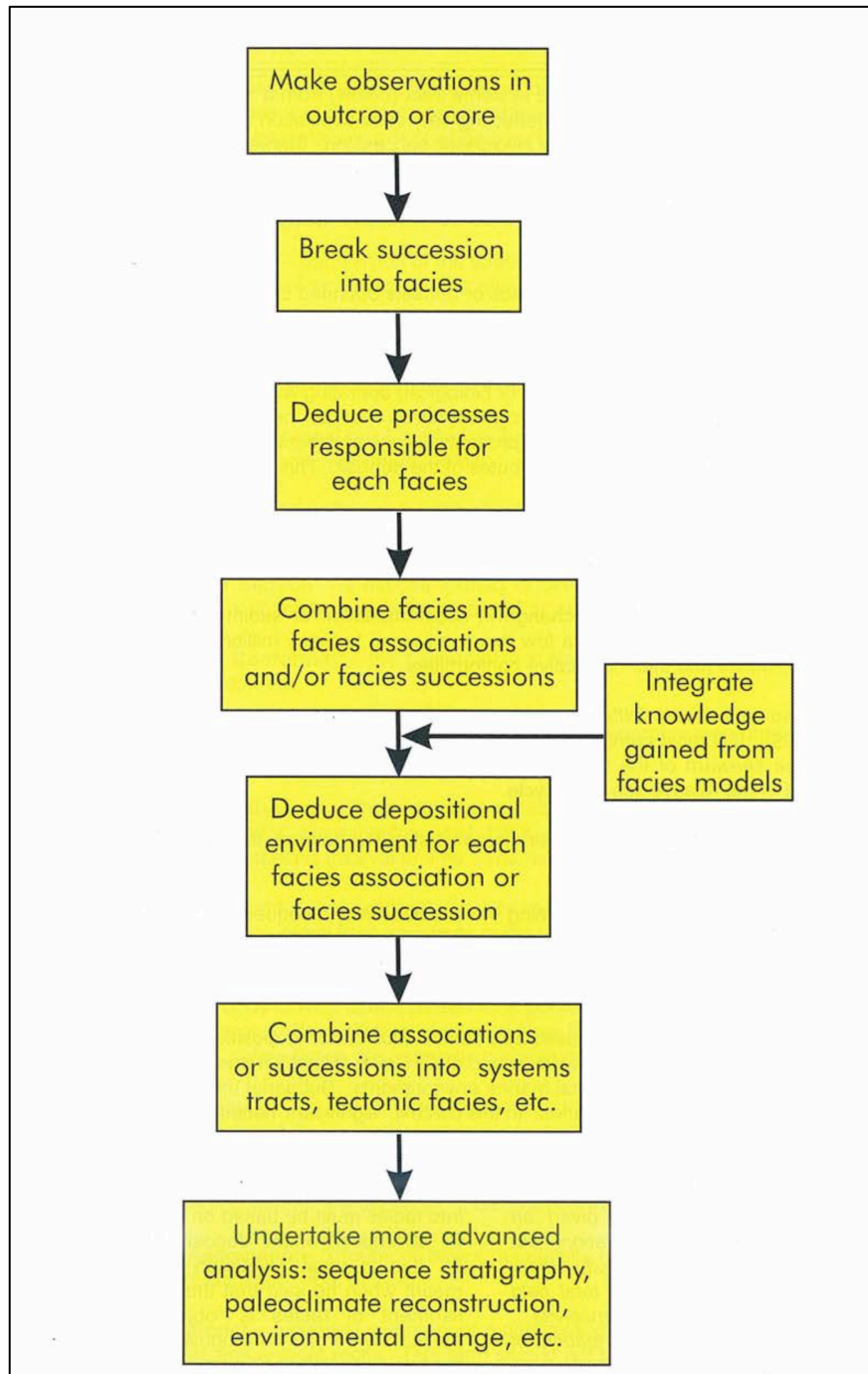


Figure 2. 5: Flow chart illustrating the processes involved in facies analysis.

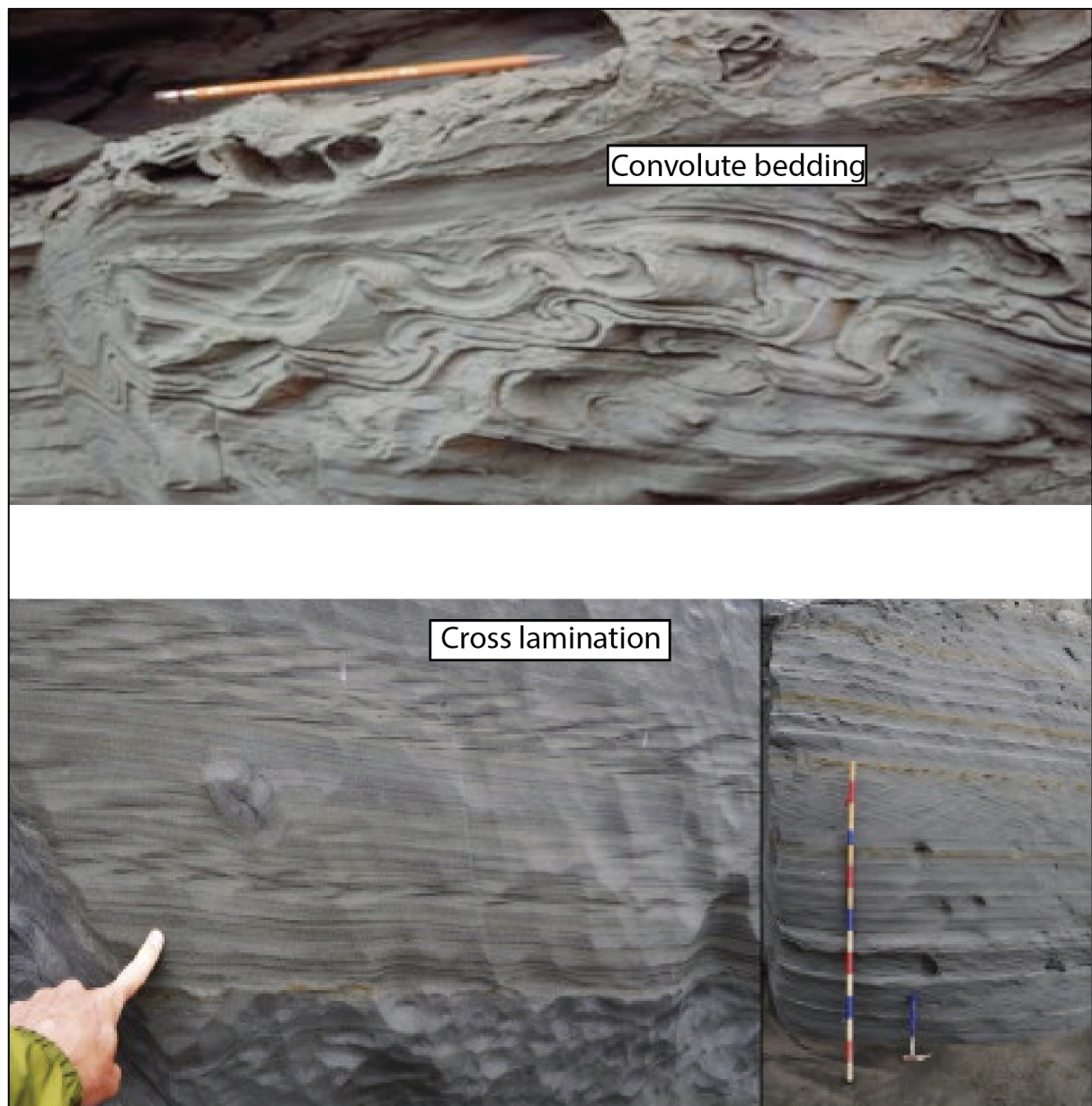


Figure 2. 6: Post depositional sedimentary structures and Primary sedimentary structures taken from the Taranaki Coast (Grain, 2008; Rotzien, et.al, 2014)

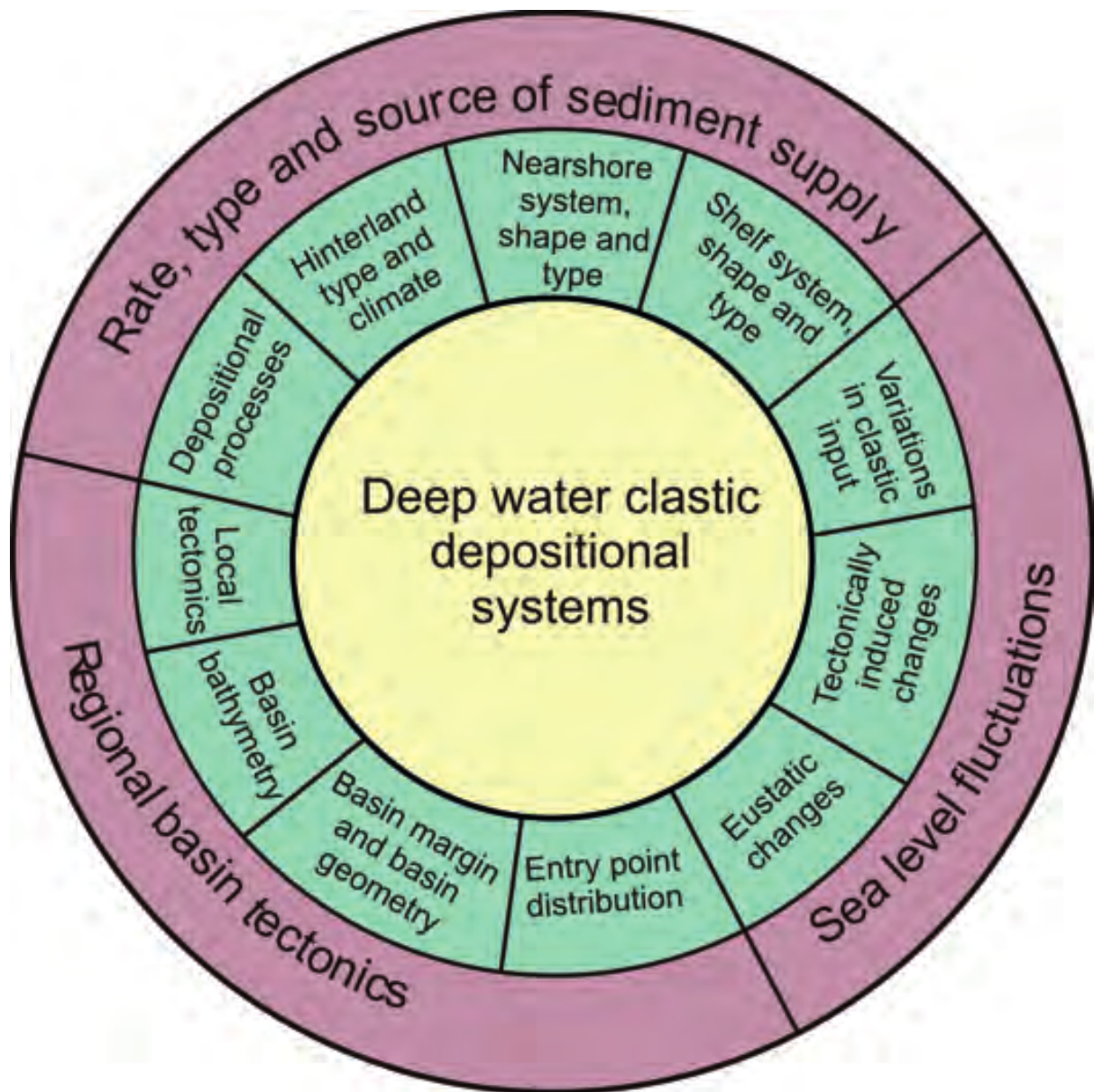


Figure 2. 7: A chart showing the main factors controlling deep-water deposition (Reading et.al, 1998).

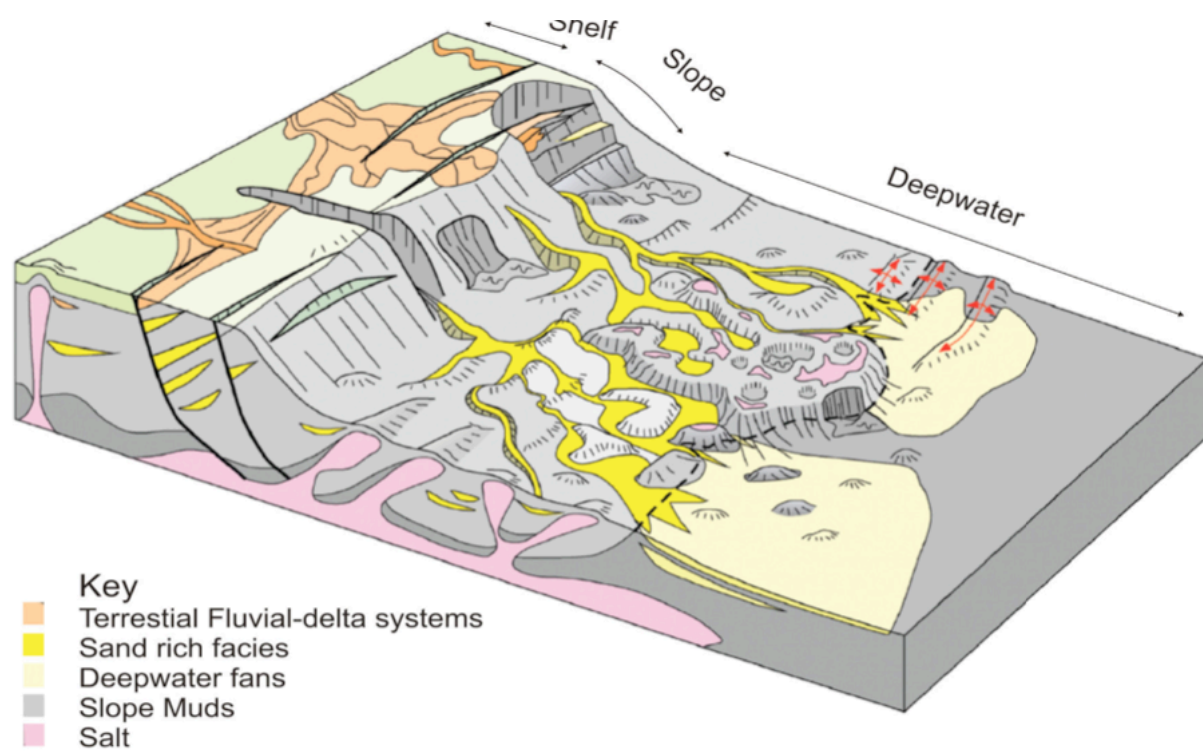


Figure 2. 8: Schematic block diagram illustrating the structural controls on depositional systems on continental margins affected by salt structures. Mayall et al. (2010)

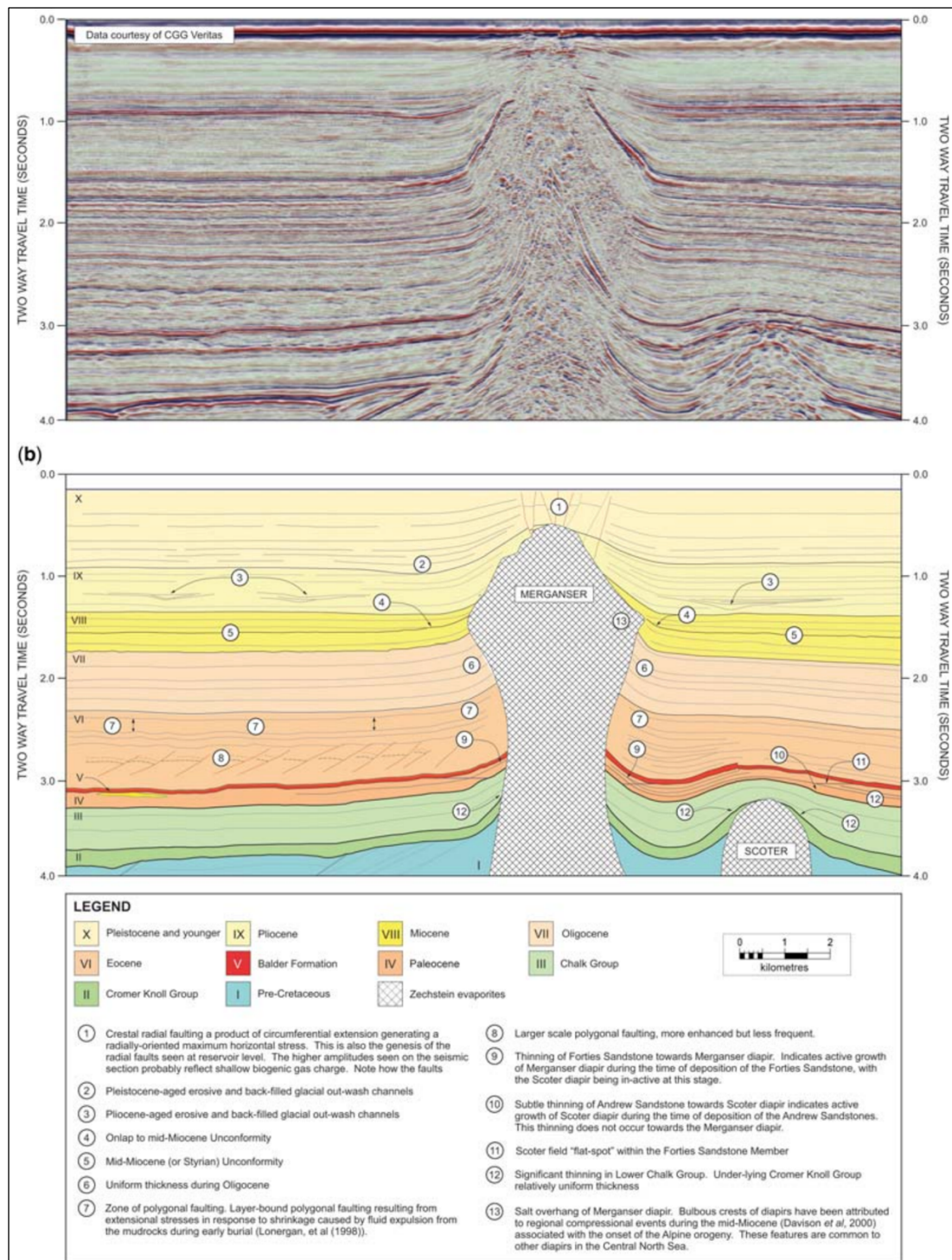


Figure 2. 9: (a) Seismic section along traverse A–B across Merganser and Scoter Diapir, CNS. (b) Geoseismic interpretation of seismic section showing Scoter and Merganser salt diapirs, principal seismic markers and stratigraphic units highlighting some key geological features after (Charles & Ryzhikov, 2015).

CHAPTER 3

SEISMIC GEOMORPHOLOGICAL ANALYSIS AND STRATIGRAPHIC ARCHITECTURE OF SUBMARINE CHANNEL SYSTEMS, TARANAKI BASIN, NEW ZEALAND

Isaac A. Odeh¹, Christopher A-L. Jackson¹, Howard D. Johnson¹, David M. Hodgson² and Ian A. Kane³.

¹*Basins Research Group (BRG), Department of Earth Science and Engineering, Imperial College London, Prince Consort Road, SW7 2AZ.*

²*Stratigraphy Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT.*

³*School of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL.*

3.1 ABSTRACT

Submarine channels are important conduits for sediment transfer from the continent to oceans. Seismic geomorphological analysis provides insights into the evolution of ancient submarine channel systems and their preservation in the stratigraphic record. However, many seismic geomorphological studies lack borehole data to constrain the lithology and petrophysical expression of various deep-water depositional elements; such information can be derived from field-based studies, but most of these are 2D or quasi-3D at best. Here, we undertake borehole-constrained seismic geomorphological analysis of Middle Miocene submarine channel systems using a high-resolution, post-stack, time-migrated, 3D seismic reflection cube (c. 1,500 km²) that is calibrated with well-logs, core, and cuttings data from seven boreholes. Seismic attribute analysis utilising seven seismic horizons (H1 – H7) mapped within two seismic units (SU1 and SU2), allow identification of three main seismically defined, depositional elements: (i) channels (ii) levee/overbank, and (iii) slope/basin-floor.

SU1 contains two types of N-S trending channel system: (1) moderately sinuous (sinuosity index (SI) = 1.15), levee-confined channels (average width and thickness of c. 342 m and 35 m, respectively), and (2) highly sinuous (SI=2.25), partly coalesced channel complexes (average width and thickness of c. 346 m and 34 m, respectively). Attribute maps of channel-fills and overbank/levee deposits within SU1 show high amplitudes. SU2 contains NW-SE trending, low sinuosity (SU2 = 1.01 – 1.40), erosionally-to-levee-confined channel-fills that migrate laterally and stack vertically. These form channel complexes confined within slope valleys, with individual channel complexes being, c. 324 – 1080 m wide and c. 32 – 104 m deep. Attribute maps of SU2 channel-fills are only weakly reflective with high amplitudes, mostly confined to the overbank or levee environment. Well data show that the channel-fill seismic facies are variable, comprising sandstone, muddy-sandstone, siltstone, and mudstone, with sandstone content decreasing upward. The levee/overbank seismic facies are overall finer grained, and characterised by muddy, very fine-to-fine-grained sandstone interbedded with siltstone and mudstone. The slope/basin floor seismic facies are mudstone-dominated.

SU1 and SU2 channel complexes also differ in that: (i) palaeoflow direction was northwards in SU1 times and northwestwards in SU2 times; (ii) SU1 channel complex-fills are sandier (20-45% sand content), compared to those in SU2 (10-18% sand content); and (iii) SU1 channel complexes are relatively unconfined and characterised by lateral migration, whereas SU2 channel complexes are more commonly confined within valley systems. The mapped basal erosion surfaces of the channel complexes are highly time-transgressive, implying that the processes controlling channel evolution were similarly diachronous. Hence, we speculate that tectonically driven re-adjustment of the basin and hinterland during the Middle Miocene (between SU1 and SU2 times) resulted in a gradual change in slope orientation from N-to-NW-dipping, and an increase in slope gradient and a relative sea level

fall, which potentially drove slope incision and increased the amounts of bypass of sand-grade material to the deeper basin.

3.2 INTRODUCTION

The morphology, geometry and stratigraphic architecture of submarine channel systems have been extensively studied in many deep-water settings (e.g. Offshore Africa; Navarre, 2002; Adeogba, 2003; Deptuck et al., 2003, 2007; Adeogba et al., 2005; Babonneau et al., 2010; Jobe et al., 2017; Amazon Fans; Damuth et al., 1983; Flood and Damuth, 1987; Damuth et al., 1988; Pirmez and Flood, 1995). In these and other locations a range of architectural elements are recognised, such as channel-fill elements (Posamentier and Kolla, 2003; Gamberi et al., 2013; Janocko et al., 2013; Hansen et al., 2017), internal and external levees (Posamentier, 2003; Kane et al., 2007a, 2007b, 2010; Kane and Hodgson, 2011; Janocko et al., 2013), lateral accretion packages (Abreu et al., 2003; Janocko et al., 2013) and channel bend mounds or nested mounds (Janocko et al., 2013; Posamentier, 2005). Field-based studies can be used to help characterise the detailed geometry and composition of these depositional elements. However, many field exposures are small relative to the scale of some deep-water depositional elements, meaning key aspects of their geometry, such as their plan-view form, remain unknown.

Seismic geomorphological analysis of seismically very well-imaged near-seabed systems help to constrain the 3D architecture, regional distribution, and stratigraphic evolution of deep-water depositional elements (Deptuck et al., 2007; Gee and Gawthorpe, 2007; Sawyer et al., 2007; Zeng, 2007; Wood and Mize-Spansky, 2009; Qin et al., 2016). However, seismic geomorphological analysis of deep-water depositional elements in 3D seismic reflection data also has its limitations, particularly when borehole data are lacking; in these cases, it is not possible to directly calibrate their lithology, petrophysics, or reservoir properties (Posamentier, 2003, 2005, 2006; Posamentier and Kolla, 2003; Kolla et al., 2007). Conversely, seismic geomorphological analysis is greatly enhanced when integrated and calibrated with borehole data (Prather, 2003).

In the Taranaki Basin, most of our understanding of the geometry, and stratigraphic architecture of submarine channels and their depositional elements comes from the study of outcrop exposure of the Upper Miocene Mount Messenger Formation along the west coast of North Island, New Zealand (Browne et al., 2005; Rotzien et al., 2014; Masalimova et al., 2016). In addition, the morphology and architecture of the Middle Miocene, deep-water Moki Formation and SI/SW Sand has been documented using either cores, well logs or 2D/3D seismic geomorphology (Bussell, 1994; De Bock, 1994; King, et al., 1995; Kamp et al., 2002, 2004; Baur et al., 2010; Grahame, 2015; Gnappagasan et al., 2016; Uruski and Warburton, 2016; Li et al., 2017).

Despite the wealth of work done in deep-water submarine systems of the Taranaki Basin, our understanding of the planform evolution and stratigraphic architecture of the Miocene submarine channels remains uncertain. Previous work focused on either the large-scale palaeogeographic evolution and seismic expression of the submarine channels in particular (Bushe and Baur, 2003; Baur et al., 2010; Baur, 2012; Gnappagasan et al., 2016; Shumaker et al., 2016), but with only limited use of well data to constrain the spatial and temporal changes in lithology.

This study presents a seismic geomorphological analysis of the middle Miocene deep-water of the Taranaki Basin, using an integrated 3D seismic, well log, core, and drill cuttings dataset. We aim to: (i) establish the planform geometries and temporal evolution of constrained channel systems, (ii) evaluate the stratigraphic architecture, architectural elements, and facies distribution present within the Moki Formation; and (iii) explore the geological controls on the observed stratigraphic architecture.

3.3 GEOLOGICAL SETTING

The tectonic evolution of the Taranaki Basin is related to the middle Cretaceous (c. 105 – 83 Ma) breakup of Gondwanaland (Knox, 1982). The Taranaki Basin extends from the Taranaki Peninsula, westward into the offshore terrain where its western boundary is poorly defined (Figure 3.1A) (King et.al., 2008; King & Thrasher, 1996; Strogon et.al., 2017). The basin is bounded to the north by the Northland Basin, to the south by the South Island, and to the west, by the Challenger Plateau (Palmer, 1985). The Australian – Pacific plate interaction in the Late Cretaceous-Palaeocene and in the Oligocene-Neogene has a major influences on the structural development of the Taranaki basin (King & Thrasher, 1996). The Australian – Pacific plate convergence during the Oligocene-Neogene is the main control on the hinterland uplift in the Taranaki basin. This compressional event has affected the Neogene basin architecture as represented by (i) the uplifting Taranaki peninsula which extend from the southern to the northern of the North Island and (ii) the widespread volcanic activities centred around the north-eastern part of the basin (King & Thrasher, 1996).

Structurally, the basin comprises three distinct structural units: the Northern and Southern units, which have been affected by late Miocene – Recent tectonic events, and the relatively stable Western Unit (Anderton, 1981; Brothers, 1986; King & Thrasher, 1996; Nodder, 1993; Pilaar & Wakefield, 1978; Wood, 1991). Faults within the Taranaki Basin strike NE-SW and, NNE-SSW (Pilaar & Wakefield, 1978; Voggenreiter, 1993; Muir et al., 2000), with the major faults being the Cape Egmont and Taranaki fault zones (Figure 3.1A). The complex structuration of the Taranaki Basin makes it part passive margin basin, and part active margin basin. In the Taranaki Basin, the tectonic fabrics present include rift transform, passive margin, platform subsidence linked to incipient subduction, foreland basin and convergent transform, volcanic-arc, fold-thrust belt, and back-arc rift (King & Thrasher, 1996)

The stratigraphic framework of the Taranaki Basin is well constrained (Pilaar & Wakefield, 1978; Palmer, 1985; Palmer & Andrews, 1993; King & Thrasher, 1996). The oldest deposits are lower Cretaceous to Eocene terrestrial, fluvial and marginal marine deposits of the Pakawau, Kapuni and Moa groups (Palmer, 1985). Widespread clastic starvation during the Oligocene resulted in the deposition of the carbonate-dominated Otaroa Group (Palmer, 1985; Hansen & Kamp, 2004; Kamp et al., 2004). From the Early Miocene to Late Pliocene there was basinward progradation with deposition of slope and basin floor sediments of the Wai-iti Group (see below) (Pilaar & Wakefield, 1978; King & Thrasher, 1996; Puga-Bernabéu et al., 2009). The Pliocene to Recent period was dominated by a shelf, slope and basin floor deposition via, basinward progradation of clinoforms of the Giant Foreset Formation (Hansen & Kamp, 2002; Kamp et al., 2004; Hansen & Kamp, 2006). Figure 3.1Bii, is regional seismic section taken across the Taranaki Basin showing the Cretaceous – Recent stratigraphic infill along the shelf to the basin floor environment.

This study focuses on the Neogene Moki Formation (Moki B of Bussell, 1994), and SI/SW Sand (Moki A of Bussell, 1994) (Figure 3.1Bi) (Palmer, 1985; King and Thrasher, 1996). This succession comprises shallow-to-deep-water deposits, which accumulated in shelf, slope and basin floor environments (see Figure 3.1Bii) (Bussell 1994; King and Thrasher, 1996; Engbers, 2002). The sandstones represent turbidite-dominated sequences (i.e. the Moki Formation and the SI/SW Sand), which were deposited during subsidence associated with the formation of the Neogene convergent plate boundary (King and Thrasher, 1996). The sands of the Moki Formation and the SI/SW Sands were derived from the Separation Point granite (Bussell 1994) and the Taranaki Peninsula, respectively. Sediment transport was through extensive (ca.100s-1000s km long) submarine channel systems, which extended from nearshore settings into the deep-water environment of the New Caledonian trough (Palmer, 1985; Uruski and Wood, 1991; King and Thrasher, 1996; Baur et al., 2010; Grahame, 2015). The channel

systems were part of submarine fans and deposited by a range of sediment gravity currents at the base of the prograding slope (King and Thrasher, 1996).

3.3.1 GROSS DEPOSITIONAL ENVIRONMENT

Analysis of planktonic foraminiferal assemblages by (Hayward, et al., 2001, 2003) provides the basis of a biostratigraphic zonation for the Cenozoic succession and the construction of gross palaeoenvironmental reconstructions (Figure 3.1C). These data have enabled subdivision of the Upper Cenozoic of the Taranaki Basin into seven zones (Geiger, 1962). Three of the seven foraminiferal zones of (Geiger, 1962) i.e., the *Globorotalia zealandica* Zone (Altonian), *Sphaeroidinella disjuncta* Zone (Clifdenian – Lilburnian), and *Globigerina nepenthes* Zone (Waiauan) corresponds to early Middle Miocene to late Middle Miocene intervals.

During the Altonian stage (early Middle Miocene), the Taranaki Basin was predominantly in bathyal water depths, with water depths increasing towards the NW (Figure 3.1Ci). The shelf-slope break this time was broadly E-W trending (Grain, 2008). Pilaar and Wakefield (1978) suggest that this change in shelf orientation could be related to a combination of (i) reactivation of major faults, such as the Mania and Taranaki faults and (ii) an uplift event, including the formation of the Mania Anticline that defines the eastern margin of the basin (Figure 3.1A). This condition continued into the Clifdenian stage and was accompanied by the southward migration of depocentres (Figure 3.1Cii). With the establishment of depocentres around the southern region, deposition of the oldest deep-water system considered in this study (SU1); began from the late Altonian to early Lilburnian (Figure 3.1Ciii). During this period, sediments were supplied to the basin via slope mass wasting processes and channels that erode into the upper slope and shelf (King & Thrasher, 1996;). During the Waiauan (late Middle Miocene), the NE-SW trending segment of the shelf-slope system may have steepened, based on a change in sediment supply direction from north to north-west (Figure 3.1Civ). It has been suggested that, this was caused by (i) repeated switches in sediment provenance as a result of convergent plate interaction between the Pacific and Australian plate boundaries, (ii) outbuilding of the shelf towards the south, and (iii) reduction in the rate of uplift of the Mania Anticline (Pilaar & Wakefield, 1978; King & Thrasher, 1996).

3.4 DATASET AND METHODOLOGY

3.4.1 SEISMIC REFLECTION DATA

This study used a time-migrated, high-resolution 3D seismic reflection survey with an aerial coverage of 1500km². The data were acquired in 1990, processed in 1997, reprocessed in 2007, and made available through the Ministry of Business, Innovation and Employment as part of New Zealand's open file petroleum report system (<https://data.nzpam.govt.nz>). Seismic reflection data were acquired using a Dual vessel operation (Quad-Quad), with four sources, four streamers, an airgun as the energy source, and NESSIE as a recording instrument. The survey has a crossline and inline spacing of 25 m and 25 m, with a vertical sampling rate of 4 ms. We estimate that the vertical resolution of the seismic data is 14 m at the depth of interest 1843 m – 2574 m subsea; this estimate is based on a dominant frequency of c. 40Hz at the depth range (extracted directly from the seismic data) and an interval velocity of c. 2600 ms⁻¹. The seismic survey is processed to zero phase with SEG normal polarity based on the European polarity convention, a negative trough represents an acoustically hard kick (positive acoustic impedance represented by red colour) whereas a positive trough indicates an acoustically soft kick (negative acoustic impedance represented by blue colour).

3.4.2 WELL DATA

Data from 8 exploration and appraisal wells (acquired in the 1976-period) were used in this study: Maui-1, -2, -3, -4, -5, -6, -7, Maui South-1 and Rahi-1 (Table 3.1). These wells are located largely in the central and southern part of the study location (Figure 3.1A). We used composite logs (calliper, spontaneous potential, gamma ray, neutron, density, and sonic logs) and available drill cuttings data (Maui-2) and core dataset (7 m length) from Maui South-1 to interpret the bulk lithology of the studied interval. Completion logs provided further information on formation lithostratigraphic formation tops and the gross stratigraphic framework of the study area. Biostratigraphic data were not available, but we used biostratigraphic information synthesized from well completion reports.

3.5 METHODOLOGY

3.5.1 WELL-TO-SEISMIC TIE AND SEISMIC INTERPRETATION

We used seismic-to-well-ties to identify and map seven key seismic horizons (H-1 to H-7 oldest to youngest) based on their reflection continuity. Mapping of these horizons enabled us to subdivide the Middle Miocene study interval into two seismic units (SU1 and SU2) (Figure 3.2A). SU1 and SU2, correspond to the Moki Formation and SI/SW Sand, respectively (Figure 3.2B).

SU1 and SU2 intervals were further iso-proportionally sliced using the technique of (Zeng, 2007;). Surface-based attributes were extracted from the iso-proportional horizons (i.e. Root-Mean-Square amplitude and Variance; Zeng, 2007; Hart, 2008;). These attribute maps were used to identify and interpret depositional elements.

Sand-rich – levee complex in the offshore Taranaki Basin are characterised by high seismic amplitude (Baur et al., 2010). Hence, volume attributes, notably Root-Mean-Square (RMS) amplitude and Variance edge were used for seismic geomorphological analysis of the middle Miocene deep-water channel system (Hart, 2008). Seismic reflection-based inferred lithologies were tested with borehole data and drill cuttings.

3.5.2 WELL-LOG INTERPRETATION

Petrophysical analysis of well-log data, supported by limited drill cuttings information from well completion reports, and core data from (<https://data.gns.cri.nz/>) were used to evaluate the thickness and lithology variations within the study interval. A combination of gamma ray (GR), density, neutron and sonic logs were used for lithological interpretation (Table 3.2). GR logs were available in all wells, and we note a consistent relationship between log response and lithologies described in core data and drill cuttings, particularly with regards to sand/mud ratio. Hence, lithology distribution was estimated based on Vshale cut-off values using the following terminology: (i) < 40% is sandstone-dominated; (ii) 40 – 70% is heterolithic; and (iii) >70% is mudstone-dominated (Table 3.3). The resulting Vshale histogram shows that Maui-1-3 and Maui-5-7 have similar proportions of sandstone-dominated, heterolithic, and mudstone-dominated intervals. Maui-1, Maui-5 and Maui-7 show relatively thick heterolithic interval. We interpret that the Vshale histogram for Rahi-1 is notable in that it is dominated by cleaner sands. Interpretation of the Vshale histogram of Maui-1, Maui-2, Maui-3, and Maui-7 records deposition within channel axis and overbank environments. Maui-6 and Maui-7 suggest deposition in a more distal environment, perhaps on the basin floor or at the margins of an overbank splay. We interpret that Rahi-1 records dominantly channel axis deposition.

Gamma ray (GR) log motif (facies) (e.g., bell-shaped, cylindrical and funnel shaped log profiles) (Figure 3.3) were also used to infer smaller-scale depositional genetic units and architectural elements, in part

based on their calibration with seismic-derived geometrical observations. The GR log motifs were integrated with a well correlation panel (Figure 3.4A (i) and (ii)) to understand the sub-regional changes in the vertical and lateral arrangement of depositional elements.

Using the GR log, a well-log correlation of the wells in the studied location (Figure 3.4B (i) and (ii)), shows the lithology distribution of the submarine channel systems in SU1 and SU2. The SU1 shows a blocky, bell-and-funnel shaped GR pattern, interpreted as stacked sandstone packages with interbedded heterolithics and mudstone. The top and base of SU1 is characterised by sharp and gradational change in GR pattern. The younger SU2 also show a blocky, cylindrical, and bell-shaped GR pattern showing an overall fining upward succession. The base and top of the SU2 shows a gradational contact. In between the SU1 and SU2, the slope and basin-floor mudstone of the Manganui Formation shows a low, irregular GR pattern. Within the Manganui Formation, thin, sandstone packages, which were not seismically resolvable were interpreted as M2A sands from existing literature (King & Thrasher, 1996).

3.6 TERMINOLOGY

In this study the following terms are used: (i) *deepwater channels* – are defined as a morphological structure formed from the downslope movement of sediment-gravity flows. Deepwater channels form channel belts that occur in many diverse forms as erosional, leveed and meandering channel belts (Janocko et al., 2013). (ii) *levee/overbank* – are defined as morphological features formed from the over-spilling of channelised flows, flanking incised valley-fills. They occur as either large, external levees flanking channel belts or smaller internal levees flanking single channels (Kane et al., 2007a). (iii) *basin floor mudstone* – a stratigraphic unit deposited by low energy settling of silt – clay-grade sediments in the slope – basin floor environment. (iv) *suprafan* – a stratigraphic unit with distinct sedimentological characteristics which indicate fan channelisation on unchannelised gravity (mostly turbidity) flows. (v) *valleys and valley-fill* – valleys i.e., incised-valley are morphological form that results from the undercutting activity of channels as they flow over older stratigraphy or bedrock. Contrary to submarine valleys, incised valleys are filled by the channelised turbiditic systems forming valley-fill (Prather, 2003); and (vi) *HAR and HARP* – are terminologies adopted in seismic stratigraphy to show seismic reflections with bright amplitude. When a given amount of high amplitude seismic reflectivity occur together, we termed them high amplitude reflection packages (HARP).

3.7 SEISMIC FACIES ANALYSIS

Three seismic facies have been identified, based mainly on their reflection characteristics, including geometry, amplitude, and continuity. The seismic facies were also calibrated with wireline log, based on (i) the three main well log-defined petrophysical facies (sandstone-dominated, heterolithics, and mudstone-dominated; and (ii) their overall GR log motifs. Appendix 1 is a series of montage of RMS amplitude attribute maps, seismic line taken through the various well penetrations and the GR log from the wells. These montages, unambiguously demonstrate the calibration of the seismic facies by well logs, cuttings, and cores. These also, gives a systematic characterisation of the seismic facies example., channel axis penetrations, levee penetrations and basin floor mudstones. Maui-2 and Maui South-1 are taken here to demonstrate the calibration of seismic, well logs and cores (Appendix 1.C and D). This is because they allow for characterisation of the lithologies associated with every documented seismic facies.

Based on this integrative approach, the three seismic facies are interpreted to represent the following deep-water depositional elements: (i) channels and intra-channel, (ii) levees/overbank deposits, and

(iii) slope/basin floor mudstones (Figure 3.5). We now describe the detailed seismic expression of these elements.

3.7.1 CHANNELS AND INTRA-CHANNELS-FILLS

To aid in the description and analysis of deep-water channel systems in the Taranaki basin, we adopt the deep-water channel hierarchical classification of (Abreu et al., 2003; Sprague & Garfield, 2005) which was modified by (Di Celma, et.al., 2011) (Figure 3.6). This classification provides a guide for understanding the geomorphic and stratigraphic evolution of the middle Miocene deep-water channel system in the Taranaki basin. In this study, the following hierarchical terms are used: (i) **channel-fill element** – a fundamental, seismically defined, depositional building blocks of deep-water depositional system which evolved from erosion, and/or shelf bypass event. The channel-fills elements comprise of genetically related channel **storey**; (ii) **channel complex** – a group of two or more genetically related channel-fills of similar architectural styles; (iii) **channel complex set** – a group of two or more genetically related channel complex of similar architectural styles; and (iv) **channel system** – a group of two or more genetically related and seismic resolvable channel complex set filled with discrete erosionally or levee-confined channel complex set of similar architectural styles.

3.7.1.1 CHANNEL-FILLS

This seismic facies comprises stacked, discontinuous, high amplitude reflections packets (HARPs; High Amplitude Reflector Packet of Pirmez and Flood, 1995) that overlies channelized erosional surfaces, that are bound laterally by inferred levee/overbank deposits. Typical channel form widths and thicknesses range from c. 342 m – 1080 m and c. 34 m – 104 m, respectively. The channels display U-shaped, concave-upward, cross-sectional geometries, with irregular, basal erosion surfaces (Figure 3.5).

Attribute maps show lateral and downslope channel migration patterns, towards the north and north-west. GR log profiles from wells drilled through these seismic facies typically comprises low values (<50) and bell-shaped to blocky GR log motifs suggesting they comprise of stacked sandstone-rich turbidites or are defined by an overall fining upward change from sandstone, to heterolithics to mudstone (GR log facies A) (Figure 3.3). A montage of RMS amplitude attribute map integrated with seismic lines, GR log and cuttings in Maui-2 (Appendix.1 C) show that the blocky GR log in SU1 and SU2 are fine to medium grain sandstone. Similarly, a montage of RMS amplitude attribute map integrated with seismic lines, GR log and cores Maui South-1 (Appendix.1 D) show that the blocky GR log in SU1 are fine to medium grain sandstone.

Similar seismic facies with similar plan-form geometries occur in a variety of deep-water settings where they are interpreted as submarine channel-fills (e.g, Fonnesu, 2003; Prather, 2003; Posamentier & Kolla, 2003; Posamentier, 2005; and 2006; Gee & Gawthorpe, 2007; Hadler-Jacobsen et al., 2007; Kolla et al., 2007; Catterall et al., 2010). Stacked channels occur within erosional valley systems and may be flanked by levees/overbank deposit (Sprague and Garfield, 2005; Mayall et al., 2006; Janocko et al., 2013). The presence of High Amplitude Reflection Packages within the axes and along the bases of the channels implies the presence of a sandstone and basal lag deposits (Posamentier, 2003;). The low amplitude reflections reflect silty to muddy, possibly heterolithic facies. The upward fining well-log profiles could reflect either lateral channel migration or gradational channel abandonment. The channel systems show a large variability in terms of their width, thickness, and infill, suggesting a wide range of channel types with mixed sediment load. This could also be a consequence of external factors which we discussed later.

3.7.1.2 CHANNEL BENDS

These seismic facies are defined by shingled reflections that form moderate-to-high amplitude mounded packets that occur on the inner bends of sinuous channels (Figure 3.5). GR log profiles from wells drilled through these seismic facies typically comprises of interbed of low API (<50) bell-to-blocky shaped log motif (Figure 3), representing a change from channels to interbedded heterolithics.

These shingled, mounded reflection packages are interpreted to represent the inner bend channel deposit (Posamentier, 2003; Janocko et al., 2013;). The inner bends of the channels are characterised by low amplitude muddy fills. Similar reflection packages were also interpreted as point bars deposit which implies stacking meander loop and meander cut-off in fluvial system.

3.7.2 EXTERNAL LEVEES/OVERBANK DEPOSIT

These seismic facies are characterised by subparallel-to-parallel, continuous, high-amplitude reflection packages that are invariably truncated by channel fills or erosional valleys. It also contains wedge-shaped reflection packages that thicken towards, and are bounded by, adjacent channels. They may also form tabular, sheet-like bodies that are 78 – 109 m thick and c.3 – 10 km wide and defined by bidirectional dips (Figure 3.5). GR log profiles are typically cylindrical to blocky, funnel and bell-shaped motifs (Figure 3.3), implying they comprises thin intervals of sandstone, interbedded with mudstone and thicker heterolithic packages. A montage of RMS amplitude attribute map integrated with seismic lines, GR log and cuttings in Maui-2 (Appendix.1 C), show that the blocky GR log in SU1 and SU2 are fine to medium grain sandstone which are mostly interbedded with claystone and mudstone.

These features resemble external levee deposits (Fonnesu, 2003; Posamentier, 2003; Prather, 2003; Janocko et al., 2013; Covault et al., 2016;). Here, the channels are hybrid (Fonnesu, 2003;), with a combination of levee-and-erosional confinement.

3.7.3 SLOPE OR BASIN FLOOR MUDSTONES

These seismic facies comprise discontinuous to continuous, subparallel-to-parallel, low-amplitude reflections contained in tabular, sheet-like packages (see Figure 3.5). Well data indicate these seismic facies are defined by motifs (GR log facies B i.e., high API values (>70), with an overall irregular motif), corresponding to mainly mudstone and high API heterolithics. A montage of RMS amplitude attribute map integrated with seismic lines, GR log and cuttings example Maui-2 (Appendix.1 C), show that the low serrated GR log in SU1 and SU2 corresponds to mudstone-rich lithologies.

Based on reflection characteristics and log motifs, we interpret this seismic facies to corresponds to slope and basin floor mudstones, similar to those described from many other deep-water settings (Hadler-Jacobsen et al., 2007; Gagnon and Waldron, 2011; Janocko et al., 2013).

3.8 STRATIGRAPHIC ARCHITECTURE

To understand the stratigraphic architecture of the middle Miocene channels systems, it is critical to understand the structures and the thickness patterns of the basin prior to sediment deposition. Seven seismic horizons (H1 – H7) were interpreted but H1 and H3 and H4 and H7 was taken to represent the base and top of SU1 and SU2 respectively and are utilised for further analysis. In this section, time-structure maps taken from base & top SU1, and base & top SU2 respectively (Figure 3.7) were

observed to gain more understanding of the overall basin structure during the middle Miocene. Within the regional Taranaki basin, the study location, forms part of the Central Taranaki basins (Figure 3.7A). Observations from the regional structure map (N10 interval from <https://data.nzpam.govt.nz>) show that the basin deepens towards the NW but deposition around local depocentres are influenced by the Cape Egmont fault Zone. Based on amplitude variations, the southwestern part of the study location is topographical higher than the north-western extend of the basin. These observations are quite visible in the subregional study location (Figure 3.7B-E). Here, structural highs as evidenced by bright amplitude are seen around the central part of the study location. These highs transitioned into structural lows which continued to the northwest and extends into the North Caledonian Trough. Apart from the Cape Egmont fault zone and the relatively inactive whitiki fault, the study location is relatively stable during the middle Miocene period.

Thickness or isochore maps from the study location showed a remarkable local thickness change to the north-west. Thickness map generated between base and top SU1 (Figure 3.8B), showed thickness change i.e., thickness increases to the northwest of the study location. Similar thickness pattern was observed between the base and top SU2 (Figure 3.8C) however, thickness map of SU2 show that the packages are thicker than they are in SU1. Thickness maps of the entire study interval (i.e., from base SU1 to top SU2) (Figure 3.8A), showed that the middle Miocene packages are thicker towards the north and northwest. This implies that the depocentres are created in the north to northwest of the study location and was infilled by a very thick Miocene sediment sourced from the southern and south-eastern part of the Taranaki basin.

The stratigraphic architecture has been evaluated based on the distribution of seismic facies and their inferred depositional elements, using both cross-sections and representative seismic attribute maps from different parts of the 3D seismic volume. The results are presented in stratigraphic order: (i) SU1 (H1-H3 in Figures 3.9 - 3.11); and (ii) SU2 (H4-H7 in Figures 3.12 - 3.15)

3.8.1 SU1 (EARLY MIDDLE MIOCENE)

SU1 comprises extensive external levee/overbank, channel-fills, and intra-channel-fills (channel inner bend) deposits. HARPs were identified within the levee/overbank and, channel-fills and interpreted to be sandstone-rich. Moderate to low amplitudes reflection package are interpreted to represent finer grained lithologies (heterolithics and basin floor mudstones).

Attribute maps extracted from the top H-1 surface (i.e., base SU1) show part of the early middle Miocene submarine channel complex (Figure 3.9). The main channel belt is located towards the west-central part of the study location area and has an average width and thickness of 342 m and 34 m, respectively (Figure 3.9). The N-S trending channel has an average sinuosity and aspect ratio (width: thickness) of 1.15 and 9.92 respectively. The H-2 and H-3 attribute maps show a channel complex (and channel complex set) that extend across the entire central part of the study area (Figures 3.10 & 3.11). The average sinuosity of these channels is c. 2.25 and the average channel width and thickness is c. 880 m and c.68 m, respectively. We interpret the shift in channel complex location to indicate the possibility of lateral channel migration or a switch in the locus of the feeder channel system.

The SU1 channel complexes have a northerly palaeo-flow direction based on planform maps. A SW-NE oriented well correlation panel, highlighting GR log motifs and vertical facies succession (coarsening and fining upward trends) is partly oriented parallel to the axis of the N-S trending channel belts, but occasionally has depositional strike trend (Figure 3.4A.i). The correlation panel, focusing on the vertical and lateral distribution of facies and genetic units (Figure 3.4B (i)), shows good continuity in lithology between Maui-6, 3 and 2, which are located to the north-central part of the

study area. These three wells show a build-up of external levees/overbank, channel margin, off-axis, and channel axis relationship (with lithological heterogeneity decreasing towards the channel axis), within the suprafan channel complex of SU1. Towards the northern part of the study location, the heterolithic facies record the highest thickness around Maui-2 and 3 and 6 implying that these wells are largely located on thick external levees and overbank environment and channel off-axis, respectively. Towards the southern part of the study location, Maui-5 was drilled entirely into the external levees and overbank of both the basin-floor, early channel-levee complex and the younger suprafan channel-levee complex respectively. We observed a good continuity within the levee/overbank facies in Maui-5, 2 and 7. A thick (50 m) sandstone unit at the top of Maui-7 correlates with a similar unit in Maui-1 but pinches out into basin floor claystone in Rahi-1. A heterogeneous interbed of sandstone and heterolithics in Maui-1 has partial continuity into the silty levee/overbank facies in Maui-7 but thins towards Rahi-1. Rahi-1 to the south, records the thickest (over 110 m) sandstone units of the channels and intra channel-fills facies of the early channel and the suprafan channel complex in SU1. This suggest that Rahi-1 was a site of sand deposition during the evolution of the early suprafan channel complex of SU1. These thick sandstones and interbeds of heterolithic facies are not correlated with similar units in Maui-1.

3.8.2 SU2 (UPPER MIDDLE MIOCENE)

SU2 is characterised by channel-fills, intra-channel-fills (channel bends) and extensive levee/overbank depositional elements. These depositional elements are characterised with HARPs identified within the external levees/overbank, channel-fills and intra-channels-fills and were interpreted to be sandstone-rich. Moderate to low amplitudes reflection packages were identified and are interpreted as interbedded siltstones and basin floor mudstones.

The H-4, and H-7 attribute maps represent the base and top of SU2 (previously termed SI/SW Sand Figure 3.12 – 3.15). Within this interval, the average sinuosity of the channel's ranges from 1.01 to 1.40 and the aspect ratio of the channels range from 10.66 to 18.19, respectively.

The H-4 and H-5 attribute maps show a change in channel morphology, becoming less sinuous (average SI=1.09) than the underlying SU1 (average SI=1.15). The orientation of the channels, changes from a northerly direction to a dominantly north-western direction (Figures 3.12 & 3.13). We noticed sinuous submarine channels (average sinuosity 1.21) located in the southern as well as the northern part of the study area. In the northern area channels (sinuosity of 1.40) are characterised by loop cut-off and increasing depths of incision through time. The average width and depth of the channels are 643 m and 53 m, respectively, and these channels occupy a relatively narrow channel belt.

The H-6 and H-7 attribute maps (Figure 3.14 & 3.15) display channels with similar geometries and orientations to those seen in H-4 and H-5, but with a slight increase in the individual channel width. Surface H-7 shows a more evolved channel complex set contained within a valley-fill. On surface H-7 three erosional channel belts with a NW flow direction were observed. At any one point in time, a single active channel was observed to have incised into the underlying buried channels a scenario observed with the Amazon channels (Damuth et al., 1983;). There is also an increase in sinuosity (1.40) of the younger channels within the channel belt. This increasing sinuosity may be related to the topography formed by the older channels within the same channel belts and the prevailing tectonic activities at the time (resulting in increased flow gradient). Overall, the SU2 interval consists of a channel complex and complex set (Sprague and Garfield, 2005; McHargue et al., 2011;) and the individual channel complex stacked laterally and aggraded through time and are confined within a valley-fill.

The channel complexes and channel complex set observed in SU2 have a NW palaeo flow direction in planform maps. The wells are oriented perpendicular to the axis of the NW-SE trending channel belts. A SW-NE correlation panel (Figure 3.4B (ii)) shows good continuity in lithology between the wells which are located to the North-central and Southern part of the study location respectively. These wells record levees/overbank, and channel margin (with lithological heterogeneity decreasing towards the channel margin), within the channel complex of SU2. GR Log motif shows a combination of patterns example; bell, funnel and cylindrical shapes and GR log facies shows a distribution of GR facies example sandstone, heterolithics and mudstone. Towards the southern part of the study location, the heterolithics facies records the highest thickness around Maui-5, Maui-7, Maui-1, and Rahi-1 implying that these wells are largely located on thick levees and overbank environment and channel margin respectively. Towards the northern part of the study location, Maui-6, 3, and 2 was drilled entirely into the levees/overbank of older channel complex. We observed a good continuity within the levee/overbank facies in Maui-5, 2 and 7. Rahi-1 to the south, records the thickest (over 110 m) heterolithics units of the channels and intra channel-fills facies of the channel complex in SU2.

3.9 SEDIMENTARY FACIES

The high-resolution sedimentological record of the middle Miocene stratigraphy in the Taranaki Basin was investigated using conventional drill core and cuttings dataset. The drill cores are drawn from Maui South-1 and the drill cuttings data are drawn from Maui-2. Maui South-1 (total cored thickness of 7 m) is located on the central part of the study location.

Sedimentary features were examined in detail using graphic log on a scale of 10 cm to represent 1 m. This high-resolution logging scale was used to investigate in great details, the bed-scale sedimentology of the middle Miocene deposits. Visual inference of the colours of the rocks was used to determine the amount of disperse clay content in the rocks. Previous works for example (Grain, 2008), utilizing cores provided the sedimentological framework for this studies. The poor core recovery restricts this analysis to a depth of about 7 m of SU1 interval. This, however, allows a detail high-resolution investigation of middle Miocene deposit type.

Four main lithofacies i.e. (i) Massive sandstone; (ii) Ripple laminated sandstone and (iii) Interbedded sandstone and mudstone and (iv) Mottled mudstone facies were identified. Table 3.4 summarises the description and interpretation of the facies identified within the middle Miocene deepwater system in the Taranaki basin.

3.9.1 MASSIVE SANDSTONE FACIES

Description: These facies are dark brown to grey in colour. Their grain size varies from very fine grain to fine grain ($>62\ \mu\text{m}$), with a framework mineralogy consisting of ($>85\%$) quartz, ($>7\%$) lithic fragment, ($<5\%$) feldspar and ($<3\%$) mudclast. These facies are generally clean, having a relatively low ($<15\%$) clay content in the brown colour facies and ($<30\%$) clay content in the grey colour sandstone facies. The grains are sub rounded to sub angular, compositionally immature and are moderately to well sorted. The thickness of this facies ranges from $<1\ \text{m}$ to $>3\ \text{m}$ (Figure 3.16). They show disperse distribution of intra-formational rip-up mud clast. The structureless sandstone facies exhibit a tabular geometry and are characterised by sharp to gradational bed contacts with the underlying and overlying beds. There is a general absence of both primary and secondary sedimentary structures.

Interpretation: Due to the massive nature of this facies and the general absence of sedimentary structures, this massive sandstone facies are interpreted to be deposited by a rapid aggradational suspension fallout from high density turbulent flow (Baas, 2004; Mutti & Ricci Lucchi, 1978; Stow &

Johansson, 2000). Also, the general lack of sedimentary structures suggests a rapid collapse fallout of sedimentary particles with no evident for reworking by tractional currents.

3.9.2 RIPPLE LAMINATED SANDSTONE FACIES

Description: These facies are grey in colour, and they have similar mineralogy and composition to the massive sandstone facies. They appear as thin units within the massive sandstone facies. The ripple laminated sandstone facies were observed around Moki-2A well in the Southern Taranaki Basin. The thickness of this facies ranges from <0.1 m to >0.16 m (Figure 3.16). The distinct difference between the massive sandstone facies and the ripple laminated facies is the presence of the current ripples which the provided bases for the interpretation.

Interpretation: Based on the general presence of primary sedimentary structures observed in this facies i.e., current ripple, this facies is interpreted to be deposited by turbidity currents modified by the migration of current ripples (Mutti and Ricci Lucchi, 1978; Stow and Johansson, 2000).

3.9.3 INTERBEDDED SANDSTONE AND MUDSTONE FACIES

Description: The interbedded facies are dominated by beds of dark brown to light grey sandstone unit and dark grey mudstone (and mottled mudstone) units. The mudstone appears laminated, massive, or mottled and the contacts between these beds are often sharp, gradational, or irregular with a general fining-upward trends. The basal sandstone facies (i.e., massive or ripple laminated) transitioned or grade into laminated or mottled mudstone facies. The thickness of these facies ranges from <0.1 m to >0.5 m (Figure 3.17).

Interpretation: The basal massive sandstone facies are interpreted as deposit of turbidity currents while the laminated or mottled mudstone facies are interpreted as background mudstone deposit that settles out of waning turbidity current in a low energy condition. The presence of mottling could suggest oxic basinal conditions and a potential intrabasinal reworking massive mudstone deposit.

3.9.4 MOTTLED MUDSTONE FACIES

Description: Mottled mudstone facies are dark grey coloured (massive or laminated (fissile)), very fine (<62 μm) claystone deposit up to <0.1 m to >0.5 m thick (Figure 3.18). No sedimentary structure or bioturbation was observed. However, the unit show internal disruption by irregular lenses of reworked intraformational lithic fragments.

