A Focus on the Sedimentology of Transgressions in Interior Seaways: Utilising Modern and Outcrop Analogues to Interpret the Subsurface Cretaceous Murta Formation, Eromanga Basin, Australia

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Statement of Author's Contributions

Chapters, intended in the future to be written as papers, presented in this thesis are co-authored. Hence, detailed statements of relative contributions are summarized and endorsed by the co-authors.

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Name of Co-Author	Dr Kathryn Amos		
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Abstract

Comprehension of the character and stratigraphic architecture of sedimentary rocks in the subsurface is derived from the observation of modern depositional processes on the surface of the Earth and field-based studies of similar depositional systems exposed in outcrop. In Australia's Eromanga Basin, the Murta Formation is a substantial hydrocarbon reservoir; however it does not outcrop, data from wells are sparse and the depositional setting has previously been interpreted to be both continental lacustrine and marginal marine.

Through extensive field and laboratory work, both for the Murta Formation and depositional analogues, this study investigates and discusses the sedimentology, stratigraphy and provenance of the Murta Formation in the Eromanga Basin. Murta Formation sediments were deposited in the Lower Cretaceous during the Berriasian to Valanginian, a key time of increased variation in global eustacy, continental breakup, climate change and just after a catastrophic mass extinction event at the Jurassic-Cretaceous boundary. Core investigations reveal that the Murta Formation is primarily composed of fine sands and muds, often arranged in coarsening up parasequences that become increasingly sand-dominated up section. The Murta Formation thickens over the Patchawarra and Poolowanna troughs, suggesting a basin depocentre in this area. Two basin-wide transgressive-regressive events are interpreted to have occurred and these most likely correspond with marine incursion in the Upper Murta Formation as the Eromanga Basin transitioned from continental lacustrine to marginal marine conditions. Zircon data indicate that sediments are sourced from mature cratons and younger volcanic provinces. This implies that the potential for unexplored reservoir presence on the western side of the basin is

substantial, as mature, clean sands in were most likely deposited there in proximal deltaic environments.

This project was motivated by research questions arising from the discovery of the Cuisinier Field, which unexpectedly yielded hydrocarbons in a new facies type within the Murta Formation. Sands within the Cuisinier system most likely represent a delta system deposited during a basin-wide marine regression and transgression event. As data for the Murta Formation are sparse, fluvial terminations in low accommodation basins are not widely-studied and marine transgressions in epicontinental seaways tend to be complex, analogue studies were also conducted. Lake Yamma Yamma in central Australia was investigated as it includes a substantial area of fluvial termination deposits at the main lake inlet, and has a similarly low-gradient basin setting to that of the Murta Formation. The geomorphology and sedimentology of deposits at the Lake Yamma Yamma site were described in detail, and controls on deposition interpreted. Based on this analogue study and literature review, ideas around the theme of fluvial termination deposits in a low gradient basin setting were applied to interpretation of the Murta Formation. The Dakota Formation, deposited at the initiation of the Cretaceous Western Interior Seaway, in Colorado, USA, was considered in detail at a specific outcrop locality and used as an analogue for the Murta Formation because it comprises a net transgressive system preserving internal transgressive and regressive cycles. Overall, the transgression was complex and piecewise. The size and shape of the deltaic features are similar to those observed in core in the Murta Formation, so thus provide a useful indicator for likely facies arrangements, as well as reservoir connectivity and geometries in the Murta Formation.

These new studies of deposits in modern and outcrop localities, in

combination with published literature, allowed an improved facies model to be developed for the Murta Formation. They also provide new insights into previously unstudied deposits, and contribute to aspects of research focus that are presently understudied. Lake Yamma Yamma has not previously been the focus of any papers despite being the largest playa lake in Queensland, Australia, and containing a substantial dryland terminal fluvial deposit, features often interpreted in the ancient record but not well studied in modern environments. As a part of this research, a new classification scheme to aid in the description and interpretation of dryland fluvial termination deposits is proposed. Although the Dakota Formation has been the focus of previous studies, the particular locality studied in this thesis has not been described in detail or assigned a comprehensive stratigraphic framework. As well as providing a detailed description of the sedimentology and a stratigraphic framework for the study area, this study also contributes new detrital zircon ages, which enabled an improved understanding of regional paleogeography. Furthermore, deposits preserved as a result of transgressions of epicontinental seas are not well understood and with no observable modern analogues, the detailed process-based understanding contributed by this study is very important in understanding similar deposits in the subsurface. In addition to contributing new perspectives on the Murta Formation of the Eromanga Basin, dryland fluvial termination deposits and the Dakota Formation of the Western Interior Seaway, the results of this thesis will provide a useful resource for the interpretation of similar systems in the geologic record.

Contents

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Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree. I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

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8th of August 2017

Date   Sandra Mann

Chapter 1: Contextual Statement

This thesis contributes an improved understanding of marginal lacustrine and marginal marine deposits, with a final focus on marine incursions. Understanding the nature and character of marine incursions is necessary for reconstructing Earth history. Identifying these through distinction between lacustrine and marine deposits is generally not well documented, and is often difficult. Understanding the nature of deposit composition and architecture in relation to marine transgressions is important for formation of consistent basin-wide stratigraphic models, which are an important tool in hydrocarbon exploration and development. The existing limited range of well-studied examples do not capture the scale or complexity of transgressions in eperic and epicontinental seaways, or the complex nature of the transgressions that occurred in the Cretaceous, in part due to climate change. This thesis contributes analysis of sub-surface, outcrop and modern deposits in order to develop an improved understanding of the nature and character of marine incursions into a marginal lacustrine environment in a low-gradient depositional basin during the Cretaceous. This work is intended to fill a knowledge gap in the understanding of Eromanga Basin fill, as well as to provide case studies that contribute to knowledge gaps relevant to the wider geoscience community.

This study was initially motivated by the 2008 discovery of a new hydrocarbon accumulation. This discovery in the Murta Formation of the Eromanga Basin challenged long-held models regarding the nature and character of the Murta Formation. The Eromanga Basin, an important resource for Australia, covers more than one-fifth of the Australian continent (over a million km^2), contains the country's largest and most important aquifer and is the most prolific onshore hydrocarbon-producing province. This study is the first to examine this reservoir target in detail. Examples of sedimentation style are explored and the broader significance of the depositional setting is considered. The goal of this work is to develop a more complete picture of the Cretaceous Murta Formation in the Eromanga Basin from a sedimentologic perspective, with a view to improve petroleum exploration and development.

The study focus includes, but is not limited, to:

- process-based sedimentology and depositional environments,
- reconstruction of depositional processes and paleogeography,
- sequence stratigraphic interpretation and significance,
- regional provenance and trends,
- scale and distribution of depositional elements.

The study is based on the following research problems:

- What is the nature of fluvial terminations in low accommodation basins? Is there any way of classifying and comparing these? What are the key sedimentary characteristics, depositional settings and sand-body geometries in these settings?

- What is the nature of marine transgressions in epicontinental seaways? Particularly as the transgression commences; what are the sedimentary features, depositional processes and preserved geometries?

- What was the depositional setting and paleogeography of the Murta Formation? Was deposition dominated by marginal marine or lacustrine conditions? What was the depositional nature of the formation across the basin and what are the key controls on deposition?

The Murta Formation in the Eromanga Basin does not outcrop in a way that allows for meaningful study. Interpretation relies on sparse well data, the quality of which is varied. To complement available data and published literature, two analogue studies were undertaken: the well exposed Quaternary sediments of the Kati Thanda- Kati Thanda- Lake Eyre Basin, Australia; and Cretaceous outcrop of the Uncomprahange Plateau, Colorado USA. These make for natural laboratories in which to examine sedimentary features and depositional environments, with similarities to those in the Eromanga Basin, which cannot be viewed directly in the subsurface.

Following this contextual statement this thesis is divided into an initial literature review, four data chapters containing original research and a conclusion. All chapters focus on understanding certain aspects of the Murta Formation, both directly and through the study of analogous deposits. This thesis is confidential to the sponsoring company for three years from the submission date.

In the next chapter (Chapter 2) a detailed literature review provides background and puts the deposits described in later chapters in a larger context by reviewing many of the existing studies on the geological setting and sedimentary fill of the basins studied. This chapter allows the original research in this thesis to be viewed within the framework of previous investigations. The review is divided into two sections. The first section covers the discovery of the Cuisinier Field, which provided the research questions for this thesis work. Interpretation of the Cuisinier Field forms the focus of Chapter 3. The second section covers the specific study sites: Lake Yamma Yamma in central Australia; the Dakota Formation in South-West Colorado; and the Eromanga Basin in Australia. This detailed literature review demonstrates the need and context for the investigations presented in subsequent chapters.

Chapter 3 presents analysis of seismic, whole core, wireline and petrographic data in order to provide a depositional model for the Cuisinier Field. Existing depositional models for the Murta Formation are not well integrated over the entire basin. The discovery of the Cuisinier Field revealed a new facies not predicted by previous depositional models. As the reservoir is largely below seismic resolution, detailed stratigraphic analysis guided the development of the depositional model. The Murta Formation is interpreted as marginal marine to continental lacustrine at Cuisinier. Within the Cuisinier region study area, Murta Formation strata comprise five facies associations that form a depositional continuum of offshore to fluvial-dominated channel fill. The primary reservoir occurs in fluvial channel fill. Reservoir sand deposition is primarily controlled by rising and falling base level causing a series of transgressions and regressions, although autocyclic processes such as bifurcation and avulsion on the delta plain and delta front are important when considering reservoir compartmentalisation. As reservoir sandbodies are largely below seismic resolution unless stacked or amalgamated, it is clear from this investigation that further process-based investigation into analogues for the Murta Formation is needed. This is the first academic work on the Cuisinier Field and the first academic work for more than twenty years to examine the Murta Formation.

Chapter 4 focuses on Lake Yamma Yamma, a locality by the sponsor company as a modern analogue for the Murta Formation. Some aspects of Lake Yamma Yamma, such as the basin gradient and tectonic setting, are thought to be similar to the Murta Formation in the Eromanga Basin. Although Lake Yamma Yamma is not the ideal representative analogue for the Murta Formation, it did provide an opportunity to describe and characterise poorly understood dryland terminal fluvial and lacustrine facies and their characteristics, geometries and interactions. Fieldwork for this study was conducted over several weeks in this remote area, over 250 km from the nearest town. In the field three hundred and fifty-two sediment samples were collected for analysis by the author with a laser particle sizer and six trenches were logged to provide an overview of sedimentary characteristics for the lake. Over thirty kilometres of Real Time Kinematic (RTK) GPS data was taken and detailed element dimension data was collected in order to provide insights into depositional element dimensions. Distinctive lithofacies, facies associations and elements which can characterise terminal fluvial lacustrine depositional environments are documented and could be used as interpretative and predictive tool in analogous settings. The formation and evolution of Lake Yamma Yamma is linked to subtle tectonic changes in the region, which had a large impact on local sedimentation. In this chapter, a preliminary new framework for classifying and comparing modern dryland fluvial terminations is also presented. This is the first work on any aspect of Lake Yamma Yamma, and one of the few focussed on sedimentology of dryland fluvial terminations.

Chapter 5 focuses on the Dakota Formation, exposed on the Uncomprahange Plateau between the towns of Montrose and Ridgway as well as around the region in south-west Colorado. The Dakota Formation is an ancient outcrop analogue for the Murta Formation, as it represents a similar process of regressive and transgressive clastic wedges deposited along an interior seaway. Fifty-seven continuous cliff-face sections were measured, each comprising between 17 m and 32 m in vertical thickness. Lithologies were examined closely with regard to bed thickness, grain size, sorting, roundness, sedimentary structures, bed continuity and lateral characteristics. A GigaPan Pro paired with an DSLR was used to capture over 40 high resolution panoramic images of exposed cliff faces. Detrital zircons from twelve rock samples were processed and analysed by the author in order to understand more about the provenance and paleogeographic history of the sediments. Distinctive lithofacies, facies associations and facies successions were identified. The size and characteristics of certain features of the formation facilitate discussion about the merits of interpreting these features as incised valleys, compared to regressive-transgressive sequences. Results from this work could be used as interpretative and predictive tool in analogous transgressive settings. Despite the Cretaceous Western Interior being a focus for many geological studies, this is the first work focussed on the sedimentology, stratigraphic and paleogeography of this local area. This chapter is not intended as a detailed basin-wide correlation for the Dakota Formation, but as a detailed localised sedimentology and stratigraphy study to be considered as an example when interpreting the Murta Formation. This chapter is unique in that it describes and discusses sedimentary processes and features which characterise the initial transgression of an epicontinental seaway.

Chapter 6 presents a basin-wide stratigraphic study of the Murta Formation throughout the Eromanga Basin, based on wireline logs, core descriptions and detrital zircon geochronology with an aim to improve the conceptual geological model and develop paleogeographic reconstructions. A total of forty-five representative cores intersecting the Murta Formation were logged, ninety-two representative wireline logs were analysed and twelve samples were processed for detrital zircon geochronology. Facies analysis results show that sediments in the lower Murta Formation were most likely deposited in a marginal lacustrine environment. Sediments in the Upper Murta Formation were most likely influenced by marine conditions as a Cretaceous seaway developed. Evidence for both depositional settings is substantial. Basin fill was most likely sourced from proximal cratons from all sides of the basin during deposition, rather than exclusively from the north-east of the basin, as previously thought. This is the first study to use detrital zircon geochronology in subsurface sediments within the Murta Formation and the first to present an integrated stratigraphic model for the formation.

Chapter 7 concludes this thesis by summarising the key points and significance of these studies and recommending further areas of research. Each of these studies plays a useful role in understanding sedimentary processes influential in the deposition of the Cretaceous Murta Formation in the Eromanga Basin. The results presented in this thesis are useful for understanding the evolution and character of clastic lacustrine to marginal marine transgressive systems through the global geological record.

Chapter 2: Background and Review of Relevant Literature

This review provides the background necessary to understand the spatial, temporal and stratigraphic context in which the original research for this thesis exists and gives an introductory framework for the investigations presented in later chapters.

The first section presents the details of the discovery of the Cuisinier Field in the Eromanga Basin, explains the importance of the Murta Formation as a reservoir target and introduces the research problems addressed in this thesis. Section two reviews the geological background of the study locations: Lake Yamma Yamma, a modern depositional environment within the Kati Thanda- Lake Eyre drainage basin, central Australia; the outcropping Dakota Formation deposited in the ancient Cretaceous Western Interior Seaway, USA; and the subsurface Murta Formation in the Jurassic-Cretaceous Eromanga Basin, Australia.

2.1. Overview of the Cuisinier Field

The Cuisinier Field was discovered on the 25th of April 2008 as a result of drilling the well Cuisinier-1 in the onshore Eromanga Basin, central Australia (Figure 1). Cuisinier-1 was designed to test hydrocarbon potential in the Jurassic Hutton Sandstone (McPhail et al., 2014). Instead, drilling results indicated conventional oil pay higher in the column, in the overlying Cretaceous (Berrasian to Valanginian) Murta Formation (Figure 2) contained in a structural and stratigraphic combination trap. Results from the well were contrary to existing recorded lithofacies and facies models (Figure 3). Existing depositional models for the Murta Formation did not predict sand-rich reservoir facies at this location.

Depositional models for the Murta Formation (Ambrose et al., 1982; Ambrose et al., 1986; Gorter, 1994; Bradley, 1993; Mount, 1981, 1982; Newton, 1986;

Zoellner, 1988; Lennox, 1986; Theologou, 1995; Hill; 1999) have been presented as lacustrine to marginal marine. The most prolific reservoir facies are contained in fluvial terminations deposited at the margins of a lake or a seaway.

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The paleoclimate during the deposition of the Murta Formation is interpreted to have been cool to temperate (White, 1994). The Early Cretaceous positioning of the Eromanga Basin is comparable to the present day latitudes of Norway and Alaska (Gorter, 1994). The Eromanga Basin was a low accommodation basin with accumulation rates similar to the overlying Paleocene-modern Kati Thanda- Lake Eyre Basin (Gravestock et al., 1995; Jansen et al., 2013), with fluvial terminations likely to be thinly bedded. A more description of the Murta Formation and the Eromanga Basin is included later in this chapter.

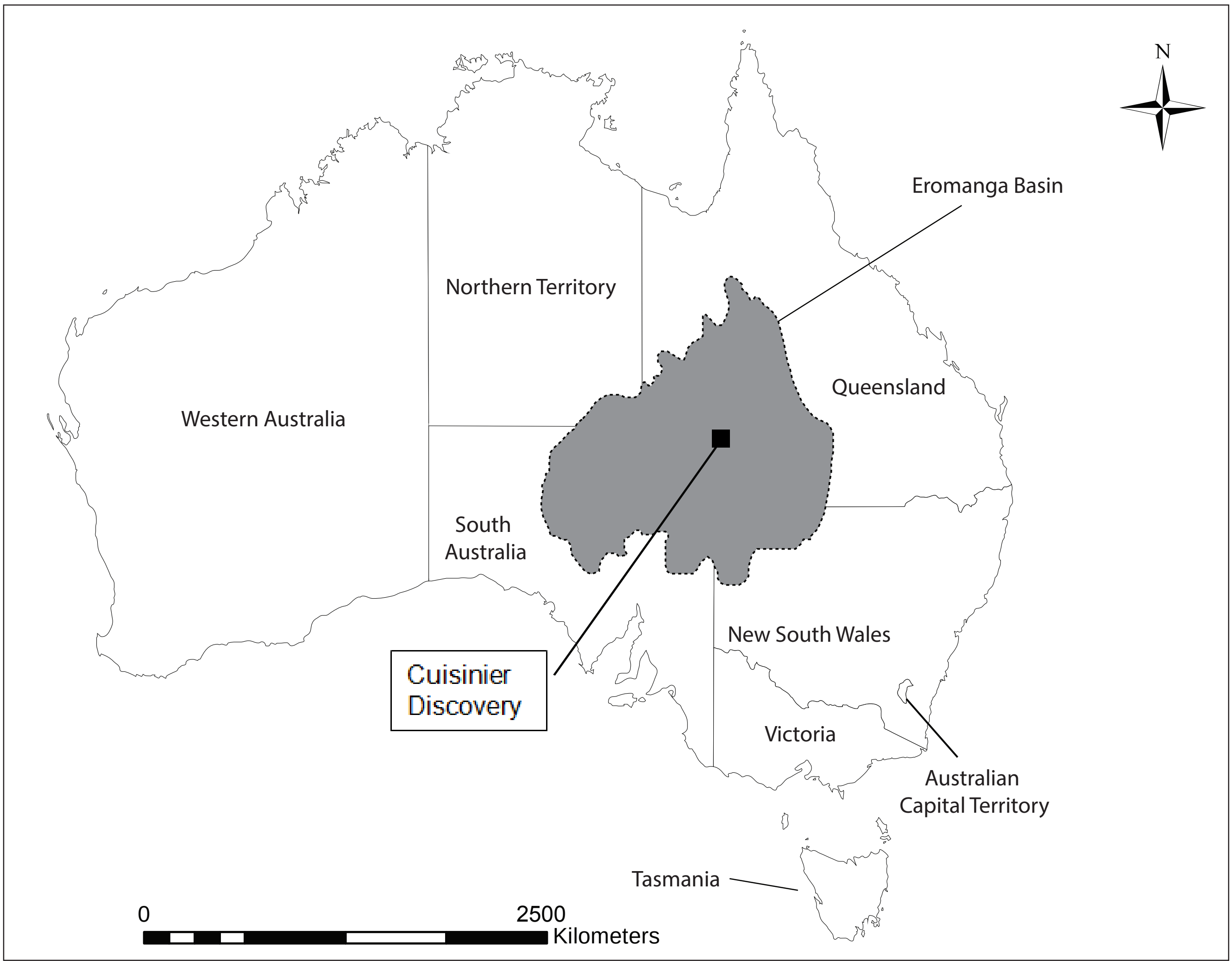


Figure 1: The Cuisinier Discovery at Cuisinier-1 is located in South-West Queensland in the Eromanga Basin.

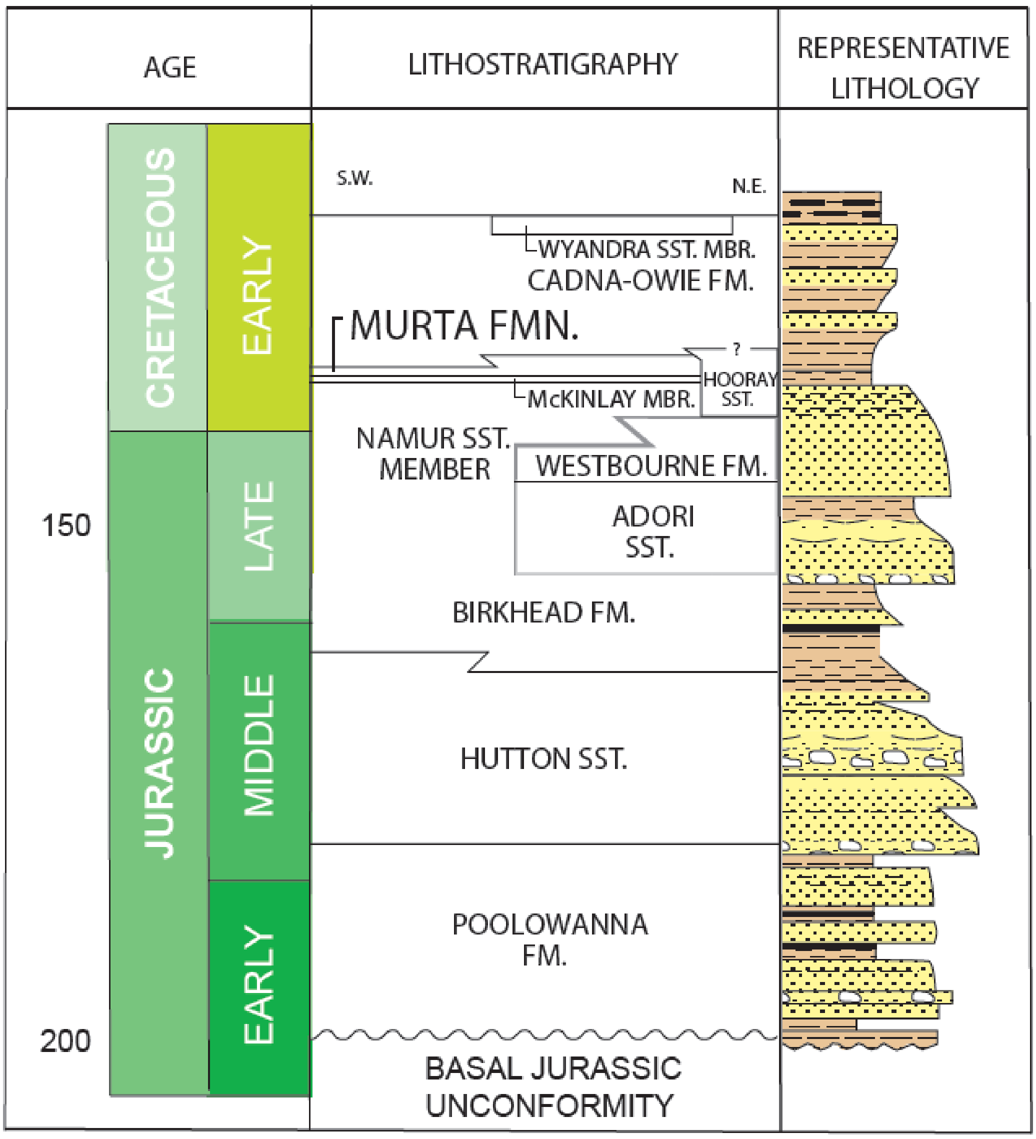


Figure 2: Cuisinier-1 was originally designed to test hydrocarbon potential within the Jurassic Hutton Sandstone. Instead, hydrocarbons were intersected in the overlying Cretaceous Murta Formation. In the lithology column yellow represents sands, brown represents muds and coals are shown in black. Yellow dotted patterns represents sands, brown striped patterns represent shales, curved fill represents cross-beds and ovals with white fill represent coarse material.

As reservoir sands exhibit a gross thickness of less than fifteen metres, seismic data were not able to resolve sandbodies. Decision making was driven by the geological model. To date, twenty-one wells have intersected oil in the Cuisinier field, seventeen of which, including a near-field exploration well (Shefu-1), were planned and drilled as this research was conducted. The near-field exploration program was a success, with Shefu-1 situated on the western flank of PL 303

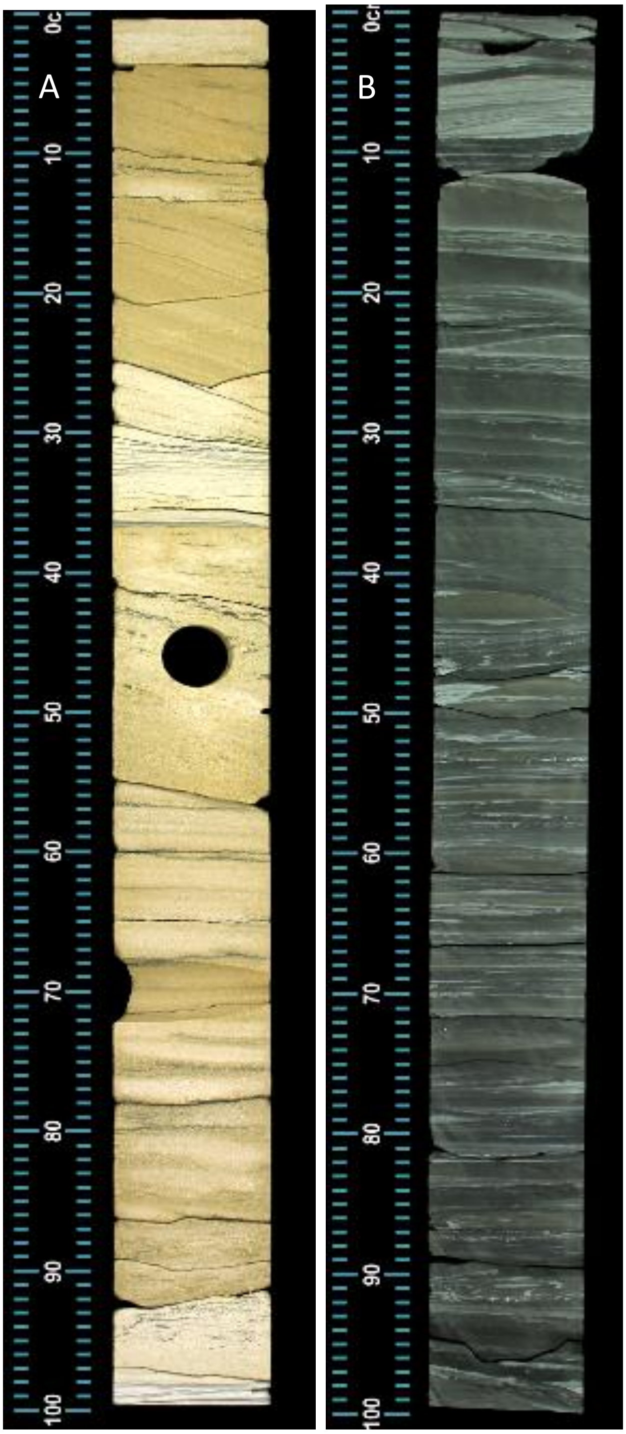


Figure 3: Cuisinier-1 was a new Murta oil discovery. Results from the well were different to those predicted by existing facies models. Lithologies such as A, cross-stratified and ripple laminated sandstone, were not expected. Lithologies such as those in core B, interbedded and interlaminated sandstone, silty sandstone, siltstone and mudstone typically characterise the Murta formation and have been intersected in approximately ninety intersections throughout the Eromanga Basin. Scale is in centimetres.

(Figure 4) approximately 5 km west of the nearest Cuisinier development well, encountering twelve metres of oil pay exhibiting virgin pressures. At Shefu-1 pay occurs structurally lower than encountered in previous wells at Cuisinier, therefore lowering the lowest known oil estimates for the area. The oil-water contact has not been intersected. Results greatly increase oil in place, given that the Shefu-1 area is well outside of areas previously included in estimates (Figure 4).

Considerable follow-up and development potential for the Murta Formation is present, given the success at this location. The Cuisinier Field discovery is an exciting example of the potential for new discoveries and raises important research questions about the sedimentary fill and paleoenvironments across the Eromanga Basin. The deposits below the Murta Formation are fully continental, and the conformable overlying formation is fully marine (Gravestock et al., 1995). Given the varied interpretations of the Murta Formation as being lacustrine and/or marginal marine, a careful interpretation of the depositional environment is called for. An improved understanding of deposition in transgressive settings, particularly in epicontinental seaways, could assist in the interpretation of deposits such as those preserved within the Murta Formation. It is likely that the reservoir targets within the Murta Formation are fluvial terminations. The depositional controls and internal architecture of deposits which occur as a result of the termination of fluvial systems in low accommodation basins and in epicontinental seaways during the transition between lacustrine and marginal marine depositional settings are not well-studied and could greatly benefit from insights gained through analogue studies.

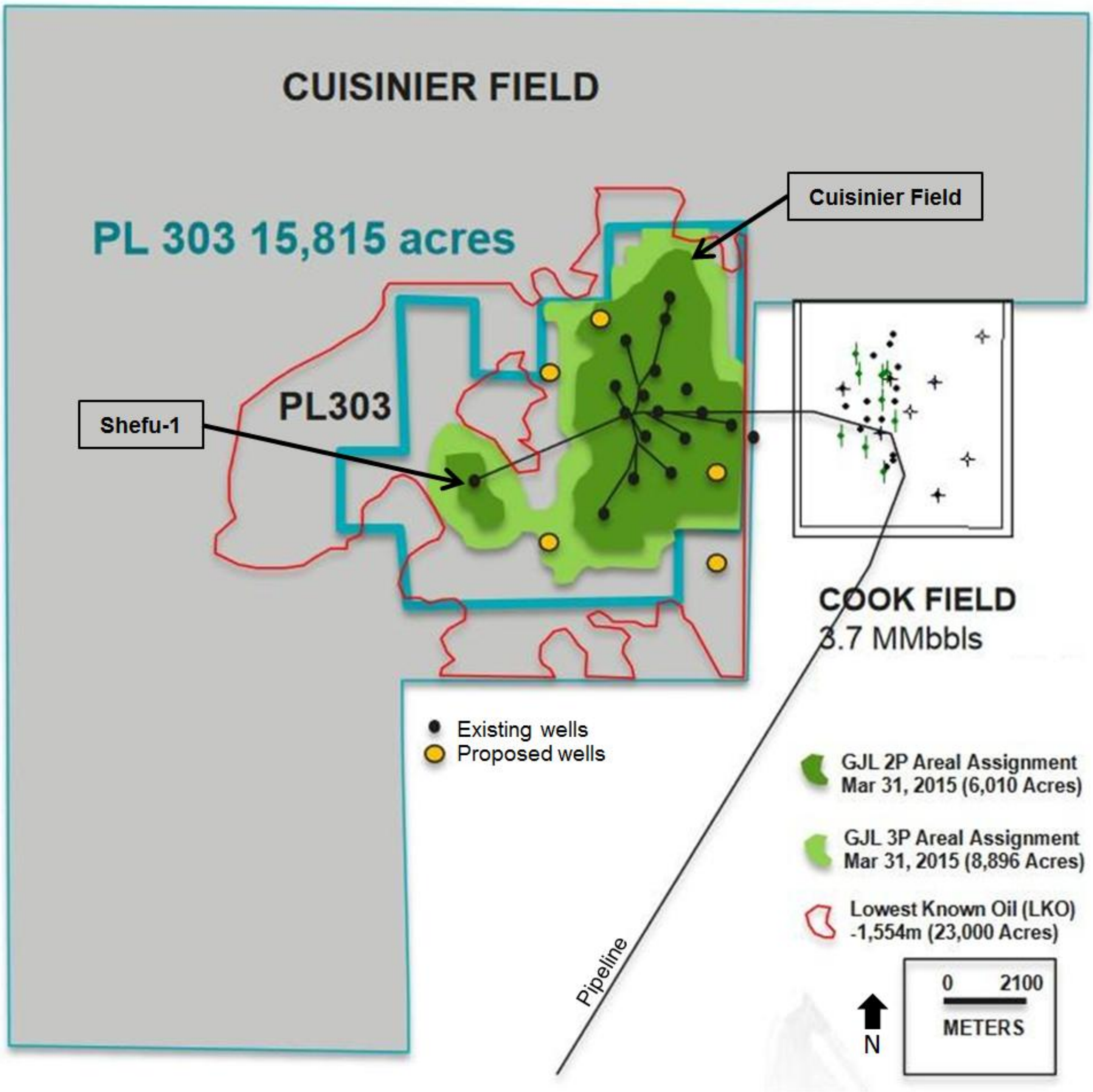


Figure 4: Results of step-out program at Cuisinier, Shefu-1, increased the lowest known oil and area assessment for the field. The oil-water contact has not been intersected. The Cook field, which is located on the next permit, produced hydrocarbons from the Hutton Sandstone and is on a different pressure gradient. The Cook field used to be the largest oil discovery in South-West Queensland, before the Cuisinier Discovery. See Figure 1 for location of the Cuisinier Field within the context of the Australian continent.

These topics can be summarised into the following research themes:

-The sedimentology, stratigraphy and morphology of fluvial terminations in low accommodation basins.

-The sedimentology and stratigraphy of marine transgressions in epicontinental seaways.

-The sedimentology, stratigraphy, depositional setting and paleogeography of the Murta Formation, including the Cuisinier Field.

This thesis investigates these research themes through the investigation of analogues. The Dakota Formation, deposited as the Cretaceous Western Interior Seaway was initiating, was studied as an ancient outcrop rock record analogue for the Cuisinier Field and the Murta Formation. The Dakota Formation has many similarities with the Murta Formation in that both were deposited in low gradient basin settings with similar depositional environments and settings. Depositional architecture is likely to be similar in these settings. The Dakota Formation was deposited in a warm temperate climate, which is different from the interpreted cool temperate to peri glacial Cuisinier Field and Murta Formation. Lake Yamma Yamma, off Cooper Creek in the Kati Thanda- Lake Eyre Basin was considered as a modern depositional analogue. This was selected as an analogue for the Cuisinier field as both were deposited in low gradient intracratonic basins. Although we do not have a detailed understanding of the climate in Australia during the Cretaceous, it is interpreted to have been cool temperate to peri glacial. This is different from the dryland setting of Lake Yamma Yamma and this must be taken into consideration when making comparisons.

This research has the potential to aid in the interpretation of not only the Murta Formation, but also similar types of deposits throughout the global geological record.

2.2. Regional Geological Background for Study Locations

2.2.1. Lake Yamma Yamma

Lake Yamma Yamma is an ephemeral dryland lake which receives flow and sediment from the western side of the Cooper Creek floodplain, between Windorah and Nappa Merrie, prior to the constriction of the Cooper Creek floodplain near the Innamincka Dome. The long axis of the lake follows the trend of the Yamma Yamma Syncline along strike. The basin base level of Cooper Creek is Kati Thanda- Lake Eyre, 700km downstream and approximately 90m lower (Queensland Government, 2016). No aspect of the Lake Yamma Yamma has been described in published literature. This region provides a natural laboratory to study modern sedimentation in an ephemeral dryland lake. Chapter 4 provides a detailed technical description of the sedimentology and near-surface stratigraphy as well as the depositional environments and processes at Lake Yamma Yamma.

Large dryland lakes far above basin base level can represent sediment sumps, which can be of importance to paleogeographic reconstructions. Lake Yamma Yamma is the largest inland ephemeral lake in Queensland, Australia. When full, Lake Yamma Yamma covers approximately 690 km^2 and reaches about 1 metre total depth. The lake fills completely approximately once every 25-30 years; however there is generally some localised seasonal inundation in the northeast section as a result of Cooper Creek overflow. Although shallow, due to a large surface area, the lake can store substantial volumes of water and is a significant contributor to transmission losses along Cooper Creek. The most recent complete filling event of the lake was in 2015, after the study presented in this thesis was conducted (Queensland Government, 2016).

Local rainfall events in the Lake Yamma Yamma region are rare and short lived. Lake Yamma Yamma is filled predominantly from Cooper Creek. Cooper Creek at Yamma Yamma receives flow from two rivers, the Thompson and the Barcoo (Queensland Government, 2016). Discharge follows a summer-dominant rainfall regime. The majority of rainfall in the catchment occurs in December, January and February (McMahon et al., 2008; Figure 5). Rainfall patterns are controlled by warm tropical air passing over the Great Dividing Range to the north east of Lake Yamma Yamma in the warmer months.

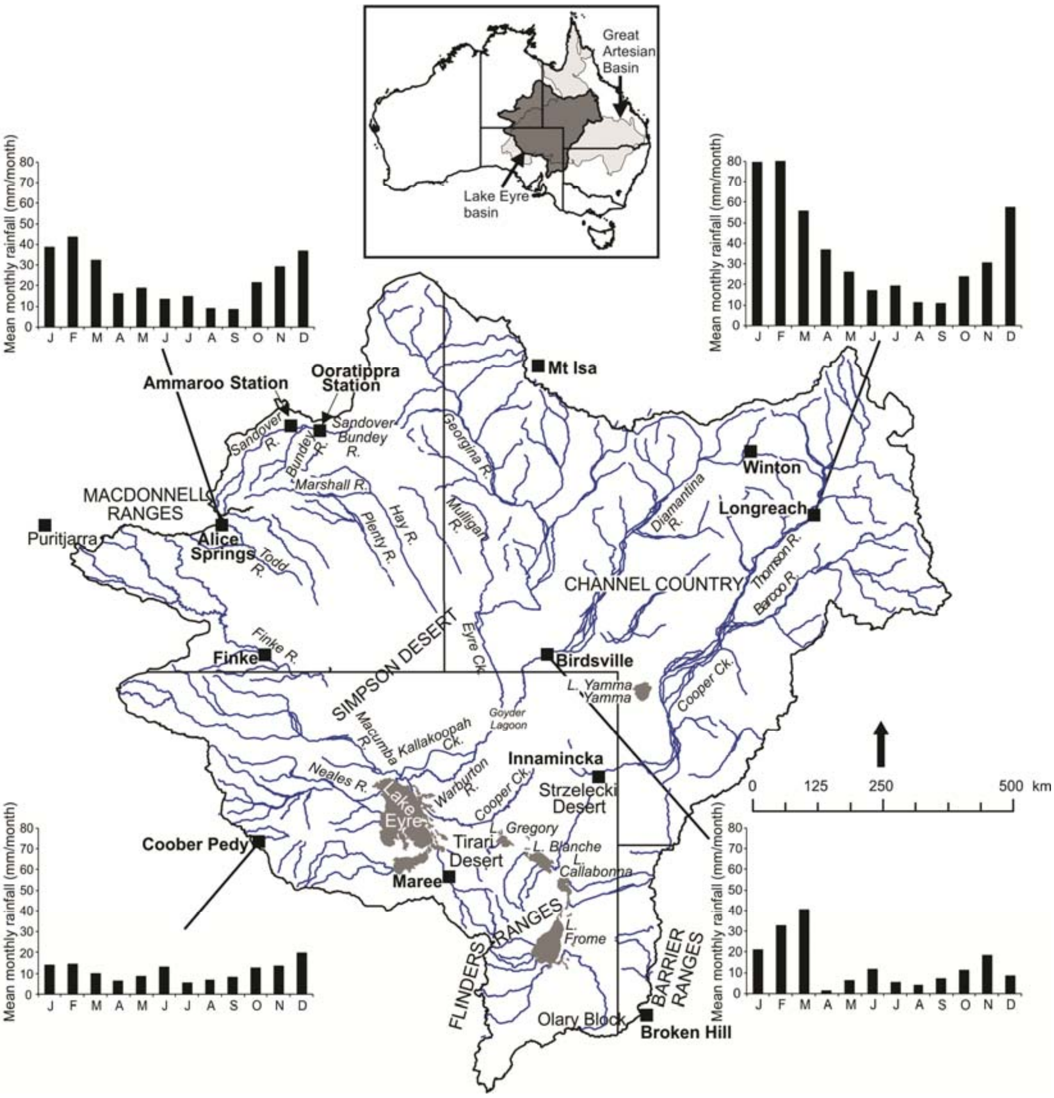


Figure 5: Overview map of the Kati Thanda- Lake Eyre basin, central Australia and mean monthly rainfall for Alice Springs airport between 1941 and 2013 (Australian Bureau of Meteorology (BOM) site number 015590), Longreach aero between 1949 and 2013 (BOM site number 036031), Birdsville airport between 2000 and 2013 (BOM site number 038026) and Coober Pedy airport between 1994 and 2013 (BOM site number 016090). The extent of the Great Artesian Basin is also shown in the inset (From Habeck-Fardy and Nanson, 2014).

Kati Thanda- Lake Eyre Basin Formation, Structure and Controls on Sediment Deposition

The Late Paleocene to Quaternary semi arid to arid Kati Thanda- Lake Eyre Basin (LEB), central Australia, one of the world's largest endorheic basins, is equal to approximately one-sixth of the Australian continent (1.14 million km^2) (Lang et al., 2004; Figure 6).The LEB is a shallow topographic depression that extends from the monsoon tropics at latitude 19° to the temperate zone at 32°. LEB rainfall patterns are dominated by moist tropical air passing over the catchment highlands (eastern highlands and northern table-lands) in the warmer months (Allan, 1990) and weakly influenced by the northern limit of westerly cold fronts on the southern margins of the basin (McMahon et al., 2008). The basin depocentre, Kati Thanda- Lake Eyre, the fourth largest playa lake in the world (Callen et al., 1986) contains Australia's lowest land surface, which is 15.2 m below sea-level on Belt Bay, Kati Thanda- Lake Eyre north (Lang et al., 2004).

A major unconformity separates the Eromanga Basin from the overlying LEB. Key characteristics of the Eromanga Basin influence the structure of the modern LEB (Senior et al., 1978), as well as contemporary Neogene-Quaternary tectonism (Senior et al., 1978; Wasson, 1983; Wells and Callen, 1986; Alley, 1998). Contemporary northwest and northeast trending anticlines generally control Quaternary drainage patterns. The youngest unit of the Eromanga Basin, the Upper Cretaceous Winton Formation (Senior, 1968) is exposed in the structural highs of the LEB (Figure 6).

During the late Paleocene, tectonic subsidence formed the large, shallow intracratonic Kati Thanda- Lake Eyre (geological) Basin (Krieg et al., 1990). The Quaternary has been a time of increasing aridity interspersed with pluvial conditions.

Immense lakes are interpreted to have formed during interglacials. A drying trend, in combination with windy conditions, in the last interglacial led to extensive dunefields which alternated with wetter periods of extensive fluvial and lacustrine sedimentation (Alley, 1998; Nanson et al., 2008).

Modern central Australia is virtually flat. Most alluvial areas within the Kati Thanda- Lake Eyre Basin are below 150 m AHD. Whether the influence of tectonics has been minor (e.g. Magee et al., 1995) or major (e.g. Quigley et al., 2010) in shaping geomorphic expression of the LEB at a regional level is a matter of ongoing debate. The role of tectonics at the local, more detailed level is important as low-gradient modern lake and rivers of this region are sensitive to subtle tectonic movements, the effects of which on sedimentation and channel pattern is substantial (Jansen et al., 2013).

The rate of sediment accretion due to tectonic alluvial impoundment upstream of the Innamincka Dome (see Figure 6 b) is interpreted to be 48 ± 21 mm ka^{-1} over the past 270 ka (Jansen et al., 2013). Based on a numerical model of intermittent erosion calibrated with Beryllium-10 measurements, Cooper Creek is interpreted to have incised at a minimum long-term bedrock incision rate of 17.4 ± 6.5 mm ka^{-1} (Jansen et al., 2013). Background bedrock denudation rates for central Australia are estimated to be considerably lower than this, at around 0.2 to 5 mm ka^{-1} (e.g. Bierman and Caffee, 2002; Belton et al., 2004; Fujioka and Chappell, 2011). The rising Innamincka Dome has resulted in the formation of an extensive Cooper Creek floodplain with accompanying anabranching channels extending hundreds of kilometres upstream (Nanson et al., 2008; Jansen et al., 2013). The lower Cooper Creek in the vicinity also appears to be affected by movement of these structures, with the formation of swamps and lagoons.

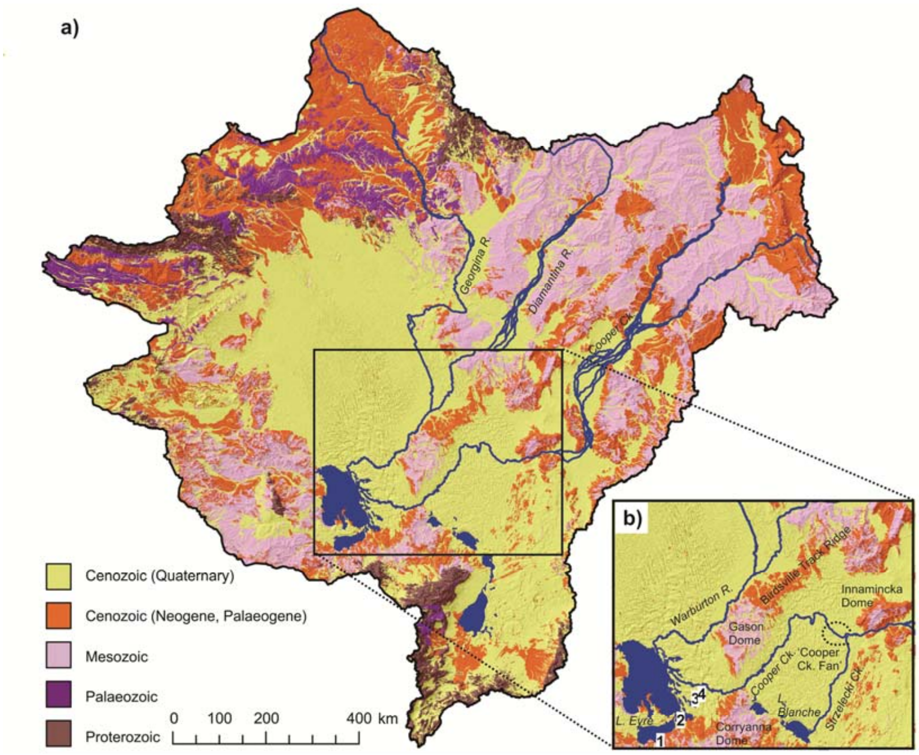


Figure 6: a) Surficial Geology and b) domes of the southeastern portion of the LEB (From Habeck-Fardy and Nanson, 2014).

Cooper Creek Geomorphology

The largest drainage catchment in the Kati Thanda- Lake Eyre Basin, and the main input point for Lake Yamma Yamma, is Cooper Creek. It has a river length of ~1500 km (including its primary upstream tributary, the Thomson River; Figure 7) and a 3000 km^2 drainage basin (Habeck-Fardy and Nanson, 2014; Figure 7). Cooper Creek comprises a complex fluvial system, often up to 60 km total floodplain width which transports mud and a minor sand load from its headwaters in central Queensland to Kati Thanda- Lake Eyre (Figure 9). Cooper Creek has been the focus of previous studies (e.g. Nanson et al., 1986; Rust and Nanson, 1986; Nanson et al., 1988; Knighton and Nanson, 1994; Fagan and Nanson, 2004; Maroulis et al., 2007; Cohen et al., 2010). Aeolian dunes, anabranching channels, braided flood channels, palaeochannels, splays and waterholes characterise the middle reaches of the Cooper Creek floodplain (Nanson and Tooth, 1999; Habeck-Fardy and Nanson, 2014; Figure 8).