Interpretation: Mottled mudstone facies are interpreted as background mudstone deposit that settles out of waning turbidity current in a low energy condition. This deposit could also be associated slumping of slope mudstone as mass flow deposit in the basin floor environment. The presence of mottling could suggest oxic basinal conditions.

3.10 FACIES ASSOCIATIONS

The middle Miocene of the Taranaki basin records a minimum thickness of >280 m. In the study location, the middle Miocene records a minimum thickness of >200 m. A total of 7 m core thickness recovered from Maui South-1 and >800 m cuttings thickness recovered from Maui-2 is used in this study. 7 m of core recovers from Maui South-1 was chosen for describing and illustrating the lithofacies discussed above. The described core interval of the middle Miocene shows repeated facies associations. The typical facies association shows a basal massive or ripple laminated sandstones which grade into interbedded laminated or mottled mudstone units. This relationship shows a typical

finning upward trend, and the basal and upper bed contacts are either sharp, irregular, or gradational. This facies association is illustrated in Figure 3.19.

3.11 INTEGRATING SEISMIC, BOREHOLE, CORE AND DRILL CUTTINGS

The availability of well, seismic, core and drill cutting data made the interpretation of lithologies more reliable. Core photos of the Middle Miocene channel system from wells drilled in the Taranaki Basin provided high resolution interpretation and validation of seismic and borehole interpretation. The interpretation of lithologies from seismic is based mainly on amplitude anomaly and attribute characteristics. Similarly, interpretation from borehole data is based mainly on physical properties. By integrating seismic (seismic lines and RMS attribute maps) and borehole data (i.e., GR log), and core and cuttings data (Appendix 1), the lithologies of the studied interval was validated to high degree of confidence.

Seismic section taken through Maui-3 and Maui-6 show blocky GR signatures going through high amplitude packages (Figure 3.20). At Maui-3, channel system of SU2 unit show two blocky GR signatures. These two blocky signatures are characterised by bright amplitude reflections (Appendix 1.B). On Maui-6, the seismic section shows GR log signatures typical of channel system in SU2 and SU1 units and overbank deposit. These GR log motifs are either blocky or serrated with the low GR response tying to high amplitude reflection packages (Appendix 1.A). In Maui-2, the seismic section shows GR log signatures typical of channel system in SU2 and SU1 units and overbank deposit. These GR log motifs are mostly blocky and serrated with the low GR response tying to high amplitude reflection packages (Appendix 1.A). Cuttings data show that the low GR log motif were interpreted to be sand-rich interval and the high GR log motif were interpreted to be mud-rich unit (Appendix 1.C). Similar characteristics was observed on seismic sections taken across Maui-1 and Maui-7 respectively (Figure 3.21). On both Maui-1 and 7, blocky GR log motif corresponds to high amplitude reflections in both SU1 and SU2. This GR log motif is representative of either channel systems, or overbank (Appendix 1.F and 1.G). Similar seismic-GR log characteristics was observed on seismic sections taken across Maui-5 and Maui South-1. The SU1 unit on seismic section display a typical blocky to serrated log motif. This could suggest the deposition of suprafan channels system of SU1 units. The SU2 unit display a blockier to finning upward log motif indicating either channel or over bank turbidite deposits (Appendix 1.D and 1.E).

Conclusions based on seismic amplitudes and electro facies could be misleading hence the need to integrate with cores and drill cuttings. Drill cuttings data show that the bell, funnel, and blocky shape electro facies correspond to sandstone lithologies. Similarly, regions with very high GR and low amplitude on seismic correspond to mudstone lithologies and the interbed of high and low GR (i.e., high, and low amplitude reflection) corresponds to overbank or heterolithics (Figure 3.22). The bell and funnel shape GR patterns show bed contacts, grains relationship and lithology transition from sandstone to mudstone and vice versa. Lithology logs from integrated GR log and drill cutting lithology show a sharp and gradational bed contact. The drill cutting composite log show that, the lithology in the study location comprises of sandstone, heterolithic, and mudstone. Composite log from depth interval corresponding to SU1 show that the corresponding GR log motif show sandstone unit interbedded with mudstone (Appendix 1.C). These sandstones appear blocky with a thickness of <4 m to >80 m. The interbedded mudstone unit show high GR signatures and have thickness of <5 m to >20 m. The SU2 unit as shown on the composite log, shows thin beds of sandstone within a thick unit of mudstones. It's possible that Maui-2 was not drilled into region of high channelisation hence the well records basin floor mudstone and thinning-out channel sands during the SU2 channel systems.

Core photos from two wells; Maui South-1 show that the sandstones are massive, and the mudstone are mottled. There are occurrences of ripple laminated sandstone in cores drawn from Moki-2A. Bed contacts observed on cores are sharp to gradational and the cored interval show a typical heterolithic facies with interbedded massive clean sandstone and mottled or laminated mudstone (Figure 3.23 and Appendix 1.D). The cored interval ties well with the GR log which is blocky with interbedded laminated mudstone and with the seismic section taken across the well Maui South-1.

3.12 DISCUSSION

We integrate 3D seismic, well log, core data and drill cuttings dataset to establish the linkages between temporal evolution and planform geometries of constrained channel systems, and the stratigraphic architecture present within the middle Miocene Moki Formation. In this section, we discuss the geomorphic and stratigraphic evolution of submarine channel-levee complex in the Taranaki Basin. We also highlight the controls on the stratigraphic evolution of these channel-levee complex and how they compare to similar systems in another basin

3.12.1 GEOMORPHIC AND STRATIGRAPHIC EVOLUTION OF SUBMARINE CHANNEL-LEVEE COMPLEX IN THE TARANAKI BASIN

The geomorphical evolution of submarine channels has been attributed to slope gradients, seafloor topography and the nature of the grains transported from the source areas into the basin floor (Janocko et al., 2013; Kane et al., 2008; Keevil, et.al., 2007; Mitchell & Clarke, 1994; Pirmez & Flood, 1995; Reading & Richards, 1994; Wynn, et.al., 2007). In the Taranaki basin, tectonics (and by extension slope gradient), and sediment source areas were highlighted to be the major factors controlling the geomorphic evolution and the stratigraphic architecture of the middle Miocene submarine channel-levee complex (Baur et al., 2010; Bushe & Baur, 2003; Grain, 2008; Wood & Mize-Spansky, 2009).

The long term geomorphological and architectural evolution of the middle Miocene deep-water depositional system has been documented in this study. The lower part of the SU1 submarine channel complex evolved as basin floor channel-levee complexes. These basin floor north-trending channel-levee complex (Figure 3.24) are the oldest channel system deposited within the basin floor mudstone (Bussell, 1994;). These channel-levee complexes are low sinuosity ($SI = 1.15$) and are likely deposited on the lower part of the prograding shelf to the south (Grain, 2008; King & Thrasher, 1996). The evolving slope and shelves to the south possibly switched position resulting in the lateral migration of suprafan basin floor channel-levee complex to a central location with the channels stretching along the entire length of the study location from south to north. These channel-levee complexes ($SI = 2.25$) form the upper part of SU1 and are heavily looped suggesting increasing lateral migration as the channels evolved (Figure 3.24A and B). We interpret that the increased sinuosity is related to the (i) increasing lateral migration during the deposition of the SU1 channel-levee complex and (ii) evolving shelves to the south or the increased gradient created by reactivated older, pre-existing faults of Cretaceous to Palaeocene age (Bussell 1994; King and Thrasher, 1996; Baur et al., 2010). The increasing structural complexity i.e. fault reactivation in South Taranaki, was documented to result in increasing basin gradient (King and Thrasher, 1996; Bull et al., 2018; Kroeger et al., 2019;). The top of SU1 on an attribute map (Figure 3.24B) shows NW-SE trending channel-levee complexes particularly to the South and Central part of the study location. A critical observation made in SU1 is that the channel systems within this unit evolved by lateral migration than vertical stacking.

In the SU1 submarine channel system, no pronounced incision of the underlying basin-floor mudstones by the older channel-levee complex set was observed. However subsequent supra-fan submarine channel-levee complex showed a rugose base suggesting some incision and erosion of the

underlying stratigraphy. Subsequent migration of the channels created a cut-and-fill relationship with the younger channels cutting into either the levees and overbank or the channel-fills of the older system. Overtime, incision, and lateral migration creates a complex architecture of the channel-system in the stratigraphic records.

The evolution of SU1 channel-levee complex was followed by a period of reduction in sand deposition. This quieter sedimentation period is characterised by dominant deposition of basin-floor mudstone and a possible sand bypass in the northern part of the study location (Bussell., 1994; De Bock, 1994; King and Thrasher, 1996).

In SU2 channel systems, we observed a more complex interplay of incision, lateral migration, and vertical aggradation, building-up a thick wedge of levees and overbank deposit that flank the valley-fill deposit. This is similar to channel systems in the Karoo basin (Flint et al., 2011; Hodgson et al., 2011). The channels initiate from incision of a single channel element cutting into the underlying mudstones. This is indicated on cross section as U-shaped valley form and could suggested sedimentation on the upper to lower slope environment. Subsequent channel incision (cut-through), migrate and aggrade vertically with deposition on the levees and overbank and in the channel-axis of the older under-fill channels. These repeated phases of incision, lateral migration and vertical aggradation creates a complex cut-and-fill relationship that overtime leads to wider and deeper valley-form. The longevity of the submarine channel systems evolution and the interplay of these phases of evolution creates a complex stratigraphic architecture preserved in the stratigraphic record.

The geomorphic evolution of submarine channel-levee complex in the Taranaki basin provides a clear understanding of the internal architectures of deepwater systems (Figure 3.25). Here, channel architectural element is a vital tool used in deciphering the stratigraphic evolution of the channel – levee complex in the Taranaki basin. The early channel evolved in a single – multiple north trending channel belt consisting dominantly of stacked channels element (Figure 3.27A and B). During the later phase of channel evolution, the channels evolved as channels complexes and stacked channel complexes set within a multiple north-western channel belt (Figure 3.24C – E, and 3.25C – E). The results presented here align to similar studies done in other basins example the Niger delta (Adeogba, 2003; McHargue et al., 2011), Offshore Angola (Abreu et al., 2003; Gee & Gawthorpe, 2007), Gulf of Mexico (Kane, Mcgee, & Jobe, 2012; Prather et al., 1998), the Amazon fans (Damuth et al., 1983) and the Karoo basin (Flint et al., 2011; Hodgson et al., 2011, Morris et al., 2014). Our results however show that, the channel and channel-fill consist of thick massive sandstones. This is typical of channel axis deposition for example (Catterall et al., 2010; Mayall et al., 2006; McHargue et al., 2011) and are similar to core interpretation of the middle Miocene Moki Formation around Mari Field (Grain, 2008). Away from the channel axis, the complexity of the internal architecture increases from the axis to off axis and the levees/overbank settings (Posamentier, 2003; Mayall et al., 2006; Kane and Hodgson, 2011; Morris et al., 2014). The lithologies forming the levees/overbank facies are heterolithic in nature i.e. consisting of thinly interbedded sandstones, siltstone and mudstones (Janocko et al., 2013; Kane & Hodgson, 2011; Kane et al., 2007b; Wynn et al., 2007). This relationship was observed in drill cuttings analysis and also in core (Grain, 2008). The levees/overbank facies pass into the basin floor mudstone facies. The basin floor mudstones are dominantly muddy in composition (Hickson and Lowe, 2002; Morris et al., 2014; Auchter et al., 2016). Our study builds on existing evidence of the complex internal architecture of submarine channel-levee complex example (Catterall et al., 2010; Flint et al., 2011; Hickson & Lowe, 2002; Janocko et al., 2013; Kane & Hodgson, 2011; Mayall et al., 2006; McHargue et al., 2011; Morris et al., 2014).

3.12.2 CONTROLS ON THE GEOMORPHIC EVOLUTION OF MIOCENE SUBMARINE CHANNELS SYSTEM IN THE TARANAKI BASIN

A range of factors have been inferred to control the morphology and stratigraphic architecture of submarine channels in the Taranaki Basin including: changes in basin geometry and orientation (King & Thrasher, 1996; Pilaar & Wakefield, 1978). For example, regional tectonic activity involving the Australian and the Pacific plates exerts a major control on the basin geometry during the Mio-Pliocene. Faulting and folding in the central and eastern part of the study area also controlled the Neogene depocentres. Inversion centred mostly in the southern part of the basin was key to the earliest sediment routing into the basin. Also, the subsequent anticlockwise rotation of the shelves towards the south-eastern, eastern, and north-eastern part of the basin played a major role in controlling the sedimentary systems and depocentres. Hence, tectonics have exerted a significant control on the source-sink configuration through time i.e., sediment staging area, the sediment provenance, and the sedimentation rate.

Base level changes are another tectonically linked control on the Middle Miocene submarine system. From the Altonian to early Lilburnian stage, the entire Taranaki basin was subsiding with depocentres around the central and North-western parts of the basin (King & Thrasher, 1996). The late Lilburnian to Waiauan marks the onset of base level rise, this was accompanied by shelf rotation and a southeast to northeast sediment provenance with a huge sediment supplied into the basin.

3.13 COMPARISON WITH OTHER SUBMARINE CHANNEL SYSTEMS

The morphology of Amazon submarine channels (Damuth et al., 1988; Pirmez and Flood, 1995) shows similarities with the Middle Miocene Submarine channels in the Taranaki Basin. The stratigraphic architecture of the Amazon channels shows stacked, levee-confined channels system (Damuth et al., 1983; Flood and Damuth, 1987;). This is like the Middle Miocene submarine channel system in Offshore Taranaki Basin where the channels are levee and erosionally-confined. Similarly, the depositional element i.e.; levees/overbank, channel-fills, and meander loop cut-off observed in the Taranaki basin, were also documented in the Amazon channels (Lopez, 2001).

In terms of the stratigraphic organisation, the Amazon channels are characterised by lateral migration and vertical aggradation (Lopez, 2001). We also observed similar stratigraphic organisation in the Middle Miocene submarine channels in the Taranaki Basin. Seismic cross section of the Amazon channel shows HARP at the base and axis of the Amazon channels and were interpreted as coarser-grained basal lags and channel-fills deposit (Manley et al., 1997;). However, our analysis of well cuttings from Offshore Taranaki basin shows that at the interval of interest, the lithological distribution of the channels is mudstone, heterolithics and very fine to fine-grained sandstone.

Attribute maps from Offshore West Africa, Offshore Angola and Offshore Nile Delta (Deptuck et al., 2007; Gee and Gawthorpe, 2007; Catterall et al., 2010; Janocko et al., 2013; Hansen et al., 2017;) reveals submarine channels with similar geomorphology and architectural element to the ones observed in the Middle Miocene submarine channels in Offshore Taranaki Basin. However, due to difference in basin physiography, Offshore West Africa; a passive margin basin, structurally controlled by growth fault and mud diapirs (Deptuck et al., 2003, 2007), Offshore Angola and Offshore Nile Delta also a passive basin controlled by salt tectonics (Catterall et al., 2010; Cross et al., 2009; Gee & Gawthorpe, 2007; Oluboyo et al., 2014), we believe that the control on the evolution, geomorphology, and the stratigraphic architecture of channels in these basins might not be entirely similar to the Taranaki basin. Architectural element such as; channel-fills, and levees were also observed though at different scales in the study location, MTD, crevasse splays and channel avulsion were not interpreted in the study location but were documented to occur in other part of the Taranaki basin (Peter R. King & Thrasher, 1996).

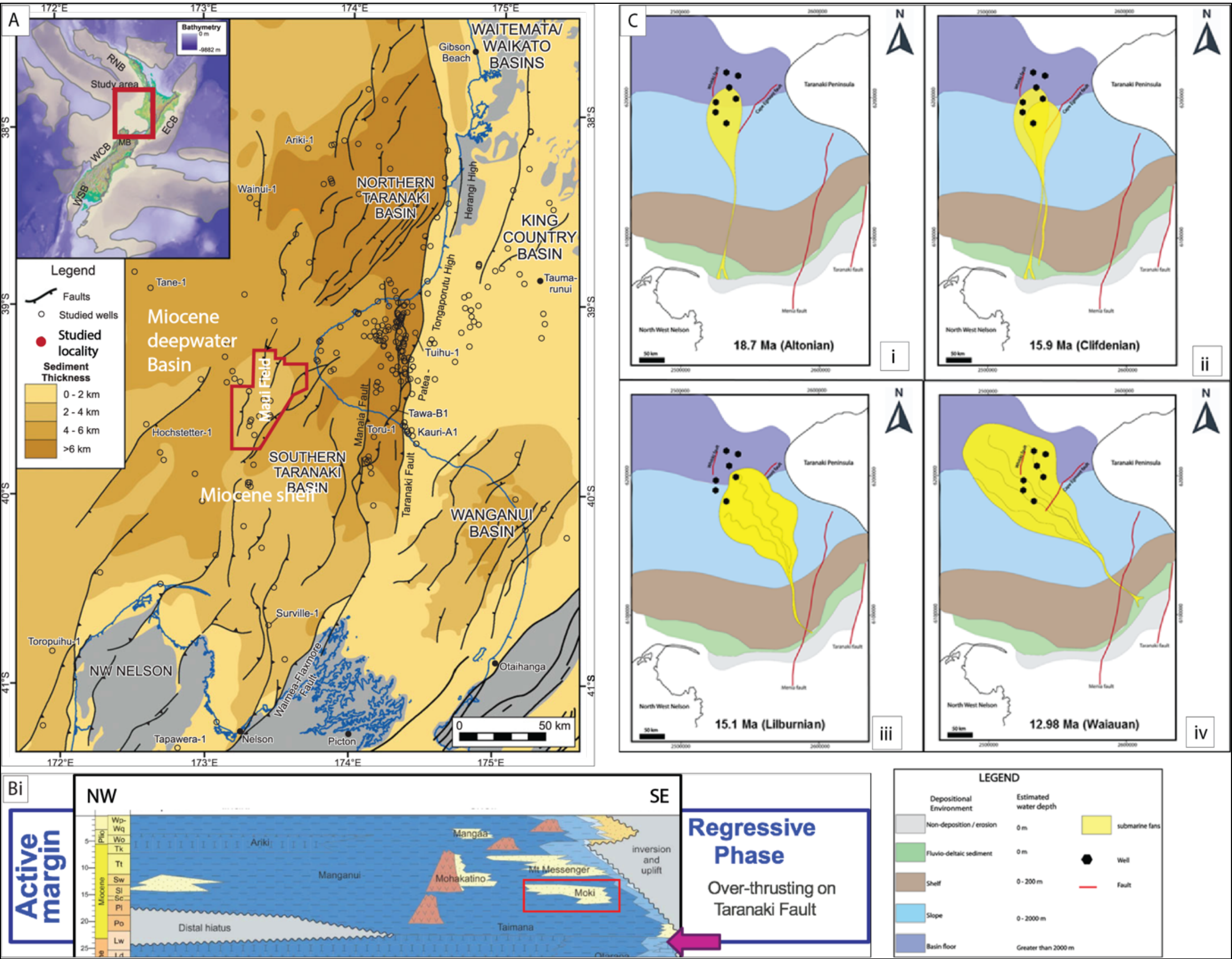
In terms of the stratigraphic organisation, submarine channels in Offshore West Africa, Angola and the Nile Delta are characterised by lateral migration and vertical aggradation of channel axis and channel margin facies (Abreu et al., 2003; Deptuck et al., 2003; Adeogba et al., 2005; Catterall et al., 2010; McHargue et al., 2011; Janocko et al., 2013; Zhang et al., 2016; Jobe et al., 2017;). We also observed similar stratigraphic organisation in the Middle Miocene submarine channels in the Taranaki Basin. The major difference of the study location from most of this basins are the occurrence of internal levees and terraces especially in Offshore West Africa (Deptuck et al., 2003, 2007;). However, we cannot say for sure if internal levees and terraces were not observed in other part of the Taranaki Basin and as such, we cannot preclude the occurrence of the internal levees and terraces in the Taranaki basin solely from the analysis data drawn from our study location.

3.14 CONCLUSIONS

This paper presents a synthesis of the geomorphic evolution, depositional elements, and the stratigraphic architecture of the middle Miocene deep-water Moki Formation in Offshore Taranaki basin. This was achieved through the interpretation of 3D seismic reflection data, well logs and drill cuttings data of the middle Miocene interval. The basin fill during the middle Miocene was deposited in two phases of similar stratigraphic architecture: (i) an older northward flowing deep-water channel system (SU1) and (ii) a younger northwest flowing deep-water channel system (SU2). These two channel systems are separated by period of reduced sand deposition in the basin. However, they show similar internal architecture comprising of finning upward channel fills, interbedded heterolithic levee/overbank deposit and the mudstone dominated basin floor deposit. The lithology distribution comprises of sandstone, heterolithics and mudstone with an increasing mudstone content.

The geomorphic evolution and stratigraphic architecture of the middle Miocene deep-water system in the Taranaki basin is related to: (i) tectonic evolution of the New Zealand landmass, (ii) the variability in the amount and type of source material and, (iii) the variations in the basin physiography and sediment staging area through time. The expression of these controls in the geomorphic evolution and the stratigraphic architecture of deep-water successions might not be the same for all setting, however the controls themselves are common to all deep-water basins.

FIGURE CAPTION



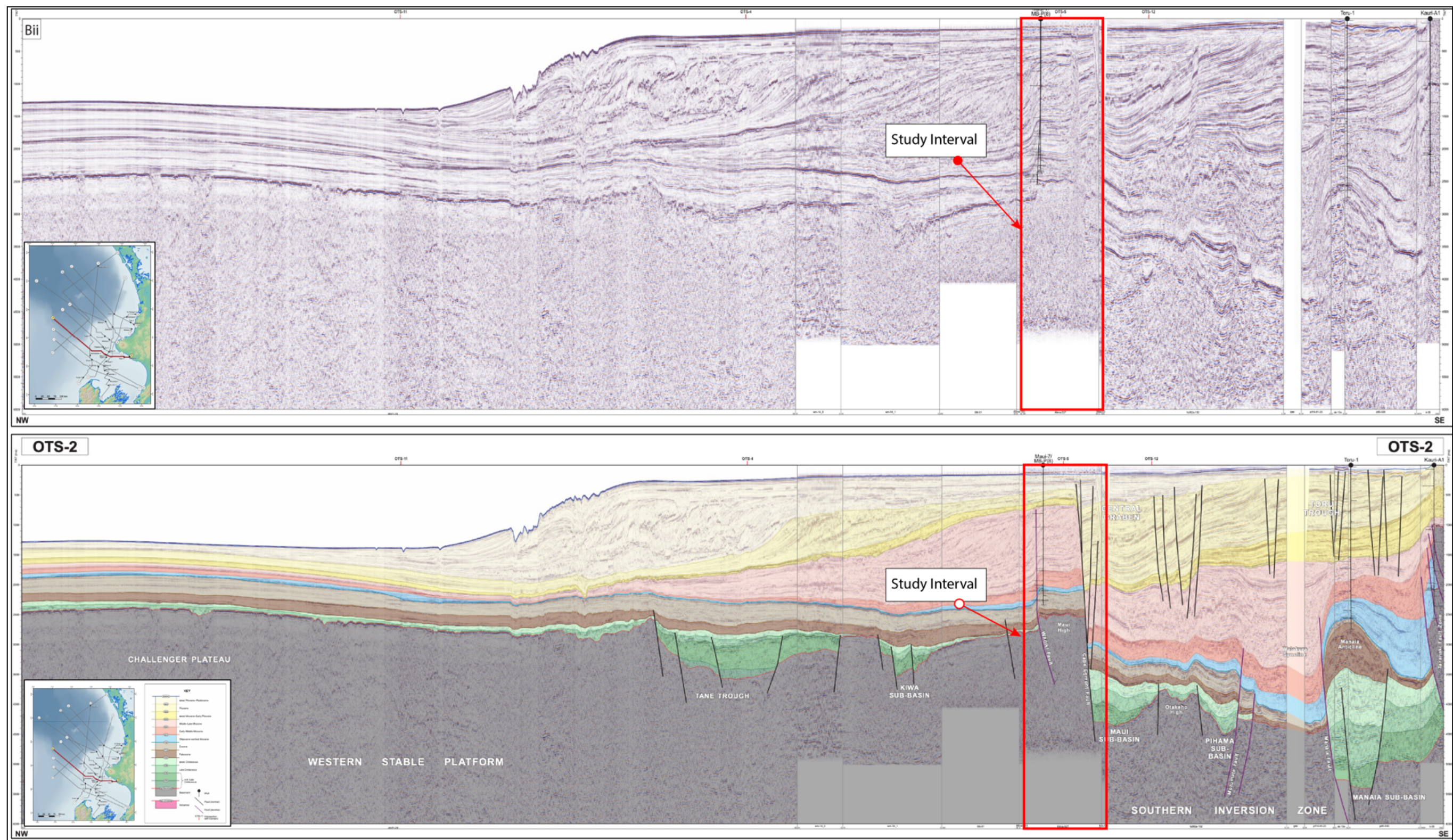


Figure 3. 1: (A) The map of Taranaki Basin showing occurrence present day major faults, selected exploration wells, 3D seismic data acquired in the basin (red lines show the 3D seismic data used for this study i.e., Maui 3D survey). Inset shows Taranaki Basin within the New Zealand Landmass (modified after Strogen et al, 2014, King & Thrasher 1996). (Bi) Tectonostratigraphic framework of the Taranaki Basin (modified after King & Thrasher 1996), (Bii) Uninterpreted and interpreted regional seismic section (OTS-2), showing the shelf to slope Taranaki Basin architecture. The study location is represented by a red rectangle (C) (i) Altonian, (ii) Clifdenian, (iii) Lilburnian and (iv) Waiauian paleogeography of the Middle Miocene submarine channel systems (modified after Grain, 2008, King and Thrasher, 1996)

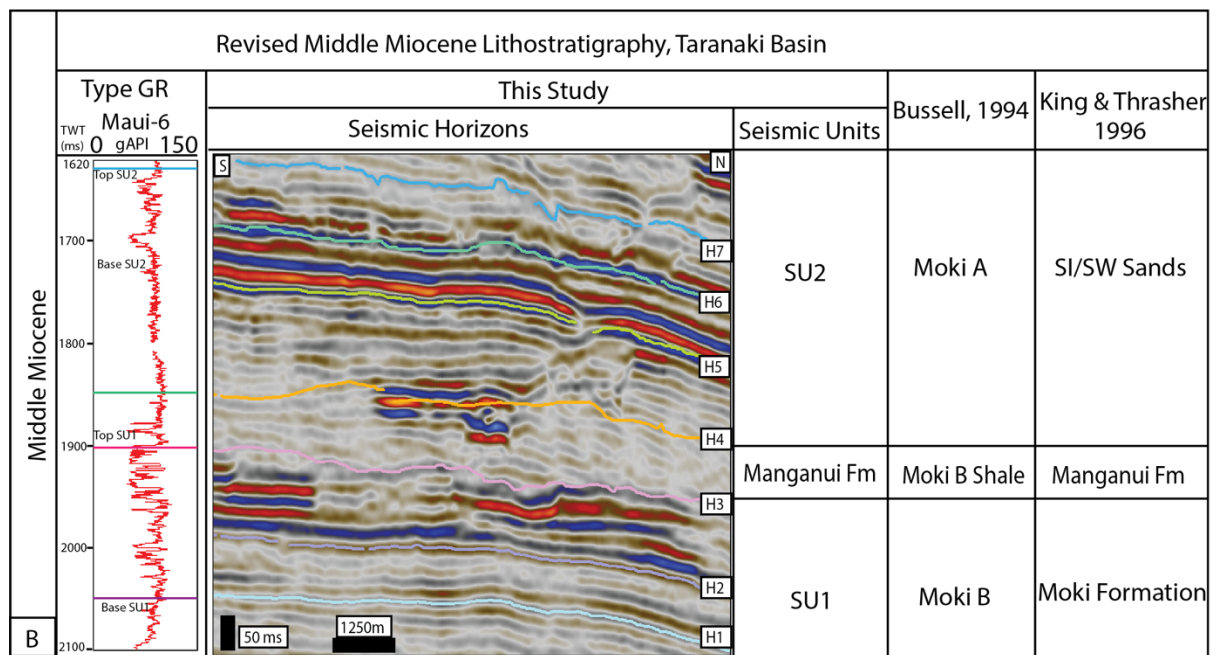
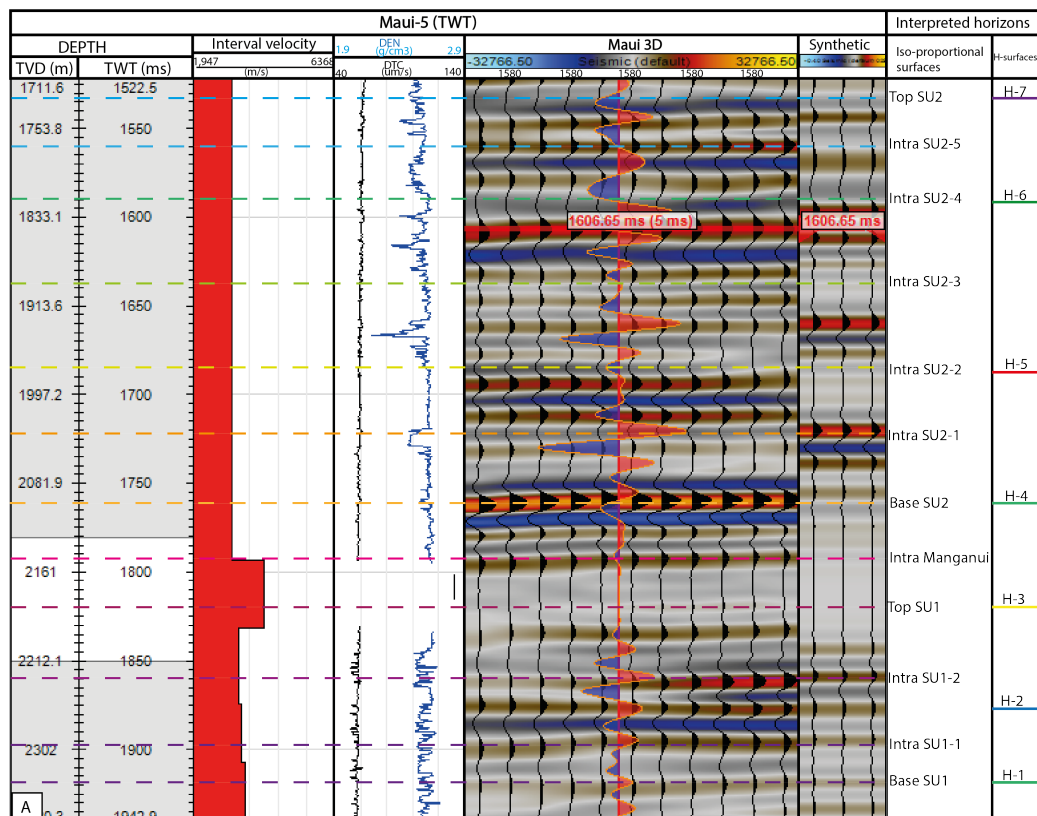


Figure 3. 2: (A) Seismic-to-well tie from well Maui-5 showing interpreted horizons H-1 – H-7, (B) A South – North seismic line showing the seven interpreted seismic horizons (H-1 to H-7) within two seismic units (SU1 and SU2) as related to other lithostratigraphic

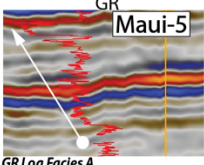
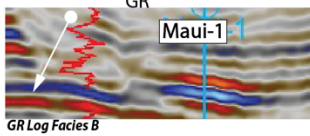
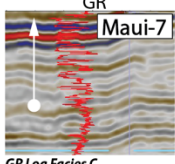
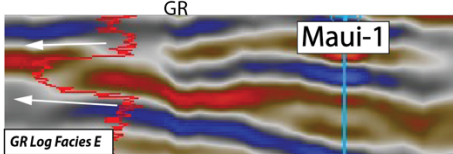
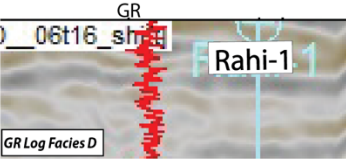
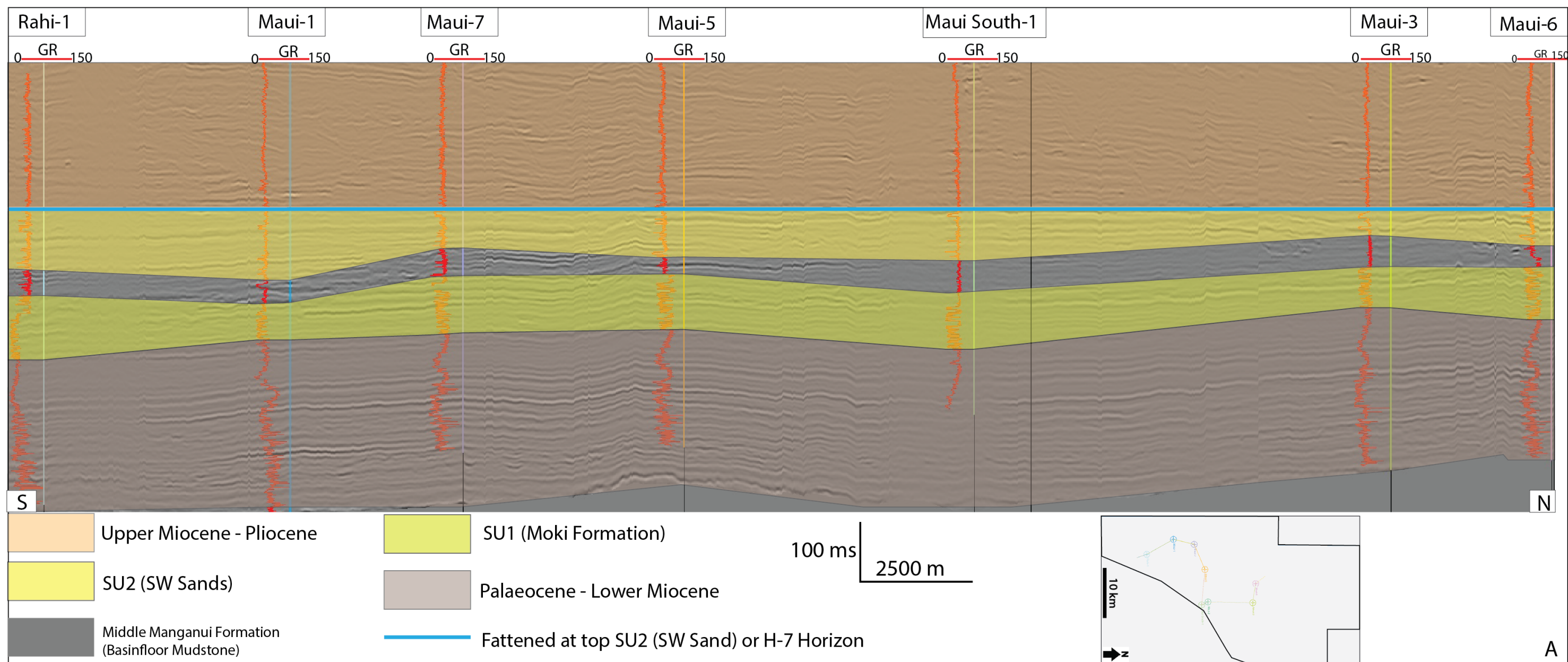
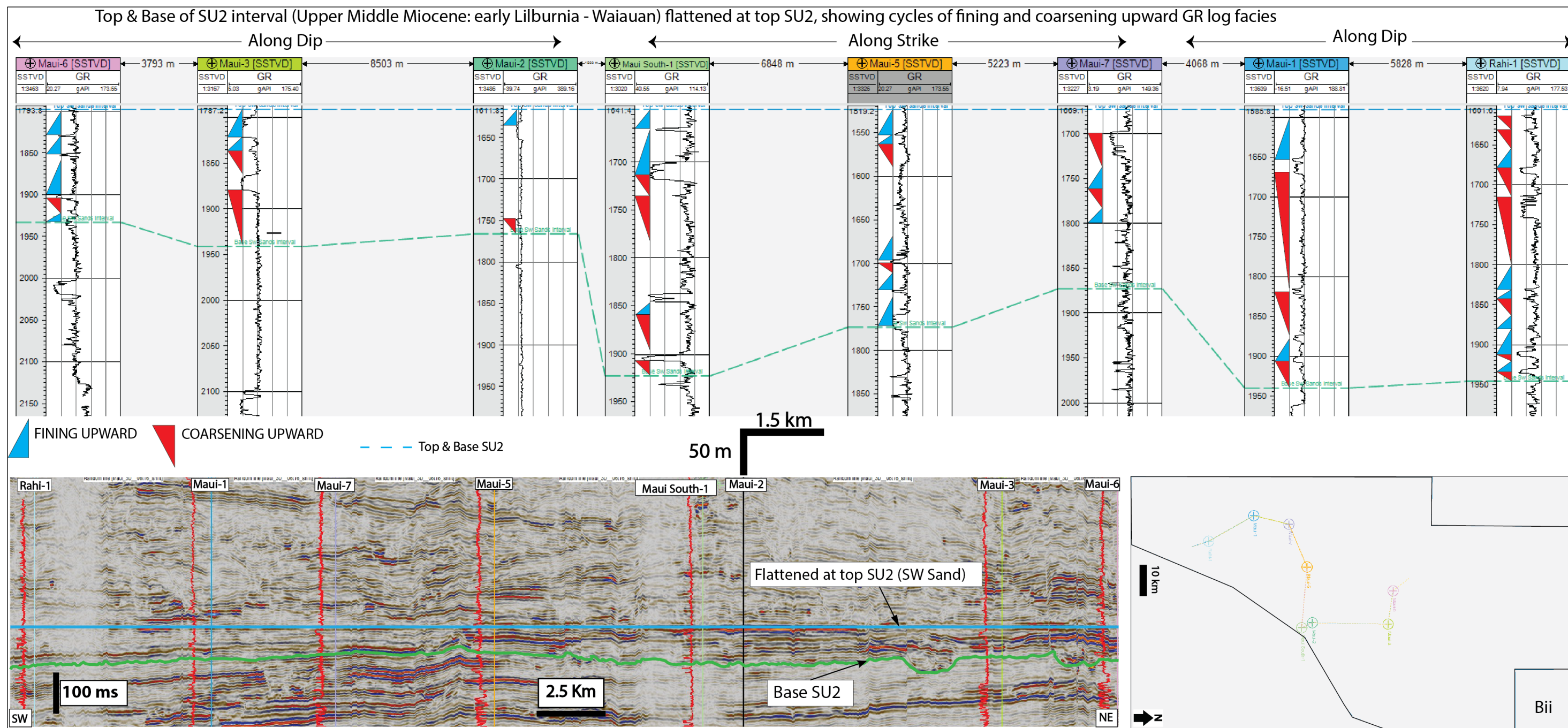
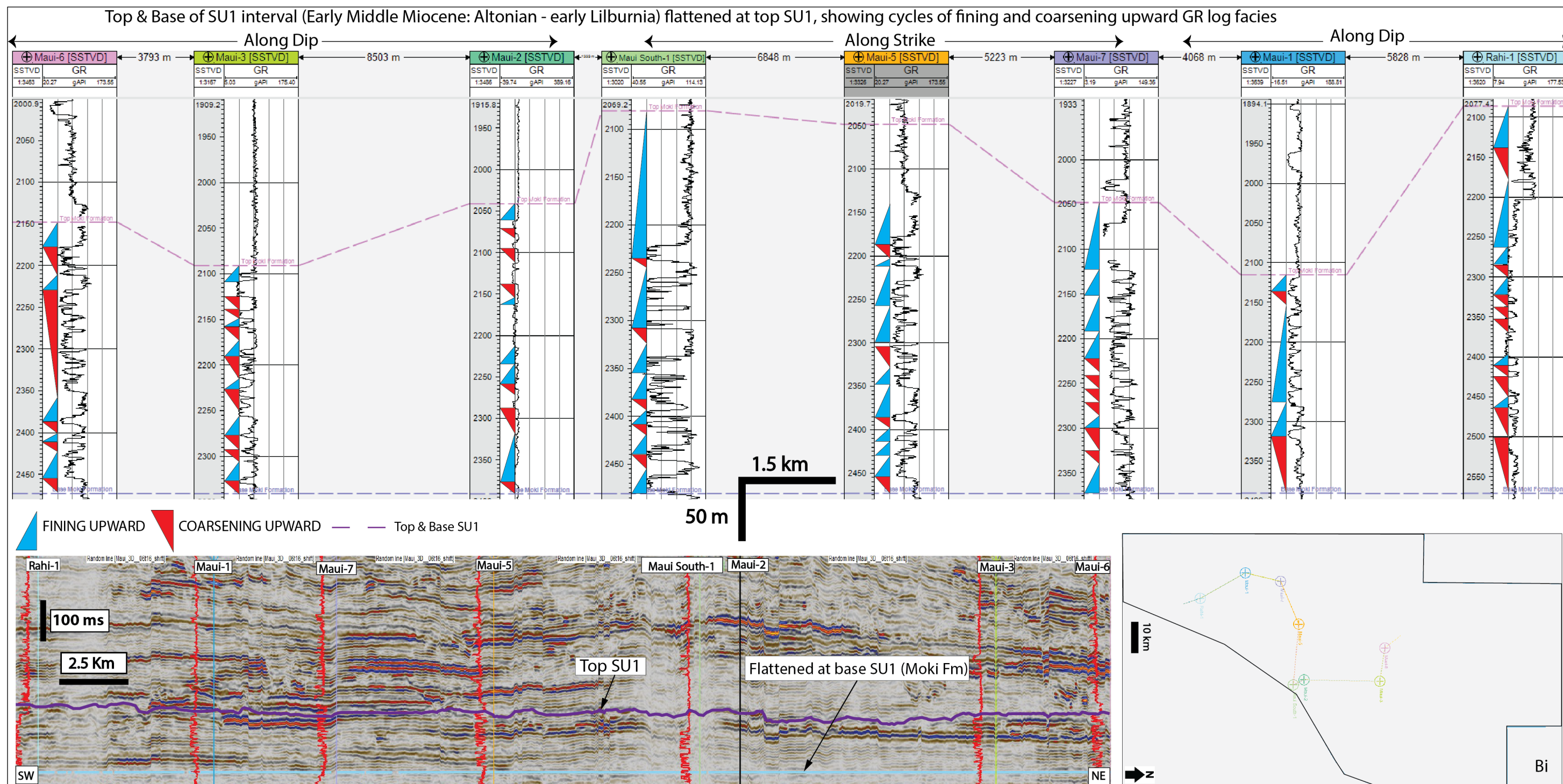
GR log Motif and Electro facies identified in the study interval			
Seismic integrated GR Log facies	GR Log Shape	Stacking Pattern	Description
 GR Log Facies A	Funnel Shape	Coarsening Upward	GR Log Facies A: This wireline log facies is characterised by low API GR log motif (0 - 50 API). The GR log trend is mostly funnel shaped, This facies has thickness range of 2 m - 82 m. Interpretation: This low API facies are interpreted as submarine channelsandstones. The log show this channel sandstones to have a sharp to gra-dational contacts with the lower or upper beds
 GR Log Facies B	Bell Shape	Fining Upward	GR Log Facies B: This wireline log facies is characterised by an upward increasing API GR log motif (bell shape). The GR log trend is usually irregular in shape and this facies have a thickness range of 2 m - 78 m Interpretation: This are interpreted as thick, interbedded, bathyl slope channels. They could also be interpreted as interbedded sandstone and overbank mudstone. The log show this facies interval to have a sharp to gradational contact with the overlaying and underlaying lithologies.
 GR Log Facies C	Serrated	Aggradating	GR Log Facies C: This wireline log facies is characterised by acylindrical GR log shape. The GR log trend is usually serrated in shape and this facies have a thickness range of 2 m - 106m Interpretation: This very low API log motif are interpreted as thick, interbedded blocky channel sandstone. They could also be interpreted as interbedded sandston and overbank mudstone. The log show this mudstone interval to have a sharp to gradational contact with the overlaying and underlaying lithologies.
 GR Log Facies D	Blocky Shape	Aggradating	GR Log Facies D: This wireline log facies is characterised by avery low API GR log motif (lower than 45 API). The GR log trend is usually blocky in shape and this facies have a thickness range of 2 m - 68 m Interpretation: This low API GR log motif are interpreted as thick, interbedded channels. They could also be interpreted as interbedded sandstone and overbank mudstone. The log show this mudstone interval to have a sharp to gradational contact with the overlaying and underlaying lithologies.
 GR Log Facies E	Serrated	Aggradating	GR Log Facies E: This wireline log facies is characterised by very high low (70 - 140 API) and very high API GR log motif (greater than 70 API). The GR log trend show a combination of log shapes (i.e. interbed of funnel, bell or cylindrical GR log shapes). They have a thickness range of 6 m - 177 m Interpretation: This GR genetic log facies could be interpreted as mudstone, crevasse slays or off-axis channel depositional element. Bed contacts are sharp to gradational with the over and underlaying facies.

Figure 3. 3: Show Gamma ray (GR) log motifs (e.g., bell shape, cylindrical and irregular vertical log profiles) and Gamma ray (GR) log facies (e.g., facies A, B and C) identified in the study location







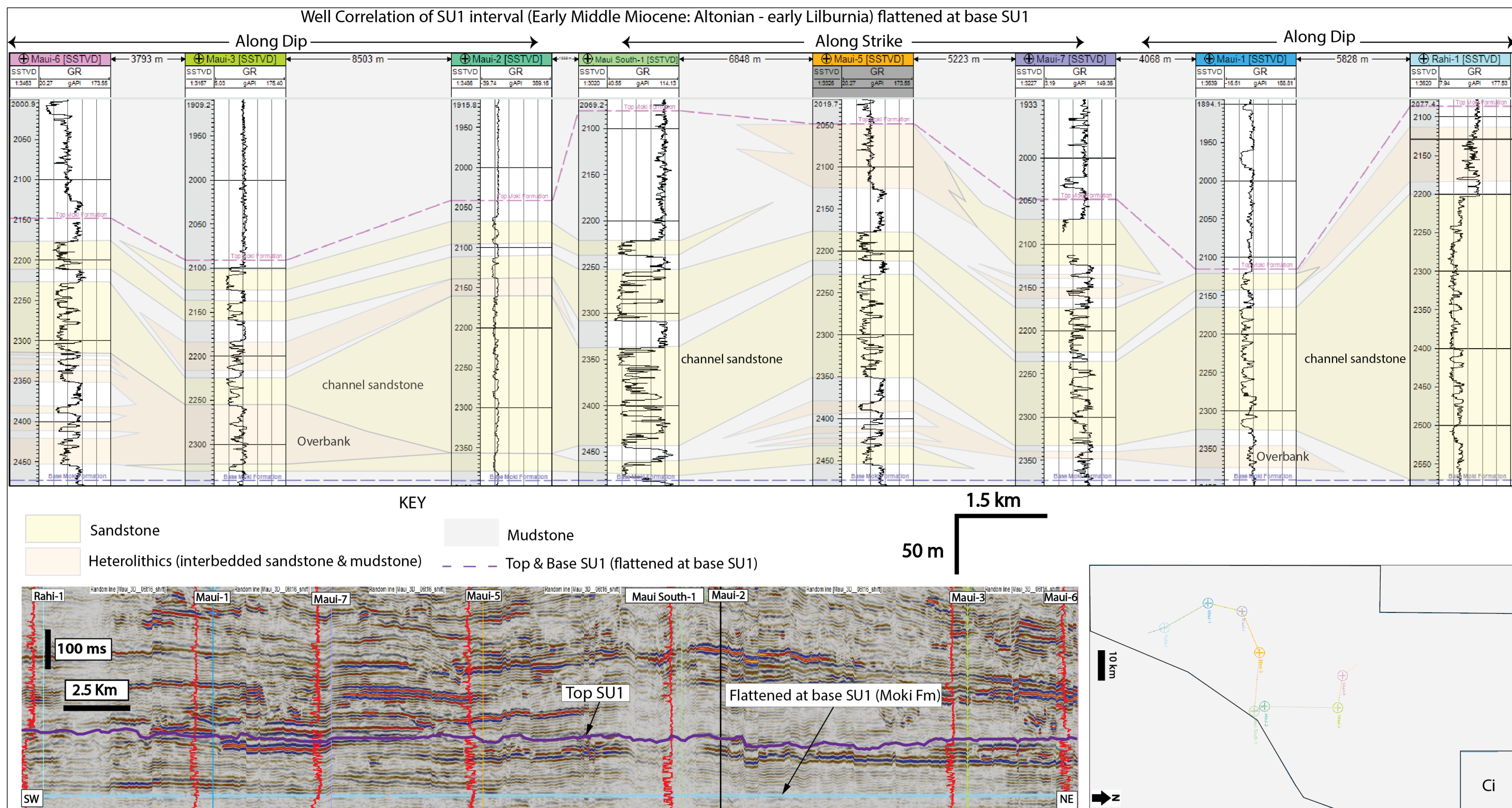


Figure 3. 4 (A) S-N flattened seismic section at large scale with wells and correlation overlay (B) & (Bii) NE-SW correlation panel of SU1 & SU2 showing integrated GR log motif to understand the sub regional vertical and lateral trends of genetic sequences (facies). This is useful for the observation of the GR Log facies within the interval of interest. (C) (i) & (ii) NE-SW correlation panel of the wells in the studied location showing lateral and vertical lithology distribution of the submarine channel systems in SU1 and SU2 respectively

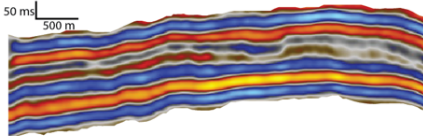
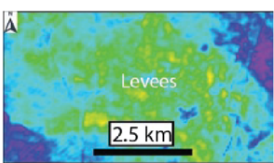
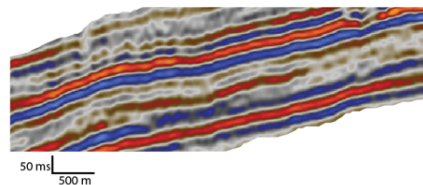
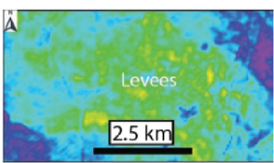
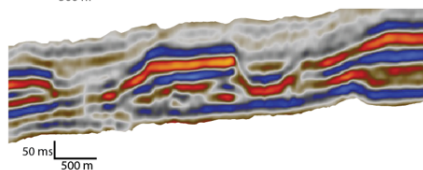
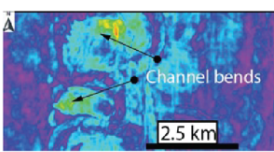
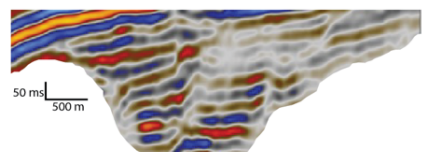
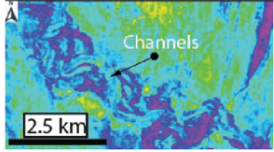
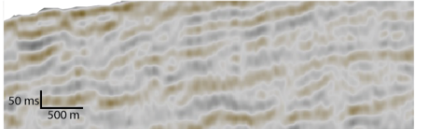
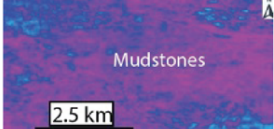
	Seismic Facies	Reflection characteristics	RMS Attribute Map	Lithology	Interpretation	Environment of deposition
SF1		Subparallel to parallel high amplitude reflection units		Interbedded mudstone, siltstone and sandstone. Thickness of 78 - 109 m and width of 3 - 10 km	Levees/overbank deposit resulting from channel over-spilling events	Levees/overbank
SF2		Subparallel to parallel high amplitude reflection units		Interbedded mudstone, siltstone and sandstone. Thickness of 78 - 109 m and width of 3 - 10 km	Levees/overbank deposit resulting from channel over-spilling events	Levees/overbank
SF3		Discontinuous, subparallel high amplitude reflection units		Sandstone unit interbedded with thinly bedded mudstone or siltstone. Thickness of 34 -104 m and width of 342 -1080 m	Erosionally-confined levee-bound sinuous channels	Channel-fills
SF4		Discontinuous, subparallel high amplitude reflection units		Valley-filled sandstone unit interbedded with mudstone or siltstone. Thickness of 34 -104 m and width of 342 -1080 m	Valley/erosionally-confined levee-bound sinuous channels	Channel-fills
SF5		Discontinuous, chaotic, low amplitude reflection units		Mudstone or claystone deposit showing units with very fine clay-grade deposit. Often very thick (>200 m)	Slope or basin-floor suspension deposit under low energy regime	Slope or basin-floor

Figure 3. 5: Generalised seismic facies (depositional element) observed within the channel systems (SU1 and SU2) in the Taranaki Basin.