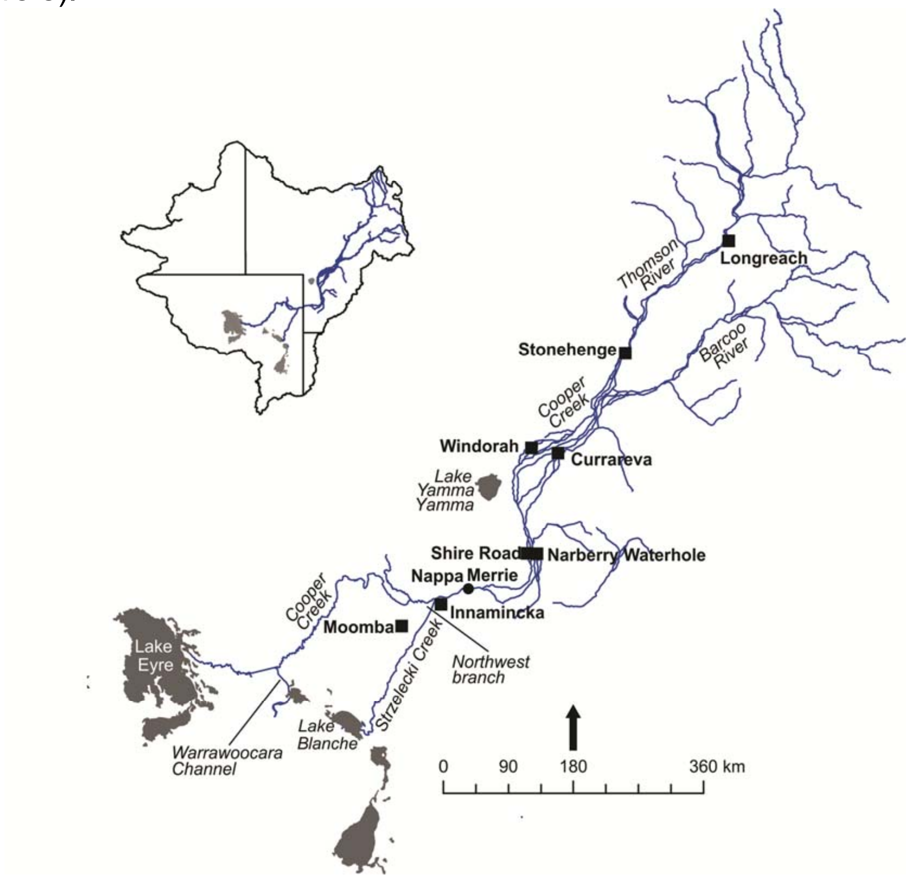


Figure 7: Cooper Creek Cooper Creek extends from the confluence of the Thompson and Barcoo Rivers to Kati Thanda- Lake Eyre in the eastern Kati Thanda- Lake Eyre basin (From Habeck-Fardy and Nanson, 2014).

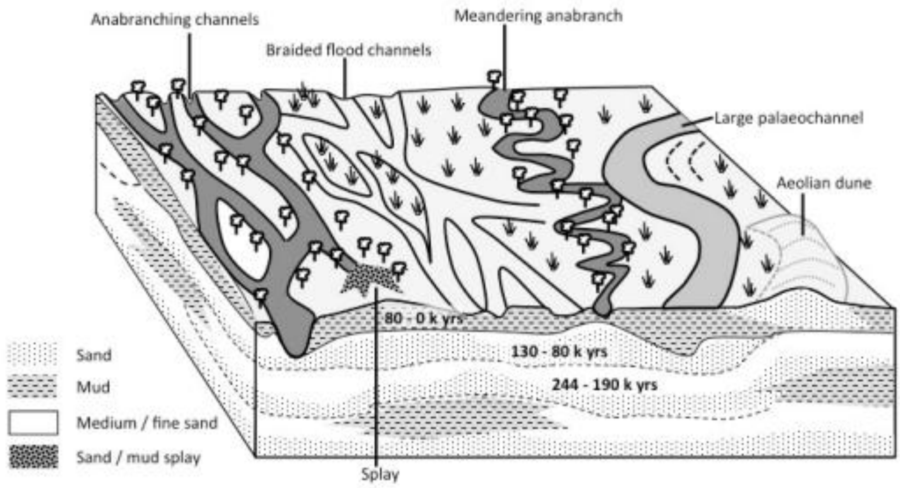


Figure 8: Schematic of the modern geomorphic elements of the middle reaches of the Cooper Creek floodplain (From Nanson and Tooth, 1999).

Anabranching channels along Cooper Creek between Windorah and Nappa Merrie near Lake Yamma Yamma tend to have one dominant main trunk, although numerous smaller sinuous small channels exist across the floodplain. These channels tend to have width-to-depth ratios of 4 to 60, steep banks formed of cohesive mud commonly lined with vegetation, low levees and a canal-like cross section. Two primary modern channel patterns coexist on the Cooper Creek floodplain; entrenched anabranching channels, which are active at high flow, and low wavelength sinuous surficial braided floodplain channels, which are active at high and low flow (Nanson et al. 1986). Mud is transported during overbank flow as bedload in the form of sand-sized mud pellets and via sinuous surficial braided floodplain channels over the floodplains (Nanson et al., 1986; Maroulis and Nanson, 1996). Mud is a product of weathering from young volcanic materials transported from upstream tributaries, primarily the Barcoo and Thomson Rivers. The anastomosing channels transport the relatively small sand bedload fraction, thought to be sourced from local tributaries, surrounding dunes and scoured from sand sheets underlying waterholes (Rust and Nanson, 1986). Channels often stem from and terminate in waterholes.

Waterholes along Cooper Creek range in length from a few hundred metres to over twenty kilometres, with typical widths of 20 to 100 m and depths of 6 to 10 m and are typically up to five times wider and three times deeper than their anabranching feeder channels (Figure 9). Over three hundred have been identified in the lower reaches between Windorah and Nappa Merrie (Knighton and Nanson, 1994). Waterholes provide focus points for erosional energy during discharge events and are important in maintaining the stability of the system (Knighton and Nanson, 2000). The majority of waterholes along the Cooper are thought to be initiated as a function of localised scouring processes during flood events (Knighton and Nanson, 1994, Knighton and Nanson, 2000). As the scouring reaches the underlying sand sheet, erodibility increases and the waterhole deepens resulting in a permanent water body. Waterholes often form at points where several anabranching channels come together to produce enough scour to form and maintain incision within the muddy floodplain. They also occur where flow converges and scours between dunes on the floodplain and where flow is concentrated along the bedrock valley side. In these locations they have enough energy to be self-maintaining (Knighton and Nanson, 1994, 2000). The depth of the water flow when flow ceases is key in determining the characteristics and permanence of a waterhole. The longevity is influenced by the frequency of inundation, depth of scoured base, groundwater interactions and water loss processes (Costelloe et al., 2003).

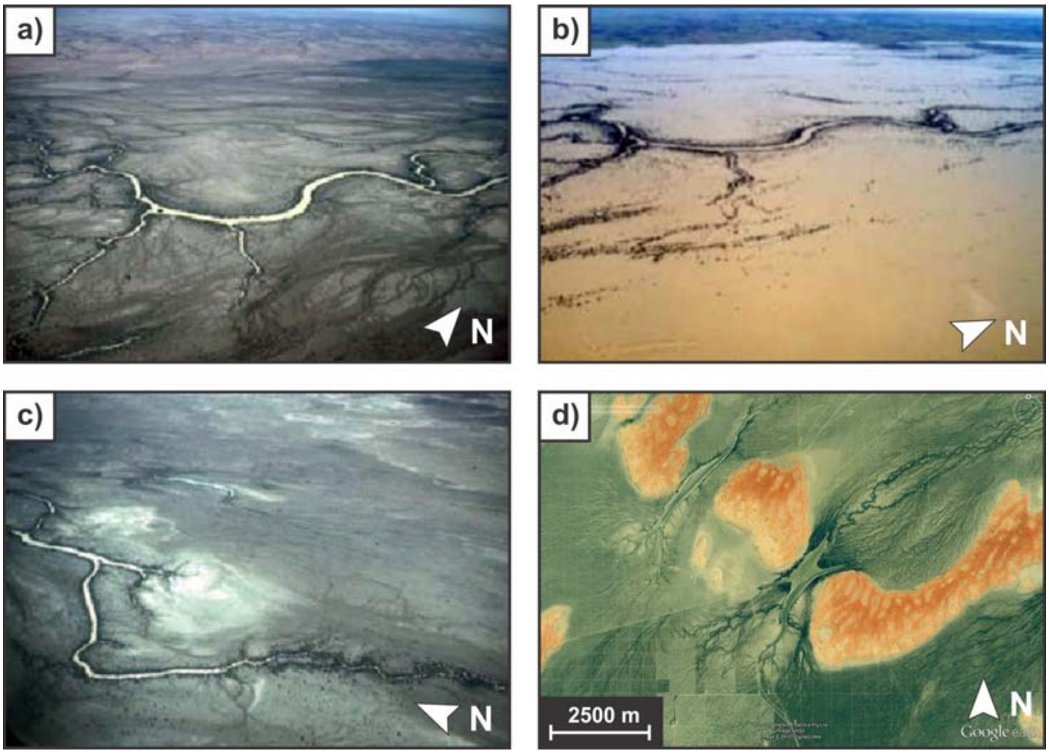


Figure 9: Waterholes on Cooper Creek (a), b), and c) are oblique aerial views, and d) a screen shot from Google Earth). a) Meringhina Waterhole (27°15'20"S, 141°58'30"E), with a dry floodplain. b) Meringhina Waterhole during the 1990 flood. c) Pritchilla Waterhole (27°09'02"S, 141°59'9"E) which shows two sediment splays, and how the bed of the waterholes can be scoured and basal sediment deposited on the floodplain. d) The two Tooley Wooley Waterholes (27°52'26"S, 141°50'29"E), showing the formation of waterholes when flood flows are confined between aeolian dunes on the floodplain (From Habeck-Fardy and Nanson, 2014).

When Cooper Creek flows, water and sediment are transported on the floodplain. Floodplain surface flow in the central region of Cooper Creek can be classified into three categories: braided, reticulate and unchannelled (Fagan and

Nanson, 2004; Figure 10). Reticulate surface patterns are related to distinct gilgai soil development and a lower flood frequency; these factors contribute to the development of intricate networks of bifurcated foodplain channels with right-angled confluences between gilgai surface features (Fagan and Nanson, 2004). Braided surface patterns occur where gilgai development is minimal and flood frequency is relatively high, resulting in the formation of wide, shallow and only slightly inset channels (Fagan and Nanson, 2004). As the width of the floodplain increases, so too does the extent of the reticulate pattern, and to a lesser degree, the braided pattern. Unchannelled regions are observed in the widest, most elevated areas of floodplain where surface irregularities are lowest. Their formation is attributed to low overbank flow power and reduced inundation frequency (Fagan and Nanson, 2004). The relationships between these surface flow patterns are cited as evidence that the channel patterns are contemporaneous (e.g. Nanson et al., 1986), rather than relict (Whitehouse, 1948; Rundle, 1977; Rust, 1981; Rust and Legun, 1983).

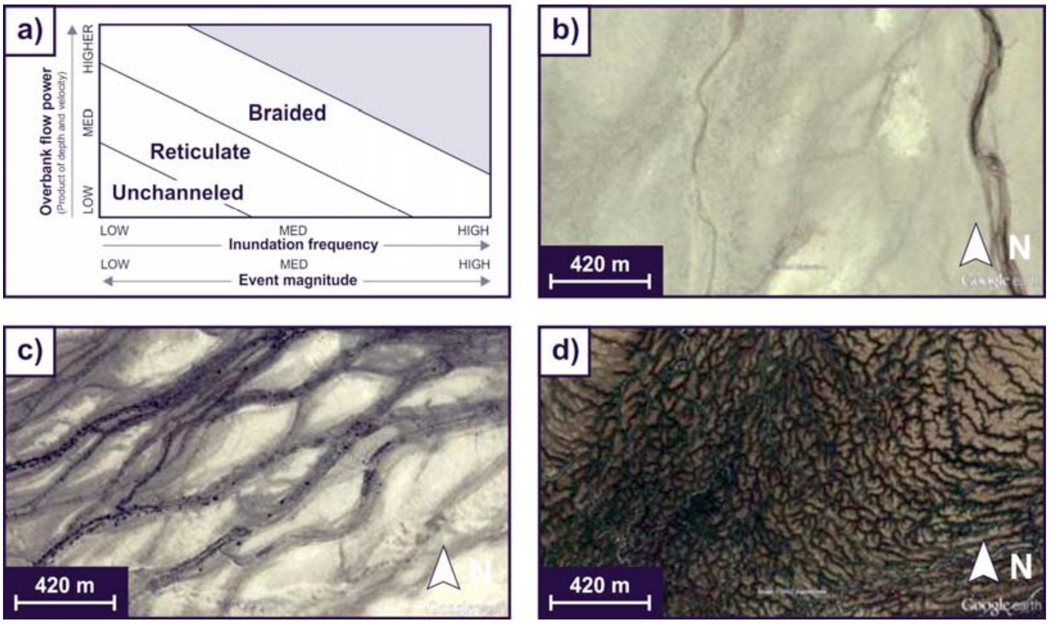


Figure 10: a) Continuum model of floodplain-surface channel pattern distribution models. The grey area occupying the top right corner designates that combinations of overbank flow power and event magnitude and inundation frequency were not found (from Fagan and Nanson, 2004). Examples of the patterns on the Cooper Creek floodplain at Wilsons Swamp, south of Ballera (screen shot from Google Earth): b) unchannelled floodplain (27°40'15"S, 141°59'00"E), c) braided flood channels (27°42'52"S, 141°43'00"E), and d) reticulate flood channels (27°50'32"S, 141°57'16"E).

2.2.2. Cretaceous Western Interior and Dakota Formation

Basin Formation, Structure and Controls on Sediment Deposition

In the Cretaceous western North American geology was dominantly influenced by the Sevier and subsequent Laramide Orogenies. North-south trending thrust faulting propagating from west to east characterised the Sevier Orogeny (DeCelles, 1994), while the loading of the over-thickened Sevier orogenic belt created an adjacent foreland basin, or foredeep, to the east as flexural loading drove subsidence (DeCelles and Giles, 1996). Faulting contributed to crustal thickening and caused the development of a plateau high along the orogenic foreland (Livaccari, 1991). Sediment from this high was shed into the adjacent basin (Johnson, 2003) (Figure 11).

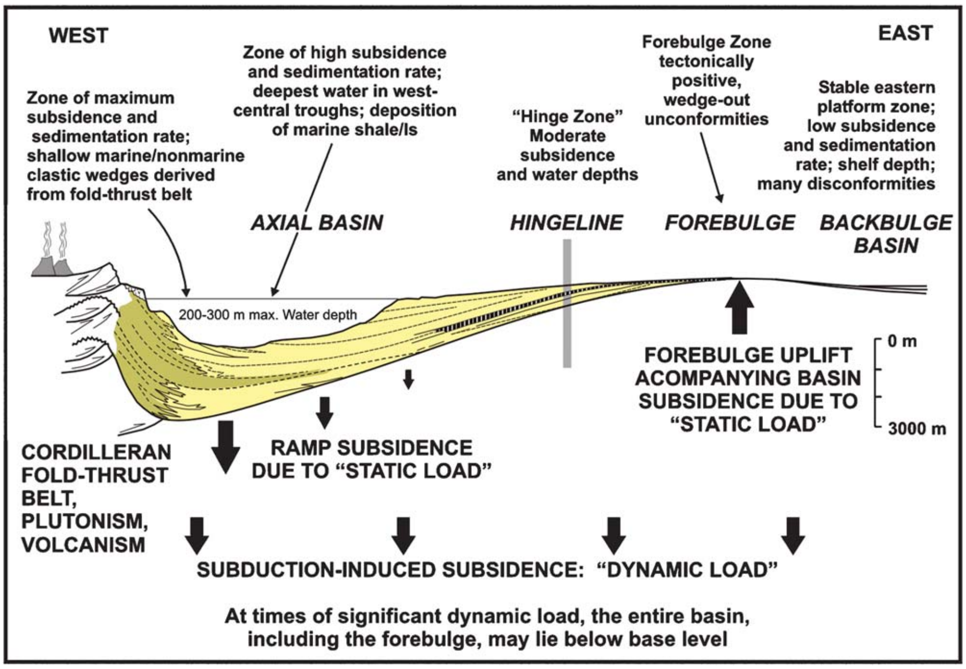


Figure 11: Schematic cartoon cross-section across the basin at a time of maximum transgression. The positions, directions and sizes of arrows indicate relative thrusting, subsidence and uplift (rebound). From Miall, 2008 after Kaufman (1977, 1984), with additional terminology from DeCelles and Giles (1996) and Catuneanu et al. (1999, 2000).

The north-south trending foreland basin formed the Western Interior Seaway (WIS) an epicontinental seaway linking the paleo-Gulf of Mexico to the Arctic Ocean

(Figure 12). There is evidence for both high-frequency tectonism (Catuneanu et al., 1999, 2000; Vakarelov et al., 2006) and orbital forcing (Elder et al., 1994; Sageman et al., 1997; Plint and Kreitner, 2007) as driving mechanisms at different times, in different parts of the basin. Local tectonic elements, reflecting reactivation of basement elements within the WIS, also had an effect on the development and sedimentation of the seaway (Figure 12). The WIS is interpreted to have been a broad depression with a reasonably uniform structure, driven by active tectonic subsidence to the west and containing a ramped shallowing to the east (Kauffman, 1977). Episodic thrusting events along this active orogen contributed to uneven rates of subsidence in the adjacent foreland basin (Jordan, 1981; Pang and Nummedal, 1995) and rates of sediment supply from the thrust front.

The WIS was active for about 100 million years and extended across several of Earth's major climatic zones, from subtropical to subarctic, generally following a cooling trend as the basin evolved and drifted northward. The Late Cretaceous was a time of highstand sea level and global greenhouse conditions. The period included a number of significant eustatic fluctuations (Haq et al., 1987; Miller et al., 2005). The interplay between eustacy, global climate, and local Sevier foreland tectonics are recorded by changes in sedimentological and stratigraphic characteristics of deposits of the Western Interior Seaway.

Transgressive systems in the WIS, particularly in the Late Cretaceous have been well investigated (Van Wagoner et al., 1995; Hancock and Kauffman, 1979; Brenner, 2000; Krystinik and Blakeney DeJarnett, 1995) and intensively modelled (Slingerland et al., 1996, Jewell et al., 1998). Modelling from paleobathymetry, temperature, salinity and wind direction data suggest that the WIS had a strong counterclockwise current pattern that occupied entire north-south extent of the seaway. Results show that the seaway exported freshened water much like Hudson Bay at the present day (Jewell et al., 1998). The WIS is thought to have influenced global ocean circulation patterns. Runoff from eastern drainages exited the seaway as a northern coastal jet; runoff from western drainages exited as a southern coastal jet. Both jets drew in surface Tethyan and Boreal waters (Slingerland et al., 1996). Sequence boundaries and maximum flooding surfaces have been documented by workers for local areas within the Western Interior Seaway, but in most cases the regional extent and significance of these surfaces have not been addressed. In some cases major sequence-bounding unconformities, with hundreds of meters of erosion, are the direct time equivalents of maximum flooding events in other parts of the basin, reflecting the tectonic complexity typical of the basin (Van Wagoner et al., 1995; Hancock and Kauffman, 1979).

Sedimentology and Stratigraphy of the Dakota Formation

Regression and transgression within the WIS resulted in the deposition of a series of clastic wedges (Figure 13; Miall 2008). The study area lies at the western part of the WIS, approximately 400 km east of the thrust front of the Sevier Orogenic belt. Original research in this thesis (Chapter 5) focuses on the basal transgressive unit, the Dakota Formation. The Dakota Formation is underlain by the Lower Cretaceous Burro Canyon Formation, and overlain by the Mancos Shale (Young, 1960). The Mancos Shale is considered to be Late Cretaceous (Young, 1960). It consists of organic-rich black shale deposited in very low oxygen conditions (Weimer, 1982). The Mancos Shale represents the offshore and open sea environment of the Cretaceous Western Interior Seaway (Weimer, 1982).

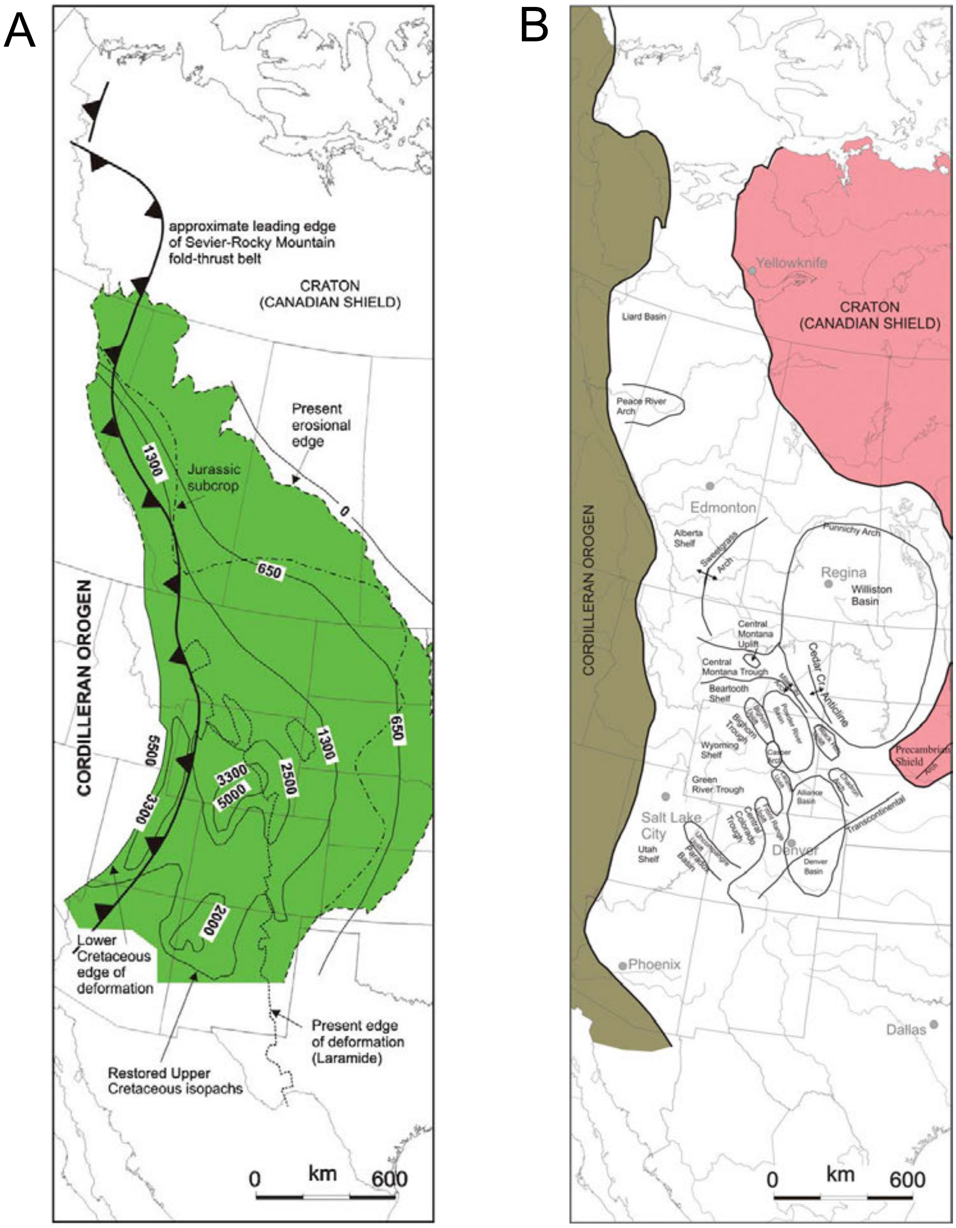


Figure 12: A The geographical location of the Western Interior Seaway, showing the present erosional edge, and reconstructed isopachs for the Upper Cretaceous, This shows the shape of the basin at its maximum extent (after Beaumont et al., 1993; Miall et al., 2008).B: Localised Tectonic elements of the Western Interior Basin. These arches and basins are attributed to reactivation of various basement elements and were all active at different times during the history of the seaway (Miall, 2008)

Terminology used to describe the Dakota Formation differs regionally throughout the Cretaceous Western Interior basins in North America. Correlation between strata and equivalents on both flanks of the Seaway has been inconsistent. The main reason for this confusion is that correlation of Dakota Formation equivalents is primarily based on lithological variation within Dakota Group, not a chronostratigraphic framework. This problem was not the focus of this thesis. A brief summary of the stratigraphy of the Dakota Formation is presented in this Chapter

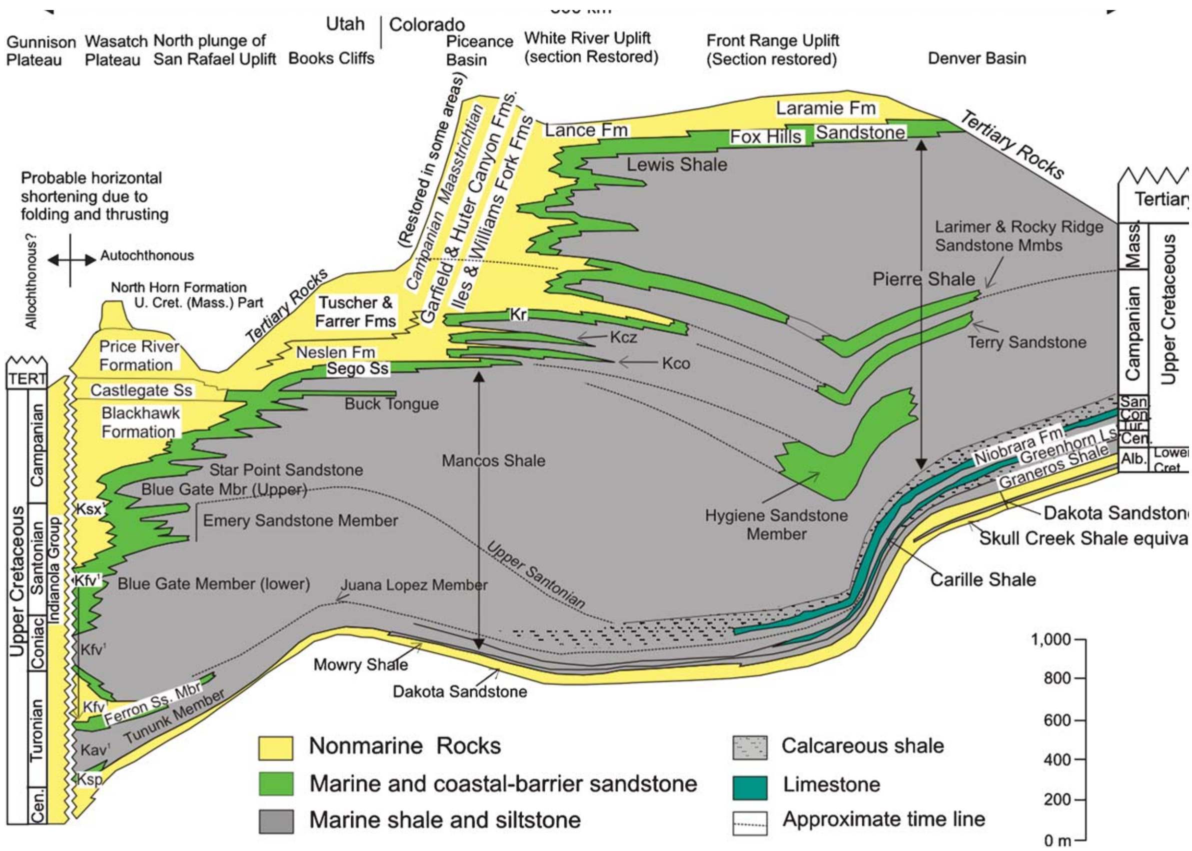


Figure 13: Stratigraphic cross-section of Cretaceous rocks from central Utah to north-eastern Colorado. Stratigraphic correlation is complicated by traditional lithostratigraphic methods and a lock of a chronostratigraphic framework. Thicknesses are based on well and outcrop control and vertically exaggerated. Key: Ksx, Sixmile Canyon Formation; Kfv, FunkValley Formation; Kav, AllenValley Formation; Ksp, Sanpete Formation; Kr, Rollins Sandstone Member; Kcz, Cozzette Sandstone Member; Kco, Corcoran Sandstone Member. From Miall, 2008, after Molenaar and Rice, 1988.

and Chapter 5 for context. If the reader is seeking detailed information beyond the scope of this thesis Antia and Fielding (2011) provide a recent in-depth discussion of basin-wide stratigraphic correlation.

The recognition of the lower most of Dakota Group strata within the type section of Meek and Hayden (1862) along the eastern edge of the Western Interior Seaway was based on the sharp vertical lithological change from red oxidized-to-carbonaceous shale, to sandstone deposits above the Jurassic Morrison formation (Dolson et al., 1991). This vertical variation was used to recognize and correlate all

Dakota Group equivalents, even those located hundreds of miles westward, southward, and south-westward of the type section, without considering the age as recognition criteria.

The unit now known as the Dakota Formation has been identified by various other names. Meek and Hayden (1861) first named this unit “The Dakota” for outcrop along the Missouri River in Dakota County, Nebraska. The first detailed study of the Dakota Group was undertaken in northern Colorado Front Range foothills particularly from Rainbow Creek in Douglas County to Boxelder Creek in northern Larimer County by Waage (1955). Waage divided Dakota Group strata into two units: the Lower Lytle Formation and Upper South Platte Formation. Waage (1955) also interpreted the depositional environment for Upper South Platte Formation as deltaic, estuarine, littoral and neritic environments around the margins of the Western Interior seaway. Later on, McKenzie (1971) studied the stratigraphy and depositional environment of Dakota Group strata from Deer Creek south of Morrison, Colorado to Boxelder Creek near the South Wyoming border. Mackenzie (1971) divided the Upper South Platte Formation of Waage (1955) into three members. These three members are: Plainview, Skull Creek, and Muddy (now the J Sandstone). Before that, Muddy strata were already divided into two members in the eastern Hogback of the Colorado Front Range by Mackenzie (1965) which are Fort Collins and Horsetooth members. Many authors use variations of the name: Dakota Sandstone, Dakota Group, Naturita Formation, Dakota Sandstone (Bartleson, 1994; Burbank, 1930; Carter, 1957; Gustason, 1985; Weimer, 1982; Young, 1960).

The Lower Cretaceous Dakota Sandstone records the initial transgression of the Cretaceous seaway across south-western Colorado. The Late Cretaceous is interpreted to have been a period of relative global sea level highstand and included a number of significant eustatic fluctuations (Haq et al., 1987; Miller et al., 2005). High organic carbon preservation during this time is associated with large volumes of off-ridge volcanism and accelerated sea floor spreading (Arthur et al., 1985), including three ocean anoxic events, which record periods of carbon isotope fluctuations and enhanced organic carbon content of sediments (Arthur and Schlanger, 1979; Jenkyns, 1980). Palynology from Upper Cretaceous coals and other terrestrial fauna records suggest this was a period of stable, temperate climate (Wolfe and Upchurch, 1987; Howell and Flint, 2003).

Although basic aspects of the Dakota Formation have been described near the study location (Serradji, 2007) these were not adequate to provide a complete analogue. The outcrop of the Dakota Formation exposed on the Uncomprahange Plateau provides a natural laboratory to study this basal transgression of the WIS. Chapter 5 provides a detailed technical description of the sedimentology, depositional environments, stratigraphy and paleoenvironments of the Dakota Formation exposed on the face of the Uncomprahange Plateau.

2.2.3. The Murta Formation of the Eromanga Basin

Geography

The Eromanga Basin is the largest onshore sedimentary basin in Australia with an area of over 1 million km^2. It also forms a major portion of the Great Artesian Basin (Veevers, 2000). The Eromanga Basin covers most of south and central Queensland, part of the south-eastern Northern Territory, northern portions of South Australia and New South Wales (Figure 14) and shares a similar history and stratigraphic sequences with the Surat Basin to the East and the Carpentaria Basin to the north. The Eromanga Basin unconformably overlies Permo-Triassic infrabasins, the Cambro-Ordovician Warburton, Amadeus and Officer Basins and Proterozoic basement in the south east. In the north-east the Eromanga Basin is adjacent to the coeval Surat Basin, and the Carpentaria and Laura Basins (Figure 14). It is overlain by the modern Kati Thanda- Lake Eyre Basin, where deposition continues to this day.

Basin Evolution and Structure

The Eromanga Basin has been interpreted to have formed as an intracratonic sag structure resulting from thermal contraction (Gallagher and Lambeck, 1989; Gray et al., 2002), dynamic topography induced by a subducted lithospheric slab (Russell and Gurnis, 1994; Matthews et al., 2011) and a foreland basin (Jones and Veevers, 1984; Gallagher and Lambeck, 1989; Gallagher, 1990; Draper, 2002). Although authors do not agree on the specific driving mechanism of basin formation, consensus generally exists that eastern Australia was dominated by convergent margin tectonics with associated volcanic and sedimentary basins from the Late Cambrian (515 million years ago) to the end of the Albian (100 ma). During this time the breakup of Gondwana commenced (Mid Jurassic), and the Australian continent is interpreted to have been at high latitudes in the southern hemisphere (Figure 15).

Sedimentation in the Eromanga Basin is considered to have occurred under two different structural regimes: flexural relaxation (commencement of sedimentation to Upper Cretaceous) and compression (Upper Cretaceous to cessation of sedimentation) (Hoffmann, 1989). Sediment infill of the basin during the Cretaceous at the time of deposition of the Murta Formation is reported to be relatively younger volcanogenic sediments derived from the east (Hoffmann, 1989; Allen et al, 1996).

Figure 14: The Eromanga, Surat and Carpentaria Basins share a similar geological history (After Hill, 1999).

Sediment recycling and cannibalisation of older formations is also likely to have occurred. Likely sources of sediment for the basin and ages are detailed in Figure 16. This is further discussed with specific relevance to the Murta Formation in Chapter 6.

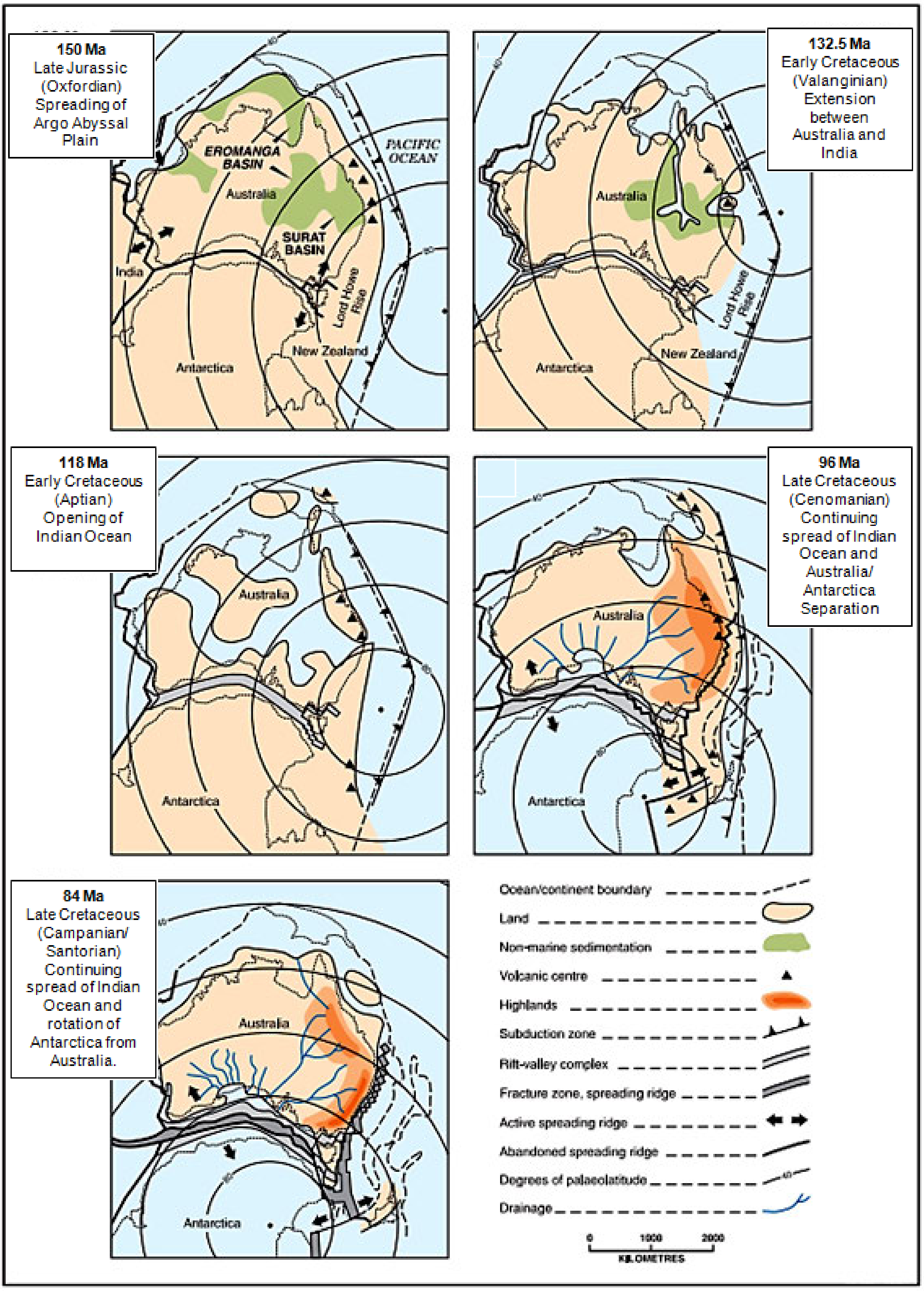


Figure 15: Australia is thought to have been at high latitudes, similar to that of Norway and Greenland today *Palaeogeographic change through the Jurassic to Cretaceous: (a) Hutton Sandstone- Birkhead Formation time (b) Cadna-owie Formation – Murta Formation time (c) Bulldog Shale – Wallumbilla Formation time (d) Winton Formation time (e) post-Winton Formation erosion. (from Alexander et al., 1998).*

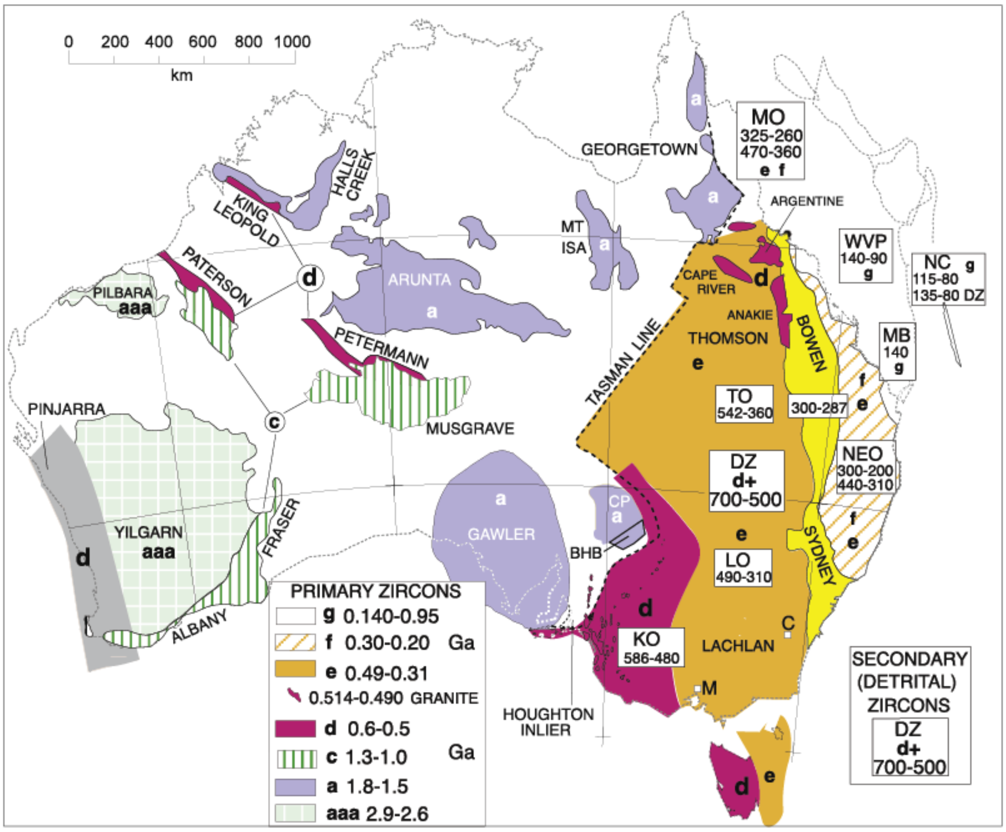


Figure 16: Primary bedrock-age province locations in Australia, shown by the patterns in the lower left. BHB = Broken Hill Block; C=Canberra; CP=Curnamona Province; KO=Kanmantoo Orogen; LO=Lachlan Orogen; M=Melbourne; MB=Maryborough Basin; MO=Mossman Orogen; NC=New Caledonia; NEO= New England Orogen; TO = Thomson Orogen; WVP=Whitsunday Volcanic Province. (From Veevers et al., 2016; After Veevers 2000; Veevers and Saeed, 2011).

The Eromanga Basin is structurally dominated by relatively subtle north-easterly and easterly trending structural anticlinal and synclinal features forming troughs and ridges (Figure 17) as a result of complex faulting styles (Figure 18). Tectonic activity and basin morphology is likely related to plate boundary activity on the eastern edge of the Australia plate and the collision of the Pacific and Australian plate after during and after deposition (Veevers, 1984; Radke, 2009). Tectonically induced changes from the Neogene to the Quaternary in central Australia have been extensive but generally of low magnitude, with fault reactivation common (Sandiford et al., 2009; Quigley et al., 2010; Kulikowski, 2016).

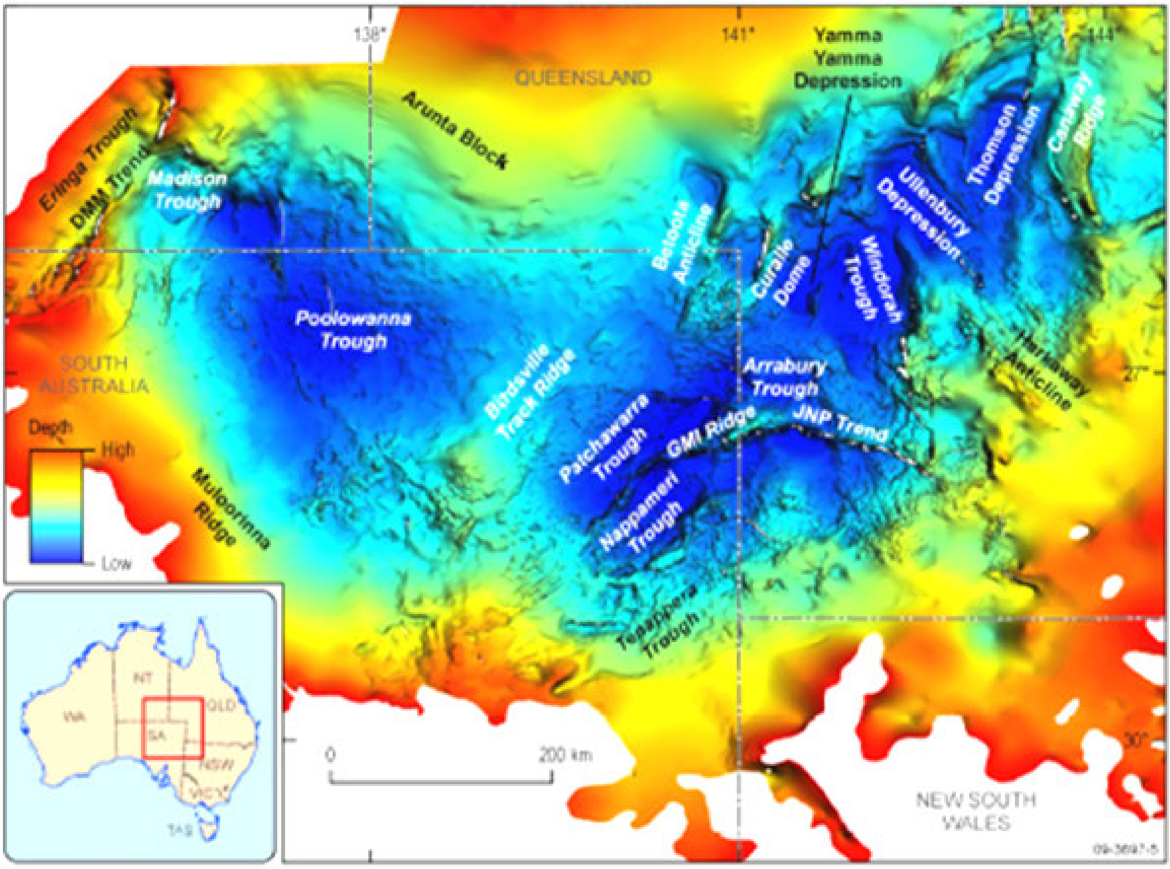


Figure 17: Regional structural features in the central Eromanga Basin expressed in the structural depth map of the Cretaceous Cadna-owie Formation (Radke, 2009).

Eromanga Basin Sedimentology and Stratigraphy

The Eromanga Basin stratigraphy (Figure 19) can be divided into three sequences — lower non-marine, marine and upper non-marine. The majority of prior studies as well as exploration and development efforts have been concentrated on the productive lower non-marine sequence, within which the focus of this study also falls. This review will focus on the Namur Sandstone, Murta Formation and Cadna-owie Formation interval (Figure 19). Much of the existing interpretation is based on lithostratigraphy and as such this review will heavily feature interpretations from this perspective.

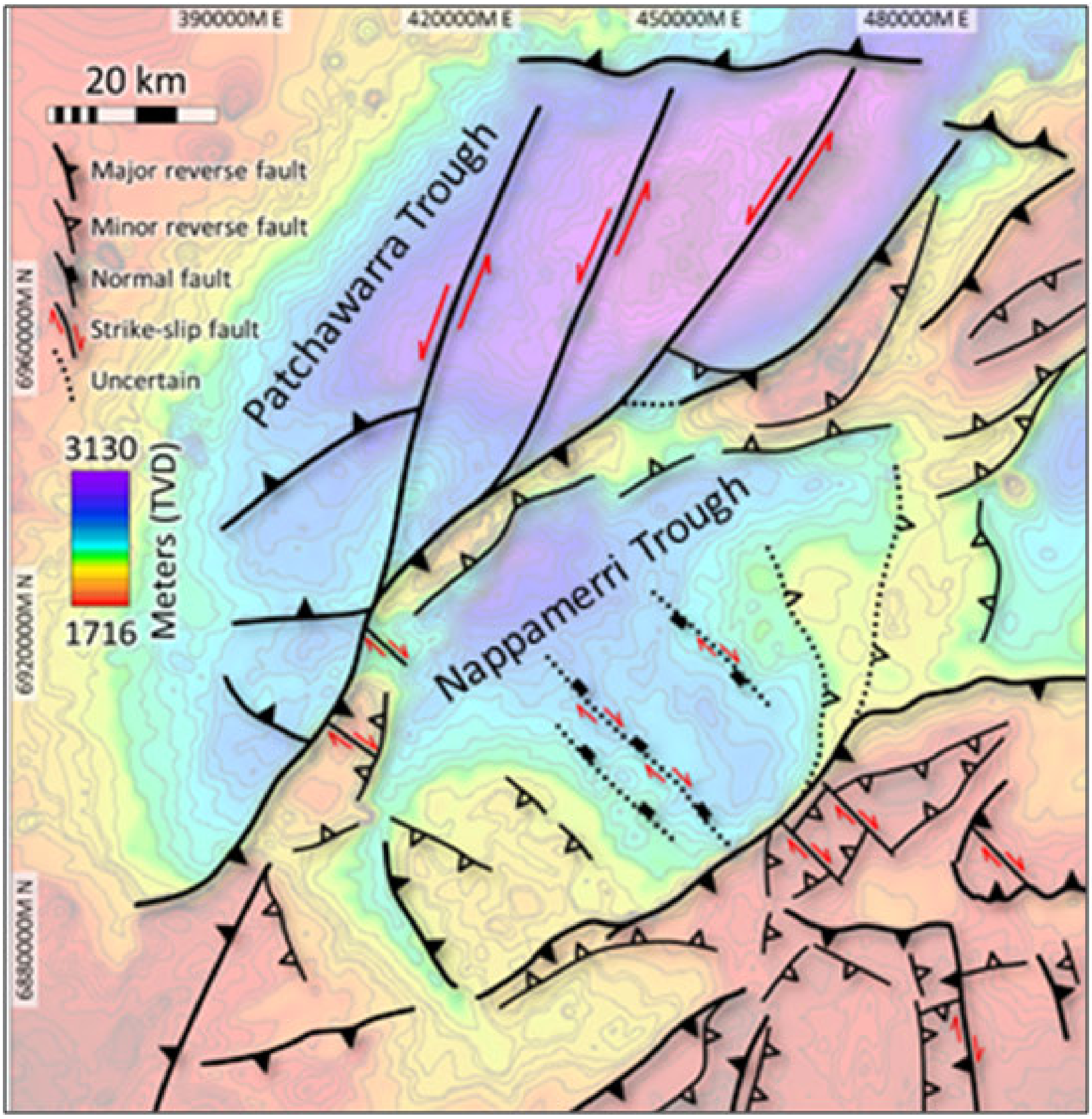


Figure 18: Structural features are caused and controlled by deep faulting. A number of fault styles can be mapped using seismic data (Kulikowski, 2016).