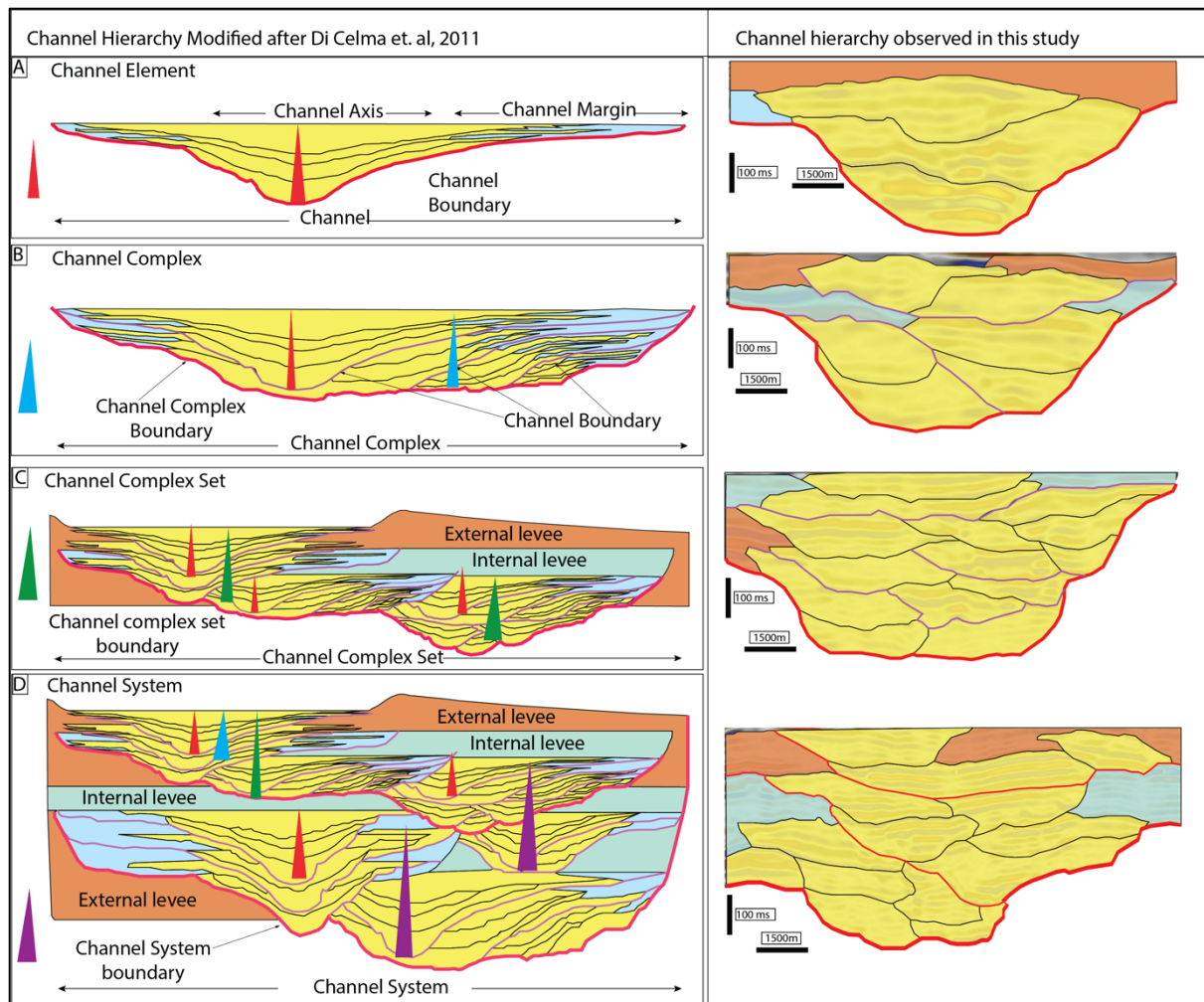


Figure 3. 6: Generalised deep-water channel hierarchical scheme modified after Di Celma et.al, 2011. A - D is the typical hierarchies observed in deep-water channels. The corresponding seismic lines shows the example channel hierarchy observed in the study location

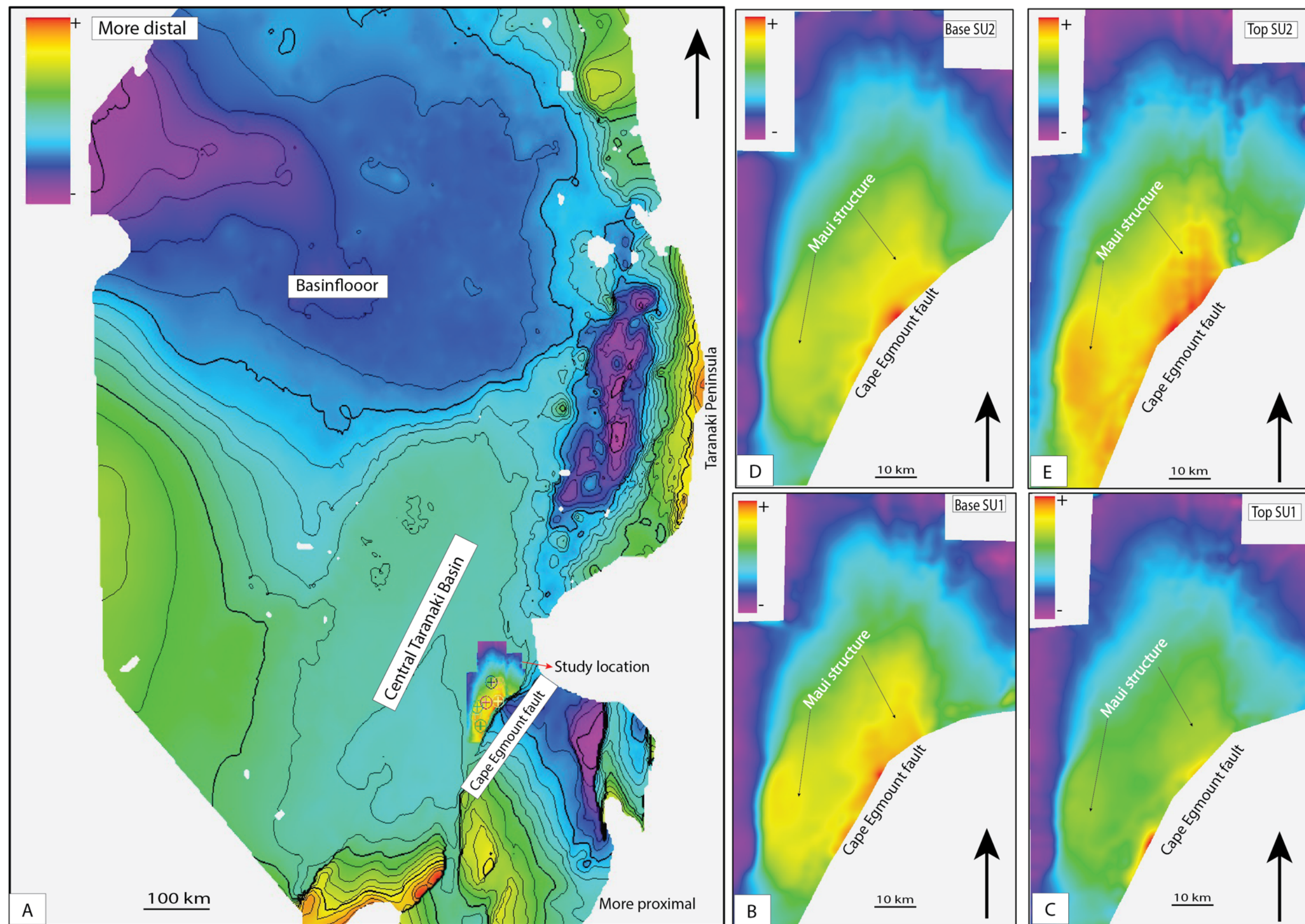


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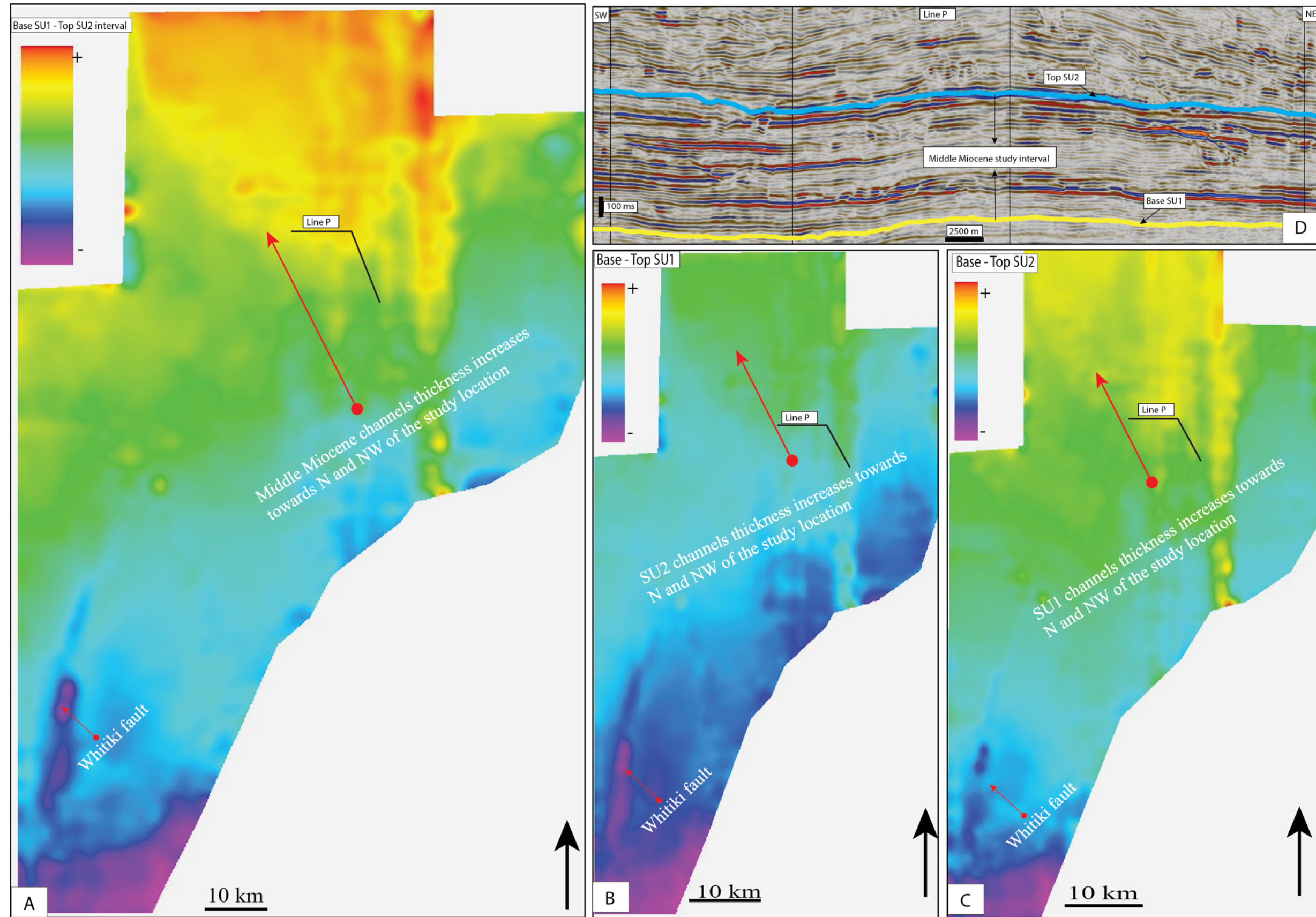


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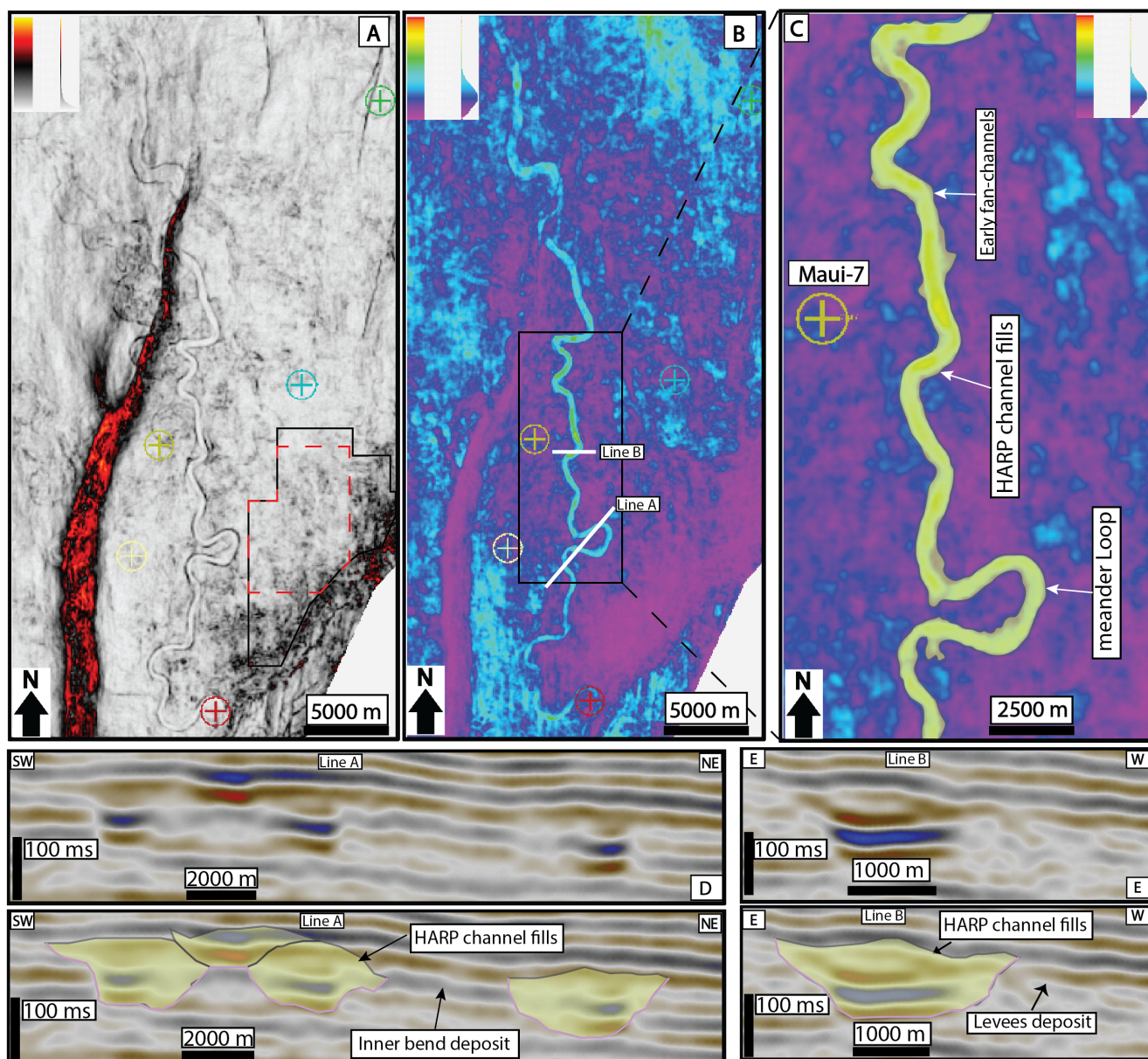


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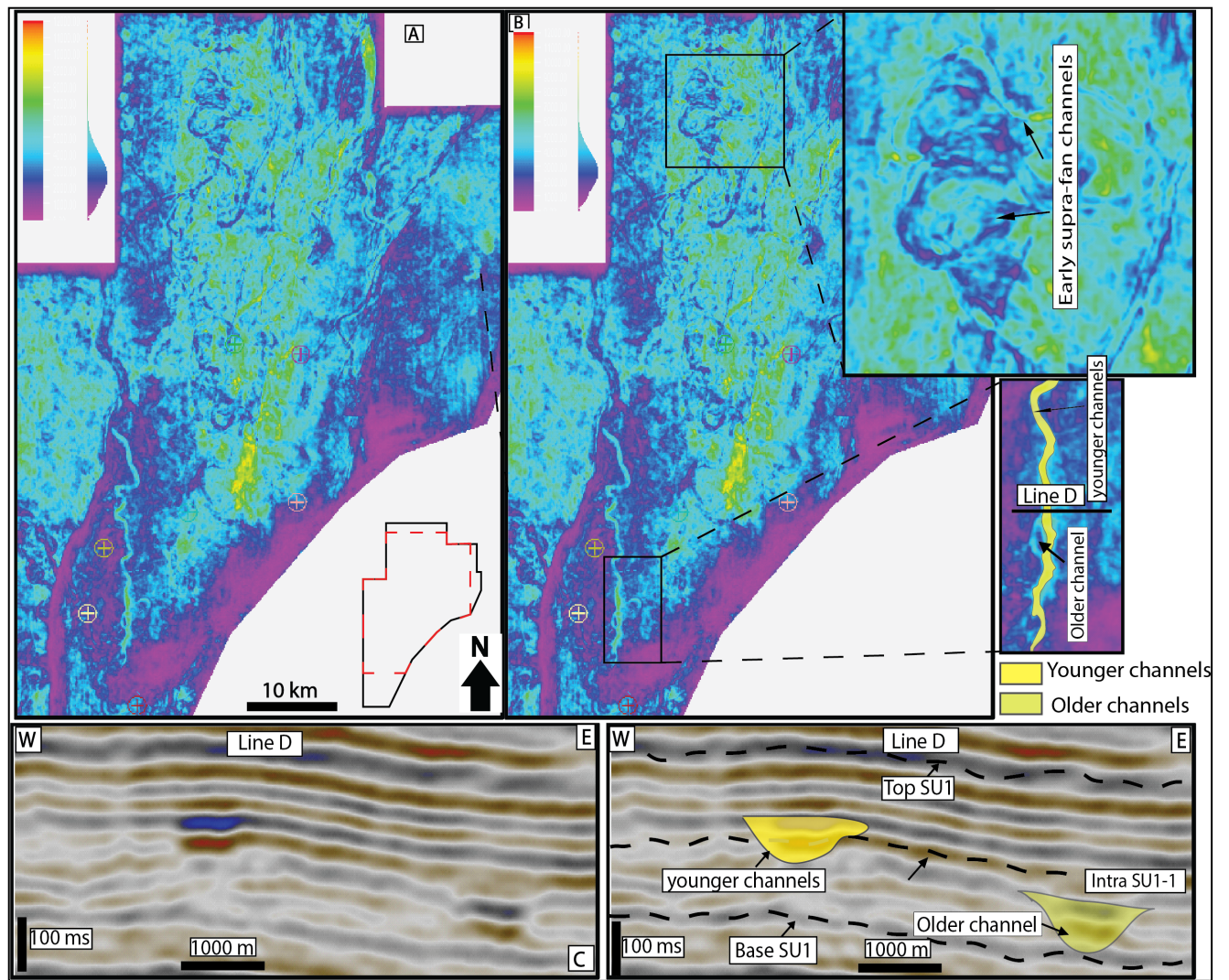


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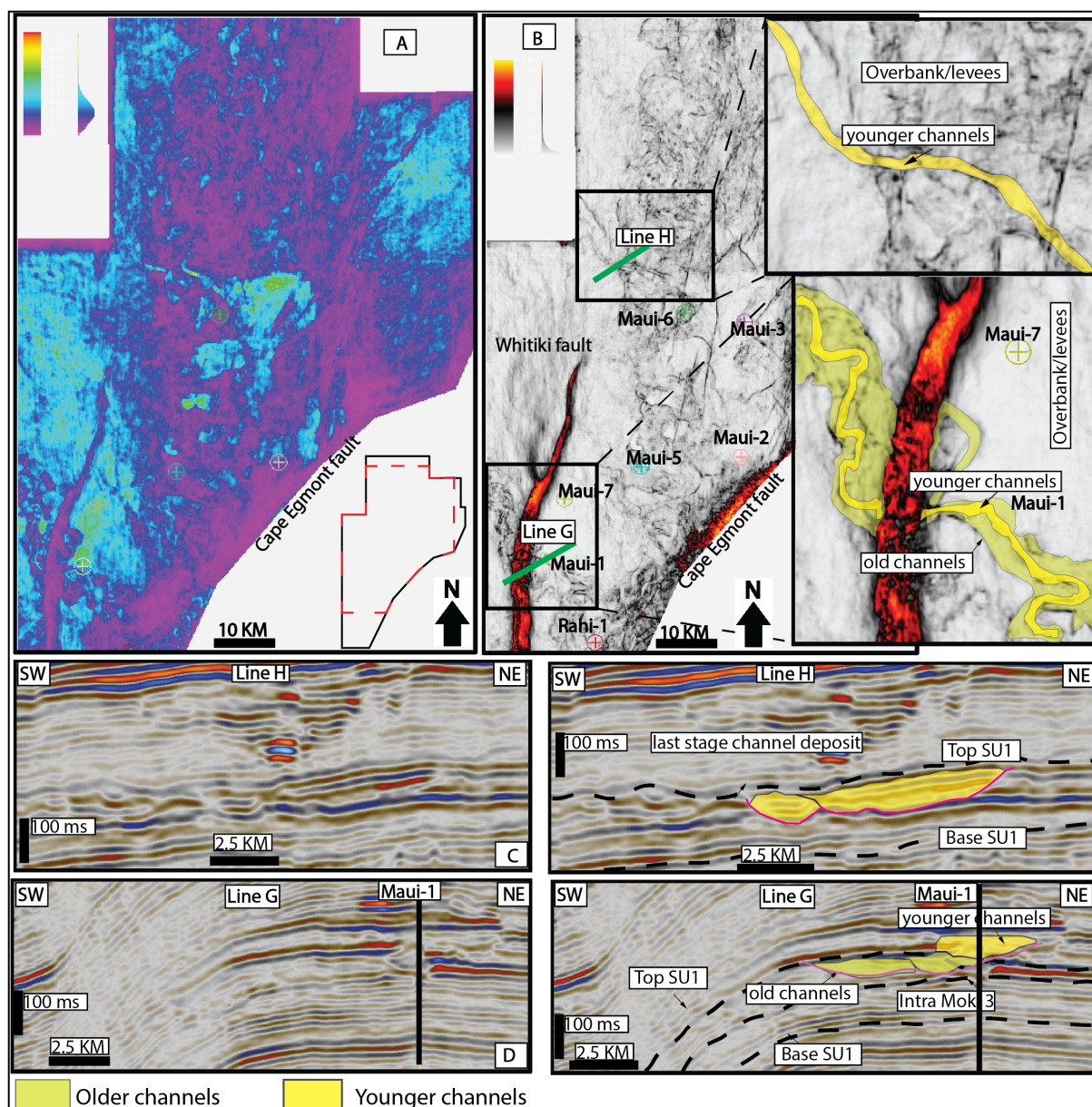


Figure 3. 11: Shows planform map extracted at top H-3. (A) RMS amplitude extraction map and (B) variance extraction map showing a northerly trending channel system. (C), and (D) are uninterpreted and interpreted seismic line showing the seismic expression of the supra-fan submarine channel-levee complex at top SU1. Note the younger NW trending channels which suggest the onset of change in channel paleo-flow direction

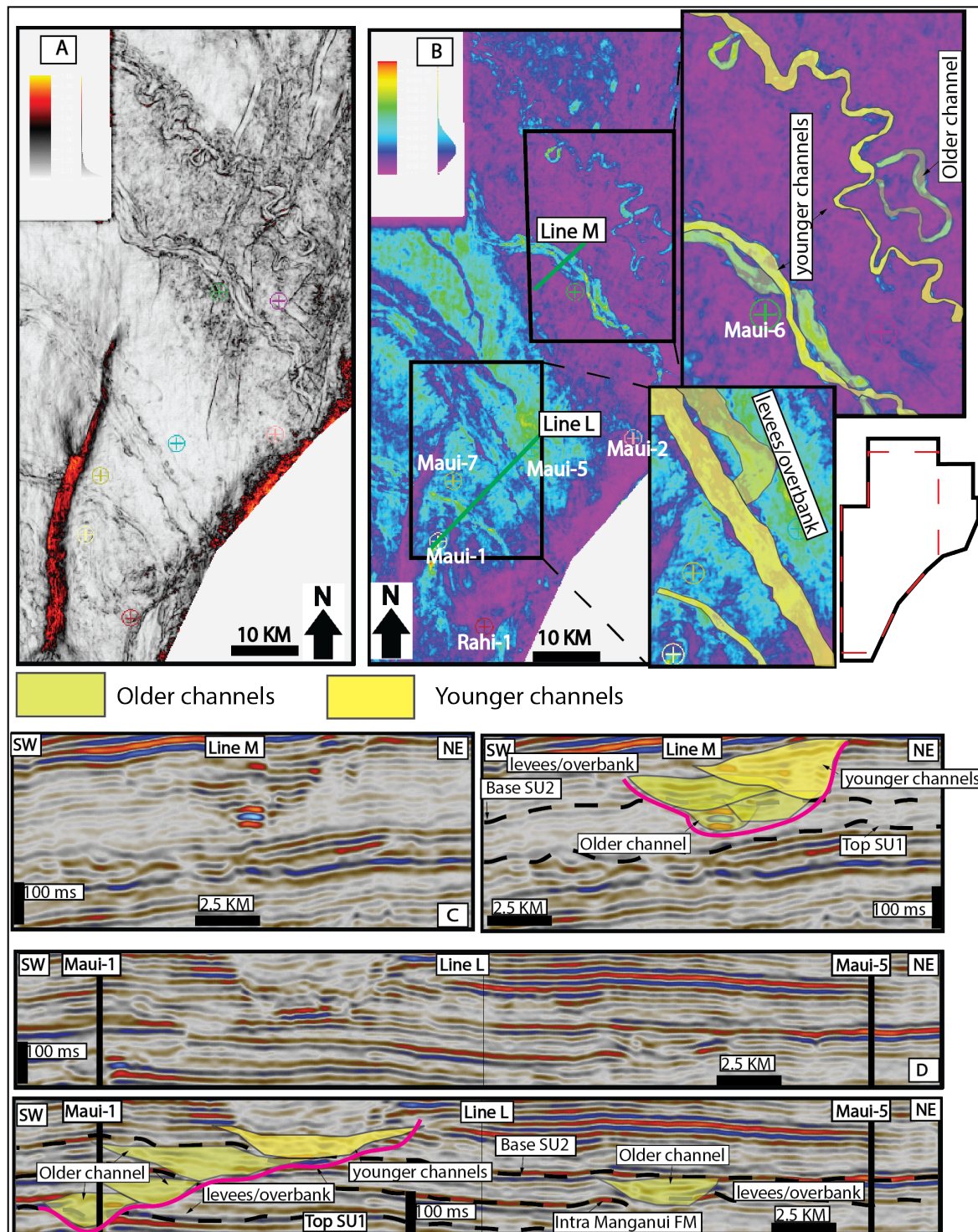


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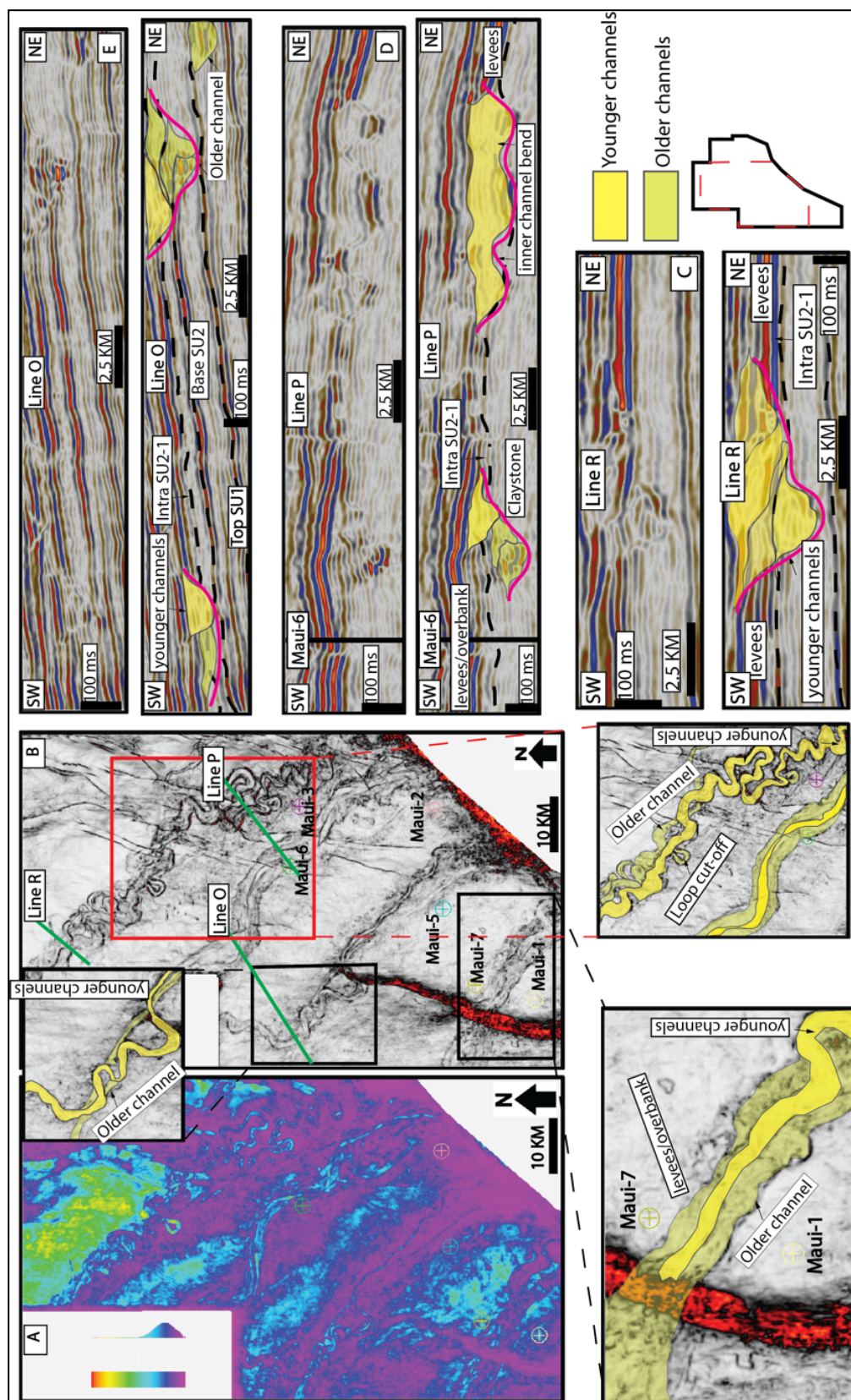


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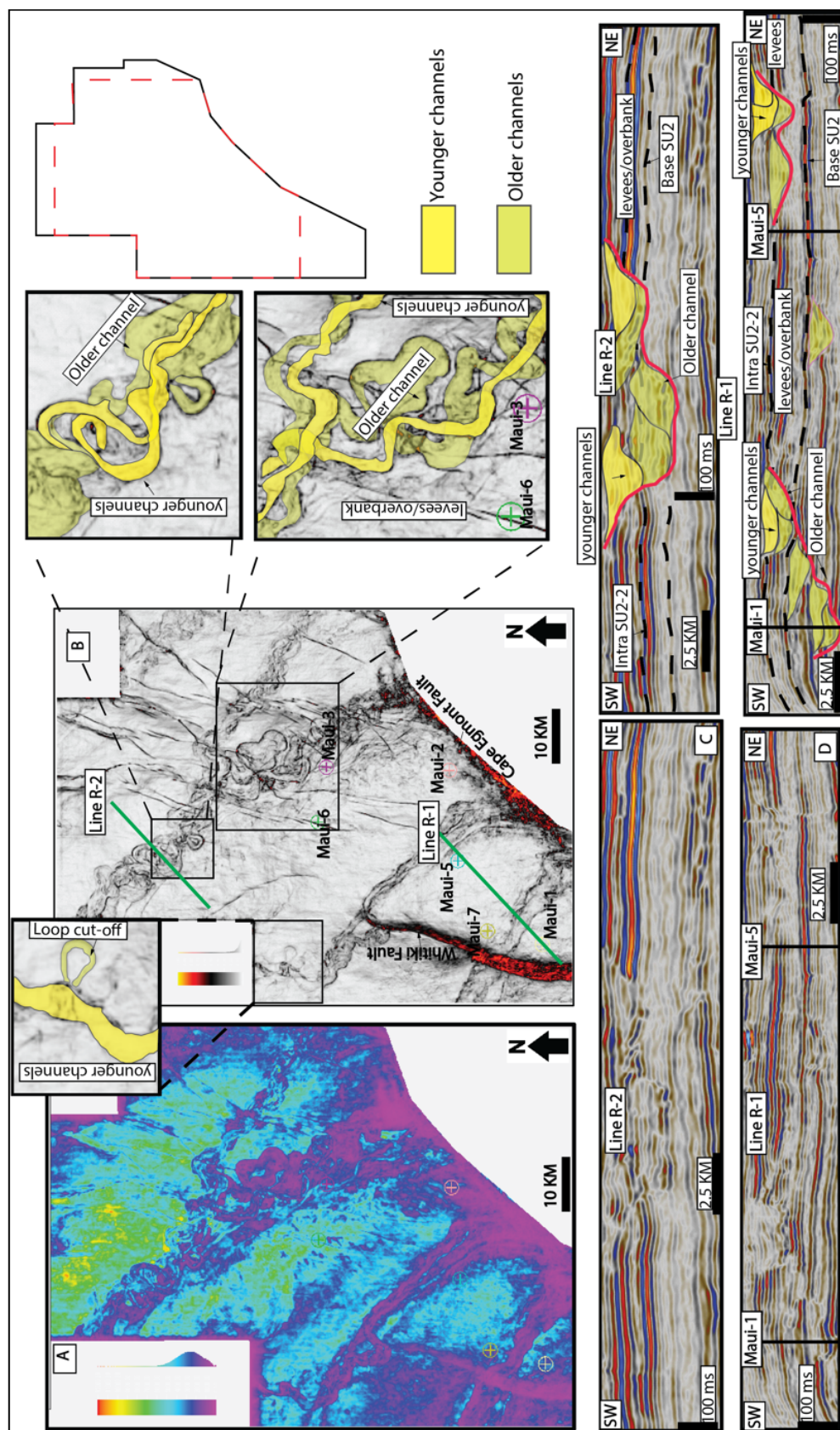
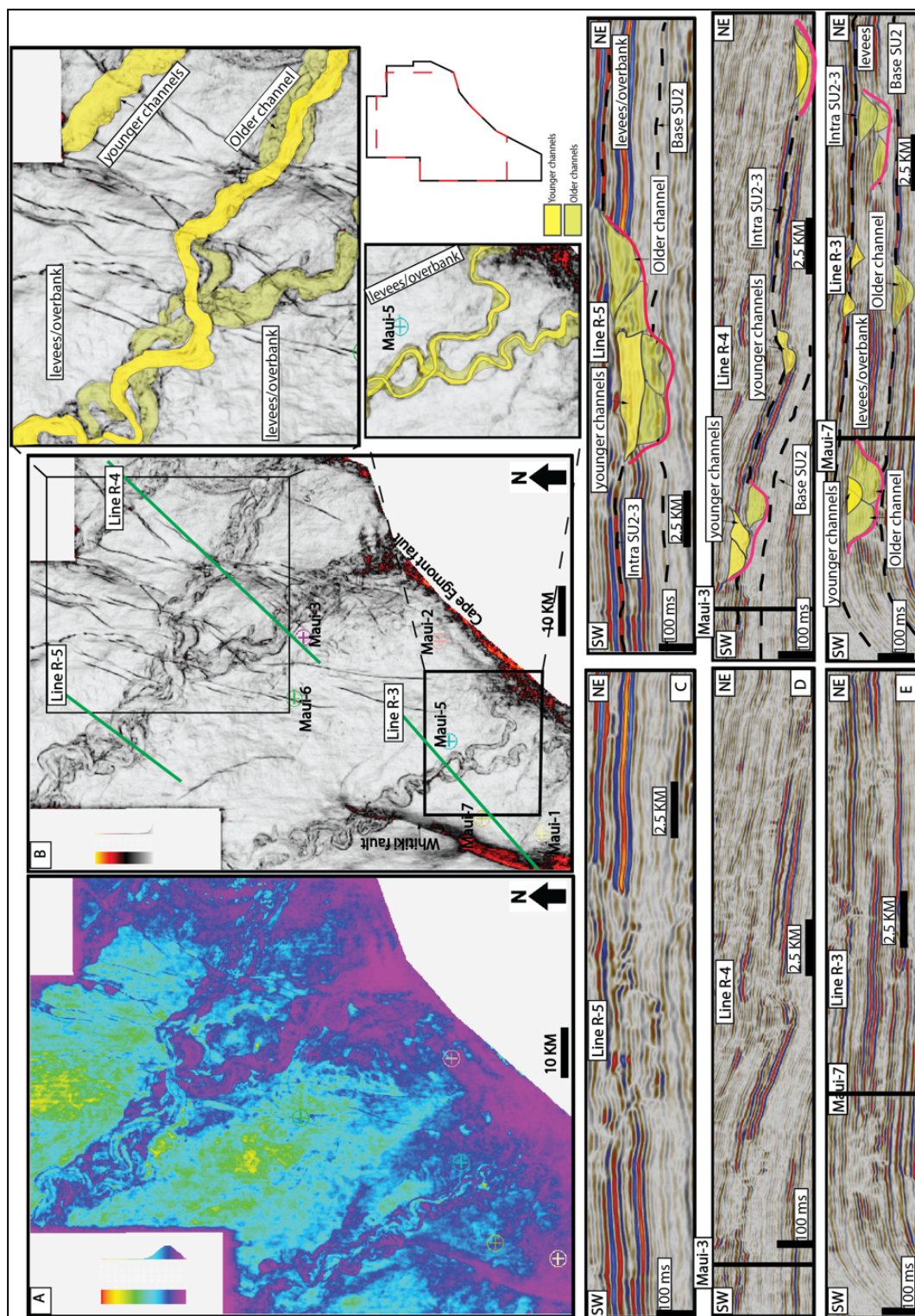


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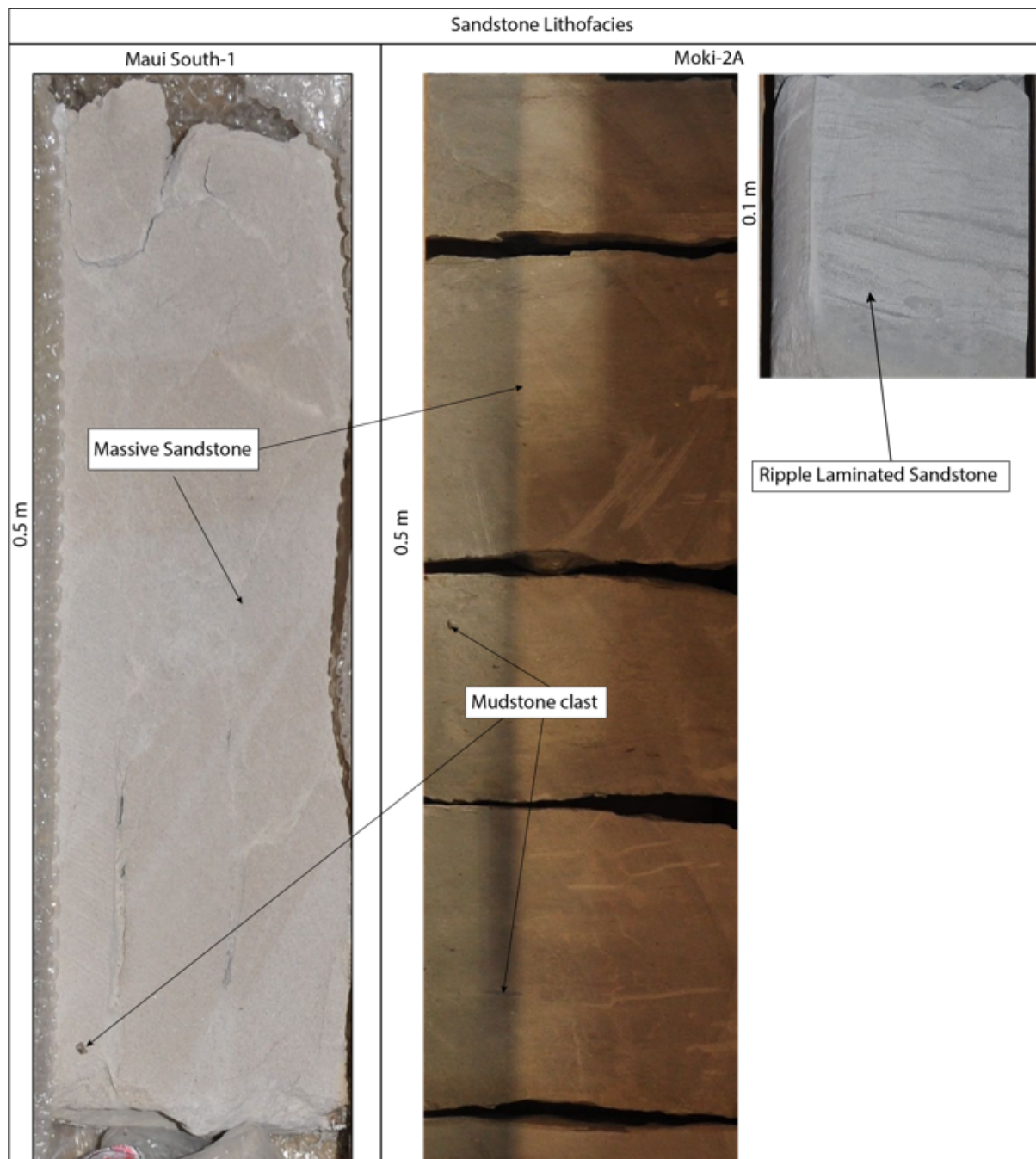


Figure 3. 16: show the core description of the Massive Sandstone and the Ripple Laminated Sandstone lithofacies from the middle Miocene study interval

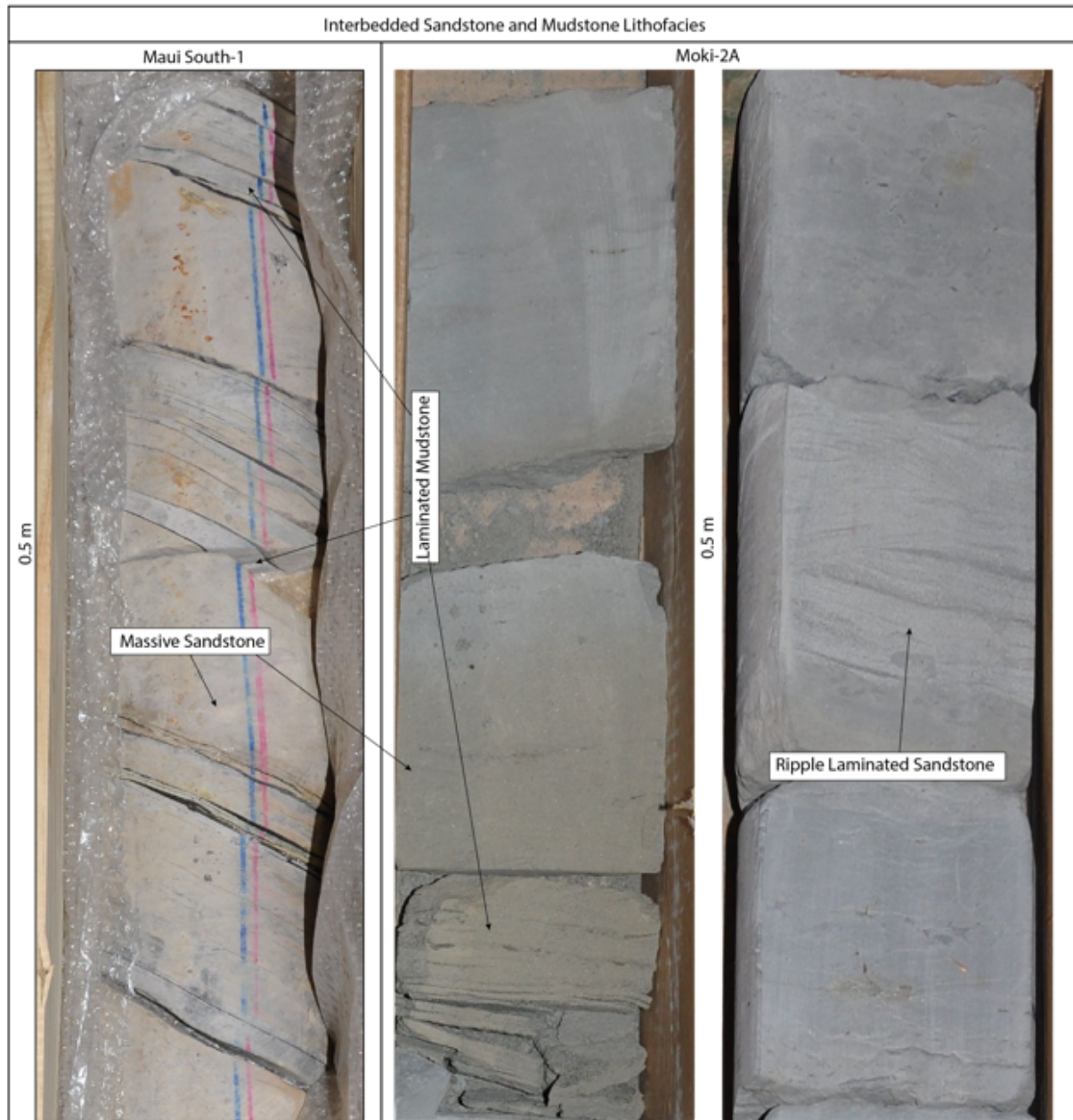


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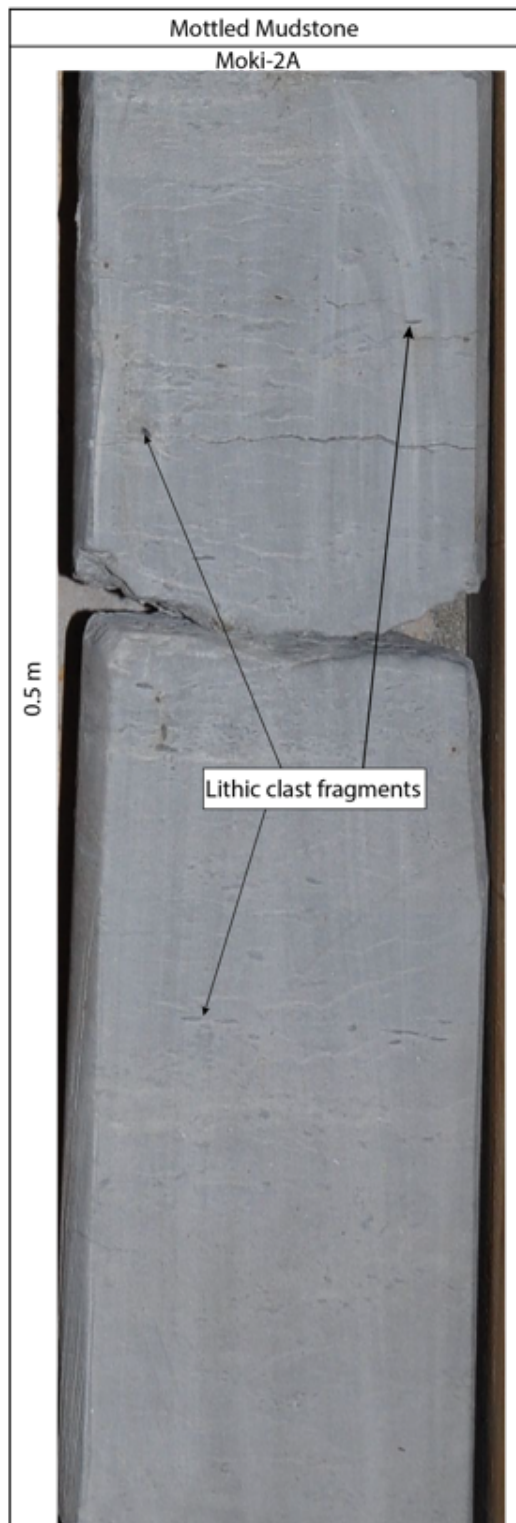


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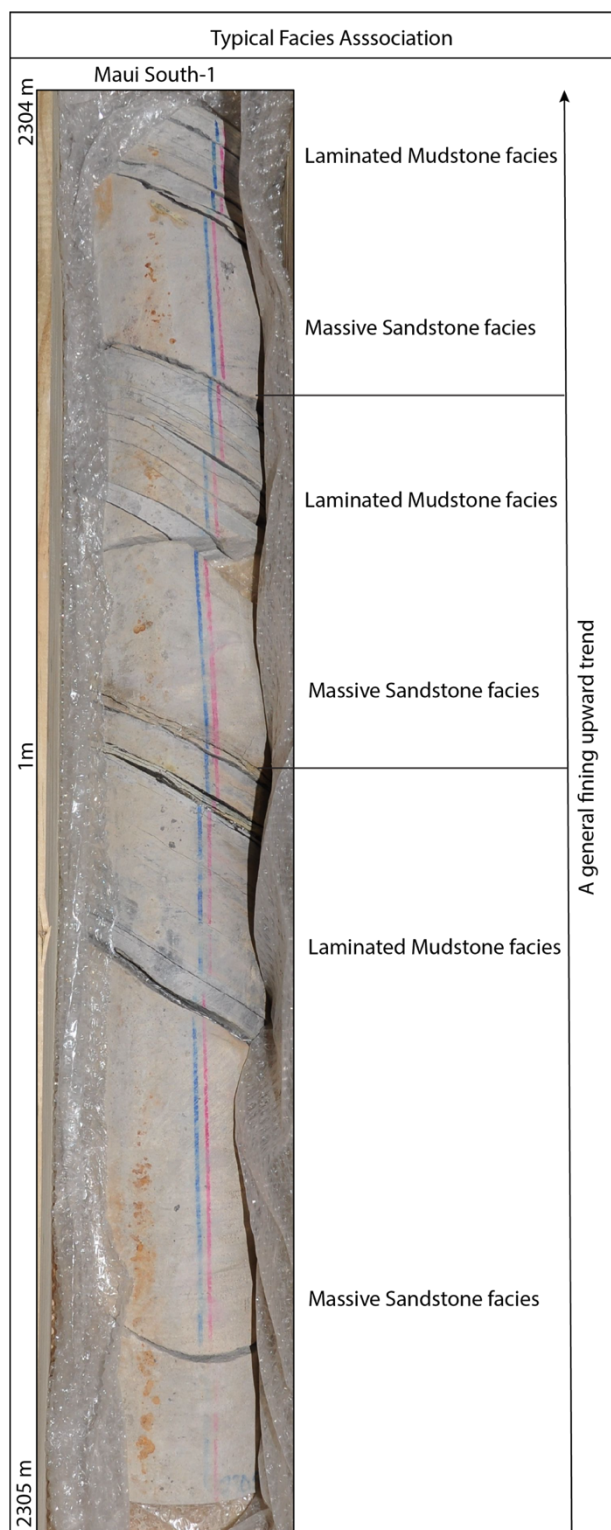


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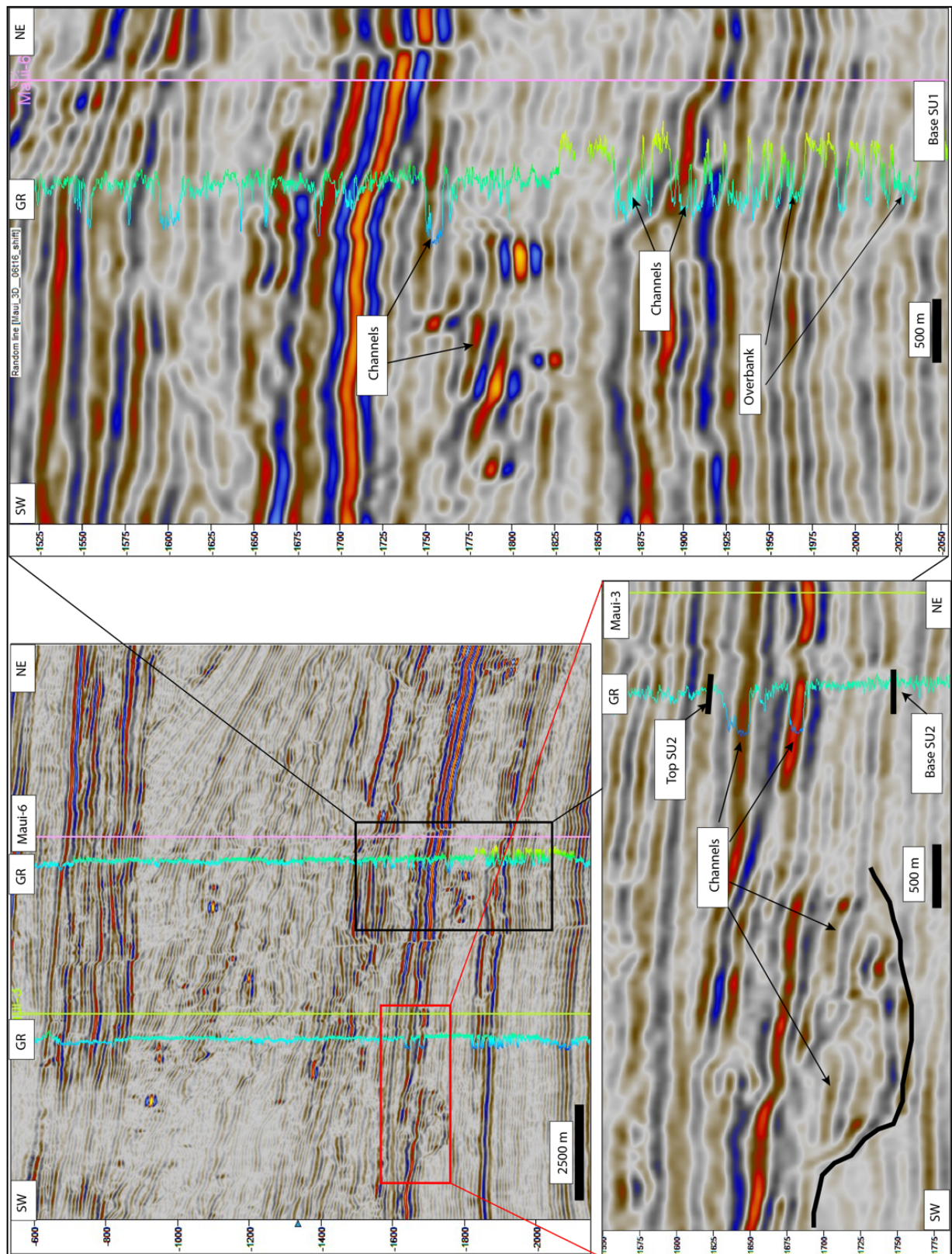


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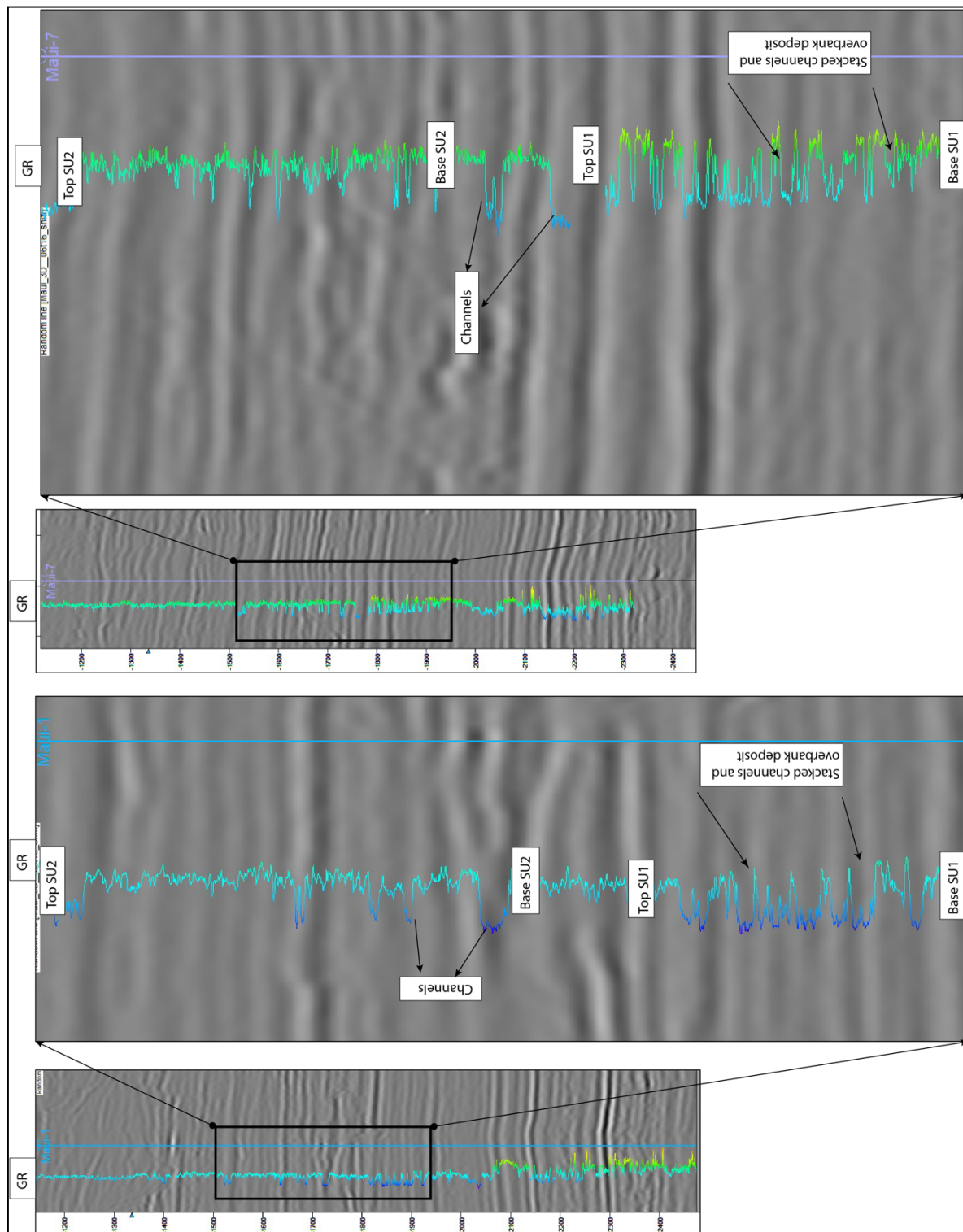


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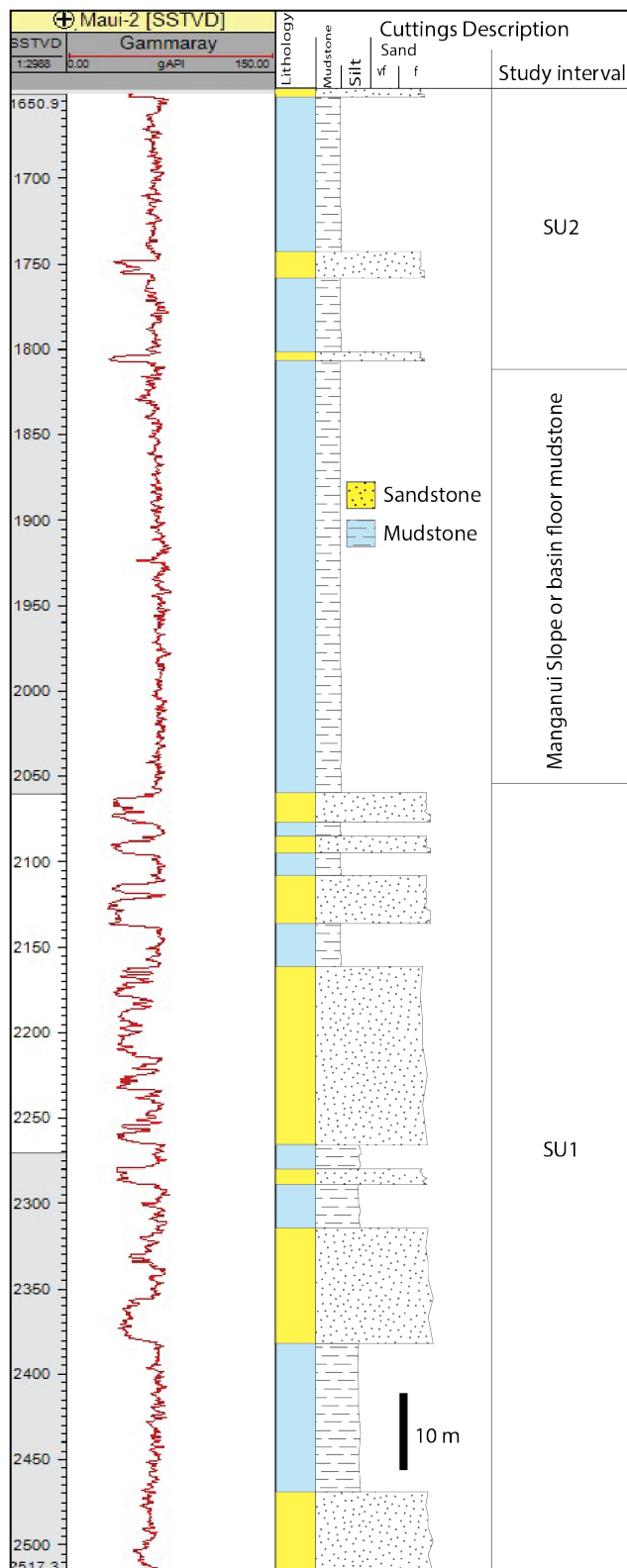


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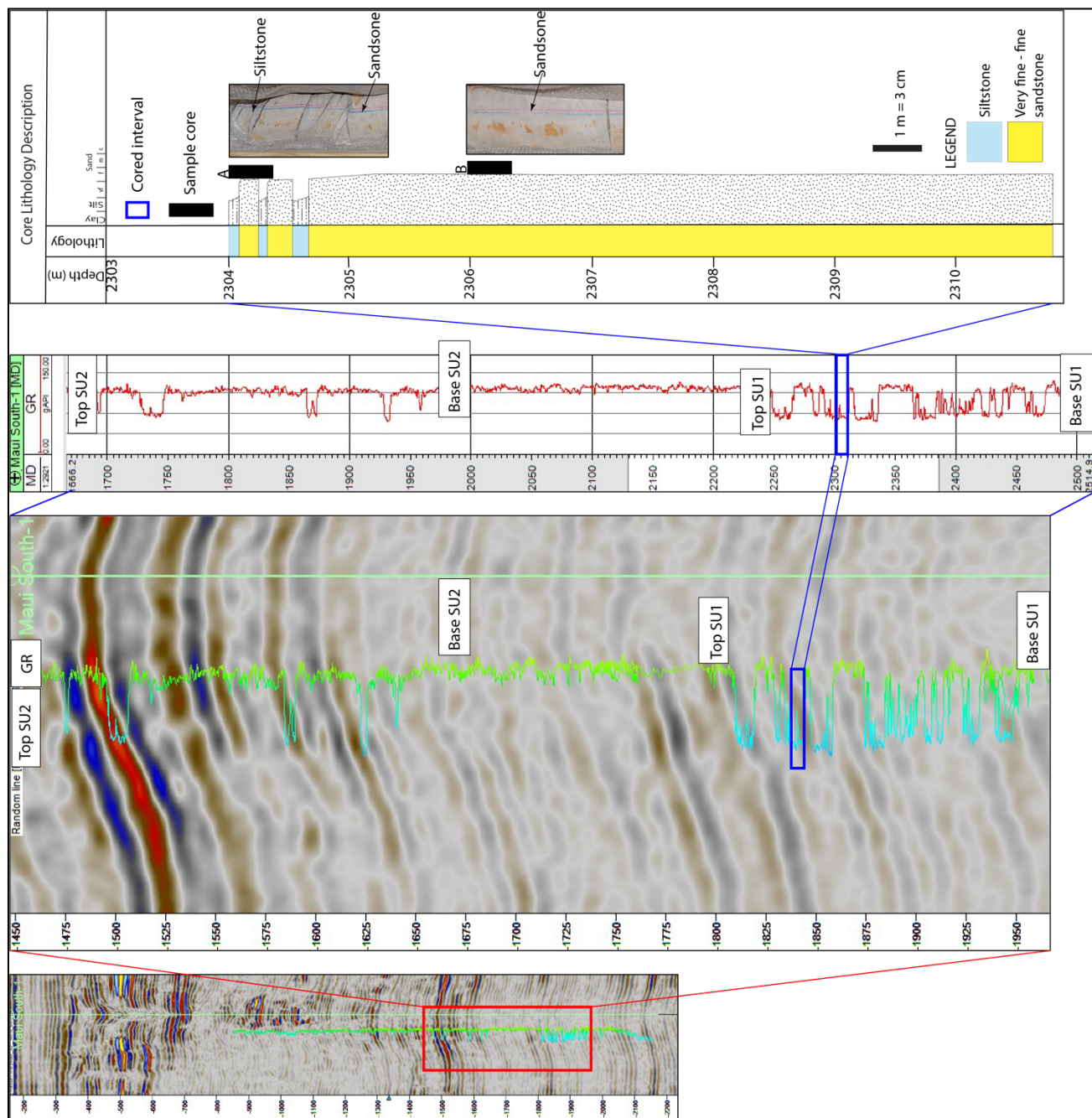


Figure 3. 23: Show the integration of seismic, wireline log (GR) and core. The show reliable lithology description and interpretation

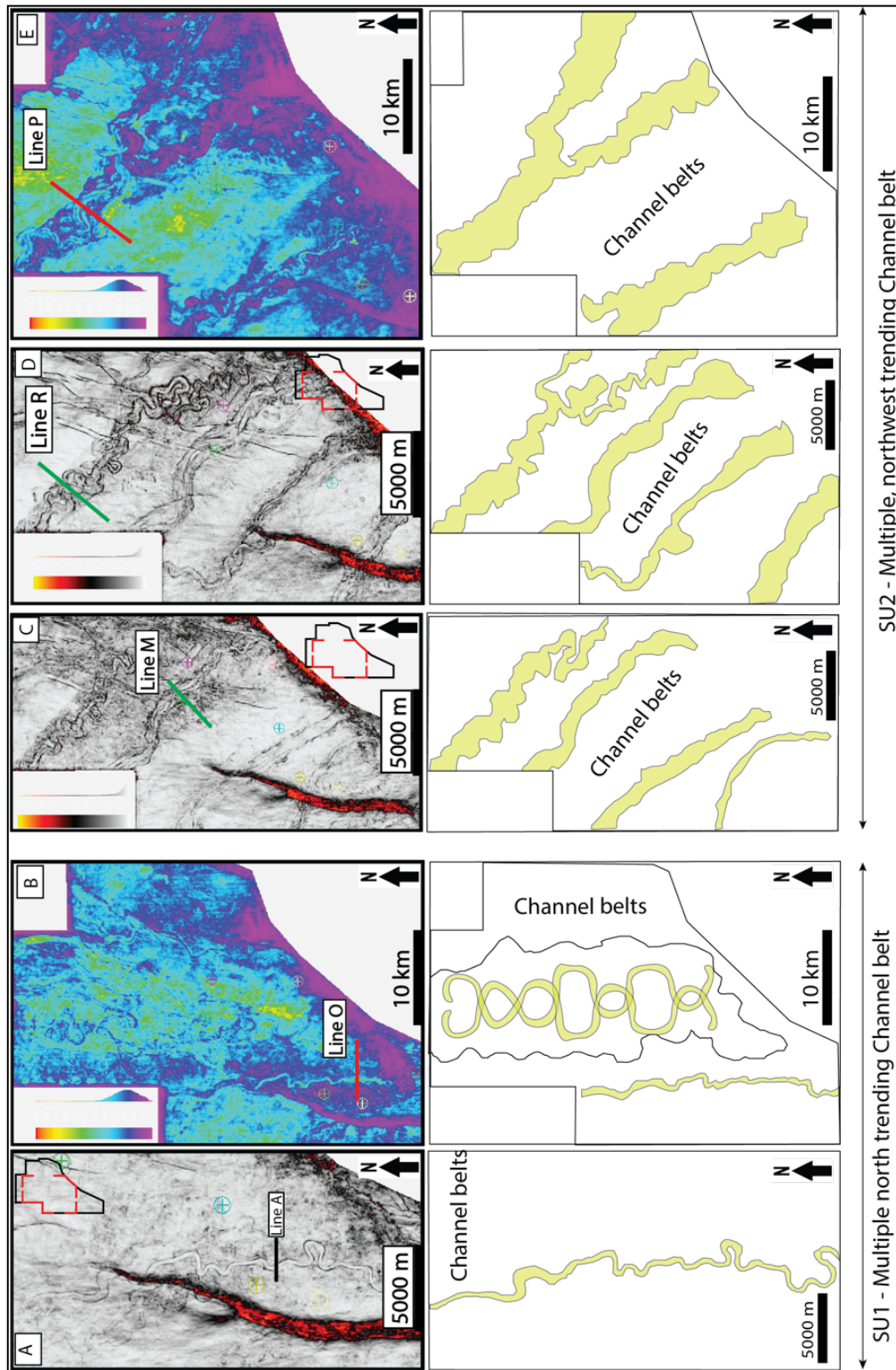


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List of available well data for the study										
Field	Well list	Cores	Biostratigraphic data	Composite log						
				CALI	SP	GR	RES	DEN	NEU	DT
Maui	Maui-1	n	n	y	y	y	y	y	n	y
	Maui-2	n	n	y	y	y	y	y	y	y
	Maui-3	n	n	y	y	y	y	y	y	y
	Maui-5	n	n	y	y	y	y	y	y	y
	Maui-6	n	n	y	y	y	y	y	y	y
	Maui-7	n	n	y	y	y	y	y	y	y
	Rahi-1	n	n	y	y	y	y	y	y	y
Wireline curve available: CALI = Caliper; SP = Spontaneous Potential; GR = Gamma Ray; RES =Resistivity; DEN = Density; NEU = Neutron; DT = Sonic. y = data available; n = data not available										

Table 3. 1: The Inventory of available data from the study interval.

Facies		A	B	C
Lithologies		Sandstone	Heterolithic	Mudstone
Wireline logs	GR (API)	<50	<10 - >70	>70
	DEN (g.cm ³)	2.2 - 2.4	2.0 - 2.4	2.24 - 2.4
	NEU (m ³ /m ³)	0.20 - 0.29	0.25 - 0.41	0.34 - 0.41
	DTC (us/ft)	75 - 90	79 - 115	92 - 115
NB: shale baseline at 70 API				

Table 3. 2: Petrophysical properties i.e., wireline log characteristics of the facies (lithologies) from the studied interval

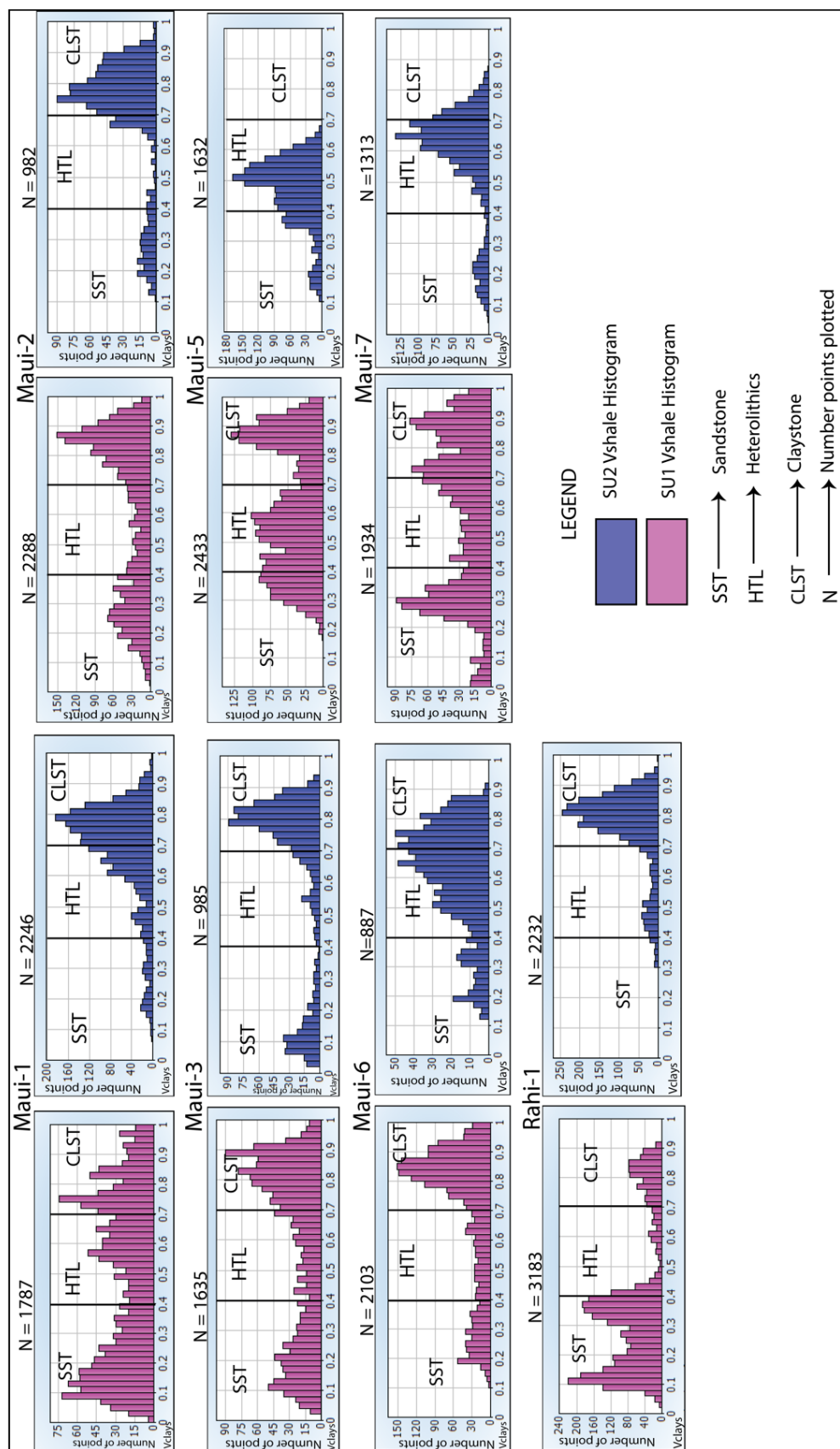


Table 3. Vshale histogram plot extracted from the analysis of GR logs of the middle Miocene interval

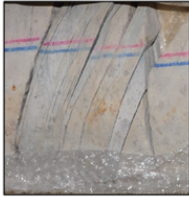
Sedimentological core facies description and interpretation of core photos from Maui South-1 and Moki-2A			
Facies	Core Photos	Description	Interpretation
Massive Sandstone		Light brown to dark in colour, fine to very fine grained, well sorted sandstone with angular to rounded mudclast embedded in its matrix	Rapid deposition of sediments transported by density turbidity current
Ripple Laminated Sandstone		Dark coloured, silt-rich sandstone, fine to very fine grained, well sorted with ripple laminations	Waning flow, low density deposit characterised by ripple lamination
Interbedded Sandstone and Mudstone		Dark grey mudstone interbedded with light brown to dark in colour, fine to very fine grained, well sorted sandstone with angular to rounded mudclast embedded in its matrix	Traction and suspension deposit of high and low density currents
Mottled Mudstone		Dark grey mudstone, often massive and structureless and disrupted by pockets of either irregular lenses of reworked sandstone clast or other lithic fragments	Low density pelagic suspension deposit at the distal reaches of the basin that has been reworked and subsequent slumping

Table 3. 4: Core lithofacies description of the middle Miocene interval

CHAPTER 4

CHARACTERISING THE INTERACTION OF THE UPPER PALAEOCENE DEEPWATER DEPOSITIONAL SYSTEM AND SALT-RELATED SEAFLOOR TOPOGRAPHY: FORTIES SANDSTONE MEMBER, SELE FORMATION, UK CENTRAL NORTH SEA

Isaac A. Odeh¹, Christopher A-L. Jackson¹, Howard D. Johnson¹, David A. Hodgson² and Ian A. Kane³

¹ *Basins Research Group (BRG), Department of Earth Science and Engineering, Imperial College London, Prince Consort Road, SW7 2AZ.*

² *Stratigraphy Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT.*

³ *School of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL.*

4.1 ABSTRACT

Deposition of the extensive upper Palaeocene (i.e., Thaenetician) deep-water depositional systems of the North Sea Basin was controlled by change in relative sea-level and fluctuations in sediment supply. In the Central North Sea (CNS), an added complication was the interaction of sediment gravity flows with dynamic seafloor topography controlled by salt diapirs. Here, the impact of salt diapirs on deep-water reservoir geometry and architecture in the CNS (Merganser and Scoter salt diapir area) is evaluated based on an integrated seismic, borehole and core facies. Seismic mapping and attribute analysis from three mapped seismic surfaces (P4, P5, & P6), shows that these systems are characterised by multiple feeder systems, including axial and lateral sediments supply routes.

The upper Palaeocene deep-water sandstone bodies in the study area are ca. 40-150 m thick and characterised by a high sandstone (i.e., 30 - 58%) content. Using core data, we identified three facies associations: turbidite sandstone, heterolithics, and basin floor mudstones. The turbidite sandstone represent the blocky or bell shape GR pattern, and in core are fine to very fine grained and either structureless or are characterised by dewatering pipes, dish structures, mudstone clast, and oxidized quartz veins. The heterolithics represents the intervals characterised by high and low GR serrated pattern, and in core comprise interbedded units that display remobilisation features. The mudstone represents the interval of low serrated GR pattern, and in core either appears massive or laminated. The seismic characteristics of the interval of interest shows; (i) subparallel to parallel, high amplitude reflection (HAR) packages interpreted as sandstones, (ii) subparallel, interbedded HAR and low amplitude reflection packages interpreted as heterolithics and (iii) low amplitude reflection packages interpreted as basin floor mudstones. The top and base reflection characteristics of the interval of interest shows continuous, parallel to subparallel, HAR packages that are only truncated by salt diapirs. Internally, the seismic characteristics of the interval of interest show chaotic characteristics. Vclay analysis shows that these packages are characterised by high sand to clay contents.

The stratigraphic architecture of the upper Palaeocene depositional system of the CNS corresponds to the development of basin floor fan systems. Individual cycles of lobe development followed a two-stage evolution; (i) fan deflection and bypass and (ii) ponding of HAR within depositional low created by salt diapirs. Evidence for salt diapir control on the pathways of the fan system is shown by (i) HAR observed on RMS attribute maps and (ii) thickness variability of the deposit around diapirs (iii) structural features related to local slumping and sliding observed in cores.

This study has implication for the stratigraphic evolution of basin floor fan system in structurally confined system and provide insights into reservoir facies distribution in salt influenced basins.

4.2 INTRODUCTION

The interaction between deep-water depositional systems and salt-related sea floor topography has been widely documented (Davison, et al., 2000; Davison, 2004; Jackson and Hudec, 2005; Gee and Gawthorpe, 2006; Brun and Mauduit, 2008; Jackson et al., 2014; Oluboyo et al., 2014; Rodriguez et al., 2019). These investigation were motivated by the occurrence of deep-water sandstone reservoirs in three main petroleum-bearing passive margins (Hudec & Jackson, 2007; Rowan & Vendeville, 2006; Vendeville & Jackson, 1992). The interaction of gravity flow processes and evolving salt-related sea floor topography resulted in the deflection and diversion of the sediment transport pathways, flow ponding, or substrate erosion resulting in complex internal stratigraphic architectures of deep-water sedimentary deposits (Clark & Cartwright, 2011; Doughty-Jones et al., 2017; Gee & Gawthorpe, 2007; Gee, Gawthorpe, & Friedmann, 2006; Mayall et al., 2010b; Oluboyo et al., 2014). A widely employed spill-and-fill model is used to explain an overall evolution from flow ponding, through flow stripping and overspilling to incision and connection of minibasins (Doughty-Jones et al., 2017; Oluboyo et al., 2014; Prather, 2003; Rodriguez et al., 2019) where sediment supply outpaces seafloor deformation. Until recently, most of our understanding of salt-sediment interactions was based on the regional and sub-regional analysis of physical modelling and 2D or 3D seismic data limited to passive margin settings, with further insights from physical and numerical modelling (Dooley et al., 2007; Gee & Gawthorpe, 2006; Oluboyo et al., 2014; Rodriguez et al., 2019; Rowan & Vendeville, 2006). The Central North Sea provides a natural laboratory for documenting salt diapir-influenced controls on deep-water depositional systems.

The stratigraphy of deepwater depositional systems, shows a wide range of lithological heterogeneity (McHargue et al., 2011; Pickering et al., 2015;). These deposits are largely channelized, especially in the slope and the base of slope, and the heterogeneity increases away from the thalweg (channel axis) of the channels associated with the submarine fan systems (Lopez, 2001; Mayall et al., 2006; McHargue et al., 2011; Covault et al., 2016;). In addition, the presence of bathymetric features generated by faults and salt diapirs, results in flow unsteadiness, non-uniformity (Kneller, et.al; 1995), and depending on the orientation of the relief, flow deflection and reflection. These flow-deposit-topography interactions results in complex internal architecture (Catterall et al., 2010; Mayall et al., 2010a; Kane, et al., 2012; Oluboyo et al., 2014). Several works have characterised and documented lithological heterogeneity around seafloor bathymetry especially salt diapirs for example (e.g. Prather, 2003; Gee and Gawthorpe, 2006; Mayall et al., 2010a; Jobe et al., 2011; Kane, McGee, et al., 2012; Oluboyo et al., 2014; Eldrett et al., 2015; Doughty-Jones et al., 2017; Rodriguez et al., 2019). The morphology of deepwater depositional systems around salts diapirs in the Central North Sea has been constrained (Jennette et al., 2000; Davison, 2004). However, here the focus is on understanding field-scale interactions between deepwater systems and the evolving salt diapirs.

This study focuses on the upper Palaeocene (Thaenetic) Forties Sandstone Member (FSM), in the UK sector of the Central North Sea Basin (CNS). An integrated 3D seismic reflection, core and well dataset provide an opportunity to analyse the interaction between deep-water depositional systems with evolving salt diapir-related basin floor topography. The primary aim is to establish the relationship between deep-water sedimentation and salt-influenced basin floor in the Merganser - Scoter area of the CNS. The objective is to characterize the distribution, geometry, and the architecture of turbidite sandstones in the distal reaches of FSM fan system, which coincides with the northern limit of Zechstein salt. This allows this part of the system to be contrasted with the more proximal, and intensively studied part of this fan system to the NW (Forties-Montrose High area), where salt diapirism is absent.

4.3 GEOLOGICAL SETTING

This study is located within Quadrant 22, and part of Quadrant 23, in the Eastern Trough of the UK Central Graben (Figure 4.1A). The Central Graben, together with the Viking Graben and the Moray Firth (Outer & Inner), are the Triassic-Jurassic aged rift systems that forms a triple junction (Van Hoorn, 1987; Boldy et al., 1990; Bishop, 1996;). The evolution of these rifted basins is related to the complex precursor fault system, which affected the North Permian Basin (Errat, 1993; Scheck, Bayer, & Lewerenz, 2003). To the East, the Central Graben is bounded by the Jaeren High, and to the West, it is bounded by the Western Platform (Davison, et al., 2000; Davison, 2005). The North-South Forties-Montrose High divided the Central Graben into the Western Central Graben and Eastern Central Graben (Trough) respectively (Erratt et al., 1999; Davison, 2004, 2005;).

The Palaeogene stratigraphic framework of the Central North Sea used in this study follows previous lithostratigraphy classification (Hartog Jager et al., 1993; Knox & Holloway, 1992; Knox et al., 1981; Mudge & Bujak, 1994; Mudge & Copestake, 1992b, 1992a; Neal, 1996; Vining et al., 1993), comprising of the Montrose and Moray Groups. The Montrose Group was deposited in a basin floor environment and comprises predominantly deep-water mudstones and associated turbidite sandstones of the Maureen and Lista formations (Knox et al., 1981). The Maureen Formation, and the associated Maureen Sandstone Member, consist of turbidite sandstones, and reworked chalk (debrites), which overlies the Upper Cretaceous Chalk Group. The Lista Formation consists of deep-water mudstones and associated turbidite sandstones of the Andrew and Balmoral Members (Figure 4.1A).

The Moray Group represents deposits of an overlying progradational shelf-slope to basin-floor succession, and consist of the Sele, Balder, Beaulieu and Dornoch Formations respectively (Mudge and Copestake, 1992b, 1992a; Mudge and Bujak, 1994;). This study focuses on the oldest member of the Sele Formation: the Forties Sandstone Member (FSM) (Jennette et al., 2000; Jones et al., 2015;), which is aerially extensive in the CNS, and forms a sand-rich belts along a distant NW-SE trending axial fairways (Hempton et al., 2005; Eldrett et al., 2015; Jones et al., 2015;). Figure 4.1A illustrate the fairways of the Forties fan system in the North Sea and the stratigraphic chart showing the FSM overlying the older Lista Formation.

Studies of the FSM from hydrocarbon fields around the Forties – Montrose High (Kunka et al., 2003; Millington et.al., 2007) shows the channel characteristics of the Forties fan in the upper slope environment. The channel systems run in NW-SE direction bearing similar internal architecture with basin floor facies. Thickness variation between the fan system at the shelf and upper slope differs from those in the basin floor. Most of the FSM fan system bypass the shelf and the upper slope area (around Forties – Montrose High) and are ponded in the mini basin created in the basin floor depocentres to the SE (Eldrett et al., 2015; Hempton et al., 2005; Jones et.al., 2015b). The very thick FSM unit in the studied location (between Merganser and Scoter) accounts for deposition in a salt-related minibasin.

4.4 DATASET AND METHODOLOGY

4.4.1 SEISMIC DATA

The 3D seismic reflection data covers an area of approximately 1350 km², extending over part of Quadrant 22 and 23. The data is time-migrated, with CDP spacing of 25 by 25 metre across inlines (3163) and crosslines (4105), with a sampling interval of 4 ms. Assuming an approximate average interval velocity of (6561 ft/s to 7217 ft/s) and frequency (42 Hz to 31 Hz), the seismic reflection data at the depth of investigation (2944 – 3100 ms) has a good to moderate vertical resolution of (11 m - 17 m). Image quality deteriorates significantly adjacent to and below the salt diapirs.

4.4.2 WELL DATA

Fifteen wells were made available for this study from two hydrocarbon producing fields (Merganser and Scoter) located along the distal margin of the East Central Graben; 6 from the Scoter field and 9 from the Merganser field (Table 1). These wells are located around the flanks of the Merganser diapir and crest of the diapirs the Scoter diapir respectively. We used composite logs (calliper, spontaneous potential, gamma ray, neutron, density, and sonic logs) in the interpretation of lithologies. Shell UK regional Formation tops data provided information on the gross lithostratigraphic framework of the study area. Core data was available from three wells; 22/30a-14z with total cored depth of 86 ft (26.21 m) is located on the flanks of the Merganser diapir, and two cored wells: 22/30a-5 and 22/30a-9 with cored depth of 583 ft (178 m) are located on the flanks of the Scoter diapir respectively. In total, 669 ft (203.91 m) depth of core was utilized for this study. Biostratigraphic data were not made available for this study.

4.5 METHODOLOGY

4.5.1 WELL-TO-SEISMIC TIE AND SEISMIC INTERPRETATION

Well-to-seismic tie (Figure 4.2A) was used to validate the information synthesized from published literature. The main aim of generating synthetic seismograms is to (i) constraining the reflection events that bound the interval of interest and (ii) assessment of the lithology and potential depositional significance of amplitude anomalies. Based on the synthetic seismogram, two seismic horizons namely, P4 - P6 (oldest to youngest) are identified and mark the base and top of the Forties sandstone Member (Figure 2B) were mapped. Iso-proportional slicing techniques (Zeng, 2007;) was employed to make iso-surface P5 between horizons P6 (Top Forties) and P4 (base Forties). These iso-surface enabled a better spatial and temporal understanding of the deepwater depositional system. It should be noted however that, due to the inherent complex basin structure, the corresponding slices cut-across stratigraphy.

Sand-rich Palaeocene fans in the CNS are characterised by high seismic amplitude (Jennette et al., 2000; Collins et al., 2015). Hence, several volume attributes, notably Root-Mean-Square (RMS) amplitude and Variance edge, (appendix 1) were used for seismic geomorphological analysis of the FSM (Hart, 2008). Seismic reflection-based inferred lithologies were tested with borehole data and core data.

4.5.2 WELL-LOG INTERPRETATION

Petrophysical analysis of well-log data, supported by limited core data information, were used to evaluate the thickness and lithology distribution of deepwater depositional systems. A combination of gamma ray, density, neutron, and sonic logs were used for lithological interpretation (Table 4.1). GR logs are available in all wells and there is a consistent relationship between log response and lithologies described in core. Facies distribution was estimated based on Vshale cut-off values as follows (Figure 4.3A & B) and was related to equivalent GR log motif: Vshale $\leq$ 40% is considered to represent sandstone, Vshale 40% - 70% represent heterolithics, Vshale $\geq$ represent mudstone or claystones.

Here, we used the Larionov equation for Cenozoic rocks (Larionov, 1969;) provided below to evaluate the shale content and sandstone – mudstone variability within the Upper Palaeocene deepwater depositional systems.

$$V_{sh} = 0.088(2^{3.7} \times I_{GR} - 1.0)$$

(Larionov, 1969) equation for Cenozoic rocks

We choose this equation because of its sensitivity and suitability for Cenozoic clastic rocks.

The resulting Vshale histogram in the Merganser and Scoter field showed that the Upper Palaeocene depositional system of the Central North Sea is sandstone- and heterolithic-dominated, with low mudstone content. Overall, Vshale analysis records an upward increase in sandstone - heterolithic ratio around Merganser diapir. Similarly, the resulting Vshale histogram in the Scoter field shows that the Forties fan is sandstone and heterolithic dominated with low mudstone content.

Gamma ray (GR) log motifs (e.g., blocky pattern, bell shape, serrated and irregular vertical log profiles) (Figure 4.3C) were also used to infer smaller-scale depositional units and architectural elements, in part based on their calibration with seismic-derived geometrical observations. Core facies analysis (Figure 4.3D) was used to validate well log facies. Using the GR log, a well-log correlation of the wells in the studied location (Figure 4.4A and B), shows the lithology distribution of the upper Palaeocene deepwater depositional systems in the studied area. The blocky-bell-serrated-, and irregular-shaped GR pattern are interpreted as stacked sandstone packages with interbedded heterolithics and mudstone. The top and base of Upper Palaeocene depositional system is characterised by sharp and gradational change in GR pattern.

4.6 RESULTS

4.6.1 REGIONAL BASIN GEOMETRY, DISTRIBUTION AND DEPOSITIONAL PATTERN OF THE UPPER PALAEOCENE DEEPWATER DEPOSITIONAL SYSTEM

The structure and geometry of the basin floor relative to the shelf-edge located to the NW (areas around Nelson) and W (areas around Gannet) of the study location, consist of depocentres created by subsidence changes between isolated salt diapirs (i.e., salt-related syndepositional low). The depocentres are recognised in the most distal part of the study location based on their geometry on planform maps and the thickness of the stratigraphy therein. The key stratigraphy consists of units that postdate the salt deposition example the upper Palaeocene (Figure 4.5). Here we focus on the distribution and patterns of deepwater depositional system of the upper Palaeocene (Forties Sandstone, Sele Formation). This section uses well correlation and core data, to describe the tectonostratigraphy of the upper Palaeocene deepwater system relative to evolving salt diapirs.

4.6.2 REGIONAL BASIN STRUCTURE AND GEOMETRY

The Central North Sea comprises of matured salt stocks with sub-vertical stems. In the studied location, the salt diapirs have a height of 1.98 km for Scoter and 8.2 km for Merganser respectively. Because of the difficulty in imaging base salt, the height measurement is not accurately determined. Similarly, the diapirs have a width of 3 km for Scoter and 4.5 km for Merganser diapir respectively (Figure 4.5A & B). The positioning of the salt diapirs are not exact because of the inaccuracy of the height and width of these salt diapirs. The Merganser diapir penetrated up to the recent stratigraphy while the Scoter is arrested by Cretaceous stratigraphy (Davison, et al., 2000; Jones and Davison, 2014; Charles and Ryzhikov, 2015; McKie et al., 2015).

The updip, most proximal part of the study area, located to the NW, is characterised by relatively thinner (56 ms TWT) Palaeogene stratigraphy that are underlain by a thick (678 ms TWT) salt layer. There is a rare occurrence of salt diapir in most proximal part of the study location, hence describing this part of the basin in the context of salt tectonics is not supported by our observation of the basin geometry on planform maps (Figure 4.5C). The rugose surface created by the salt diapir are filled by

the upper Palaeocene stratigraphy which are generally thin in the proximal part of the basin. The most distal part of the study location is characterised by NW – SE oriented salt-related syndepositional low that are up to (>2 km) long and (> 3 km) wide around Merganser and Scoter diapirs and (> 6 km) long and (> 4 km) wide around Scoter and Machar diapirs respectively. The stratigraphy within these depocentres is relatively thick (up to 120 ms TWT) and typically overlain thin salt layer (Figure 4.5D). The bounding salt diapirs have rugose and faulted tops and are align along a pre-existing NW – SE fault plane. The depositional packages of the distal depositional low are internally deformed by the movement of the salt diapirs and are characterised by a bowl-shape geometry suggesting syndepositional deposition of deepwater deposit during the vertical subsidence of minibasin and movement of the salt. The term ‘Mini-basins’ and ‘ponding’ as used frequently in the text, are not mini-basins which is exemplified by the Gulf of Mexico. Despite the accepted usage of the term ‘Mini-basins’ and ‘ponding’ in many salts influenced basins, e.g., the Gulf of Mexico, Brazil and Lower Congo basin, a re-assessment of this study show that, we might be looking at some elongated mini basin characterised by the lateral confinement of fan-lobe in syndepositional lows between isolated salt diapirs (Figure 4.5E).

We interpret the rugose relief created by the underlying salt layer to be as result of differential evacuation of salt layers (Dooley, Jackson, & Hudec, 2009; Jackson et al., 2014). This interpretation was supported by the differential thickness observed in the infilled stratigraphy overlying the salt interval.

4.6.3 SEISMIC STRATIGRAPHY AND SEISMIC FACIES ANALYSIS

Four seismic facies SF1 – SF4 (Table 4. 2), have been identified in this study and is utilised to characterise the Forties Sandstone. In this section, the reflection character of the Forties sandstone has been described and interpreted based on these four seismic facies scheme

4.6.3.1 BASE FORTIES SANDSTONE MEMBER SEISMIC REFLECTION CHARACTER

Description: The base Forties Sandstone Member is also characterised by continuous, laterally extensive, subparallel seismic reflection packages, which conformable with the overlying interval (Figure 4.6A and B). However, there is some disruption around the Merganser diapir. The base Forties Sandstone Member reflection is characterised by positive reflection polarity defining a decrease in acoustic impedance.

RMS amplitude map extracted from P4 (base Forties Sandstone) show similar distribution of NW – SE trending amplitude reflection packages (Figure 4.7A). However, around the study location (i.e., the Merganser and Scoter fields), there is a deflection and lateral confinement of bright amplitude packages which extend to the Northern, Southeastern, and Southern flanks of the diapirs. Generally, attribute maps extracted for this study show a general NW – SE trending bright amplitude reflection packages representing sandstone-rich Forties fan system.

Interpretation: The reflection marking the base Forties was interpreted as a conformable, and continuous seismic reflection which is only disrupted by salt structures. The rugose character of the base Forties also suggests the impact of the inherent basal Lista stratigraphy. Interpretation suggest that, reflections marking the base Forties represents T65 sequences of previous authors (Hempton et al., 2005; Eldrett et al., 2015;). The bright amplitude reflection suggests a change in lithology from the mudstones (Lista shale) to the Sandstone (FSM). The variability in the reflection coefficient and acoustic impedance suggest that deposition was associated with multiple fan-lobe systems.

4.6.3.2 TOP FORTIES SANDSTONE MEMBER SEISMIC REFLECTION CHARACTER

Description: The top of the Forties Sandstone Member is characterised by a thick, laterally extensive, bright amplitude reflection. In some places, these reflections appear disrupted, becoming low amplitude (Figure 4.6A & B). The top reflection packages show a concordant relationship with the underlying stratigraphy. The reflection below the top Forties Sandstone Member reflection is expressed as a negative reflection polarity. Generally, the reflections underlying the top Forties Sandstone Member show variable polarity with changes from positive to negative. These define the variability in acoustic impedance in response to facies changes.

RMS amplitude map extracted from P6 (top Forties Sandstone Member) shows elongate bright amplitude packages with a general NW – SE trend (Figure 4.7C), mainly to the northern and southern parts of the study location. Attributes maps show that, amplitude reflectivity decreases towards and the SE of the study location.

Interpretation: Despite showing a conformable relationship with the underlying reflections, the top Forties Sandstones Member (FSM) reflection likely bypassed our area of interest or the system has less sand content as compared with the base Forties. (Eldrett et al., 2015;) show that the T75 sequences represent the top Forties Sandstone packages. These sequences are widespread, and sediment mostly bypassed the study location, depositing mostly around Pierce, and the Sterling area (Hempton et al., 2005; D. W. Jones et al., 2015a). The northern and southern occurrence of the bright amplitude reflection packages was interpreted as a possible bypass or the basinward progradation of the Forties further down the basin floor.

4.6.3.3 INTERNAL SEISMIC REFLECTION CHARACTER OF THE FORTIES SANDSTONE MEMBER

Description: Internally, the Forties Sandstone Member is characterised by variable parallel to subparallel, continuous to discontinuous, bright, and low amplitude reflection packages. The bright amplitude reflection packages are thick and are distributed mostly around the flanks of the salt diapirs. Seismic cross section from the most proximal and distal part (Figure 4.6A & B), shows similar characteristics described above. Generally, the character of the internal reflections of the Forties Sandstone changes from positive to negative, defining the variability in acoustic impedance and the presence of sand or shale dominated lithologies. The thickness and amplitude reflection character suggest complex internal architecture of the Forties sandstone.

RMS amplitude map extracted from P5 shows similar distribution of the bright amplitude reflection packages, which trends NW – SE (Figure 4.7B). However, unlike the P6 attribute map, a brighter amplitude reflection to the Northcentral and further SE part of the study location was observed. There is clear distribution of high amplitude packages around this salt diapir. To the SE side of the Merganser diapir, we observed bright amplitude reflection packages deflected and ponded between Merganser and the subtle topography created by Scoter diapir.

Interpretation: Interpretations suggest that, the internal bright amplitude internal reflections of the Forties represents T70 sequences of (Eldrett et al., 2015). The internal reflection of the Forties was interpreted as a conformable, continuous seismic reflection which are only disrupted by salt structures. The occurrence of the bright amplitude reflection packages was interpreted as the ponding of the Forties around the salt diapirs.

The upper Palaeocene deepwater depositional system generally shows a NW – SE (axial fans) and W – E (side fans i.e. fan systems sourced from the Western, lateral axis)) trending fan system (Jennette

et al., 2000.; Hempton et al., 2005; Eldrett et al., 2015; Jones et al., 2015b;). This pattern was clearly observed on the attribute maps extracted from the Forties Sandstone interval. Attribute maps show the dominant sediment conduit trend is NW – SE. This trend continues down to the Western edge of the Viking Graben. The regional extent of the source and ultimate destination of the Forties sandstone was limited by the data available study. However, our understanding from previous works suggests that the axial (NW – SE) and side fans (W – E) are sourced from the Nelson and Forties – Montrose and the Gannet areas respectively.

Analysis of seismic cross section, and RMS amplitude attributes maps shows that; understanding the areas of thickest Forties fan sandstone deposition can be locally predicted especially in areas where there are existing (pre-existing) salt structures (our case study). An isopach map extracted from the studied interval shows similar thickness trends observed by (Kilham, et.al., 2015); a general NW – SE thinning with local thickening around salt diapir syndepositional low (Figure 4.8). The thickness (isopach) map show that the areas of thickest Forties fan is laterally confined by the salt diapirs.

Petrophysical analysis of wireline log cross-plot, Vclays histogram and core data shows that, the Forties Fan system comprises of sandstone, mixed sandstone-mudstone (heterolithics) and lower proportion of mudstones suggesting that the Forties fan system is a compositionally sand-rich fan system. However, there are regional limitation particularly in places where there are no salt diapirs i.e., the most proximal part of the Central North Sea. This is because the presence of salt diapirs create local accommodation space (depositional low) for sediment deposition. This depocentres are clearly identified as having thick (high amplitude) Forties Sandstone deposition (Figure 4.7). The gross thickness of the Forties Sandstone Member observed on well section within the study location varies between 50ft – 450ft (15-138 m).

4.6.4 DISTRIBUTION AND DEPOSITIONAL PATTERN OF THE UPPER PALAEOCENE DEEPWATER DEPOSITIONAL SYSTEM

The temporal and spatial pattern and distribution of the upper Palaeocene deepwater depositional system is described using borehole and core data. Observations made from well data are further tied and validated with seismic data. Typically, deepwater sandstones display a variety of patterns on GR logs, such as blocky-or-bell-shaped (Figure 4.3C). These sandstones display a sharp or gradational bed contacts. Internally, these sandstones are characterized by low GR values (<50 API) and are abruptly bounded by mudstone or heterolithic units. Interbedded sandstone and mudstone units are characterised by serrated GR logs patterns (Figure 4.3C) and displays intervals of low GR values (<50 API) as sandstone and interval of high GR values (>70 API) as mudstone. Mudstone are represented by interval of high GR values (>70 API), and they typically display an irregular GR pattern with a general high API.

Core data indicate that the sandstones are fine-to-very fine grained, sub-angular to sub-rounded grains, and are poorly to moderately sorted. Typically, the sandstones are typically structureless, texturally immature and contain traces of authigenic pyrite and glauconite. The mudstone is typically clay material, which appear either massive or fissile. Using core data, we group the upper Palaeocene depositional system into three facies association namely, turbidite sandstone, heterolithics and basin floor mudstones. The turbidite sandstone represent the blocky-or-bell shaped GR patterns and are either structureless or comprise dewatering or dish structures. The heterolithics represents the intervals characterised by high and low GR serrated pattern and comprise of interbedded structureless sandstone and mudstones. Internally, the heterolithics display common slumping and mass wasting features. The mudstone represents the interval of low serrated GR pattern (Figure 4.3C)

Two key correlation panels from the Merganser and Scoter area are used to illustrate the overall geometry and distribution of the upper Palaeocene deepwater depositional system (Figure 4.4A & B). These panels are flattened at top Forties which is a regional stratigraphic surface that can be correlated across the entire study area. By calibrating wireline logs with seismic reflection data, the large-scale regional correlation provided information on vertical and lateral thickness variations. Locally, changes in wireline logs motif or log curve provides insight into the lateral and vertical facies variation. Here, gamma ray (GR), neutron-density (NEU/DEN), and sonic (DT) logs from 15 wells was utilized to understand and discriminate the (sub) regional lithological distribution and well log correlation of the Forties Fan system. The position of the wells relative to the salt diapirs allows us to constraint the variability in deep-water sedimentology and stratigraphic architecture around salt diapirs. The halokinetic sequences, herein referred to as units controlled by salt diapirs varies in geometry and orientation from the Merganser and Scoter fields. The thinning of the package towards the salt structures indicates that the entire interval was halokinetically-controlled. Around the Merganser field halokinetic sequences onlap diapir, which saw that the diapir was active during the deposition of the upper Palaeocene deep-water depositional system and were later dragged up by continued diapir growth. Around the Scoter field, (Charles & Ryzhikov, 2015) suggested that diapir growth ended during the deposition of the Cretaceous chalk, the upper Palaeocene depositional system conform to the up dome topography created by the inactive Scoter salt diapir (Alsop et al., 2000; Davison, 2004).

Well correlation 1 is orientated NW – SE across Merganser field, and well correlation 2 orientated NW – SE across Scoter field respectively. Around Merganser, the wells are located on the flanks of the Merganser diapir i.e., on the SE side of the diapirs while around Scoter diapir, the wells are located on the crest and flanks of the diapir. Wells 22/30A-9 and 22/30A-5 are located on the northern and southern flanks of the diapir respectively, wells 22/30A-12, SCS01, SCS02, SCS03 are located on the crest of Scoter diapir. Unfortunately, the wells are located around salt diapirs, so poor seismic quality is a major constrain in utilising seismic to aid well calibration. These well correlations provide information that complies with the lithostratigraphic, chronostratigraphic, and the depositional framework of the Central North Sea. Correlating these genetic units (Formation tops) between wells in each sub regional study location (fields) shows a general thickness variation within study interval.

The Merganser structure is salt a stock that has a diameter of (> 4 km). The Merganser diapir has remained active and has interacted with the depositional systems from the Cretaceous till recent (Davison, et al., 2000; Davison, 2004). Well log correlation for Merganser field (Figure 4.4A), shows the correlation of the biostratigraphically-constrained genetics units (T75, T70 and T65 cycles) of the deepwater depositional unit. Thickness variability within these T-cycles, and their regional correlation indicates the inherent halokinetic and salt diapir control on the lateral continuity of the upper Palaeocene deepwater depositional system. At Merganser diapir (well correlation 1), the thickest (100ft – 160ft) T75 cycle (youngest genetic unit of the Forties Sandstone) was encountered at wells 22/30A-14Z, MG A01S1, MG A01S2, and MG A02S2 respectively. These wells recorded such a thick sandstone because of their location relative to the salt diapirs. A similar pattern observed at the T75 cycle was also observed at T70 cycle. However, the T70 cycle represents the thickest (100ft – 200ft) cycle of the Forties Sandstone Member (FSM) deposit encountered at MG A01S2 and MG A02S2 respectively. T65 is the oldest genetic unit of the Forties Sandstone in the study location. In terms of thickness, the T65 cycle show the maximum thickness of (150ft) at 22/30A-14Z. However, the T65 cycle is the thinnest of the Forties Sandstone genetic units and is missing or not identified at MG A02. The Scoter structure is a salt stock with a diameter of (< 2 km). The Scoter diapir has been inactive at early Cretaceous but has created a topography for subsequent stratigraphy. Well correlation for the Scoter field (well correlation 2) (Figure 4.4B), shows the biostratigraphically-constrained sandstone deposit of the T75, T70 and T65 cycles. We observed a uniform and constant thickness in T75 (<100ft)

and T70 (200ft – 300ft) with the T70 showing the thickest Forties Sandstone deposit. However, the T65 is thin, and is missing in 22/30A-12 to the SE of Scoter diapir. The two well log correlation shows a general SE, local increase in the thickness of the Forties Sandstone particularly in the T70 cycles on the down-current direction of the salt diapirs. The thickness variability was related to the possible salt movement and the likely ponding of these fans around these salt diapirs.

Information synthesized from a regional inter-well correlation (Figure 4.9) shows that, the Forties Sandstone thickens away from the diapir flanks. Around the Merganser field, i.e., Zone A – B, the well correlation records deposition on the down-and-updip flanks of the salt diapirs. Zone C, which is the syndepositional low, the well correlation records a thick Forties sandstone deposition. This implies that, SE and E of the Merganser field, there is a more deeper accommodation space (Figure 4.7). This may suggest the inactivity of the Scoter diapir relative to the active Merganser diapir (Jennette et al., 2000; Davison, 2004; Eldrett et al., 2015;). Similarly, Zone D records deposition on the updip and crest of the Scoter diapir. We notice the thin stratigraphy on the diapir crest. Zone E, records deposition on the downdip flank of the Scoter diapir. The extent of the Forties away from the study location is unknown, however, studies show that, the Forties Sandstone exhibit thickness variability in the East Central Graben wedging out towards the Western Viking Graben (Eldrett et al., 2015).

Lithology identification using NEU/DEN cross-plot and in some place cases DT/DEN cross-plot from both the Merganser and Scoter diapir (Figure 4.10) was utilized to characterise the lithology of the Forties Sandstone. Around the Merganser diapir (Figure 4.10A), NEU/DEN cross-plot show a ternary mixture of sandstone, silty sandstone, or muddy sandstone (here refer to as heterolithics) and claystone/mudstone lithology distribution within the Forties Sandstone Member. Around the Scoter diapir (Figure 4.10B), NEU/DEN and DT/DEN (well 22/30A-5), also shows similar lithology distribution. Some anomalous values are noted with low density, suggesting the likely presence of fluids (e.g., gas) associated with the Forties Sandstone. Tool precision and calibration are not 100% reliable but, these cross plots gave a clue that support our analysis and interpretation of the lithologies in the respective wells.

4.7 DISCUSSION

This study provides an analysis of the spatial and temporal distribution of the Thaenetic-aged deepwater depositional system and their interaction with evolving salt diapirs (i.e., the Merganser and Scoter diapirs) in the Central North Sea using 3D seismic reflection, well data and core data respectively. The key observation is the change in thickness over a short distance as recorded on the subregional and regional well correlation panels (Figures 4.4 and 4.9). Despite the good correlation of some units within this interval, lateral and vertical facies variability have implications, for local control on their deposition and distribution patterns by evolving salt diapirs.

4.7.1 SEDIMENTOLOGY AND STRATIGRAPHIC ARCHITECTURE

The Thaenetic-aged deepwater depositional system deposited in the Central Graben are fine to very fine grain, poorly to moderately sorted and they occur in packages up to 450 ft (138 m). The upper Palaeocene deepwater depositional system studied here are similar in terms of their grain size and petrophysical properties to age-equivalent deep-water deposits identified elsewhere in the North Sea Basin example the Norwegian Graben (Dmitrieva, Jackson, Huuse, & Kane, 2018a) and the Central Graben (Jennette et al., 2000). Core data show that these deposit display a variety of sedimentary structures and are interpreted as either turbidite, debrite or mudstone (Jennette et al., 2000; Hempton et al., 2005; Millington et al., 2007; Eldrett et al., 2015). The turbidites are interpreted as the deposit of fully turbulent fluidal flows while the debrites are interpreted as the deposits of

concentrated laminar flows. The basin floor mudstone is interpreted as deposit of suspension fallout. Flow transformations has been documented to explain the origin and linkages between turbidite and debrites deposition in the study location (Davis et al., 2009b; Haughton et al., 2009).

Attribute maps shows our study location to document distal lobes and no other depositional elements were identified hence the sheet nature of the reflection on seismic cross section. The invaluable information provided by core data enabled us to examine in detail, the vertical facies and thickness variability within the deepwater depositional system. Beds normally transitioned vertically from basal massive structureless sandstone, which locally preserve dewatering pipes/dish structures, into debrites and are capped by basin floor mudstone. The interval separating the basal sandstone and the linked debrite shows interbed of dark and light minerals. This implies that the flow depositing this units is either turbulent or laminar in nature and was later transformed along the flow length into linked turbulent and laminar flow. Our core data limits our lateral quantification of facies variation however, previous studies show that, similar facies architecture were observed further down the distal part of the basin example around Pierce, Lomond, Everest and Arran fields respectively (Davis et al., 2009b; P. Haughton et al., 2009; Pierce et al., 2018).

4.7.2 LATERAL CONFINEMENT OF SUBMARINE LOBES IN ELONGATED MINIBASIN: IMPLICATION FOR STRATIGRAPHIC COMPLEXITY RELATED TO SALT DIAPIRISM

The Thaenetician-aged deepwater submarine fan-lobe deposited in the Central Graben, are laterally confined within elongated minibasin depositional lows (depocentres) formed from subsidence changes between isolated salt diapirs. This is a direct contrast to the classic mini basin and ponding style observed in most salt influenced passive margin basin example the Gulf of Mexico, Offshore Angola and Brazil (Gee & Gawthorpe, 2006; Hudec & Jackson, 2007; Jones et.al., 2012; Rodriguez et al., 2019). Thickness variability within the Thaenetician-aged depositional unit shows that the structural control on sedimentation patterns was in existence before and during the deposition of the Forties fan systems. Furthermore, RMS attribute map from the Forties sandstone shows large-scale, asymmetrical basin configuration, and several topographic features that controlled the development of the Forties Sandstone across the basin floor (Figure 4.12). Thus, the upper Palaeocene Forties depositional system interacted with relief generated by an already existing and actively growing salt diapir during its depositional history.

Several styles of salt-sediment interaction, for example; local *diversion* of fan-lobe by pre-existing salt diapirs, *deflection* of fan-lobe by salt related relief, *lateral confinement* and *ponding* of fan-lobes within depositional lows created salt by diapirs related subsidence have been documented in many salt influenced basins (Gee and Gawthorpe, 2006; Mayall et al., 2010b; Oluboyo et al., 2014; Spsychala et al., 2017;). Lateral confinement of fan-lobes in depositional lows by salt diapirs, are commonly observed in the study location. These fans are confined to the NE and SW of the diapirs and are oriented parallel to the salt diapirs trends (Figure 4.12). Whether these diapirs were actively growing or dormant (i.e., outpaced by sedimentation) during the Forties fan deposition, remains a challenge. However, the syndepositional growth of salt diapirs as seen in a NW-SE seismic section (Line K in Figure 13), is supported by the coeval onlap and thinning of the Forties fan towards the diapir, thickening of the Forties fans away from the diapir and confinement of the Forties fan in the syndepositional low respectively (Stewart and Clark, 1999; Cartwright et al., 2001; Davison, 2004; Mayall et al., 2010a;).

The argument for lateral confinement of fan lobes within syndepositional lows as against ponding within mini basin is supported: (i) submarine fan-lobe flow direction in relation to the orientation of the salt structures and (ii) the rate of sedimentation in relation to rate of diapir growth. The NW-SE submarine flow direction are parallel to the NW-SE salt diapir orientation in the Central North Sea as

can be seen in RMS attribute maps extracted from base and top Forties (Figure 4.12). These depositional lows are shaped and are confined parallel to these diapirs orientation. This implies that, most depocentres in the Central North Sea, are aligned parallel, along the orientation of the diapirs. Hence, seismic sections taken along the NE and SW side of the diapirs (Figure 4.14), show thick packages of laterally confined Forties Sandstone. Similarly, the salt diapirs were shown to have outpaced sedimentation especially around Lomon, Merganser and Machar diapirs. This in turn act as funnel for confining submarine flows laterally along the orientation of the diapirs. This is observed by the distribution of bright amplitude reflection on the NE and SW part of the diapirs (Figure 4.14).

The relative distribution of the Forties genetic sequences supports the structural control on the Forties fan system. The relative confinement of the T65 sandstones to the east of Merganser, and Scoter salt diapirs suggest that the west and east sandstone fairway was constrained to the east by salt diapirs (Figure 4.7). The development of T70 lobe complexes in these areas suggests that the flows were mostly depositional in nature and are mostly confined and within syndepositional structural lows. The T75 lobe complex was preferentially distributed to the North and South of the Merganser, and Scoter diapirs. This suggests a possible bypass of flows in our study location and a more distal preferential deposition possibly around Peirce fields. The Forties lobe complexes in the T65–T75 sequences shows a distinct diversion to the south of the Merganser, Scoter, and Machar diapirs. We show that the bifurcation is as a result of the remnant bathymetric expression of the older stratigraphy and salt diapir relief (Hodgson et al., 1992; Kilhams et al., 2014;). The topography of these older stratigraphy and earlier fans may have provided some confinement and mounding to flows from side-fans, which were apparently deflected into an axial orientation.

The interaction between the Forties fans and the pre-existing salt diapirs results in complex stratigraphic architecture preserved in the sedimentary record. In cases where the rising salt diapir outpaced fan sedimentation, these submarine fans were seen diverging or deflected around the diapirs, for example around Merganser and Machar diapir. This results in change in flow path with an implication for variable flow characters i.e. erosive and depositional (Eldrett et al., 2015; Gee & Gawthorpe, 2006; Hodgson et al., 1992). A complex stratigraphic pattern is created with downdip shaling of the Forties against the Merganser diapir. In cases where the Forties fan sedimentation outpaced salt diapir relief example around the Scoter field, our study shows that, the Scoter diapir was buried by the Forties fan. The Forties fan system (T65 – T75) interacted with the salt diapirs at different scales and hence exhibited either an erosive or depositional architecture. The sediment was mostly deposited in the structural lows formed parallel to the orientation of the Merganser, Scoter and Machar diapir. Seismic cross-section (Figure 4.13) shows (i) low amplitude reflection and thinning of packages towards the diapirs (example Merganser and Machar) suggesting either a poor reflectivity because of the salt diapirs or basin floor mudstones or debrites facies (ii) Ponding or confinement of the Forties sandstone in syndepositional lows and (iii) Forties sandstone packages at the crest of the Scoter suggesting a possible inactivity of the Scoter at the time of Forties deposition.

The results of this study show that a detailed understanding of the interactions between evolving topography and sedimentary systems in deepwater setting occur at different range of temporal and spatial scales shown in the study. This has implication for constraining reservoir location and geometry as part of hydrocarbon exploration.

4.8 CONCLUSIONS

The main conclusions of this 3D seismic and borehole – based study of the upper Palaeocene Forties fan system, Sele Formation, UK Central North Sea are:

- In the Central North Sea, the Forties fan systems comprises of a series of high frequency, genetically linked sequences (T65 – T75, oldest to youngest) deposited during a relative rise and fall in sea level.
- Seismic reflection character of the Forties Fan system comprises of parallel to subparallel, bright amplitude reflection packages. The reflection marking the top Forties fan (P6) is characterized by subparallel to parallel, continuous to sub-continuous reflection character. The reflection marking the base Forties fan (P4) is characterised by parallel to subparallel, bright amplitude reflection packages. Internally, the Forties show intervals of interbedded low–medium amplitude packages with bright amplitude packages (P5). Overall, the reflection packages marking the Forties Fan interval are truncated or deformed in places by salt diapirs.
- Seismic Attribute maps at P4 – P6 shows the distribution of the fan system within a general NW – SE axial as well as W – E lateral fairways. Around our study location, the Forties fan system occurs primarily as fan-lobes, and they continue to the distal part of the basin. Isopach map shows that the thickness of the Forties fan decreases towards the SE however, in our study location, high thickness variability was recorded because of the control on the sedimentation of the Forties fan by salt diapirs. Relative distribution of the bright amplitude reflection around salt diapirs as observed on attribute maps further suggest structural controls on the fan system.
- W – E well correlation of the Forties fan system across the Merganser and Scoter fields shows the lateral continuity of the Forties fan system. Well section shows the increasing thickness variability of the Forties Fan system with the highest thickness recorded around Scoter fields. Lithology cross plots and Vclays histogram shows the dominant lithology to be Sandstone and heterolithics.
- Several styles of salt-sediment interaction for example, local *diversion* of fans by pre-existing salt diapirs, *deflection* of fans towards a syn-depositional structural low, and *lateral confinement* and *ponding* of fan-lobes towards salt related relief i.e., salt diapirs were observed.
- We established that our area of study is in the distal fairways of the Forties fan system. We show that in lobe-dominated setting, the Forties fan system exhibit a heterogeneous stratigraphic architecture influenced by seafloor topography during diapir ascent. Overall, depending on the rate of ascent or descent of the diapir, relative to high or low rate of sediment supply from the source areas, the lateral confinement of the Forties fans reflects in the complex stratigraphic architecture of the Forties Sandstone
- Seismic and borehole-based studies such as this add confidence to the interpretation of submarine fan-lobes in salt diapir influenced distal setting. They provide key insights that can aid in better understanding of salt-sediment interaction.