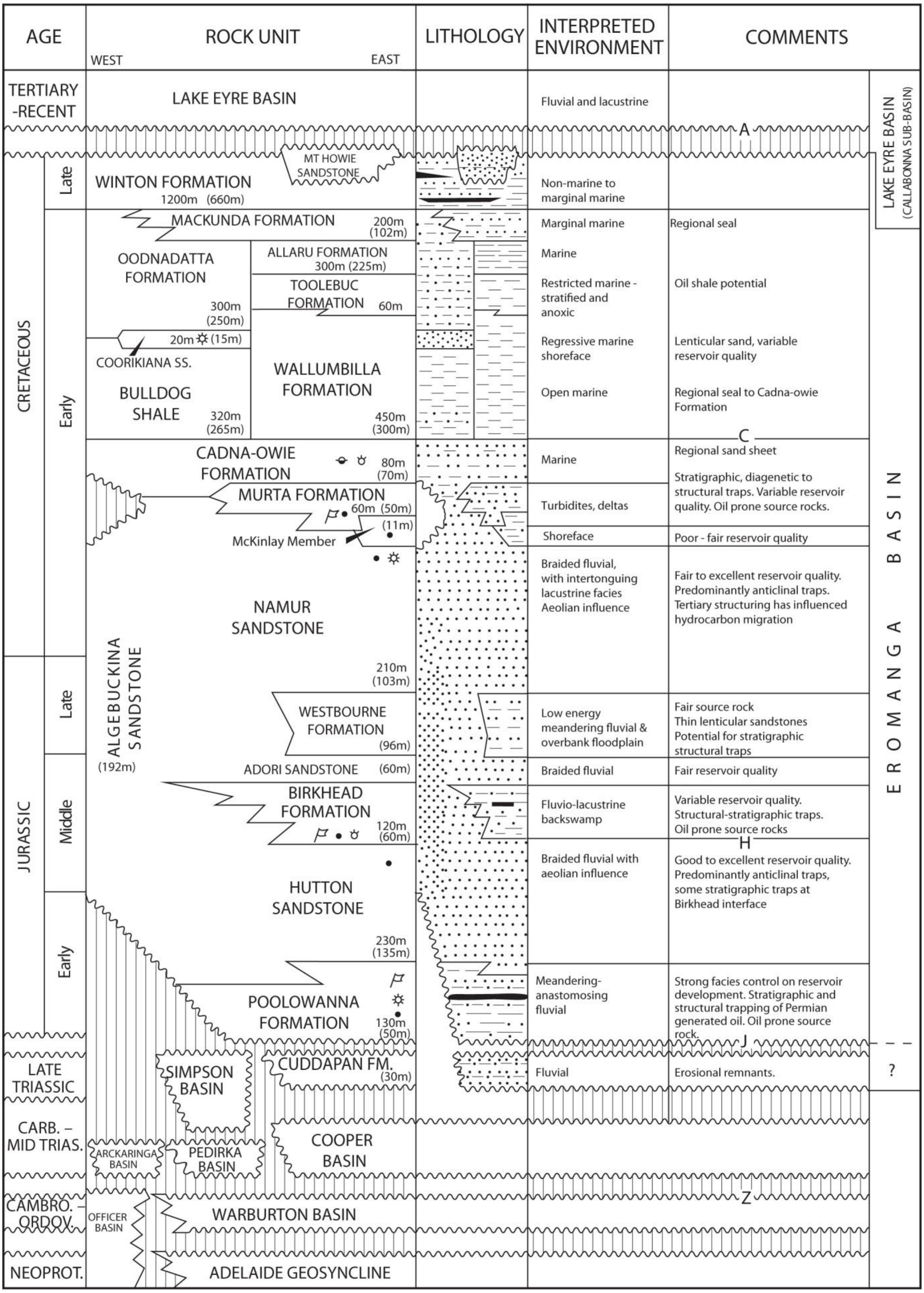


Figure 19: Geological summary of the Eromanga Basin. Numbers in rock units represent maximum thickness (unbracketed) and average thickness (bracketed). A, C, H, J and Z in the comments represent seismic horizons (Radke, 2009).

Basin Initiation to Late Jurassic Westbourne Formation

Fluvial conditions dominated the area bound to become the Eromanga Basin as a compressive regime eased in the late Permian, as recorded by the deposition of the Nappamerri Group sediments (Apak et al., 1997, Kantsler et al., 1983). The upper Nappamerri Group sediments mark an erosional unconformity that separates the underlying Cooper Basin from the overlying Jurassic to Cretaceous Eromanga Basin (Figure 17). Erosion of up to 500 m of Nappamerri Group sediments occurred due to reactivation of basement faults during the Upper Triassic Hunter-Bowen Orogeny (Alexander et al., 1998, Apak et al., 1997, Kantsler et al., 1983; Mavromatidis, 2006). Subsequently, during the Late Triassic, formation of the Eromanga Basin was initiated.

The Callovian Hutton Sandstone (see Figure 19), the original target of the Cuisinier-1 well, overlies the Poolowanna Formation and is comprised predominantly of poorly sorted coarse to medium-grained feldspathic sandstone (at the base) and fine-grained well-sorted quartzose sandstone (at the top) with minor carbonaceous siltstone, mudstone, coal and rare pebble conglomerate, overlies basal Jurassic Poolowanna sediments. It is widely interpreted to represent deposition within a braided fluvial environment (John and Almond, 1987; Burger, 1986). The Hutton Sandstone was interpreted as a prograding alluvial fan system (Moore et al., 1986) with aeolian and lacustrine elements.

Namur Sandstone, Murta Formation and Cadna-owie Formation

The Namur Sandstone, Murta Formation, McKinlay member and Cadna-owie Formation are considered as a sedimentary package in this literature review. As these formations have gradational boundaries and no major unconformities exist between them, they are considered to be genetically linked and represent a transition from continental to marine depositional settings (Gravestock et al., 1995).

Namur Sandstone

The Neocomian Namur Sandstone overlies the Westbourne Formation and consists of continental, medium- to coarse-grained, pale grey and buff, cross-bedded quartzose and pebbly sandstone with conglomerate beds and minor thin claystone lenses (Gravestock et al., 1995). Conglomerate interbeds consist of lithic and quartz pebbles, carbonaceous mudstone intraclasts and fossilised plant fragments. A low sinuosity to braided fluvial environment is interpreted as the depositional setting for the Namur Sandstone. Mud lenses are interpreted to represent channel abandonment deposits. In Queensland the lower part of the Hooray Sandstone is equivalent to the Namur Formation (Theologou, 1995).

McKinlay Member

The silty sandstone transition between quartz-rich fluvial Namur Sandstone and siltstone and mudstone of the overlying Murta Member is informally referred to as the McKinlay Member. The McKinlay Member consists of buff, very fine- to medium-grained sandstone interbedded with dark grey carbonaceous and micaceous siltstone (Gravestock et al., 1995). The McKinlay Member is interpreted to have been deposited within a fluvio-deltaic depositional environment. Five lithofacies have commonly been described and interpreted in the McKinlay Member: channel fill, abandoned channel, lagoon, barrier backshore and barrier shoreface (Theologou, 1995; Figure 20). The McKinlay Member is often absent in the Cooper region, or interpreted as part of the Murta Formation. For this study, the McKinlay Member will be interpreted as part of the Murta Formation.

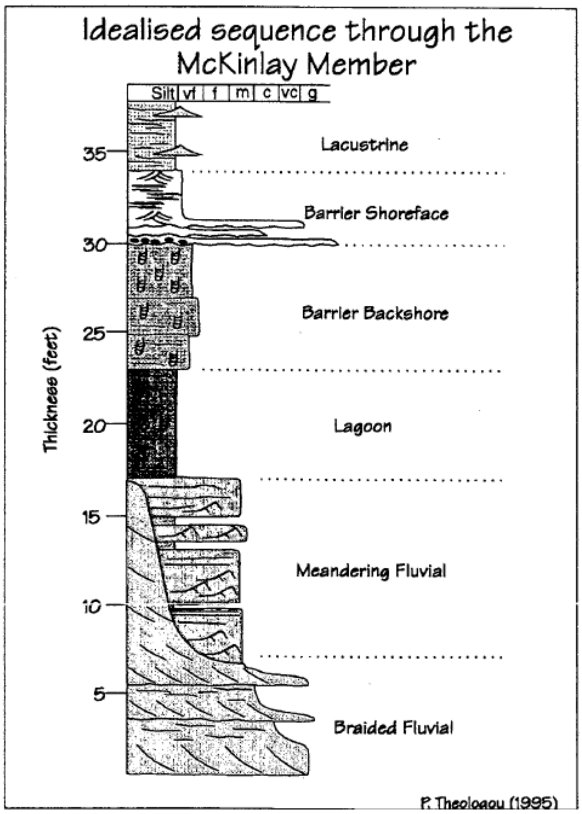


Figure 20: Idealised sequence through the Namur Formation and McKinlay Member used as a facies model in the Dullingari area (Theologou, 1995).

Murta Formation

The Berrasian to Valanginian Murta Formation gradationally overlies the Namur Sandstone, and sometimes the McKinlay Member. The Murta Formation consists of interbedded and interlaminated sandstone, silty sandstone, siltstone and lesser mudstone, intraformational conglomerate and coal (Gravestock et al., 1995). The Murta Formation is equivalent to the upper Hooray Sandstone in Queensland (Gorter, 1994). A type section for the Murta Formation is at Dullingari North 1, 1469.14–1526.13 m (Mount, 1981). The reference section for the Murta formation is Dullingari-9 (Theologou, 1995). A maximum thickness of just over 90 m is reached in the Nappamerri Trough (see Figure 17 for location). The sequence inter-tongues with the Namur Sandstone Member on a regional scale and the upper contact with the Cadna-owie is gradational.

Depositional models for the Murta Member (Ambrose et al, 1982 and 1986; Gorter 1994; Bradley, 1993; Mount, 1981, 1982; Newton, 1986; Zoellner, 1988; Lennox, 1986; Theologou, 1995; Hill; 1999) have been presented as lacustrine to marginal marine. Interpretation has been previously conducted at a field and semi-regional scale.

Originally a depositional model which defined the Murta Member as a mainly fine-grained lacustrine sequence intervening between braided-fluvial sediments of the Namur Sandstone Member and the overlying, marginal marine Cadna-owie Formation was proposed (Ambrose et al., 1982; Ambrose et al., 1986). The model was mainly derived from work on the South Australian section of the Eromanga Basin. A regional reduction in thickness and sand content from the north-northeast to the southwest was interpreted to represent a depositional pattern where the main source of sediment into the "Murta Lake" was from the north and east (Ambrose et al. 1982; 1986).

A lacustrine setting was also interpreted in the Queensland sector. A lacustrine delta, sourced from the north was proposed to have provided sediment to the Nockatunga, Thungo, Winna and Dilkera Fields for the Murta Formation (Lennox, 1986). A transgressive lacustrine shoreface was proposed as the depositional setting for the Murta Formation at Maxwell (Hill, 1999).

The Murta Lake was interpreted to have covered an area of over 50,000km^2. Strong fluvial-deltaic influences are interpreted in the north and east of the formation (Ambrose et al. 1982; 1986; Mount, 1981, 1982). Carbonate cementation was interpreted to represent low-stand periods in the lake. Mount (1981, 1982) and Ambrose et al. (1986) interpret open lacustrine, lacustrine fan delta, distributary channel and lacustrine shoreline depositional environments.

Evidence for marine influence in the upper Murta Member has been interpreted (Zoellner, 1988; Powell et al., 1989). The presence of Botryococcus (a planktonic cyanobacterium) and land plant spores and pollen is considered to indicate a lacustrine to paralic environment (Michaelsen and McKirdy, 1989). Estuarine depositional environments are interpreted in the Murta Formation (Zoellner, 1988; Gorter, 1994).

The McKinlay Member and Murta Formation have previously been considered as a genetic package (Theologou, 1995). A drowned river valley was used as a depositional model for the basal McKinlay Member and a transgressive lake barrier-bar system for the Upper Murta Member. The drowned valley was interpreted to form part of a lacustrine transgressive sequence tract (e.g. Reinsen, 1992; Dalrymple et al., 1992).

The upper part of the McKinlay Member is interpreted by Theologou (1995) to have been deposited as part of a transgressive lake barrier-bar system which transgressed rapidly over the lake (e.g. Reinsen, 1992; Galloway, 1986; Kraft and John, 1978; Figure 21). Sand packages are either designated as prograding lacustrine deltas or a prograding wave dominated shoreline facies. As the formation is interpreted as lacustrine, the absence of tides is often implied (Theologou, 1995) and hence the flood tidal delta and tidal flat components of this facies models are ignored, however lithologies similar to these facies exist. Rapid transgression was interpreted to reduce preservation potential (Theologou, 1995).

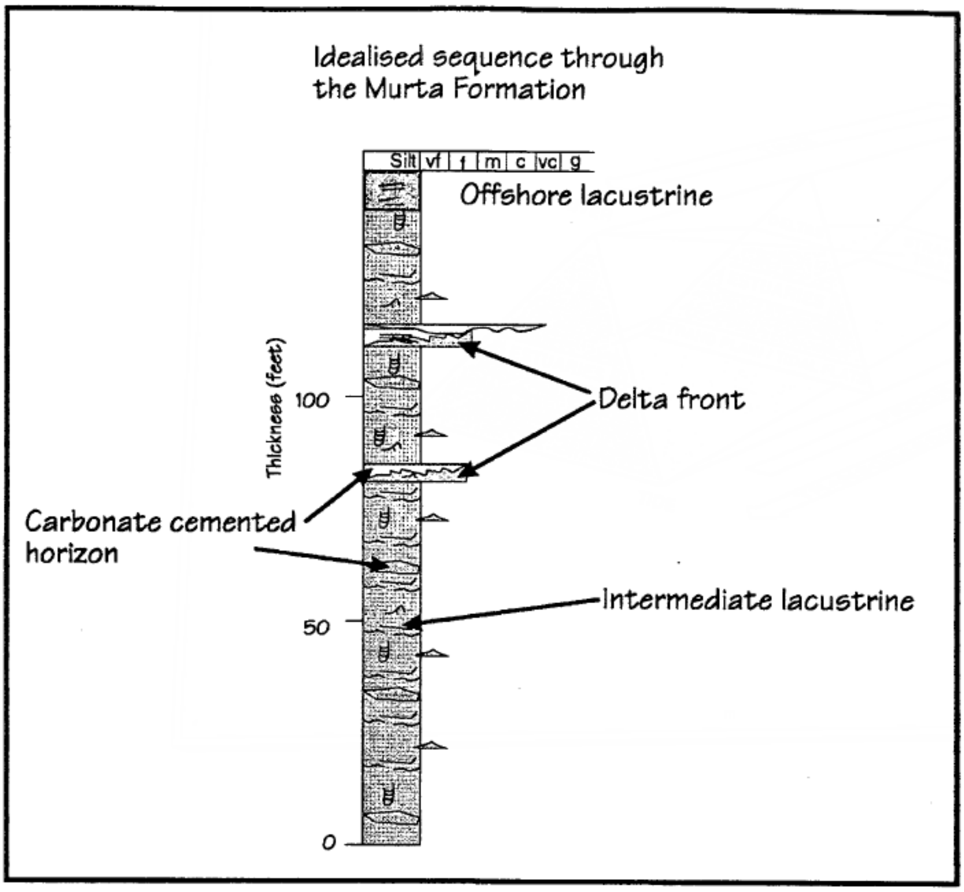


Figure 21: Idealised sequence through the Murta Formation used as a facies model for the Murta Member in the Dullingari area, South Australia (Theologou, 1995).

A depositional model featuring a lake system with vegetated islands was interpreted for the Murta Formation (Gorter, 1994). Sequence stratigraphic concepts are invoked (Figure 22). Base level rise and fall is invoked in order to interpret erosional surfaces and channel incision. Slow base level rise and infill of channels by sediment reworked by transgression is interpreted to form “estuarine” deposits, although no evidence of marine influence is presented. Continued transgression is interpreted to form basin-wide shoaling cycles and maximum transgression results in mud-rich condensed section.

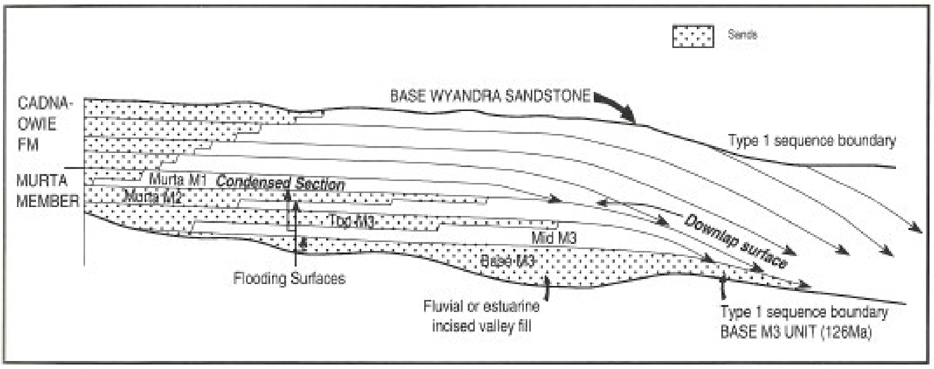


Figure 22: Schematic cartoon of stratal patterns in the Murta Member in the Queensland sector. The Murta Formation and the Cadna-owie Formation are considered to have been deposited together in a ramp basin setting. Sand is stippled and mud is white (Gorter, 1994).

The Murta Formation shows pervasive cementation. The main cement types are siderite and undifferentiated carbonate (Gravestock, et al., 1983; Staughton, 1985; Zoellner. 1988, Green et. al. 1989 and Schulz-Rojahn, 1993). Siderite cementation shows features of early and late diagenesis (Zoellner, 1988; Theologou, 1995). The process of methanogenesis is likely required for the formation of siderite cement containing dissolved sulfates in brackish or marine sediments, but in freshwater swamps the correct anaerobic conditions for the formation of siderite may also exist only a few metres below the sediment water interface even in the absence of methanogenesis (Curtis and Coleman 1986; Gautier, 1982; Gautier and Claypool, 1984). Therefore, the presence of siderite does not infer a particular depositional environment. Carbonate cementation is through to have occurred as a result of carbon dioxide migrating up from the underlying Cooper Basin and reacting with formation water (Schulz-Rojahn, 1993). Calcite is also present in glenodites, calcite pseudomorphs (De Lurio and Frakes, 1999), within the Murta Formation.

The paleoclimate during the deposition of the Murta Formation is interpreted to have been cool to temperate and after the long Jurassic period of uniformly warm and wet climate and thriving vegetation dominated by conifers, cycads and ferns which had continued into earliest Cretaceous times, a sudden change in conditions and flora occurred. The commencement of Gondwana break-up caused eustatic sea level rise, inundating vast areas of the continent and causing the climate to change (White, 1994). A cool temperate climate is inferred for the Eromanga Basin during the deposition of the Murta Formation based on the presence of microflora pollen from Podocarpacean and Araucarean conifers (McKellar, 1996; Gorter, 1994). Megafloral studies inferred humid, warm-temperate to cool temperate conditions determined by the presence of Ginkgoales. The Early Cretaceous positioning of the basin is comparable to the present day latitudes of Norway and Alaska (Figure 14). The climate at these present-day latitudes is cold temperate to sub-arctic and subject to seasonality. It is possible that periglacial conditions could have existed (Gorter, 1994).

Cadna-owie Formation

The Murta Formation is overlain conformably by a marginal marine to open marine shale and sandstone package, the Cadna-owie Formation. The Cadna-owie Formation is a pale grey siltstone and mudstone with very fine to fine-grained sandstone interbeds and minor carbonaceous claystone (Moore and Pitt, 1984). Sections of marine siltstones and mudstones, representing deeper-water depositional environments are dominant within the formation toward the centre of the basin (Moore and Pitt, 1984).

Overlying Lithology

The Cadna-owie Formation is often capped by the Wyandra Sandstone medium to coarse-grained, quartzose to labile sandstone with scattered pebbles

(Senior et al., 1978). The Wyandra Sandstone is interpreted contain estuarine to paralic depositional environments and represent regression after deposition of the fully marginal marine Cadna-owie Formation (Etheridge et al., 1986).

Regional Petroleum Exploration and Development

Prior to exploration in the Eromanga Basin the geologically similar Surat Basin was the main focus of hydrocarbon exploration in Australia. The first economic gas accumulation in Australia was found in a deep water bore in the Surat Basin and was used to light the town of Roma, Queensland, in 1908. The first commercial oil in Australia was found in 1961 at the Moonie Oil field in the Surat Basin (Beddoes, 1973).

The Eromanga Basin has been explored with the intent of finding hydrocarbons since 1924 (Armstrong and Barr, 1986). Exploration intensity increased in the 1950s when licences covering the Cooper and Eromanga basins were acquired by local oil companies. In 1957, Innamincka-1 was the first exploration well was drilled in the Cooper/Eromanga sequence. Gas was first discovered six years later in the Cooper Basin in 1963 at Gidgealpa field and the first sizeable oil was the Tirrawarra field in 1970 (Lavering et al., 1986). The first economical commercial scale hydrocarbon discovery, gas in the Namur sandstone, was made by Namur 1 in 1976. Oil was first discovered in 1977 with an uneconomic flow from Poolowanna-1 in the Poolowanna Trough. The first economic oil flow from the Eromanga Basin sequence was from the Hutton sandstone in 1978 in Strezlecki-3 (2400 BOPD) from the Hutton Sandstone. Oil shows in the same well in the Namur Sandstone and Birkhead Formation encouraged explorers to look beyond the Hutton (Lavering et al., 1986). In 1979 Dullingari North-1 discovered economic oil (450

BOPD) in the Murta Formation (Sprigg, 1986). While the Hutton Sandstone has been the most prolific producer of the sequence to date, most of the Eromanga Basin has proved prospective, with shows or production from the Early Jurassic all the way to the Albian (see Figure 20).

The Dullingari Murta Field was discovered in 1979 at Dullingari-North-1 in 1979 and was the first well to discover oil in the Murta Member (Mount 1981; Mount 1982). Initially this discovery was missed as it was not the target formation and mud returns were not monitored; however later volumetrically calculated reserves were 9.1 million barrels of oil in place (Robinson and Butler, 1989). Two main reservoirs are interpreted, a shoreline-bar sand and a proximal turbidite lacustrine fan. The reservoirs are approximately 1 ft thick and separated by shale barriers approximately 4 ft thick. Wells are heavily fracture stimulated and the field proves to be more complex than initially interpreted (Robinson and Butler, 1989).

Oil was discovered in the Murta Member, the Hutton Sandstone and the Wesborne Formation at Jackson in December 1981, and initially contained Australia’s largest discovered recoverable onshore reserve, with 111 million barrels of oil in place (Dodman and Rodregues, 1989). The Murta Member reservoir at Jackson consists of sandstone, interbedded with siltstone and minor claystone and is interpreted as a lacustrine shoreline deposit. Reservoir characteristics and continuity vary widely throughout the field. The reservoir is driven by a thin but strong aquifer and the producing interval is on average 2.4 m. Although the Murta reservoir is a valuable producer, reservoir characteristics are still poorly understood.

The Eromanga Basin is the most prolific onshore oil basin in Australia; but still is generally under explored, with an exploration well density of 1 well per 436 km^2.

Over 2,474 (825 exploration, 1,649 development) wells have penetrated sediments in the basin and 105408 km of 2D and 17421 km^2 of 3D seismic lines have been shot in the basin. Petroleum exploration in the Eromanga Basin has traditionally been concentrated in the portion underlain by the Cooper Basin. About 60 MMbbl (8.4 x 10^6 kL) of oil was predicted as a yet-to-find volume in the Eromanga Basin (Alexander, 1998). Although this figure was calculated in 1998, it is still widely cited today.

Vertical and lateral migration of oil from the underlying Permian Cooper Basin is generally accepted as the main source of oil in the Eromanga Basin. The Poolowanna, Birkhead and Murta Formations within the Eromanga Basin also contain organic-rich shales that are oil-prone and in places mature for oil generation (Alexander, 1998). Traps within the Eromanga Basin tend to be subtle but can hold relatively large volumes due to their broad lateral extent. Trapping mechanisms are dominantly structural (anticlines with four-way dip closure or drapes over pre-existing highs) although a stratigraphic component is acknowledges in recent discoveries.

Relatively new oil discoveries in the late 2000s and into the 2010s on the western flank of the Cooper Basin have challenged the suggestion that the Eromanga Basin is mature for exploration. Two subtle play types, which have not been previously explored for in the region, are evident. The dominant play is in the structurally controlled in the Namur Sandstone, while the secondary is a stratigraphic mid-Birkhead Formation trap which has proved depositionally complex and a challenge to delineate and produce economically (Hall et al., 2015). These new discoveries, along with the Cuisinier discovery, show that the Eromanga Basin holds potential for new discoveries, but effective exploration and development requires critical analysis and creative new ideas.

Effective exploration and development requires data-driven geological models and creative scientific thinking to fill in the gaps when data is sparse. This thesis aims to add data and ideas to the base of existing knowledge in order to improve exploration in the Eromanga Basin. Chapter 3 provides interpretation for the Cuisinier Field and Chapter 6 provides a new regional study for the Murta Formation of the Eromanga Basin. Chapter 4 provides a new study of the previously unstudied Lake Yamma Yamma and Chapter 5 provides a study of the Dakota Formation outcrop, sites which could be used as analogues for the Murta Formation in the Eromanga Basin.

2.3. References

Ainsworth, R.B. 2010. Prediction of Stratigraphic Compartmentalization in Marginal Marine Reservoirs. In: Jolley, S.J, Fisher, Q.J., Ainsworth, R.B., Vrolijk, P. and Delisle, S. (eds.), Reservoir Compartmentalization. Geological Society of London Special Publication No. 347, pp 199–218.

Ainsworth, R.B., Hasiotis, S.T., Amos, K.J., Krapf, C.B.E., Payenberg, T.H.D., Vakarelov, B.K., Sandstrom, M.L. and Lang, S.C. 2012. Tidal signatures in an intracratonic playa lake. Geology, v. 40, pp 607-610.

Ainsworth, R.B., Vakarelov, B.V., and Nanson, R.A. 2011. Dynamic Spatial and Temporal Prediction of Changes in Depositional Processes on Clastic Shorelines: Toward Improved Subsurface Uncertainty Reduction and Management. American Association of Petroleum Geologists Bulletin, v. 95, pp 267-297.

Alam, M.M., Crook, K.A.W., and Taylor, G., 1985, Fluvial herring-bone cross-stratification in a modern tributary mouth bar, Coonambele, New South Wales, Australia: Sedimentology, v. 32, p. 235–244.

Alexander, E.M., Gravestock, D.I., Cubitt, C. And Chaney, A. 1998. Lithostratigraphy and environments of deposition. In: Gravestock, D.I., Hibburt, J.E. & Drexel, J.F. (eds), The petroleum geology of South Australia, vol. 4, Cooper Basin. Primary Industries and Resources SA, Report Book 98/9, pp 69-115.

Allan, R.J. 1990. Climate. In: Tyler, M.J., Twidale, C.R., Davies, M., Wells, C.B. (Eds.), Natural History of the Northeast Deserts. Royal Society of South Australia Inc., Adelaide.

Allen G., Lang S., Musakti O. & Chirinos A. 1996. Application of Sequence Stratigraphy to Continental Successions: Implications for Mesozoic Cratonic Interior Basins of Eastern Australia. In Mesozoic Geology of the Eastern Australia Plate Conference, pp. 22-26. Geological Society of Australia Inc. Extended Abstracts No. 43, Queensland, Australia.

Alley N.F. 1998. Cainozoic stratigraphy, palaeoenvironments and geological evolution of the Lake Eyre Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 144 pp 239-263.

Alley, N.F. and Lindsay, J.M. 1995. Tertiary. In: Drexel, J.F. and Preiss, W.V. (Eds), The geology of South Australia, Vol. 2, The Phanerozoic. South Australia. Geological Survey. Bulletin, 54: pp150-217.

Allison, P.A., and Briggs, D.E.G. 1993. Palaeolatitudinal sampling bias; species diversity and the end-Permian extinction event: Geology, v. 21, pp 65–68.

Ambrose G., Suttill R. & Lavering I. 1982. A Review of the Early Cretaceous Murta Member in the Southern Eromanga Basin. In Moore, P.S. & Mount T.J. eds. Eromanga Basin Symposium, Summary Papers, pp 92-109. Geological Society of Australia & Petroleum Exploration Society of Australia, Adelaide.

Ambrose G., Suttill R. & Lavering I. 1986. The Geology and Hydrocarbon Potential of the Murta Member (Mooga Formation). In the Southern Eromanga Basin. In Gravestock D.I., Moore P.S. & Pitt G.M. eds. Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin. GSA, Special Publication No. 12, pp 71-84.

Antia, J. and Fielding, C.R. 2011. Sequence stratigraphy of a condensed low-accommodation succession: Lower Upper Cretaceous Dakota Sandstone, Henry Mountains, southeastern Utah. AAPG Bulletin, 95(3), pp 413–447.

Apak, S.N., Stuart, W.J., Lemon, N.M. and Wood, G. 1997. Structural Evolution of the Permian - Triassic Cooper Basin, Australia: Relation to hydrocarbon trap styles. AAPG Bulletin, 81(4), pp 533-555.

Armstrong J.D. and Barr T.M. 1986. The Eromanga Basin. An overview of exploration and potential. In: Gravestock D., Moore P.S. & Pitt G.M. (ed.) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. G.S.A Spec. Publication No. 12, pp 25-38.

Arthur M.A., Dean W.E., Schlanger S.O. 1985. Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes of atmospheric CO_2, In: Sundquist ET, Broecker WS (eds) The carbon cycle and atmospheric CO_2 natural variations.

Arthur, M. A., and Schlanger, S. O. 1979. Cretaceous ‘‘oceanic anoxic events’’ as causal factors in development of reef-reservoired giant oil fields, AAPG Bull., 63, pp 870 – 885.

Baganz, O.W. Baganz, O., Bartov, Y., Bohacs, K. M., Nummedal, D. 2012. Lacustrine sandstone reservoirs and hydrocarbon systems American Association of Petroleum Geologists, AAPG Hedberg Research Conference. AAPG Memoir ; 95.

Bartleson, B. 1994. Dakota Sandstone and associated rocks near Gunnison, Colorado: Geological Society of America, Rocky Mountain Section, 46th annual meeting. Abstracts with Programs Geological Society of America, v. 26, pp 3.

Beaumont, C., Quinlan, G. M., and Stockmal, G. S. 1993. The evolution of the Western Interior Basin: causes, consequences and unsolved problems, in Caldwell, W. G. E. and Kauffman, E. G. eds., Evolution of the Western Interior Basin, Geological Association of Canada (Special Paper 39), pp 97 117.

Beddoes L.R.1973. Oil and gas fields of Australia, Papua New Guinea and New Zealand. Tracer Petroleum & Mining Publications, Sydney.

Belton, D.X., Brown, R.W., Kohn, B.P., Fink, D., Farley, K.A. 2004. Quantitative resolution of the debate over antiquity of the central Australian landscape: implications for the tectonics and geomorphic stability of cratonic interiors. Earth Planet. Sci. Lett. 219, pp 21-34.

Bierman, P.R., Caffee, M. 2002. Cosmogenic exposure and erosion history of Australian bedrock landforms. Geol. Soc. Am. Bull. 114, pp 787-803.

Billi P. 2007. Morphology and sediment dynamics of ephemeral streams terminal reaches in the Kobo basin (northern Welo, Ethiopia). Geomorphology, 85 pp 98–113

Blakey, R. C., and P. J. Umhoefer. 2003. Jurassic-Cretaceous paleogeography, terrane accretion, and tectonic evolution of western North America: Geological Society of America, 2003 annual meeting. Abstracts with Programs Geological Society of America, 35, pp 558.

Blum, M., Kocurek, G., Swezey, C., Deynoux, M., Lancaster, N., Price, D., Pion, J.C.1998. Quaternary wadi, lacustrine, aeolian depositional cycles and sequences, Chott Rharsa Basin, southern Tunisia. In: Alsharhan, A., Glennie, K., Whittle, G., Kendall, C. (Eds.), Quat. Deserts Climatic Change. Balkema, Rotterdam, pp 539–552.

Bohacs, K.M., Carroll, A.R., and Neal, J.E. 2000a. Lessons from large lake systems-Thresholds, nonlinearity, and strange attractors: Geological Society of America Abstracts with Programs, v. 32, no. 7, pp A-312.

Bohacs, K.M., Carroll, A.R., Neal, J.E., and Mankiewicz, P.J. 2000b. Lake-basin type, source potential, and hydrocarbon character: An integrated sequencestratigraphic–geochemical framework, in Gierlowski-Kordesch, E., and Kelts, K., eds., Lake basins through space and time: American Association of Petroleum Geologists Studies in Geology v. 46, pp 3–37.

Bohacs, K.M., Neal, J.E., Carroll, A.R., Reynolds. D.J. 2000c. Lakes are not small oceans! Sequence stratigraphy in lacustrine basins [abs.]: American Association of Petroleum Geologists Annual Meeting Expanded Abstracts, v. 9, pp 14.

Boyd, R., Dalrymple, R.W., Zaitlin, B.A. 2006. Estuary and incised valley facies models. In: Posamentier, H.W., Walker, R.G. (Eds.), Facies Models Revisited. SEPM Special Publication, vol. 84, pp 171–234..

Bradley G. 1993. Depositional Facies and Reservoir Analysis of the Murta Member – Thungo and Maxwell Fields. Report Prepared for Minora Resources NL. (Unpublished)

Brenner, R., Ravn, G., Ludvigson, B., Joeckel, A., Witzke, E., Zawistoski, & Kvale. (2000). Late Albian kiowa-skull creek marine transgression, lower dakota formation, eastern margin of western interior seaway, U.S.A. Journal of Sedimentary Research, 70(4), 868-878.

Burbank, W. S. 1930, Revision of geologic structure and stratigraphy in the Ouray District of Colorado, and its bearing on ore deposition: Proceedings of the Colorado Scientific Society, v. 12, pp 151-232.

Burger, D. 1986. Palynology, cyclic sedimentation, and palaeoenvironments in the Lafe Mesozoic of the Eromanga Basin. In: Gravesfock D., Moore P.S. & Pitt G.M. (ed.) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. G.S.A Spec. Publication No. 12, pp 53-70.

Callen, R.A., Alley, N.F. and Greenwood, D.R. 1995. Lake Eyre Basin. In: Drexel, J.F. and Preiss, W.V. (Eds), The geology of South Australia, Vol. 2, The Phanerozoic. South Australia. Geological Survey. Bulletin, 54, pp 189-194.

Carter, W. D. 1957. Disconformity between lower and upper Cretaceous in western Colorado and eastern Utah: Geological Society of America Bulletin, v. 68, pp 307-314.

Catuneanu, O. , Abreu, V. , Bhattacharya, J.P. , Blum, M.D. , Dalrymple, R.W. , Eriksson, P.G. , Fielding, C.R. , Fisher, W.L. , Galloway, W.E. , Gibling, M.R. , Giles, K.A. , Holbrook, J.M. , Jordan, R., Kendall, C.G.St.C. , Macurda, B. , Martinsen, O.J. , Miall, A.D. , Neal, J.E. , Nummedal, D. , Pomar, L., Posamentier, H.W. , Pratt, B.R. , Sarg, J.F. , Shanley, K.W. , Steel, R.J. , Strasser, A., Tucker, M.E. , Winker, C. 2009. Towards the standardization of sequence stratigraphy. Earth Science Reviews, 92(1), pp1–33.

Catuneanu, O., Sweet, A., and Miall, A. D. 2000. Reciprocal stratigraphy of the Campanian–Paleocene Western Interior of North America. Sedimentary Geology, v. 134, pp 235–255.

Cohen, T.J., Nanson, G.C., Larsen, J.R., Jones, B.G., Price, D.M., Coleman, M., Pietsch, T.J. 2010. Late Quaternary aeolian and fluvial interactions on the Cooper Creek Fan and the association between linear and source-bordering dunes, Strzelecki Desert, Australia. Quat. Sci. Rev. 29, pp 455-471.

Costelloe, J.F., Grayson, R.B., Argent, R.M., McMahon, T.A. 2003. Modelling the flow regime of an arid zone floodplain river, Diamantina River, Australia. Environ. Model. Softw. 18, pp 693–703.

Curtis C.D., Coleman M.L. 1986. Controls on the precipitation of early diagenetic calcite, dolomite and siderite concretions in complex depositional sequences. pp 23-33 in: Roles of Organic Matter in Sediment Digenesis SEPM Spec. Publ. 38.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology 62, pp 1130 – 1146.

De Lurio, J.L. and Frakes, L.A.1999. Glendonites as a paleoenvironmental tool: implications for early Cretaceous high latitude climates in Australia. Geochimica et Cosmochimica Acta, 63(7), pp1039–1048.

DeCelles, P. G. 1994. Late Cretaceous–Paleogene synorogenic sedimentation and kinematic history of the Sevier thrust belt, northeast Utah and southwest Wyoming. Geological Society of America Bulletin, v. 106, pp 32–56.

DeCelles, P. G. and Giles, K. A., 1996, Foreland basin systems. Basin Research, v. 8, pp 105–123.

Dodman, A. P., Rodregues, J.T. 1989. The Jackson Oil Field development. In: O'Neil, B.J., (ed.), The Cooper and Eromanga Basins, Australia. Proceedings of Petroleum Exploration Society of Australia, Society of Petroleum Engineers, Australian Society of Exploration Geophysicists (SA Branches), Adelaide, pp 19-28.

Dolson, J.C., Muller, D.S., Evetts, M.J., and Stein, J.A. 1991. Regional paleotopographic trends and production, Muddy Sandstone (Lower Cretaceous), central and northern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, pp 409–435.

Draper J.J. 2002. Geological setting: in Draper JJ (editor) Geology of the Cooper and Eromanga basins, Queensland. Queensland Government, Natural Resources and Mines, Queensland Mineral and Energy Review Series, pp 57–59.

Elder, W. P., Gustason, E. R., and Sageman, B. B. 1994. Correlation of basinal carbonate cycles to nearshore parasequences in the Late Cretaceous Greenhorn seaway, Western Interior, U.S.A. Geological Society of America Bulletin, v. 106, pp 892–902.

Ericksen, M. C. and Slingerland, R. 1990. Numerical simulations of tidal and wind-driven circulation in the Cretaceous Interior Seaway of North America. The Geological Society of America Bulletin, 102(11), pp 54–62.

Etheridge L., Mcminn A., M., Walsk Ll., Davies B. 1986. Lake Stewart DDH 1 - Eromanga Basin petroleum stratigraphic drill hole. N.S. W. Geological Survey. Quarterly Notes, 61, pp 16-30.

Fagan, S.D., Nanson, G.C. 2004. The morphology and formation of floodplain-surface channels, Cooper Creek, Australia. Geomorphology 60, pp 107-126.

Fischer, C., Gaupp, R., Dimke, M., & Sill, O. 2007. A 3D High Resolution Model of Bounding Surfaces in Aeolian-Fluvial Deposits: An Outcrop Analogue Study from the Permian Rotliegend, Northern Germany.(Author abstract). Journal of Petroleum Geology, 30(3), pp 257-274.

Fisher, J.A., Krapf, C.B.E., Lang, S.C., Nichols, G., and Payenberg., T.H.D. 2008. Sedimentology and architecture of the Douglas Creek terminal splay, Lake Eyre, central Australia: Sedimentology, v. 55/6, pp 1915–1930.

Fouch, T.D., Lawton, T.F., Nichols, D.J., Cashion, W.B. and Cobban, W.A. 1983. Patterns and timing of synorogenic sedimentation in Upper Cretaceous rocks of central and northeast Utah. In:

Mesozoic Palaeogeography of West-Central United States (Eds M.W. Reynolds and E.D. Dolly), pp 305–336. Rocky Mountain Section, SEPM Denver, Colorado.

Fraser and Hester, 1977, Sediments and sedimentary structures of a beach-ridge complex, southwestern shore of Lake Michigan: Journal of Sedimentary Petrology, v. 47, p. 1187–1200.

Friend, P.F. 1978. Distinctive features of some ancient river systems in A.D.Miall, Fluvial sedimentology, Canadian Society of Petroleum Geologists, Memoir 5: pp 531-542.

Fujioka, T., Chappell, J. 2011. Desert landscape processes on a timescale of millions of years, probed by cosmogenic nuclides. Aeolian Research 3, pp 157-164.

Fujioka, T., Chappell, J., Field, L.K., Rhodes, E.J. 2009. Australian desert dune field initiated with Pliocene-Pleistocene global climate shift. Geology 37, pp 51-54.

Gallagher, K. 1990. Permian to Cretaceous subsidence history along the Eromanga-Brisbane Geoscience Transect; In Finlayson D.M. (ed) The Eromanga-Brisbane Geoscience Transect: A guide to basin development across Phanerozoic Australia in Southern Qld Bureau of Mineral Resources, Australia. Bulletin 232 pp 133-151.

Gallagher, K., Lambeck, K. 1989. Subsidence, sedimentation and sea-level changes in the Eromanga Basin, Australia. Basin Research, 2(2), pp115–131.

Galloway W.E. 1986. Genetic Stratigraphic Sequences in Basin Analysis 1: Architecture and Genesis of Flooding-Surface Bounded Depositional Units. The American Association of Petroleum Geologists Bulletin 73, No. 2, pp 125-142.

Gautier D.L. 1982. Siderite concretions: indicators of early diagenesis in the Gammon Shale (Cretaceous). Journal of Sedimentary Petrology Vol. 52 No. 3; pp 859-871.

Gautier D.L., Claypool G.E. 1984. Interpretation of Methanic diagenesis in ancient sediments by analogy with processes in modern diagenetic environments. In McDonald D.A. & Surdam P.C. (eds) Clastic Diagenesis. AAPG Memoir 37, pp 111-123.

Gorter J.D. 1994. Sequence Stratigraphy and the Depositional History of the Murta Member (Upper Hooray Sandstone), Southeastern Eromanga Basin, Australia: Implications for the Development of Source and Reservoir Facies. APEA Journal, pp 644-673.

Gravestock D., Griffiths M. & Hill A. 1983. The Hutton Sandstone - two separate reservoirs in the Eromanga Basin, South Australia. APEA Journal Vol. 23, part 1; pp 109-119.

Gravestock D.I., Benbow M.C., Gatehouse C.G., Krieg G.W. 1995. Eromanga Basin. In JF Drexel and WV Preiss eds, The geology of South Australia, Volume 2, The Phanerozoic, Bulletin 54. Geological Survey of South Australia, pp 35–41.

Gray, A.R.G., McKillop, M., McKellar, J.L. 2002. Eromanga Basin Stratigraphy: in Draper JJ (editor) 'Geology of the Cooper and Eromanga basins, Queensland'. Queensland Government, Natural Resources and Mines, Queensland Mineral and Energy Review Series, pp 30–56.

Green P.M., Eadington P.J., Hamilton P.J. & Carmichael D.C. 1989. Regional diagenesis - an important influence in porosity development and hydrocarbon accumulations within the Hutton Sandstone, Eromanga Basin. In: O'Neil, B.J., (ed.), The Cooper and Eromanga Basins, Australia. Proceedings of Petroleum Exploration Society of Australia, Society of Petroleum Engineers, Australian Society of Exploration Geophysicists (SA Branches), Adelaide, pp 19-28.

Gustason, E. R., Kauffman, E. G. 1985. The Dakota Group and the Kiowa- Skull Creek Cyclothem in the Canon City-Pueblo area, Colorado. In L. M. Pratt, E. G. Kauffman, and F. Zelt (ed.), Socitey of Econmic Paleontologists, Mineralogists, Field Trip Guidebook No. 4; 1985 Midyear Meeting, Golden, CO. pp 72-89.

Habeck-Fardy, A. and Nanson G. 2014. Environmental character and history of the Lake Eyre Basin, one seventh of the Australian continent. Earth-Science Reviews, 132, pp 39–66.

Hall, L., Hill, T., Wang, L., Edwards, D., Kuske, T., Troup, A., Boreham, C. 2015. Gas prospectivity of the Cooper Basin. APPEA 2015.

Hancock, J., & Kauffman, E. (1979). The great transgressions of the Late Cretaceous. Journal of the Geological Society, 136(2), 175-186.

Helland-Hansen, W. & Hampson, G.J. 2009. Trajectory analysis: concepts and applications. Basin Research, 21(5), pp 454–483.

Hill A.J. 1999. Maxwell Murta Formation Depositional Setting. Report Prepared for Santos Ltd (Unpublished).

Hoffmann K.L. 1989. The Influence of pre-Jurassic Tectonic Regimes on the Structural Development of the Southern Eromanga Basin, Queensland. In O'Neil B.J. ed. The Cooper & Eromanga Basins Australia. pp.315-328. Proceedings of the Cooper and Eromanga Basins Conference, Adelaide, 1989.

Howell, J.A. and Flint, S.S. 2003. Siliciclastics case study: the Book Cliffs. In: Coe, A. (ed.) The Sedimentary Record of Sea-level Change. Cambridge University Press, Cambridge, pp 135–208.

Jansen, J.D., Nanson, G.C., Cohen, T.J., Fujioka, T., Fabel, D., Larsen, J.R., Codilean, A.T., Price, D.M., Bowman, H.H., May, J.H., Gliganic, L.A. 2013. Lowland river responses to intra- plate tectonism and climate forcing quantified with luminescence and cosmogenic 10-Be. Earth Planetary Science Letters 366, pp 49-58.

Jenkyns, H. 1980. Cretaceous anoxic events: from continents to oceans. Journal of the Geological Society, 137(2), pp 171–188.

Jewell, P., Lingerland, R., Kump, L., Arthur, M., Fawcett, P., Sageman, B., & Barron, E. (1998). Estuarine circulation in the Turonian Western Interior seaway of North America: Discussion and reply. Geological Society of America Bulletin, 110(5), 691-694.

John B.H., Almond C.S. 1987. Lithostratigraphy of the lower Eromanga Basin sequence in south-west Queensland. APEA Journal Vol. pp 196-214.

Johnson, R.C. 2003. Depositional framework of the Upper Cretaceous Mancos Shale and the lower part of the Upper Cretaceous Mesaverde Group, Western Colorado and Eastern Utah, in Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta–Piceance Province, Utah and Colorado: U.S. Geological Survey, Digital Data Series DDS-69-B, Chapter 10.

Jones J. G., Veevers, J. J. 1983. Mesozoic origins and antecedents of Australia's Eastern Highlands. Journal of the Geological Society of Australia. 30, pp 305-322.

Jordan, T. E. 1981.Thrust loads and foreland basin evolution, Cretaceous, western United States. American Association of Petroleum Geologists Bulletin, v. 65, pp 2506–2520.

Kantsler, A.J., Prudence, T.J.C., Cook, A.C. and Zwigulis T.C. 1983. Hydrocarbon Habit of the Cooper/ Eromanga Basin, Australia, The APEA Journal, Volume 23, Part 1, pp 75 - 92.

Kauffman, E. G. 1984. Paleobiogeography and evolutionary response dynamic in the Cretaceous Western interior seaway of North America, in Westerman, G. E. ed., Jurassic–Cretaceous biochronology and paleogeography of North America. Geological Association of Canada, St. John's, Nfld., (Special Paper 27), pp 273–306.

Knighton, A.D., Nanson, G.C. 1994. Waterholes and their significance in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 9, pp 311–324.

Knighton, A.D., Nanson, G.C. 2000. Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. Geomorphology, 35(1), pp 101–117.

Kraft J.C., John C.J. 1979. Lateral and vertical facies relations of transgressive barrier. AAPG Bulletin Vol. 63 No. 12; pp 2145-2163.

Krieg G.W., Alexander E.M., Rogers P.A. 1993. Eromanga Basin: in Drexel JF and Priess WV (editors) 'The geology of South Australia. Volume 2, The Phanerozoic, Chapter 8 Late Palaeozoic'. Geological Survey of South Australia, Bulletin 54, pp 101–127.

Krystinik, L., Blakeney DeJarnett, B., (1995). Lateral variability of sequence stratigraphic framework in the Campanian and Lower Maastrichtian of the Western Interior Seaway. Sequence stratigraphy of foreland basin deposits. 11-25.

Kulikowski, D., Amrouch, K., Cooke, D. 2016. Geomechanical modelling of fault reactivation in the Cooper Basin, Australia, Australian Journal of Earth Sciences, 63, 3, pp 295-314.

Lang, S. C., Payenberg, T.H.D., Reilly, M.R.W., Hicks, T., Benson, J. And Kassan, J. 2004. Modern Fluvial Analogues for dryland sandy fluvial-lacustrine deltas and terminal splay reservoir. APPEA Journal, 2004, pp 329–56.

Laveping L.H., Passmore V.L., Paton L.M. 1986. Discovery and exploitation of new oilfields in the Cooper-Eromanga Basins. APEA Journal Vol 26, part 1, pp 250-259.

Lennox C.L. 1986. Early Cretaceous Sedimentology and Depositional Facies at Nockatunga Oilfield, Cooper-Eromanga Basin, Queensland. Unpublished B.Sc. Honours Thesis, University of New South Wales.

Livaccari, R.F. 1991. Role of crustal thickening and extensional collapse in the tectonic evolution of the Sevier-Laramide orogeny, western United States. Geology, 19(11), pp1104.

Magee, J.W., Bowler, J.M., Miller, G.H., Williams, D.L.G. 1995. Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan gulf, Lake Eyre, South Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 113, pp 3-42.