LIST OF TABLES

List of available well data for the study											
Field	Well list	Composite log	Biostratigraphic data	Core	CALI	SP	GR	RES	DEN	NEU	DT
Scoter	22/30A-5	y	n	y	y	y	y	y	y	n	y
	22/30A-9	y	n	y	y	y	y	y	y	y	y
	22/30A-12	y	n	n	y	n	y	y	y	y	y
	SCS01	y	n	n	y	n	y	y	y	y	y
	SCS02	y	n	n	n	n	y	y	y	y	n
	SCS03	y	n	n	y	n	y	y	y	n	n
Merganser	22/30A-14	y	n	n	y	n	y	y	y	y	y
	22/30A-14Y	y	n	n	y	n	y	y	y	y	y
	22/30A-14Z	y	n	y	y	n	y	y	y	y	y
	MG A01	y	n	n	n	n	y	y	y	y	y
	MG A01S1	y	n	n	y	n	y	y	y	y	y
	MG A01S2	y	n	n	y	n	y	y	y	y	y
	MG A02	y	n	n	n	n	y	y	y	y	n
	MG A02S1	y	n	n	n	n	y	y	n	n	n
	MG A02S2	y	n	n	y	n	y	y	y	y	y
Wireline curve available: CALI = Caliper; SP = Spontaneous Potential; GR = Gamma Ray; RES = Resistivity; DEN = Density; NEU = Neutron; DT = Sonic. y = data available; n = data not available											

Table 4. 1: List of available well data available for the study – Wireline log in all the wells and core data in selected wells

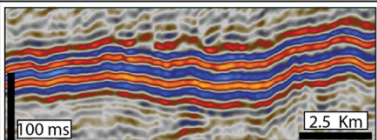
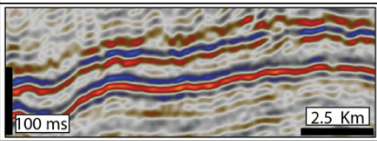
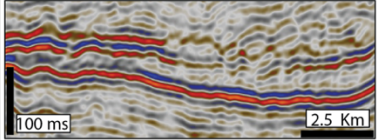
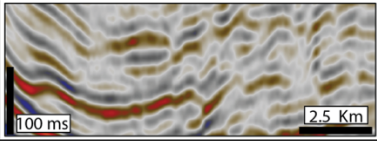
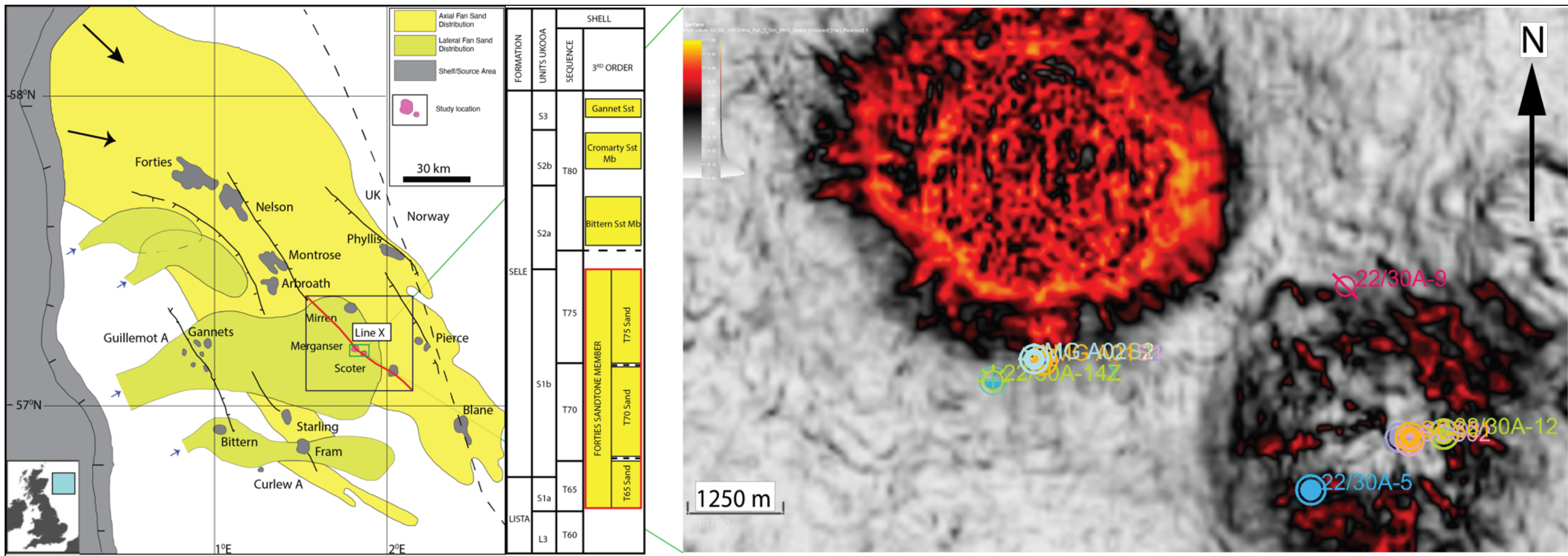
Sesimic Facies	Seismic cross section	Reflection character	Interpretation	Depositional Facies
SF1		Continuous to subparallel bright amplitude reflection	Massive sandstone deposited at the axis of the submarine fans	Sheet sandstone, lobes and fans
SF2		Continuous to subparallel bright amplitude reflection packages interbedded with low amplitude reflection packages	Sand-rich Interbedded sandstone, siltstone and mudstone. Likely Off-axis heterolithics deposit or hybrid event beds	Interbedded sheet sandstones, debrites and pelagic mudstone
SF3		Continuous to discontinuous subparallel high to medium amplitude packages interbedded with low amplitude chaotic reflection packages	Mud-rich Interbedded sandstone, siltstone and mudstone. Off-axis heterolithics deposits, debrite or hybrid beds	Hybrid event bed
SF4		Discontinuous, subparallel low amplitude reflection packages	Basinal, pelagic mudstone or claystone deposit.	Basinal mudstone or mud rich debrite

Table 4. 2: Seismic facies scheme showing the seismic expression of the equivalent core facies within the Forties Sandstone member, Sele Formations

LIST OF FIGURES



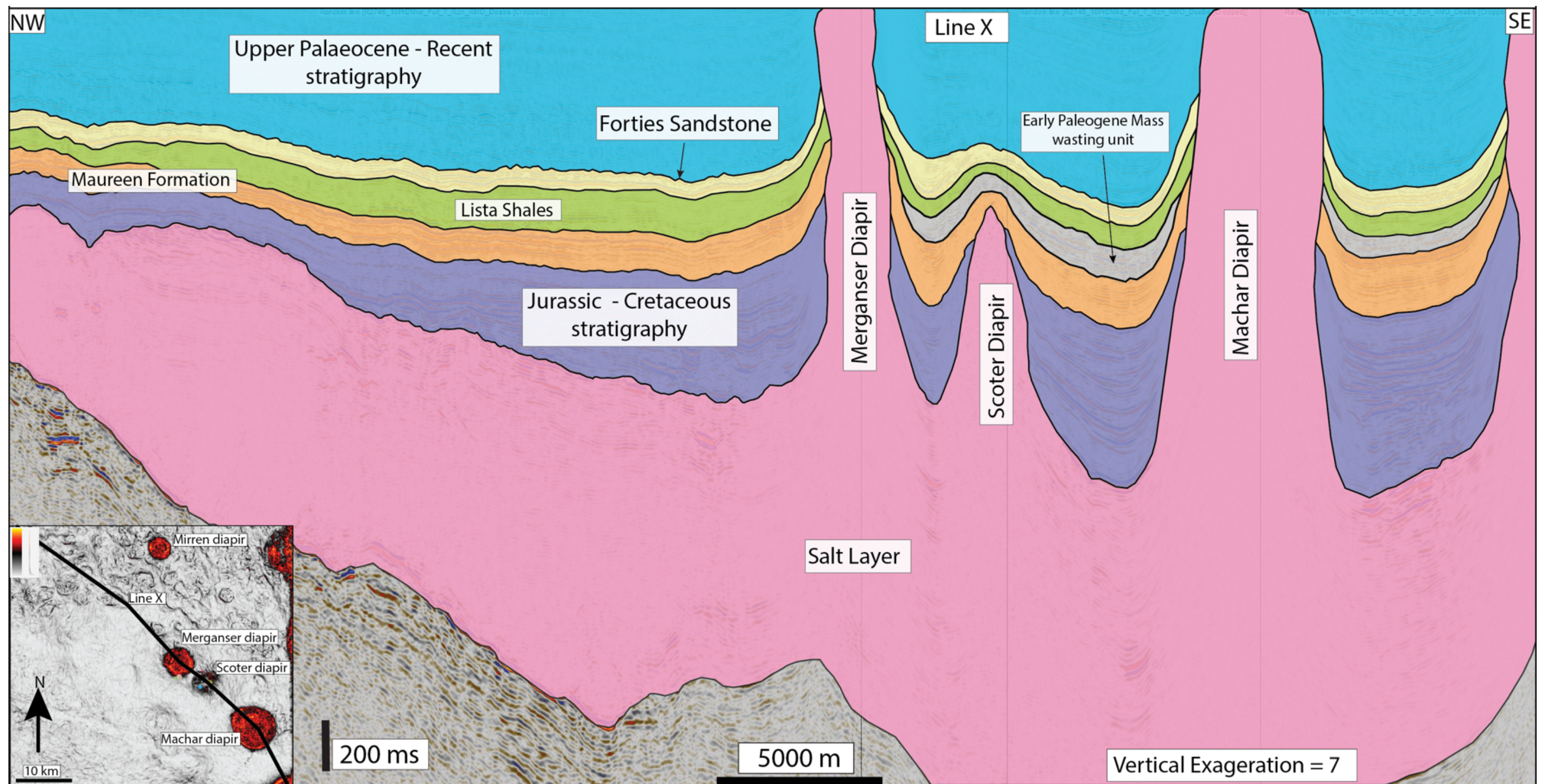


Figure 4. 1: (A) Map of the North Sea showing the NW and Westerly sourced submarine fan system (black box highlights the study location within the Central North Sea) and the stratigraphic chart showing the lithostratigraphic chart of the study location in the Central North Sea modified after (Eldrett et al; 2015). (B) NW – SE regional seismic line X taken across the study location. It highlights the tectonostratigraphy of the Central North Sea. Interval in light yellow represents the upper Palaeocene depositional system (Forties Fan system (lower Sele Formation)) and the light pink represent the Salt layer and the diapirs in the Central North Sea. This figure show both the Merganser and Machar diapir truncating the Palaeocene stratigraphy while the Scoter was arrested at Palaeocene interval

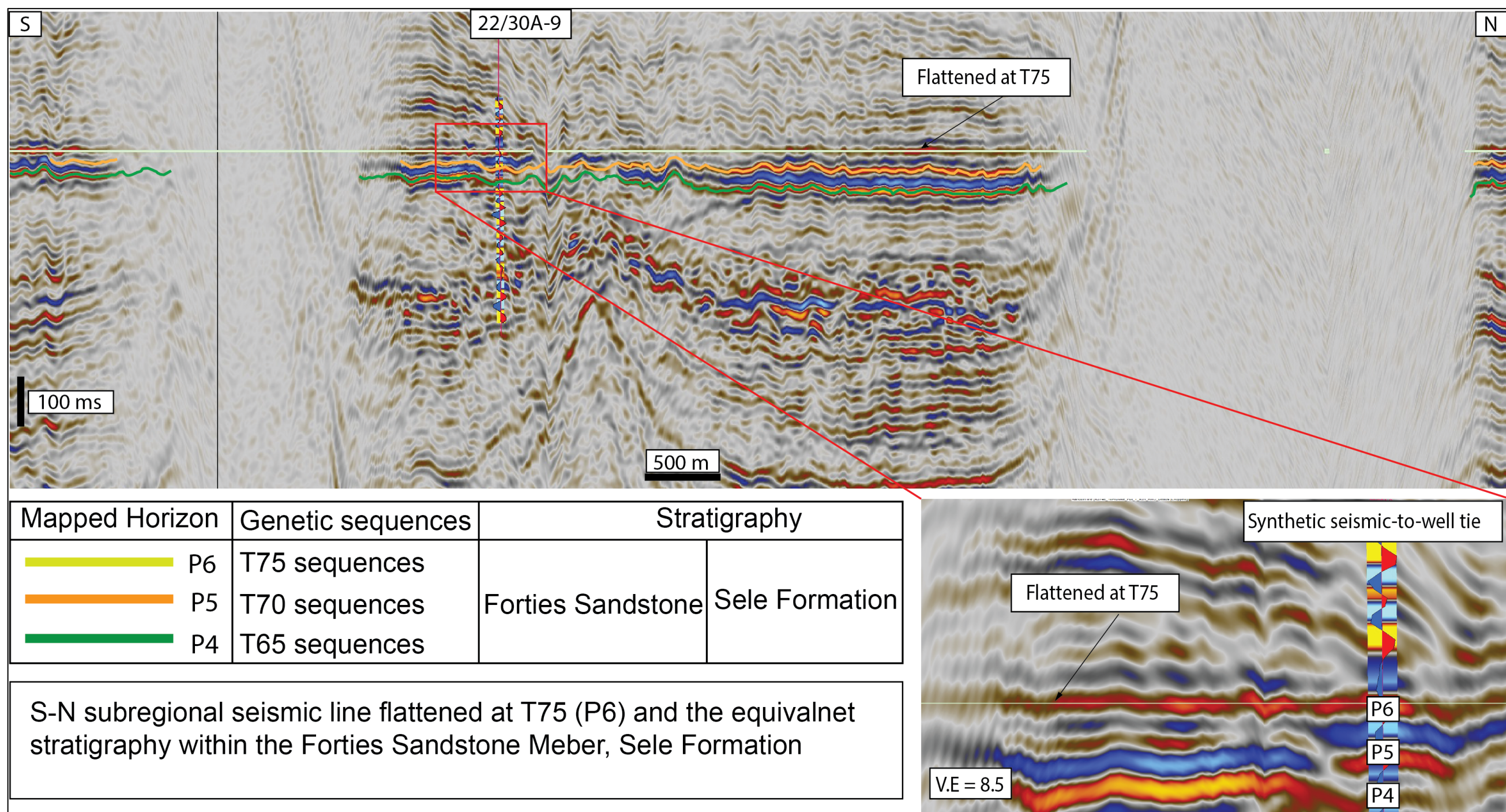
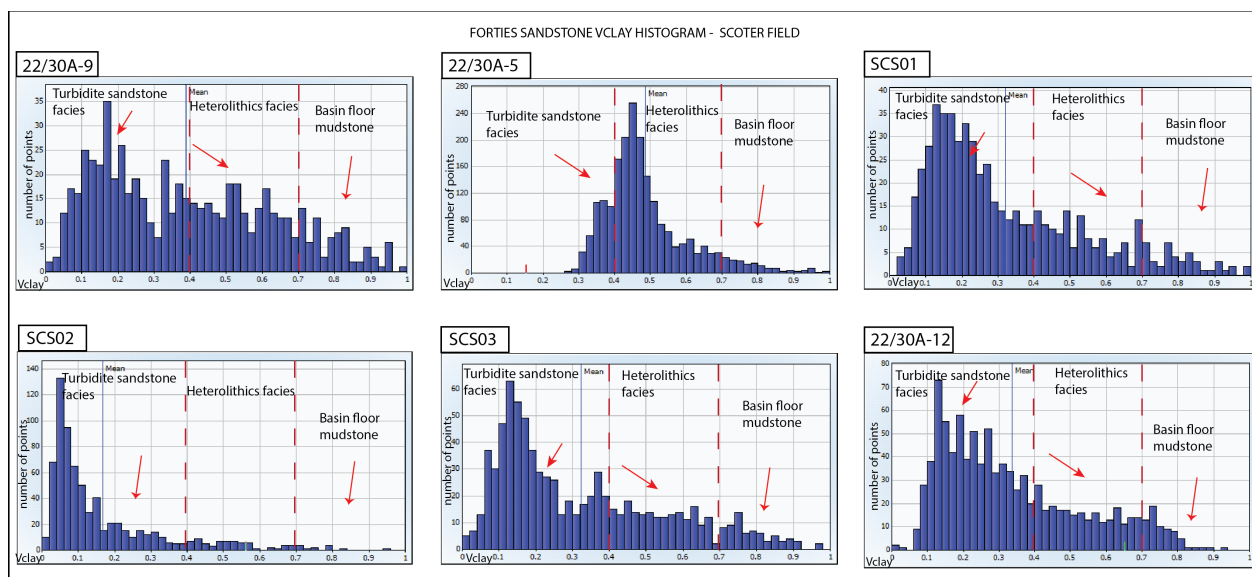
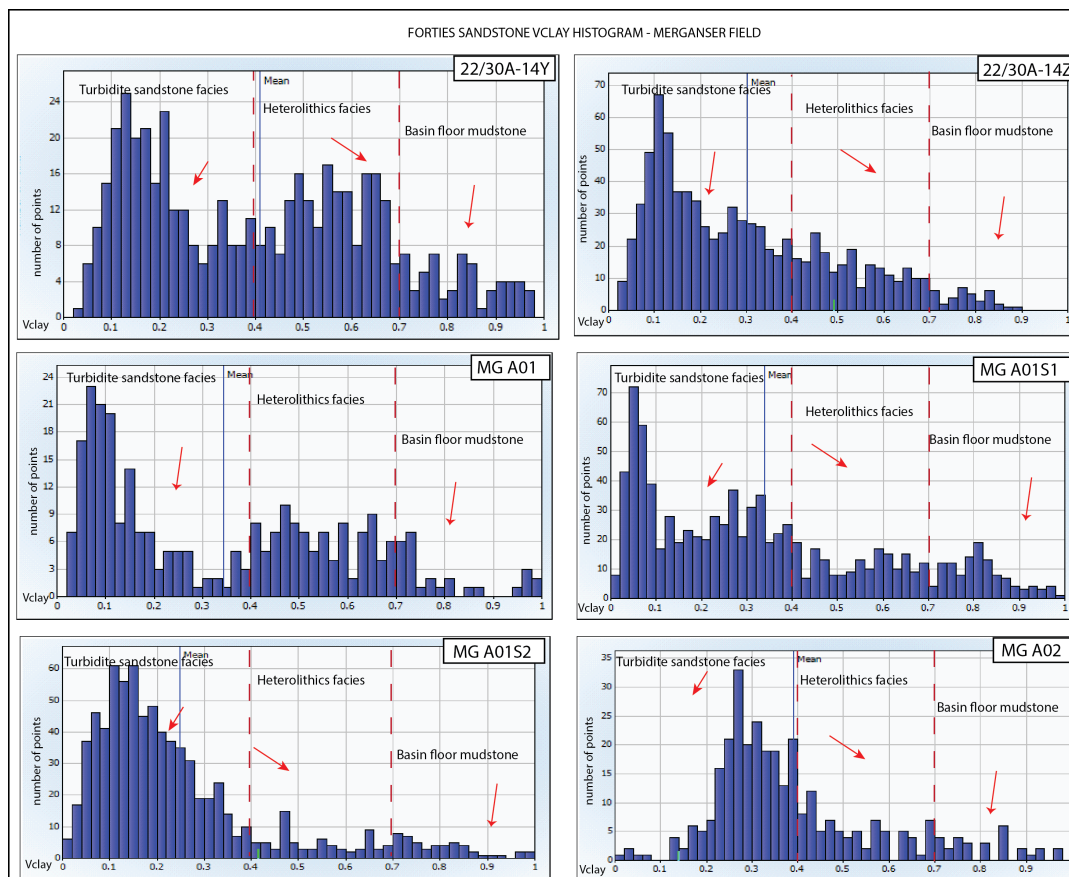


Figure 4. 2: Seismic-well-ties highlighting the base (P4) and top (T75) Forties Sandstone mapped seismic horizons. An S – N Regional seismic line showing the mapped horizon and the equivalent stratigraphy within the Forties Sandstone member, Sele Formation



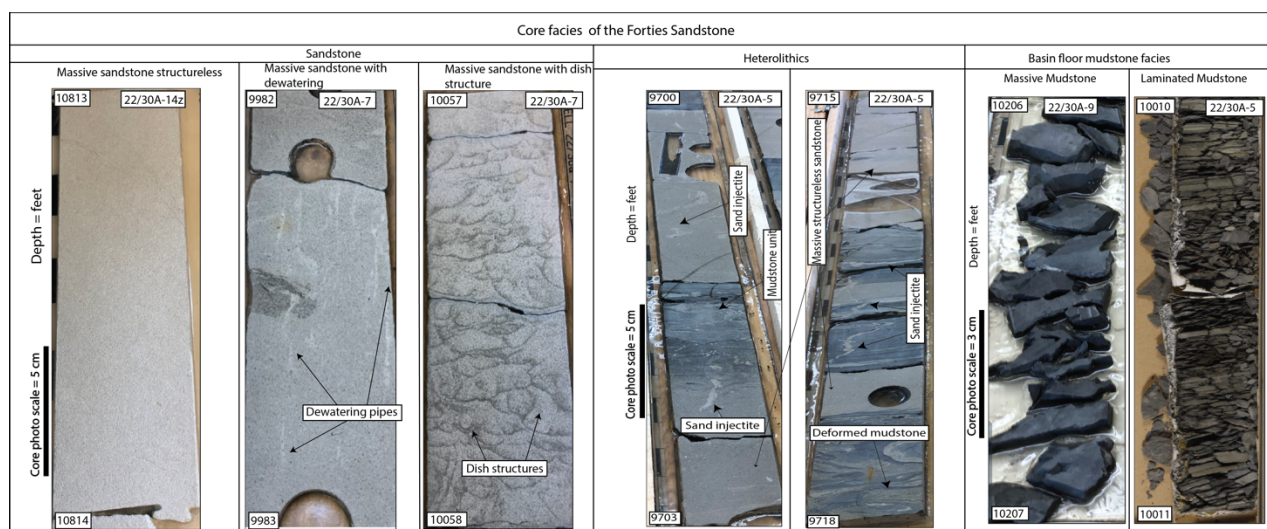
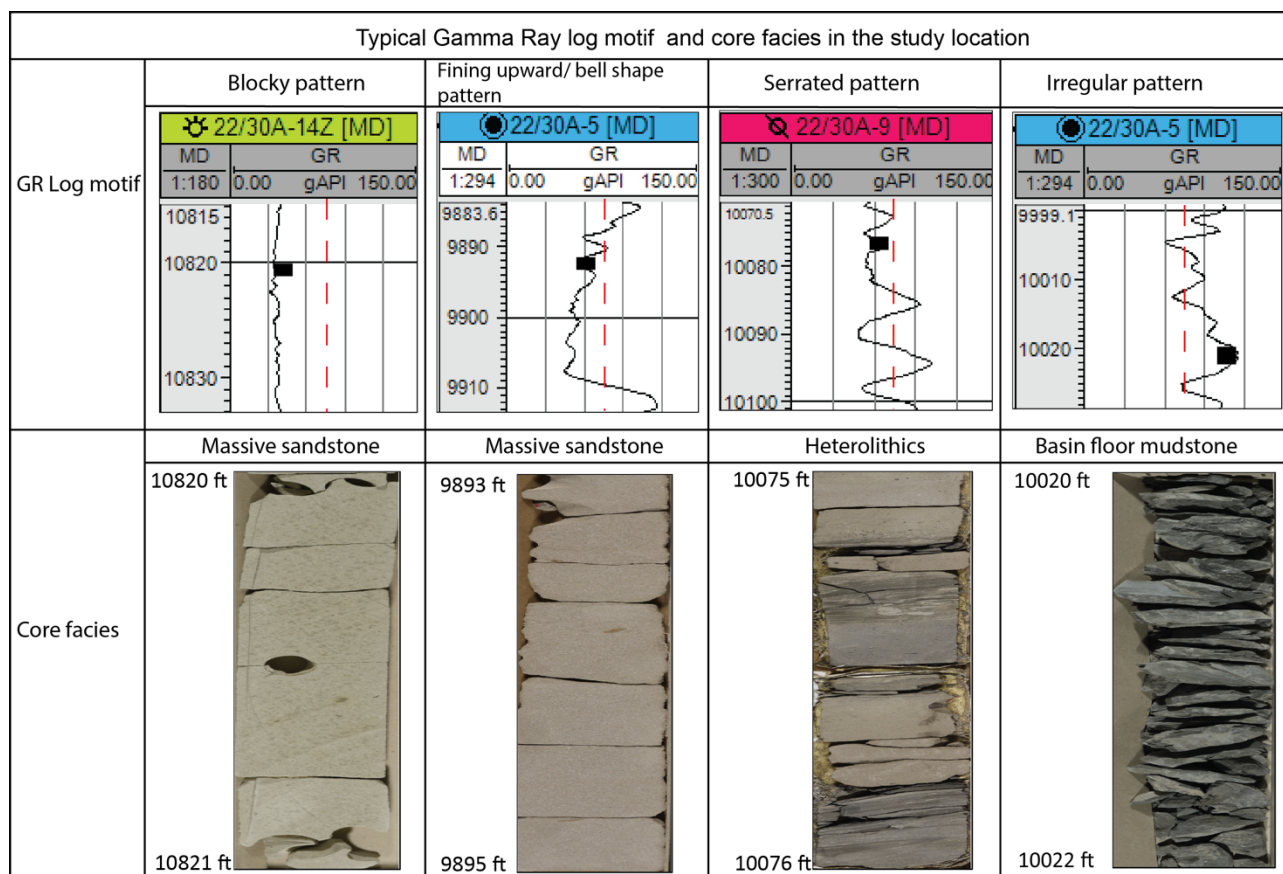
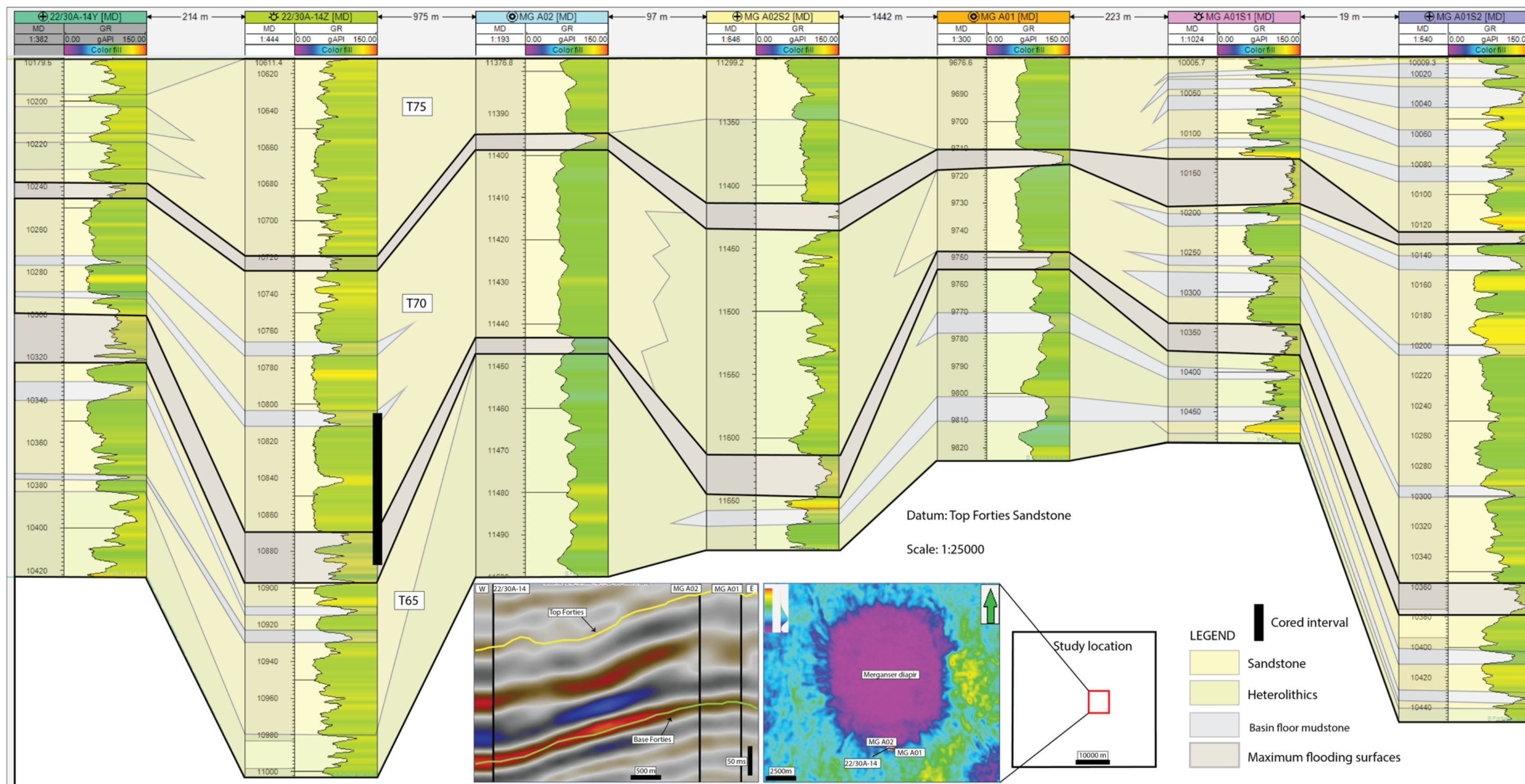


Figure 4. 3: Forties Sandstone Vclays histogram constructed from wells in the Merganser Field. The histogram shows a high ratio of sandstone to heterolithics distribution (B) Forties Sandstone Vclays histogram constructed from wells in the Scoter Field. The histogram shows a high ratio of sandstone to heterolithics distribution (C) Show four typical GR log motif and the corresponding core facies identified in the study location (D) Typical core facies identified in the study location. The sandstone facies comprise of massive structureless sandstone, dewatering sandstone, and dish structured sandstone facies. The heterolithics comprises of interbedded sandstone and mudstone. The mudstone shows internal deformation (debrite) and other soft sediment structures i.e., sand injectites. The basin floor mudstone is either massive or laminated



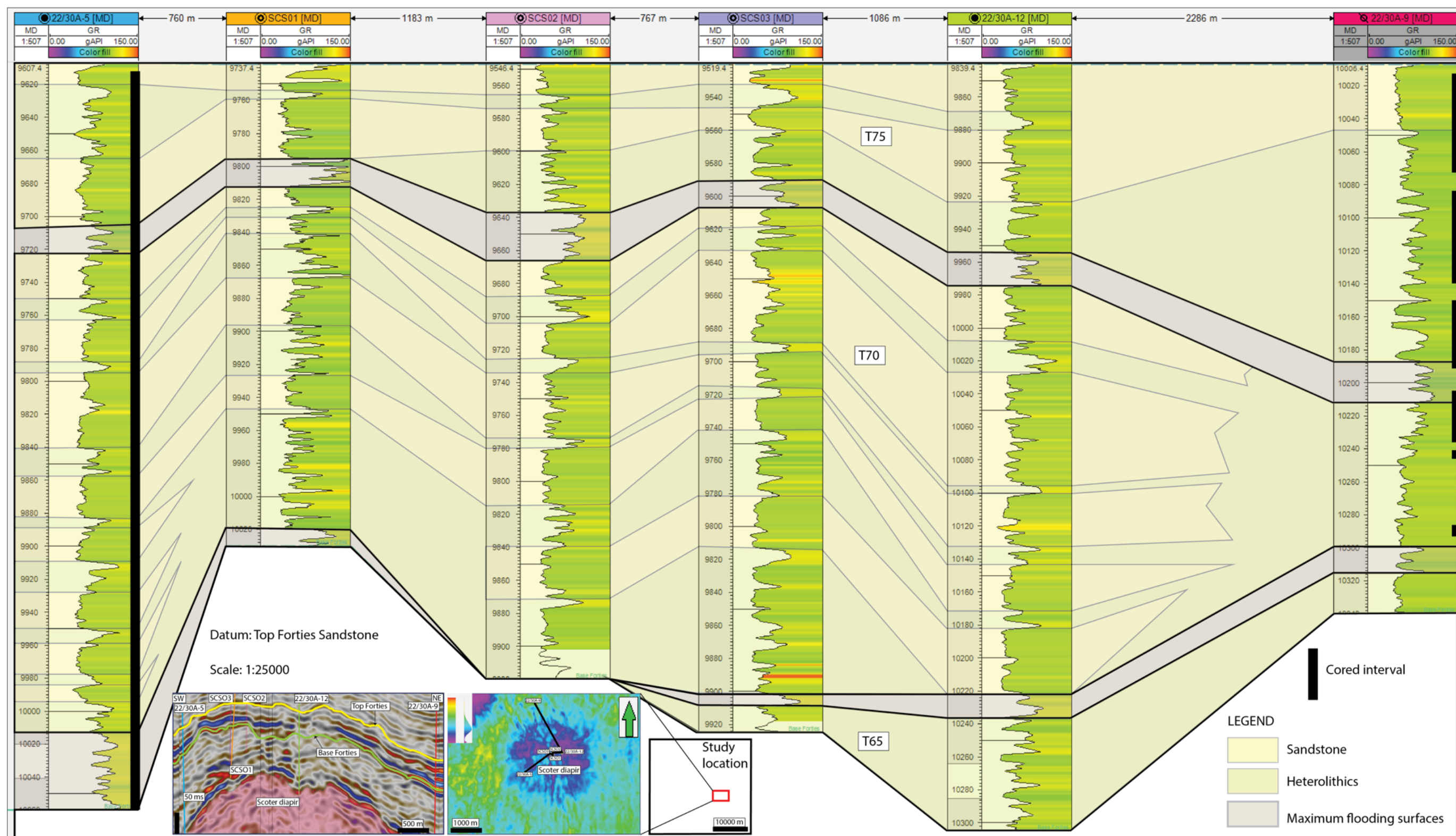


Figure 4. 4: West – East Sub regional Well Correlation panel of the Forties Sandstone across the Merganser Field (B) A NW – SE Sub regional Well Correlation of the Forties Sandstone across the Scoter Field

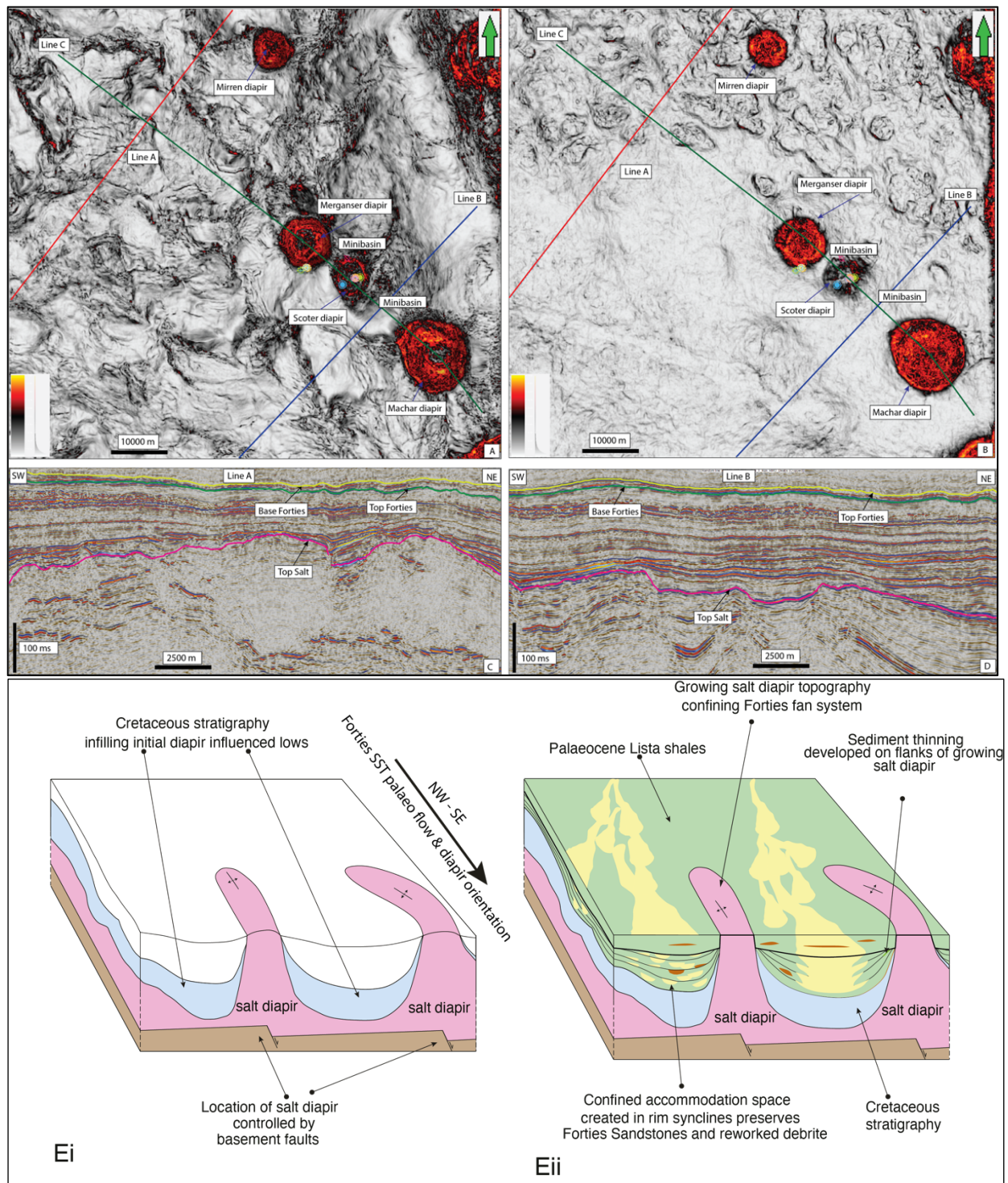


Figure 4. 5: Regional basin structure documented from variance attribute map extracted at top salt and base Forties Sandstone. (A) At top salt, map show the rugose topography created by the halokinesis (B) at base Forties Sandstone, much of the rugose surface created by the salt layer has been buried by the Cretaceous to early Palaeocene stratigraphy. However, there are perturbing salt diapirs i.e., Merganser, Scoter, Machar, and Mirren diapirs. Seismic cross section: (C) line A taken at the most proximal part of the study location and (D) line B taking at the most distal part of the study location shows the gently dipping stratigraphy. Locally, the dips increased in regions of salt diapir. Also observed is the variability in the thickness of the Thenetian-aged Forties Sandstone Member. (E) 3D Cartoon showing elongated minibasin created between Merganser and Scoter (focus of this study), and confined Forties Sandstone Member.

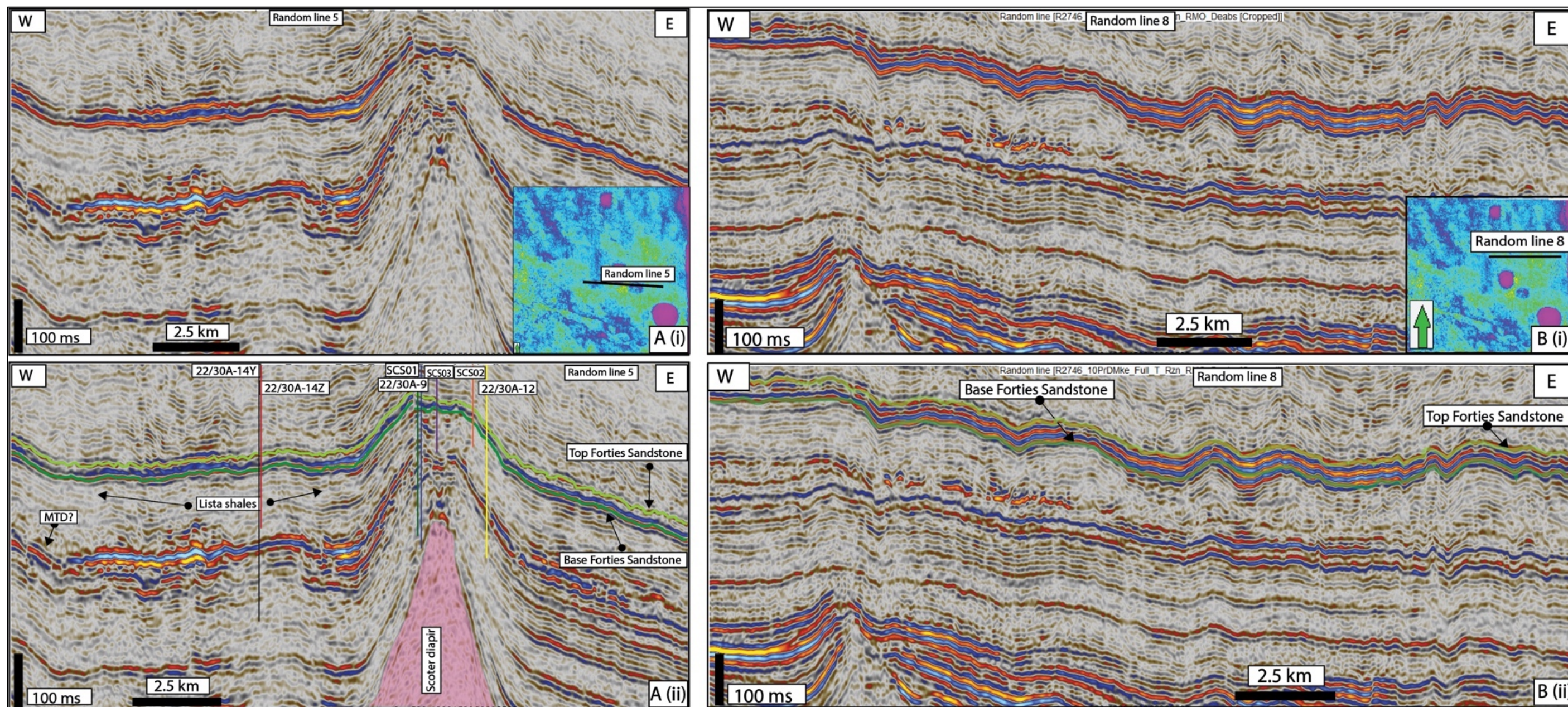


Figure 4. 6: A (i) and (ii) Uninterpreted and interpreted W – E seismic line taken across the flank of Merganser and the crest of Scoter diapir, highlighting the seismic character of the Forties fans system B (i) and (ii) uninterpreted and interpreted W – E seismic line taken from the northern part of the study location highlighting the seismic character of the Forties fans. We noticed the sheet nature of reflections marking the top, base, and internal character of the Forties sandstone. Away from the diapirs, the reflection marking the top and base of Forties sandstone are parallel, continuous bright amplitude reflection. Around Merganser and Scoter, these reflections are distorted by the bathymetry created by salt diapirs

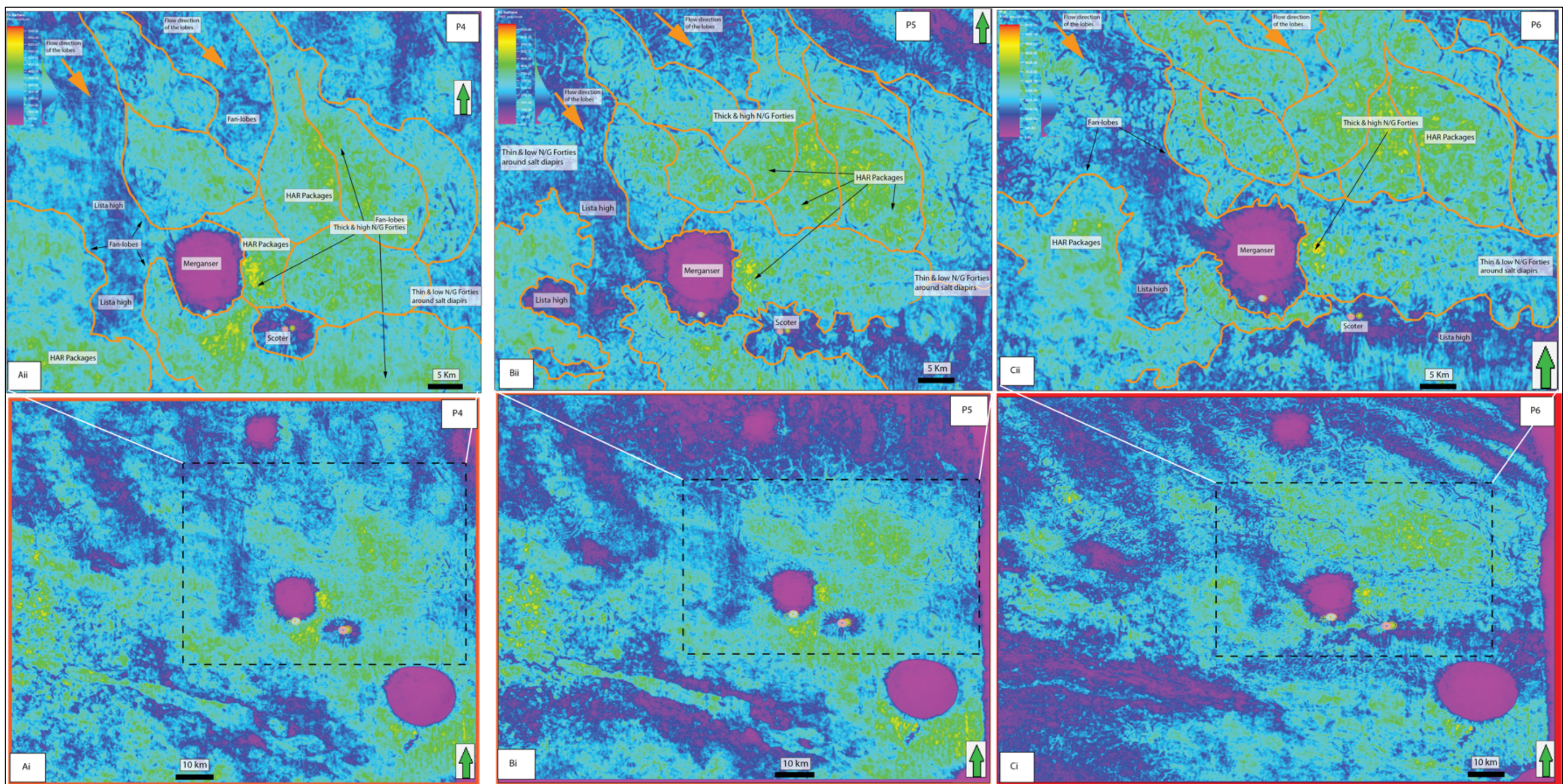
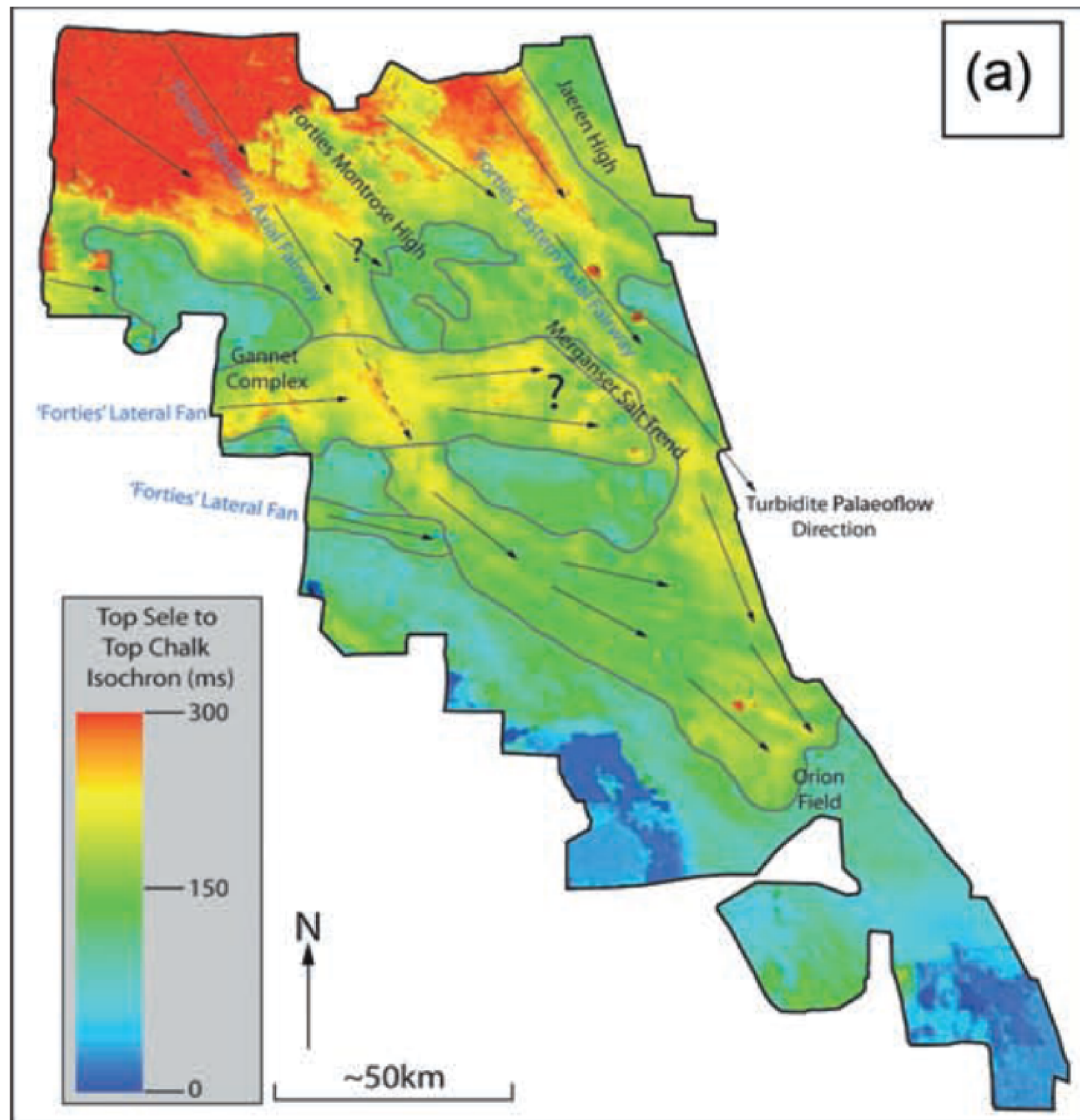


Figure 4. 7: Highlights (Ai) and (Aii) uninterpreted and interpreted RMS amplitude attribute map extracted at P4, (Bi) and (Bii) uninterpreted and interpreted RMS amplitude attribute map extracted at P5, and (Ci) and (Cii) uninterpreted and interpreted RMS amplitude attribute map extracted at P6. These maps show the upper Palaeocene deepwater depositional system occurring as discrete fan system with a general NW – SE and W – E trends. The bright amplitude reflectivity was related to sandstone facies or heterolithics and was validated by available core data.



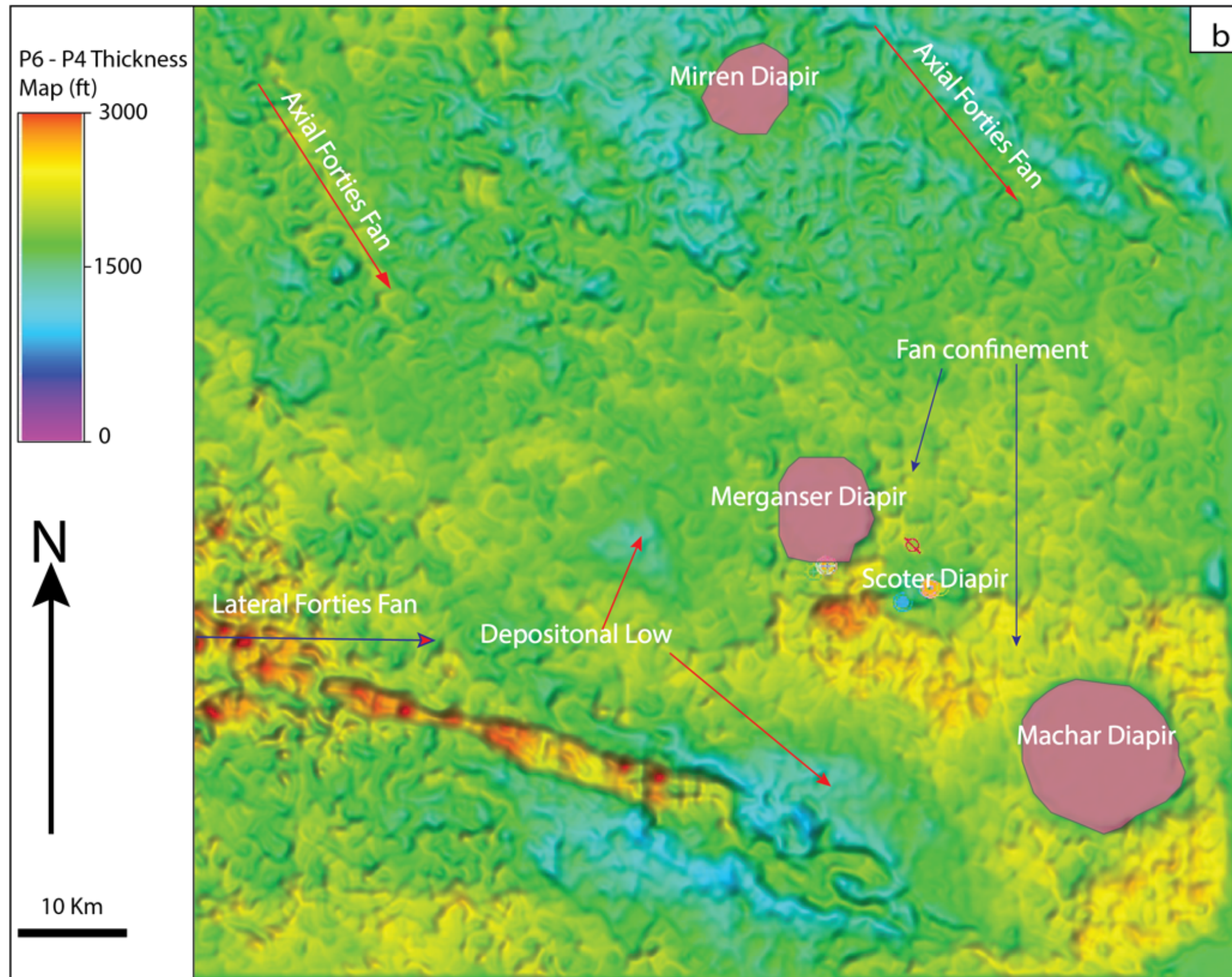


Figure 4. 8: Highlights; (a) Isochron map extracted from top Chalk to top Sele Formation, (Kilhams et al., 2015) (b) Isochron map extracted from top P6(Top Forties) to top P4 (base Forties). These Isopach maps shows similar patterns to that of Kilhams et al; 2016 which shows a general NW – SE decreasing thickness pattern in the upper Palaeocene deepwater depositional system in the Central North Sea

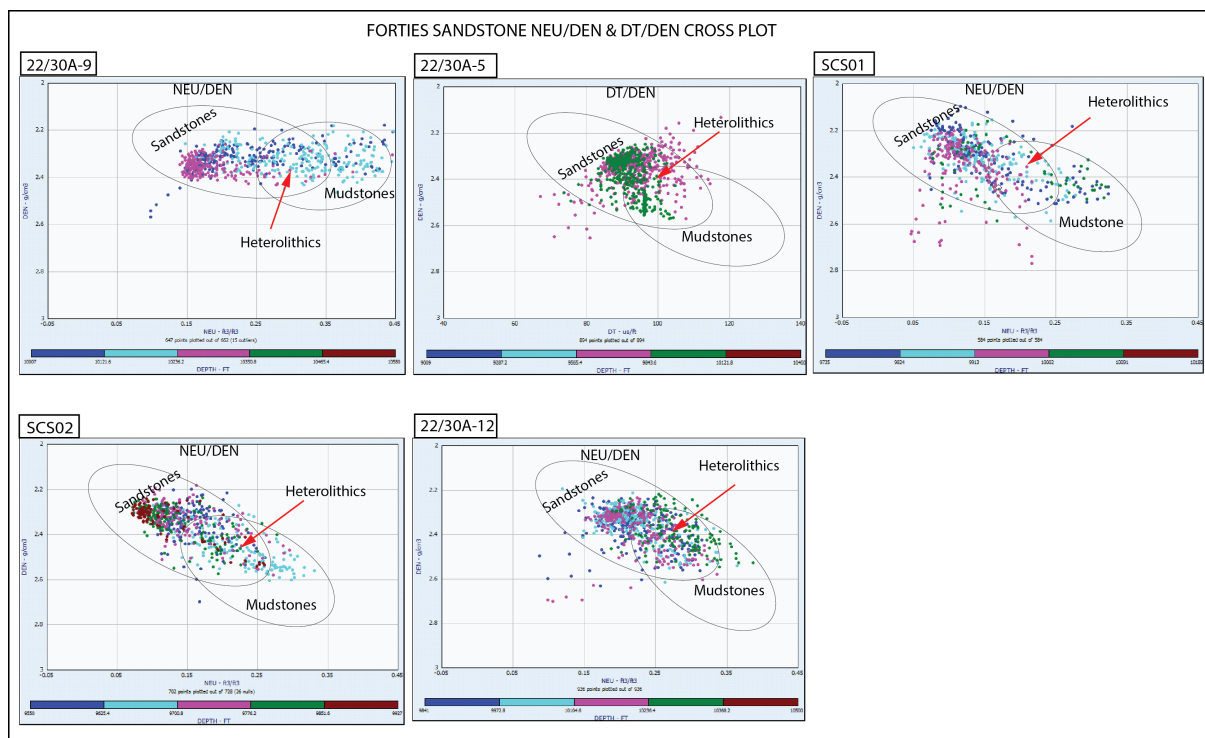
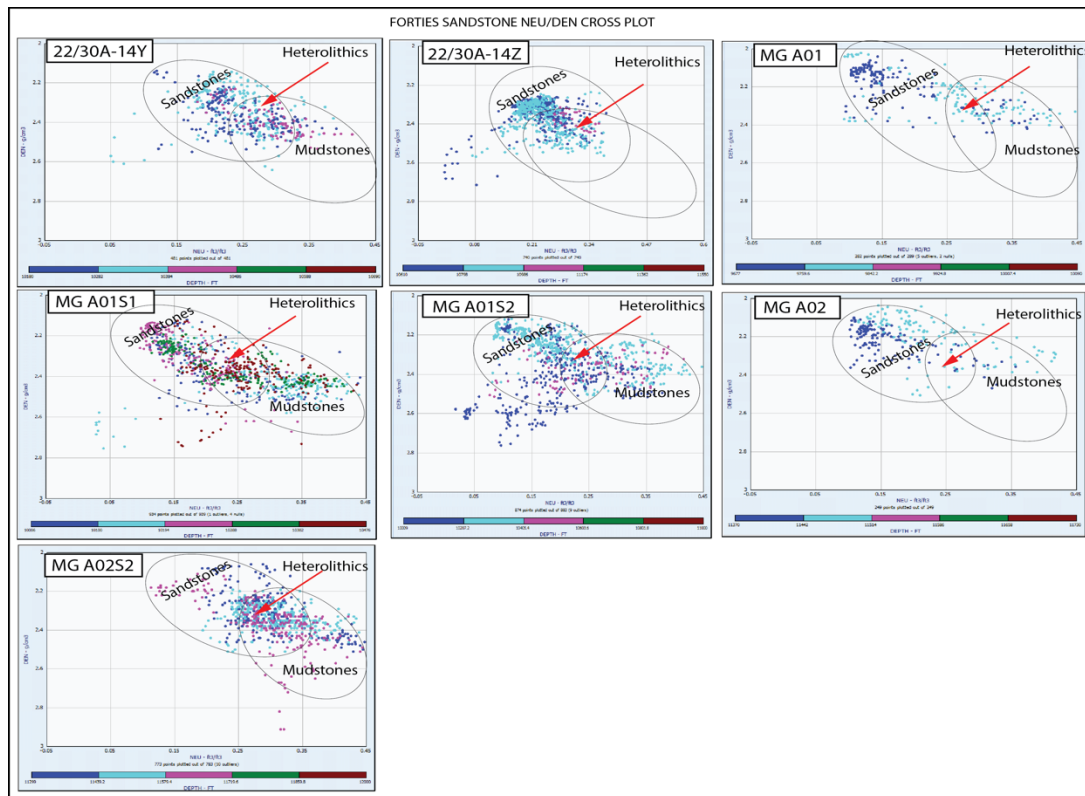


Figure 4. 10: (A) Forties Sandstone NEU/DEN cross plot around Merganser Field (B) Forties Sandstone NEU/DEN cross plot around Scoter Field. The lithology log cross-plots shows that the dominant lithologies are sandstone, heterolithics and mudstone

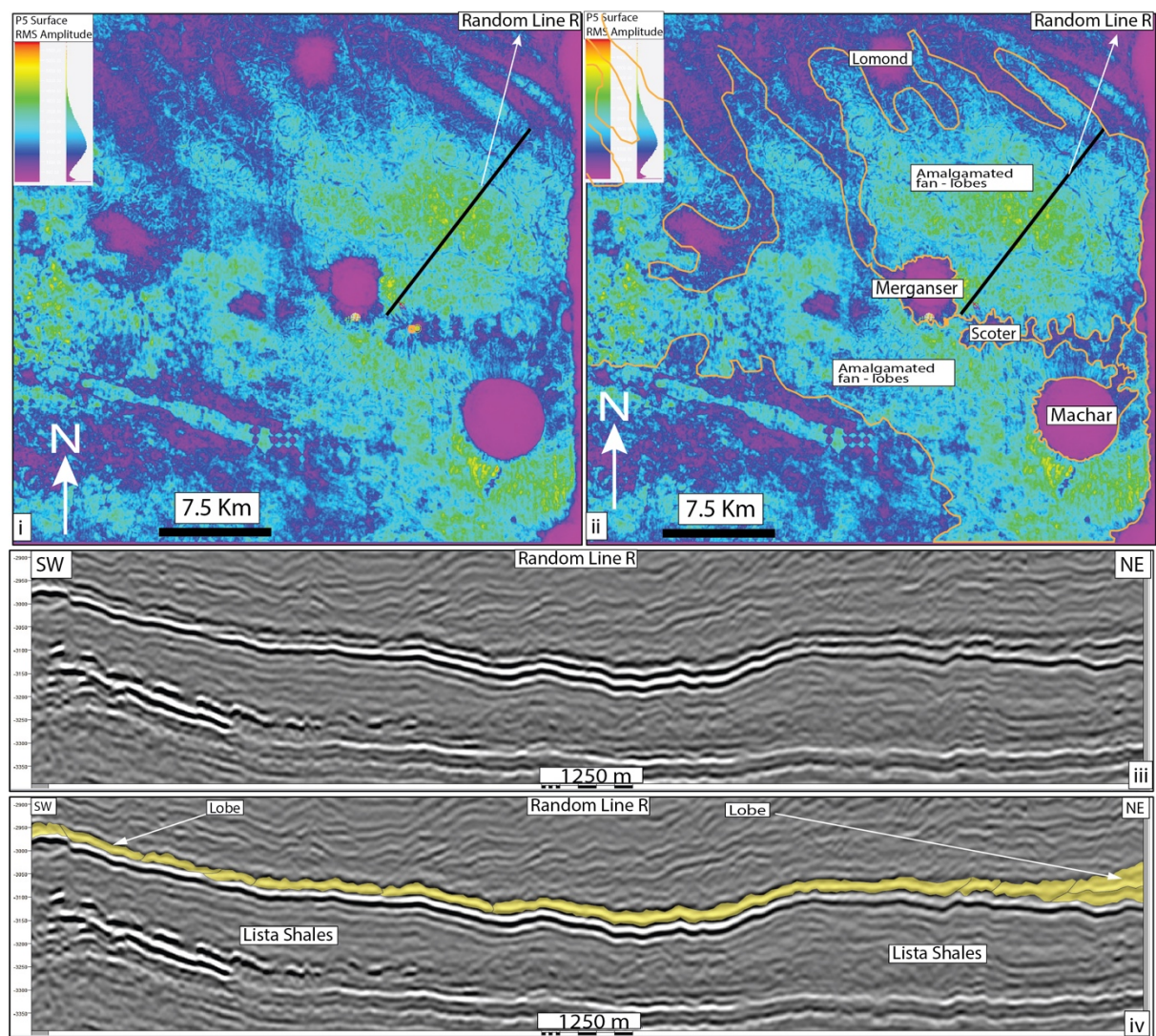


Figure 4. 11: RMS attribute map showing the distribution of the submarine fan-lobe in the study location. Random line R was taken along SW-NE to highlight the cross section seismic character of the lobes

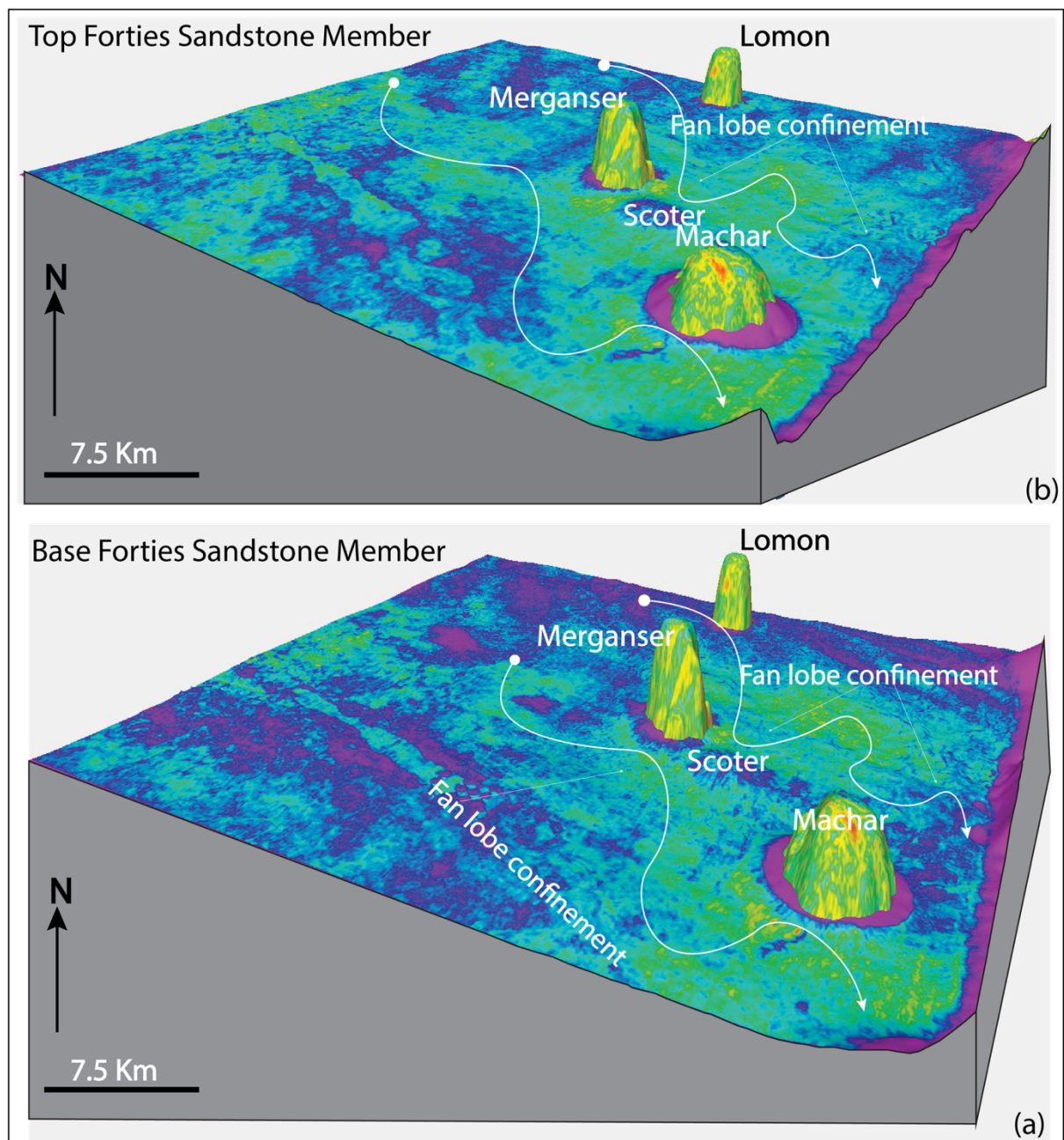


Figure 4. 12: (a) and (b) show RMS amplitude map extracted at base and top Forties. This map shows the basin configuration and the lateral confinement of the fan-lobe system by the NW-SE oriented Salt diapirs. The diapir orientation are aligned along a ridge hence depocenters are the depositional oriented parallel to the diapirs

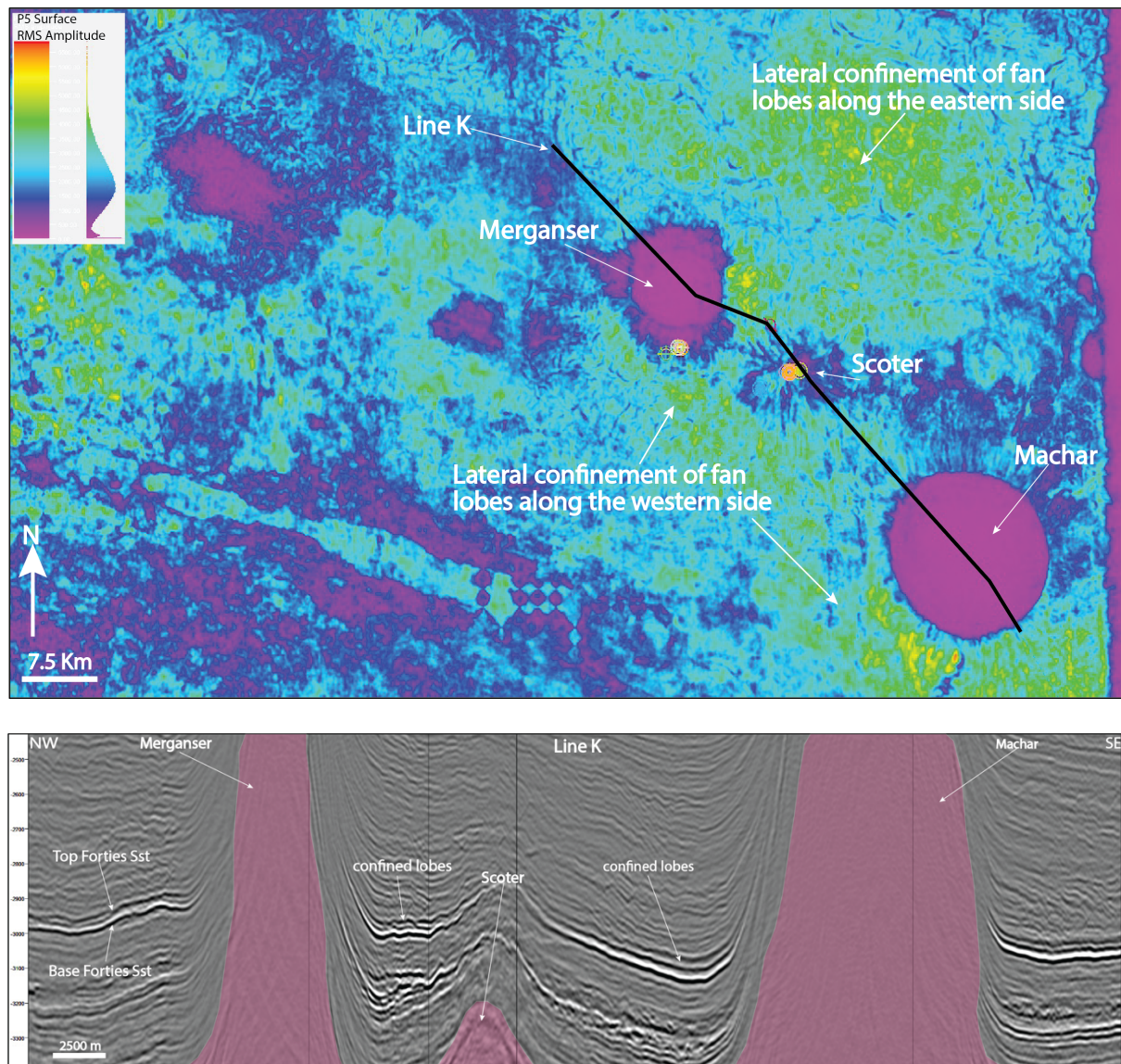
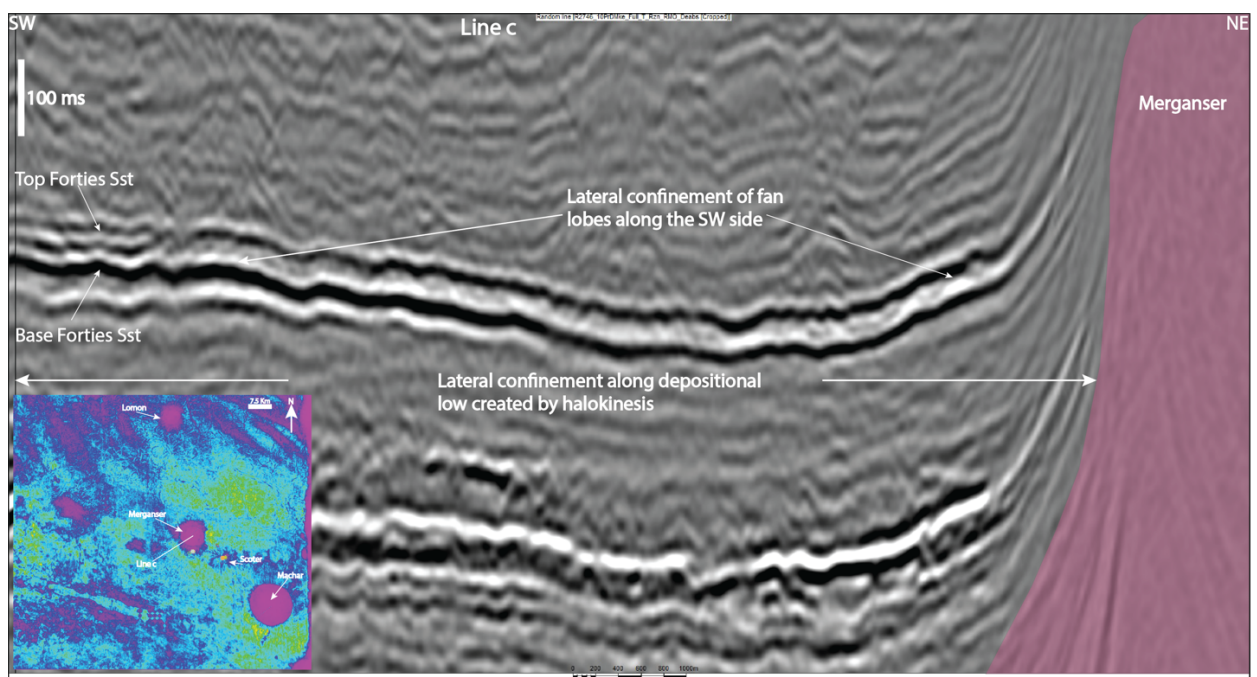
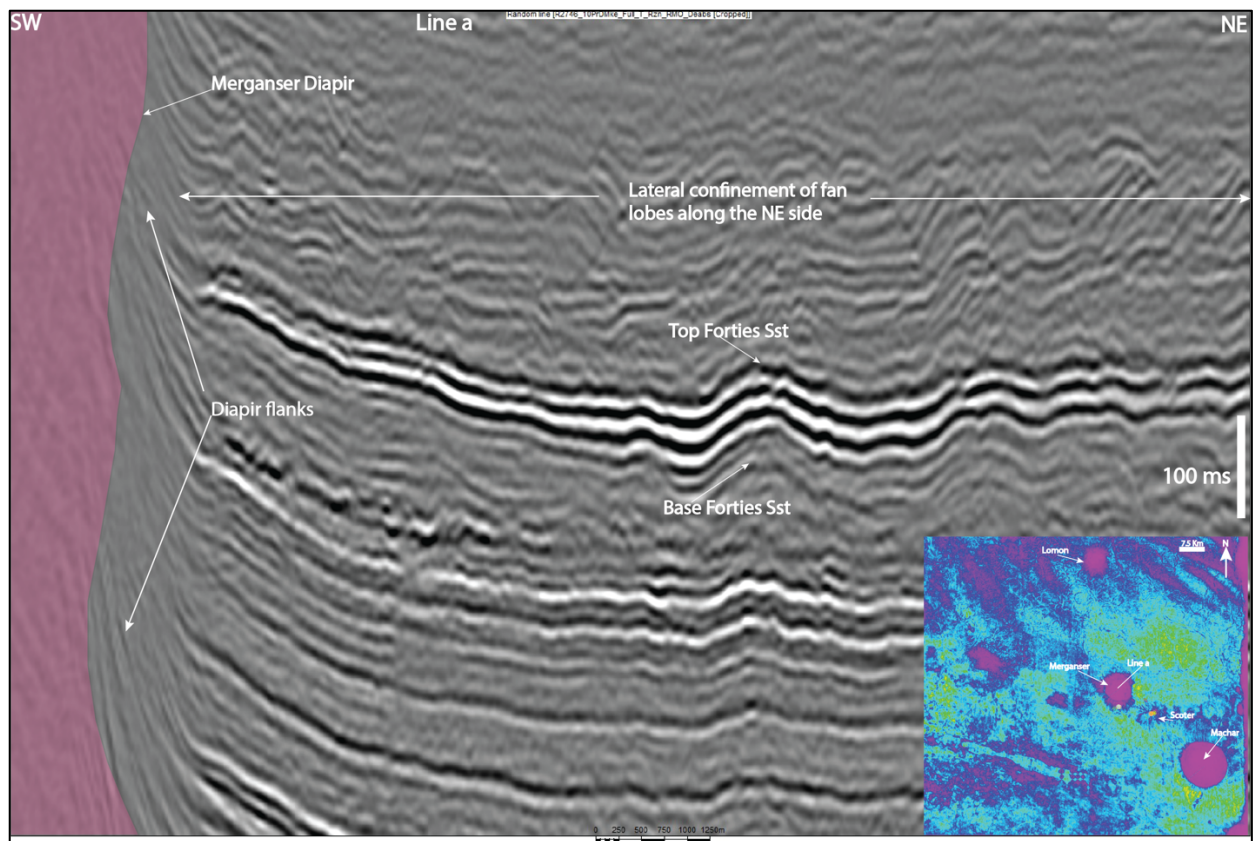


Figure 4. 13: RMS attribute map showing the distribution of the confined submarine fan-lobe in the study location. Line K was taken along NW-SE direction to highlight the cross section seismic character of the lobe. Confined lobes are seen ponded in subsidence related depositional lows between isolated diapirs



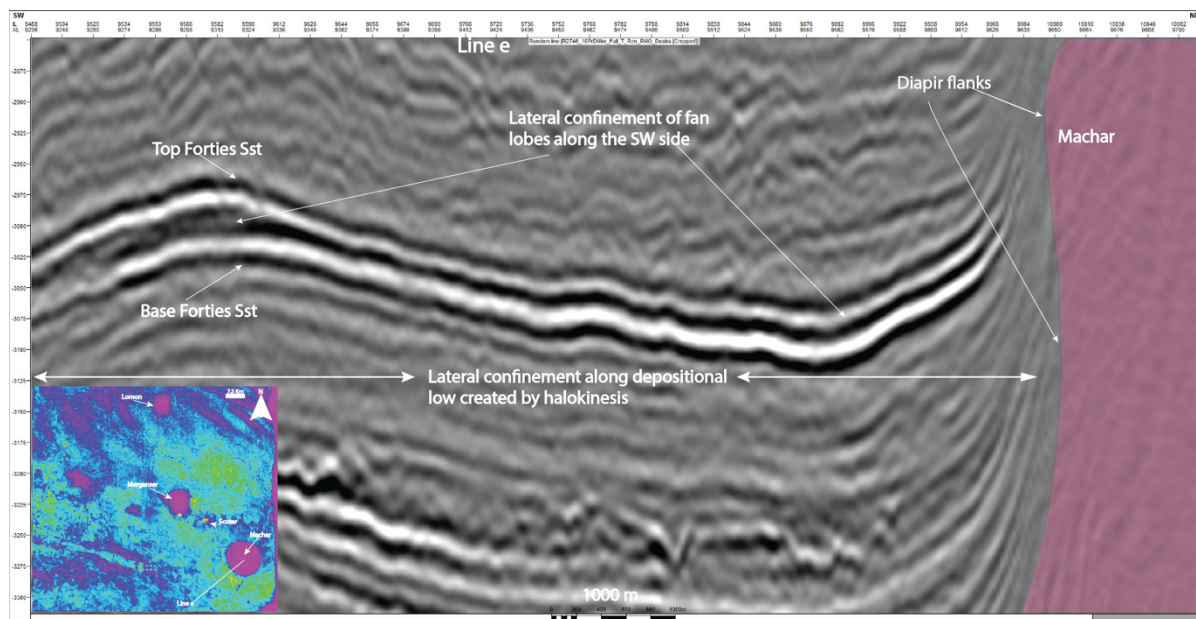
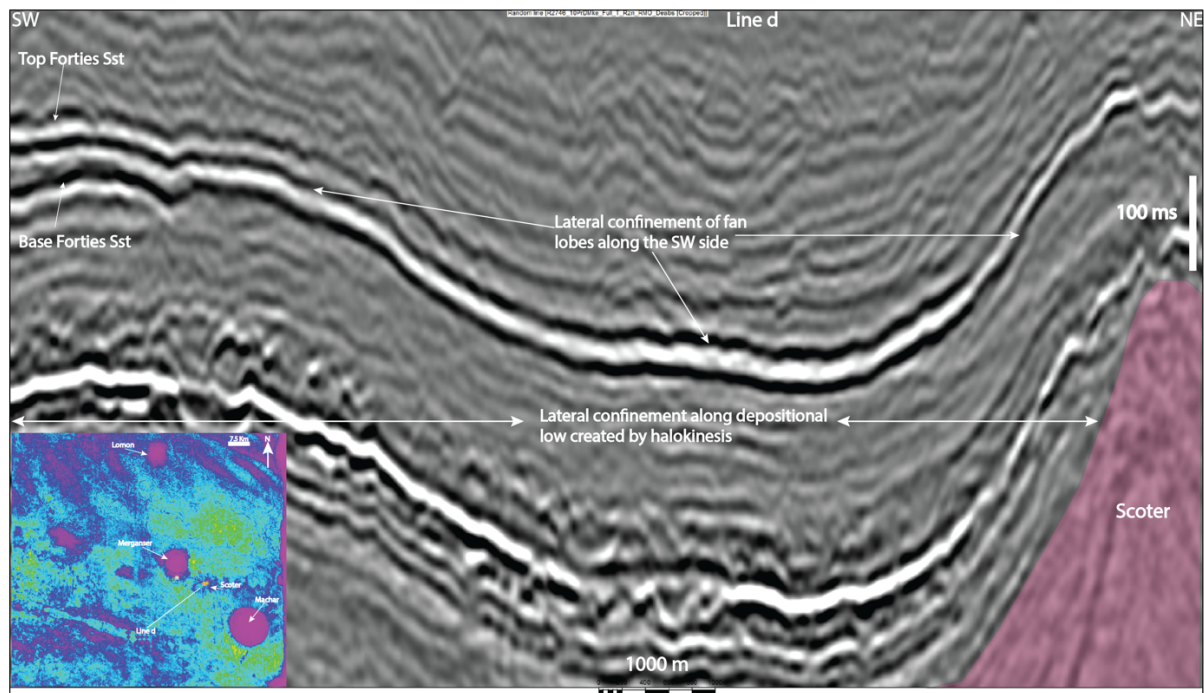


Figure 4. 14: Show seismic line a, c, d, and e, taken along a SW-NE direction highlighting the cross section seismic character of the lobes confined in parallel fashion to the diapir orientation. Notice the thickness difference to the packages ponded between isolated diapirs. This suggest that more accommodation is created parallel to the diapirs than in-between the diapirs.

CHAPTER 5

INTERACTION OF SALT DIAPIRS WITH UPPER PALAEOCENE DEEP-WATER DEPOSITIONAL SYSTEM AND IMPLICATION FOR COMPLEX STRATIGRAPHIC ARCHITECTURE AND FACIES DISTRIBUTION: FORTIES SANDSTONE MEMBER, SELE FORMATION, CENTRAL NORTH SEA

Isaac A. Odeh¹, Christopher A-L. Jackson¹, Howard D. Johnson¹, David A. Hodgson² and Ian A. Kane³.

¹*Basins Research Group (BRG), Department of Earth Science and Engineering, Imperial College London, Prince Consort Road, SW7 2AZ*

²*Stratigraphy Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT*

³*School of Earth and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL*

5.1 ABSTRACT

A range of gravity-flow deposits are observed in deep-water depositional systems, for example, mud-poor massive sandstones interpreted as turbidites, clast-rich, deformed, silty mudstones interpreted as debrites, and basin floor mudstones. When they occur in basins with bathymetric features example salt diapirs, their flow path is often controlled and obstructed, resulting in complex stratigraphic architecture archived in the sedimentary record. In this study, we utilized a 793 ft (242 m) thick core dataset drawn from two exploration fields (i.e., Merganser and Scoter) in the Central North Sea to document the interaction between salt diapirs and upper Palaeocene deep-water depositional systems. A variety of facies for example, turbidites (deposit of turbidity current), debrites (deposit of debris flows) and basin floor mudstone (deposit of suspension fallout) are observed and are distributed in the flank of the Merganser diapir and the flank and the crest of the Scoter diapir respectively. The turbidite and the debrite show soft sediment structures (i.e., dewatering pipes, dish structures, and mud clast) typical of rapid deposition under a fluid state. We show that an upward transition from turbidite to debrite and basin floor mudstone is common, with the contact being either planar, sharp, or gradational. Based on the vertical relationship of these facies, the nature of the bed contacts, and the composition of the beds, we interpret these intervals as being deposited from high density turbulent flow event which transformed into a mud-rich cohesive rheology due to flow deceleration or due to turbulent flow interaction with intrabasinal bathymetric features. Slumping from diapir flanks and crest, local flow mixing of the originally transformed turbulent gravity flow by radial fault and the diapir walls resulting from flow diversion, deflection and ponding exert a complex relationship on the facies architecture.

Keywords: Submarine fans, deep-water depositional system, salt diapirs, Forties Sandstone, Hybrid event bed, Turbidite, debrite, basin floor mudstone

5.2 INTRODUCTION

Deposit of deep-water depositional system are traditionally identified to comprise of two end-member deposit; i.e. turbidites (deposit of turbidity current in which particle support mechanism is non cohesive, fluid turbulence) and debrites (deposit of debris flows in which particle support mechanism is fluid cohesion) (Baas, 2004; Bouma, 1962; Bruhn & Walker, 1997; Walker, 1978; Lowe, 1982; Mutti & Ricci Lucchi, 1978; Mutti, 1977; Mutti et.al., 2009; Normark et al., 2002; Stow, 1982; Stow & Johansson, 2000; Walker, 1976; Wynn et al., 2007). Recent improvement in our understanding of deep-water systems show that a wide range of deposit type has been identified (Jackson et al., 2009; Stevenson et al., 2015; Kane et al., 2017; Southern et al., 2017; Spsychala et al., 2017;). Many of these deposits do not conform to the classical Bouma succession and are hence classed as deposit of flows transitional between turbidity currents and debris flow i.e. showing component of cohesive and non-cohesive flows and are thus referred to as hybrid event beds (*sensu* Haughton et al., 2009;).

The architecture of deep-water deposit has been widely studied and the linkage between the processes and the depositional architecture of deep-water deposit has also been documented (Bouma, 1962; Bruhn & Walker, 1997; Walker, 1978; Lowe, 1982; Mutti & Ricci Lucchi, 1978; Mutti, 1977; Mutti et.al., 2009; Normark et al., 2002; Walker, 1976). Observation from many subsurface datasets shows that the architecture of deep-water depositional system consists of different deposit type i.e. massive sandstone, massive sandstone showing a range of primary or secondary depositional structures, siltstones, heterolithics and mudstones (Bouma, 1962; Bruhn & Walker, 1997; Cullis et.al., 2018; Walker, 1978; Hansen et al., 2015; Kane et al., 2007b; Lowe, 1982; Morris et al., 2014a; Mutti & Ricci Lucchi, 1978; Mutti, 1977; Mutti et al., 2009; Normark et al., 2002; Stow et al., 1999; Stow, 1982; Stow & Johansson, 2000; Walker, 1976). More recently, several studies showed the existence of co-genetic or linked-debrites and a basal turbidite components respectively and basin floor mudstone forming a new class of deep-water bed type called hybrid event beds or linked turbidite-debrite facies (Haughton et al., 2003; Talling, 2004; Haughton et al., 2009;). Generally, deep-water deposits shows a typical vertical relationship i.e. comprising of a typical Bouma succession or a basal clean, structureless or structured sandstone division interpreted as turbidite and an upper chaotic, poorly sorted, muddy division interpreted as transitional to debris flow deposit, an upper, thin, fine grained sandstone or mudstone division interpreted as the deposit from dilute low turbidity current (Bouma, 1962; Lowe, 1982; Stow, 1982; Stow and Johansson, 2000; Haughton et al., 2003; Davis et al., 2009a; Hodgson, 2009).

The depositional fate of deep-water systems is often control by a range of allocyclic factors example; faults, mud diapirs (or volcanoes), seamount, salt diapirs and older stratigraphy (Adeogba, 2003; Gee & Gawthorpe, 2006; Jackson et al., 2014; Kane, Mcgee, et al., 2012; Oluboyo et al., 2014). Intrusive salt structures i.e. salt diapirs are a common structural features in many deep-water depositional system example; Offshore Angola, Offshore Brazil, GOM, the North Sea basin and the Eastern Mediterranean (Clark & Cartwright, 2011; Davison, 2004; Gee & Gawthorpe, 2006; Jackson et al., 2014; Oluboyo et al., 2014; Rodriguez et al., 2019). Local topography created by salt diapirs has been documented to be the dominant control on deep-water depositional systems. These structural features often divert, deflect, confine and dictate the course of deep-water depositional system (Davison, 2004; Kane, Mcgee, et al., 2012; Mayall et al., 2006, 2010a; Prather, 2003). The relationship between deep-water depositional system and the pre-existing salt diapirs often determine the distribution of reservoir facies and their internal architecture (Mayall et al., 2010b).

The syn-and-post-depositional influence of salt diapirs on deep-water depositional system has been widely documented by several authors, using a robust database of subsurface data (Gee & Gawthorpe, 2006; Kane & Pontén, 2012; Mayall et al., 2010b; Oluboyo et al., 2014; Rodriguez et al., 2019). This

research project provides a study of the distribution, and description of the internal architecture of sediment gravity deposits around salt diapirs using core dataset from an over 10 km long, salt diapir confined and controlled, upper Palaeocene deep-water system. Our study contrast with studies done with subsurface dataset (example seismic reflection data) having little or no core (lithology) controls. Here, we present a study on the interaction between the upper Palaeocene deep-water depositional system and the Triassic-aged salt diapirs using core dataset from the U.K Central North Sea. We aim to (i) establish the distal architectural response of deep-water depositional system to salt diapirs (ii) discuss the vertical and lateral facies variability within sediment gravity deposit in salt diapir influenced setting; and (iii) discuss the implication of salt diapirs in controlling the upper Palaeocene deep-water depositional system in the Central North Sea.

5.3 GEOLOGICAL SETTING AND TECTONOSTRATIGRAPHIC FRAMEWORK OF THE CENTRAL NORTH SEA PALAEOGENE

The study location is within Quadrant 22 and 23 of the Central North Sea (Figure 5.1a). The Central North Sea tectonostratigraphic evolution is related to the tectonic extension, uplift and volcanism that affected the entire North Permian Basin and North Atlantic margin (Ziegler, 1975:). The basin evolution model favours that of a rifted margin due to extensive Permo-Triassic tectonic extension. The North Sea Rift is characterised as a three-armed rift system comprising of the Viking Graben, Inner and Outer Moray Firth basins and the Central Trough (Gowers and Sæbøe, 1985; Erratt et al., 1999;). The tectonic history of the Central North Sea mirrors the structural fabric of the entire North Sea basin. From the Triassic to the Permian, the North Sea is characterised by regional extension and Zechstein evaporate sequence deposition (Hodgson et al., 1992;). The Jurassic and Cretaceous time show active faulting towards the proto North Atlantic (Errat, 1993; Erratt et al., 1999:). Thermotectonic sag and basin inversion was recorded across the entire NW Europe with the thermal sagging becoming punctuated throughout the Central North Sea in the Tertiary (Ziegler, 1975).

The stratigraphy of the Palaeocene Central North Sea is shown in (Figure 5.1b). Originally proposed by (Deegan and Scull, 1977;), the Palaeogene stratigraphic framework of the Central North Sea has been modified by many authors using biostratigraphy, well and seismic correlation (Stewart, 1987; Knox and Holloway, 1992; Mudge and Copestake, 1992b, 1992a; Den Hartog Jager et al., 1993;). The lithostratigraphic unit within the Palaeogene comprises of the Montrose and the Moray Group (Knox and Harland, 1979; Knox et al., 1981; Knox and Holloway, 1992; Mudge and Copestake, 1992b, 1992a;). Because this study is focused on the Forties fan system, emphasis will be made on the Forties stratigraphic unit. The Forties Sandstone (Thenetian – Ypresian) forms the older unit within the Sele Formation. It overlies the older Lista Formation (Selandian – Thenetian) and forms one of the discrete fan system in the Central North Sea (Knox and Holloway, 1992; Mudge and Copestake, 1992a; Hempton et al., 2005;). Based on biostratigraphy, sequence stratigraphy and associated well data, the sand presence and thickness maps of these fan system have been published (Stewart, 1987; Mudge and Copestake, 1992a; Den Hartog Jager et al., 1993;). The Forties has a Northwest/West provenance, depositing sediments in the basin floor and topographical lower area of the Central Graben and the South Viking Graben (Kilhams et al., 2012;). In the Central Graben, the Forties forms a thick, southeasterly-trending lobe with a sheet-like geometry. The stratigraphic architecture of the Forties fan is dominated by stacked channel sandstone heterolithic and basin floor mudstone respectively. More recently, (Haughton et al., 2003; Davis et al., 2009; Haughton et al., 2009;) document that, the internal architecture of the Forties shows thick succession of co-genetic and linked-debrites herein referred to as hybrid event beds (*sensu* Haughton et al., 2009;).

5.4 DATASET AND METHODOLOGY

The study is based on sedimentological investigation of core data drawn from two hydrocarbon producing fields (Merganser and Scoter) located along the distal margin of the East Central Graben (Figure 1a). Merganser field (two cored wells: 22/30a-7, and 22/30a-14z with total cored thickness of 210 ft (64 m)) is located on the flanks of the Merganser diapir and Scoter field (two cored wells: 22/30a-5 and 22/30a-9 with cored thickness of 583 ft (178 m)) is located on the crest of the Scoter diapir respectively (Table 5.1). In total, 793 ft (242 m) thick core was utilized for this study.

Sedimentary features were examined in detail using graphic log on a scale of 1 cm to represent 2 ft. This high-resolution logging scale was used to investigate in great details, the bed-scale sedimentology of sediment gravity flow deposits. A standard grain size chart and hand lens was utilized to determine the maximum and minimum grains sizes. Visual inference of the colours of the rocks was used to determine the amount of disperse clay content in the rocks. Also, dilute hydrochloric acid was used to infer carbonate-rich units within the cored intervals. Markov chain analysis was used to have a good understanding of the vertical facies' variability. Previous works for example (Haughton et al., 2003; Hempton et al., 2005; Davis et al., 2009; Haughton et al., 2009; Eldrett et al., 2015;), utilizing cores provided the sedimentological framework for this studies. Emphasis was laid on grain size, sedimentary structures, and individual bed boundaries. Observation of these features allows a good understanding of flow processes and the process linkage as preserved in the sedimentary record. Despite the vertical and lateral extent of the entire Forties fan system, our dataset restricts us to a region around distal lobe fringes, which is confined by salt diapirs. This, however, allows a detail investigation of deposit type and flow processes in the distal, lobe fringes controlled by sea floor bathymetry (i.e., salt diapirs and older stratigraphy).

5.5 SEDIMENTARY FACIES

Three main facies association i.e. (i) Turbidite sandstone; (ii) Debrites and (iii) Basin floor mudstone was identified. Several sub-facies related to these three main facies association were also identified and described in the studied core interval. Table 5.2 summarises the description and interpretation of the facies identified within Forties Sandstone.

5.5.1 TURBIDITE SANDSTONE FACIES

These facies comprise of four subfacies namely, massive structureless sandstone; massive structured (dewatered and dish structure) sandstone and banded sandstone facies (Figure 5.2)

5.5.1.1 MASSIVE STRUCTURELESS SANDSTONE FACIES (A1)

Description: These facies are dark brown to beige in colour. Their grain size varies from very fine grain ($>62\ \mu\text{m}$) to coarse grain ($<800\ \mu\text{m}$), with a framework mineralogy consisting of ($>85\%$) quartz, ($>8\%$) lithic fragment and ($<7\%$) feldspar. These facies are generally clean, having a relatively low ($<20\%$) clay content. The grains are sub rounded to sub angular, compositionally immature and they exhibit poor to moderate sorting. The thickness of this facies ranges from $<1\text{ft}$ to $>30\text{ft}$. They show minor distribution of intra-formational rip-up mud clast. The structureless sandstone facies exhibit a tabular geometry and are characterised by sharp to gradational bed contacts with the underlying and overlying beds. There is a general absence of both primary and secondary sedimentary structures.

Interpretation: Due to the massive nature of this facies and the general absence of sedimentary structures, this structureless sandstone facies are interpreted to be deposited by aggradational suspension fallout from turbulent flow (Baas, 2004; Mulder & Alexander, 2001; Mutti & Ricci Lucchi, 1978; Stow & Johansson, 2000; Talling, 2012, 2013). Also, the general lack of sedimentary structures

suggests a rapid collapse fallout of sedimentary particles with no evident for reworking by tractional currents.

5.5.1.2 MASSIVE STRUCTURED (DEWATERING (A2) AND DISH STRUCTURED (A3)) SANDSTONE FACIES

Description: These facies are dark brown to beige in colour. Their grain size varies from very fine ($>62\ \mu\text{m}$) to fine grain ($<200\ \mu\text{m}$), with a framework mineralogy like the associated structureless facies i.e., consisting of ($>85\%$) quartz, ($>8\%$) lithic fragment and ($<7\%$) feldspar. However, we noticed variable modal distribution of minerals. These facies are generally clean having a variable ($>20\% - <30\%$) clay content. The grains are sub rounded to sub angular, compositionally immature and they exhibit poor to moderate sorting. They occurred either as standalone dewatered sandstone facies, dish-structured sandstone facies or they occur together within the same unit. The thickness of this facies ranges from $<1\text{ft}$ to $>30\text{ft}$ when it occurs as dewatered sandstone facies and $<1\text{ft}$ to $>20\text{ft}$ when it occurs as dish-structured facies. They show minor distribution of intra-formational rip-up mud clast. Like the structureless facies, the structured sandstone facies exhibit a tabular geometry and are characterised by sharp to gradational bed contacts with the underlying and overlying beds. Secondary sedimentary structures were observed i.e., dewatering pipes, and dish structures and provided bases for the interpretation.

Interpretation: Because of the general presence of sedimentary structures observed in this facies, they are interpreted to be deposited by a rapid suspension fallout from turbulent flow with the sandstone still having some initial fluid and an unconsolidated nature prior to subsequent depositional process (Mutti and Ricci Lucchi, 1978; Stow and Johansson, 2000; Mulder and Alexander, 2001; Baas, 2004; Talling, 2012;). The deposition of the denser overlying units squeezes out the fluid trapped within these facies during deposition.

5.5.1.3 BANDED SANDSTONE FACIES (A4)

Description: The banded sandstone facies are generally characterised with alternating light and dark bands. The grain size varies from $>0.06 - <63\ \mu\text{m}$, and they are $<1\ \text{m}$ thick. The lighter band show cleaner, sandstone with characteristics loading structures on the underlying darker band while the darker bands show argillaceous mudstone or muddy sandstone. Except for the loading structures, no sedimentary structures were observed in the banded sandstone facies. Similar facies was observed in the Cretaceous Britannia sandstone slurry flow deposit (Lowe and Guy, 2000;) however, they appear to be thicker ($>10\ \text{m}$), containing both primary and secondary sedimentary structures.

Interpretation: The banded sandstone facies are attributed to flows transitional between fully laminar (cohesive debris flows) and fully non-laminar flows (turbulent flows) (Lowe and Guy, 2000; Houghton et al., 2003;). They are characterised with episode of near bed turbulent flow dampening. Based on the classification criteria of (Lowe and Guy, 2000;), we further interpreted the banded sandstone facies as megabands (thickness exceeds $50\ \text{cm}$) and arenaceous banded sandstone facies (lighter component of the band are thicker)

5.5.2 DEBRITES FACIES

These facies comprise of two subfacies namely, muddy debrite facies and reworked chalk debrite facies (Figure 5.3)

5.5.2.1 MUDDY DEBRITE FACIES (D1)

Description: Muddy debrites are dark coloured, poorly sorted, argillaceous siltstone or argillaceous sandstone deposits in which the grains are mud supported (Figure 3). Their thickness ranges from (< 0.6 m – 3 m) and they comprise of variable amounts of lithic and mud clast fragments which show no preferred orientation. Internally, these deposits are sheared and deformed, and they also show minor loading structures and greenish (chlorite?) bands.

Interpretation: Loading structures suggests density variability within the flows which deposited the debrite. The greenish (chlorite) bands or clast suggest either the sediments are mineralogically immature or a possible illitization of clay minerals. Muddy debrites are interpreted to be deposited by en-masse freezing of debris flows (Davis et al., 2009a; Haughton et al., 2003) or localised mass wasting around salt diapirs.

5.5.2.2 REWORKED CHALK DEBRITES (D2)

Description: Chalk debrites are whitish to dark coloured, internally deformed deposit (figure 5.3). They contain greenish mineral and whitish clast fragment (1mm - <30 mm). Their thickness ranges from (0.30 m – 2 m) and they show internal banding and shearing.

Interpretation: We interpret this deposit as reworked chalk deposit because of their reaction with hydrochloric acid. The presence of greenish minerals and mud clast could suggest in situ remobilization typically around a bathymetric feature.

5.5.3 BASIN FLOOR MUDSTONE FACIES

Description: Basin floor mudstone facies are dark coloured, massive, or laminated (fissile) very fine (<62 µm) claystone deposit up to 4 m thick (Figure 5.4). No sedimentary structure, bioturbation or lithic fragment was observed. They however show variable colours i.e., dark brown (when oxidised), and greenish colour. This unit occurs in association with other sediment gravity flow deposit or reworked chalk, and they show sharp or gradational contact with the underlying and overlying units.

Interpretation: Basin floor mudstone facies are interpreted as background mudstone deposit that settles out of waning turbidity current in a low energy condition. This deposit could also be associated with flows responsible for the deposition of the underlying debrites or amalgamated sandstone facies (Talling, 2004, 2012;). The lack of bioturbation could suggest anoxic basinal conditions.

5.5.4 HYBRID EVENT BED

Hybrid event beds are considered as the deposit of a single gravity-driven event (Figure 5.5). The beds generally display a bipartite association i.e. (an upper mud rich debrite and a lower turbidite succession) or a tripartite association i.e. (an upper thinly bedded low density turbidite, a middle mud rich debrite, a lower turbidite succession). A complete event beds within the Forties fan in the studied location has thickness range of between <0.6 m and 5 m.

Description: Hybrid event bed are thin to thick bedded (>0.4 m – 5 m) units and they comprise of a lower turbidite rich unit, a transitional middle unit and mud rich upper debrite unit (Figure 5.5). The upper debrite units are <0.3 m – 0.6 m thick and could either be (i) a poorly sorted, dark coloured, argillaceous sandstone with internally sheared and deformed framework and comprises of mud clast fragments or (ii) a poorly sorted, argillaceous mudstones or siltstone unit which contain larger clast fragments within muddy matrix. The fabrics within the upper unit show no preferred orientation and they are characterised with a patchy (i.e., having larger clast fragment within finer matrix) architecture. The upper debrite unit show either a gradational or sharp bed contact. Sand injection,

loading structures and dewatering pipes is observed mostly at the base of the Upper debrite unit. The middle unit consist of a transitional banded sandstone facies. Here preferred orientation of the mica minerals in observed. An alternation of light coloured, and dark coloured minerals was observed. They mostly occur as thin laminae, usually less than (<0.09 m) thick. The lower turbidite unit are <0.3 m – 2.1 m thick, poorly – moderately sorted, beige colour, very fine to fine grained sandstone. They could both be (i) massive, structureless sandstone unit, (ii) massive, dewatered sandstone unit (iii) massive sandstone with dish structures and (iv) sandstone unit showing both dewatering and dish structures. The sandstone unit show the same framework mineralogy as the turbidite sandstone facies. They also show some mud clast and lithic fragment. The boundaries between the lower turbidite and the upper debrite can either be gradational or sharp. It is mostly gradational when the lower turbidite unit transitioned into banded sandstone unit. When the lower turbidite is overlain by the upper debrite without the intervening banded sandstone unit, it's mostly sharp bed boundaries. Depending on the thickness of the upper debrite and lower turbidite unit, the hybrid event bed can be classified as argillaceous or sand rich event beds.

Interpretation: The poor sorting, lack of prefer orientation of clast and mica minerals and the presence of large clast within an argillaceous mudstone matrix suggest that the upper division is deposited from a cohesive debris-flows (Hodgson, 2009;). Also, internal deformation, and shearing of the upper debrite unit suggest bulking and en masse freezing of a cohesive debris-flows (Amy et al., 2009;). There are several theories for the deposition of the transitional banded sandstone unit. However, their occurrence within hybrid event beds suggest deposition from flows transitional between non cohesive, turbulent flow and cohesive, debris-flow (Lowe et al., 2003;) (Figure 5.9). The poor sorting, textural immaturity, and massiveness supports the mechanism of a rapid suspension fallout from high density turbidity currents (Haughton et al., 2009;). Sedimentary structures i.e., dewatering pipes and dish structures suggest soft sediment deformation which implies that the lower turbidite unit was still wet and unconsolidated when the cohesive component of the flow was depositing.

5.6 FACIES HETEROGENEITY WITHIN THE UPPER PALAEOCENE DEEP-WATER DEPOSITIONAL SYSTEM

5.6.1 VERTICAL FACIES HETEROGENEITY

The Forties fan show a vertical facies transition with high or low density turbidite sandstone overlain by debrites and in some cases, basin floor mudstone (Figure 5.7). We determined the vertical facies arrangement using facies transitions observed on the lithology logs. Using the logs, 7 facies (grouped into 3 facies association) were observed and analysed for vertical facies relationship (Figure 5.6). The facies are massive structureless sandstone, dewatered sandstones, dish structured sandstones and banded sandstone facies (all these facies formed the turbidite sandstone facies association), muddy debrites, and reworked chalk debrite forms the debrite facies association whiles the massive and laminated mudstone facies form the basin floor mudstone facies association. We employed a statistical approach by utilizing Markov chain analysis (Figure 6) to test facies recurrence (either random or common) within the Forties Sandstone. Our aim of using Markov chain analysis was to have a good understanding of the vertical facies' variability.

The vertical facies transition deduced from the transition diagram shows that, in general, the massive structureless sandstone are overlain and (underlain in some instances) by the muddy debrite facies (D1) and basin floor mudstone facies (BM). Upward transition from the massive structureless sandstone facies (A1) to banded sandstone (A4) or reworked chalk debrite (D1) are uncommon. The massive structureless sandstone facies (A1) are more commonly overlain by either dewatered sandstone facies (A2) or overlain and underlain by dish structured sandstone facies (A3), muddy

debrite (D1) or basin floor mudstone (BM). Where the massive structureless sandstone facies (A1) are overlain by dewatered sandstone facies (A2), these commonly pass vertically into either muddy debrite (D1) or reworked chalk (D2). Where the massive structureless sandstone facies (A1) are overlain by dish structured sandstone facies (A3), there is no vertical transition into either of the debrite facies. Thus, the vertical facies transition shows a strong association between the turbidite sandstone facies, the debrites and the hemi pelagic mudstone facies. It should be noted however that, no facies observed within the Forties sandstone rarely occur as stand-alone facies.

A test of significance was applied to determine whether the facies transition relationship generated by the sedimentary processes is random or common. This was made possible by using Chi-square (χ^2) test (Figure 5.6b). A null hypothesis (H_0) was proposed which assumes that the facies transition was random rather than common. Chi-square test is used to either reject or uphold the null hypothesis. The degree of freedom (DF) for this analysis is calculated to be (36^0) . Taking the 7 facies used in this analysis, from the Chi-square table, we used a limiting value of 90% confidence level to determine the Chi-square (χ^2) value at (36^0) DF to be 47.21. Because the Chi Square computed from the probability matrices (221.62) is higher than Chi square at 36^0 degree of freedom and at 90% confidence level, the H_0 hypothesis was rejected which implies that the facies relationship reflects a common rather than random sedimentary processes.

The composite beds within the Forties fan (Figure 5.7a) is composed of a basal thin to thick bedded turbidite sandstone facies (A1 – A3), a transitional (A4 with a rare occurrences), and an overlying (D1) linked debrite or (BM) basin floor mudstone *sensu* (Haughton et al., 2009;). In the studied cored interval, the vertical relationship shows a dominance of basal H1 facies overlain by H3 facies. H4 of a composite event beds of (Haughton et al., 2009;) are likely not deposited or preserved within the stratigraphic records. Generally, the H1 facies could be >8 m thick and consist of a massive sandstone facies with or without dewatering pipes and dish structures.

The contacts between the underlying turbidite and the overlying debrite or basin floor mudstone is either (i) gradational with a general upward fining grain size relationship i.e., a general increase in mud content or (ii) sharp with a well-defined grain size break. Some sharp bed contacts also show undulose relationship which is often associated with sheared clastic dykes or sills (injectites) which could be up to 0.15 m (in height) and <0.03 m (in width).

The synthesis from this analysis points to the fact that flow transformation is a major process that shaped sediment transport and deposition in the Central North Sea. The vertical facies association show that the basal facies are turbidite deposited from the initial turbidity currents. The later phase of the flow must have transformed as evidenced from the transition into debrite facies. The waning part of the flow is indicated by the capping deposition low energy deposit of basin floe mudstone. This relationship can be seen in well 22/30A-9 (Figure 7B) from the Merganser field. The presence of the chalk debrite suggest the possibility of a localised slumping of reworked cretaceous chalk into the Forties Sandstone.

5.6.2 LATERAL FACIES HETEROGENEITY

The Forties Sandstone as previously discussed, is characterised by complex internal facies architecture. For better visualization, a pie chart plot of the cored intervals was done to show facies distribution in each cored well (Figure 5.8A). The pie chart shows that, in all the wells, there is a common occurrence of turbidite (massive structureless, dewatered and dish structures sandstone), muddy debrite and hemi pelagic mudstone. There is also a common variation in thickness of the facies with the turbidite being the thickest facies followed by the muddy debrite and the hemi pelagic mudstone. This assertion was validated by the total thickness facies pie chart in (Figure 5.8A).

Having looked at the facies distribution in each well in pie chart plot, this observation is utilised to highlight the lateral change in facies character of sediment gravity flow deposit within a variety of distance (<1 km to >2.5 km) taken along the dip section of the Forties fan fairway (Figure 5.8D). The distribution and thickness of high density turbidites, and linked debrite i.e., composite hybrid event beds were described. Starting from the wells around Merganser (to the west of the study interval), we observed a composite bed with thick basal turbidite (A1-A3) and thin linked debrite (D1). Within approximately 2.975 km, there is a local increase in the thickness and the distribution of the linked debrites. The Reworked chalk are not laterally continuous and are mainly distributed around Merganser fields with also few occurrences around Scoter. Further down to the wells around Scoter fields (to the East of the studied location), there was a general decrease in the thickness of high density turbidite (A1-A3). Here, the composite bed shows a dominance of linked debrites. A3 facies show variable thickness while the linked debrite and basin floor mudstone show an increase in thickness and distribution.

General interpretation of these facies shows similar internal architectures and bed contacts but a variable facies thickness and distribution towards the Scoter fields. GR log correlation of cored intervals show the increase in facies variability from wells drilled on the flanks of the diapir to the wells located in confined depocenters for example increasing variability from 22/30A-14z to 22/30A- and 22/30A-9 (Figure 5.8E). This could result from the bathymetric effects of salt diapirs. We believe that Forties sandstone were deposited in syndepositional low (confined depocenters) created by the movement of the Merganser and Scoter salt diapirs respectively. The variable distribution of the facies within the upper Palaeocene deep-water depositional system (See Figure 5.8A) could be related to the complex interaction with salt diapirs.

5.7 STRATIGRAPHIC DISTRIBUTION AND ARCHITECTURE OF THE UPPER PALAEOCENE DEEP-WATER SYSTEM IN RESPONSE TO SALT DIAPIR

The upper Palaeocene deep-water depositional system is vertically and laterally extensive. There are however bathymetric features (salt diapir) which control its distribution and facies variabilities. Several facies have been documented within Forties sandstone i.e. turbidites, heterolithics, mudstones, linked debrites and hybrid event beds (Haughton et al., 2003; Hempton et al., 2005; Davis et al., 2009b; Haughton et al., 2009; Eldrett et al., 2015;). Based on the accounts of previous works, we placed the deposit of the Forties fan in the study location, within their stratigraphic context. The turbidite sandstones, linked debrites and basin floor mudstone facies are similar in thickness and distribution to the units described around Everest, Lomond and Pierce fields (Haughton et al., 2003; Haughton et al., 2009;). The sandstone facies within the distal sheets or lobe fringes could either be structureless or consist of dewatering pipes and dish structures. These beds are dominantly clean (mud poor) with a little proportion of dirty (mud-rich) sandstone. They are characterised by coarsening upward or fining and thinning upward units. The core photograph from the study location shows different stacking patterns (i.e., thickening and thinning upwards) are shown in (Figure 5.7). These facies typically show high density turbidite (amalgamated) sandstone facies with a thin or (lacking) debrite caps and rarely show basal erosional structures. The overall finer grain size (fine to very fine grained) in the high density turbidite sandstone facies, the lack of erosional features at the bases of this depositional elements and the nature of the deposits within these facies (i.e., massive structureless or dewatering pipes and dish structures), supports our non-channelized and tabular (massive) interpretation. The upward thickening or coarsening within this depositional element suggest a progradation of sheet sandstones with the more distal, fan fringe deposit underlying the units' representing periods of sheet sands retrogradation. Because this study is core based, and is characterised by numerous salt diapir control, huge uncertainties exist as most of our deduction are inferred from core observation. The temporal and spatial variation in the energy of sediment gravity-

flow, the volume of the transported sediment and the possible lobe stacking or avulsion could account for the vertical and lateral facies variability within this facies (Kneller, 2003; Amy and Talling, 2006; Deptuck et al., 2007; Hodgson, 2009; Prelat and Hodgson, 2013; Hodgson et al., 2016).

The key features that highlight the stratigraphic response of the upper Palaeocene deep-water depositional system to salt diapirs are (i) secondary sedimentary structures i.e., dewatering pipes, dish structures, slumping and (ii) mechanical features i.e., high angle dipping sandstone intrusion (injectites), and oxidized quartz vein. The secondary sedimentary structures are post depositional in origin. Dewatering pipes and dish structures are soft sediment features that results from the rapid deposition of sediment retaining a huge amount of connate fluid. Density contrast between the individual sandstone, siltstone and mudstone beds leads to the trapped fluids moving upward in the form of dykes and pipes and dish. Whether or not these features are directly linked to the existing salt diapirs remains a challenge. However, we believe that, because salt features obstruct the flow path of the sediment routing, the sudden availability of accommodation space and the rapid slumping and shading of unconsolidated sediment from the crest and flanks of the diapir during ascend into the depositional low (minibasins) results in the complex architecture.

5.8 DISCUSSION

5.8.1 INFLUENCE OF SALT DIAPIRS

Structural features i.e. mobile substrates example salt diapirs, have been established to control submarine sedimentary systems in many deep-water setting for example; Offshore West Africa, Angola and the Gulf of Mexico (Doughty-Jones et al., 2017; Gee & Gawthorpe, 2006; Kane et al., 2012; Mayall et al., 2010a; Oluboyo et al., 2014; Posamentier & Kolla, 2003; Rodriguez et al., 2019). In the Central North Sea, the interaction between actively growing salt diapirs, older fault fabrics, and pre-existing stratigraphy with submarine sedimentary systems, is the primary control on the Palaeogene sedimentary architecture and distribution. The Forties fan system flowed in south-eastern to eastern direction and were largely deposited around downbuilding salt diapirs in the Central Graben (Davison et al., 2000; Davison, 2004; Jones and Davison, 2014;). Several studies have highlighted the influence of salt diapirs in controlling the upper Palaeocene deep-water system by either deflecting, diverting or ponding/confining sediment gravity deposit (Davison, 2004; Eldrett et al., 2015; Johnson, Leslie et.al., 2005).

Around Merganser field where the salt diapir show a syn-depositional relationship between the growing salt diapir and the sediment gravity deposit, well 22/30A-14Z (Figure 5.7) showed steeply dipping dewatering structures and high angle shearing. This suggest that the diapir was still active and the Forties fan was either diverted, slumped, and rotated by the Merganser diapir in a rapid but fluid, unconsolidated form. The mechanical features i.e., sheared high angle sandstone injection and oxidized quartz vein are a direct response to the mechanical influence of salt diapirism. The soft sediment structures are sheared and are dip at a high angle (i.e., $>35^{\circ}$) suggesting a rotational effect of salt diapirs. The oxidized quartz vein infilled suggest a series of radial and concentric fault that impacted the stratigraphy.

Around Scoter field where the diapir growth was arrested and the diapir topography was subsequently subdued by the Upper Cretaceous and Palaeocene stratigraphy, the thickness of the Forties Sandstone as recorded in the wells (Figure 5.7), was within a uniform range from the crest to the flank of the diapir. It is possible that the Cretaceous Chalk deposit of the Ekofisk Formation must have acted as a strong resistance to the diapir growth. Little or no impact on the flow path of the Forties fan was created by the Scoter diapir. However, (Charles & Ryzhikov, 2015; Davison, 2004) show that, the

Palaeocene turbidite appears to thin on the crest of Scoter diapir. This usually result in rapid lateral changes in facies geometry and distribution. Based on our analysis of core data, the sedimentary fabrics and structures of the Forties Sandstone suggest that the Forties Sandstone was deposited in a rapid and unconsolidated fashion. Because of the syn-kinematic relationship between the Forties fan system and the growing salt diapirs, slumping of unconsolidated sediments occurs on flanks of this diapir due to local gradient changes. Soft sediment structures example slump folding and faulting, injectites, and shearing of poorly consolidated sediments was observed in the Forties Sandstone deposit around Merganser diapir. Slide blocks of older stratigraphy (Lista Formation) was documented by (Charles and Ryzhikov, 2015;) to occur within the deposit of Forties on the flanks of Merganser diapir. Though rare in occurrences, thin unit of chalk debrite have been cored in some wells in the study location. The nature of the chalk clast suggests a reworked Cretaceous chalk that was uplifted by the growing diapir and subsequently remobilised and redeposited as chalk debrite down the flank of the diapir. Numerous occurrences of chalk debrite was recorded in the Central North Sea example Machar, Jenny and Kyle fields (Davison, 2004; Ward et al., 2012;).

Our deduction from the interaction between actively growing salt diapirs, and salt related topography with the depositional system show that, local gradient changes created by salt related topography, exerted a major control on the distribution of the facies, facies association and the stratigraphic architecture of the Palaeocene Forties Sandstone. Our work shows that, the Forties fan system evolved originally as an initial high-density turbulent flow that along the flow length, transformed into a flow with turbulent and debris flow component (Figure 5.9). On the basin floor where there are topography and structural features created by salt diapirs, the flow path and depositional fate of the Forties fan was hugely controlled by these features resulting in the deposition of fan-lobes (Figure 5.10). Local flow mixing of the originally transformed turbulent gravity flow by radial fault and the diapir walls resulting from flow diversion and deflection also exert a complex relationship on the facies architecture.