Maroulis, J.C., Nanson, G.C. 1996. Bedload transport of aggregated muddy alluvium from Cooper Creek, central Australia: a flume study. Sedimentology 43, pp 771-790.

Maroulis, J.C., Nanson, G.C., Price, D.M., Pietsch, T. 2007. Aeolian-fluvial interaction and climate change: source-bordering dune development over the past 100 ka on Cooper Creek, central Australia. Quat. Sci. Rev. 26, pp 386-404.

Matthews, K.J., Hale, A.J., Gurnis, M., Müller, R.D., DiCaprio, L. 2011. Dynamic subsidence of eastern Australia during the Cretaceous: Gondwana Research, v. 19, no. 2, pp 372–383.

Mavromatidis, A. 2006. Burial/exhumation histories for the Cooper–Eromanga Basins and implications for hydrocarbon exploration, Eastern Australia. Basin Research, 18(3), pp 351–373.

McGookey, D. P., J. D. Haum, L. A. Hale, H. G. Goodell, D. G. McCubbin, R. J. Weimer, and Walf, G. R. 1972. Geological Atlas of The Rocky Mountain Region, Rocky Mountain Association of Geologists, 331 pp.

McKellar J.L. 1996. Palynofloral and Megafloral Indications of Palaeoclimate in the Late Triassic, Jurassic, and Early Cretaceous of Southeastern Queensland. In Mesozoic Geology of the Eastern Australia Plate Conference, pp 336-371. Geological Society of Australia Inc. Extended Abstracts No. 43, Queensland, Australia.

McKenzie, D. B. 1971. Post-Lytle Dakota Group on the west flank of Denver Basin, Colorado: The Mountain Geologist, v. 8, pp 91-131.

McMahon, T.A., Murphy, R.E., Peel, M.C., Costelloe, J.F., Chiew, F.H.S. 2008. Understanding the surface hydrology of the Lake Eyre Basin: part 1 - rainfall. J. Arid Environ. 72, pp 1853-1868.

McPhail, A., Massey, T., Navaharo, E. 2014. Cuisinier Field Development Report. Internal Santos Unpublished Report.

Meek, F. B., Hayden F. V. 1861, Description of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska, by the exploring expedition under the command of Capt. Wm. F. Reynolds, U. S. Top. Engineers; with some remarks on the rocks from which they were obtained: Philadelphia. Acad. Nat. Sci. Proc, v. 13, pp 415-447.

Miall, A.D., Catuneanu, O., Vakarelov, B., and Post, R. 2008. The Western Interior Basin, in Miall, A.D., ed., The Sedimentary Basins of the United States and Canada: Sedimentary basins of the World, v. 5 (K.J. Hsü, Series Editor): Amsterdam, Elsevier Science, pp 329–362.

Michaelsen B.H., Mckirdy D.M., 1989. Organic facies and petroleum geochemistry of the lacustrine Murta Member (Mooga Formation) in the Eromanga Basin, Australia. in: ONeil, B.J., (ed.), The Cooper and Eromanga Basins, Australia. Proceedings of Petroleum Exploration Society of Australia, Society of Petroleum Engineers, Australian Society of Exploration Geophysicists (SA Branches), Adelaide, pp 541-558.

Miller, G.H., Mangan, J., Pollard, D., Thompson, S., Felzer, B., Magee, J. 2005. Sensitivity of the Australian Monsoon to insolation and vegetation: implications for human impact on continental moisture balance. Geology 33, pp 65-68.

Molenaar, C.M., and Rice, D.D. 1988. Cretaceous rocks of the Western Interior Basin, in Sloss, L.L., ed., Sedimentary cover—North American craton, U.S.: Geological Society of America, The Geology of North America, v. D2, pp 77–82.

Moore P.S. 1986. An Exploration Overview of the Eromanga Basin. Geological Society of Australia Special Publication, No. 12, pp 1-8

Moore P.S., Pitt G.M. 1984. Cretaceous Subsurface Stratigraphy of the Southwestern Eromanga Basin: a Review. Special Publication, South Australian Department of Mines and Energy, 5: pp 269-286

Mount T.J. 1982. Geology of the Dullingari Murta Oilfield. In Moore P.S. & Mount T.J. eds. Eromanga Basin Symposium. Summary Papers. GSA and PESA, Adelaide. Australian Sedimentologists Special Group, Wollongong, pp 307-337.

Mount, T.J. 1981. Dullingari North 1, an oil discovery in the Murta Member of the Eromanga Basin. APEA Journal 21(1) pp 71-77.

Nanson, G.C., Chen, X.Y., Price, D.M. 1992. Lateral migration, thermoluminescence chronology and colour variation of longitudinal dunes near Birdsville in the Simpson Desert, central Australia. Earth Surf. Process. Landf. 17, pp 807-819.

Nanson, G.C., Chen, X.Y., Price, D.M. 1995. Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 113, pp 87–102.

Nanson, G.C., Jones, B.G., Price, D.M., Maroulis, J.C., Coleman, M., Bowman, H.H., Cohen, T.J., Pietsch, T. 2008. Alluvial evidence for major climate and flow-regime changes during the Middle and Late Quaternary in eastern central Australia. Geomorphology 101, pp 109-129.

Nanson, G.C., Jones, B.G., Price, D.M., Maroulis, J.C., Coleman, M., Bowman, H.H., Cohen, T.J., Pietsch, T. 2008. Alluvial evidence for major climate and flow-regime changes during the Middle and Late Quaternary in eastern central Australia. Geomorphology 101, pp 109-129.

Nanson, G.C., Price, D.M., Short, S.A. 1992. Wetting and drying of Australia over the past 300 ka. Geology 20, pp 791-794.

Nanson, G.C., Rust, B.R., Taylor, G. 1986. Coexistent mud braids and anastomosing channels in an arid-zone river: Cooper Creek, central Australia. Geology 14, pp 175–178.

Nanson, G.C., Rust, B.R., Taylor, G. 1986. Coexistent mud braids and anastomosing channels in an arid-zone river: Cooper Creek, central Australia. Geology 14, pp 175–178.

Nanson, G.C., Tooth, S. 1999. Arid-zone rivers as indicators of climate change. In: Singhvi, A.K., Derbyshire, E. (Eds.), Palaeoenvironmental Reconstruction in Arid Lands. Oxford and IBH Press, New Dehli.

Nanson, G.C., Young, R.W., Price, D.M., Rust, B.R. 1988. Stratigraphy, sedimentology and Late Quaternary chronology of the Channel Country of western Queensland. In: Warner, R.F. (Ed.), Fluvial Geomorphology of Australia. Academic Press, Sydney.

Newton, C.B. 1986. The Tintaburra oilfield. APEA Journal 26(1) pp 334-352.

Nichols G.J., Fisher, J.A. 2007. Processes, facies and architecture of fluvial distributary system deposits. Sedimentary Geology, 195(1), pp 75–90.

North C. P., Warwick G. L. 2007 Fluvial fans: myths, misconceptions, and the end ofthe terminal-fan model. Journal of Sedimentary Research 77: pp 693-701.

Pang, M., and Nummedal, D. 1995. Flexural subsidence and basement tectonics of the Cretaceous Western Interior Basin, United States. Geology, v. 23, pp 173–176.

Plint, A. G., and Kreitner, M. A. 2007. Extensive, thin sequence spanning Cretaceous foredeep suggest high-frequency eustatic control: Late Cenomanian, Western Canada foreland basin. Geology, v. 35, pp 735–738.

Posamentier H.W., Allen G.P., James D.P., Tesson M. 1992. Forced Regressions in a Sequence Stratigraphic Framework: Concepts, Examples, and Exploration Significance. The American Association of Petroleum Geologists Bulletin 76, No. 11, pp 1687-1709.

Posamentier, H.W., Allen, G.P. (Eds.) 1999. Siliciclastic Sequence Stratigraphy—Concepts and Applications. SEPM Concepts in Sedimentology and Paleontology, vol. 7. pp 216.

Powell T.G., Boreham C.J., McKirdy D.M., Michaelsen B.H., Summons R.E. 1989. Petroleum Geochemistry of the Murta Member, Mooga Formation, and Associated Oils, Eromanga Basin. The APPEA Journal 29, pp114-129.

Queensland Government. 2016. Wetland mapping — Lake Yamma Yamma 100K map tile — 7145, WetlandInfo, Department of Environment and Heritage Protection, Queensland, <https://wetlandinfo.ehp.qld.gov.au/wetlands/facts-maps/tile-100k-lake-yamma-yamma/>.

Quigley, M.C., Clark, D., Sandiford, M. 2010. Tectonic geomorphology of Australia. Geol. Soc. Lond. Spec. Publ. 346, pp 243-265.

Radke, B. 2009. Hydrocarbon and geothermal prospectivity of sedimentary basins in central Australia; Warburton, Cooper, Pedirka, Galilee, Simpson and Eromanga Basins, Geoscience Australia. Record, 2009/25, pp 161.

Robinson, P.A., Butler, G.F. 1989. Development of the Dullingari Murta Oil Field. In n O'Neil BJ (editor) The Cooper and Eromanga Basins, Australia. Proceedings of the Cooper and Eromanga Basins Conference, Adelaide 1989. Petroleum Exploration Society of Australia, Society of Petroleum Engineers, Australian Society of Exploration Geophysicists (SA Branches), pp 405–416.

Rundle, A.S. 1977. Channel Patterns of Multiple Streams. Unpublished PhD thesis, Macquarie University, Sydney.

Russell, M., Gurnis, M. 1994. The planform of epeirogeny: vertical motions of Australia during the Cretaceous. Basin Research 6, pp 63–76.

Rust, B.R. 1981. Sedimentation in an arid-zone anastomosing fluvial system: Cooper's Creek, central Australia. J. Sediment. Res. 51, pp 745–755.

Rust, B.R., Legun, A.S. 1983. Modern anastomosing fluvial deposits in arid central Australia and a carboniferous analogue in New Brunswick, Canada. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. Blackwell, Oxford.

Rust, B.R., Nanson, G.C.1986. Contemporary and palaeochannel patterns and the Late Quaternary stratigraphy of Cooper Creek, southwest Queensland, Australia. Earth Surf. Process. Landf. 11, pp 581-590.

Sageman, B. B., Rich, J., Arthur, M. A., Birchfield, G. E., and Dean, W. E. 1997. Evidence for Milankovitch periodicities in Cenomanian–Turonian lithologic and geochemical cycles, western interior, U.S.A. Journal of Sedimentary Research, v. 67, pp 286–302.

Sandiford, M., Quigley, M., De Broekert, P., Jakica, S. 2009. Tectonic framework for the Cenozoic cratonic basins of Australia. Aust. J. Earth Sci. 56, pp 5-18.

Schulz-Rojahn J.P. 1993. Calcite Cemented Zones in the Eromanga Basin: Clues to Petroleum Migration and Entrapment? APEA Journal, pp 63-76.

Senior, B.R., Mond, A., Harrison, P.L. 1978. Geology of the Eromanga Basin. Bur. Miner. Resour. Bull. 167.

Senior, D. 1968. Durham Downs, Queensland. 1:250,000 Map Sheet SG/ 54-15, Explanatory Notes. Bureau of Mineral Resources, Geology and Geophysics.

Serradji, H. 2007. Depositional Environments and Sequence Stratigraphy of the Lower Cretaceous Dakota Sandstone in South-western Colorado, Unpublished Masters thesis, University of Kansas.

Slingerland, R. 1986. Numerical computation of co-oscillating palaeotides in the Catskill epeiric sea of eastern North America: Sedimentology, v. 33, pp 487–497.

Slingerland, R., Kump, Lee R., Arthur, Michael A., Fawcett, Peter J., Sageman, Bradley B., & Barron, Eric J. (1996). Estuarine circulation in the Turonian Western Interior seaway of North America. The Geological Society of America Bulletin, 108(8), 941-952.

Sloss, L.L., Krumbein, W. C., and Dapples, E. C. 1949. Integrated Facies Analysis, in Sedimentary Facies in Geologcal History, Longwell, C. R., chair; Geological Society of America, Memoir 39, pp 91-124.

Sprigg R.C. 1986. The Eromanga Basin in the search for commercial hydrocarbons. In: Gravestock D., Moore P.S. & Pitt G.M. (ed.) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. G.S.A Spec. Publication No. 12, pp 9-24.

Staughton, D.B. 1985. Diagenetic history and reservoir quality evolution of the Strzelecki hydrocarbon field, Cooper/Eromanga basins, South Australia. Unpublished Honours Thesis, Monash University, Melbourne.

Theologou, P. 1995. Murta Formation/McKinlay Member of the Murteree Ridge Nappacoongee- Murteree Block Improved Oil recovery project. Unpublished PhD thesis, University of South Australia.

Tooth, S. 1999. Downstream changes in floodplain character on the Northern Plains of arid central Australia. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI, International Association of Sedimentologists, Special Publication No. 28. Blackwell Scientific Publications, Oxford.

Tooth, S. 2000. Process, form and change in dryland rivers: a review of recent research. Earth Sci. Rev. 51, pp 67–107.

Tooth, S. 2005. Splay formation along the lower reaches of ephemeral rivers on the Northern Plains of arid central Australia. J. Sediment. Res. 75, pp 636–649.

Tooth, S., Nanson, G.C. 1999. Anabranching rivers on the Northern Plains of arid central Australia. Geomorphology 29, pp 211–233.

Tooth, S., Nanson, G.C. 2000. The role of vegetation in the formation of anabranching channels in arid central Australia. Geomorphology 34, 33–54.an ephemeral river, Northern Plains, arid central Australia. Hydrol. Process. 14, pp 3099–3117.

Tooth, S., Nanson, G.C. 2004. Forms and processes of two highly contrasting rivers in arid central Australia, and the implications for channel pattern prediction. Geol. Soc. Am. Bull. 116, pp 802–816.

Ulicny, D. 1999. Sequence stratigraphy of the Dakota Formation (Cenomanian), southern Utah: interplay of eustasy and tectonics in a foreland basin: Sedimentology, v. 46, pp 807-836.

Vakarelov, B. K., Bhattacharya, J. P., and Nebrigic, D. D. 2006. Importance of high-frequency tectonic sequences during greenhouse times of earth history. Geology, v. 34, pp 797–800.

Valdes, P. J. 1993. The influence to the Western Interior Seaway on climate modelling of the Cretaceous.; 1993 SEPM meeting abstracts with program, stratigraphic record of global change, pp 69.

Van Wagoner, J., Bertram, George T, & American Association of Petroleum Geologists. (1995). Sequence stratigraphy of foreland basin deposits : Outcrop and subsurface examples from the Cretaceous of North America / edited by J.C. Van Wagoner and G.T. Bertram. (AAPG memoir ; 64). Tulsa, Okla.: American Association of Petroleum Geologists.

Veevers J.J., Belousova E. A., Saeed A. 2016. Zircons traced from the 700–500 Ma Transgondwanan Supermountains and the Gamburtsev Subglacial Mountains to the Ordovician Lachlan Orogen, Cretaceous Ceduna Delta, and modern Channel Country, central-southern Australia. Sedimentary Geology, 334, pp 115–141.

Veevers, J.J. 1984. Phanerozoic Earth history of Australia. Clarendon Press Oxford.

Veevers, J.J. 2000. Billion-Year Earth History of Australia & Neighbours in Gondwanaland. GEMOC Press, Sydney.

Veevers, J.J., Saeed, A. 2011. Age and composition of Antarctic bedrock reflected by detrital zircons, erratics, and recycled microfossils in the Wilkes Land–Ross Sea– Marie Byrd Land sector (100°–240° E). Gondwana Research 20, pp 710–738.

Waage, K. M. 1955. Dakota Group in northern Front Range foothills, Colorado: U.S. Geological Survey Professional Paper 274-B, pp 15-51.

Waclawik, V.G., Lang, S.C., Krapf, C.B.E. 2008. Fluvial response to tectonic activity in an intracontinental dryland setting: the Neales River, Lake Eyre, central Australia. Geomorphology 102, pp 179-188.

Wasson, R.J. 1983a. The Cainozoic history of the Strzelecki and Simpson dunefields (Australia), and the origin of the desert dunes. Geomorphol. Suppl.bd 45, pp 85-115.

Weimer, P. C. 1982. Upper Cretaceous stratigraphy and tectonic history of the Ridgway area, northwestern San Juan Mountains, Colorado: The Mountain Geologist, v. 19, pp 91-104.

Wheeler, H.E. 1964. Base level, Lithosphere Surface, and Time-Stratigraphy, Geological Society of America Bulletin, July 1964, v. 75, no. 7, pp 599-610.

White, M.E., 1994. After the Greening: The Browning of Australia, Kangaroo Press, Kenthurst.

Whitehouse, F.W. 1948. The geology of the Channel Country of southwestern Queensland. Queensland Bureau Investigation Tech. Bull. 1, pp 10-28.

Wolfe, G., Upchurch, P. 1987. North American nonmarine climates and vegetation during the Late Cretaceous. Palaeogeography, Palaeoclimatology, Palaeoecology, 61(C), pp 33–77.

Young, R. G. 1960. Dakota Group of Colorado Plateau: AAPG Bulletin, v. 44, pp 156-194.

Zhou, S. 1989. Subsidence History of the Eromanga Basin, Australia. In O'Neil B.J. ed. The Cooper & Eromanga Basins Australia. pp 329-335. Proceedings of the Cooper and Eromanga Basins Conference, Adelaide, 1989.

Zoellner, E. 1988. Geology of the Early Cretaceous Murta Member, Mooga Formation, in the Cooper Basin Area, South Australia and Queensland. Flinders University PhD Thesis (Unpublished).

Chapter 3: A New and Noteworthy Oil Discovery: Integrated Stratigraphic Analysis of the Fluvial-Deltaic Cuisinier Field, Eromanga Basin, Australia

3.1. Abstract

The 2008 discovery of new reservoir facies in the Murta Formation provides an opportunity and need to develop a new facies model for the Cuisinier Field. Existing depositional models for the Murta Formation in the Eromanga Basin are inconsistent; the Murta Formation has previously been interpreted as marginal marine and as continental lacustrine. This chapter contributes new geological data on a fluvial termination in the low accommodation Eromanga Basin, and raises questions about potential marine influence. Seismic, conventional core, wireline and petrographic data were integrated in order to provide a new description and interpretation of the Murta Formation in the Cuisinier region. As the reservoir is largely below seismic resolution, detailed stratigraphic analysis primarily guided the development of the depositional model. Within the study area, Murta Formation strata comprise five facies associations that form a depositional continuum of offshore, pro-delta, delta front, shoreline and fluvial-dominated channel fill. The primary reservoir occurs in fluvial channel fill. Reservoir sand deposition is largely controlled by rising and falling base level in a series of transgressions and regressions. Autocyclic processes such as bifurcation and avulsion are important when considering reservoir compartmentalisation. This work provides a depositional model for the Cuisinier Field which will guide appraisal and development with an aim to minimize capital expenditure.

3.1. Introduction

Petroleum accumulations of the Eromanga Basin represent Australia's largest and most prolific onshore hydrocarbon resource. The Eromanga Basin is estimated to host approximately 130 MMstb of undiscovered oil (Alexander, 1998), an important portion of which is trapped in Early Cretaceous Murta Formation deposits. Effective development and production of these reserves requires a detailed understanding of stratal architecture, including the location and nature of internal baffles, barriers and compartments within the reservoirs. The Eromanga Basin is under-explored (approximately 1 well per 58 km^2) and subsurface mapping has been a persistent challenge in the Murta Formation due to the thin sub-seismic resolution of reservoir sandbodies and the occurrence of lateral facies changes over distances of a few hundred metres.

A new and important oil field was discovered in the Murta Formation of the Eromanga Basin, the Cuisinier Field. This field is particularly noteworthy as the reservoir was discovered in the Early Cretaceous Murta Formation contrary to the planned Mid-Jurassic target. Lithologies recorded were contrary to those predicted in the Murta Formation. The absence of an integrated basin-wide facies model and the complex, interfingering nature of the facies, together with the sub-seismic nature of reservoir sandbodies, makes development decisions difficult. Improved depositional environment interpretation and stratigraphic correlations within the region will help to provide a better estimation of the size of individual sandbodies, and therefore better predict reservoir continuity. New data from drilling and coring operations in the Cuisinier field provide an opportunity to develop high resolution sedimentological and stratigraphic models that better delineate the allo-cyclic and auto-cyclic controls on the distribution of facies and geometric stacking patterns of Murta Formation strata. The aim of this study was to better understand the distribution of reservoir sand and depositional controls on sedimentological heterogeneities in the Murta Formation of the Cuisinier Field. As well as enabling improvements to production efforts, it is anticipated that an improved understanding of stratigraphy at this location may aid in regional exploration.

3.2. Geological Setting

The Jurassic to Cretaceous Eromanga Basin (Figure 1A) covers approximately one million square kilometres; approximately one fifth of the Australian continent. During the Mid-Jurassic breakup of the supercontinent Gondwana commenced and as a result, from the Jurassic until the start of the Cretaceous the eastern part of Australia consisted of large, shallow interconnected sedimentary basins, the Eromanga, Carpentaria and Surat Basins, which covered approximately a third of the Australian continent (Mount, 1981). These basins preserved similar lithologies. In the Eromanga Basin, continental and marginal marine lithologies are preserved. The Early Cretaceous Murta Formation overlies the terrestrial Namur Sandstone and underlies the fully marine Cadna-owie Formation (Mount, 1981; Figure 2).

The breakup of Gondwana caused eustatic sea level rise which inundated vast areas of the continent (White, 1994). Previous investigation of the Early Cretaceous paleoclimate of south-eastern Queensland (McKellar, 1996; Gorter, 1994) interpreted a cool temperate climate. This interpretation is based on the presence of microflora pollen from Podocarpacean and Araucarean conifers, but megafloral studies inferred humid, warm-temperate to cool temperate conditions determined by the presence of Ginkgoales (Gorter, 1994). Paleolattitude investigations of the south-eastern Eromanga Basin suggest that the Early Cretaceous positioning of the basin is comparable to the present day latitudes of Norway and Alaska, inferring a colder and potentially glacial climate (White, 1994).

Early work in the Eromanga basin focussed on the Early Cretaceous stratigraphy as a genetic package at a basin scale. Initial studies (i.e. David and Woolnough, 1926) and later summaries (Krieg et al. 1993; Drexel and Preiss, 1995;

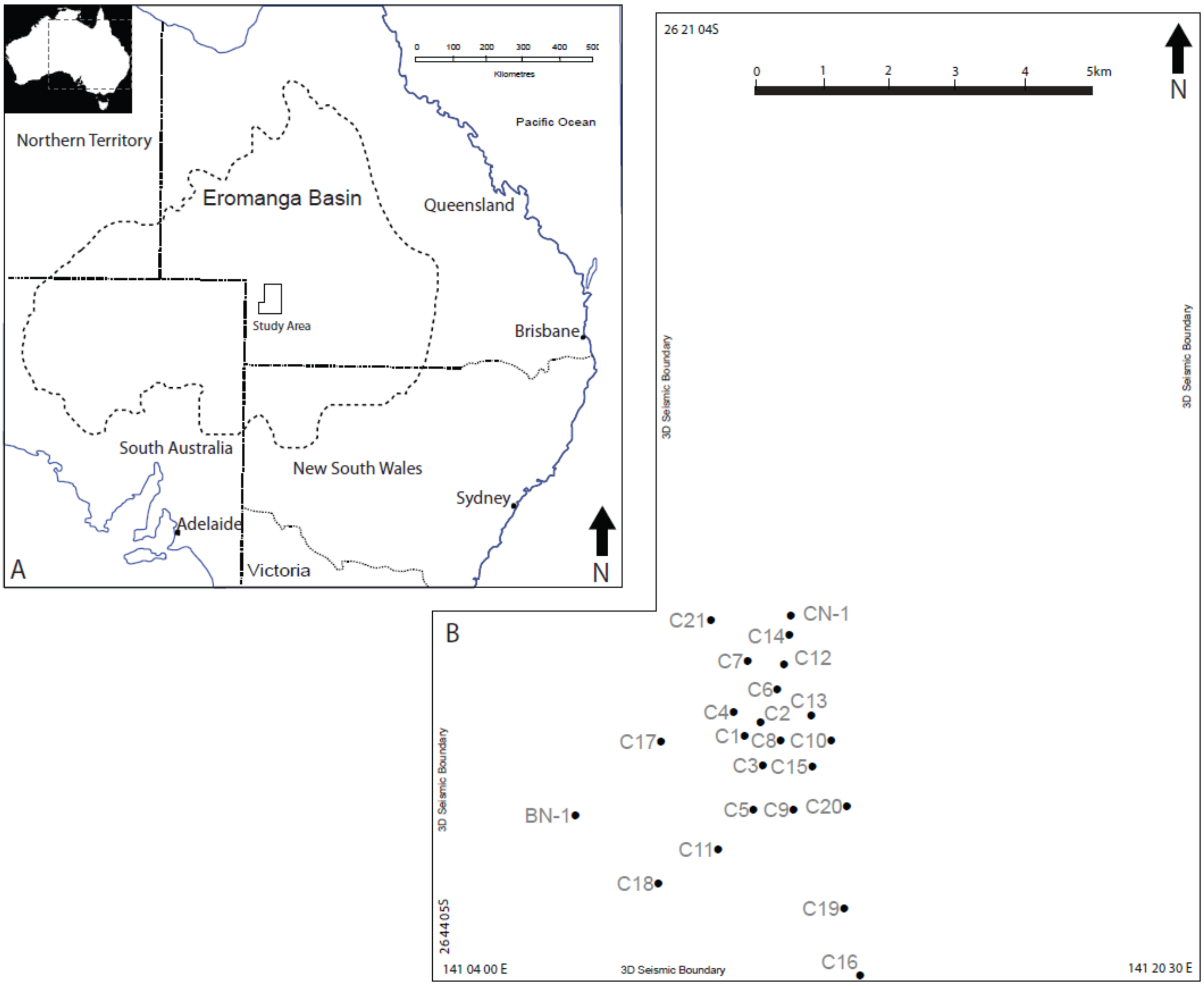


Figure 1: A. The location of the study area and the Eromanga basin in the context of the Australian continent (After Hill, 1999). States and capital cities within Australia are included for geographical reference. Inset shows the extent of the main map in the context of the Australian continent. B. Well locations for the Cuisinier Field and the location of the 3D seismic survey used in this study. Locations compiled from Santos Ltd well completion reports.

Alley and Frakes, 2003) considered the Murta Formation to have been deposited in a purely lacustrine environment and suggested widespread distribution of dropstones and diamictitie inferred glacial depositional conditions. Other authors working at a similar scale (Wopfner, 1970, Frakes and Francis, 1988, Markwick and Rowley 1998, Sheard, 1990) invoked methods such as tree rafting, large faunal bioturbation and very high energy fluvial systems as the processes responsible for depositing these lithologies throughout the basin.

Following the first discovery of economic oil in the Murta Formation (Figure 2) in north-east South Australia Mount (1981, 1982) described the depositional environment of the Murta Formation at this location as continental lacustrine. The Murta Formation is divided into five distinct packages based on grain size variation. Lacustrine deltaic distributary mouth bar, crevasse splay and lacustrine turbidite elements are interpreted and two depositional models are presented; a 'deltaic' model and a 'shoreface bar' model (Mount, 1981; Mount, 1982). 'Lake Murta' was envisaged as being wide and shallow during the deposition of the Murta Formation, with very low angle slopes to depositional surfaces. This has led previous workers to interpret the wave and tide energies as being very low, and dissipated in a broad swath parallel to the shoreline (Mount, 1981; Mount, 1982). Lennox (1986) presented a similar fine-grained freshwater lacustrine-deltaic depositional model for south-west Queensland.

Mount (1981, 1982) influenced semi-regional studies, and the Murta Formation was classified as a fine grained lacustrine sequence (Ambrose, 1982, 1986) throughout the Eromanga Basin. The Murta Formation was reported to interfinger with the Namur Sandstone and gradationally transition into the Cadna-owie formation in the Jackson area, southwest Queensland (Powell et al., 1989). A regional trend of reduction in thickness and sand content from the north-northeast to the southwest was interpreted to reflect a depositional pattern where the main source of sediment into 'Lake Murta' was from the north and east (Ambrose, 1982, 1986), even though some of the wells in the southern section of the basin contained cleaner sands and were beyond the interpreted depocentre of the lake.

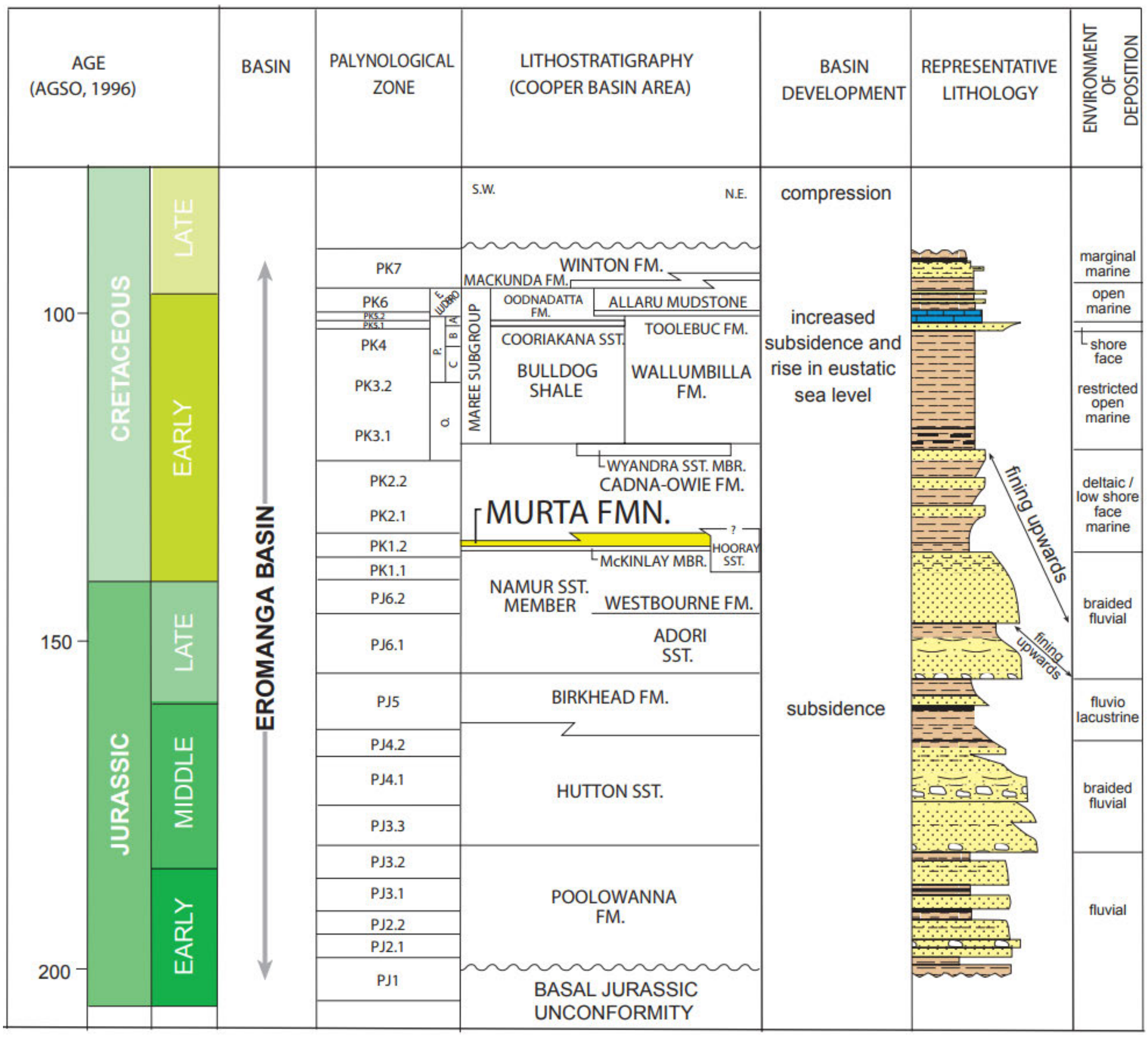


Figure 2: Stratigraphic table for the Eromanga Basin. The Murta Formation is highlighted in yellow. Geological age, palynological zone, lithostratigraphic table, basin development, representative lithology and environment of deposition from Santos Ltd., 2013. Abbreviations used FM.= Formation, SST.= Sandstone, MBR.= Member.

Potential marine influence was interpreted on a basin scale in the Murta Formation. Lithofacies analysis, elevated boron concentrations, modern marine-like trace element results, fluorapatite nodules, glauconite pellets and calcispheres were cited as evidence of a brackish to marginal marine environment (Naylor et al., 1988;

Zoellner, 1988 and Powell et al., 1989). A large lake system with estuaries and vegetated islands was interpreted as the depositional setting during the mid Murta time in the South-west Queensland area, based on core and wireline log analysis (Gorter, 1994). After a basal highstand, a rapid drop in base level caused erosion and channel incision. Slow base level rise and infill of channels by sediment reworked by transgression formed “estuarine” deposits. Continued stepwise transgression and regression formed coarsening up and fining-up sequences and resulted in sub-areal deposits and vegetated surfaces interfingered with subaqueous deposits. Maximum transgression occurred at the top of the Formation. Overlying highstand deposits represented a gradational transition from the upper section of the Murta Formation into the Cadna-owie Formation (Gorter, 1994). Although Gorter (1994) uses sequence stratigraphic and marginal marine terms and the presented model infers marine influence, it is not explicitly discussed.

Depositional models for the Murta Formation are inconsistent and sometimes contradictory. Factors such as the presence or absence of marine influence, the number and character of depositional sequences and well as the overall mud or sand rich nature of the facies are all contentious. Existing models failed to predict the occurrence of sand facies in the Cuisinier Field. Previous wells in the Murta Formation have been dominated by mud, but the Cuisinier discovery provides evidence for clean sand-rich facies in the Murta Formation. Detailed integrated analysis of the Cuisinier Field is an essential first step in understanding distribution of reservoir sand and depositional controls on depositional heterogeneities in the region.

3.3. Data and Methods

This chapter presents an integrated study in which detailed stratigraphic investigation is primarily used to provide a process-based interpretation of the early Cretaceous Murta Formation at the Cuisinier Field, South-West Queensland (Figure 1A). A conceptual geological model and paleogeographic reconstructions are presented.

Geophysical interpretation was undertaken using the greater Cuisinier 3D data set which included the compiled Cuisinier, Cook, and Cuisinier North 3D seismic surveys (Figure 1B). Rock physics work was conducted, as well as inversion and other attribute work. Interpretation was conducted on the full stack volume and inversion volumes, primarily rotated AI-Vp-Vs. Schlumberger Petrel, ffA GeoTeric and Ellis Paleoscan were used to organise and review, reduce noise from and extract horizon slices from seismic data.

Stratigraphic interpretation was undertaken primarily from analysis of core and secondarily from examination of wireline logs. At the time of analysis twenty-one wells had been drilled at the Cuisinier Field (Figure 1B). Wireline log suites were run for each well. Conventional full hole core was available from two wells, Cuisinier 4 (50.2 m total core length) and Cuisinier 7 (15.0 m total core length). Both of these cores were logged and interpreted. Facies associations are identified based on lithology, grain size, sorting, sedimentary structures and trace fossils, and are characterized and interpreted using facies analysis. Sampling for petrographic analysis was undertaken in reservoir sands and twenty thin sections were analysed. Core data was tied back to wireline log data from these two wells, allowing wireline data from all twenty-three wells to be fully utilised in the study.

3.4. Results and Interpretation

3.4.1. Facies Associations

Seventeen lithofacies and twelve facies were recognised in core from Cuisinier 4 and 7 (Figure 3A-D; Figure 4A-C). They are interpreted to have been deposited and reworked primarily via fluvial and wave action. Facies have been grouped into five associations interpreted to be representative of (i) offshore/ deepwater, (ii) prodelta, (iii) delta front, (iv) shoreline and (v) channel fill depositional environments. Bioturbation intensity (BI) was recorded according to the Taylor & Goldring (1993) scheme, with 0 representing no bioturbation and 4 representing extreme bioturbation (Figure 3C). Trace fossil diversity and ichnofacies classification follows models presented by MacEachern and Bann (2008). Descriptions and interpretation for facies associations are detailed in the following paragraphs.

FA-1 Offshore

Observations

Facies Association 1 (FA-1) is composed of thinly interbedded (millimetre and sub millimetre scale) light grey to very dark grey claystone, mudstone and occasional sandstone beds (Figure 4A). Occasional sandstone beds are thin and quartz rich with sharp bases. Sand packages with sharp and erosive bases often transition rapidly into fine grained muds. Mud packages are very finely laminated. Overall, beds exhibit a fining and thinning upward trend. The presence and character of interpreted *Thalassinoides*, *Planolites*, *Skolithos* and *Phoebichnus* suggest a *Cruziana* icnofacies assemblage (MacEachern & Bann, 2008).

Interpretation

A predominantly *Cruziana* ichnofacies, fine grain size and the abundance of planar lamination in FA-1 suggests a low-energy environment below wave base. Mudstone beds are interpreted to have been deposited due to suspension fallout during very low energy periods. Minor thin clean ripple-laminated sands with sharp bases could have been deposited as a result of density flows or due to seasonal events such as high river discharge and/or storm events (Bhattacharya & MacEachern, 2009; Capelle et al., 2016). Depositional character suggests that this facies association was deposited in an offshore or deepwater environment proximal to a prodeltaic setting. FA-1 is interpreted to be the base of a gradational transition between the Murta Formation and overlying Cadna-owie Formation.

FA-2 Prodelta

Observations

Facies association 2 (FA-2) is composed of thinly interbedded sandstones, siltstones and mudstones. Beds are generally fining and thinning up section. Individual layer thicknesses range from 0.2 cm to ~10cm and individual bed thicknesses range from 2cm to 60cm. Linsen bedding, wavy bedding, sand-starved ripples, current ripples, planar laminations and soft sediment deformation are present within this FA. Dewatering structures are present but rare. The presence and character of *Ophiomorpha*, *Zoophycos*, *Planolites, Skolithos* and *Rhizocorallium* suggest a mixed *Cruziana* and *Skolithos* icnofacies assemblage (MacEachern & Bann, 2008). *Skolithos* elements occur more often in the sand layers but are less common in the mud layers.

Interpretation

Overall thinning and fining upward of beds represents a decrease in energy up section. A very fine sand grain size along with the abundance of mud, starved ripples and planar lamination suggest a low energy depositional environment away from tidal and wave energy (Bhattacharya & MacEachern, 2009). From overall facies character a prodelta environment is interpreted. A *Cruziana* and *Skolithos* ichnofacies assemblage supports this interpretation. The abundance and character of *Planolites*, *Skolithos* and *Rhizocorallium* in sand beds may indicate that they were carried to the location from further upstream during a storm event but did not thrive in the depositional environment.

FA-3 Delta Front and undifferentiated delta plain

Observations

This facies association consists of moderately sorted, moderately well-rounded very fine to fine-grained sandstones and mudstones that exhibit flaser, wavy and lenticular stratification (*cf*. Reineck & Wunderlich, 1968; Figure 3A; Figure 4A) and an overall coarsening upward pattern. Flaser bedding is more common at the top of the FA, as the FA becomes more sand rich. Asymmetric current ripples, planar lamination, dewatering structures, soft sediment deformation, wave-modified current ripple laminae, massive sandstone beds and starved ripples are common. Mud drapes (<0.5 cm) are preserved in cross bedding on the face of foresets with a slope of 10-30°. Sand is generally quartz-rich, although muscovite and biotite rich layers also exist. Bioturbation and soft sediment deformation can be intense (BI = 4), but bioturbation can also be absent. Siderite cementation is present. Trace fossils include *Macaronichnus*, *Ophiomorpha*, *Planolites*, *Skolithos* and *Conichnus*, suggesting a predominantly *Skolithos* trace fossil assemblage (MacEachern & Bann, 2008).

Interpretation

Sand was deposited predominantly as current ripples migrating in response to unidirectional subaqueous currents. The interbedded and heterolithic nature of sandstone and mudstone beds suggests temporal changes in current velocities, particularly in flaser, wavy and lenticular stratification. Although this could be attributed to tidal activity throughout the environment (Van Straaten & Kuenen, 1957; Reineck & Wunderlich, 1968; Oomkes, 1974; Staub & Gastaldo, 2003; Legler et al., 2013), no unequivocal tidal indicators were observed in the core. Temporal changes in current velocities could potentially occur in an exclusively wave and fluvial dominated depositional environment. High variation intensity of bioturbation by an impoverished *Cruziana* and *Skolithos* ichnofacies is consistent with deposition in a stressed environment characterized by fluctuating energy levels, a mobile sediment substrate and/or restricted salinities (MacEachern & Bann, 2008). In deltaic ststems mouth bar deposits are indistinguishable from terminal distributary channel fill deposits and mouth bars can infill the terminal distributary channels (van Heerden and Roberts, 1988). A high bioturbation index suggests a higher concentration of mouth bars over terminal distributary channel deposits, although changes in bioturbation intensity may also be attributed to salinity changes. Differentiation between mouth bar and the terminal distributary channel deposits is not made in this case as both occur in a similar depositional environment. Some parts of this FA could be interpreted to be floodplain deposits, crevasse splays, overbanks and levees however lack of evidence of subareal exposure indicators and a lack of rootlets or climbing ripples means that interpretation is less likely. This FA could also represent the lower delta plain as well as the delta front, as similar processes occur in these environments and it is difficult to discriminate between the two with available data.

FA-4 Shorelines

Observation

Facies Association 4 consists of thin (20 cm - 30 cm) stacked beds of very fine-grained and lower fine-grained sandstone, with a sharp base and either a sharp, rippled or a gradational top. Wave ripples, low amplitude HCS, occasional planar lamination and planar tabular cross beds are present (Figure 4A). Trace fossils include *Protovirgularia*, *Thalassinoides* and *Skolithos*, suggesting a mixture of *Psilonichnus* and *Skolithos* ichnofacies. Wave rippled beds coarsen upward and are topped with strata containing planar cross stratified and planar laminated sands and muds. In general FA4 overlies FA5, which results in a coarsening up, then fining upward pattern.

Interpretation

The preservation of sandstone beds with HCS indicates deposition as a result of episodic storm events in water depths between the effective storm-wave base and fair-weather wave base (Dott & Bourgeois, 1982; Duke, 1985; Keen et al., 2012). The abundance of wave ripples compared to HCS beds suggests that storm events were less common or rarely preserved, while the presence of planar stratified and planar cross stratified sands suggests that upper shoreface and nearshore bars are preserved. FA4 appears to be preferentially cemented with calcite and siderite. This could be due to the chemical composition of the depositional environment causing precipitation of the cement, but it should be noted that this FA is often the stratigraphically highest porous and permeable formation below a regional seal, so cement precipitation in this FA may be opportunistic and related to fluid flow later in the life of the rock. FA4 is interpreted as a shoreline deposit. Shorelines may be stacked and highly bioturbated. This interpretation is supported by the occurrence of a mixed *Psilonichnus* and *Skolithos* ichnofacies (MacEachern & Bann, 2008).

FA-5 Fluvial-dominated Deposits

Observation

Facies Association 5 (FA5) primarily consists of two types of channel fill- cross bedded sandstones (Figure 3A) and mud-clast rich sandstones (Figure 3B). The base of the FA is composed of very coarse sand to granules. Cross bedded sandstones have sharp planar to erosional bases and consist of trough cross-bedded, planar cross bedded, current rippled and planar laminated fine to medium-grained moderately-rounded sands. Trough cross-beds occur in sets that are generally 20 to 40 cm thick, but can reach a maximum of 1 m. Sets are stacked into cosets that occur in sandstone beds defined by a sharp erosional base and with a top marked by abrupt fining in grain size or by a sharp erosional contact at the base of the overlying unit. Occasionally very well rounded mud clasts and very coarse moderately rounded sand grains are preserved on the face of foresets. Trough cross stratification is observed low in the FA, sometimes in association with mud clasts. Foreset angle generally decreases up section, with a maximum dip angle of ~30° and a minimum of 2-5°. Current ripples and planar laminations are observed near the top of packages. For the mud-clast rich sandstones planar cross bedding, simple and bifurcated flaser features, ripples and planar lamination are preserved, with mud-clast rich beds suspended in massive structureless sands and cross-stratified sands. In the basal two-thirds of the FA, interbedded relatively clean sands and sands with mud clasts of various forms are abundant (Figure 3B). Type A1, A2, B1, B2, B3 and B4 mud clasts are identified (classification scheme for shale clasts: Johansson and Stow, 1995). Smaller, rounder mud clasts are associated with cross-stratified sands and larger, more angular mud clasts seem to occur in massive structureless beds. Soft sediment deformation is present (Figure 3A). Mud clasts are sometimes preserved on low angle foresets (10-20°). At 1653.98 m, dropstones and a very thin (~0.2 cm) coal wisp are observed near the top of a very gradually fining up sequence (Figure 3B). Overall, sand intervals in this FA fine up and individual beds thin up section. No soil or coal horizons are present. Bioturbation is low in FA 5 deposits (BI= 0 to 0.5), with a low abundance of *Planolites* and *Skolithos* traces (Figure 3C).

Interpretation

The rhythmicity, erosional bases, formation of co-sets and preservation of trough cross-stratified, planar cross-stratified, current rippled sands is typical of fluvial dominated distributary channel deposits. Sediment deposition due to a local reduction in flow velocity caused the subsequent growth and development of sand-rich mid-channel bars and subsequent channel avulsion (Wright, 1977). Bar deposits consisting of high-angle cross-stratified sand are interpreted to have formed by avalanching on the lee-side of subaqueous dunes. The occurrence of these processes over time most likely led to an amalgamation of bar deposits (Hinds et al., 2004; Crerar and Arnott, 2007; Bhattacharya & MacEachern, 2009). The abundance of mud-clasts in the mud-clast rich sandstones, as well as their size and character, suggests that the system was proximal but occasionally subject to erosional flows.

Erosion and inclusion of material from an overbank or a previously abandoned channel setting could provide this source. If flow in the system was ephemeral, mud clasts could have originated from the bed itself, such as in terminal splay settings in Lake Eyre (Fisher et al., 2008). The association of larger more angular mud clasts with massive sands and smaller, rounder mud clasts with cross-bedded sand and suggests that sediments were sometimes preserved proximal to the source, and at other times clasts were carried to more distal locations and preserved. Relatively unorganised coarser grained deposits and slumping near and at the base of the facies association probably represent rapid deposition. The appearance of dropstones and a coal wisp at ~1654 m could indicate ice rafting, although as no other evidence of a glacial environment is observed, are probably a product of Cretaceous faunal activity. A lack of pedogenesis or coal horizons suggests a lack of soil or peat forming environments. Potentially deposition was relatively rapid, with too little time for a soil horizon to form, and in an environment which was not conductive to swamp and peat formation.

An alternate interpretation for this FA, particularly the mud-clast rich sandstones, is that it was deposited by hybrid flow bed or sandy turbidite in a submarine depositional environment. Characteristics of part of this FA including the relative absence of fossil plant material and the presence of a massive basal clean sand, topped by a debritic mud-clast rich bed, particularly between 1655.20- 1656 m in Cuisinier 4, are similar to submarine beds in the Agadir Basin, Marnoso-Arenacea Formation and the Mississippi Fan (Talling et al., 2007; Sumner et al., 2012; Talling et al., 2012). Although submarine flows are highly variable in character (Talling, 2013; Strachan, 2008), this interpretation is not favoured at the Cuisinier location due to the size and shape of the mud clasts, the relative lack of dewatering structures, the presence of strong planar and trough cross stratification, the lack of consistent repeated structure within beds and the small vertical thickness of the

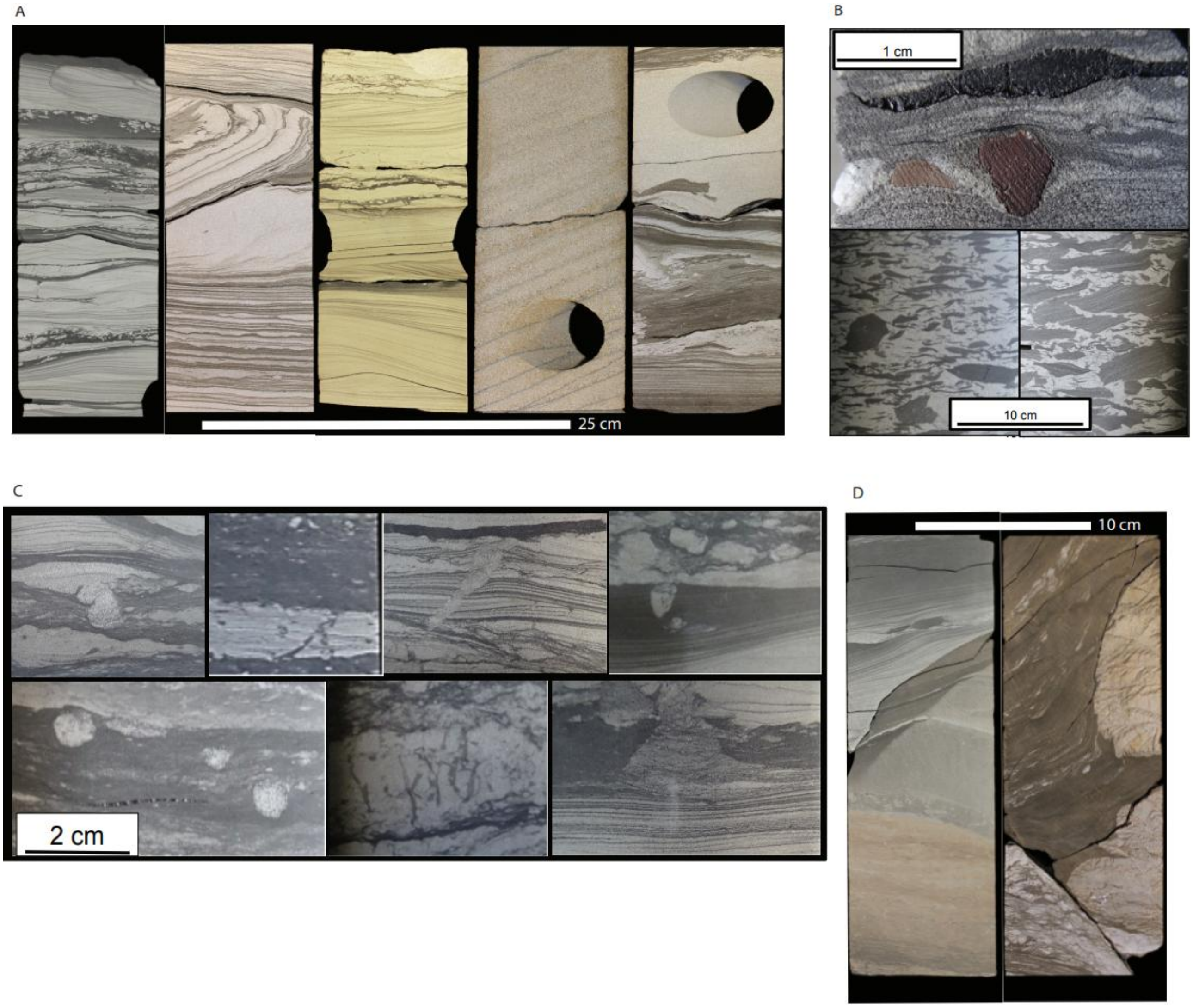
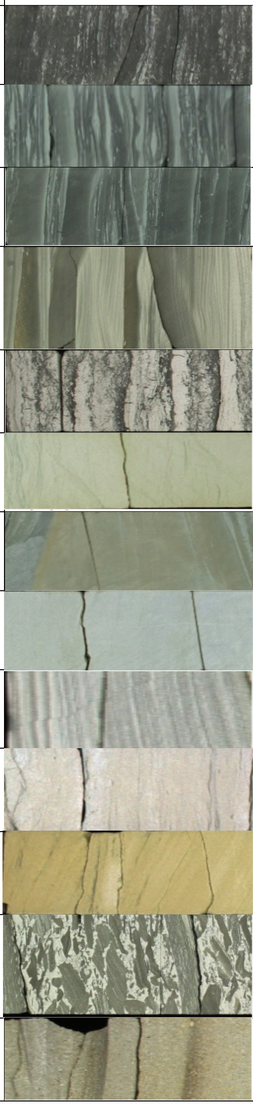


Figure 3: A. Sedimentary textures in core at Cuisinier 4 (C4) and Cuisinier 7 (C7). From L-R Typical linsen bedding with bioturbation (C4 1666.01 m), interbedded sandstone and mudstone with soft sediment deformation structure (C4 1660.30 m), wavy bedding consisting primarily of sandstone with mud layers (C4 1627.23 m), cross bedded sandstone (C4 1639.7 m), interbedded sandstone and mudstone with mudclasts and bioturbation (C4 1657.05 m). B. Prominent clast textures in core. Clockwise L-R: dropped clasts of pebble size composed of igneous and clay rich material (1654.00 m), mudclasts with planar internal structure (1661.50 m), mudclasts with no internal structure (1659.50 m). C Trace fossils photos- Horizontal, oblique and vertical burrows and some escape traces were observed. Traces are not complex and are indicative of infaunal deposit feeders living close to or under the sediment interface. Traces include Skolithos, Teichichnus, Planolites and Chondrites, as well as potential Rhizocorallium and Zoophycus. Traces observed indicate depositional environments from a sandy backshore to the sublittoral zone. D Significant chemical alteration in cored section. L-R Siderite cementation (C7 1637.75 m), cone-in cone calcite concretion (C4 1649.27 m).

package (less than six metres) observed in core. Interpretation of adjacent facies as delta front also does not support a submarine interpretation for this facies association. Additionally facies virtually identical to those in FA5 have been interpreted as part of a fluvial deltaic system (e.g. Hinds et al., 2004), and as fluvial channel fill as a result of bank collapse (Crerar and Arnott, 2007, Figure 10C within that reference), which seems to be the most likely scenario for deposition of FA5.

3.4.2. Petrography and Cementation

In samples taken from sands in FA2, FA 3, FA 4 and FA 5, framework grains are primarily composed of sub-angular to sub-rounded, moderately well sorted quartz arenites (Figure 5). Accessory minerals include feldspar, biotite, muscovite, lithics, glauconite (particularly in FA2; Figure 5), carbonaceous grains and potential volcanic rock fragments. Grain size ranges from lower very fine to very coarse with minor silt and clay. Very coarse and granule-sized sands are generally suspended within a finer grained sand matrix. Matrix grains consisted primarily of clay (kaolinite and illite) and consisted of less than ten percent of the bulk rock volume. Quartz overgrowths form grain-welding silica cements (Figure 5). Clay precipitation appears to post-date silica precipitation. Calcite and siderite cementation are also present, but are concentrated in discrete beds and not dispersed throughout the formation. Due to growth and overgrowth patterns, the cementation timing was likely clay, quartz, calcite then siderite. Larger scale cone-in cone calcite cementation structures were also observed in the core (Figure 3D).



Lithofacies Grouping	Lithofacies	Description	Typical photograph	Interpretation
	Fm, Fl, Fb, Sr	Organic-type mud (clay) interbedded with minor sand.	1641.5 m	Deep water
	Fl, Sr, Ss	Thin (millimetre scale) interbedded mud and fine sand. Evidence for reworking of sand.	1621.7 m	Prodelta
	Fl, Sl	(centimetre scale) Interbedded mud and fine sand.Fining and coarsening up beds.	1622.2 m	
	Sr, Fl	Interbedded mud and sand. Thicker (1-4 cm) mud beds and finely interbedded sand and mud.	1626.0 m	Delta Front Distributary channel overbank and termination and/or mouth bar
	Fb, Sb	Interbedded sand and mud, heavily bioturbated. Probably LG4 with bioturbation.	1644.1 m	
	Sr, Fl	Fine sand, generally well rounded, well sorted, some mud ripples.	1629.9 m	Shoreline
	Sc	Fine sand, cemented. Siderite cement.	1623.5 m	
	Sk	Sand with calcite cement.	1632.2 m	
	Fl, Sl	Very finely laminated mud and sand.	1639.1 m	Channel Fill
	Sp, Sr, Fl	Sand, flaser bedding, some mud, moderately sorted.	1651.7 m	
	Sp	Subrounded, well sorted fine sand. Generally cross bedded.	1638.3 m	
	Smu	Majority of formation consists sub-angular mud clasts (0.25-3 cm) in generally well sorted fine sand	1659.5 m	
	G, Sp, Sr	Isolated pebbles, granules in fine sand matrix.	1665.1 m	

Legend

Planar cross bedding	Flaser bedding
Planar Lamination	Gravel-Pebbles
Ripples	Hummocky cross stratification
Calcite cementation	Lenticular bedding
Carbonate cement	Mud rip up clasts
Coal Wisps	Soft sediment deformation
Dolomitic cement	Wavy bedding
Siderite cement	Dropped Clast
Stylotites	Rootlet
Fault or fracture	Paleocurrent vector
Burrows, undifferentiated	Skolithos
Burrows, vertical	Teichihnus
Burrows, horizontal	Planolites
	Chondrites

Code	Description
C	Coal
G	Granule
Fb	Mud, bioturbated
Fd	Mud, deformed
Fl	Mud, laminated
Fm	Mud, massive
Sb	Sand, bioturbated
Sd	Sand, deformed
Sc	Sand, cemented
Sh	Sand, horizontal bedding
Sk	Sand, with carbonate
Sl	Sand, laminated
Sm	Sand, massive
Sp	Sand, cross bedding
Sr	Sand, rippled
Ss	Sand, reworked
Smu	Sand, mud intraclasts

Figure 4: A. Lithofacies key, legend, description and basic interpretation for Cuisinier 4 and Cuisinier 7 core logs (Figures 4B and 4C). Core photographs and depths are reference sections from Cuisinier 4 core.

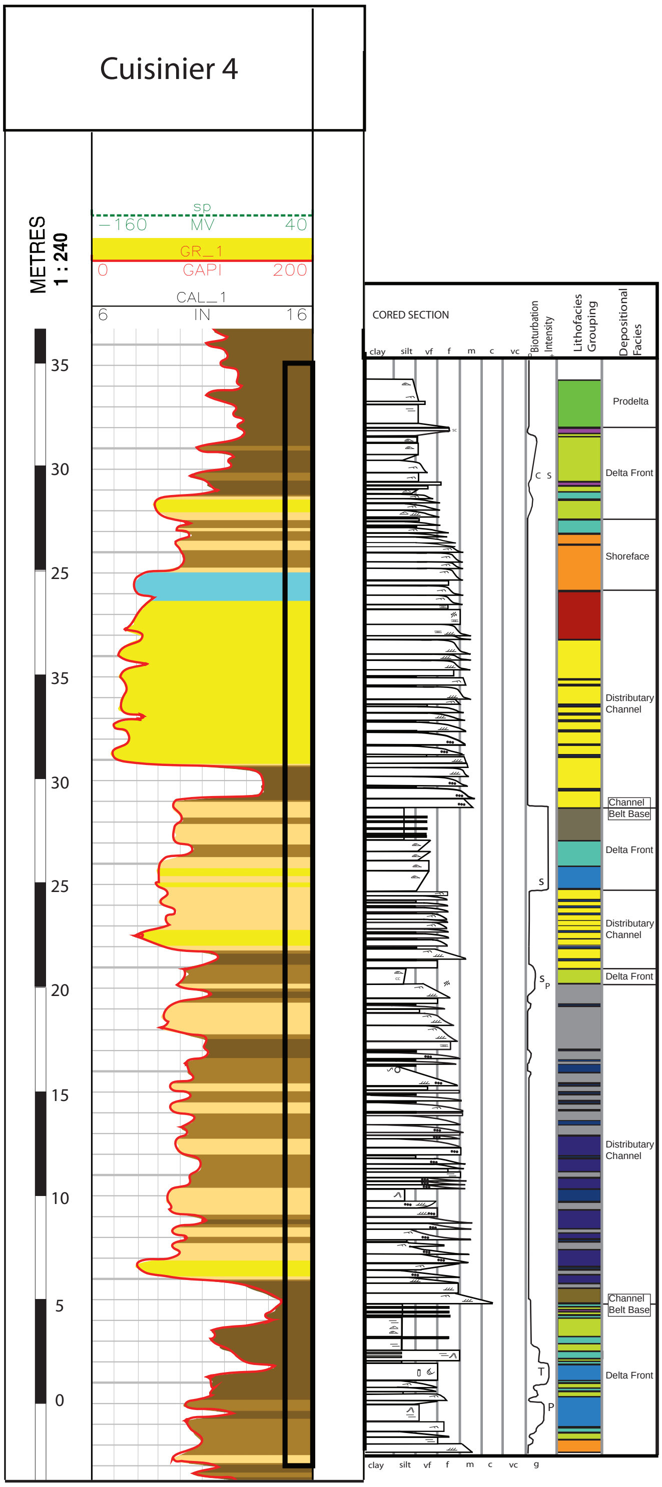


Figure 4: B. Interpreted core and corresponding gamma ray log for Cuisinier 4. In the gamma ray log, yellow corresponds to sands, orange represents silts and brown corresponds to muds.

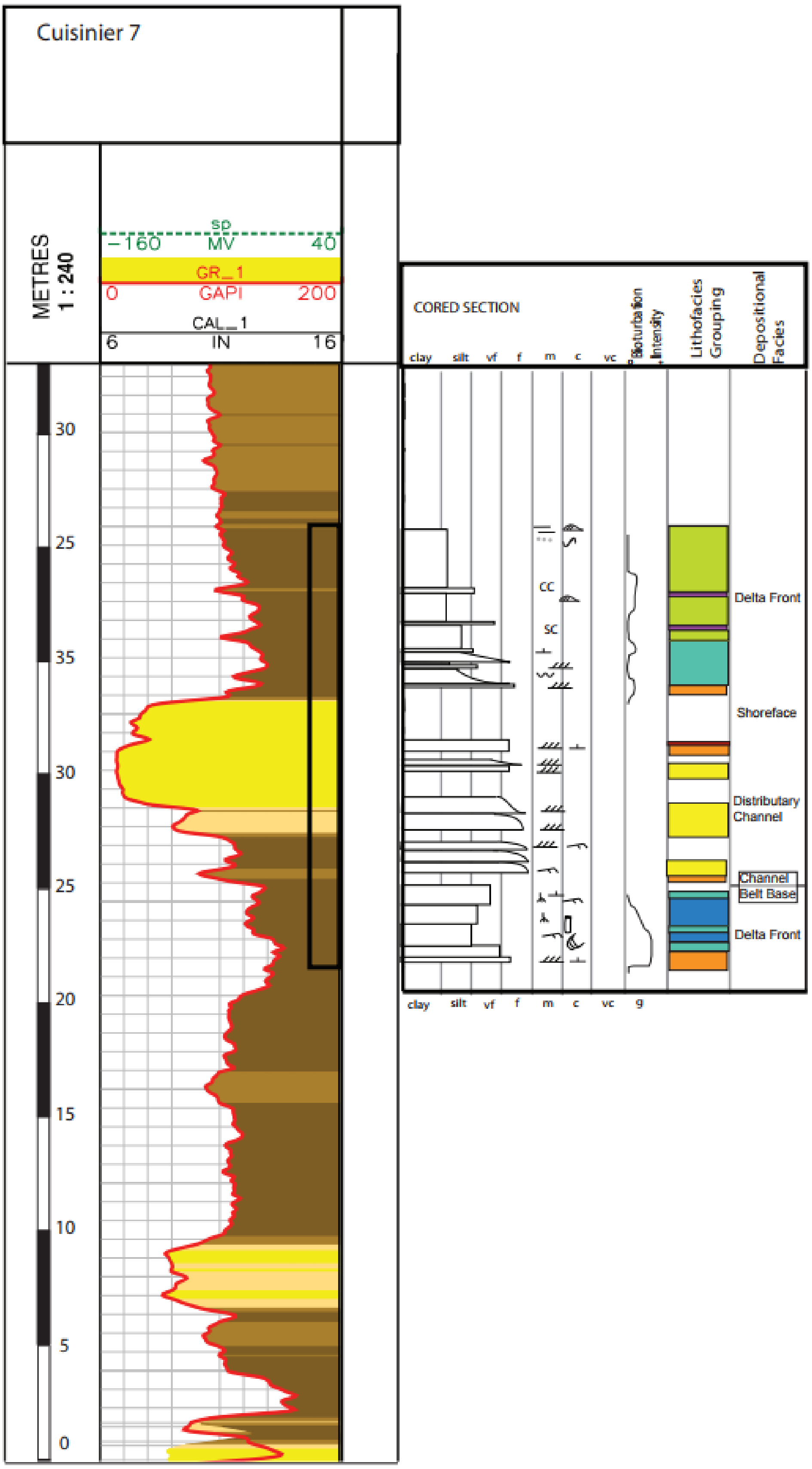


Figure 4: C. Interpreted core and corresponding gamma ray log for Cuisinier 7. In the gamma ray log, yellow corresponds to sands, orange represents silts and brown corresponds to muds.

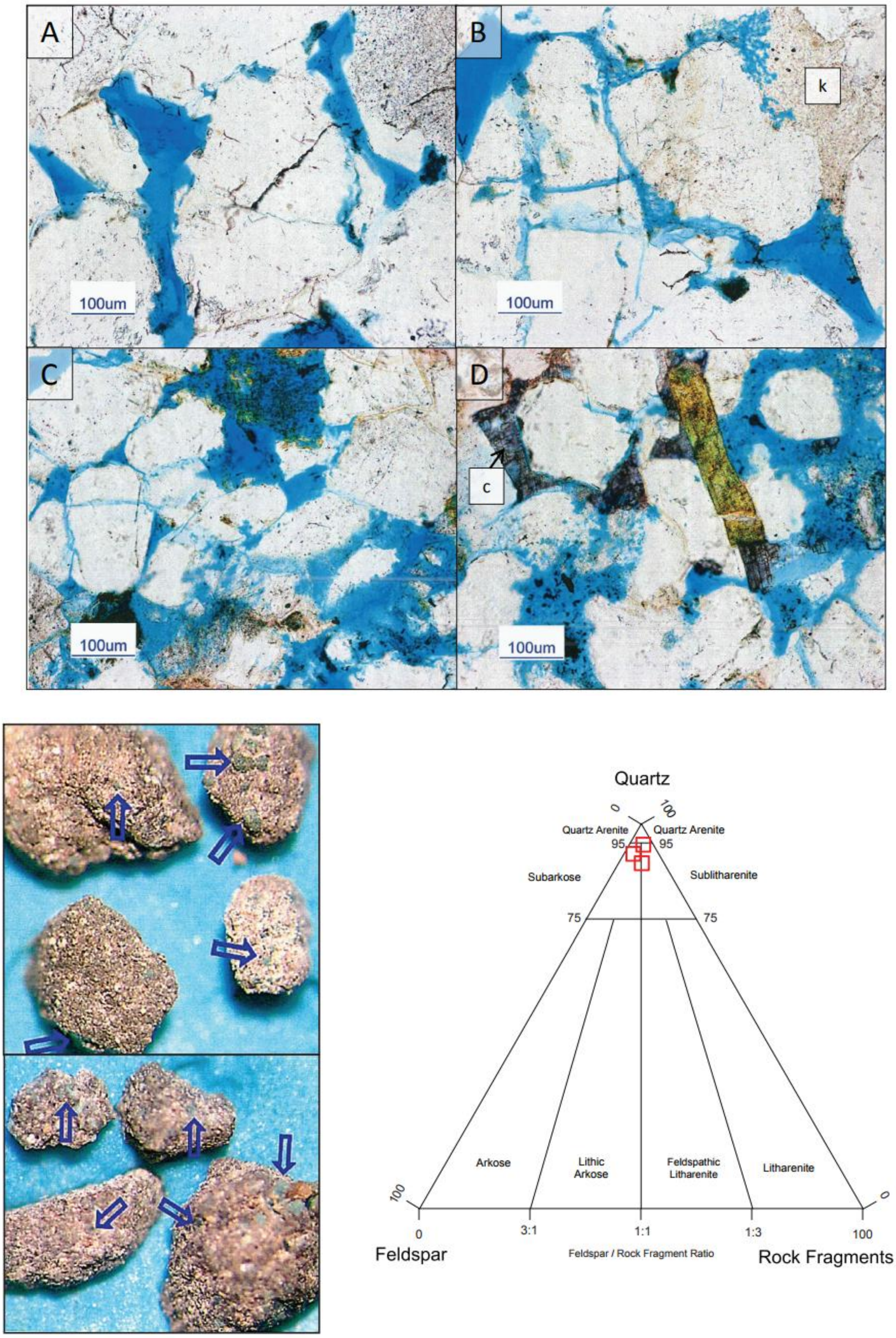


Figure 5: Clockwise, from top: Representative 200x plane light thin section images images for samples from channel fill facies. A and B show lower medium grained, moderately sorted quartz arenite with a good intergranular pore system. Cements are mainly quartz overgrowths. Minor pore lining illite and localised kaolinite (k) are present. C and D show lower fine grained moderately sorted subarkose. Intergranular pores are partially filled with quartz overgrowths, kaolinite and calcite (c). Calcite cement overprints quartz cement. Ternary composition plot (Folk, 1968) shows that three main categories of samples analysed fall in the Quartz arenite, sublitharenite and subarkose quadrants. Cuttings from Cuisinier 3 and Barta North 1 show glauconitic pellets, as indicated by the blue arrows.

The rounding and mineralogy of grains suggests a relatively proximal but quartz rich source for sands, particularly in FA5. The presence of glauconite, in FA2 suggests a mid-shelf to upper-slope depositional setting with low rates of sedimentation or potentially a cold climate, although the presence of glauconite alone is not sufficient to determine depositional environment (Chafetz and Reid, 2000). Cementation from calcite and siderite appears to have occurred after initial quartz and clay cementation, most likely from the movement of ion-rich fluids through rock after compaction and lithification. Such cementation is common in the Murta Formation in the Eromanga Basin in porous and permeable sediments below competent regional seals (Theologou, 1995).

Cone-in-cone cementation structures (Figure 3D) are common as a recrystallised form of CaCO3 in carbonate rocks undergoing deep burial diagenisis. It is suggested that this feature would have grown before the majority of compaction occurred due to the soft sediment deformation surrounding the feature. This feature may be related to the compaction of carbonate-rich micrite clays (Usdowski, 1963) or the result of carbonate supersaturation (increased alkalinity) of lake water generated by microbial degradation of organic matter. It is suggested that the zone of supersaturation must be “immobilised stratigraphically”, (i.e. it needs to be a below a seal) and the stratigraphic height needs to be relatively constant (relative quintessence, no sudden subsidence or uplift) for this type of cementation to occur (Martin, 1999). Similar examples of this feature are present in the Mississippian Carboniferous in Derbyshire, UK (Stow, 2005). Potentially this feature could be related to glenodites which are ikaite ($CaCO_3$) concretion nodules, common in the overlying Cadna-owie Formation and Bulldog Shale, and interpreted to only grow in mud on the seafloor when the water temperature is below 5^{o}C.

3.4.3. Trace Fossils and Palynology

Horizontal, oblique and vertical burrows and some escape traces were observed in core (Figure 3C). Generally traces were simple and indicate infaunal deposit feeders living close to or under the sediment interface. The abundance and characteristics of these traces generally indicates a cold to temperate freshwater to brackish anoxic environment. In sediments containing abundant escape traces, relatively rapid sedimentation is inferred. Traces in this study are similar to those observed in depositional environments from the sandy backshore to the sublittoral zone (MacEachern & Bann, 2008). Although no direct evidence for large faunal bioturbation was observed, this should not be ruled out as mechanism for soft sediment deformation (e.g. Cuisinier 4 1669.90 m to 1670.15 m), or dropstones transport (e.g. Cuisinier 4 1653.90 to 1654.00 m) particularly considering small sample size of the core and the high intensity of infaunal bioturbation at these locations.

A palynological sample from cuttings at the top of the formation in Cuisinier-1 was found to be very similar in composition to other Murta Formation samples, and dominated by fern spores and bisaccate pollen. The presence of *Cicatricosisporites* spp*, Cyclosporites hughesii* and *Dictyotosporites speciosus* are together diagnostic of assignment to palynological zone PK1.2.2 (Wood, 2011; Price, 1997). These assemblages are characteristically found in the Murta Formation throughout the Eromanga Basin and together with a lack of abundant and diverse dinoflaggelate flora generally suggest a non-marine depositional environment or a marginal marine environment with a significant influx of freshwater.

3.4.4. Seismic Data Analysis

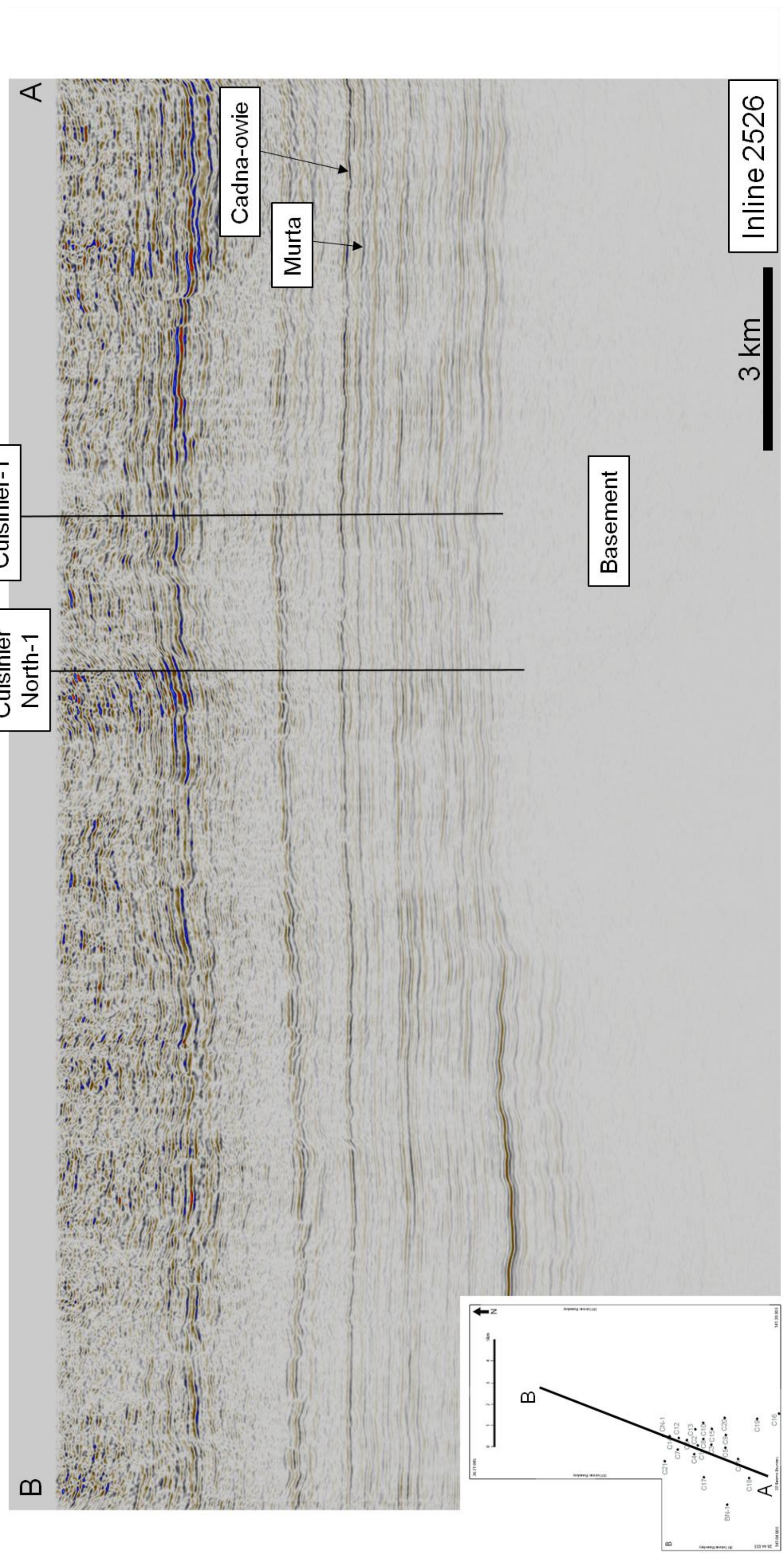
Results

The top reservoir horizon for the Cuisinier field is characterised by a moderate amplitude trough maximum (Figure 6). The seismic reflector is stronger and more continuous in the southwest of the survey and reduces in amplitude and continuity north eastward (Figure 7). Intense polygonal faulting is observed in overlying Early Cretaceous Formations (Figure 8A). A high reflectivity package of cemented sandstones and limestones at the top of the Wallumbilla Formation encased in clay rich sediments marks the beginning of the strongly developed polygonal fault pattern which terminates in the Murta, but may still affect reservoir imaging (Figure 8B). These faults make it more difficult to predict reservoir distribution due to dimming below faults (Figure 8C).

Proportional slicing and amplitude extraction along the top Murta reservoir horizon shows northwest-southeast amplitude trends (Figure 7A and 7B). There is a weak relationship between amplitude and reservoir presence. The combination of thin reservoir sands (typically <10 m) interbedded with silts and muds and polygonal faulting makes seismic interpretation difficult. Two approximately perpendicular trends are observed; a north-west to south east feature and a subtle curving feature running approximately south-west to north-east (Figure 7B).

From core and wireline data (Figure 4; Figure 5; Figure 9), it was observed that reservoir sandbodies were largely below seismic resolution, so only highly stacked or amalgamated sandbodies can potentially be observed on seismic, necessitating an emphasis on sedimentological and stratigraphic interpretation.

Figure 6: Next page. Uninterpreted but labelled seismic line through the seismic survey showing the nature of the Murta and Cadna-owie reflectors and wells Cuisinier North-1 and Cuisinier-1.

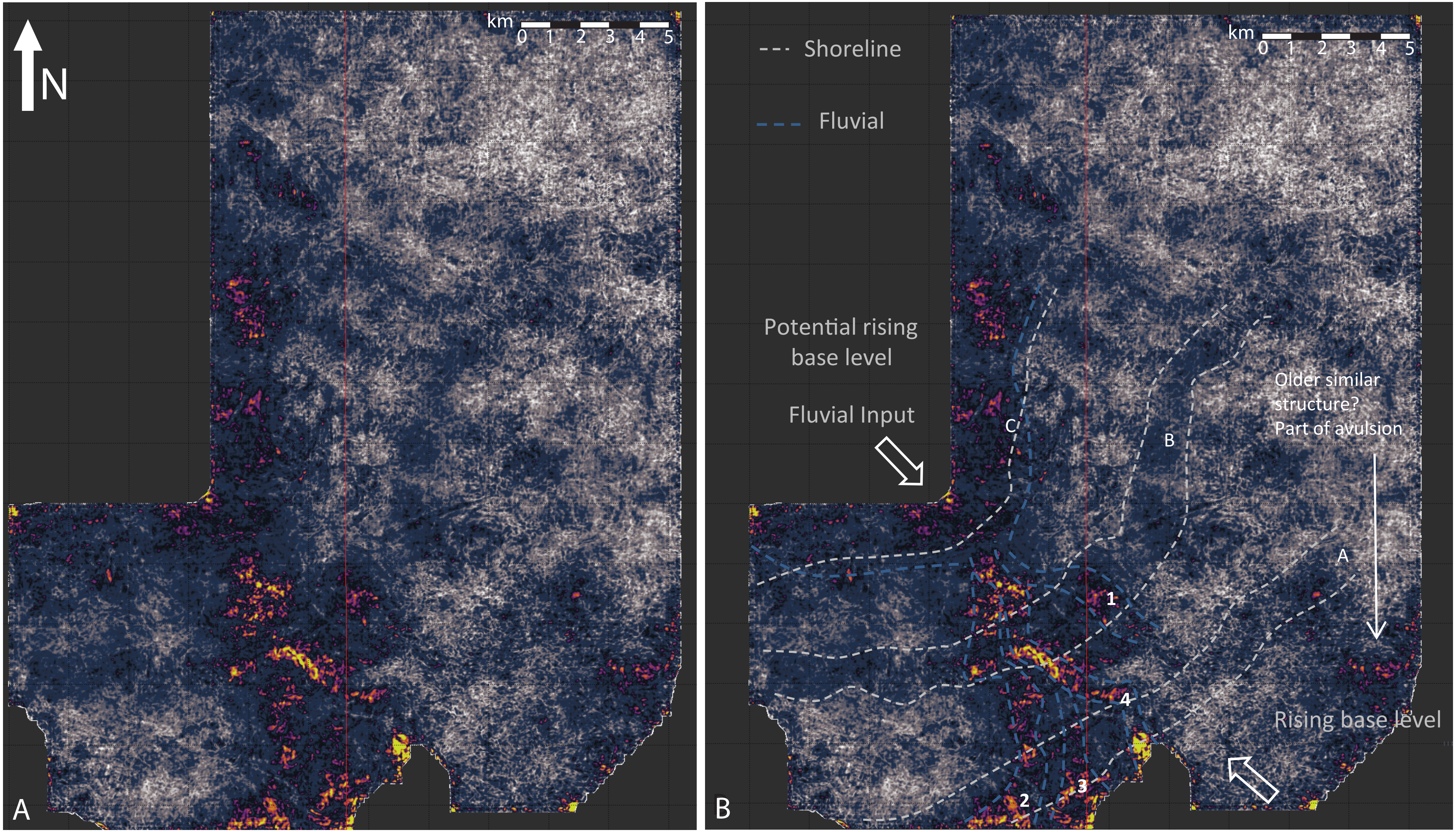

A
B
Cuisinier North-1
Cuisinier-1
Cadna-owie
Murta
Basement
3 km
Inline 2526

Interpretation

The seismic reflector for the Cuisinier reservoir is stronger and more continuous in the southwest of the survey area (e.g. Figure 6), suggesting that the reservoir is well developed there, and reduces in amplitude and continuity north eastward, suggesting that the reservoir is poorly developed there. Seismic attribute analysis suggests the presence two amplitude trends (Figure 7). A north-west to south east feature is interpreted to correlate with a high sand content fluvial dominated system. Fluvial influence is interpreted due to the fan-like shape of the sandbodies. Incision into surrounding mud-rich deposits is inferred due to the sharp change in lithology. The subtle curving features running approximately south-west to north-east are interpreted to represent shorelines due to the perpendicular nature of these features to the interpreted fluvial features and the curved shape of the features. These tie well to the shorelines interpreted in core and wireline logs. The dimming of amplitudes within these domains is not necessarily indicative of sand-body discontinuity and may represent subtle polygonal faults.

Ultimately individual reservoir sandbodies in the Murta Formation at the Cuisinier Field are below seismic resolution. Attribute analysis is likely to reveal stacked or amalgamated sandbodies, but individual reservoirs, as well as internal baffles, barriers and compartments are impossible to image with currently available data. Stratigraphic changes control the quality and distribution of reservoir sand units. Improved stratigraphic correlations within the region can help to provide a better estimation of the size of individual sandbodies, and therefore better predict reservoir continuity.

Figure 7: Next page. Interpreted RMS amplitude and sweetness maps highlighting sandbodies for the top reservoir (DC70) in the Murta Formation from the Cuisinier 3D survey. A. Uninterpreted image. B. Interpreted image. A to C are interpreted as shoreline ridges. 1 to 4 are interpreted as fluvially influenced sandbodies.


N
km
0 1 2 3 4 5
A
Shoreline
Fluvial
Potential rising base level
Fluvial Input
km
0 1 2 3 4 5
C
B
Older similar structure?
Part of avulsion
A
1
4
Rising base level
2
3
B

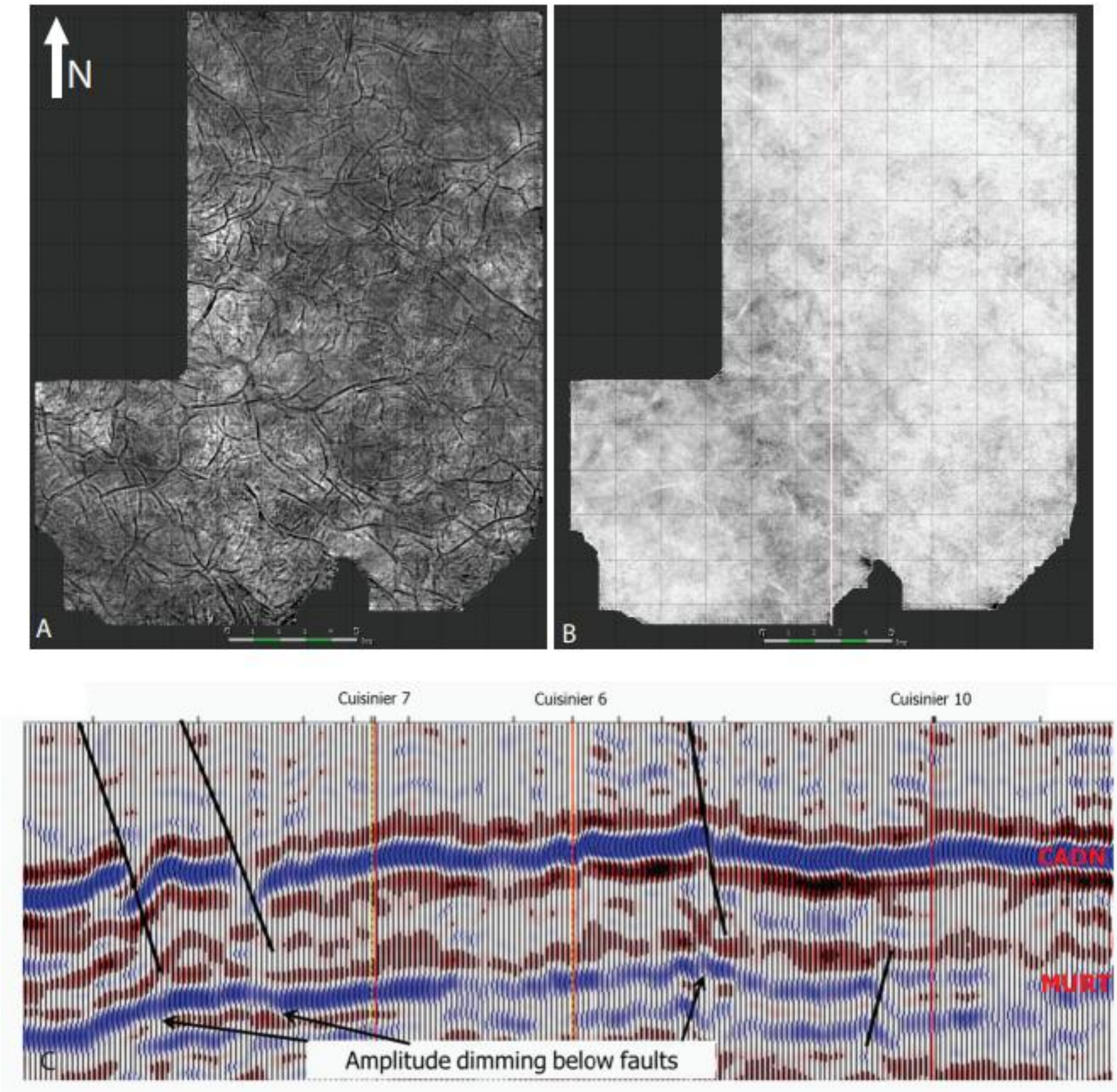


Figure 8: Fault coherency attribute maps for the Cuisinier 3D seismic survey. A. Polygonal faulting at the base of the Cadna-owie Formation, just above the Murta Formation. B. Polygonal faulting continues down to the interpreted top reservoir slice and may affect reservoir performance. C. Amplitude dimming beneath faults along the reservoir horizon. Cadn=Cadna-owie Formation, Murt=Murta Formation.

3.4.5. Stratigraphic Architecture

Reservoir presence and quality were recognised as primary risks when analysing this field. Reservoir sands within the Murta Formation are characteristically thinner than 10 metres, potentially channelized and laterally discontinuous in morphology. Neighbouring wells typically display orders of magnitude variation in porosity and permeability. To aid in stratigraphic prediction eight correlatable surfaces were used to describe the stratigraphy in the Murta Formation at the Cuisinier Field. These are labelled DC10 to DC80 sequentially from the base of the Formation (Figure 9). The intervals between these surfaces are named after the basal surface, for example the strata between the DC50 and DC60 surface is referred to as the DC50 interval.

From the base of the DC10 surface to the base of DC40 surface, the system is mud dominated with minor shallowing and deepening events occurring. Two examples of these shallowing and deepening events are the DC30 and DC40 surfaces, which are interpreted to represent two closely-spaced flood events. Above the DC40 surface, a gradual decrease in gamma ray log values is interpreted as a coarsening up or shallowing up sequence. This marks the beginning of the first major regression event in the region. The DC50 surface is interpreted as a sequence boundary in the Murta Formation. From core interpretation, reservoir sands directly above the DC50 surface are interpreted to include shoreline sands (FA4), lowstand fluvial channel sands (FA5) and transgressive systems tract sands (most likely FA4 and reworked FA5). As base level rose, transgressive conditions eroded and reworked the sands on and below the DC50 sequence boundary.

Above the DC50 surface the maximum point of transgression is preserved by the DC60 maximum flooding surface. A second coarsening up or shallowing up sequence terminates with the second main sequence boundary for the Murta Formation, the DC70 surface. Reservoir facies above the DC70 surface are similar to those previously described for the DC50 sequence boundary (FA4 and FA5); however there is a higher percentage of fluvial reservoir facies (FA5). There is a further small shallowing event at the very top of the Murta indicated as the DC80 surface but this is a minor event compared to the DC50 and DC70 sequence boundaries. Above the DC80 (in the Cadna-owie Formation), sedimentation becomes increasingly mud-dominated as deep water conditions begin to impose on the basin.

The key reservoir within the Cuisinier Field occurs above the DC70 surface where fluvial FA5 deposits exhibit localised thickening. Where a greater net sand thickness is encountered the sequence boundary is interpreted to have eroded deeper into the underlying FA2, FA3 and FA4 deposits. Multiple sand trends have been interpreted within the DC70- DC80 interval in the Cuisinier field. One interpretation simplifies reservoir sands into two categories: System A (Figure 9 T1) and System B (Figure 9 T2). These are thought to have formed separate potentially inter-connected compartments. System A is interpreted to have the thickest sand accumulations where the depth of incision of the sequence boundary is greatest (e.g. Cuisinier 1 and 4). This sand trends from north-west to south-east and is an amalgamation of fluvial deposits (FA5) that generally fine upwards into TST Shoreface sands (FA4). System B has a relatively thin amalgamation of fluvial channels (FA5) deposited in the TST (e.g. Cuisinier 6, 7 and 10). These sands are deposited between thin HST Shoreface sands below and TST Shoreface sands (both FA4) above.

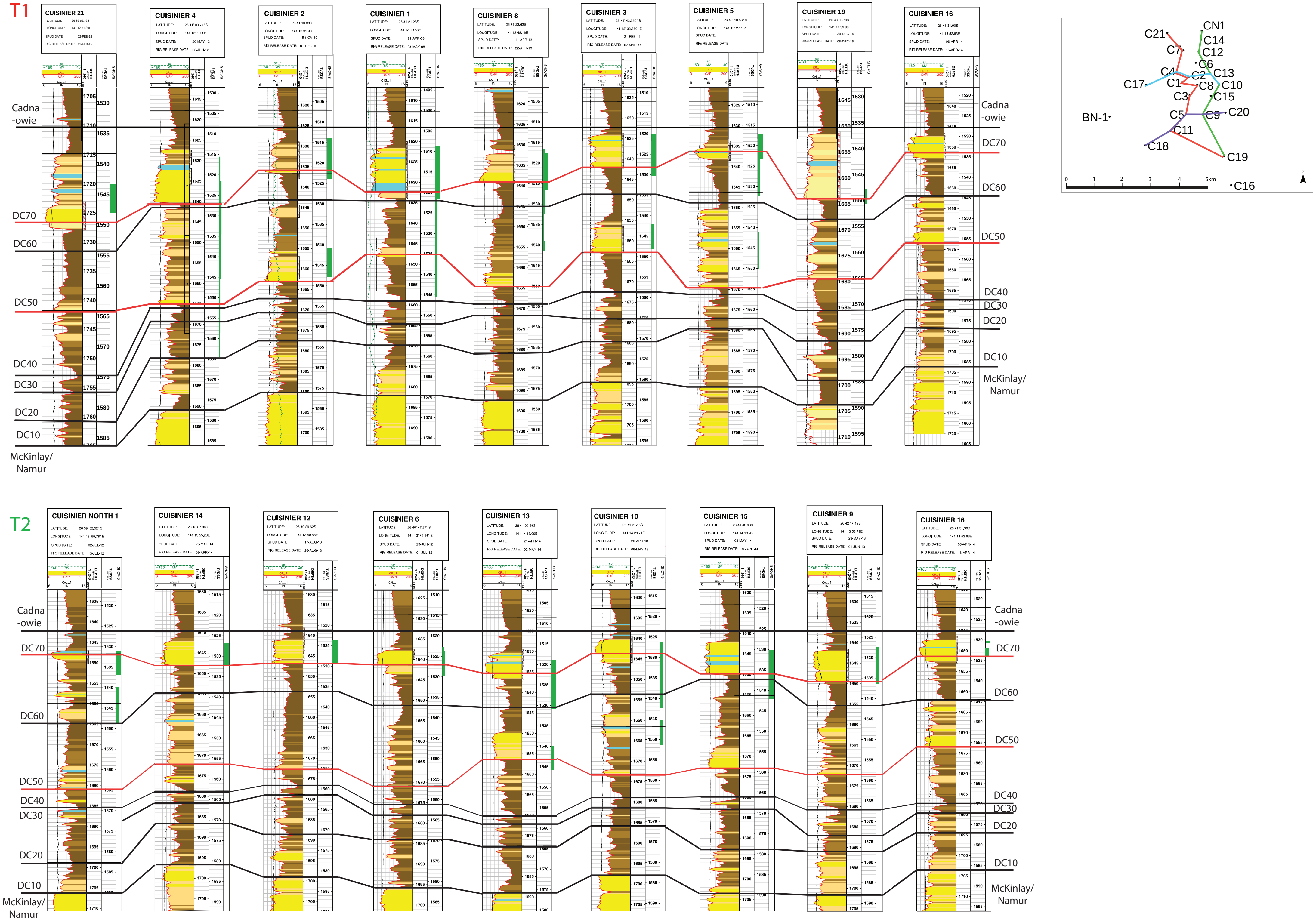
An alternate interpretation is that System A and System B represent separate avulsion lobes of a deltaic system. It could be inferred that System A was deposited before System B, as System A contains fluvial sequences with potential abandonment tops (e.g. Cuisinier 1, Cuisinier 2). Prediction of reservoir sands away from well control is difficult. The Murta DC70 sequence boundary defines the extent of reservoir sands. This boundary is best defined by well intersections.

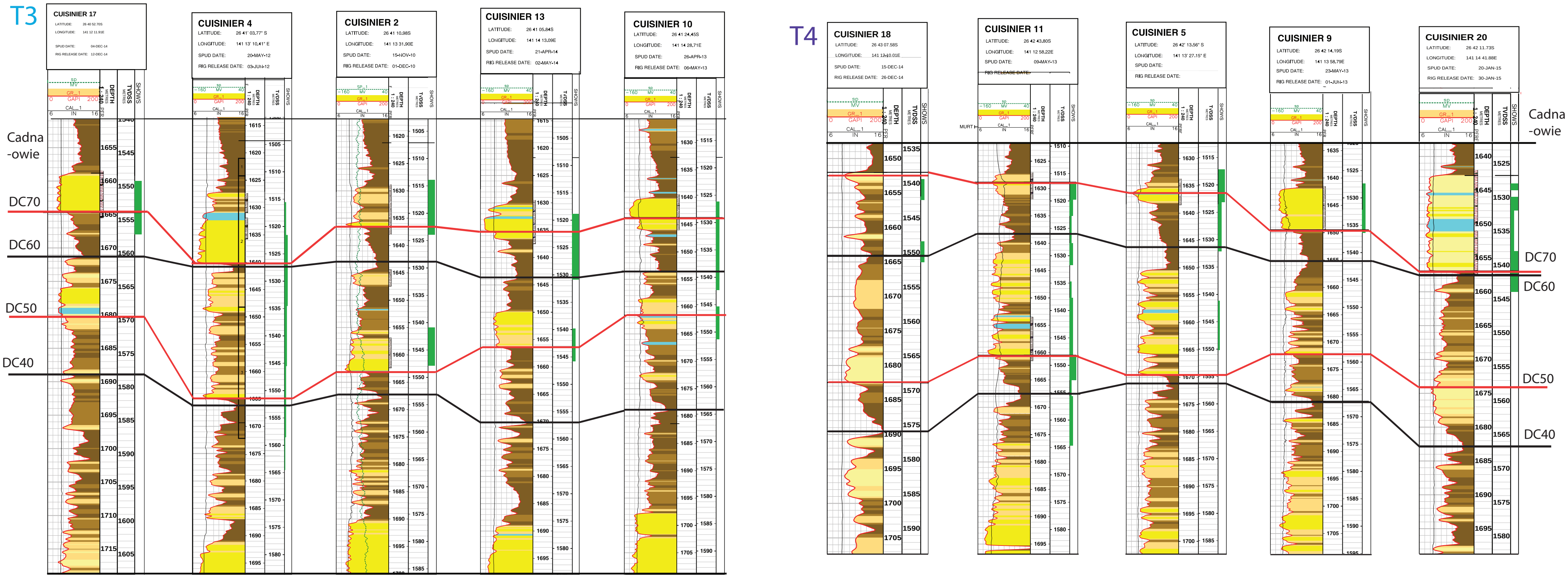
Very limited data from initial bottom hole pressure surveys indicate connected reservoir between Cuisinier 6, 13 and 10 and potentially between Cuisinier 1, 4 and 3 (see Figure 1 for Location and Figure 9 for well log motifs), however reservoir pressure decline over time will be able to provide more information on potential connection and compartmentalisation. This model is probably an oversimplification, and mechanisms aside from depositional character such as post-depositional cementation and subtle faulting probably contribute to reservoir compartmentalisation.