5.8.2 COMPARISON WITH OUTCROP-BASED SEDIMENTOLOGICAL STUDIES

Sediment gravity deposits have been well studied in outcrop exposures in the Gottero Sandstone, North-west Italy (Fonnesu, Felletti, Haughton, et al., 2018;), Miocene Marnosa-arenacea Formation in the Northern Italian Apennines (Talling, 2012), the Permian Skoorsteenberge Formation in the Karoo Basin, South Africa (Hodgson, 2009) and the West Crocker Formation, Sabah, NW Borneo (Jackson et al., 2009), the Basque-Cantabrian Basin, Pyrenes (Cumberpatch et al., 2021; Roca et al., 2021). These outcrop case studies provided a thorough account of the architecture of sediment gravity deposit. In all these cases, sediment gravity flows will normally deposit a suite of deposit for example, linked and unlinked debrite, associated low and high density turbidite, and basin floor mudstone. It should be noted however, that the structural complexity in our study location i.e., salt diapir related topography, has not been documented in these case studies. Core based studies such as the one presented here, have been extensively utilised in the studies of sediment gravity flow deposit, allowing for detailed analysis and high-resolution description of subtle features. However, outcrop-based studies allow for larger scale analysis and description of textures, and bedding contacts traced over a long distance. (Jackson et al., 2009) show that a large (>1m) clast of shale or laminated heteroliths observed at the base of a linked debrite in the West Crocker Formation, NW Borneo could easily be misinterpreted as typical fine-grained interval separating basal turbidite and the overlying genetically unrelated debrite. Outcrop based studies also help in discriminating between insitu bedded units and reworked, exotic features for example (Hodgson, 2009;) described hybrid beds with upper carbonaceous division. (Charles and Ryzhikov, 2015;) show that, some of the mudstone unit interpreted as basin floor mudstone facies could likely be Lista slide block. Depending on core quality, such reworked, slump and slide features of older stratigraphy could likely be given a different interpretation which often

leads to incorrect description of the processes of deposition. The origin of sedimentary structures observed in cores were better understood in outcrop-based studies and their distribution within linked debrite and turbidite, were better substantiated. The interpretation of the structural implication of these sedimentary structures, provided a basis for understanding the origin, evolution, and process linkages of linked debrite and turbidite within a hybrid event bed unit.

5.9 CONCLUSION

The main conclusions of this sedimentological study of the interaction between the upper Palaeocene deep-water depositional systems and salt diapir, Central North Sea are:

- Three main gravity-flow deposits facies; (i) clean, fine to medium-grained, massive structureless to structured (i.e. consisting of dewatering pipes and dish structures), poorly-graded sandstones interpreted as the deposits of high-density turbulent gravity-flows (turbidites), (ii) clast-rich, silty mudstones interpreted as having been deposited en masse by weakly-turbulent or cohesive gravity flows (debrites) and (iii) fine grained, massive to laminated clay-rich deposit interpreted as suspension fallout (hemi pelagic mudstone).
- The turbidite facies comprises of four subfacies namely, massive structureless sandstone; massive structured (dewatered and dish structure) sandstone and banded sandstone facies. Typically, these facies are dark brown to beige in colour. Their grain size varies from very fine grain ($>62\ \mu\text{m}$) to coarse grain ($<800\ \mu\text{m}$), with a framework mineralogy consisting of ($>85\%$) quartz, ($>8\%$) lithic fragment and ($<7\%$) feldspar. These facies are generally clean, having a relatively low ($<20\%$) clay content. The grains are sub rounded to sub angular, compositionally immature and they exhibit poor to moderate sorting. The sandstone facies exhibit a tabular geometry and are characterised by sharp to gradational bed contacts with the underlying and overlying beds. Depending on the presence of soft sediment structures, we classify these facies into either structureless or structured and banded facies (based clay mineral alignment). The structureless sandstone facies are interpreted to be deposited by aggradational suspension fallout from turbulent flow. The Structured facies (consisting of dewatering pipes or dish structures) are interpreted to be deposited by a rapid suspension fallout from turbulent flow with the sandstone still having some initial fluid and an unconsolidated nature prior to subsequent depositional process. The banded sandstone facies are attributed to flows transitional between fully laminar (cohesive debris flows) and fully non-laminar flows (turbulent flows) (Lowe and Guy, 2000; Haughton et al., 2003;).
- The debrite facies comprises of two subfacies namely, muddy debrite facies, and reworked chalk debrite facies. Muddy debrites facies are dark coloured, poorly sorted, argillaceous siltstone or argillaceous sandstone deposits in which the grains are mud supported. Chalk debrite are dark grey in colour and clast supported by muddy carbonate matrix. The debrites facies are interpreted to be deposited by en-masse freezing of debris flows (Davis et al., 2009a; Haughton et al., 2003) or localised mass wasting around salt diapirs. Debrites typically overlie turbidites, with the contact between the two units being either gradational and planar or sharp and highly erosive, with upwards injection of sand from the lower turbidite interval into the upper debrite interval being common.
- The basin mudstone facies are dark coloured, massive, or laminated (fissile) very fine ($<62\ \mu\text{m}$) claystone deposit up to 4 m thick. No sedimentary structure, bioturbation or lithic fragment was observed. Basin floor mudstone facies are interpreted as background mudstone deposit that settles out of waning turbidity current in a low energy condition. The lack of bioturbation could suggest anoxic basinal conditions.
- Due to data limitations, the origin of linked debrites within the Forties Sandstone Member is not fully understood. However, based on clast size, type, and bed contacts, it seems likely that

a turbulent flow phase initially entered the basin. Flow transformation may have led to change in flow behaviour which results in the deposition of a sand-rich unit with turbidite characteristics. Ingestion of muddy material from within the flow length, may have both contributed to flow transformation. Also, local salt interaction with uplifted older stratigraphy might result in carbonate rich unit which was reworked and deposited as chalk debrite. The preservation of the linked debrite in distal lobate areas may indicate either bypass of the associated flow phase in the shelves or a local flow transformation event.

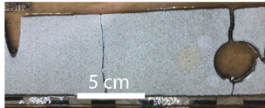
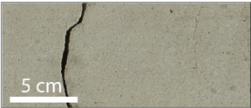
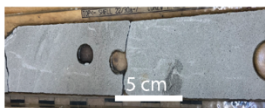
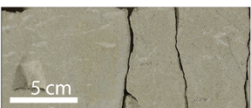
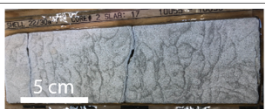
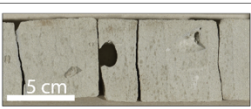
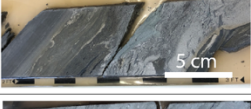
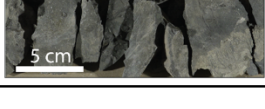
- Core-based-studies such as this provides a high-resolution description and interpretation of co-genetic turbidite-debrite facies observed in the subsurface.
- Existing salt diapirs were shown to have deflect, divert, dictate, or pond the upper Palaeocene deep-water depositional system within the minibasins (depositional low). Local slumping and sliding from the diapir flanks were also identified as the major salt induced control on the distribution and facies complexity

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Table 5. 1: Table showing the list of data available for this study. Core data and wireline log data was available for all wells except for 22/30A-7 (which has no wireline data)

List of available well data for the study									
Field	Cored Well	Biostratigraphic data	Composite log						
			CALI	SP	GR	RES	DEN	NEU	DT
Scoter	22/30A-5	<i>n</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>n</i>	<i>y</i>
	22/30A-9	<i>n</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>
Merganser	22/30A-7	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>	<i>n</i>
	22/30A-14Z	<i>n</i>	<i>y</i>	<i>n</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>	<i>y</i>
Wireline curve available: CALI = Caliper; SP = Spontaneous Potential; GR = Gamma Ray; RES = Resistivity; DEN = Density; NEU = Neutron; DT = Sonic. <i>y</i> = data available; <i>n</i> = data not available									

Table 5. 2: Various lithofacies identified within the upper Palaeocene deep-water depositional system. These lithofacies are grouped into subfacies and facies association. The core photos and depositional process of all the lithofacies within the studied interval is described

Facies Association	Facies	Core photo		Depositional process
Turbidite Sandstone	Structureless Sandstones A1			Description: Beige to light colour, very fine to fine grain size. There is a few occurrence of medium to coarse grain size. Mineral composition is quartz which is subrounded to subangular (>68%), feldspar (10%) and lithic fragment (< 1%). It appears massive with no visible sedimentary structures. Poor sorting. Interpretation: Deposited by a high density turbidity current where fallout rate suppresses the formation of sedimentary structures.
	Dewatered Sandstones A2			Description: Beige to light colour, very fine to fine grain size. Mineral composition is quartz which is subrounded to subangular (>68%), feldspar (10%) and lithic fragment (< 1%). It appears massive with visible dewatering sedimentary structures. It also show dish structures in some intervals. Poorly to moderately sorted Interpretation: Deposited by a high density turbidity current with high fallout rate trapping fluid which escape during loading or compaction.
	Dish-structured Sandstones A3			Description: Beige to light colour, very fine to fine grain size. There is no occurrence of medium to coarse grain size beds. Mineral composition is quartz which is subrounded to subangular (>68%), feldspar (10%) and lithic fragment (< 1%). It appears massive with visible dewatering sedimentary structures. It also show dish structures in some intervals. Poorly to moderately sorted. Interpretation: Deposited by a high density turbidity current with high fallout rate trapping fluid which escape during loading or compaction.
	Banded Sandstones A4			Description: Alternating dark and light coloured bands. Dark bands consist of mud rich layer while the light bands consist of lower mud content. Dark bands are thinner than the light bands. Interpretation: Deposited by a transitional flow with higher mud content at the rear of the flow followed by the light bands containing less mud content.
Debrite	Muddy debrite D1			Description: Dark coloured, clay to silty grain size, well sorted, deformed and sheared facies. Sand injectites and loading structures are observed. Have sharp or gradational contacts with underlying and overlying beds. Interpretation: Deposited by high density cohesive, laminar flow.
	Reworked chalk debrite D2			Description: Light to dark grey, clay size grains, consisting of whitish carbonate clast. Some of the pseudonodules are made of greenish mineral fragments. Interpretation: Deposited en masse by turbulent gravity flows rich in reworked carbonate by active diapirs. This is typical of reworked chalk debrite.
	Basin floor Mudstone BM			Description: Dark to dark grey coloured, clay to silt grain size, well sorted, laminated to massive facies. Interpretation: Basin floor suspension deposit or a wanning flow low concentration gravity flows which is mud laden. This facies was interpreted as basin floor mudstone.

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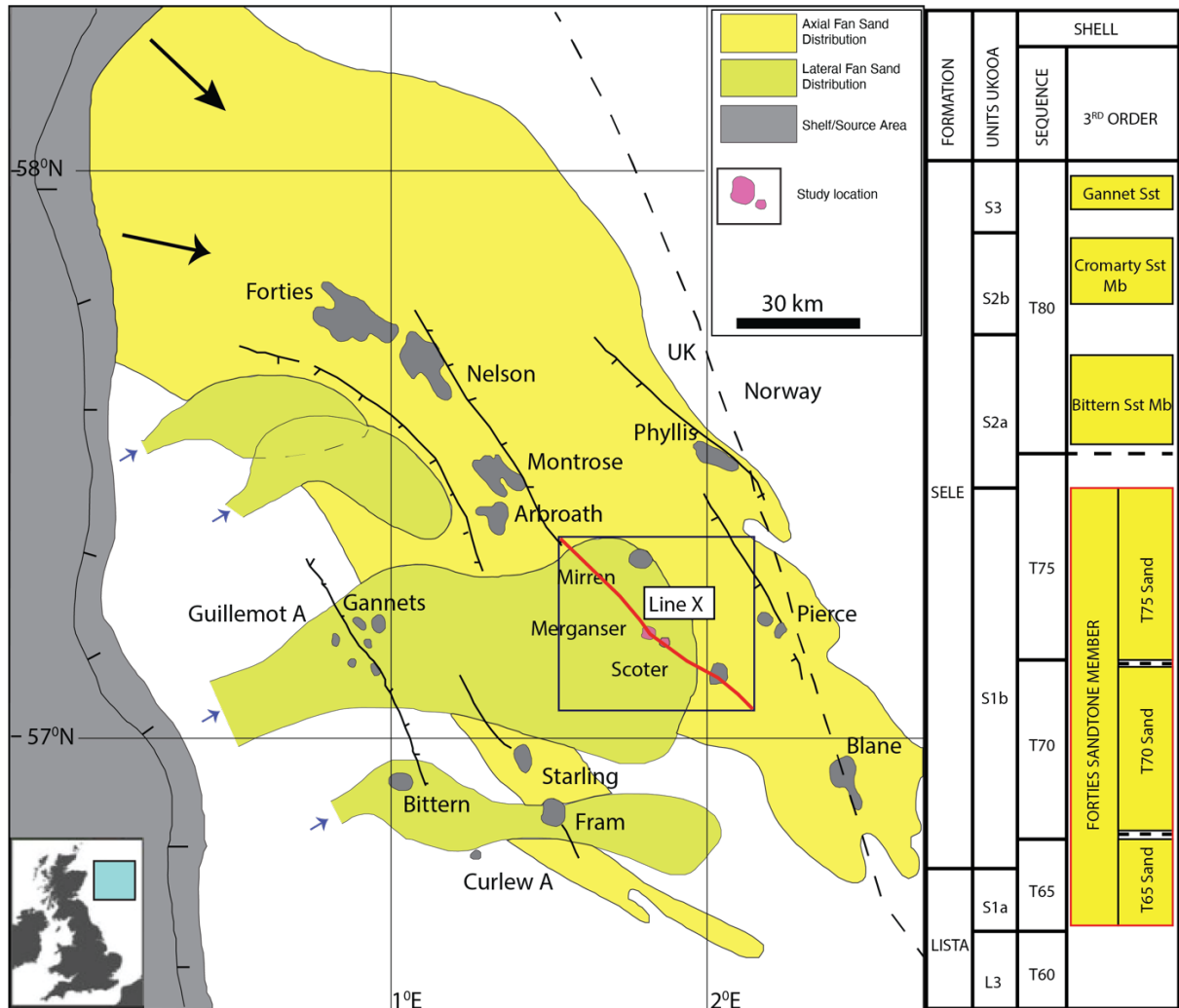


Figure 5. 1: (a) The study location shown in the black box within a wider Forties fan system represented in yellow modified after (b) Generalized stratigraphic framework for the Palaeocene Forties fan system, East Central Graben of the Central North Sea. The red box highlights the upper Palaeocene interval

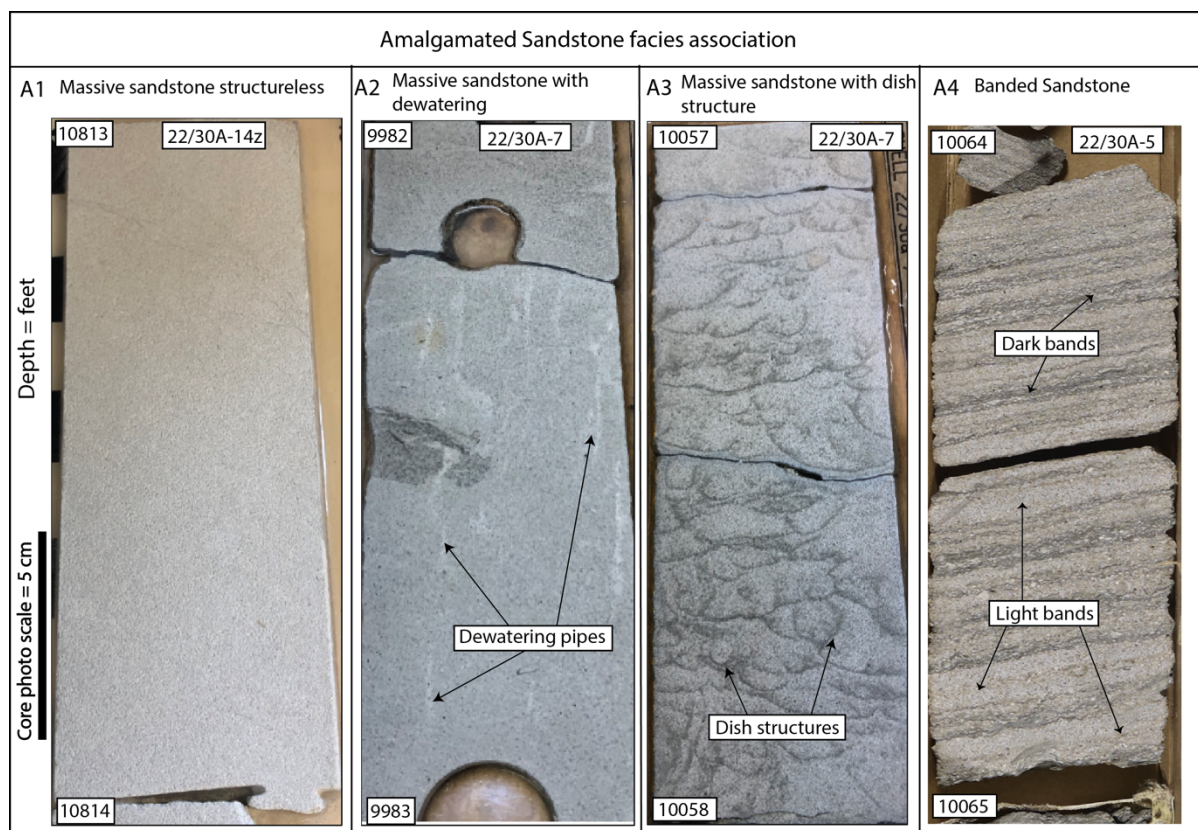


Figure 5. 2: Representative core photograph of the Amalgamated turbidite facies association. A1 represent the Massive structureless sandstone – i.e., it is massive with no visible sedimentary structures preserved. A2 represent the massive dewatering sandstone – with numerous dewatering pipes observed. A3 represent massive sandstone with dish structures, and A4 represents the Banded sandstone facies

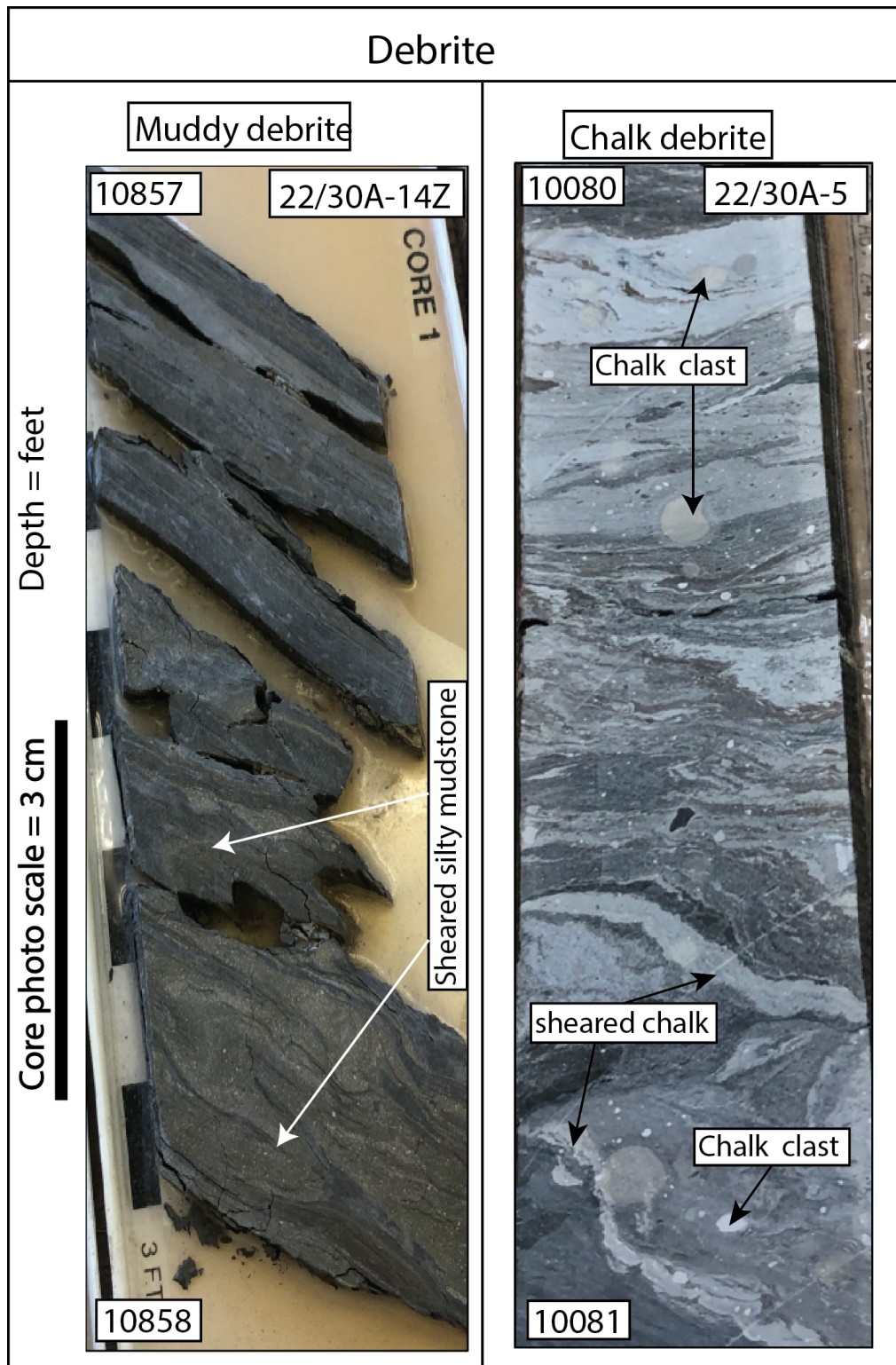


Figure 5. 3: Representative core photograph of the Debrite facies association. D1 represent the Muddy debrite – debrite variant rich in muddy matrix. D2 represent the Chalk debrite – debrite variant rich in reworked chalk matrix

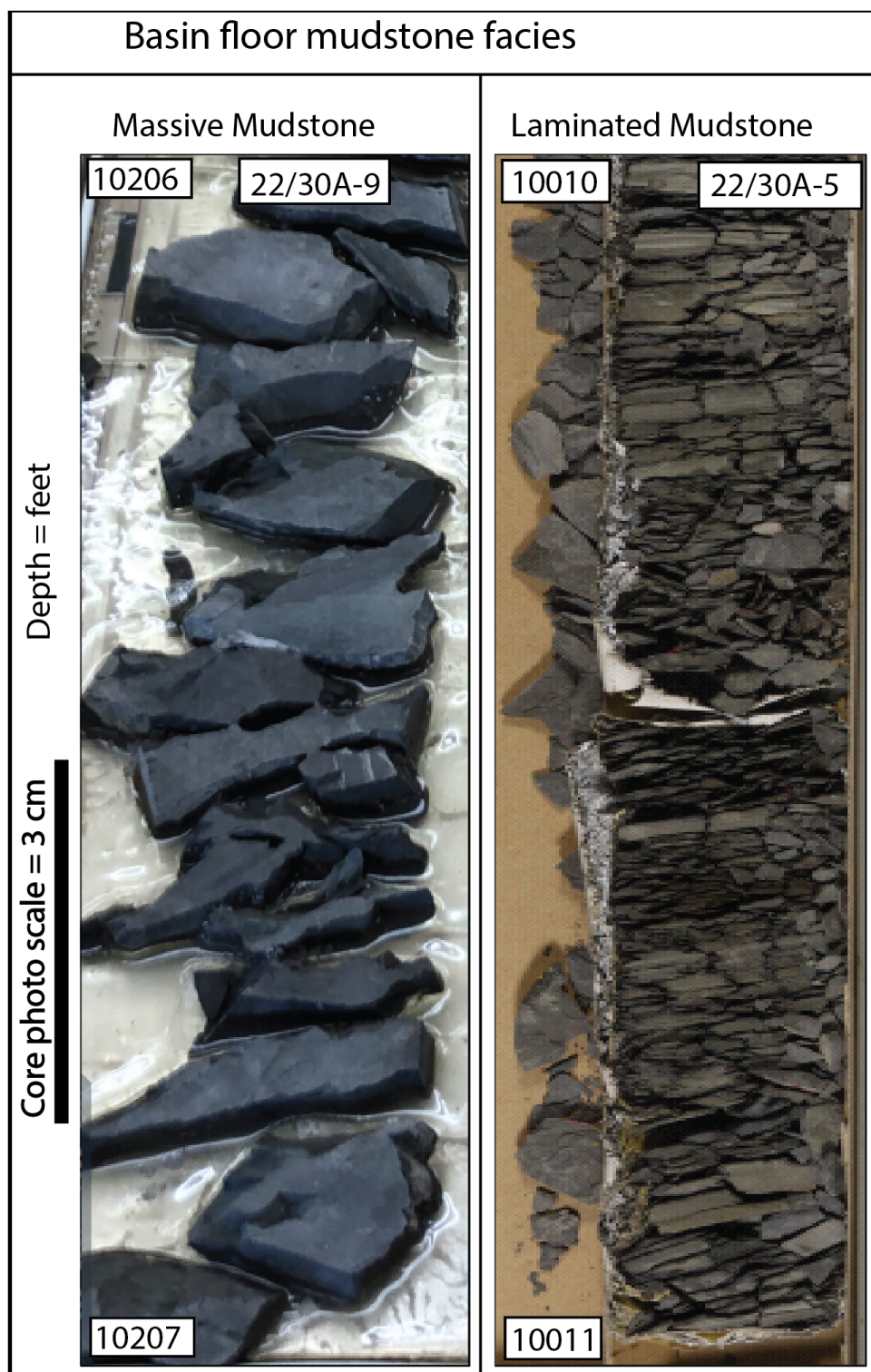


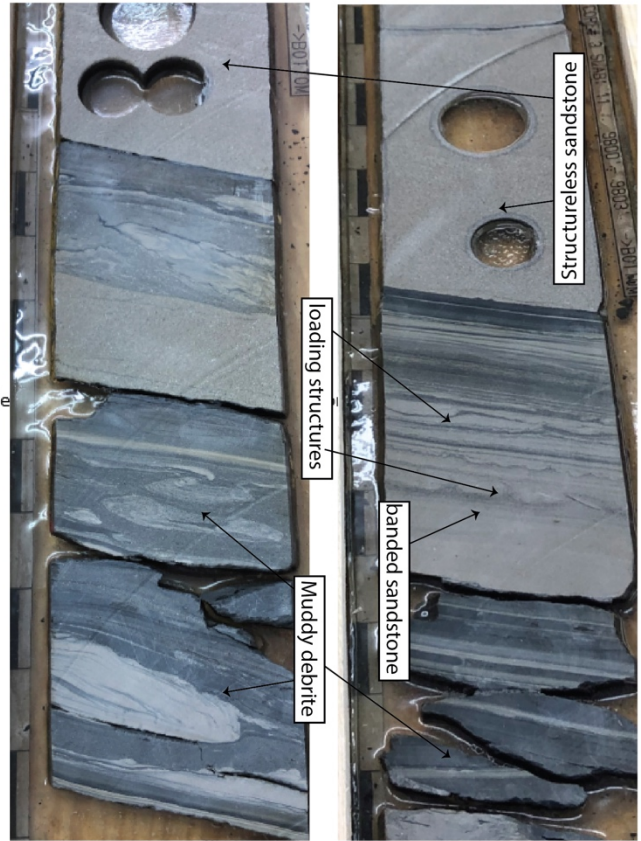
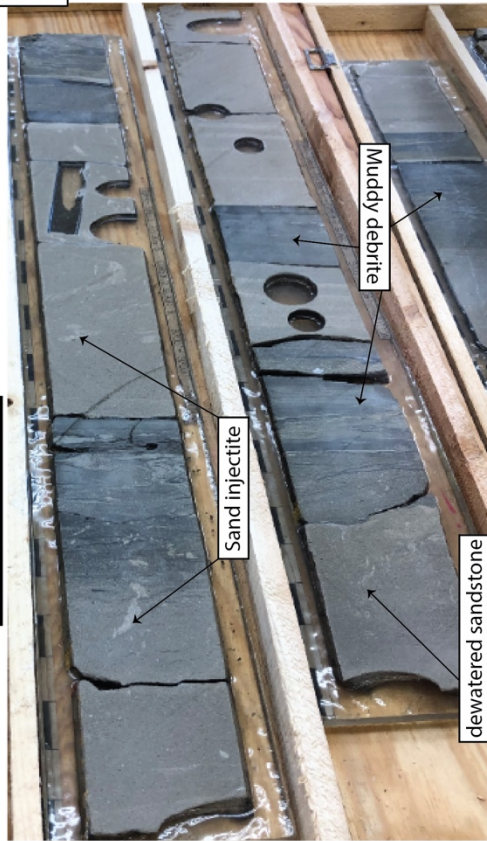
Figure 5. 4: Representative core photograph of basin floor mudstone facies association. Massive mudstone appears massive with no observed fissility, and laminated mudstone facies shows fissility

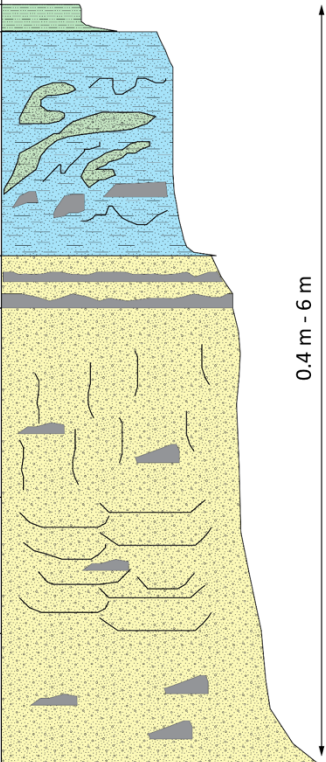
Facies distribution in hybrid event bed

22/30A-5

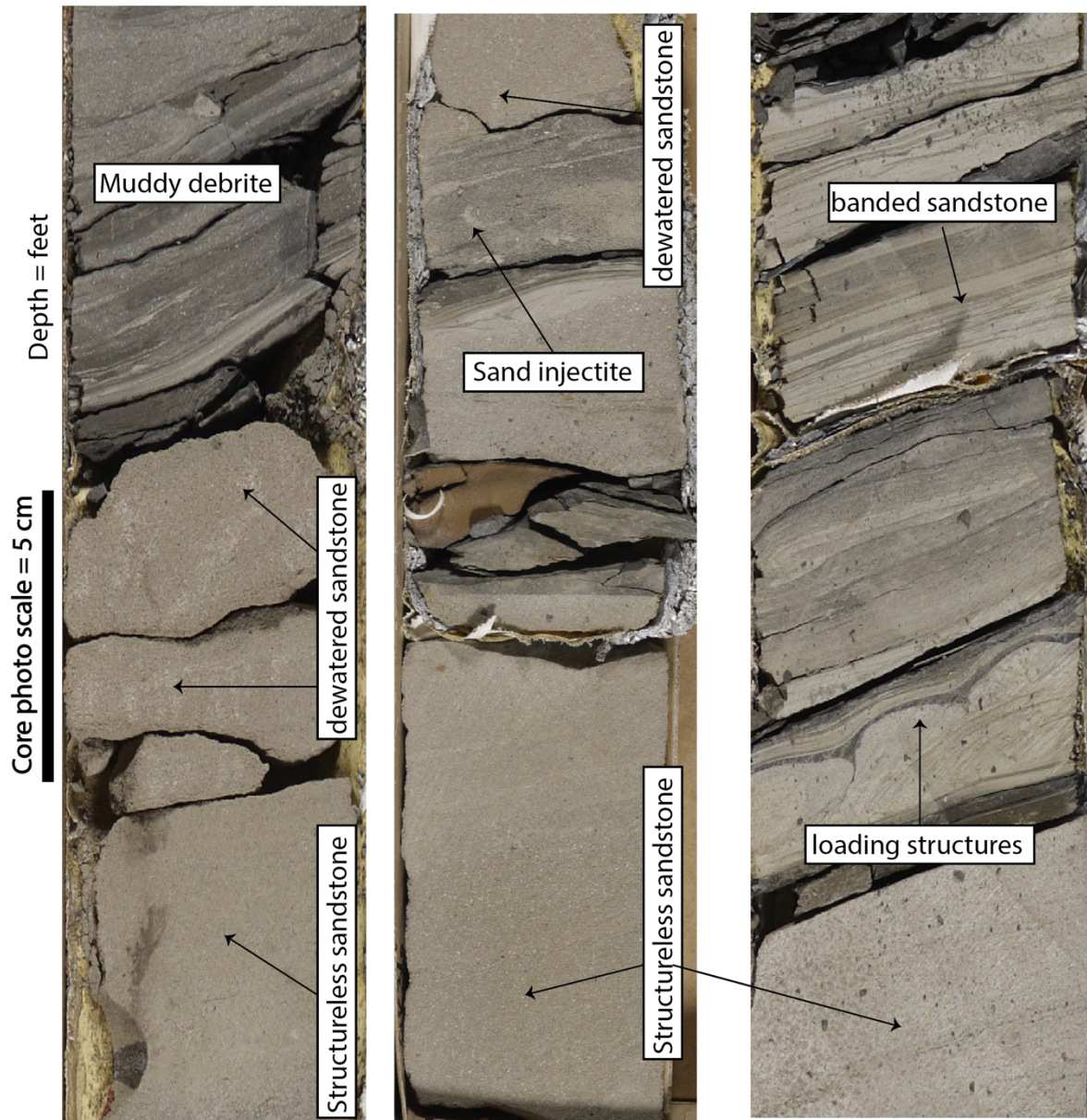
Depth = feet

Core photo scale = 5 cm



Haugton et al, 2019	This study			Division	Interpretation
H5	BM			Laminated or massive mudstone	Suspension fallout
H3	D			Muddy sand, sand patches, injections, outsized granules, shear fabrics. Sometimes consist of fragment of carbonaceous materials	Non laminar, cohesive debris flows, locally modified by salt diapirs and sand injection
H2	A4			Alternating lighter and darker sand and mud layers	Transitional flows with turbulent supression
H1	A	A3 A2 A1		Graded to ungraded, structureless and dewatered, or dish structured clean sand, with floating mudclast	Progressive aggradation beneath non-cohesive, high density turbidity currents

Sandstone dominated hybrid event bed



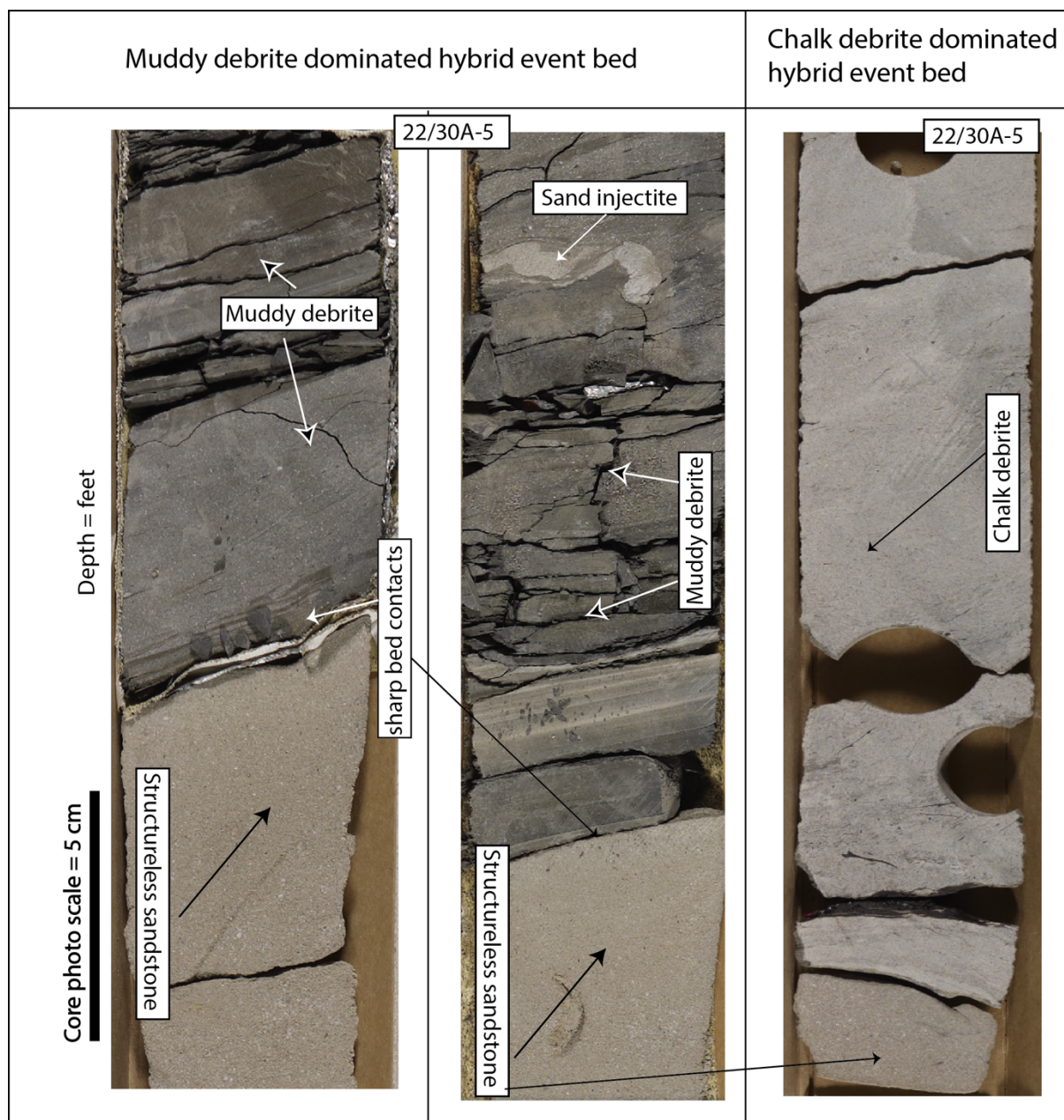


Figure 5. 5: (A) Representative core photograph of hybrid event bed distribution within the Forties Sandstone. Here, we noticed the relationship between the basal turbidites, the overlaying linked debrites and the capping hemi pelagic mudstone. (B) Anatomy of Hybrid event bed. The basal Amalgamated turbidite facies is separated from the linked debrite by a transitional zone of banded sandstone facies. The top of the event in the study location is capped by hemi pelagic mudstone. (C) Representative core photograph showing sandstone dominated hybrid event bed distribution within the Forties Sandstone. Here, we noticed the dominance of the thicker basal turbidites, and a thinner overlaying linked debrites. (D) Representative core photograph of debrite dominated hybrid event bed distribution within the Forties Sandstone. Here, we noticed a thinner basal turbidites, and a thicker overlaying linked debrites. Chalk debrite dominated hybrid bed are rare our study location. This variant of hybrid beds shows the linked-debrite to be rich in carbonate material

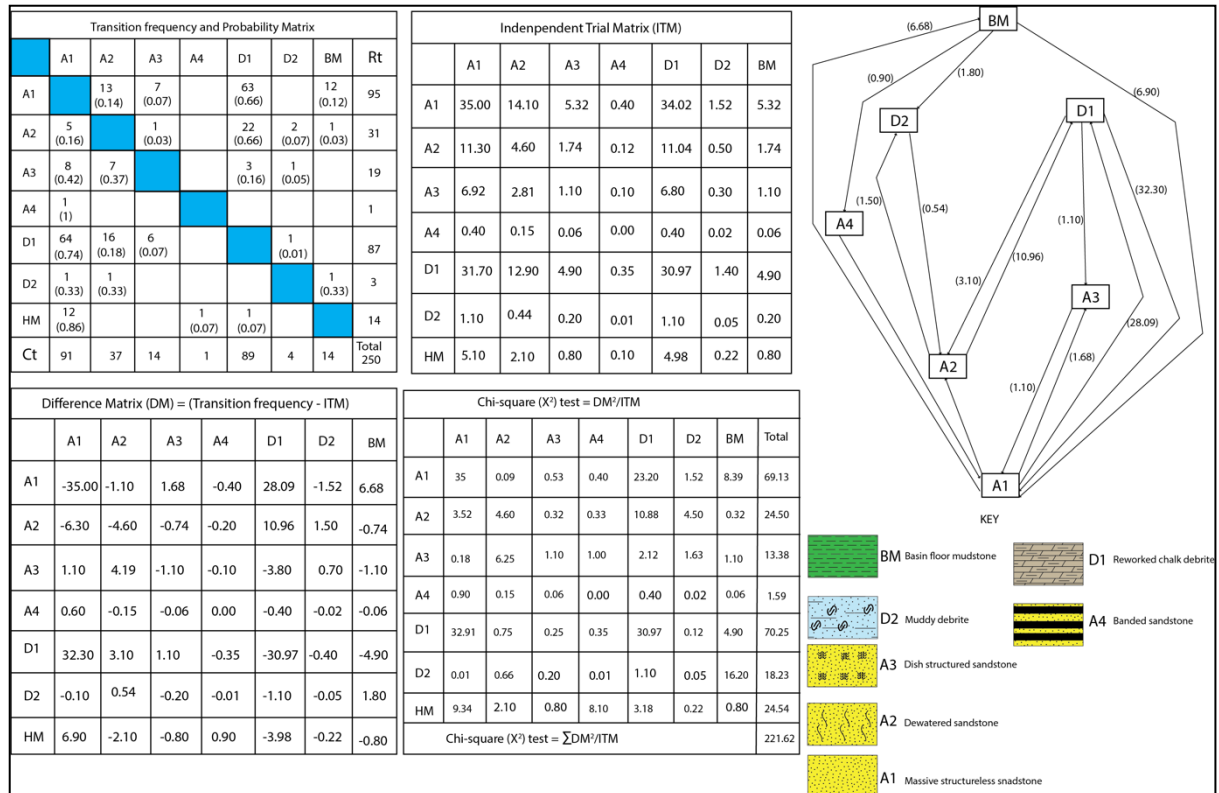
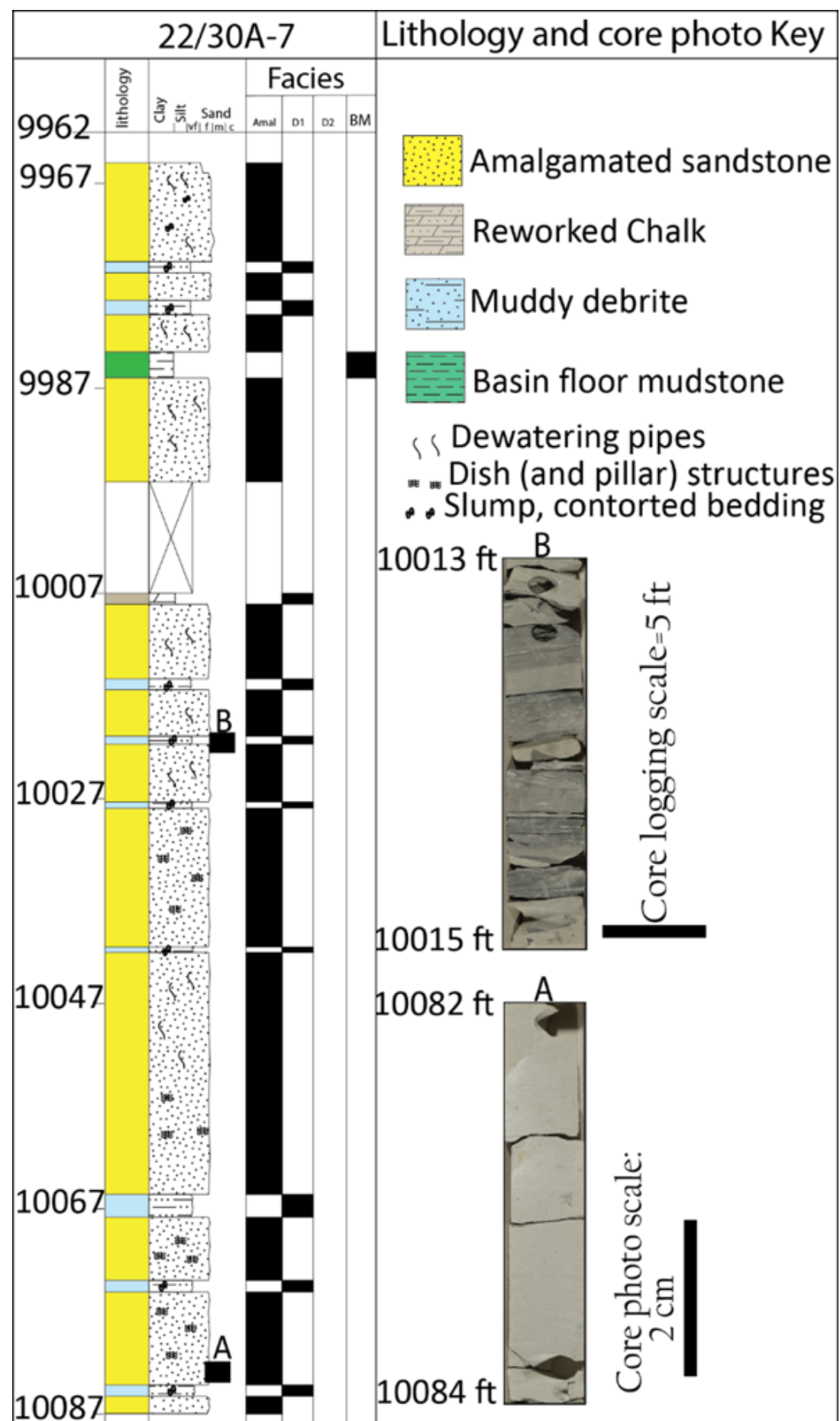
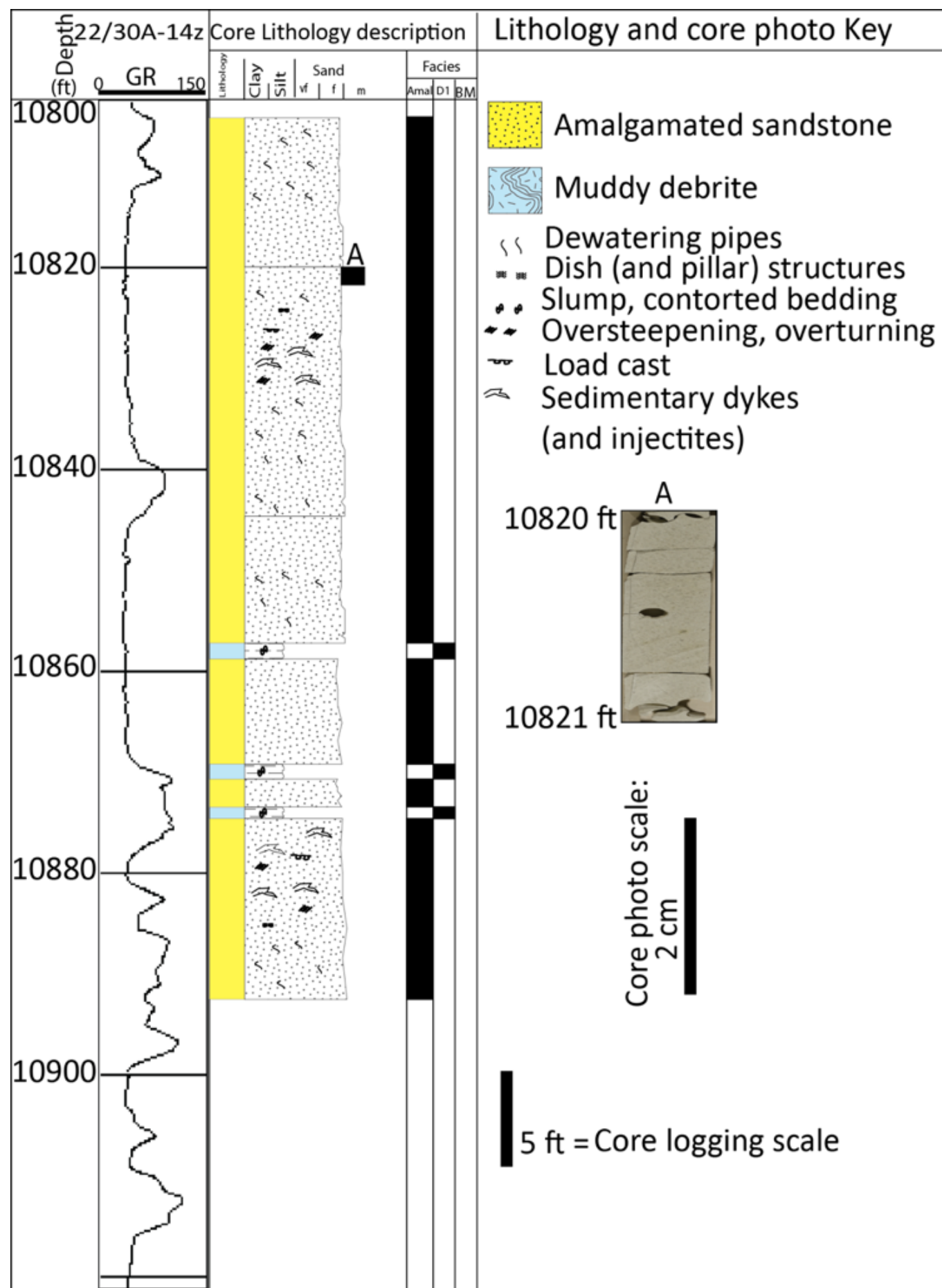


Figure 5. 6: Statistical analysis of the vertical facies relationship: Transition diagram and transition tree diagram shows the vertical facies transition within the Forties Sandstone



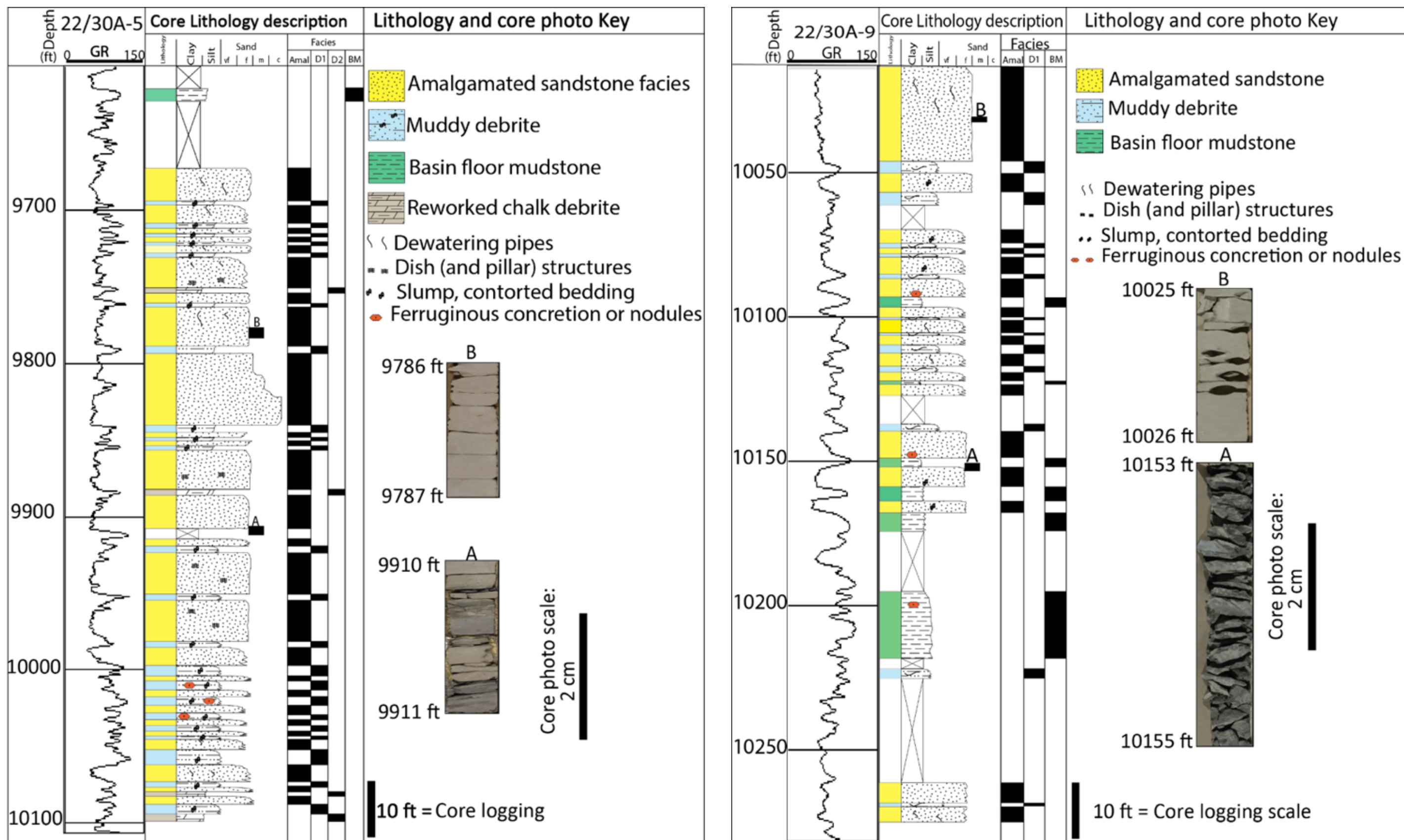
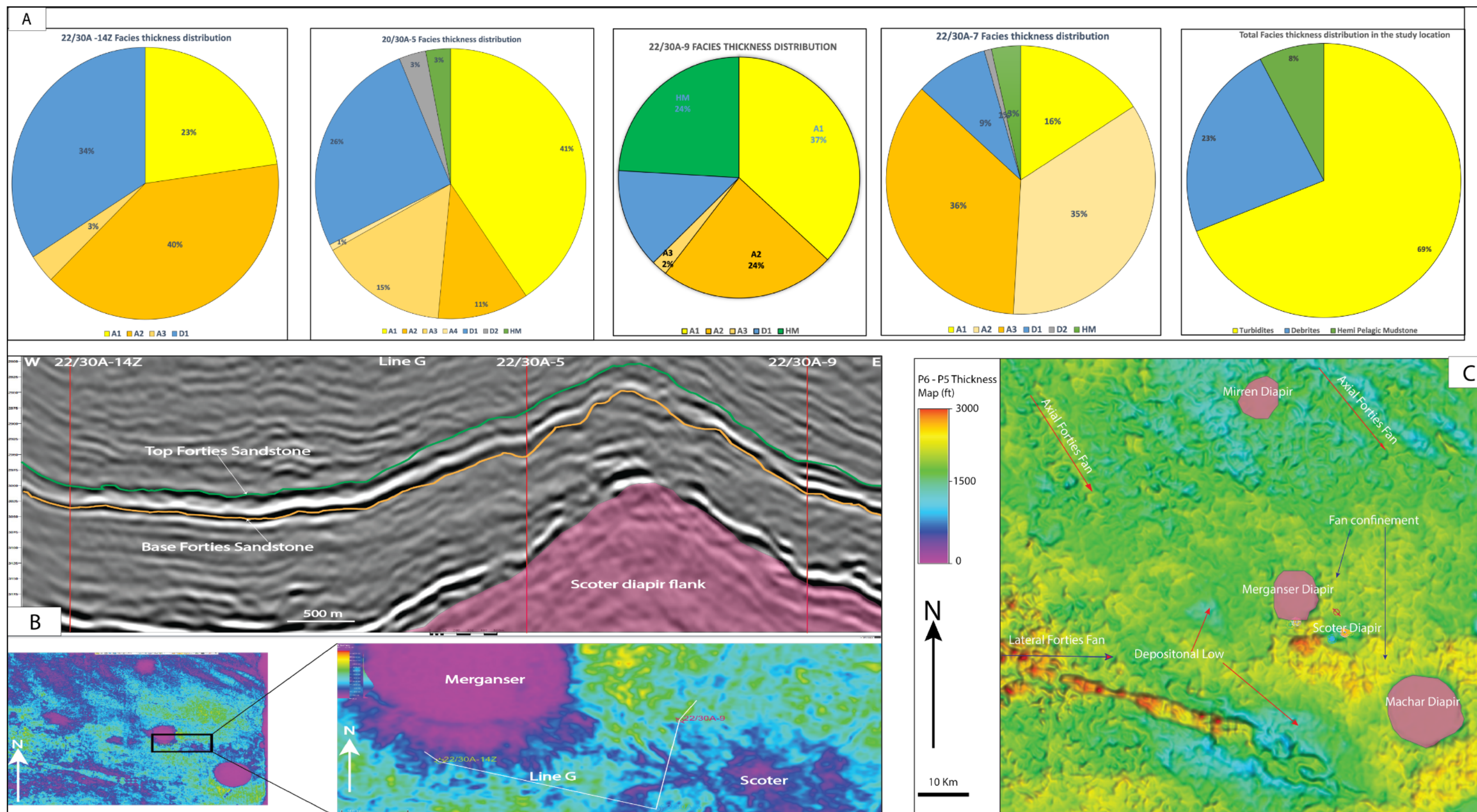


Figure 5. 7: Logging of the Forties in the studied well around Merganser field. (A) and (B) shows core logging highlighting the vertical facies relationship within the Forties Sandstone interval from wells 22/30A-14z and 22/30A-7 respectively. 7C and D: Logging of the Forties fan in the studied well around Scoter field. (C) and (D) shows core logging highlighting the vertical facies relationship within the Forties Sandstone interval from wells 22/30A-5 and 22/30A-9 respectively