The secondary reservoir within the Cuisinier Field occurs above the DC50 sequence boundary, where fluvial sediments display localised thickening, much the same as above the DC70 boundary, however no compartmentalisation or correlation trends are clear. A weak trend exists between the sands above the DC50 and DC70 boundary. Sometimes where the DC70 FA5 sands are well developed, the DC50 sands appear to be poorly developed.

The opposite is also sometimes true; where DC50 sands are well developed, DC70 sands are poorly developed (e.g. Cuisinier 3, 16, 13 and 18). This trend is particularly evident in Cuisinier 10, Cuisinier 12, Cuisinier 3, Cuisinier 1, Cuisinier 5 and Cuisinier 11 (see Figure 9). This pattern could be due to paleotopographical changes in the low gradient, low accommodation space basin setting. As the DC50 sand was deposited it could have created relative paleo-highs in areas of thicker deposition.

Figure 9: Over the following two pages. Field scale wireline correlations. T1 and T2 run roughly north-south through the field and T3 and T4 run approximately east-west. DC refers to a surface. Red lines represent sequence boundaries and black lines represent stratigraphic markers. Black boxes represent core obtained. Green lines represent oil saturation. Stippled boxes represent reservoir flow zones. On the gamma ray logs yellow represents sandstone, blue represents carbonates, siltstones are coloured orange and mudstones are coloured brown. The depositional element interpretation column follow the key for gamma ray logs shown in Figure 4A.


T1
CUISINIER 21
CUISINIER 4
CUISINIER 2
CUISINIER 1
CUISINIER 8
CUISINIER 3
CUISINIER 5
CUISINIER 19
CUISINIER 16
Cadna
-owie
DC70
DC60
DC50
DC40
DC30
DC20
DC10
McKinlay/
Namur
CN1
C21
C14
C7
C12
C6
C4
C2
C13
C17
C1
C8
C10
C3
C15
BN-1
C5
C9
C20
C11
C18
C19
C16
0
1
2
3
4
5km
T2
CUISINIER NORTH 1
CUISINIER 14
CUISINIER 12
CUISINIER 6
CUISINIER 13
CUISINIER 10
CUISINIER 15
CUISINIER 9
CUISINIER 16



T3
CUISINIER 17
CUISINIER 4
CUISINIER 2
CUISINIER 13
CUISINIER 10
Cadna
-owie
DC70
DC60
DC50
DC40
T4
CUISINIER 18
CUISINIER 11
CUISINIER 5
CUISINIER 9
CUISINIER 20
Cadna
-owie
DC70
DC60
DC50
DC40

Deposition of the DC70 sand could have been concentrated in paleo-lows where the DC50 was not deposited.

3.4.6. Depositional Model

The Murta Formation within the Cuisinier study area preserves deposition from fluvial-dominated to deep-water marine environments, during a long term complex overall transgression event, punctuated by at least two major regressive events (Figure 9). Facies slice maps for the most regressive and most transgressive facies in key reservoir intervals indicate the overall transgressive nature of the formation, with progressive backstepping form the south-west to the north-east evident (Figure 10).

The lower Murta Formation in the Cuisinier Region consists primarily of prodelta, delta plain and undifferentiated delta front deposits due to minor shallowing and deepening events. Deposition of this stratum was followed by a major shallowing event, preserving delta front and shoreline deposits. The upper section of the Murta

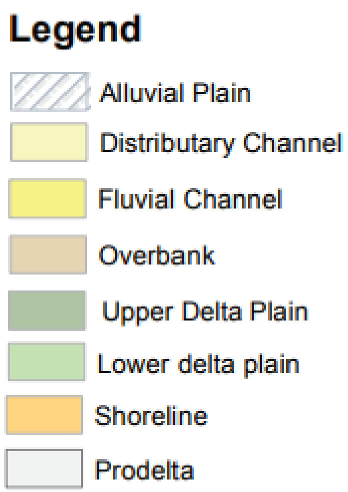
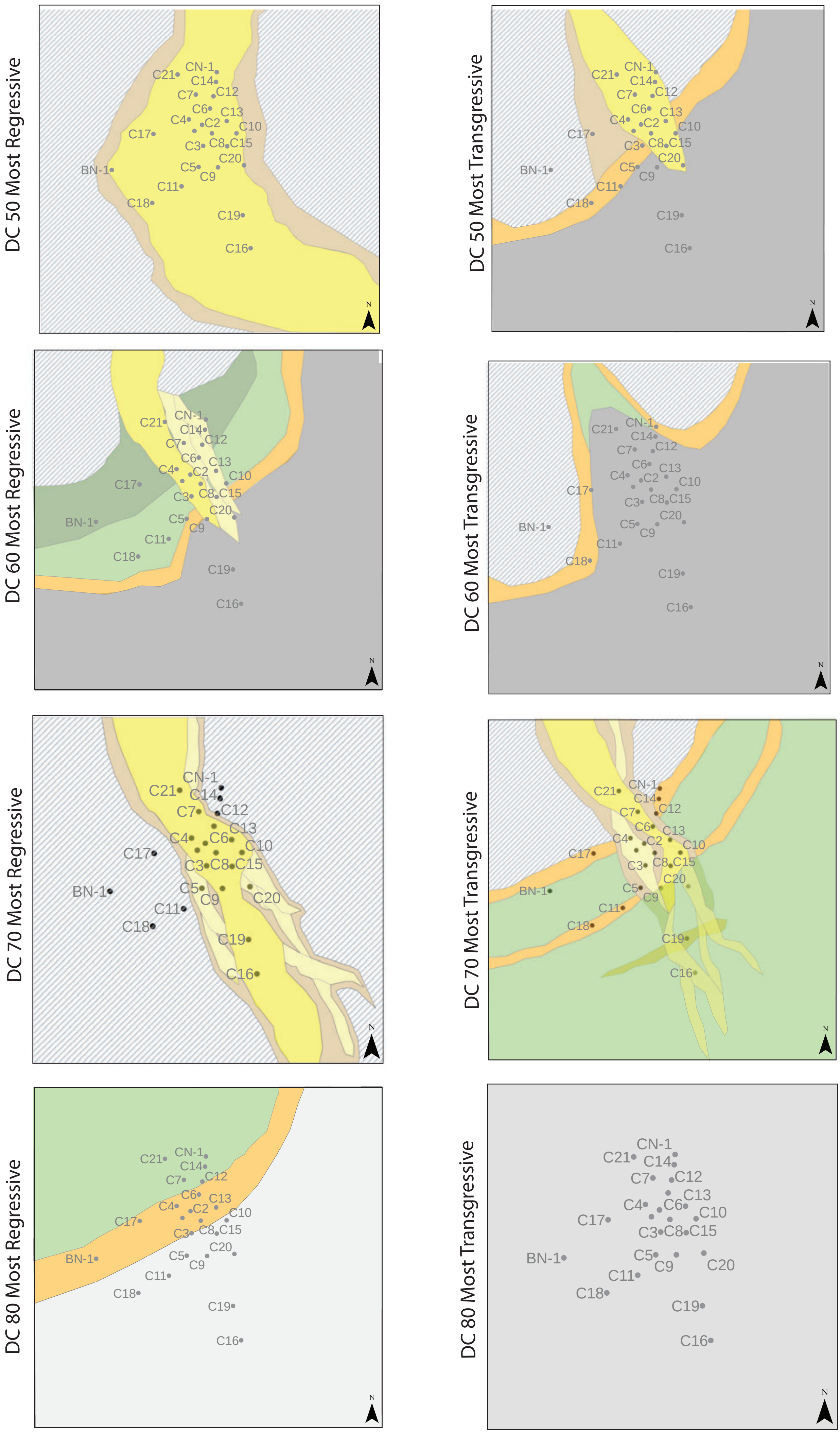


Figure 10: Left and next page. Paleogeographic cartoons, showing continued transgression over the course of the formation. Time between time slices is not equal. Transgression and regression maps show maxima of these potential events. Intervals are approximate. Environments are generalised and represent one realisation of what the area may have looked like at the time of deposition. As more data is obtained, more details should be added. For scale, see Figure 1.


DC 50 Most Regressive
DC 50 Most Transgressive
DC 60 Most Regressive
DC 60 Most Transgressive
DC 70 Most Regressive
DC 70 Most Transgressive
DC 80 Most Regressive
DC 80 Most Transgressive
CN-1
C21
C14
C7
C12
C6
C13
C4
C2
C10
C17
C3
C8
C15
C20
BN-1
C5
C9
C11
C18
C19
C16
N

Formation preserves lowstand fluvial-dominated FA 5 sediments, interpreted to have been deposited at the maximum extent of the shallowing as a result of a major regression across the region. These deposits are topped by shoreline deposits due to a regional transgression. Another similar regressive and transgressive event occurred, preserving fluvial-dominated FA 5 deposits. Autocyclic events such as bifurcation, avulsion and lobe switching are interpreted to have controlled sand deposition during this regressive event. Fluvial-dominated FA 5 deposits which form major reservoirs, and FA 4 shoreline deposits which form minor reservoirs for the Cuisinier field were most likely deposited in a fluvial and wave dominated deltaic setting. Continued transgression resulted in the deposition of prodelta (FA2) and offshore (FA1) facies of the Murta Formation. Deposition of the Murta Formation is terminated by a gradual transition into the marine transitional mud-dominated Cadna-owie Formation.

3.5. Discussion

After over 40 years of exploration, new facies have been discovered and new play concepts are being developed for the oil bearing Murta Formation of the Eromanga Basin. Effective development and production of these reserves requires a detailed understanding of stratal architecture. This paper provides detailed stratigraphic analysis and process-based interpretation of a new Murta Formation reservoir in the Cuisinier Field. Five facies associations are interpreted from limited data. An idealised facies association package from distal to proximal is: (i) offshore, (ii) prodelta, (iii) delta front, (iv) shoreline and (v) channel fill depositional environments. Channel fill and shoreline depositional settings are the primary reservoirs. Prodelta, delta front and offshore mud rich facies provide seals, as well as mud-rich internal baffles and barriers. The Murta Formation reservoirs in the Cuisinier region were most likely deposited as a part of a small fluvial and wave influenced delta, with autocyclic processes responsible for sand distribution. Evidence exists for marine and continental influenced deposition.

Evidence for marine influence on sediment deposition is present in the Upper Murta Formation at the Cuisinier Field. The abundance of HCS, wave ripples and planar stratification suggest that sedimentation occurred around a large body of water. Pervasive flaser and linsen bedding could indicate deposition during regularly alternating high energy and low energy environments, such as those in tidal flats. Deposits similar to those in FA3, Delta Plain and Delta Front, could be interpreted as Inclined Heterolithic Stratification (IHS) deposits. IHS can deposit in channels through a process whereby during ebb- or flood-tidal flow, high energy is focused within tributary channels and sand deposits amalgamate. Mud layers are deposited during intervening slack-water periods. Successions similar to those in FA3 have been observed within marine bars of the Holocene Colorado delta (Meckel, 1975). Although this interpretation is probable, no explicitly bi-directional bedforms are observed, so tidal influence cannot be unequivocally invoked.

The presence of glauconite pellets in FA2 (Figure 5), suggests a relatively cold, marine, mid-shelf to upper slope to tidal flat shallow water depositional environment with slow rates of deposition (Triplehorn, 1965). Glauconite is widely reported at the base of marine transgressive sequences, although transportation after formation and the variation in formation environments throughout the geological record constrains its use as a specific environmental indicator on a presence or absence basis (Chafetz, 2000). Geochemical findings, including glauconite pellets, from previous studies (Zoellner, 1988; Powell et al., 1989) have been used to infer the Murta Formation was deposited in a brackish to marine environment and this data from the Cuisinier Field can be considered as complementary to this.

Limited evidence exists for lateral migration of channels is observed in the reservoir sections. Vertical accretion may have been accentuated by rising relative base level which commonly enhances vertical aggradation in marginal marine settings (e.g. Tornqvist, 1993). The net result was the development of vertically-accreting, low-sinuosity channels. These are similar to aggrading anastomosed channels of the Rhine-Muse delta (Tornqvist, 1993), or straight channels in the Mahakam River Delta, Borneo (Gastaldo, 1992). Gorter (1994) observed similar deposits on the southern side of the Eromanga Basin in the Murta Formation with vegetated islands and a relatively straight anastomosing channel pattern. Limited evidence was also presented for lateral migration at this location.

The Cretaceous was a period of global sea level highstand and included a number of major eustatic fluctuations (Haq et al., 1987; Miller et al., 2005). A commonly cited example of marine encroachment onto a continent to form an epicontinental or eperic seaway during the Cretaceous is the Cretaceous Western Interior Seaway. Regression and transgression along the Western Interior Seaway resulted in the deposition of a series of clastic wedges along the margins of the Seaway (Miall, 2008). Potentially the Eromanga Basin could have experienced similar processes throughout the Cretaceous and during the time that the Murta Formation was being deposited.

Evidence for lacustrine influence on sediment deposition is dominant throughout the Murta Formation. The dominance of current ripples, unidirectional bedforms and very fine planar lamination suggests a lacustrine deltaic depositional setting. A lack of unequivocal tidal indicators such as bi-directional bedforms could be an indication that tidal activity was not present. The overall thin-bedded nature of the reservoir is similar to those observed in marginal lacustrine environments, even considering the wide and shallow nature of the basin. This is consistent with aspects of previous interpretation for the Murta Formation in other locations in the Eromanga Basin (e.g. Mount, 1981; Mount, 1982; Ambrose, 1982; Ambrose, 1986; Lennox, 1986; Theologou, 1995).

A lack of abundant and diverse dinoflagellate flora was observed from the sample at Cuisinier. Continental pollens were observed. These along with a lack of corals, echinoids, brachiopods, cephalopods or graptolites may indicate that deposition occurred in a freshwater lacustrine depositional environment. However runoff from a continental environment into any body of water could have transported continental pollens and a cold environment may inhibit growth and preservation of faunal species.

Interpretation of seismic attributes shows a delta with a radial fan nature with avulsions, which is similar to classic fluvio-lacustrine and fluvial dominated deltas. The high-angle (about 90º) intersections between main channels and associated tributaries in common in modern tidal channels formed on tidal flats (e.g. Meckel, 1975; Gastaldo et al., 1995; Olariu, 2012) were not observed. Based on limited planform data from seismic attributes, a fluvio-lacustrine or fluvial dominated deltaic depositional setting is more likely.

If the mud-clast rich fluvial dominated FA5 facies in the DC50 cycle are interpreted as an ephemeral river terminating into a playa lake setting, terminal splay processes similar to those that occur in the modern depositional Kati Thanda- Lake Eyre Basin, central Australia, could have been responsible for deposition of the DC50 sand. Terminal splays are common features of many rivers and deltas which form as a result of flow deceleration leading to sediment deposition (Tooth, 2005; Fisher, 2008) and feature mud-rip up clasts, ripples, cross bedding and thinly interbedded sands and muds. The Kati Thanda- Lake Eyre depositional basin, one of the world's largest endoreic basins, is equal to approximately one-sixth of the Australian continent and has experienced extreme wetting and drying cycles (Habeck-Fardy and Nanson, 2014), so terminal splay deposits could interfinger with deltaic deposits. The Kati Thanda- Lake Eyre Basin has a very low basin gradient, similar to conditions through to have been present during deposition of the Murta Formation in the Eromanga Basin, so incision depths and dynamics could be similar.

Previously described localised and basin-wide depositional models for the Murta Formation are inconsistent and sometimes conflicting. The degree of marine influence and the number and character of lithofacies and sedimentary sequences is not consistent between interpretations. This interpretation of data from the Cuisinier region supports some aspects of most of the previously described facies models for the Murta Formation, but the absence of an integrated basin-wide facies model makes the delineation of the allo- and auto-cyclical controls influencing the distribution and character of lithofacies and sedimentary sequences difficult. A robust regional study could provide insight into whether surfaces interpreted here are regionally or only locally correlatable. The presence or absence of marine influence and potential connectivity with the open ocean could be further investigated. Furthermore, a regional study could aid in exploration within the Eromanga Basin. As reservoir sandbodies are below seismic resolution, studies of analogues and deposits formed as a result of similar processes may improve the understanding and hence the capacity to predict reservoir presence for the region.

3.6. Conclusion

The Murta Formation within the Cuisinier study area preserves deposition during a long term complex overall transgression event, punctuated by at least two major regressive events. The Murta Formation at Cuisinier is interpreted to be net transgressive from south-west to north-east, with deposition most likely continental at the base and increasingly brackish as the top, which grades into fully marine deposition. The transgression most likely occurs slowly in a piecewise fashion, with eight sequences interpreted over the Murta Formation. Five facies associations are interpreted and these correspond with offshore, prodelta, delta front, shoreline and channel fill depositional environments. The new fluvial channel fill facies has not previously been described in the Murta Formation.

This work contributes a better understanding of the distribution of reservoir sand and depositional controls on sedimentological heterogeneities in the Cuisinier Field within the Murta Formation. This will enable more efficient production and minimize capital expenditure during development. As reservoir sandbodies are largely below seismic resolution, unless stacked or amalgamated, further investigation into analogues with similar depositional processes is recommended. A basin-wide study of the Murta Formation would also help to highlight the differences between autogenetic controls and allogenetic controls on sediment deposition.

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3.8. References

Ainsworth, R.B., Vakarelov, B.K. and Nanson, R.A., 2011. Dynamic Spatial and Temporal Prediction of Changes in Depositional Processes on Clastic Shorelines: Toward Improved Subsurface Uncertainty Reduction and Management. AAPG Bulletin, v. 95, pp 267-297.

Alexander, E.M., Gravestock, D.I., Cubitt, C. And Chaney, A., 1998. Lithostratigraphy and environments of deposition. In: Gravestock, D.I., Hibburt, J.E. & Drexel, J.F. (eds), The petroleum geology of South Australia, vol. 4, Cooper Basin. Primary Industries and Resources SA, Report Book 98/9, pp 69-115.

Alley, N.F. and Frakes, L.A., 2003. First known Cretaceous glaciation: Livingston Tillite Member of the Cadna-owie Formation, South Australia. Australian Journal of Earth Sciences, 50(2), pp139–144.

Ambrose G., Suttill R. & Lavering I., 1982. A Review of the Early Cretaceous Murta Member in the Southern Eromanga Basin. In Moore, P.S. & Mount T.J. eds. Eromanga Basin Symposium, Summary Papers, pp 92-109. Geological Society of Australia & Petroleum Exploration Society of Australia, Adelaide.

Ambrose G., Suttill R., Lavering I., 1986. The Geology and Hydrocarbon Potential of the Murta Member (Mooga Formation). In the Southern Eromanga Basin. In Gravestock D.I., Moore P.S. & Pitt G.M. eds. Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin. GSA, Special Publication No. 12, pp 71-84.

Bhattacharya, J.P. and MacEachern, J.A., 2009, Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: JSR, v. 79/4, pp 184-209.

Cappelle, M., Stukins, S., Hampson, G., & Johnson, H., 2016. Fluvial to tidal transition in proximal, mixed tide-influenced and wave-influenced deltaic deposits: Cretaceous lower Sego Sandstone, Utah, USA. Sedimentology, 63(6), pp 1333-1361.

Chafetz H.S. and Reid, A., 2000. Syndepositional shallow-water precipitation of glauconitic minerals. Sedimentary Geology, 136(1), pp29–42.

Crerar, E.E. & Arnott, R.W.C., 2007. Facies distribution and stratigraphic architecture of the Lower Cretaceous McMurray Formation, Lewis Property, northeastern Alberta. Bulletin of Canadian Petroleum Geology, 55(2), pp 99–124.

David, A. and Woolnough, M., 1926. Central Australia field mapping notes presented in Sheard, M.J. 2009. Explanatory notes for CALLABONNA 1:250 000 geological map, sheet SH 54-6 Geological Survey of South Australia. Report Book 2009/01.

Dott, R.H. and Bourgeois, J., 1982. Hummocky stratification: significance of its variable bedding sequences. Geol. Soc. Am. Bull., 93, pp 663–680.

Drexel, J.F., and Preiss, W.V., 1995. The geology of South Australia: Mines and Energy South Australia, Geological Survey of South Australia, Bulletin 54.

Duke, W.L., 1985. Hummocky cross-stratification, tropical hurricanes, and intense winter storms. Sedimentology, 32, pp 167–194.

Fisher, J.A., Krapf, C.B.E., Lang, S.C., Nichols, G., Payenberg, T.H.D., 2008. Sedimentology and architecture of the Douglas Creek terminal splay, Lake Eyre, central Australia: Sedimentology, v. 55/6, pp 1915–1930.

Gastaldo, R.A., 1992. Sediment facies, depositional environments, and distribution of phytoclasts in the recent Mahakam River delta, Kalimantan, Indonesia. Palaios, 7(6), pp 574–590.

Gorter J.D., 1994. Sequence Stratigraphy and the Depositional History of the Murta Member (Upper Hooray Sandstone), Southeastern Eromanga Basin, Australia: Implications for the Development of Source and Reservoir Facies. APEA Journal, pp 644-673.

Habeck-Fardy, A. and Nanson G., 2014. Environmental character and history of the Lake Eyre Basin, one seventh of the Australian continent. Earth-Science Reviews, 132 (2014), pp 39–66.

Haq, Bilal U., Hardenbol, Jan & Vail, Peter R., 1987. Chronology of fluctuating sea levels since the Triassic. (Vail sea level curves). Science, 235, pp 1156.

Hinds, D.J, Aliyeva, E, Allen, M.B, Davies, C.E, Kroonenberg, S.B, Simmons, M.D, Vincent, S.J., 2004. Sedimentation in a discharge dominated fluvial-lacustrine system: the Neogene Productive Series of the South Caspian Basin, Azerbaijan. Marine and Petroleum Geology, 21(5), pp 613–638.

Johansson, M. and Stow, D.A.V., 1995. A classification scheme for shale clasts in deep water sandstones. Geological Society, London, Special Publications, 94(1), pp 221–241.

Keen, T.R., Slingerland, R.L., Bentley, S.J., Furukawa, Y., Teague, W.J. and Dykes, J.D., 2012. Sediment Transport on Continental Shelves: Storm Bed Formation and Preservation in Heterogeneous Sediments. In: Sediments, Morphology and Sedimentary Processes on Continental Shelves: Advances in Technologies, Research, and Applications (Eds M.Z. Li, C.R. Sherwood and P.R. Hill), IAS Spec. Publ., 44, pp 295–310.

Krieg G.W., Alexander E.M., Rogers P.A., 1993. Eromanga Basin: in Drexel JF and Priess WV (editors) ‘The geology of South Australia. Volume 2, The Phanerozoic, Chapter 8 Late Palaeozoic’. Geological Survey of South Australia, Bulletin 54, pp 101–127.

Frakes L. A. and Francis, J. E. 1988. A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous. Nature, 333(6173), pp 547–549.

Legler, B., Johnson, H.D., Hampson, G.J., Massart, B.Y.G., Jackson, C.A., Jackson, M.D., El-

Barkooky, A. and Ravnås, R. 2013., Facies model of a fine-grained, tide-dominated delta: Lower Dir Abu Lifa Member (Eocene), Western Desert, Egypt. Sedimentology, 60, pp 1313–1356.

Lennox C.L., 1986. Early Cretaceous Sedimentology and Depositional Facies at Nockatunga Oilfield, Cooper-Eromanga Basin, Queensland. Unpublished B.Sc. Honours Thesis, University of New South Wales.

MacEachern, J.A. and Bann, K.L., 2008. The Role of Ichnology in Refining Shallow Marine Facies Models. In: Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy (Eds G.J. Hampson, R.J. Steel, P.M. Burgess and R.W. Dalrymple), SEPM Spec. Publ., 90, pp 73–116.

Markwick, P.J., Rowley, D.B., 1998. The geologic evidence for Triassic to Pleistocene glaciations: implications for Eustacy. In: Pindell, J.L., Drake, C.L. (Eds.), Paleogeographic Evolution and Non-Glacial Eustasy, Northern South America, SEPM Special Publication. SEPM Special Publication No.58. SEPM, Tulsa, pp 17 – 43.

Martin K.R., 1988. Petrology and diagenesis of reservoir rocks from the Murta M4 subunit, Dullingari oil field, Cooper - Eromanga Basin, S.A. Unpublished report to Santos Ltd.

McKellar J.L., 1996. Palynofloral and Megafloral Indications of Palaeoclimate in the Late Triassic, Jurassic, and Early Cretaceous of Southeastern Queensland. In Mesozoic Geology of the Eastern Australia Plate Conference, pp. 336-371. Geological Society of Australia Inc. Extended Abstracts No. 43, Queensland, Australia.

Meckel, L.D.,1975. Holocene sand bodies in the Colorado Delta area, northern Gulf of California, in Deltas, models for exploration: Houston Geological Society, pp 239-265.

Miall, A.D., Catuneanu, O., Vakarelov, B., Post, R., 2008. The Western Interior Basin, in Miall, A.D., ed., The Sedimentary Basins of the United States and Canada: Sedimentary basins of the World, v. 5 (K.J. Hsü, Series Editor): Amsterdam, Elsevier Science, pp 329–362.

Miller A., Kenneth G., Kominz, Michelle A., Browning, James V., Wright, James D., Mountain, Gregory S., Katz, Miriam E., Sugarman, Peter J., Cramer, Benjamin S., Christie-Blick, Nicholas, and Pekar, Stephen F., 2005. Phanerozoic Record of Global Sea-Level Change. Science 310, no. 5752, pp1293-298.

Mount T.J., 1982. Geology of the Dullingari Murta Oilfield. In Moore P.S. & Mount T.J. eds. Eromanga Basin Symposium. Summary Papers. GSA and PESA, Adelaide. Australian Sedimentologists Special Group, Wollongong, pp 307-337.

Mount, T, J., 1986. Geology of the Dullingari Murta Oilfield. Moore, P., Mount, T. J., & Petroleum Exploration Society of Australia. South Australian Branch. (1982). Eromanga Basin Symposium : Summary papers / compiled by P.S. Moore & T.J. Mount. Adelaide, S. Aust: Geological Society of

Australia and Petroleum Exploration Society of Australia.

Mount, T.J. 1981. Dullingari North 1, an oil discovery in the Murta Member of the Eromanga Basin. APEA Journal 21(1) pp 71-77.

Olariu, C, Steel, RJ., Dalrymple, RW., Gingras, MK., 2012. Tidal dunes versus tidal bars: The sedimentological and architectural characteristics of compound dunes in a tidal seaway, the lower Baronia Sandstone (Lower Eocene), Ager Basin, Spain. Sedimentary Geology, 279, pp 134.

Oomkes, E., 1974. Lithofacies relations in the Late Quaternary Niger Delta complex. Sedimentology, 21, pp 195–222.

Powell T.G., Boreham C.J., McKirdy D.M., Michaelsen B.H., Summons R.E., 1989. Petroleum Geochemistry of the Murta Member, Mooga Formation, and Associated Oils, Eromanga Basin. The APPEA Journal 29, pp 114-129.

Price P.L., 1997. Permian to Jurassic palynostratigraphic nomenclature of the Bowen and Surat Basins: in Green PM (editor) The Surat and Bowen Basins, south-east Queensland. Queensland Minerals and Energy Review Series, pp 137–178

Reineck, H.E. and Wunderlich, F., 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, 11, pp 99–104.

Santos Ltd., 2013. Stratigraphic table for the Cooper-Eromanga Basins. Internal Company Report.

Schulz-Rojahn J.P., 1993. Calcite Cemented Zones in the Eromanga Basin: Clues to Petroleum Migration and Entrapment? APEA Journal, pp 63-76.

Scotese, M., 2013. Atlas of Earth History, PALEOMAP Project, Arlington, Texas.

Sheard, M.J., 1990. Glendonites from the southern Eromanga Basin in South Australia: palaeoclimatic indicators for Cretaceous ice. Geological Survey of South Australia, Quarterly Geological Notes 114. pp17-23

Staub, J.R. and Gastaldo, R.A., 2003. Late Quaternary sedimentation and peat development in the Rajang river delta, Sarawak, east Malaysia. In: Tropical Deltas of Southeast Asia- Sedimentology, Stratigraphy, and Petroleum Geology (Eds F. Hasan Sidi, D. Nummedal, P. Imbert, H. Darman and H. Posamentier), SEPM Spec. Publ., 76, pp 71–78.

Stow, D.A.V., 2005. Sedimentary rocks in the field : a colour guide / Dorrik A.V. Stow., London: Manson Publishing.

Strachan, L.J., 2008. Flow transformations in slumps: a case study from the Waitemata Basin, New Zealand. Sedimentology, 55(5), pp 1311–1332.

Sumner, E.J., 2012. Facies architecture of individual basin-plain turbidites: Comparison with existing models and implications for flow processes. Sedimentology, 59(6), pp1850–1887.

Talling, P., Amy, L., Wynn, R., Blackbourn, G., & Gibson, O., 2007. Evolution of Turbidity Currents Deduced from Extensive Thin Turbidites: Marnoso Arenacea Formation (Miocene), Italian Apennines. Journal of Sedimentary Research, 77(3), pp 172-196.

Talling, P.J., 2012. Subaqueous sediment density flows: Depositional processes and deposit types. Sedimentology, 59(7), pp 1937–2003.

Talling, P.J., 2013. Hybrid submarine flows comprising turbidity current and cohesive debris flow: Deposits, theoretical and experimental analyses, and generalized models. Geosphere, 9(3), pp 460–488.

Taylor, A.M. and Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. J. Geol. Soc., 150, pp 141–148.

Theologou, P., 1995. Murta Formation/McKinlay Member of the Murteree Ridge Nappacoongee-Murteree Block Improved Oil recovery project. Unpublished PhD thesis, University of South Australia.

Tooth, S., 2005. Splay formation along the lower reaches of ephemeral rivers on the Northern Plains of arid central Australia. J. Sediment. Res. 75, pp 636–649.

Törnqvist, T.E., 1993. Fluvial sedimentary geology and chronology of the Holocene Rhine-Meuse delta, The Netherlands (Vol. 166). Koninklijk Nederlands Aardrijkskundig Genootschap.

Triplehorn, D.M., 1965. Morphology, Internal Structure, and Origin of Glauconite Pellets. Sedimentology, 6(4), pp 247–266.

Usdowski, H. E., 1963. Die Genese der Tutenmergel oder Nagelkalke (cone-in-cone cementation). Beit. Mineral Petrography, 9, pp 95-110.

Van Heerden, I.L., And Roberts, H.H., 1988. Facies development of Atchafalaya Delta, Louisiana: a modern bayhead delta: American Association of Petroleum Geologists, Bulletin, v. 72, pp 439–453.

Van Straaten P. and Kuenen, PH., 1957. Accumulation of fine grained sediments in the Dutch Wadden Sea Geologie en Mijnbouw, 19, pp 329–354.

Veevers J.J., 1984. Phanerozoic Earth history of Australia. Clarendon Press Oxford.

White, L.T. Gibson G.M. and Lister GS., 2013. A reassessment of paleogeographic reconstructions of eastern Gondwana: Bringing geology back into the equation. Gondwana Research, 24(3-4), pp 984–998.

Wood,G., 2011. Murta Palynology report. Internal to Santos Ltd.

Wopfner, H., Freytag, I.B., Heath G.R., 1970. Basal Jurassic– Cretaceous rocks of the western Great Artesian Basin, South Australia: stratigraphy and environment. AAPG Bulletin 54, pp 383–416.

Wright, D.L., 1977, Sediment transport and deposition at river mouths: a synthesis: Geological Society of America, Bulletin, v. 88, pp 857–868.

Zoellner E., 1988. Geology of the Early Cretaceous Murta Member, Mooga Formation, in the Cooper Basin Area, South Australia and Queensland. Flinders University PhD Thesis (Unpublished).

Chapter 4: The Dryland Terminal Splay to Delta Continuum: A Modern Sedimentary Investigation from Lake Yamma Yamma, central Australia

4.1. Abstract

In dryland settings, interactions between fluvial and lacustrine systems are complex and diverse. We propose that the deposits which accrete at the fluvial-lacustrine interface in dryland settings can be classified into four categories: (Type 1) perennial rivers terminating into perennial lakes, (Type 2) ephemeral rivers terminating into perennial lakes, (Type 3) ephemeral rivers terminating at a landform which is not a body of water or dry lake, (and) (Type 4) ephemeral rivers terminating into ephemeral lakes, which may be wet (4A) or dry (4B). This study presents a detailed case study, which includes analysis of sediment characteristics and geomorphology, a facies model and depositional element descriptions, for a previously unstudied Type 4 deposit, accreting in Lake Yamma Yamma, Queensland, Australia. Satellite imagery, inundation frequency maps, geological maps, hydrological data and digital elevation models were analysed in an initial desktop study. Sediment observations and descriptions, over three hundred and fifty sediment samples for particle size analysis, and over thirty kilometres of Real Time Kinematic GPS data were collected over approximately two months in the field. Analysis of these data enabled the deposits to be described in detail and the likely controls on deposition to be interpreted. Twelve main depositional elements are described. Proximal fluvial-dominated elements, medial lacustrine-influenced depositional elements and marginal lacustrine deposits were sand-dominated, but distal elements were generally mud dominated, with suspension fallout processes responsible for deposition.

When flow into Lake Yamma Yamma from Cooper Creek commences, terminal splay style deposition occurs, but as flow intensity increases, deltaic *deposition occurs and becomes more influential. Incision of channels through aeolian dunes influences the morphology of upper and lower delta plain systems. Locally-sourced terminal splay complexes provide sand-rich sediment to the lake, with shorelines and barrier islands formed during times of high lake level. These deposits at Lake Yamma Yamma are compared to other studied dryland fluvial termination deposits. We conclude that at Lake Yamma Yamma, changes in climate and variability in accommodation space play a role in deposit characteristics, but local tectonic activity is the main controlling factor for sediment character, geomorphology and sand bed thickness.*

4.2. Introduction

Interactions between fluvial and lacustrine systems in dryland settings are diverse and complex (Al-Masrahy and Mountney, 2015). Permanent, intermittent and ephemeral fluvial systems occur in many dryland regions including parts of India, Saudi Arabia, the United States and Australia (e.g. Schenk and Fryberger, 1988; Nanson et al., 2002; Tooth, 2000; Glennie, 1987). Continental drylands have been widespread at times through Earth history (George and Berry, 1993; Turner et al, 2001; Hinds et al, 2004; Scherer et al, 2007; Abbasi et al, 2013). A significant locus of deposition in these settings, and thus a key area of interest, is the termination of fluvial systems into playa lakes; the equivalent of a lacustrine delta in a perennially wet humid system, and described here as terminal fluvial deposits.

Published studies of terminal fluvial deposits in drylands have not been comprehensively reviewed. A range of different descriptive terminologies have been applied without an attempt to establish a broader context for classification. Although climate, local tectonic regime and variability in accommodation space play a role in deposit characteristics such as thickness, stacking patterns and preservation potential, fundamental sediment transport processes and geomorphologies share similarities. We propose, based on published studies of modern dryland terminal fluvial deposits, that dryland terminal fluvial deposits can be classified into four categories, based on simple fundamental hydrologic conditions. The categories are: (1) a perennial river terminating into a perennial lake, (2) an ephemeral river terminating into a perennial lake, (3) an ephemeral river terminating on a landform which is not a body of water or dry lake, e.g. a floodplain, and (4) an ephemeral river terminating into an ephemeral lake, which may be wet (4A) or dry (4B), a temporal variation in the same system with depositional processes changing at the river terminus depending on environmental conditions.

Type 1 deposits, perennial rivers terminating into perennial lakes, form fluvio-lacustrine deltas, dominated by subaqueous deposition. Described examples include the Ural Delta and the Emba Delta, which have formed where the Ural and Emba rivers terminate into the Caspian Sea (Richards et al., 2017). Type 1 deposits share similar depositional characteristics to comparatively well-studied marine deltas (e.g. Galloway, 1975; Ainsworth et al., 2011), except for a key difference which is that they lack the tidal influence that occurs in many marine deltas. They are, however, likely to be very similar in terms of their facies and morphology to marine deltas, but influenced only by wave and fluvial controls (W, F, Wf and Fw of Ainsworth et al, 2011).

Type 2 deposits, ephemeral rivers terminating into perennial lakes, also form deltas. This is a rare depositional setting due to the relatively small number of perennial lakes in dryland environments. Deltas deposited under these conditions form low gradient fluvial-dominated alluvial fan deltas (Blair and McPherson, 2008).

A well-described example is the Rose Creek fan delta of west-central Nevada (Blair and McPherson, 2008). Type 2 deposits may occur in tectonically active basins with steep gradients, which allow for the presence of a stable perennial lake in a dryland setting. As these deltas are deposited there are two modes of deposition: alluvial-dominated when the ephemeral river is dry and fluvial-dominated when the ephemeral river flows. As a result fluvial deposits can be interbedded with alluvial gravity-driven deposits.

Type 3; ephemeral rivers terminating at landforms which are not a body of water or dry lake, have been described as terminal fans (Friend, 1978, Kelly and Olsen, 1993), floodouts (Tooth, 1999; Tooth, 2000), ephemeral mud-prone interdune fluvial terminations (e.g. Stanistreet and Stollhofen, 2002), fluvial distributary systems (Nichols 1987; Nichols and Hirst 1998; Nichols and Fisher, 2007) and ephemeral stream terminal distributary systems (Billi, 2007). Although these deposits are well-described, deposit character is highly varied; there is no distinct sedimentary succession, and no single facies model can predict deposit character (North and Warwick, 2007). Type 3 deposits share process-based characteristics with crevasse splays and ephemeral floodplain features formed by overland flow (Jorgensen and Fielding, 1996; Taylor, 1999).

Type 4 consists of ephemeral rivers terminating into ephemeral lakes, which may be wet (4A) or dry (4B). Where the ephemeral lake is wet (4A), deposition is dominantly subaqueous, similar to that described in a delta (Type 2), but will likely be influenced by wetting and drying, aeolian reworking and subaerial flow. Where the ephemeral lake is dry (4B), deposition is dominated by subaerial unconfined flow (similar to Type 3), which can evolve in scale from a single lobe to a larger distributary system. Depositional character is likely to be influenced by aeolian reworking. Examples of Type 4 depositional systems include fluvial terminations fed by ephemeral rivers in the Turkana basin, northern Kenya (Frostick and Reid, 1986), the Elliot Formation of the Karoo Basin (Turner, 1986), the Río Colorado in Salar de Uyuni Bolivia (Donselaar et al., 2013; Li and Bristow, 2015), the Huesca fluvial fan in the Ebro Basin, Spain (van Toorenenburg et al., 2016), the Chott Rharsa system, southern Tunisia (Blum et al., 1998), Kati Thanda- Lake Eyre margin terminal splays complexes in the Kati Thanda- Lake Eyre Basin (Lang et al., 2004; Fisher et al., 2008) and Coongie Lakes margin terminal splays in the Kati Thanda- Lake Eyre Basin (Costelloe, 2009).

Two facies models describe the characteristics of Type 4 marginal terminal fluvial systems in the Lake Eyre Basin: confined and unconfined (Lang et al., 2004; Fisher et al., 2008; LEBARG, 2010). The confined facies model is defined by a sandy low-sinuosity fluvial channel belt that becomes a network of bifurcating, downstream narrowing distributary channels. These are filled with sand fining upward or simple compound bars, commonly overlain by desiccated mud-plugs. Narrow crevasse splay channels occur until flow becomes unconfined, and resultant splay deposits amalgamate laterally to form fining upward middle-ground bar deposits. Amalgamated deposits are likely to coarsen upward overall. Aeolian reworking is pervasive. The unconfined facies model is simpler. Sheet-flood processes dominate deposition. Shallow bars separate wide and shallow distributary channels. Topographies are relatively subdued. Deposits generally consist of fining upward sheet-like deposits with abundant climbing ripples, parallel and/or upward convex parallel lamination and small scale 2D and 3D dunes. Both confined and unconfined facies occur at a range of scales (LEBARG, 2010). These conclusions were drawn from study of five fluvial termination deposits in Kati Thanda- Lake Eyre, with deposit area ranging from 0.1 – 89 km^2, fluvial catchment area ranging from <100 – 361 000 km^2 and proximal deposit grain size ranging from muddy silt to medium sand (LEBARG, 2010). Confined and unconfined deposits may overlie or occur adjacent to one another and terminal splay complexes overlie and interfinger floodplain, playa and lake floor sediments (Fisher et al., 2008). Temporal and spatial variability occurs as a result of lobe stacking, wind-tide reworking and aeolian deflation in the short term, as well as medium and long term climatic wetting and drying cycles (LEBARG, 2010; Fisher et al., 2008).

Process-based facies models are not explicitly presented for the other published examples of Type 4 dryland terminal fluvial deposits. Chott Rharsa system, southern Tunisia (Blum et al., 1998), ephemeral rivers in the Turkana basin, northern Kenya (Frostick and Reid, 1986), the Elliot Formation of the Karoo Basin (Turner, 1986) or the Coongie Lakes margin terminal splays in the Kati Thanda-Lake Eyre Basin (Costelloe, 2009). Inspection of limited sedimentary log data from these studies reveals the highly variable nature of these deposits. Grain size, sorting, bed thickness, stratigraphic stacking pattern and lateral extent all vary between locations.

Although relatively common in drylands globally, Type 4 deposits are generally understudied and underrepresented in the literature compared to their Type 1, 2, 3 and marine deltaic counterparts. A range of descriptive terminologies are applied without a broader context for classification. A context for classification could help to facilitate more productive comparisons and improve interpretation of ancient deposits. Furthermore, Type 4 terminal dryland fluvial deposits display no distinct sedimentary succession. Deposits are highly varied. No single facies model can predict deposit character. More field studies are required in order to characterise

		Description	Range of terminology	Modern Example	Key References
Category 1		perennial rivers terminating into perennial lakes	lake delta, fluvio-lacustrine delta	Ural Delta and Emba Delta terminating into the Caspian Sea	Galloway, 1975; Blair and McPherson, 2008; Ainsworth, 2011; Richards et al., 2017
Category 2		ephemeral rivers terminating into perennial lakes	lake delta, fan delta, lacustrine delta	Rose Creek fan delta of west-central Nevada	
Category 3		ephemeral rivers terminating at landforms which are not a body of water or playa lake	terminal fans, floodouts, fluvial distributary systems, ephemeral stream terminal distributary systems	Hoanib River flood deposits of Namib Desert; Ephemeral stream terminations in the Kobo basin, northern Welo, Ethiopia; ephemeral rivers on the Northern Plains of central Australia	Nichols 1987; Kelly and Olsen, 1993; Tooth, 2000; Stanistreet and Stollhofen, 2002;Billi, 2007; Nichols and Fisher, 2007
Category 4	**A**	ephemeral rivers terminating into ephemeral lakes, which are wet	fluvial terminations fed by ephemeral rivers, fluvial termination systems, terminal splays, marginal terminal fluvial systems	Fluvial terminations fed by ephemeral rivers in the Turkana basin, northern Kenya; Chott Rharsa system, southern Tunisia; Lake Eyre margin terminal splays in the Lake Eyre Basin, central Australia	Frostick and Reid, 1986; Turner, 1986; Blum et al., 1998; Lang et al., 2004; Fisher et al., 2008; Costelloe, 2009
	B	ephemeral rivers terminating into ephemeral lakes, which are dry			

Table 1: Summary of framework for categories of terminal dryland fluvial deposits discussed within this paper.

these deposits and develop a predictive facies model.

Although relatively common in drylands globally, Type 4 deposits are generally understudied and underrepresented in the literature compared to their Type 1, 2, 3 and marine deltaic counterparts. A range of descriptive terminologies are applied without a broader context for classification. A context for classification could help to facilitate more productive comparisons and improve interpretation of ancient deposits. Furthermore, Type 4 terminal dryland fluvial deposits display no distinct sedimentary succession. Deposits are highly varied. No single facies model can predict deposit character. More field studies are required in order to characterise these deposits and develop a predictive facies model.

In order to start filling this knowledge gap, this study describes a detailed case study of a Type 4 deposit that has not previously been described. We present an analysis of sediment characteristics and geomorphology, a summary facies model and descriptions of depositional elements. The interpretation of process controls is emphasised. Our observations are compared with published studies of dryland fluvial terminations and illustrate the diversity of such deposits in dryland settings. This study highlights a lack of context for description of fluvial termination deposits, and the need for more detailed case studies to enable better understanding of the processes and controls of such deposits.

4.3. Regional Setting and Background

Lake Yamma Yamma is the largest dryland lake in Queensland, Australia (~800 km^2), located near the northeast corner of the South Australian and Queensland borders (Figure 1A). Lake Yamma Yamma is an example of a structurally controlled playa lake which has formed upstream of the basin depocentre. The ultimate base level is Kati Thanda- Lake Eyre, ~750km downstream and ~90m lower. Structural controls on the lake include intraplate tectonism and large scale folding. The long axis of the lake follows the trend of the Yamma Yamma Syncline along strike and the lake is constrained by structural highs to the east, west and south (Figure 1B).

Lake Yamma Yamma has not previously been the focus of any scientific studies, although in 1967 as part of a regional economic exploration study a shallow borehole (Barrolka-1, 103 m TD; Figure 2) was drilled in the centre of the lake (Senior, 1970; Gregory et al., 1967). A basic lithology log from the hole shows that approximately 100 m of mud (silt and clay), bands of evaporitic gypsum and thin sands are preserved vertically below the lake. Sand intervals are up to 2 m, but typically around 50 cm thick, and make up approximately 23% of the total length of the hole. No other sedimentary details were described. Material from the borehole was not kept. Lithologies from this borehole could represent many years of ongoing lacustrine sedimentation are preserved in the subsurface in the region, and could suggest that Lake Yamma Yamma is a long-established and persistent feature, rather than an transient surface landform.

Lake Yamma Yamma fills primarily as a result of Cooper Creek overflow, and when full, covers approximately 690 km^2 and reaches 1 metre total depth. The lake fills completely approximately once every three decades; however there is generally some local seasonal inundation in the northeast section of the lake as a result of minor Cooper Creek overflow (Queensland Government, 2016).

Cooper Creek comprises a complex fluvial system, with up to 60 km total floodplain width. The system transports a minor sand load and mud, often as

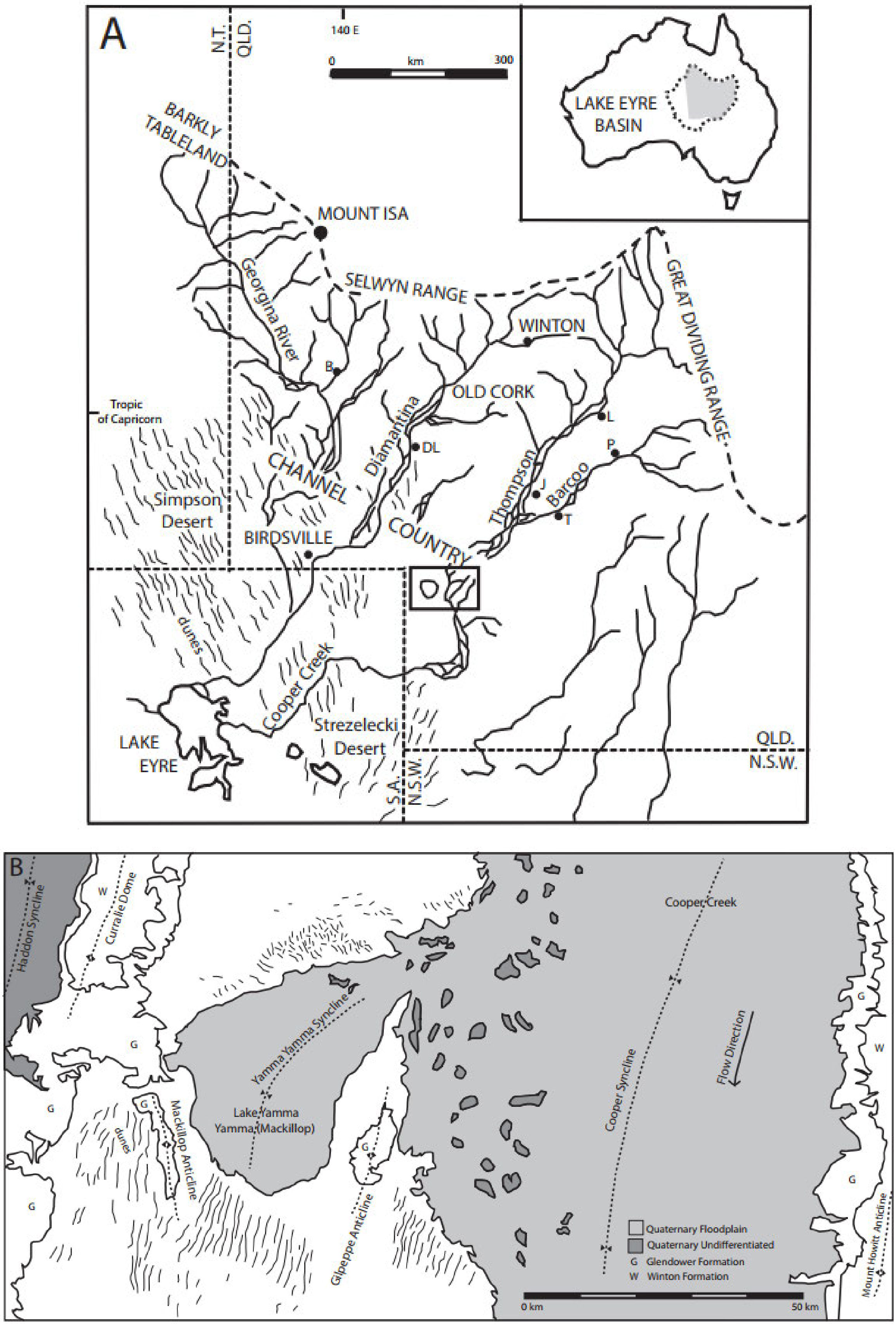


Figure 1: A. The location of Cooper Creek in the context of the Kati Thanda- Lake Eyre Basin. B.The Lake Yamma Yamma region, showing basic spatial and geological characteristics of Lake Yamma Yamma and the Cooper Creek floodplain in the study area.

aggregates (Maroulis and Nanson, 1996; Rust and Nanson, 1989), from its headwaters in central Queensland south west to Kati Thanda- Lake Eyre (Figure 1A). Along Cooper Creek sediment is preserved in synclines and local sediment sinks, including Lake Yamma Yamma, above the primary intra-continental depocentre base level at Kati Thanda- Lake Eyre (Jansen et al., 2013). Cooper Creek is the most intensively described of the Kati Thanda- Lake Eyre drainage basin rivers and has been the focus of many studies (e.g. Nanson et al., 1986; Rust and Nanson, 1986; Nanson et al.,1988; Knighton and Nanson, 1994; Fagan and Nanson, 2004; Maroulis et al., 2007; Cohen et al., 2010; Jansen et al., 2013). Aeolian dunes, anabranching channels, braided flood channels, palaeochannels, splays and waterholes characterise reaches of the Cooper Creek floodplain closest to Lake Yamma Yamma (Tooth and Nanson, 1999). Channels along Cooper Creek near Lake Yamma Yamma tend to have one dominant main trunk, although numerous sinuous small channels can exist across the floodplain. Dominant main trunk channels tend to have low but highly variable width to depth ratios (e.g. 4 to 60), steep banks formed of cohesive mud commonly lined with vegetation, low levees and a canal-like cross section (Knighton and Nanson, 1994).

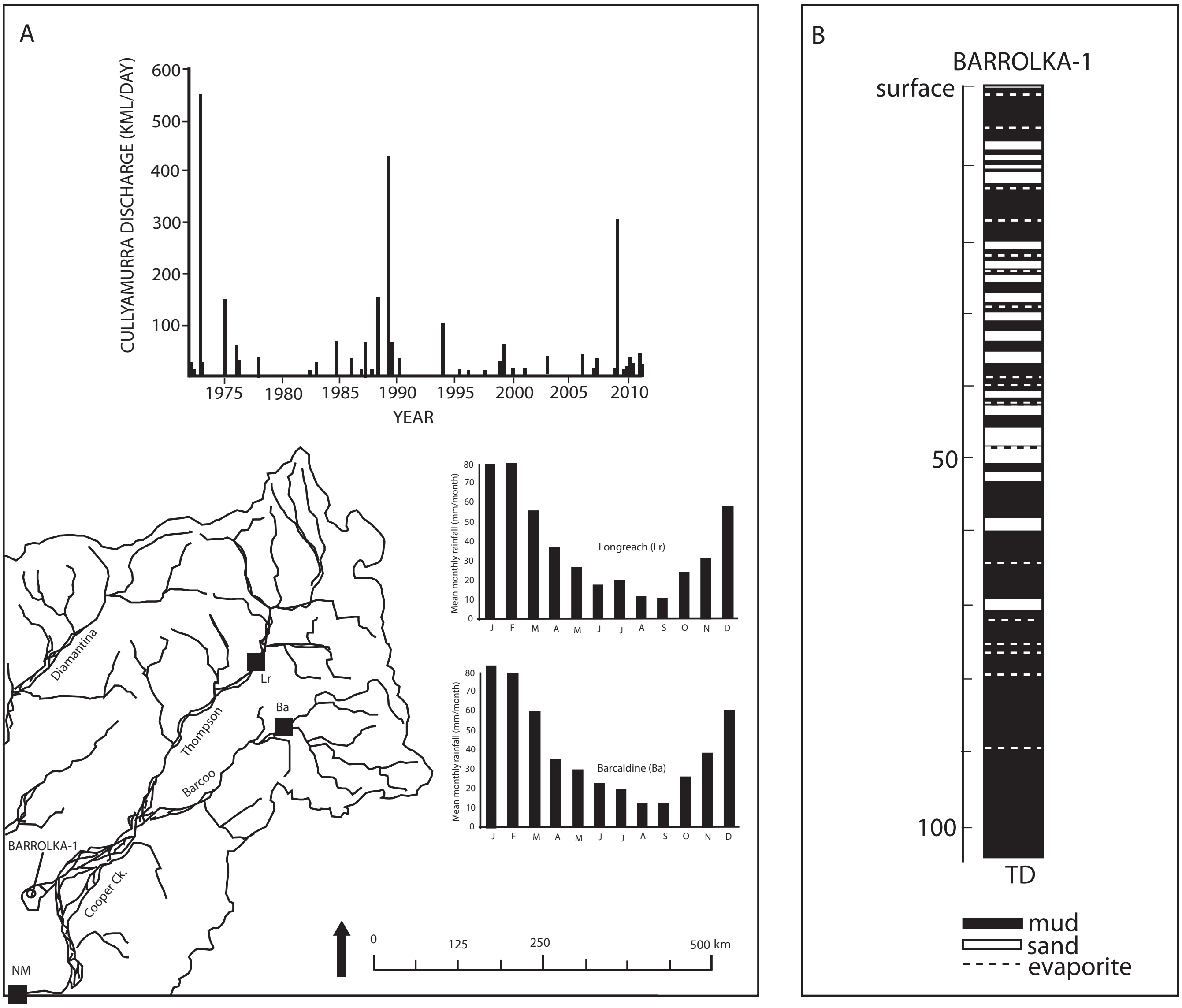


Figure 2: A. Hydrological characteristics of Cooper Creek catchments and drainage systems upstream and downstream of Lake Yamma Yamma. Mean monthly rainfall at Longreach and Barcaldine, on the Thompson and Barcoo Rivers (Bureau of Meteorology, 2016). Discharge records at Cullyamurra waterhole (near the South Australia border) (Bureau of Meteorology, 2016). B. Barrolka shallow exploration borehole lithology. Drilled in 1967 on the lake bed at Lake Yamma Yamma. Sand, mud and evaporate (gypsum) lithologies are preserved. Location is shown in Figure 2A. Adapted from Gregory et al., 1967.

The convergence of two rivers, the Thompson and the Barcoo, form Cooper Creek. Rainfall events in these two rivers catchments results in flow events on Cooper Creek. Rainfall data taken at Longreach and Barcaldine (Figure 2; BOM, 2016), within the Thompson and Barcoo catchments respectively, show a summer-dominant rainfall regime (Figure 2). Rainfall from these catchments can cause slow-moving large flows along Cooper Creek which reach and potentially fill Lake Yamma

Yamma weeks after initial rainfall events. Closer to the lake, the mean monthly maximum rainfall (data range from 1988 to 2015; BOM 2016) at Tanbar station (Map, Figure 2) was 32.5 mm in January and the mean monthly minimum was 8.9 mm in both August and September, with an annual mean of 216.5 mm, a quarter of that at Longreach and Barcaldine. These localised rainfall events cause rapid ephemeral flows, with small rivers flowing for hours to days. Stage height and daily discharge records along Cooper Creek illustrate the variable river hydrology. Data at Cullyamurra (Figure 2) shows multiple flow events, with decade scale larger magnitude flood events. Mean monthly maximum temperatures at Ballera (Map, Figure 2) between 2002 and 2015 were 39.4°C in January and 25.6°C in June. Lake Yamma Yamma has an average annual pan evaporation of 3200 mm and an average annual global solar exposure of 22 MJ/m^2 (BOM, 2016). As a result of these conditions and as the Cooper Creek floodplain widens where Lake Yamma Yamma is located (between Windorah and Cullyamurra) flow transmission losses exceed 75% on average (Knighton and Nanson, 1994).

4.4. Methods

As this represents the first such study of Lake Yamma Yamma, satellite imagery, inundation frequency maps (Geoscience Australia, 2014), geological maps (1:100,000, DMP Queensland 2010), hydrological data (BOM, 2016) and digital elevation models (Geoscience Australia, 2014) were used to undertake a remote sensing study of the region prior to a field campaign. As the surface sedimentology of the area had not been described previously, conducting fundamental descriptive field based work was a priority. Data collection was deliberately designed in order to capture a wide range of depositional settings. Sediment observations and descriptions, three hundred and fifty-two sediment samples, over thirty kilometres of Real Time Kinematic (RTK) Geographic Positioning System (GPS) data and detailed element dimension data were collected at the site (Figure 3).

Field work was conducted with an aim that field observation and quantitative grain size data from trenches, transects and sediment samples could be used to provide the basis for facies classifications Sediment was described visually (lithology, sorting, rounding, presence of aggregates) and grain size estimates were taken qualitatively (range, dominant grain size, multiple populations) both from surface sediments and six shallow (up to 1.8 m) trenches. Sediment samples taken were representative of facies within geomorphic elements (levee, dune, inter-distributary floodplain) (cf. Brierley and Hickin, 1991). Where geomorphic elements exceeded 20 m, samples were taken every 5-10 m in order to capture variability. Minimum sediment sample size was a cube with a 20cm edge, with more sediment collected for larger grain sizes. Surface lag, where present, was sampled separately from the material below.

Real Time Kinematic (RTK) GPS data, accurate to centimetre scale, was collected primarily along transects to capture major topographic changes between the lake and surrounding fluvial and aeolian features. Data was captured at a detailed resolution, with an average of 5 m between data points, which decreased to 0.2 m where large changes were observed over a short distance. Element dimension data was collected using a laser range finder and three dimensional element relationships were observed. Analysis of lithofacies, architectural and geomorphic elements provided the basis for sedimentary process interpretations. All of this work was conducted by the author at the field site in September and October 2014.

Grain size was analysed from field samples in the laboratory using a Beckman Coulter LP13320 Laser Particle Sizer (LPS). In preparation for LPS analysis samples were oven dried at 50°C and sieved through a 2 mm mesh (Gale and Hoare, 1991). Organics were removed from clastic material through chemical digestion using 30% hydrogen peroxide (Lewis, 1984) and the clastic fraction was disaggregated using physical methods and through the addition of a chemical dispersant. The fraction smaller than 2 mm was analysed in the LPS using 2 micron filtered fresh water as a solvent with samples transported at a constant velocity in the aqueous liquid module. The larger fraction was incrementally sieved and weighed. Grain size analyses were repeated with non-disaggregated duplicates of samples that had not undergone the afore-described disaggregation process to assess the potential for sediment transport as aggregates. All other conditions were kept constant. Grain size distributions for all analyses were normalised using the R project for statistical computing (R core Team, 2012) and comprehensive statistics computed. Presented grain size distributions are a weighted average for the entire sample. All of this work was completed for over 350 samples by the author of this thesis. Unprocessed data is available in Chapter 8: Appendices.

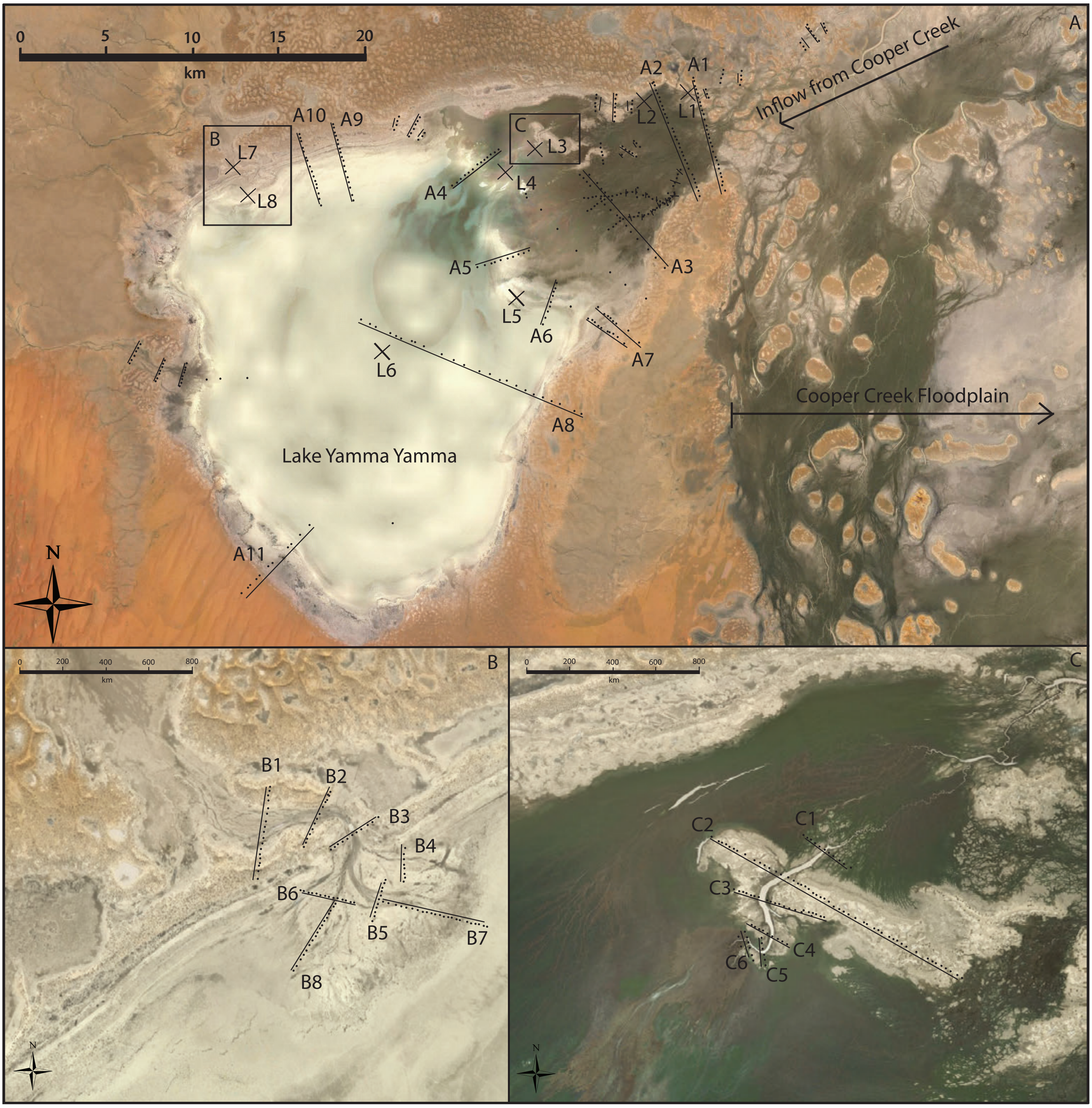
4.5. Results and Interpretation

4.5.1. Geomorphology and Topography

Primary inflow to Lake Yamma Yamma occurs to the north east of the lake (Figure 3A). A combination of DEM and field topographic data show that the maximum change in elevation from the deepest point of the lake to the inflow point to Lake Yamma Yamma in the north-east is 5.2m. The minimum elevation in the study area was 90.2 m, on the lake floor, and the maximum elevation point in the study area was recorded at 124.3 m, to the north of Lake Yamma Yamma at Curralie Dome. Linear parallel features on the northern margin of the lake had an elevation of approximately 100.1 m, making the total elevation from the lake floor to the lake margin 9.9 m.

Aside from the primary input point from Cooper Creek, smaller systems terminating into Lake Yamma Yamma transport material from the Curralie Dome, Mackillop Anticline and Gilpeppe Anticline structural highs to Lake Yamma Yamma (distances of tens of kilometres; Figure 4). These systems experience very rare (approximately once every 10-15 years) ephemeral flows as a result of local rainfall. They are estimated to hold water up to 5% of the time (Figure 5) and are back-filled when the lake holds water sourced from Cooper Creek. These localised systems cut through linear features parallel to the current north-west shoreline of Lake Yamma Yamma, which are self-organised into parallel rows. The shoreline features closest to the lake represent highstand shoreline deposits and the shoreline features further away from the lake are interpreted to be paleoshorelines, based in their morphology and sedimentary characteristics.

Gross depositional environment changes are interpreted based on changes in planform morphology, remote sensing data, vegetation, slope and inundation frequency. When considering the lake in a traditional deltaic framework (i.e. Bhattacharya and Walker, 1992) distinct aeolian, shoreline, upper delta plain, lower delta plain, delta front, prodelta and lacustrine (lake/ playa floor) regions can be identified (Figure 4). This is not to imply that these gross depositional environments are explicitly conformal to the definitions provided for deltas, but given the lack of classification framework and diverse terminology for dryland fluvial termination settings, they provided a useful broad scale first pass method of discriminating between depositional settings in a way that allowed for further detailed description in the field.



× Logged section

\ RTK GPS Transects

• Surface sediment sample

Figure 3: Satellite image with logged section locations (crosses), sample locations (dots), transects (solid lines) and major geomorphic features. Imagery captured 18/10/2012. A. shows main delta and lake. B. shows enlarged localised terminal fluvial system. C. shows enlarged waterhole and dune on lower delta plain.

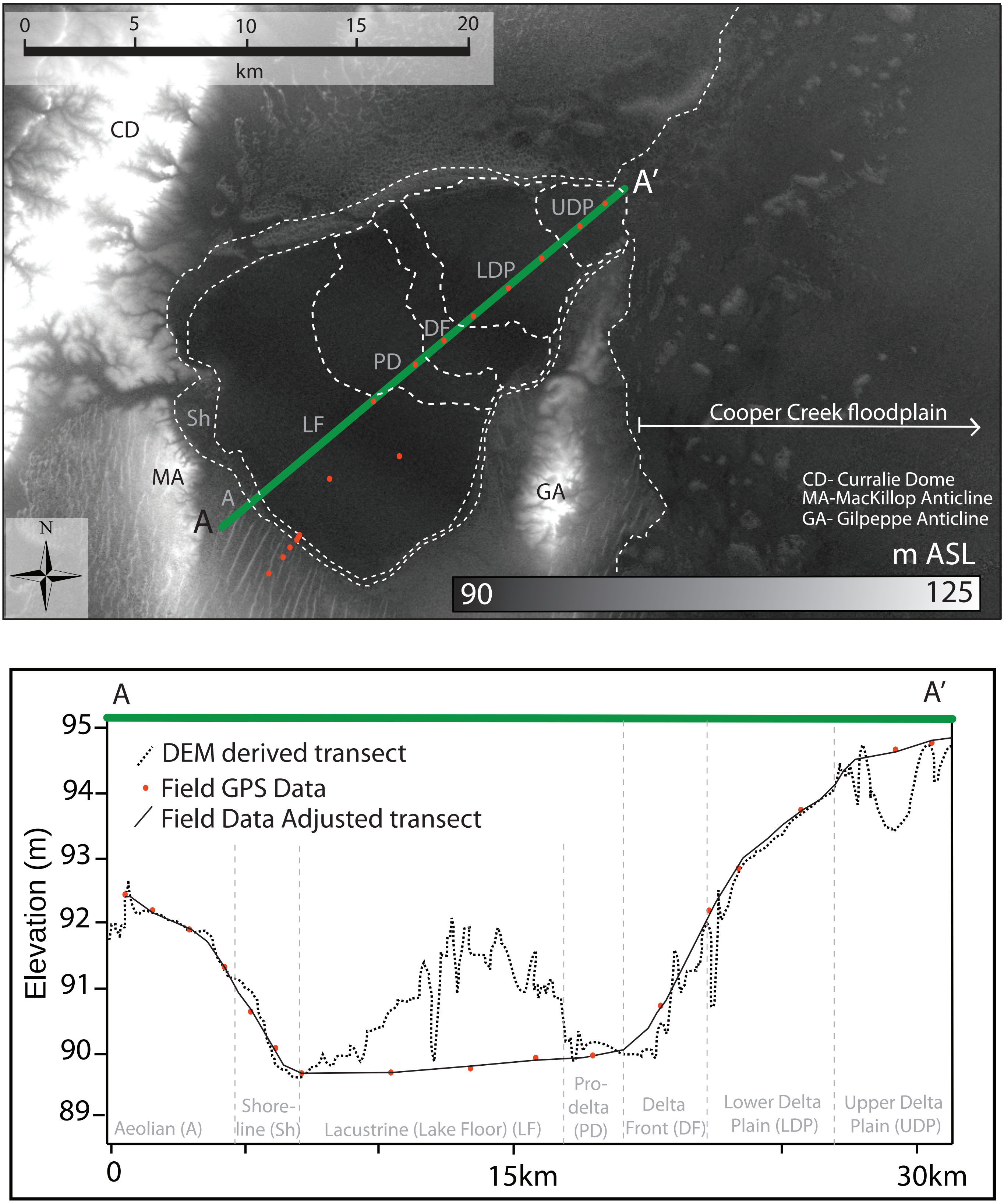


Figure 4: Digital Elevation Model from SRTM data (Geoscience Australia, 2015). Interpreted gross depositional elements shown in white. Structural highs from geological map. Transect constructed from DEM data and adjusted field data.

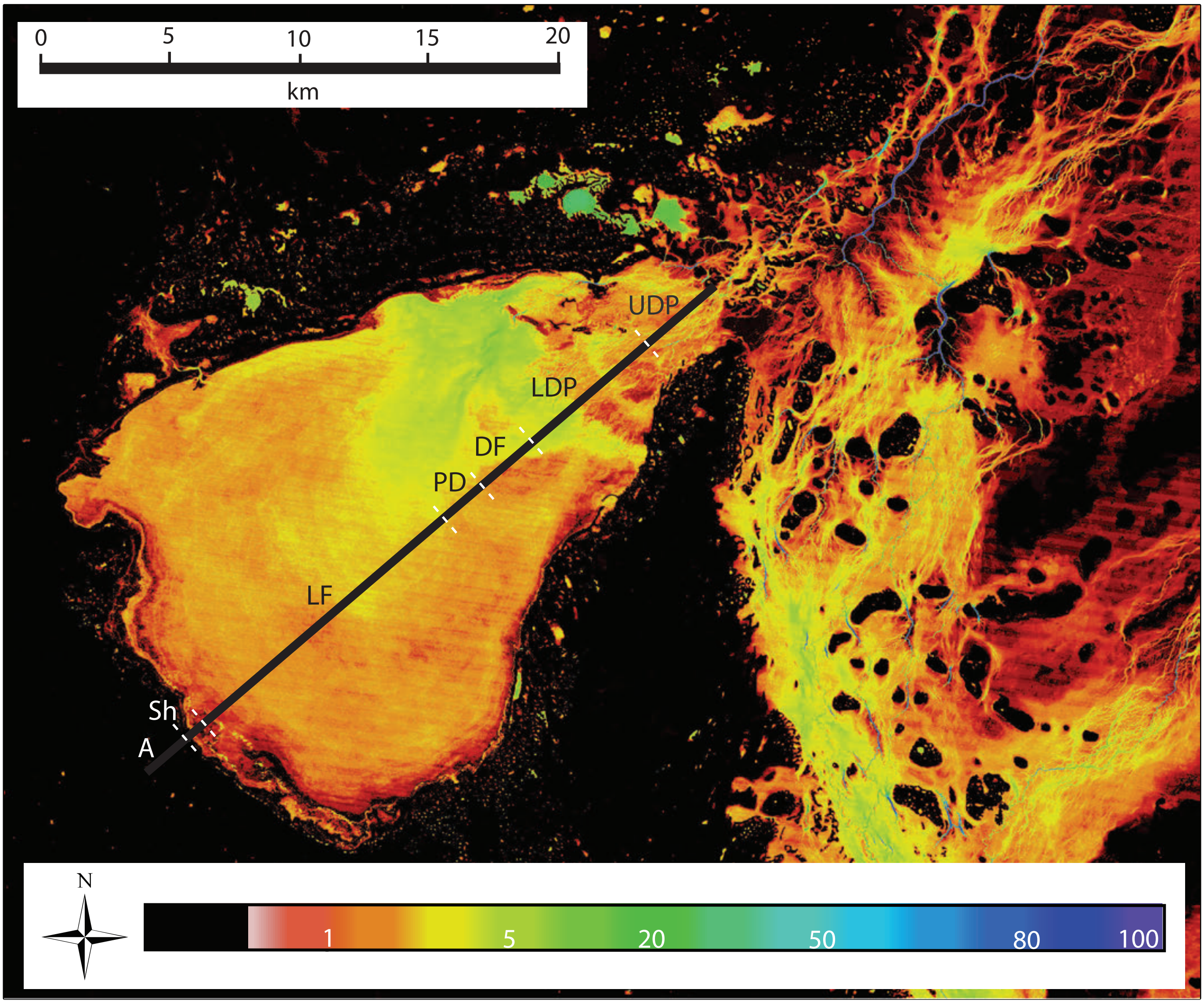


Figure 5: Inundation Frequency Map, showing the percent of time that water is present in different areas (Geoscience Australia, 2015). Interpreted gross depositional elements divisions and transect line from Figure 4 shown.

Frequency inundation data shows that the currently active locus of deposition of the inlet from Cooper Creek to Lake Yamma Yamma is to the north-west, with a central transition zone and a mostly inactive lobe to the south-east. Major large waterholes in north-west of the upper and lower delta plain hold water 80-100% of the time, compared with channels in the south-west of the upper and lower delta plain that hold water 1-5% of the time (Figure 5). The lake bed nearest to the prodelta in the north-west holds water 5-20% of the time, compared to 1-5% of the time in the south-west. The middle of the delta features elements of both the north-west and the south-west, but channels are shallower and more sinuous and the region is more vegetated.

Near the location of inlet channel terminations the planform of the inlet from Cooper Creek to Lake Yamma Yamma exhibits different morphologies in the north-west and south-east lobes. The active lobe in the north-west has a traditional birdfoot planform shape, as would be expected in a fluvial-dominated system (Ainsworth et al., 2011, e.g. Mississippi Delta). In the south-western lobe, the termination morphology is comparatively linear, similar to that expected from a wave-dominated shoreline (Ainsworth et al., 2011, e.g. Rhone Delta). This substantiates an interpretation that this south-eastern lobe is not the dominantly active lobe at present, and indicates that wave reworking during lake inundation phases is significant; as is also indicated by shorelines/beach ridges in other parts of the lake.

4.5.2. Lithofacies

Observed lithofacies are described below and briefly summarised in Figure 6. These were grouped to form facies associations (Figure 10), which formed the basis for depositional element classification (Figure 11).

Evaporite

A halite and/or gypsum crust and discrete salt layers were observed on the lake bed and in the lake vertical sections. These lithofacies are likely to have been deposited out of suspension as evaporation occurs.

Carbonaceous Mud (F_c)

This facies consists of very thinly bedded horizons of carbonaceous mud. Calcium carbonate horizons are interpreted to have formed in-situ after deposition.

Evaporation and low rainfall likely plays a part in the precipitation of these.

Clay (organic rich) (C_l, Cl_b)

This facies consists of the finest lithofacies; generally a polymodal, poorly sorted mud with over fifty percent clay content. Medium grey in colour, with high organic content this facies generally features millimetre scale laminations and mudcracks which may be locally disrupted due to bioturbation.

This facies is interpreted to have been deposited from suspension in standing pools of water during no-flow or waning flow periods. Sediments of this facies have the potential to be transported as aggregates, however finely laminated structures suggest suspension fallout as a depositional mechanism in this case.

Silt (F_m, F_b)

This facies contained primarily fine silt. Medium grey in colour, this facies is deposited from very low velocity flow or as a result of wind action.

Very fine sand sized aggregates (F_m, F_b, F_a, S_m)

This facies consists of fine silt with minor clay, coarse silt and very fine sand particles. Light grey in colour, with moderate organic content, this facies is generally massive, with localised mud cracks. This facies is interpreted to have been transported and deposited as very fine sand sized aggregates. Particle size analyses repeated with non-disaggregated samples are stable at a coarser grain size. Aggregation can be observed in the field. Thin mud aggregate beds interbedded with fine sand facies are common.

Very fine silt to fine sand (F_m, F_b, S_m)

This facies consists of very poorly sorted polymodal very fine silt to fine sand. Clay content is minimal. Grey light brown, with low organic content, this facies is generally massive, with no visible sedimentary structures. This facies is interpreted to have been transported and deposited as a mixture of poorly sorted fine sand sized aggregates, due to repeated with non-disaggregated samples being consistently coarser. This facies is interpreted to have been deposited out of suspension from low velocity flow. Aggregates in are likely to be less stable, and more likely to be broken up than those in Facies B, due to lower clay content.

Poorly sorted medium silty fine sand (S_m, S_t, S_p, S_r, S_d)

This facies consists of poorly sorted medium silty fine sand, mode 245.45µm. Mud content varies from 20% to 8%. This facies contains trough cross bedding, ripple cross bedding and planar cross bedding. This facies is interpreted to be material sourced locally from dunes. Facies D is interpreted to be fluvially reworked material. Facies D2 and D3 (the ones containing the mud spike) are generally associated with less reworked dune material. The similarity of these facies is interpreted to represent the dynamic nature of the dune area and the erosion of the dunes by fluvial energy.

Coarse Sand (S_r, S_p, S_t)

This facies consists of well sorted, unimodal, coarse sand. Light straw brown, this facies contains ripple structures, planar cross bedding, and trough cross bedding. Grains are generally well to moderately well rounded. Lithofacies can also be interpreted to have been transported through fluvial energy as bedload during flooding events.

Cobbles

Coarse clasts of 5cm-20cm width were observed in and around inter-delta dunes, but are considered to have been transported to the site and manipulated by indigenous Australians and are therefore excluded from this sedimentology study. This interpretation is favoured as these clasts showed evidence of being sharpened, ground and shaped into tool-like objects and anthropogenically arranged. Where observed these coarse clasts were not disturbed. Further study could reveal the anthropological significance of these features.

4.5.3. Grain Size Observations and Statistics

Field observations showed that within the field area two main types of sand were present; a well-rounded poorly sorted medium to coarse quartz sand and a very fine to medium moderately rounded moderately well sorted feldspathic sand. The quartz sand shared many characteristics with the lake-bordering aeolian dunes and often appeared to have frosted edges, indicating that it is most likely sourced from aeolian dunes surrounding the lake. Major catchments of the Cooper Creek contain felspathic granites, particularly surrounding the Great Diving Range and hence the felspathic sand is interpreted to be fluvial sand transported to Lake Yamma Yamma from Cooper Creek. Although clastic silts were observed, most silt was observed to be organic in nature. Mud was observed primarily as aggregates, but also as a product of suspension fallout. Poorly sorted sands were observed to be a mixture of sand and fine-sand sized mud aggregates, which slaked to very fine sand sized mud aggregate particles when wet. Laminated silt and clay deposits as a product of suspension fallout were common in waterhole on the upper and lower delta plains and on the lake bed.

The range of the mean of the absolute disaggregated grain sizes for all samples decreased from proximal to distal gross depositional environments (Figure 9A). The largest change in mean range was from delta plain to delta front. The large

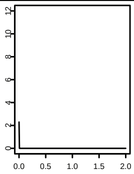
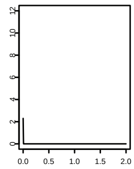
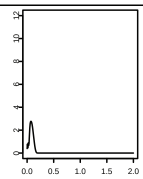
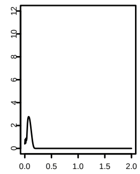
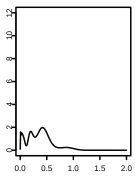
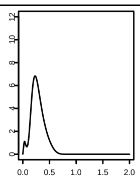
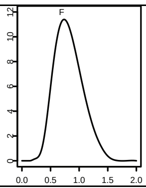
Lithofacies Group	Lithofacies	Sedimentary structures if present	Grain Size graph (absolute)	Interpretation
Evaporite/ Chemical	n/a Salt crust	Planar lamina	n/a	Deposition out of suspension as evaporation occurs
Carbonaceous Mud	F_c	Planar lamina, massive		Deposition of organic material and silt from low velocity flow
Clay	C_l, Cl_b	Planar lamina		Deposition out of suspension from standing water
Silt	F_m, F_b, F_r	Planar lamina, ripples		Very low velocity flow, some aeolian deposition
Very fine sand sized aggregates	F_m, F_b, F_a, S_m	Ripples, planar cross bedding		Bedload transport as aggregates
Very fine silt to fine sand	F_m, F_b, S_m	Soft sediment deformation, planar and trough cross bedding		Bedload transport primarily as aggregates, secondarily in suspension
Poorly sorted medium silty fine sand	S_m, S_t, S_p, S_r, S_d	Planar and trough cross bedding, Planar lamina		Bedload transport
Well Sorted Medium Sand	S_r, S_p, S_t	Planar and trough cross bedding		Bedload transport
Coarse Sand	S_r, S_p, S_t	Soft sediment deformation, trough cross bedding, planar cross bedding, massive	n/a need to include >2mm fraction	Bedload transport during high flow events

Figure 6: Lithofacies grouped primarily by grain size, with a description of characteristics such as sedimentary structures and grain size distribution.For a more detailed description, see 4.5.2. Lithofacies.

range in means is attributed to the sampling of multiple depositional elements in the different gross depositional environments. For example, the upper delta plain had remnant dunes, which were composed of medium to coarse sand, as well as mud-filled waterholes, where clay had settled out of suspension. In comparison, the prodelta region was predominantly muddy with some poorly sorted silt and fine sand

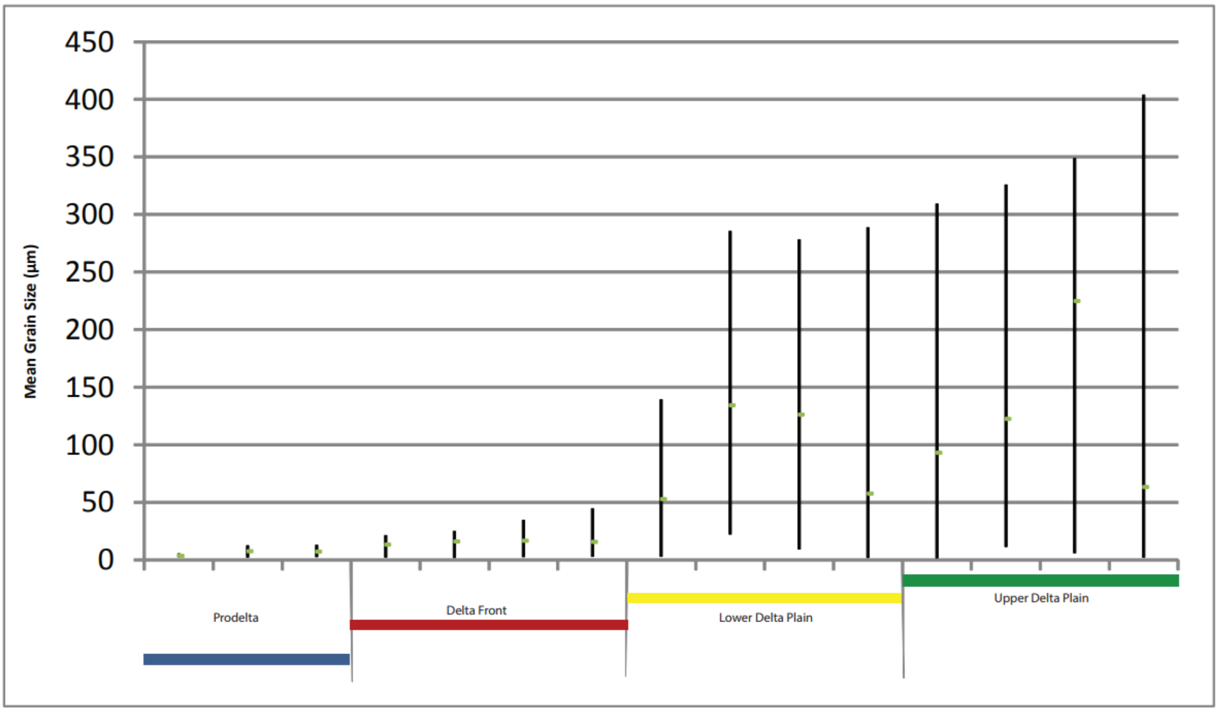


Figure 7: A. Disaggregated mean grain size arranged from distal to proximal gross depositional environment. Vertical lines represent the P90-P10 range. Horizontal green ticks show the mean.

at higher elevations. Therefore the average of the means is biased toward the most common depositional element's grain size within a specific gross depositional environment. The decreasing proximal to distal grain size is attributed to the decrease in depositional energy away from the main fluvial source, Cooper Creek. The grain size of mud aggregate particles classifies as silty sand sized, and when disaggregated these fall within the clay and silt size range (Figure 9B). The small change in grain size in aggregate samples suggests that aggregates in

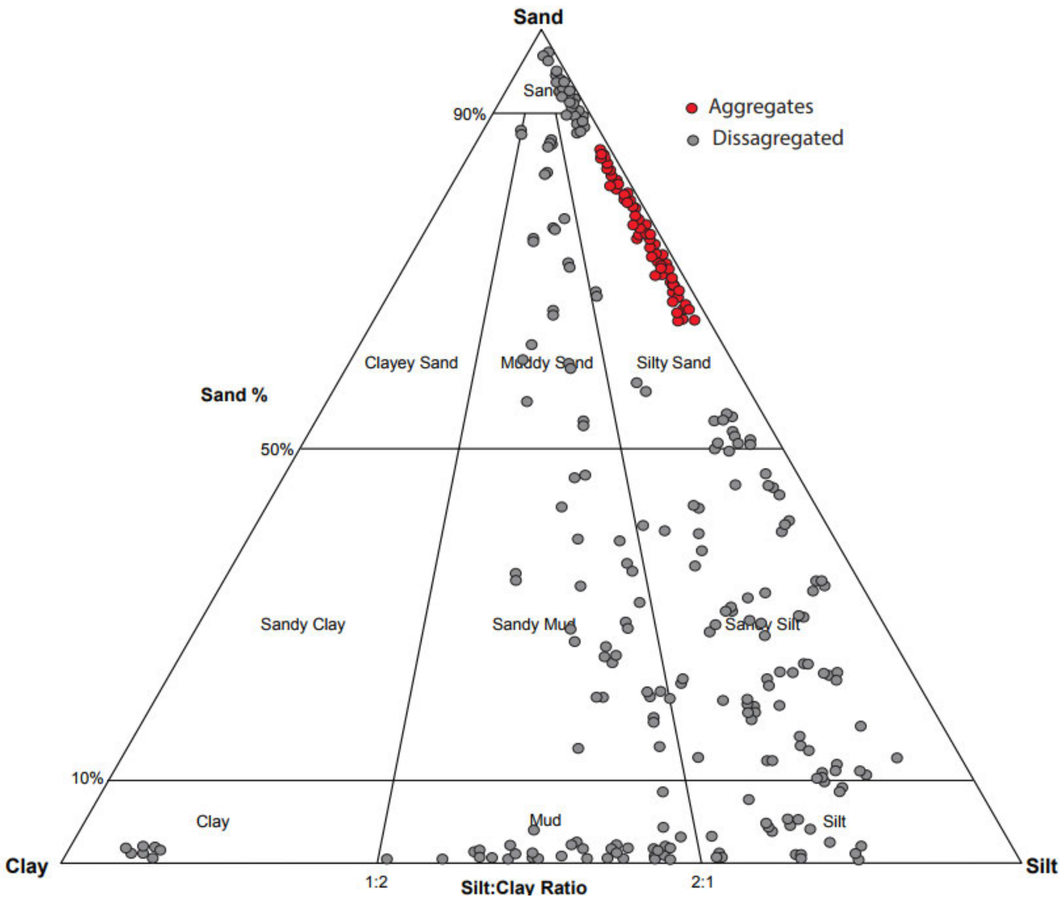


Figure 7: B. Aggregates and disaggregated samples shown by sand, silt and clay proportions. See Figure 3 for all sample locations.

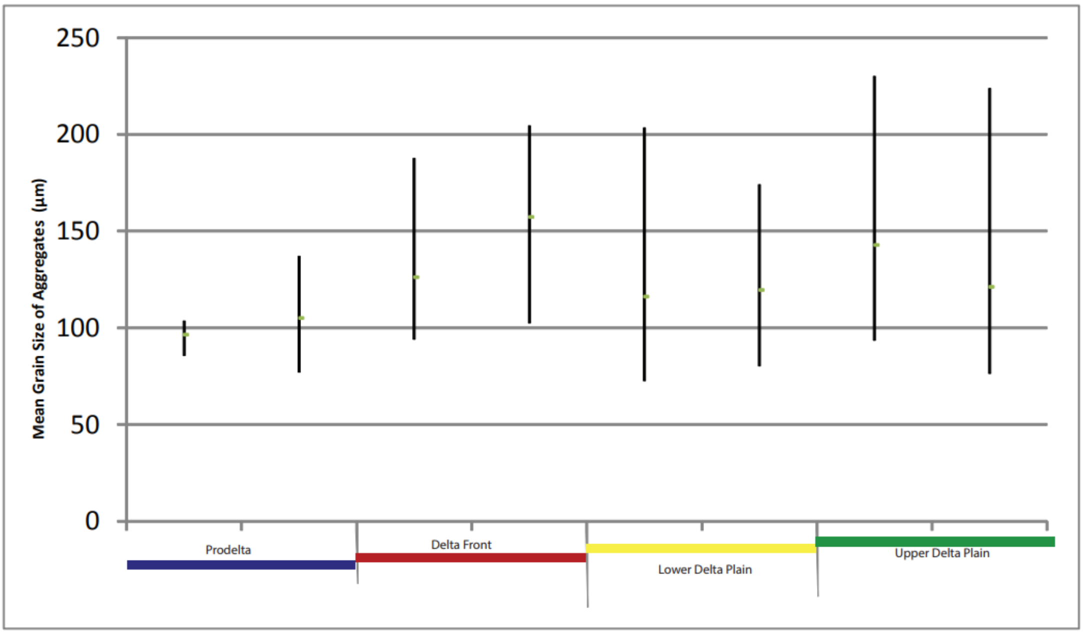


Figure 7: C. Aggregates mean grain size arranged from distal to proximal gross depositional environment. Vertical lines represent the P90-P10 range. Horizontal green ticks show the mean.

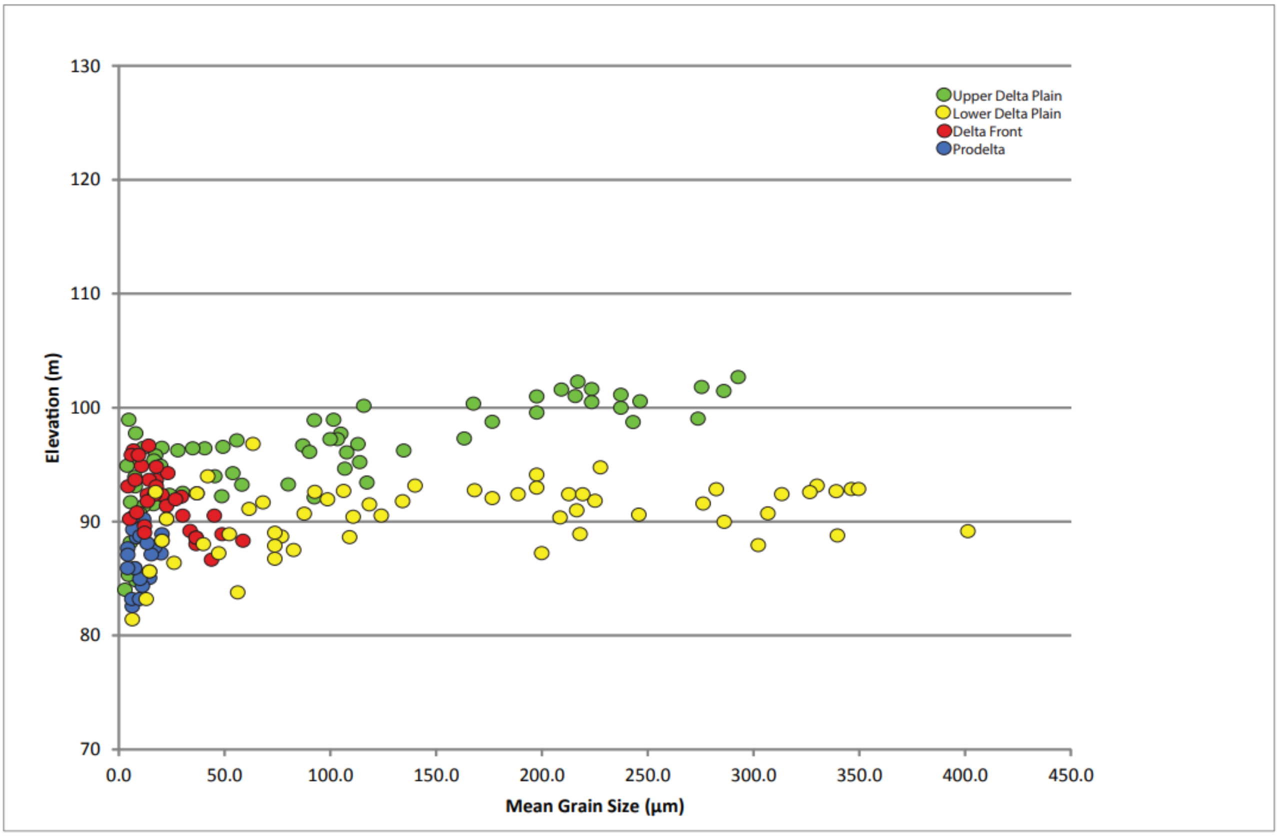


Figure 7: D. Change in disaggregated mean grain size with elevation arranged into gross depositional environment. See Figure 3 for all sample locations.

the Lake Yamma Yamma region tend to converge to a single mean grain size. The range of mean aggregate grain size is larger on the upper delta plain and lower delta plain regions and smaller on the delta front and prodelta (Figure 9C). This trend could be the result of reduced transport energy distal to the source or physical abrasion of aggregates during transport.

Distinctive trends were observed when absolute disaggregated grain size was considered against elevation (Figure 9D). Samples from the upper delta plain and lower delta plain showed weak positive increasing trends, whereas prodelta and delta front samples did not show distinct trends but tended to cluster around the lower grain size region. This dataset was limited to unimodal samples. Means from unimodal samples were considered to be not comparable those of bi- and tri-modal samples. Many samples exhibited grain size distributions with multiple modes, indicating that multiple sediment size populations exist within the sample.