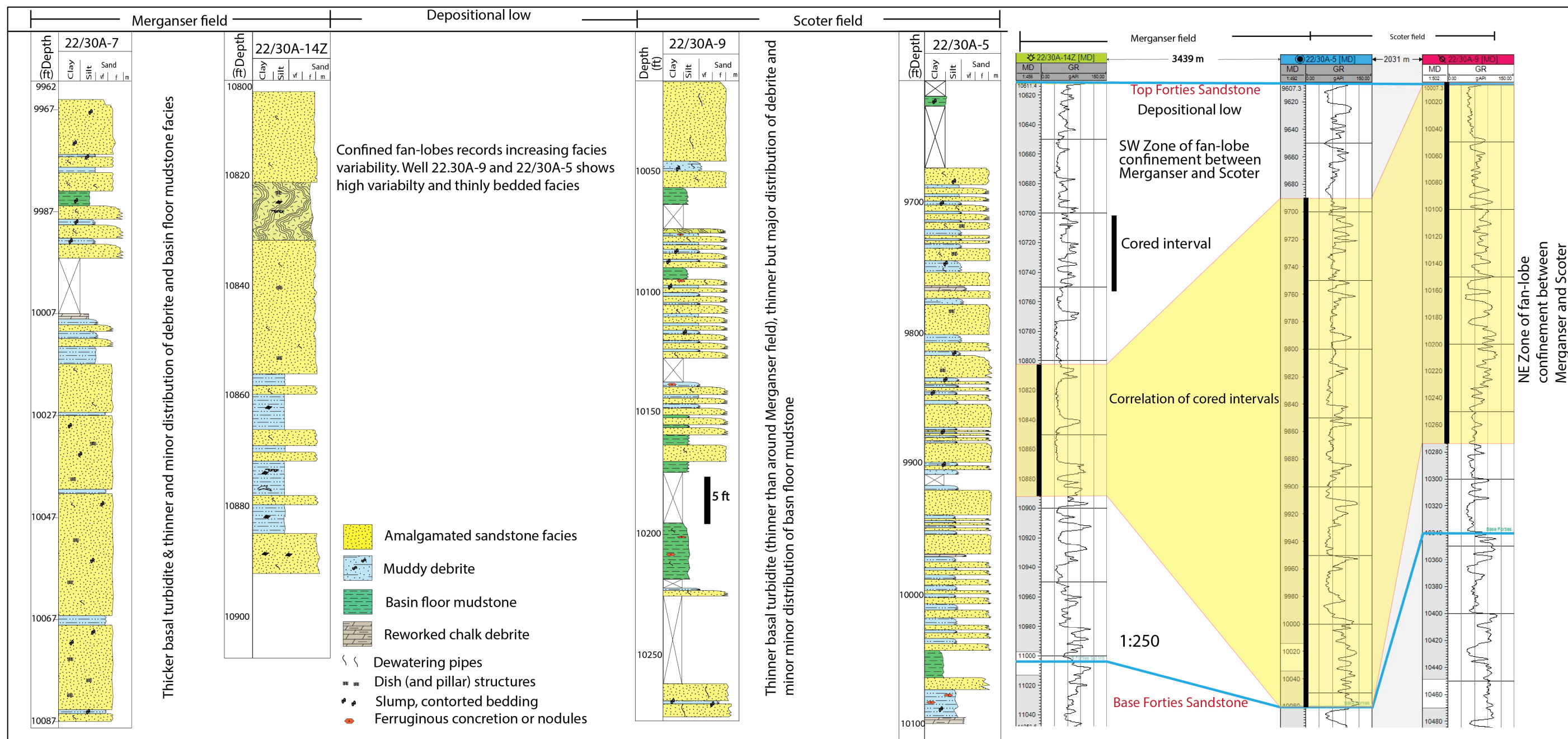


Figure 5. 8: (A) Pie charts showing the pictorial facies variation and distribution in each cored well (B) seismic line G showing the thickness of the Forties interval (C) Forties Isopach map (D) & (E) Lateral facies heterogeneity within the Forties fan observed from the Merganser to Scoter fields. Core logging shows that the basal turbidite sandstone are thicker around Merganser field (22/30A-7 and 22/30A-14Z) and thinner around Scoter fields. There is also the increasing distribution of the linked debrites around Scoter fields. This could be related to the ponding of transformed cohesive flow

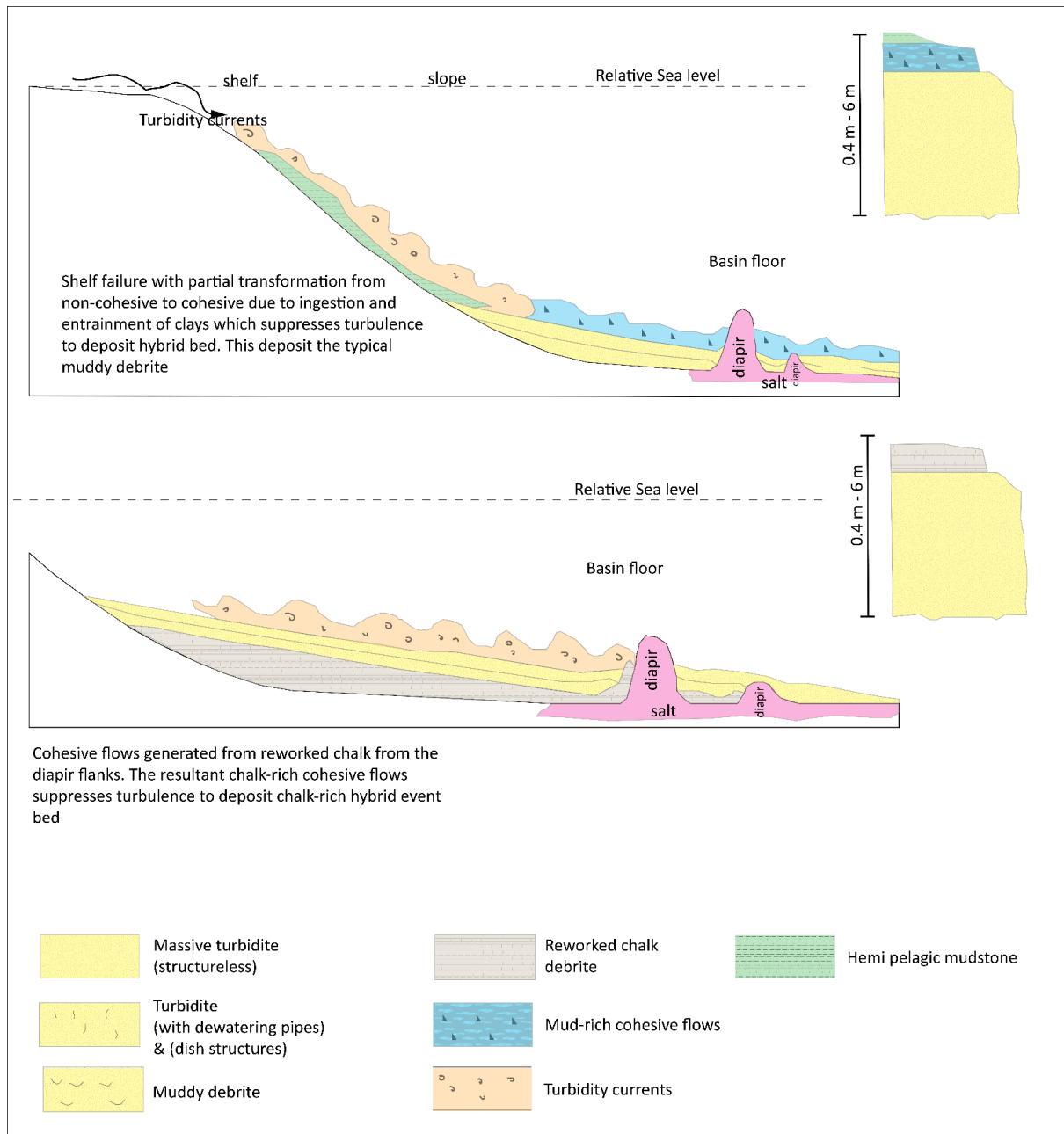


Figure 5. 9: Cartoon of the flow evolution and origin of the two types of hybrid bed identified in this study (modified after Hodgson, 2009). Graphic log motif of each representative deposit is shown. (A) Flows associated with turbidity current is interpreted to be sourced from collapse of a shelf-edge delta-top i.e. (Sele delta) with partial flow transformation because of mud ingestions and entrainment resulting in the suppression of turbidity behaviour of the flow. (B) Chalk debrite are interpreted to develop through the interaction of turbulent flows with raised older chalk stratigraphy around salt diapirs

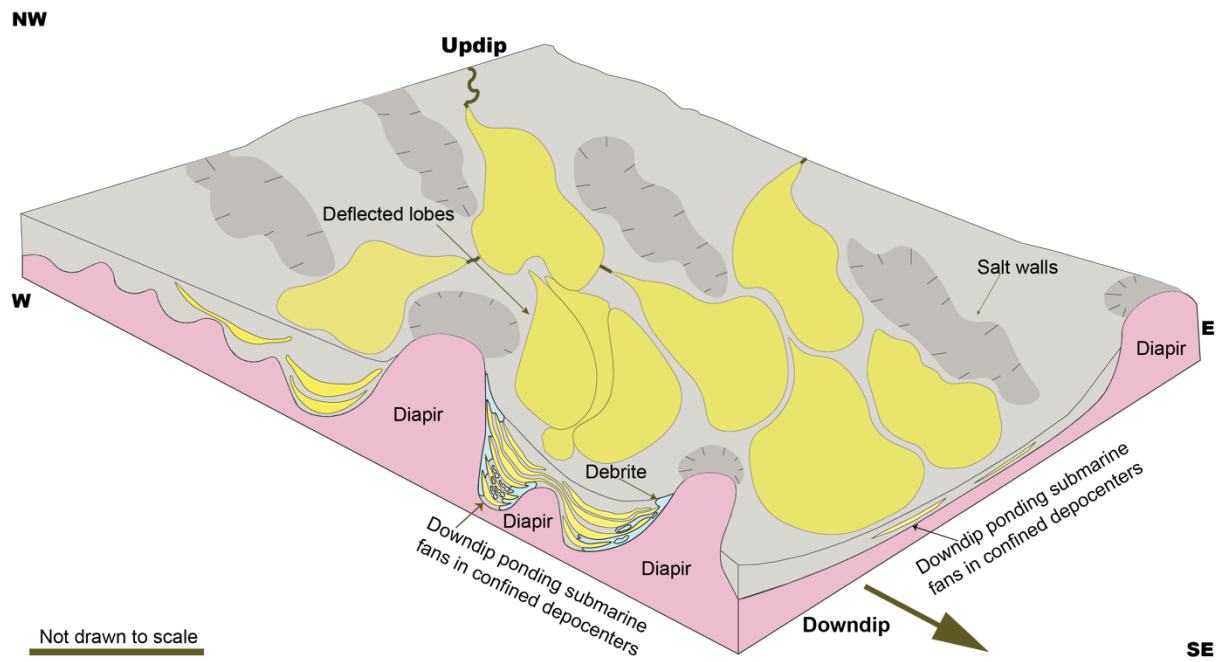


Figure 5. 10: Schematic Cartoon showing the interaction between the upper Palaeocene deep-water system and salt diapirs. Here, the distal lobes are mostly deflected, diverted, or ponded. When ponded, the local gradient created results in slumping and sliding from the diapir flanks

CHAPTER 6

6.1 DISCUSSION

The results of the analysis discussed in this thesis are presented in three chapters (chapters 3-5). Using 3D seismic, borehole, core and drill cutting dataset, the geomorphic expression, geometry, and depositional architecture of deep-water depositional systems (slope to basin floor environment) in two case studies (i.e., Offshore Taranaki Basin, New Zealand and Central North Basin, UK) was documented. Chapter 3 addresses the seismic geomorphology, geomorphic evolution, and the stratigraphic architecture of the middle Miocene deep-water channel systems in offshore Taranaki Basin. This chapter relates geomorphic expression to the internal architecture of deep-water systems and the control on their evolution. Chapter 4 analyses in detail, the interaction of the upper Palaeocene deep-water depositional system and salt-related seafloor topography in the Merganser and Scoter area of the Central North Sea Basin. This study characterises the distribution, geometry, and the internal architecture of turbidite sandstones in the distal reaches of FSM fan system. Finally, chapter 5 analyses the sedimentology and the stratigraphic architecture of salt-influenced deep-water deposits. This chapter discusses the facies variation and heterogeneity of the FSM around the Merganser and Scoter diapirs. While the first case study; chapter 3, analyses the geomorphic evolution and the stratigraphic architecture channels in a typical channel dominated deepwater systems without salt-diapir control, chapters 4-5 (complementary chapters), analyses the interaction, sedimentology, and the stratigraphy of deep-water submarine fans in lobe dominated, salt-induced basin floor environment. Hence, this thesis allows for comparison of deepwater sedimentology and stratigraphy in basin without salt control and basin with salt-induced basin floor environment. These three chapters presents a set of results that addresses deepwater sedimentology and stratigraphy in slope to basin floor environment in the offshore Taranaki and the CNS Basin respectively. In this section, the result of this thesis is discussed under three main themes which synthesizes and integrates the key finding; (i) The variability of channel dominated, and lobe dominated deepwater setting – Insight from the Taranaki Basin and the Central North Sea, (ii) Characterizing the internal architecture of deepwater systems – Insight from the Taranaki Basin and the Central North Sea (iii) controls on the geomorphic evolution deepwater channels system in the slope and basin floor environment. Finally, this discussion highlights potential applications of this work, the limitations and some key areas which need to be further developed.

6.1.1 THE VARIABILITY OF CHANNEL DOMINATED, AND LOBE DOMINATED DEEPWATER SETTING – INSIGHT FROM THE TARANAKI BASIN AND THE CENTRAL NORTH SEA

Submarine channel systems occur in variable forms in many deepwater systems. For example, in the Taranaki Basin, deepwater systems are dominated by the middle to upper Miocene channel systems confined within channel belts. In contrast to the Taranaki Basin, the Central North Sea is dominated by fan-lobes system. These variability are described in many deepwater basins example Offshore West Africa, Angola, Brazil and the Gulf of Mexico (Abreu et al., 2003; Adeogba et al., 2005; Deptuck et al., 2007; Gee & Gawthorpe, 2007; Janocko et al., 2013; Jobe et al., 2015; Kane et al., 2008; Keevil et al., 2007; McHargue et al., 2011; Mitchell & Clarke, 1994; Oluboyo et al., 2014; Pirmez & Flood, 1995; Posamentier et al., 2007; Reading & Richards, 1994; Wynn et al., 2007).

Seismic geomorphology analysis is one of the key tools utilised in describing the variability of deepwater systems. Channel systems and lobes are differentiated based on their geomorphic expression, distribution, palaeoflow directions, cross-sectional geometries, and their stratigraphic architectures. In channel dominated systems for example the Taranaki Basin, channel systems are distributed majorly, based on their palaeoflow direction for example, centrally (i.e., SU1) and later

northwesterly (i.e., SU2), and geomorphic expression and geometries (Figure 3.9 – 3.15). Cross-sectional seismic geometries of channel dominated deepwater systems for example the channel system observed in the Taranaki Basin, show channel system that are leveed or erosionally confined within the channel belts. These channel systems are typical confined within erosional, or irregular conduit with aspect ratios of 9.92 – 18.19 indicating that the channel systems vary from less erosional to highly erosive and incisional characteristics. Shumaker et al., (2018) links aspect ratios to submarine channel incisional nature and noted that, increasing or decreasing aspect ratios has implication for the scale of the channels.

In the Taranaki Basin, the increasing aspect ratio implies an increasing channel belt width as the channel evolved. Generally, erosional channel belt are formed by a simple cut-and-fill process, and are characterised by channel mounds at the channel bends (Janocko et al., 2013). The presence of heavily looped channel bends in earlier channel belt suggests increasing lateral migration as the channels evolved (Figures 3.14 and 3.15). The seismic section showed that the erosional channel belt in the Taranaki Basin is characterised by erosive bases downcutting into the older stratigraphy. A more complex interplay of incision, lateral migration, and vertical aggradation, housed within a U-shaped valley fill was observed. This resulted in a thick wedge of levees/overbank deposits which flank the aggrading valley fill deposit (Figure 3.15). Within each erosional container, series of channel element, channel complex, and channel complex set are confined and aggrade forming the container fills. Our analysis showed that, these channels will continue to incise and erode older stratigraphy until the channel bypass, forming a new channel belt (Hodgson et al., 2011). This compares favourably with the geomorphic expression of other documented deepwater channel systems, such as in the Karoo basin, South Africa (Flint et al., 2011; Kane & Hodgson, 2011), offshore West Africa (Deptuck et al., 2007; Pr  lat, et.al., 2010) among others. This study confirms that, the common stratigraphic evolution of submarine channel-levee complex, from incision to late-stage aggradation in deepwater systems, is ubiquitous. The complexity associated with deepwater channel architectures is due to the repeated cycles of incision, deposition and aggradation, including the interaction between lateral and vertical migrations of channel elements (Covault, et.al., 2016; Di Celma, et.al, 2011; Jobe, et.al, 2016).

In lobe dominated deepwater system for example the Central North Sea, lobes are observed on planform maps as low relief elongate features that are distributed at the seaward termination of submarine fans system (Adeogba et al., 2005) (Figure 4.8). This planform geomorphology is typical of lobe system in many deepwater fan systems example the Amazon and Zaire Fan (Babonneau et.al., 2004; Deptuck & Sylvester, 2017; Pirmez & Flood, 1995). In the Central North Sea, the lobe system is stratigraphically unconfined but structurally confined by salt diapirs. The dimension, shape and architecture of lobe deposit depend on several factors for example the submarine flow properties and the sea floor morphology. In the Central North Sea, submarine flow transformation from an initial turbulent to debris flows, exert a huge control on lobe dimension and its internal architecture. Similarly, the presence of other sea floor topography for example salt diapir in the Central North Sea, confined and deflect the pathways of those lobe system. This is evident on the planform maps by the distribution of bright amplitude reflection confined around the salt diapirs. The cross-sectional geometry as observed from seismic cross section, indicates a constant thickness reflection that wedge out in zone of weak reflection implying lobe stacking boundary. No evidence of basal erosion was observed however, compensational stacking of basin floor lobes is common. Unlike the lobes system of the Amazon fan, Congo-Zaire fan and the Niger Delta submarine systems (Adeogba et al., 2005; Deptuck et al., 2003, 2007), the Central North Sea is characterised by lobe system that are constantly confined by salt structures. This is similar to what is observed in the Lower Congo basin, Gulf of Mexico, and Offshore Angola (Gee & Gawthorpe, 2006; Oluboyo et al., 2014; Posamentier, 2003; Rodriguez et al., 2019).

6.1.2 CHARACTERIZING THE ARCHITECTURE OF DEEPWATER SYSTEMS – INSIGHT FROM THE TARANAKI BASIN AND THE CENTRAL NORTH SEA

The architecture of submarine system is the archived geomorphic processes observed on planform maps. In channel dominated deepwater systems for example the Taranaki Basin, the depositional architecture comprises of channels, levees/overbank, and mudstone (Labourdette & Bez, 2010; Picot et.al., 2016). Similar depositional architectures are observed and described in many channels dominated deepwater systems. In lobe dominated system, similar depositional architectures are observed (Masalimova et al., 2016; Morris et al., 2014b). In most cases, the presence of external control on these systems is/are responsible for the variability in the internal architecture.

In channel dominated deepwater system like the Taranaki Basin, the channel system is confined within channels belts. The sediment-laden submarine channel is initially routed into the basin and depending on the type of load it is carrying; the channel offloads the sediment at any given suitable hydraulic condition. The notable area of its deposition will be on the overbank, the channel axis or off-axis. This continues until the channel is abandoned or bypasses its initial course forming another belt. The channel will grow laterally or vertically, stacking a complex depositional architectures overtime. In the Taranaki basin, the channel axis of any channel belt will show pocket of high amplitude reflection packages on seismic cross section, which is interpreted on wireline log (GR log) as a blocky low GR motif. Core and cutting description show this GR log motif to be massive or ripple laminated sandstone (Figure 3.19). The off-axis depositional architectures are characterised by variable reflection on seismic, serrated GR log motif and interbedded sandstone, siltstone, and mudstone lithologies on cores or cuttings description. The off axis will extend into the overbank environment, sharing similar internal characteristics and pinching out into basin floor mudstone. In the Taranaki basin, the mudstones are mainly of the slope or basin floor facies which have been incised or eroded by channel system. Within the channel belts, these architectures are a common occurrence, aggrading vertically as they evolved overtime. This similar facies and lithology distribution have been previously described in other deepwater basin (Brunt & McCaffrey, 2007; Janocko et al., 2013; D. Stow & Smillie, 2020).

In lobe dominated deepwater system, lobes, like the distal termination of most submarine fans, deepwater systems are characterised by stacked lobes. In contrast to the Central North Sea, other lobe dominated systems for example the Lower Congo basin, Offshore Angola, (Oluboyo et al., 2014), showed the existence of minor channels within the lobes. These lobes appear to show compensational stacking with constant thickness in any given lobe element. Generally, lobes are not confined within any belt since they represent the termination of submarine fan system. This isn't the case in basins that has structural confinement caused by bathymetric features like the salt diapirs. The behaviour of submarine lobe around salt-induced structural features (e.g., salt diapirs), depends on their orientation, size, and growth rate relative to the pathways of deepwater systems. When lobes are confined, post depositional features such as slumping and soft sediment structures are very common in its architecture as observed in the Central North Sea (this study). The preserved stratigraphic architecture analysed from core data, show that slumping of unconsolidated sediments occurs on flanks of this diapir due to local gradient changes hence the widespread distribution of this features around Merganser diapir. Similarly, thin unit of chalk debrite have been cored in some wells in the study location suggesting uplifted and reworked Cretaceous chalk that was subsequently remobilised and redeposited as chalk debrite down the flank of the diapir as seen around Machar, Jenny and Kyle fields (Davison, 2004; Ward et al., 2012;). The General lithologies of this lobe system comprises of thick amalgamated turbidite succession, debrites, and basin floor mudstone. These lithofacies are stacked laterally and vertically. The turbidite are massive or containing post depositional structures such as dewatering pipes or dish structures. The structural effect is manifested by the presence of overturned sedimentary structures, slumping and internal contortion of the lithologies.

This study has shown that although similar lithologies i.e., sandstone, siltstone, mudstone or heterolithics are described in both channel dominated and lobe dominated systems, the complexity in their internal architecture varies remarkably and often control by the basin physiography. Channels will most likely be confined erosionally or be leveed. In the case of lobes, they are mostly not confined unless if influenced structurally for example when lobes confined in salt influenced minibasin or salt-influenced syndepositional lows. In this case, they may exhibit complex internal architecture.

6.1.3 CONTROLS ON THE GEOMORPHIC EVOLUTION OF DEEPWATER CHANNELS SYSTEM IN THE SLOPE AND BASIN FLOOR ENVIRONMENT

A range of factors i.e. autocyclic and allocyclic factors, have been inferred to control the morphology and stratigraphic architecture of submarine channels in deepwater basins (Cecil, 2003; Clark & Cartwright, 2011). Autocyclic controls such as channel avulsion and migration, are instantaneous events which result in changes in physical sedimentology (Cecil, 2003). Allocyclic controls, such as tectonic activity, climate change and eustasy, the basin geometry, orientation and source of sediment (Cecil, 2003; Lopez, 2001).

In channel dominated deepwater system for example the Taranaki Basin, the control on the evolution of deepwater channel system are either autocyclic or allocyclic (e.g. King & Thrasher, 1996; Pilaar & Wakefield, 1978). For example, regional tectonic activity involving the Australian and the Pacific plates exerts a major control on the basin geometry during the Mio-Pliocene. Faulting and folding in the central and eastern part of the study area also controlled the Neogene depocentres. Inversion centred mostly in the southern part of the basin was key to the earliest sediment routing into the basin. Also, the subsequent anticlockwise rotation of the shelf towards the south-eastern, eastern, and north-eastern part of the basin played a major role in controlling the sedimentary systems and depocentres (King & Thrasher, 1996). Tectonic activity also exerted a significant control on the loci of sediment deposition, including sediment staging area, the sediment provenance, and the sedimentation rate. Base level changes are another tectonically linked control on the Middle Miocene submarine system. From the Altonian to early Lilburnian stage, the entire Taranaki basin was subsiding with depocentres around the central and North-western parts of the basin (King & Thrasher, 1996). The late Lilburnian to Waiauan marks the onset of base level rise, this was accompanied by shelf rotation and a southeast to northeast sediment provenance with a huge sediment supplied into the basin. No further analysis was done to prove this assertion however, previous studies example (Baur, 2012; Browne et al., 2005; Peter King, 2000; Palmer & Andrews, 1993; Shumaker, 2016; Shumaker et al., 2018), show that the entire submarine systems in the Taranaki basin has largely been shaped by autocyclic and allocyclic factors. These and other factors have had huge impact on the evolution of deepwater channels in the Taranaki Basin. This study did not qualitatively and empirically show evidence to support the influence of allocyclic and autocyclic factors except for the change on channel morphology seen on attribute maps. However, geochronology study done by (Rotzien et al., 2014; & Shumaker, 2016), used heavy mineral analysis to describe the provenance and the implication of internal & external factors in changing sediment provenance location.

In lobe dominated deepwater setting for example the Central North Sea, a range of allocyclic and autocyclic factors, such as sediment supply, sea-level changes and local basin morphology (i.e. salt-induced seafloor), are the common controls on the evolution of upper Palaeocene deepwater channel systems in the Central North Basin (Hempton et al., 2005; Jennette, et.al., 2000; Kneller, 2003; McHargue et al., 2011; Posamentier & Kolla, 2003). This study has shown that salt diapirs modify seafloor morphology by generating topographic highs and lows, resulting in variation is seafloor regional and local gradient causing changes in sediment routing and distribution (Gamboa & Alves,

2015; Gee & Gawthorpe, 2006; Oluboyo et al., 2014). In the offshore West Africa and the Espírito Santos Basin, (Gamboa & Alves, 2015; Gee & Gawthorpe, 2006; Oluboyo et al., 2014) show that the geometry and architecture of deepwater channels changes in relation to the evolving salt diapirs. This study has shown that, important variation in geometry and architecture of deepwater lobes, increases adjacent to salt diapirs. The rate of sedimentation and the relative movement of salt diapirs also affect the deposition of the Upper Palaeocene depositional system. In the Gulf of Mexico, (Kane, et al., 2012) has shown that cycles of salt growth and withdrawal results in distinct channel evolution from channel migrating away from the growing salt structures. Numerous studies have shown that the interactions between salt structures (i.e. salt diapirs) and turbidity currents are associated with the size, shape, uplift rate of salt structures, incidence angle between regional flow direction and structural strike (Doughty-Jones et al., 2017; Gee & Gawthorpe, 2006; Kane, et al., 2012; Mayall et al., 2010b; Oluboyo et al., 2014). Deepwater lobes in the CNS are laterally confined by depositional lows or elongated mini basin and are deposited in depocentres created by isolated salt diapirs.

6.2 GENERAL STUDY APPLICATION

The general approach used in this thesis involves; (i) study of the stratigraphic evolution and internal architecture of deepwater channels and (ii) study of the facies distribution and its control by salt diapirs. This approach can be used to analyse the temporal geomorphology of deepwater channel systems and also to understand how those structures affects the geometry and internal architecture of channel systems (Posamentier, Davies, et.al., 2007; Posamentier, 2003; Wood & Mize-Spansky, 2009). The method adopted in this thesis has been widely applied to the study of gravity-driven deepwater systems, such as those in offshore West Africa, offshore Brazil, and the Gulf of Mexico (Doughty-Jones et al., 2017; Gamboa & Alves, 2015; García et al., 2015; Gee & Gawthorpe, 2006; Kane, et al., 2012; Mayall et al., 2006; Oluboyo et al., 2014) where submarine channels interact with salt structures to understand their linked geomorphic and stratigraphic evolution. 3D seismic data has allowed for subsurface seismic geomorphology analysis which has proven to be a vital tool for understanding subsurface process sedimentology. This allows for the application of surface geomorphic techniques to ancient and modern (Posamentier, 2003; Prather, 2003; Prather et al., 2012).

The synthesis from this thesis provides a vital tool for prospecting for reservoir facies evolution, geometry, and distribution. Deepwater turbidite has proven to be prolific reservoirs for hydrocarbon, the ability to visualize their planform morphology and internal architecture makes reservoir prediction more reliable, reducing risk and uncertainty associated with such activity. The analyses use in this thesis can be useful in developing reservoir models for complex deepwater reservoirs (Prather et al., 2012). These models can then be applied to reservoir facies distribution prediction in complex deepwater settings.

6.3 FURTHER WORK

Having a SE extension of 3D seismic coverage of the study area would allow for a more regional study of the channel systems that can be traced down-dip to further deeper areas and the Caledonian Trough where they appear to terminate. This would extend the lengths of some of the systems already studied, and hence allow for a better understanding of whether if there was a channel bypassing of shelf and basin floor during that evolution of this deepwater channel systems.

Constraining channel evolution documented in chapters 3 and 4 to deepwater channel systems in other settings is a useful approach. This will allow full studies for a range of other submarine channel

systems, crossing salt diapirs with different shapes. This will lead to a better insight about submarine channel responses to growing structures and how they relate or vary in different settings.

Physical modelling techniques (Bolla et.al., 2014; Kneller & Buckee, 2000; Straub, et.al., 2007; Wynn et al., 2007), calibrated to observe numerical relationships and seismic data might be the way forward in understanding how submarine channels initiate incision around salt diapirs. This type of approach would be needed to understand the dynamics of turbidity currents and how they initiate, and maintain incision through time, for a better understanding of the variation in channel geometry (P. J. Talling, 2012).

Salt tectonics is vital to understanding the evolution of depositional system in many deepwater settings. The interaction of sediment gravity deposit with evolving salt-induced seafloor topography is complex hence the need to constrain the responds of deepwater channels to salt diapirs. A detailed reconstruction of salt movement is key to understanding the spatial and temporal evolution and distribution of reservoir facies in many deepwater systems, particularly the stud area.

CHAPTER 7

CONCLUSIONS

The main conclusions of this thesis are as follows:

This thesis presents a synthesis of the geomorphic evolution, depositional elements, and the stratigraphic architecture of channel dominated deepwater system (e.g., the Taranaki Basin) and lobe dominated deepwater system (e.g., the Central North Sea). The channelized portion of deepwater system is mostly characterised by channels system confined within levee or erosional belts that grow by aggradation until the channel is abandoned or bypassed. Regardless of the internal architecture, similar geomorphic expression of channel system in channel dominated deepwater is observed. For example, seismic geomorphology of the middle Miocene deepwater system in the Taranaki basin is like the geomorphic expression described in most passive margin basins for example in the West African passive margin basins.

Lobes are known as distal termination of submarine fans. In lobe dominated deepwater system i.e., deepwater system characterised by the dominant distribution of lobes as compared to channels, these lobes are observed to be stratigraphically unconfined. However, this thesis has shown that when they occur in deepwater basin influenced by salt diapirs, they are mostly confined within depositional lows between isolated diapirs.

While the seismic cross section of channels in channel dominated system show conspicuous U or V-valley form features, seismic cross section of lobes in lobe dominated deepwater system show a saucer pan form that thins into adjacent lobe body in a compensational stacking fashion. There is a diverse lithology distribution, and this increases significantly towards the channel margin and into the overbank and shaling out into the basin floor mudstone. In contrast to that, there is reduced facies variability in the lobes dominated systems.

While the dominant lithologies i.e., sandstone, siltstone, heterolithics and mudstone are common in deepwater systems, their thickness, vertical distribution, and lateral variation varies significantly. In channel dominated systems, channels tend to show remarkable vertical facies variation. This could be related to the vertical aggradation and stacking patterns of the channels as it evolved. In contrast to that, the lobe dominated system tend to show remarkable lateral facies variation.

Lobe dominated deepwater setting (for example the CNS) are characterised by a more complex architecture than a channel dominated deepwater system (for example the Taranaki basin). This is because, the salt diapirs interacts with the deposition of this lobe facies creating a temporal in the submarine flow regime. In the CNS local mixing, slumping, and reworking of older stratigraphy are some of the influences the salt diapirs had the evolving lobe system.

The study has shown that even not all depocentres created between isolated salt diapirs are mini basin. However, in the CNS mini basins observed appears elongated and has different physiography to minibasin observed in other salt influenced basins example the GoM and Offshore Brazil. In this case, the typical fill and spill model does not apply. Lobes and by extension channels can only be laterally confined to a depositional low created by this diapir. This can only happen when the flow path of the fans is parallel to the orientation of the salt structures. In the CNS, the salt diapirs is oriented parallel to the flow direction and path. On this account, submarine fans can only be diverted, deflected, ponded, or laterally confined within elongated mini basin. This was observed using RMS attribute map used to map out the modification in the flow path.

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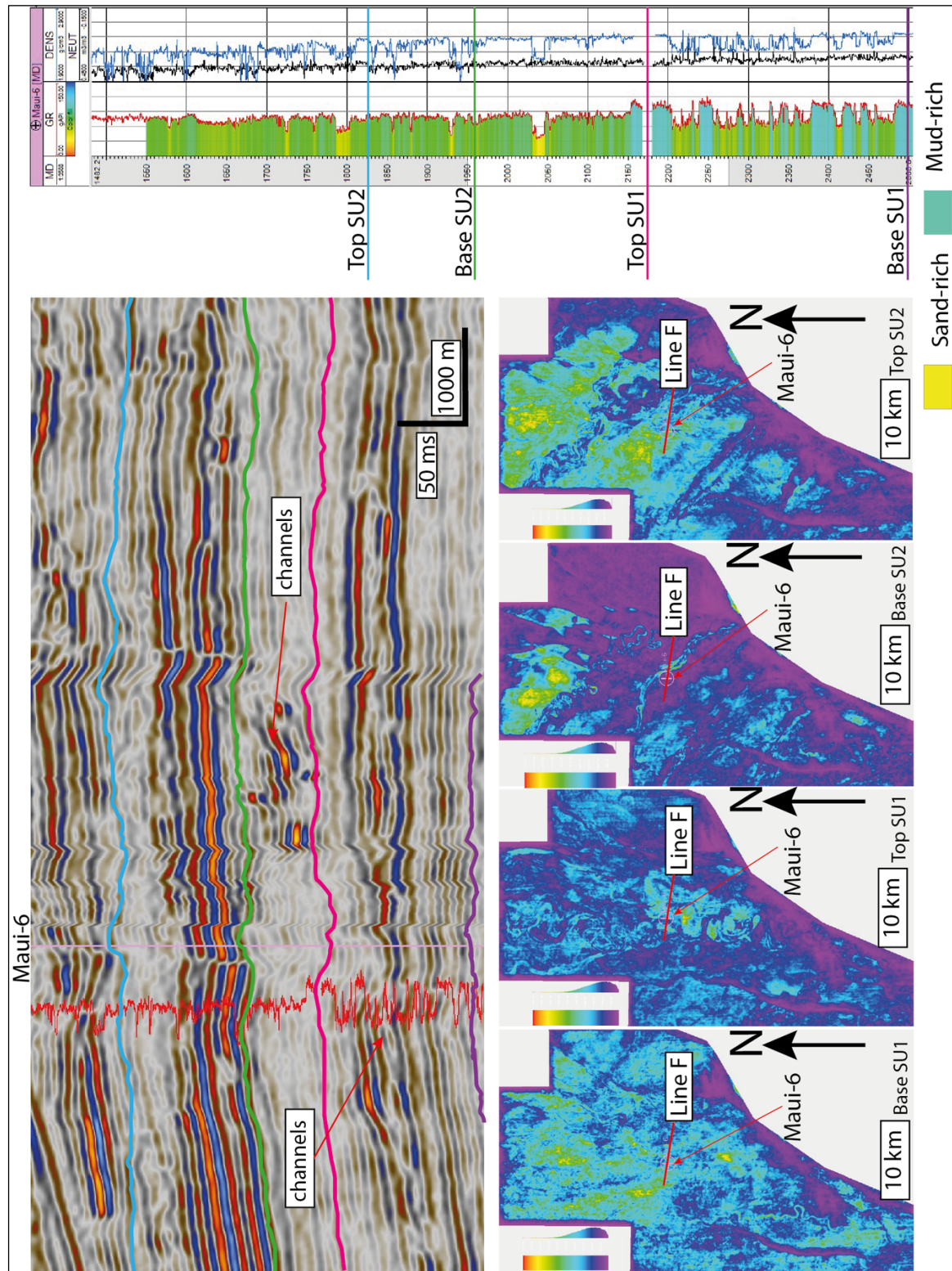
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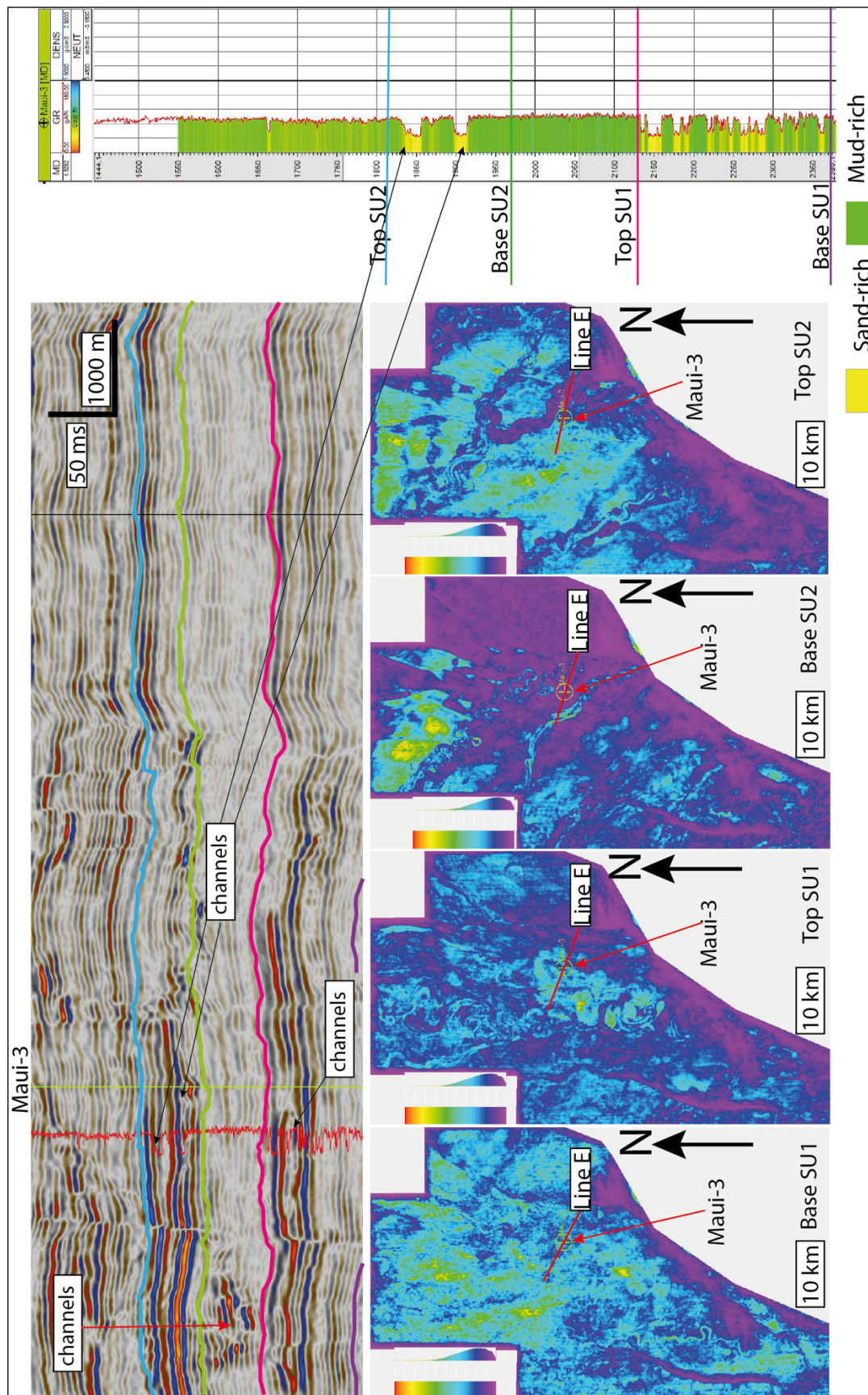
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APPENDIX

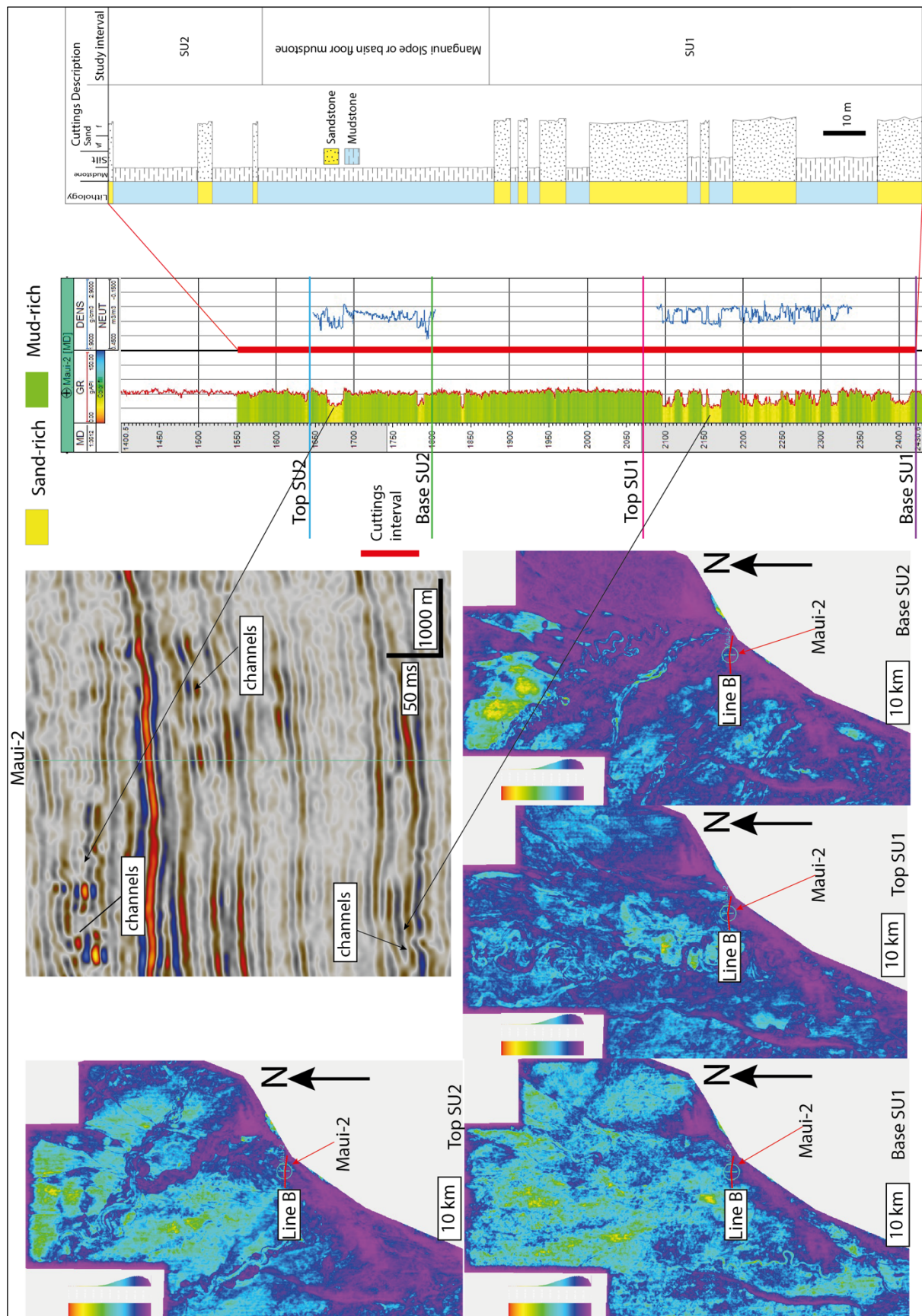
APPENDIX 1.A – H: Clearly demonstrate the calibration of the seismic facies by well logs. For each well, a montage of an amplitude map, a seismic line through the well penetration and the gamma log from the well was generated. This gives a systematic characterisation of the seismic facies e.g., channel axis penetrations, levee penetrations etc



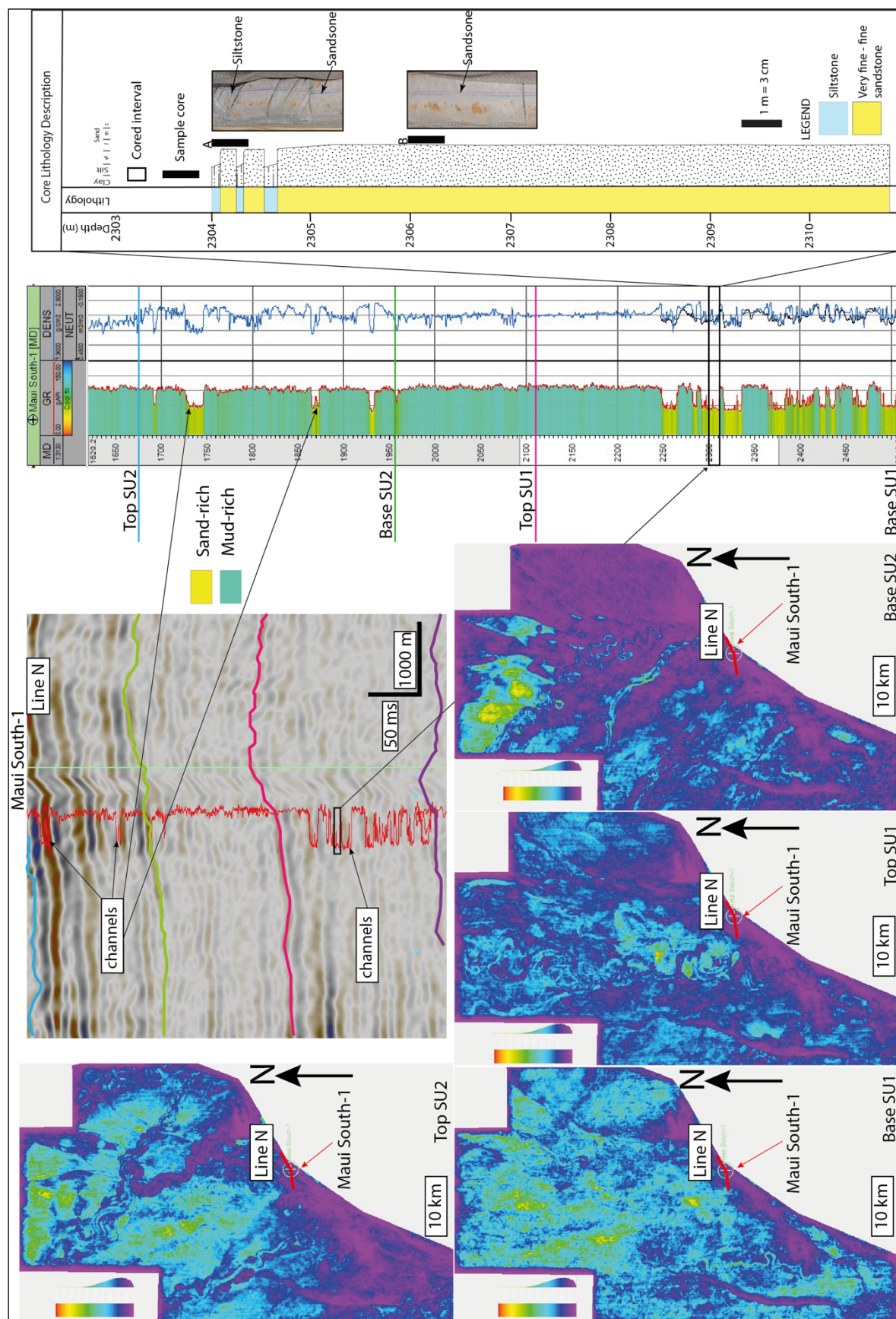
Appendix 1. A



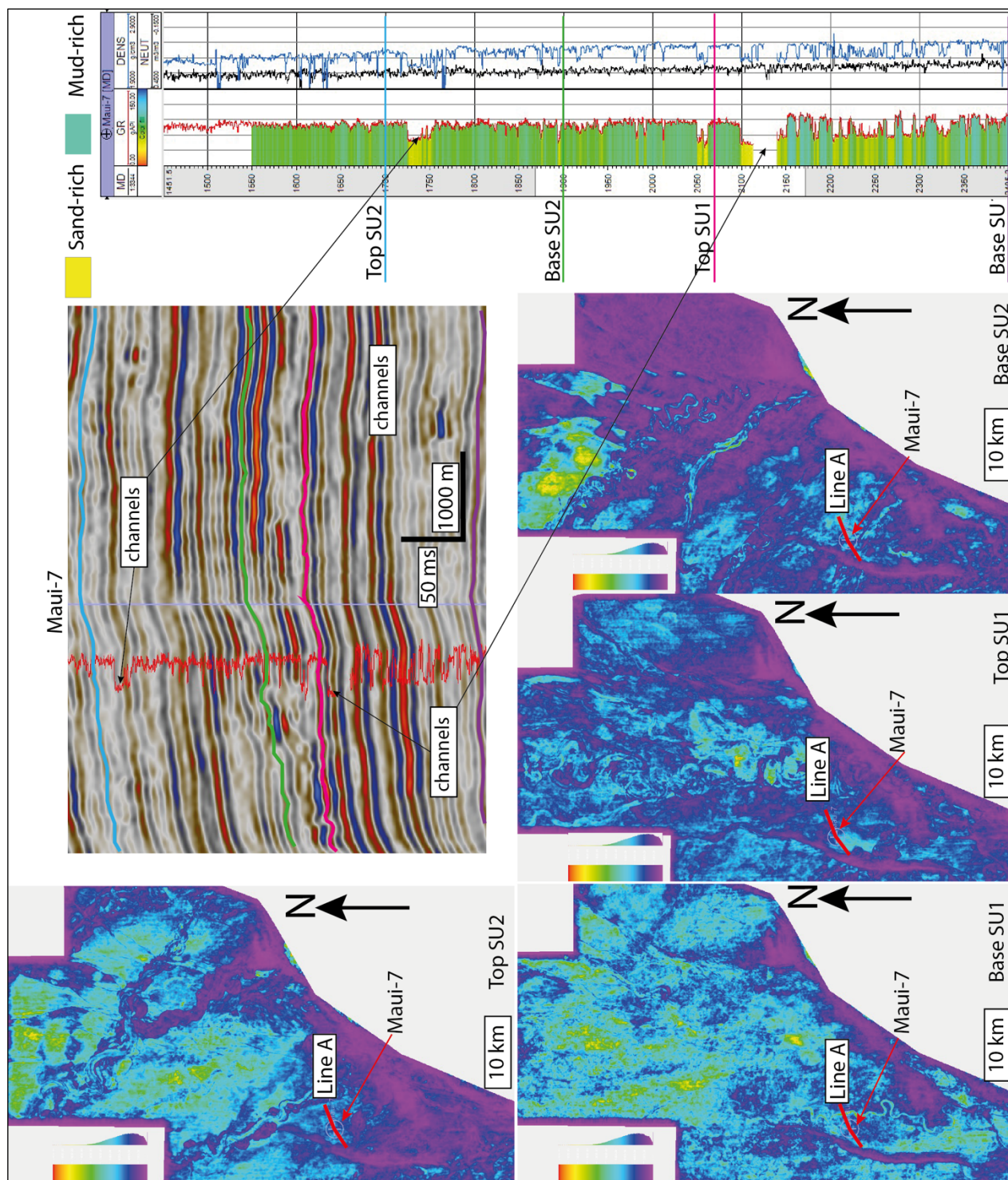
Appendix 1. B



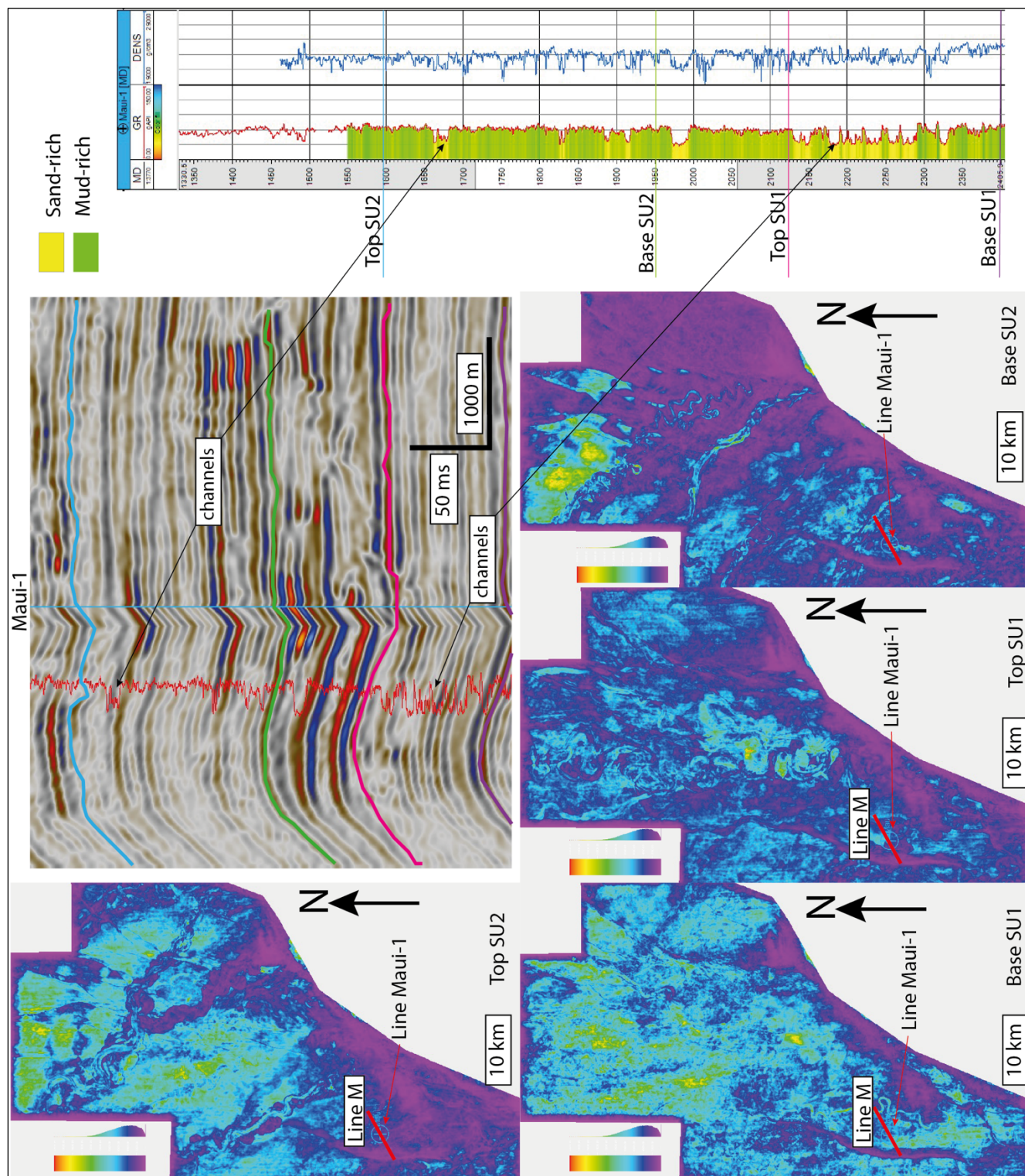
Appendix 1. C



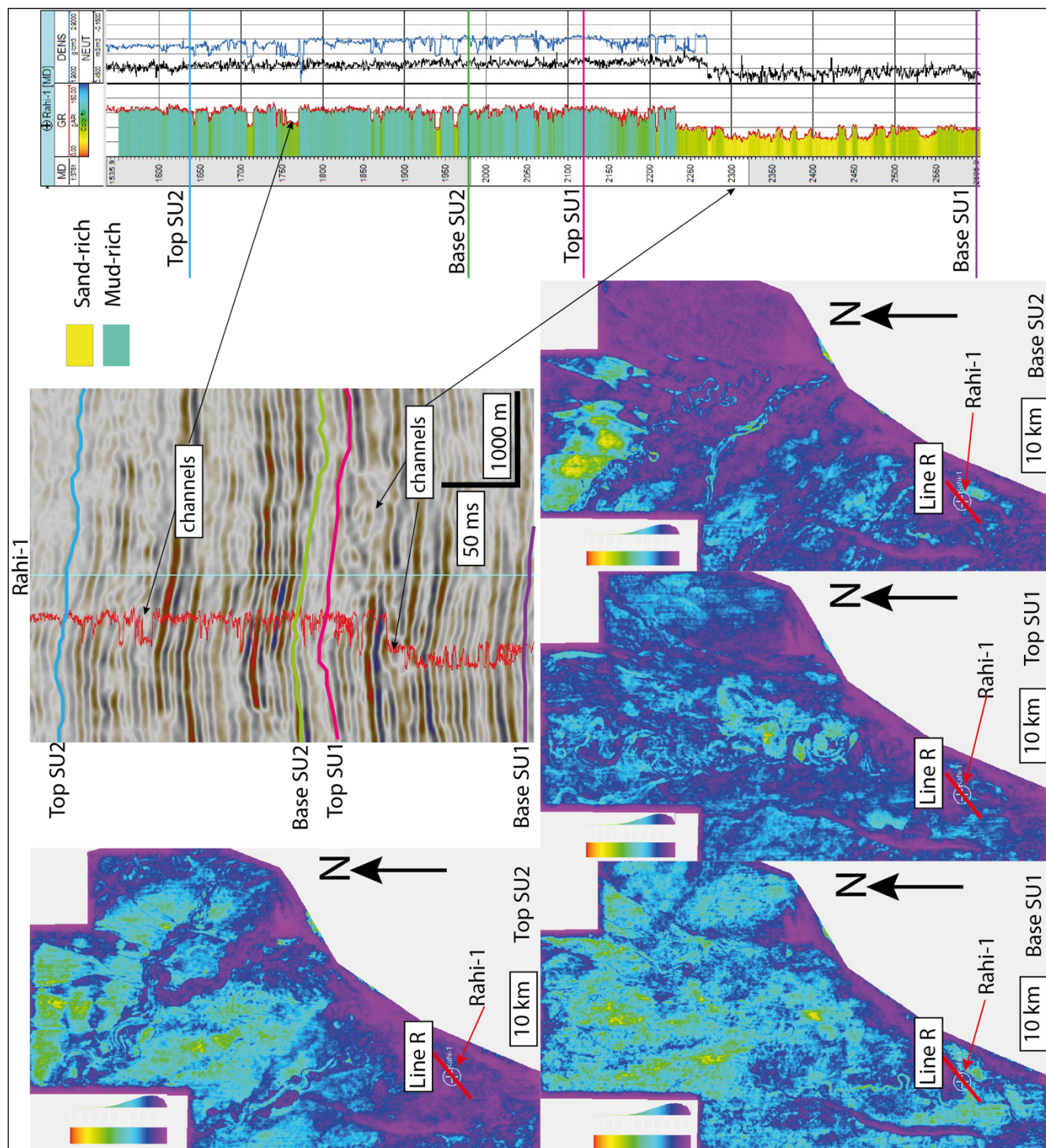
Appendix 1. D



Appendix 1. F



Appendix 1. G



Appendix 1. H