4.5.4. Depositional Elements

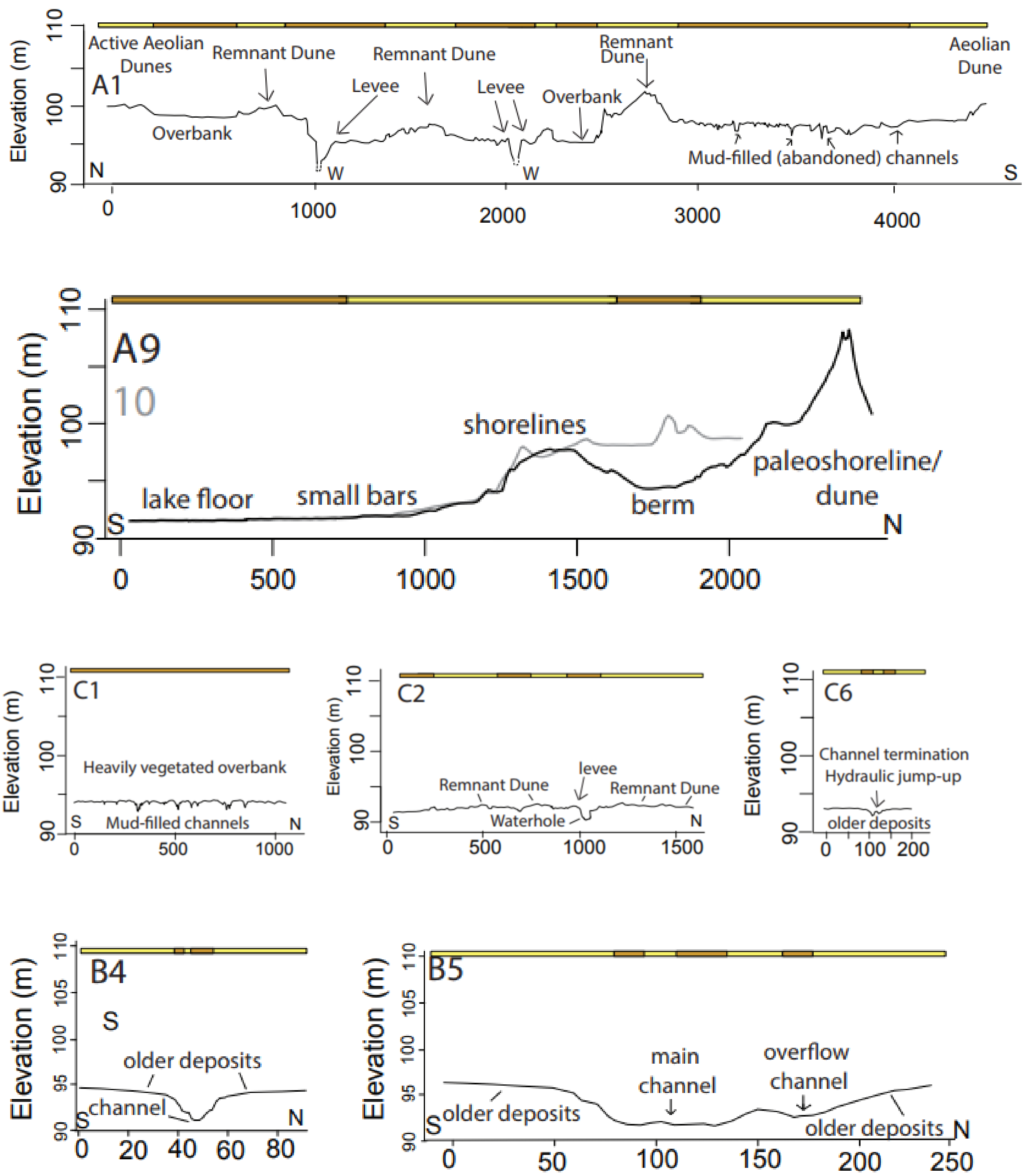
Proximal Fluvial-Dominated Elements

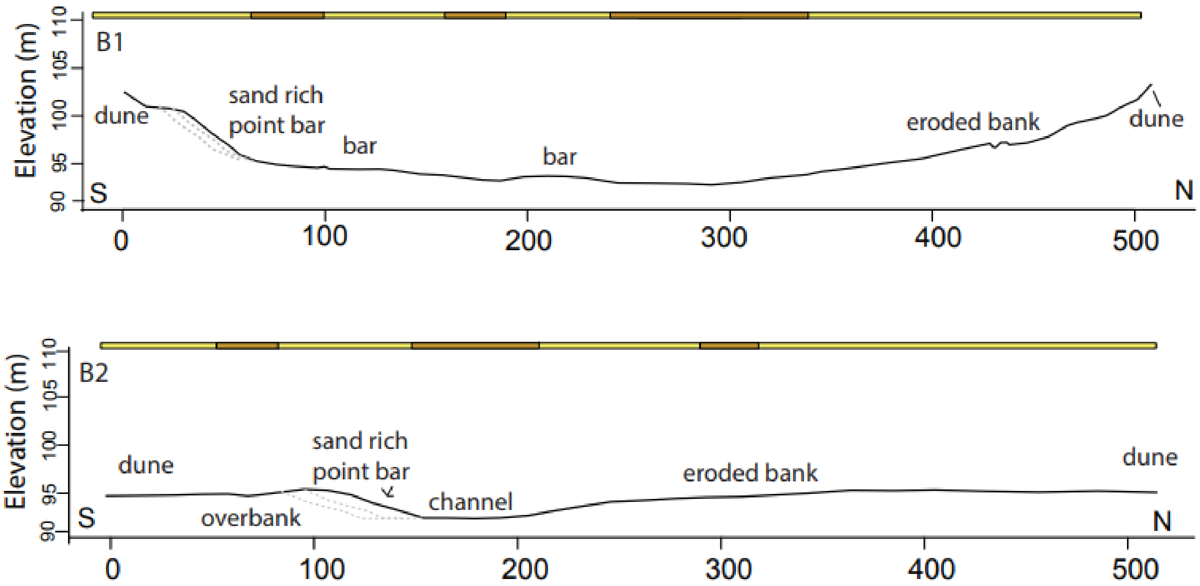
Upper Delta Plain

Fluvial-dominated deposits in the upper delta plain region (Figure 12, deltaic features, upper delta plain) contained metre scale cross-bedded and ripple laminated fluvial fining up sequences interbedded with thick planar laminated mud packages (Figure 8). Grain size changes and boundaries between beds were sharp. Poorly sorted beds with erosional bases containing rip-up mud clasts and trough cross beds with interbedded sand and mud aggregates (e.g. Figure 9) characterised the base of such packages.

Across the upper delta plain a change in elevation of 3-5 m was present between the lower northern lobe which is active during high and low flow events, and the higher the southern lobe which is active only during high magnitude flow events (Fig. 6, A1). Waterholes to the south-west of the lake delta consist of the lowest bankful depth (up to 0.8 m deep and up to 150 m wide) mud filled channels. In the north-western region of the delta plain, channels are narrower and deeper (up to 43 m wide and over 8.4 m deep).

Figure 8: Topographic cross sections. Elevation in m ASL. Colour bars above transects represent dominant field grain size observations. Yellow is sand and brown represents mud. Horizontal axis is distance in metres. Locations are shown in Figure 3A.Continues on the next page.





Waterholes

One of the most distinctive features of the upper delta plain is the waterholes, segments of large channels of enlarged width and depth which exhibit very similar 'chain of ponds' morphology, character and processes as those at Cooper Creek (e.g. Knighton and Nanson, 2000). These waterholes occur between non-active dune systems on the north-western side of the delta. Formation is interpreted to be primarily through dune constriction process, but the waterholes to the far northern side also exhibit some characteristics of valley side flanked waterholes. The termination of a waterhole is generally marked with a hydraulic jump-up on a metre scale, bifurcation and an increase in sinuosity. Smaller connecting channels tend to occur orthogonal to delta waterholes.

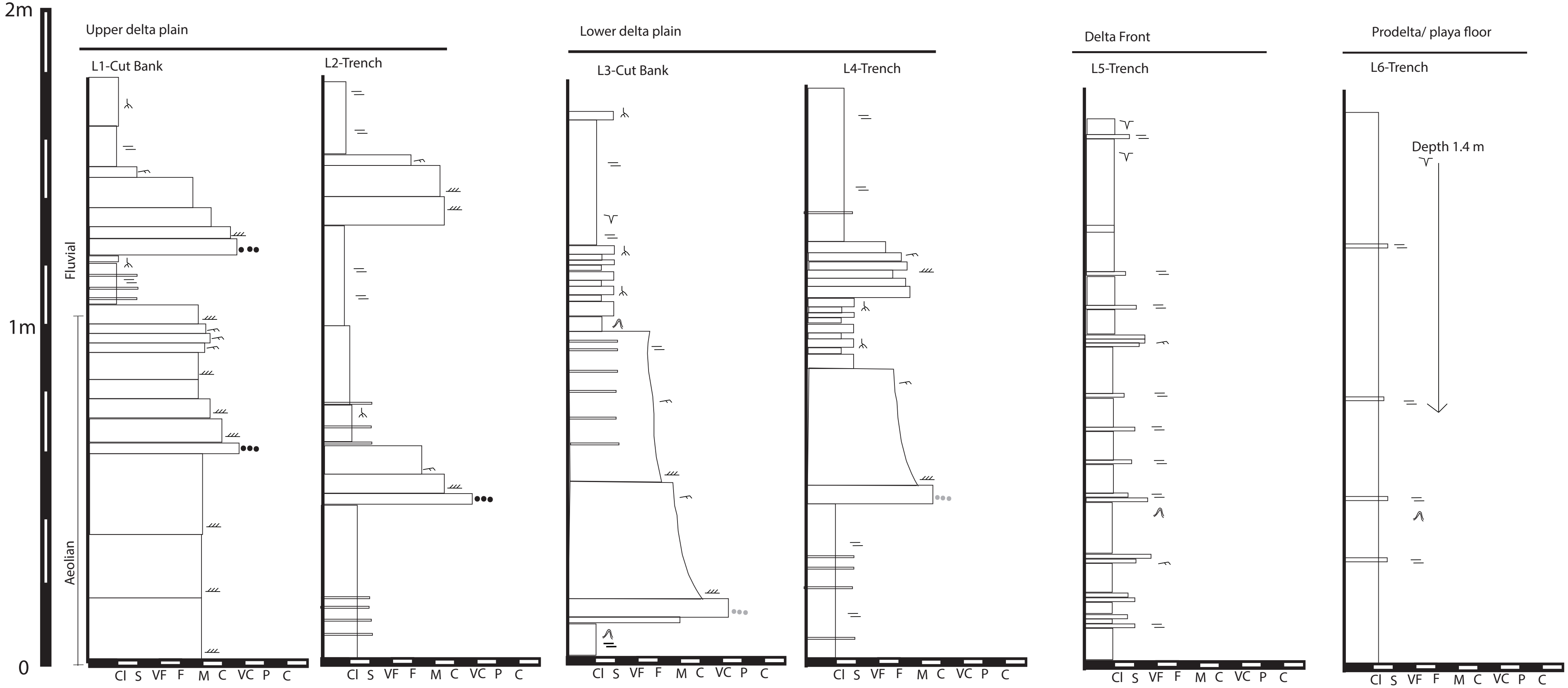
Waterholes contain two elements, trunk channels and distributary channels. Channel fill is generally fine grained clays and silts (C_{lm}, C_l, C_{lb}, F_m, F_b, and F_a). Subtle and strong planar laminations are present, although some beds appear massive. Localised bioturbation exists, with tracks, simple and complex burrows and roots present in sediment. Suspension fallout is interpreted as the primary depositional mechanism for channel fill. Waterholes often had associated levees and overbank deposits.

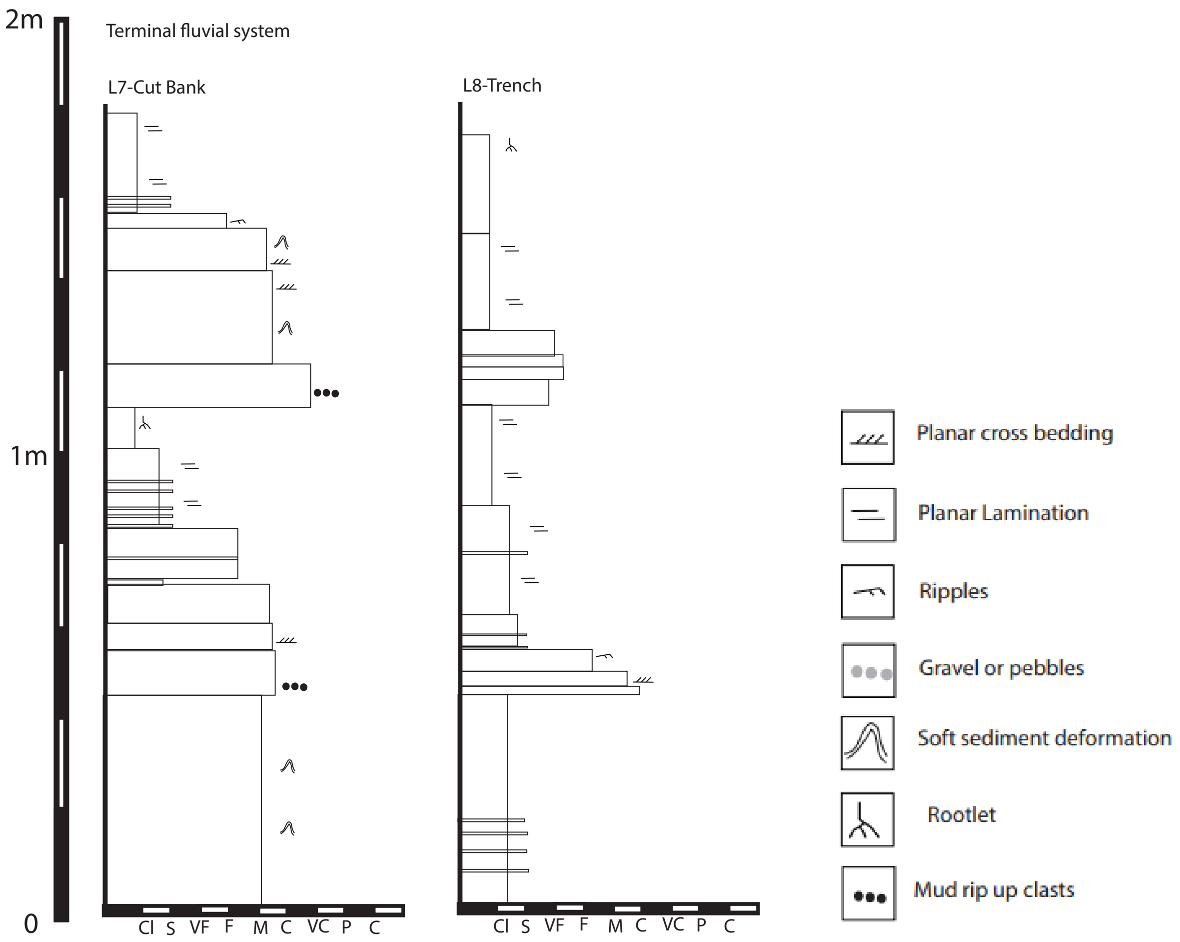
These waterholes trap and hold water at relatively high local elevations (up to Up to 4 m above the base level of Lake Yamma Yamma). Developed levees of up to 0.87 m, over bank deposits and erosional scour on remnant dunes suggest that when flow occurs it is not constrained to waterholes.

Waterhole Dune Complex

Topographic transects C1 to C6 (Figure 6) provide precise topographical information for a waterhole-dune complex on the lower delta plain. Transect C2 (Figure 6) taken where the waterhole is the widest and deepest (23.2 m wide, 3.1 m depth) shows a semi-rectangular waterhole cross section with a silt-rich levee flaked by the remnants of dunes which have been destroyed by incision. This waterhole is roughly half the width and depth of those measured on the upper delta plain. Transect C1, upstream from C2 recorded shallow (less than 1.8 m deep) and narrow (maximum 15 m wide) mud and vegetation filled channels. Small levees flank the main channel, suggesting that flow is not confined to within the channels during flow events. Transect C6, downstream of C1 and C2 captures the hydraulic jump-up at the termination of the waterhole. The hydraulic jump-ups bench caused the waterhole channel to bifurcate and eventually terminate.

Figure 9: Next two pages.Sedimentary logs capture grain size and sedimentary structures in cut banks and trenches in different depositional environments at Lake Yamma Yamma. Locations correspond to crosses shown in Figure 3.


2m
1m
0
Upper delta plain
Lower delta plain
Delta Front
Prodelta/ playa floor
L1-Cut Bank
L2-Trench
L3-Cut Bank
L4-Trench
L5-Trench
L6-Trench
Fluvial
Aeolian
Depth 1.4 m
Cl S VF F M C VC P C
Cl S VF F M C VC P C
Cl S VF F M C VC P C
Cl S VF F M C VC P C
Cl S VF F M C VC P C
Cl S VF F M C VC P C



Terminal Splay Sheets

The termination of the waterholes after hydraulic jump up and bifurcation, particularly in the lower delta plain, is expressed as a splay sheet (cf. Fisher et al., 2008). Generally these can be split into two categories: sand-rich structured sheets and poorly sorted massive deposits. These are difficult to distinguish from remote sensing data only. The sand rich structured sheets tend to occur more at channel terminations toward the North West. The sand-rich structured sheets and poorly sorted massive deposits are not mutually exclusive and may occur

Figure 10: Next page. Photographs of common deposits. Top row: Basal fluvial package. Mud aggregate lens, cross beds, mud aggregates accumulated on the face and toe of foresets. Soft sediment deformation in lower delta plain deposits BASE L-R: Soft sediment deformation was abundant throughout the study area. Mudcracks on the lake floor commonly exceeded depths of 1 m, due to ongoing desiccation. Mud aggregates accumulate on the face and toe of foresets in cross stratification.


0 5 10 15 20 cm
0 5 10 15 20 cm
0 10 20 30 40 cm
0 10 20 30 40 cm

together as stacked deposits. The sand rich structured sheets display similar characteristics to fluvio-deltaic deposits, and are similar to the proximal splay element from the Douglas creek terminal splay (Fisher et al., 2008). Soft sediment deformation structures are common.

Deltaic-altered Transitional Features

Waterholes are flanked by sand rich high relief erosional dune structures. When high flow events occur, waterholes become the primary flow conduits and these primarily erosional dune structures become depositional features, as overbank sediments are deposited. Waterholes are scoured and post terminus lobes become part of the lower delta plain. The regular terminal splay character of these features is altered by high-energy flow and the features become part of the larger delta system.

Medial Lacustrine-influenced Depositional Elements

Lower Delta Plain and Delta Front Channels

Terminal fluvial deposits in the lower delta plain region showed overall fining up sequences interbedded with planar laminated silt and clay beds. The base of the fining up sequences was characterised by poorly sorted thin beds containing mud aggregates, silt, sand and mud rip-up clasts topped by cross beds with mud aggregates on the face of predominantly sandy foresets (e.g. Figure 7 A, B). Current ripples (e.g. Figure 7) and soft sediment deformation verging on ball and pillow structures (e.g. Figure 7) were common.

Floodplain channels in the southern lower delta plain display reticulate channel morphology (e.g. Fagan and Nanson, 2004) particularly near channel terminations. These channels exhibit a maximum 1 m bankful depth and form a dense network of channels with simple form which experience very little change along the length of the channel. These channels are filled with poorly sorted clays and silts (Cl_m, Cl_l, Cl_b, F_m, F_b, F_a) and organic material. Material deposited outside of the channels is nearly identical to that deposited outside of the channels (Cl_m, Cl_l, Cl_b, F_m, F_b, F_a). Occasional discontinuous sand layers (S_l) occur on a millimetre scale within and outside of the channels. Gilgai is well developed and interpreted to play a role in the formation of the reticulate pattern.

Floodplain channels is the central lower delta plain contain very similar sedimentary features to those in the southern lower delta plain, with a slightly higher sand content. These channels exhibit characteristics reticulate floodplain flow styles in Cooper Creek (Fagan and Nanson, 2004) and appear to be a transition zone between the south and north. The increasing sand content in the northern region appears to inhibit widespread gilgai development, which results in a transitional pattern between braided and reticulate channels.

Terminal fluvial deposits in the delta front region were composed of interbedded muds, fine sands and silts, with some rare fining and coarsening up sequences. Mud was observed to have been deposited as silt sized aggregates, but some millimetre scale planar lamination was also present.

Distal Elements

Playa Lake and Prodelta

The prodelta and playa lake bed is composed of fine clastic and chemical sediment (Cl_m, Cl_l, Cl_b, F_m, F_b, F_a). During flood events, the lake bed is inundated with water and sediment, and sediment is deposited out of suspension. During this time the lakebed experiences bioturbation and an influx of organic matter. Evaporation causes shallowing, exposing laminated sediment and organic matter. Desiccation cracks, up to 1 m deep, soft sediment deformation structures, finely laminated silts and muds were observed. Desiccation crack are sometimes filled with silts, muds and sands, observed to be deposited through aeolian processes.

A diverse range of sedimentary structures were observed in the prodelta and playa lake floor deposits. Soft sediment deformation including sediment escape, slumping, flame structures, ball and pillow structures (Figure 7) as well as large (0.5-1.5 m wide and 0.5-1.2 m) and polygonal desiccation cracks of many scales (Figure 7) were observed. A sedimentary log from a trench in the playa lake floor (Figure 8) recorded predominantly clay with interbedded silt layers.

Marginal Lacustrine Depositional Elements

Shorelines

Linear features parallel to the north-western side of the lake margin are composed of sand rich lithofacies (S_r, S_p, S_t). Wave ripples, planar lamination, low angle cross planar stratificant, lenticular, wavy and flaser bedding were observed in these settings. Away from the centre of the lake, the lake bed elevates slightly (1-2°). The margin is characterised by an initial sharp elevation of 5-6 m and a subtle elevation of 1-2 m, then modern active dune fields dominate the landscape. The initial elevation changes are interpreted to represent shoreline deposits during lake highstands. Shoreline deposits are thinly bedded, less than 20-30cm and are altered by deflation and bioturbation.

Transects A8, A9, A10 and A11 (Figure 6) capture the transition from lacustrine to shoreline to aeolian depositional environments. For transects A9 and A10 (Figure 6) a maximum elevation change of 16.45 m over a distance of 2 km was recorded. Sand bars (up to 0.3 m) accompany aggregated shoreline (up to 3.6 m) and berm deposits. The second ridge (up to 11.4 m) was composed of interbedded paleoshoreline and dune deposits. These shorelines were likely deposited during lake highstands.

Shoreline deposits on the north-west margin of the lake record the former extent of highstand and falling stage lacustrine conditions. These are similar, but narrower and thinner to those described around Kati Thanda- Lake Eyre (Magee et al., 1995), Lake Ngami (Shaw et al., 2003; Burrough et al., 2007) and Etosha Pan (Brook et al., 2007). As in the afore mentioned cases, they are interpreted to be a product of wave reworking at a time of greater water supply (highstands) and/or reduced evaporation rates.

Barrier islands and estuary

When Lake Yamma Yamma fills, remnant dunes around the south eastern edge of the lake appear to form barrier islands. Laminated sands and small ripples preserved in the reworked sediment deposited on the remnant dunes suggest minor wave action onlapping onto the remnant dune. A break in the dune forms a relatively narrow inlet which allows the interdune area to flood, forming a protected backwater lagoon isolated from the floodwaters of the lake. Sediment deposition in the backwater consists of laminated silts and organic rich muds (F_m, F_b, C_l, C_{lb}).

Aeolian Dunes

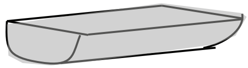
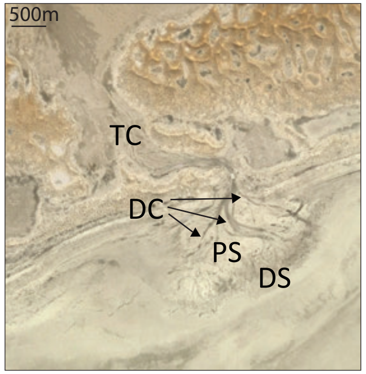
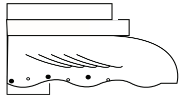
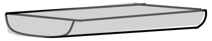
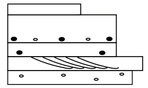
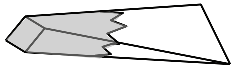
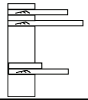
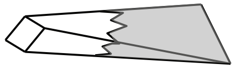
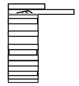
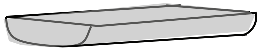
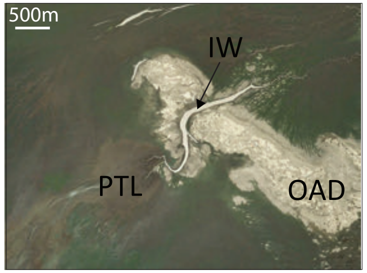
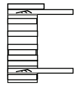
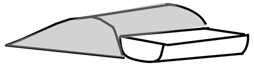
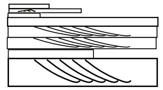
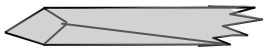
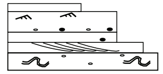
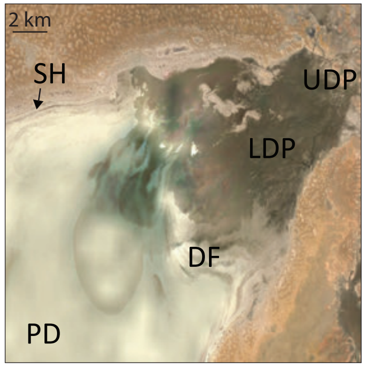
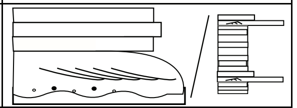
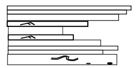
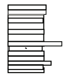
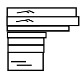
Modern transverse and longitudinal dunes dominate the landscape around Lake Yamma Yamma and influence the development of fluvial channels in the region. Dunes are similar to those described around the Kati Thanda- Lake Eyre Basin (Fitzsimmons et al., 2009). As the focus of this study is fluvio-lacustrine sediments, dunes were not studied in detail; however they are important in the overall morphology of Lake Yamma Yamma.

Smaller Scale Localised Fluvial Terminations on Lake Margins

Small localised distributary channels distribute sediments from local highs to the lake floor. Localised distributary channels vary in morphology and sedimentology from those in the main channel. Localised channels can be divided into three main elements: distributary channel, proximal splay and distal splay.

Sedimentary logs in the major trunk channel and a smaller distributary channel of a localised terminal fluvial system showed vastly different characteristics. The major trunk channel log showed thicker beds with pervasive soft sediment deformation, current ripples and planar cross bedding where bedding was preserved. These were interbedded with mud and silt intervals with planar lamination. The distributary channel log showed thinner beds with more pervasive planar lamination, minor planar cross bedding and ripples.

Figure 12: Next page. Deposition element summary, with elements grouped by complex. Schematic, typical field log, location, length and width are included.

Depositional Complex	Element	Schematic	Field Location	Length	Width	Field Log Example (Cl S VF F M C VC P)
Terminal Splay	Trunk Channel		TC 	1-2 km	300 m	
	Distributary Channel		DC	<1 km	150 m	
	Proximal Splay		PS	0.8 -1.2 km	200 -500 m	
	Distal Splay		DS	1-2 km	1-4 km	
Transitional	Incised Waterhole		IW 	2km	<200 m	
	Overbank Altered Dune		OAD	1-3 km	100-500 m	
	Post Terminus Lobe		PTL	200 -500 m	100 -500 m	
Deltaic	Upper Delta Plain		UDP 	1-5 km	0.5-2 km	
	Lower Delta Plain		LDP	2-8 km	1-2.5 km	
	Delta Front		DF	1-2 km	3-4 km	
	Prodelta		PD	20-25 km	25-30 km	
	Shoreline		SH	Up to 10 km	2 to 5 m	

Transects B1, B2, B4 and B5 (Figure 6) capture topographic data around a lake margin fluvial termination (location shown in Figure 3B). The major trunk channel is captured in B1 and B2. The channel has a wider and shallower cross section than the canal-like waterholes. Widening may be caused by reversed flow during major filling events in Lake Yamma Yamma. Sand rich point bars on the edge of the channel and small braid-like sand bars were observed. B4 and B5 capture the distributary channels and represent two common morphologies. B3 and B6 capture similar information and B7 and B8 show a decrease in elevation of 5 metres over approximately 600 m.

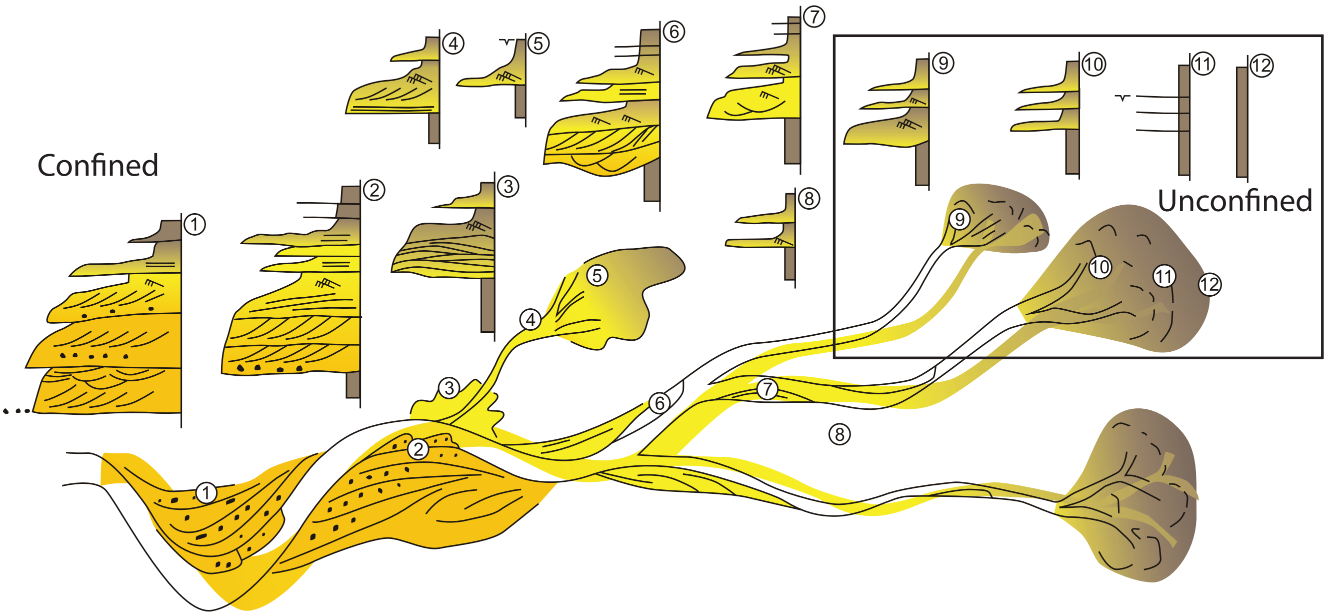
Base level, and hence depositional style for terminal fluvial systems is controlled by lake level. When the lake is dry, the terminal points of localised distributary channels take the form of terminal splay complexes (e.g. Fisher et al., 2008). When the lake is filled, the terminal points of localised distributary channels experience deltaic depositional styles. Deltaic deposition differs from terminal splay type deposition in that splay deposits are generally more likely to be massive, more likely to contain soft sediment deformation, coarser, more poorly sorted and contain more mud aggregates than deltaic deposits.

4.6. Discussion

Sedimentary Characteristics and Depositional Model

When Cooper Creek experiences major flow events, flow is diverted into Lake Yamma Yamma. Initially, terminal splay style deposition occurs. Here, the initial terminal fluvial deposit is confined. As flow velocity increases, deltaic depositional processes become more prevalent and terminal splay deposits are reworked. Unconfined deposition occurs in medial and distal environments. Incision through existing dune systems influences the morphology of upper and lower delta plain systems. Reworking of dune material and sediment carried from Cooper Creek heavily influence the depositional character in medial and proximal depositional settings. Locally sourced terminal splays also provide sand-rich sediment to the lake, with shoreface and barrier island facies formed during highstands. Aeolian and deflation processes and rework sediment during falling stage and lowstand events. Sustained lake filling and sufficient wave fetch allow for wave reworking of deltaic deposits, resulting fluvial- and wave-influenced delta geomorphologies and shorelines (Figure 5).

River geomorphology and discharge greatly affects terminal fluvial styles. Terminal splay and deltaic styles at Lake Yamma Yamma largely reflect floodplain surface flow styles on the Cooper Creek floodplain. Depositional settings at Lake Yamma Yamma share characteristics with braided, reticulate and unchannelled (Fagan and Nanson, 2004) floodplain surface flow styles. The upper delta plain lobe to the north, active during low flow events, is similar in morphology and channel cross-sectional characteristics to the braided channel styles in Cooper Creek (Fagan and Nanson, 2004; Figure 5). The lower delta plain and upper delta plain, active at only very high flow discharges (Figure 5) share a similar channel pattern, bar shape and grain size to reticulate channel patterns (Fagan and Nanson, 2004). Although these channel morphologies are similar to Type 3 deposits on Cooper Creek, they represent Type 4 deposits (where ephemeral rivers terminate into ephemeral lakes). It is important to note that these categories do not exist in isolation; over time, a dryland terminal fluvial deposit may change and evolve through these classifications. An example of system that originated as a lacustrine delta (Type 1) but which is now entirely subaerial (Type 3) is the terminus of the Ruo Shui at the western end of



	Channel width at mouth (m)	Deposit width (km)	Deposit length (km)	Deposit Area (km^2)
Mean	153	2.12	2.15	7
Standard Deviation	265	3.18	2.85	15
Median	42	0.80	0.87	0.4
Maximum	1096	12.67	11.38	68
Minimum	6	0.30	0.21	0.04

Figure 14: Idealised unconfined and confined facies models for Kati Thanda- Lake Eyre. Depositional can occur at a range of scales (LEBARG, 2010).

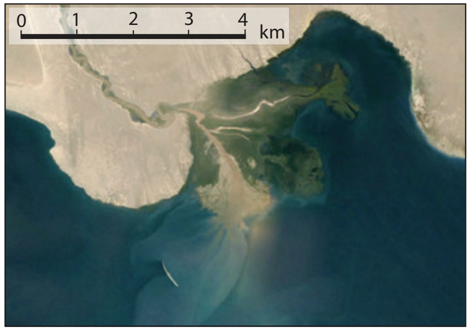
Inner Mongolia (North and Warwick, 2007). A similar change in deposition type could have occurred as the Lake Yamma Yamma terminal fluvial deposit evolved.

Sedimentary data and models are not explicitly presented for Type 4 deposits such as the Chott Rharsa system, southern Tunisia (Blum et al., 1998), ephemeral rivers in the Turkana basin, northern Kenya (Frostick and Reid, 1986), the Elliot Formation of the Karoo Basin (Turner, 1986) or the Coongie Lakes margin terminal splays in the Kati Thanda- Lake Eyre Basin (Costelloe, 2009). Terminal fluvial deposits from this study do however display similarities to Type 4 deposits described around the margin of Kati Thanda- Lake Eyre (Fisher et al., 2008 and Tooth, 2005; LEBARG, 2010; Figure 14). Both confined and unconfined type deposits are interpreted at Lake Yamma Yamma. Confined deposits similar to those at around the margin of Kati Thanda- Lake Eyre occurred in the upper delta plain areas. Confined deposits were also observed around the lake margins at Lake Yamma Yamma, and these shared similar facies characteristics to those at Kati Thanda- Lake Eyre. At both locations sand-dominated low-sinuosity fluvial channel belt evolved into networks of bifurcating, downstream narrowing channels. These were filled with sand fining-upward or simple compound bars, commonly overlain by desiccated mud-plugs. At Lake Yamma Yamma they tend to partly infill erosional topography cut by high energy flood waters. Overall, confined deposits had linear fluvial tracts, mud was locally ponded and the systems were marked by an abrupt termination dominated by unconfined flow processes. Unconfined deposits tended to occur in the delta front and prodelta. Lake Yamma Yamma deposits are generally smaller than those observed at Kati Thanda- Lake Eyre (Figure 12; Figure 13), however they are not outside of the range of dimensions observed at Kati Thanda- Lake Eyre which ranged from 0.1 to 89 km^2 (LEBARG, 2010).

Figure 15: Next page. Summary including similarities and differences between sedimentation at Lake Yamma Yamma and other terminal fluvial deposits.

Category 1

- Dryland perrenial river flows into perennial lake. Most similar to LYY during large and ongoing flow events after initial splay deposition.
- Deltaic processes similar, subaqueous deposition, but density currents not as dominant for LYY.
- Facies model similar to LYY, upper and lower delta plain near identical.



Sarygamysh Delta, near Caspian Sea, classic fluvial delta (many studies)

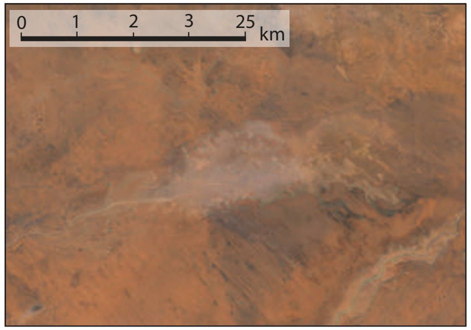
Category 2

- Dryland ephemeral river flows into perennial lake. Most similar to LYY during initial flow events after initial splay deposition.
- Deltaic processes similar, subaqueous deposition, and subaerial deposition.
- Facies model similar to LYY, upper and lower delta plain near identical.

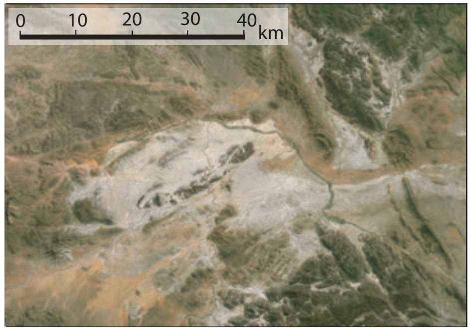
Walker Lake Delta, central western Nevada, USA

Category 3

- Dryland ephemeral rivers terminate through floodout mechanism. Most similar to LYY during initial formation and because of low gradient, low energy.
- Terminal splay processes similar, terminates on to dry land.
- Facies model similar-largely dependent on source river, but similar to TSC's.



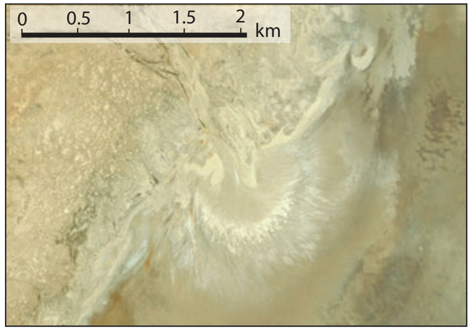
Sandover River Floodouts, NT, central Australia (Tooth, 2005)



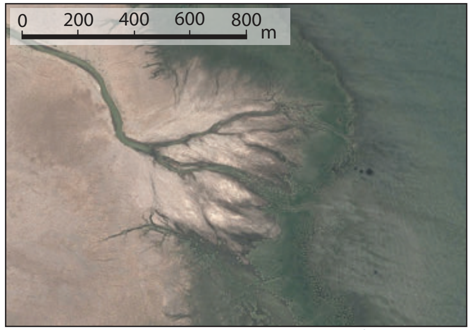
Mud prone creeks and floodout pans, Namibia, Africa (Stanistreet and Stollhofen, 2002)

Category 4

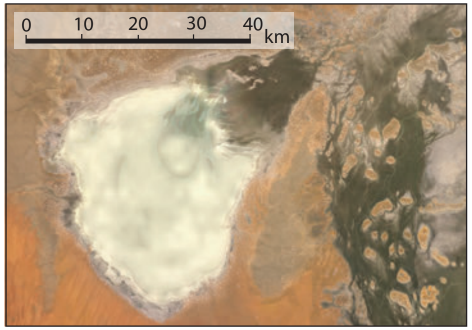
- Dryland ephemeral river flows into lake with wetting, drying cycles. Most similar to LYY during seasonal flow events.
-Subaerial and subaqueous depositional process interaction similar to LYY.
- Preserves both deltaic and terminal splay facies, transitional facies concepts very similar to LYY.



Douglas Creek Terminal Splay, Lake Eyre, Australia (Fisher et al., 2008)



Tulu Bor, Lake Turkana, Kenya (Frostick and Reid, 1986)



Lake Yamma Yamma terminations, this study

Tectonic controls on sedimentation

Intraplate tectonism is thought to result in large scale folding and tilting responsible for deformation patterns that affect the regional drainage as well as creating local accommodation space en-route to the intra-continental depocentre, Kati Thanda-Lake Eyre (Rust and Nanson, 1986; Knighton and Nanson, 1994; Habeck-Farby & Nanson, 2014; Jansen et al., 2013). At Lake Yamma Yamma, a combination of contemporaneous tectonic activity and relief from tectonic elements such as the Curralie Dome, Glipeppee Anticline and MacKillop Anticline provide barriers to flow, causing a change in local base level, as well as fluvial slope and creating accommodation to form a local sediment trap. Hundreds of metres of interbedded thin sands, silts, clays and evaporatic gypsum intersected in the Barrolka-1 borehole (Figure 2) suggest that the Lake Yamma Yamma is not a transient feature and this tectonic influence has been creating sediment accommodation space for a substantial period of time. This also suggests that, even in a low-accommodation basin such as this one, preserved sequences from these types of depositional environments could exceed 100m in the subsurface.

Observations from modern sedimentation at Lake Yamma Yamma suggest tectonic tilting north-westward and the creation of accommodation space in the Yamma Yamma Syncline, contemporaneous with modern sedimentation. The deepest and most commonly active flow path from Cooper Creek to Lake Yamma Yamma is on the north-western side of the floodplain. Inundation frequency maps suggest that the north-western side of the lake floor is inundated 15-20% of the time, compared to the south-eastern side, which is inundated 1-5% of the time (Figure 5). Substantial permanent to semi-permanent waterholes are more frequent on the north western side of the connection between Cooper Creek and Lake Yamma Yamma. These cut through recently active dune systems. Waterholes which form small surface features where the rate of deposition exceeds the rate of scour and excavation are generally located on the south-eastern side of the connection between Cooper Creek and Lake Yamma Yamma. Small localised distributary channels on the north-west side of the lake show signs of being filled from reversed flow (i.e. flow from the main delta); evidence includes sedimentary structures and changes in channel geometries. To the south-west of the lake, active dune systems are starting to encroach on the lake bed. From inundation frequency maps, it was observed that small chains of lakes to the north-west of the delta are filled when the lake is filled (Figure 5). No such features exist on the south-east side of the lake.

Tectonic tilting of the basin toward the north-west in the Cooper Creek area contemporaneous with modern sedimentation is also supported by evidence from other studies conducted on the Cooper Creek (Habeck-Farby & Nanson, 2014). There are five main lines of evidence: (1) the small waterholes where the rate of excavation exceeds the rate of deposition are generally located on the east of the floodplain; (2) signs of meandering palaeochannels, that Rust and Nanson (1986) interpreted to indicate previous sand-dominated flow-regime phases are more clearly visible on the east of the floodplain implying a shift of flow westward, less reworking and greater preservation of these older channel-forms in the east; (3) the main flow path for Cooper Creek lies on the west of the floodplain; (4) the dunefield on the west of the floodplain south of Windorah appears to have been partially invaded by anastomosing channels; (5) the tributaries on the eastern side of the valley are forming small fans onto the floodplain surface whereas the Cooper floodplain appears in contrast to be invading the tributary valleys on the western side (Knighton and Nanson, 1994). When considered together, this evidence suggests tectonic tilting of the Cooper valley, in which Cooper Creek runs and Lake Yamma Yamma is contained, north-westward.

Classification Scheme

The classification scheme presented in this chapter to describe dryland terminal splay to delta continuum provides a useful framework with which to compare dryland terminal fluvial deposits. As these types of systems are relatively understudied compared to their marginal marine counterparts (e.g. Ainsworth et al., 2011), a wide range of descriptive terminologies are used (see introduction of this chapter), which makes a clear comparison of sedimentary characteristics difficult. This classification scheme is a starting point for a more in depth comparison of deposits. A more detailed comparison between Kati Thanda- Lake Eyre and Lake Yamma Yamma fluvial termination deposits is planned, outside the scope of this thesis. Further work should also include extending the classification scheme to include examples of ancient deposits. The work in this chapter has focussed on modern sediments, due to the nature of the case study presented, but the integration of ancient deposits would provide a useful tool for subsurface interpretation. Integration of ancient deposits would also be useful given the few modern dryland fluvial termination deposits that have been studied from a sedimentologic perspective.

4.7. Conclusions

This chapter presents new data from a previously unstudied dryland fluvial – lacustrine system in a low-accomodation basin; Lake Yamma Yamma, central Australia. In order to place this study in the context of published literature, a review of described modern dryland fluvial termination deposits is presented, and a new classification scheme is proposed. The categories are: (Type 1) a perennial river terminating into a perennial lake, (Type 2) an ephemeral river terminating into a perennial lake, (Type 3) an ephemeral river terminating on a landform which is not a body of water or dry lake, e.g. a floodplain, and (Type 4) an ephemeral river terminating into an ephemeral lake, which may be wet (4A) or dry (4B), a temporal variation in the same system with depositional processes changing at the river terminus depending on environmental conditions. Under the classification scheme, the focus of this study at Lake Yamma Yamma, where Cooper Creek provides inflow, is classified as a Type 4 deposit, where an ephemeral river terminates into an ephemeral lake, which may be wet or dry. Few detailed studies of the sedimentology of these types of deposits exist. In this study, we provide a detailed facies and geomorphic element description, as well as a process-based model for deposition. Twelve main depositional elements are described. Proximal fluvial-dominated elements, medial lacustrine-influenced depositional elements and marginal lacustrine deposits were sand-dominated, with mud generally observed as aggregates. Distal elements were generally mud dominated, with suspension fallout processes responsible for deposition.

When Cooper Creek experiences major flood events, some of this flow is diverted into Lake Yamma Yamma. Initially, terminal splay style deposition occurs. As the *volume of water in Lake Yamma Yamma rises, deltaic deposition commences and becomes more dominant, with sediment deposition patterns reflecting this. Incision through existing dune systems influences the morphology of upper and lower delta plain systems. Reworking of dune material and sediment carried from Cooper Creek heavily influence the sedimentology of the lake. Locally-sourced terminal splay complexes provide sand-rich sediment to the lake, with shorelines and barrier islands formed during times of high lake level.*

The formation of Lake Yamma Yamma is linked to subtle tectonic changes in the region. New data from this study suggests the observed overall tilting of the Cooper Creek floodplain to the west, combined with gentle domal uplift causing synform and anticline formation in the region is responsible for the location, morphology and characteristics of the system. Lake Yamma Yamma shows a similar depositional style to both confined and unconfined marginal terminal fluvial systems in the Kati Thanda- Lake Eyre Basin, although differences in climate, local tectonic regime and variability in accommodation space play a role in deposit characteristics such as stacking patterns, sand bed thickness and preservation potential.

4.8. Acknowledgements

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4.9. References

Abbasi, I.A., Hersi, O.S., Al-Harthy, A., Al-Rashdi, I., 2013. Lithofacies attributes depositional system and diagenetic properties of the Permian Gharif Formation from Haushi–Huqf area, Central Oman. Arabian Journal of Geosciences, 6 (12), 4,931–45.

Ainsworth, R.B., Vakarelov, B.K., Nanson, R.A., 2011. Dynamic Spatial and Temporal Prediction of Changes in Depositional Processes on Clastic Shorelines: Toward Improved Subsurface Uncertainty Reduction and Management. AAPG Bulletin, v. 95, p. 267-297.

Almasrahy, M.A., Mountney, N.P., 2015. A classification scheme for fluvial–aeolian system interaction in desert-margin settings. Aeolian Research, 17, 67-88.

Bhattacharya, J.P., Walker, R.G., 1992. Deltas. In: Facies Models: Response to Sea-Level Change (Eds R.G. Walker and N.P. James), pp. 157–177. Geological Association of Canada, St Johns

Billi P., 2007. Morphology and sediment dynamics of ephemeral streams terminal reaches in the Kobo basin (northern Welo, Ethiopia). Geomorphology 85:98–113

Blair, T.C., Mcpherson, J.G., 2008. Quaternary sedimentology of the Rose Creek fan delta, Walker Lake, Nevada, USA, and implications to fan- delta facies models. Sedimentology, 55(3), pp.579–615.

Blum, M., Kocurek, G., Swezey, C., Deynoux, M., Lancaster, N., Price, D., Pion, J.C.,1998. Quaternary wadi, lacustrine, aeolian depositional cycles and sequences, Chott Rharsa Basin, southern Tunisia. In: Alsharhan, A., Glennie, K., Whittle, G., Kendall, C. (Eds.), Quat. Deserts Climatic Change. Balkema, Rotterdam, pp. 539–552.

BOM, 2016, Bureau of Meteorology Historical Data Pages, Open source data for the Commonwealth of Australia 2017, URL: http://www.bom.gov.au/

Brierley G.J., Hickin E, J., 1991. Channel planform as a non-controlling factor in fluvial sedimentology: the case of the Squamish River floodplain, British Columbia. Sedimentary Geology, 75 (1991) 67-83.

Brook, G. A., E. Marais, P. Srivastava, T. Jordan., 2007. Timing of lake-level changes in Etosha Pan, Namibia, since the middle Holocene from OSL ages of relict shorelines in the Okondeka region. Quatern. Int. 175, 29– 40.

Burrough, J. C., 2007. Multiphase Quaternary Highstands at Lake Ngami, Kalahari, Northern Botswana. Palaeogeography, Palaeoclimatology, Palaeoecology, vol. 253, no. 3, pp. 280–299.

Cohen, T.J., Nanson, G.C., Larsen, J.R., Jones, B.G., Price, D.M., Coleman, M., Pietsch, T.J.,

2010. Late Quaternary aeolian and fluvial interactions on the Cooper Creek Fan and the association between linear and source-bordering dunes, Strzelecki Desert, Australia. Quat. Sci. Rev. 29, 455-471.

Costelloe, J., Irvine, E., Western, A., & Herczeg, A., 2009. Groundwater recharge and discharge dynamics in an arid zone ephemeral lake system, Australia. Limnology and Oceanography, 54(1), 86-100.

DMP Queensland, 2016, Digital Geoscience Data. The State of Queensland, Queensland Government, 2016 URL: https://www.business.qld.gov.au/industry/mining/geoscience-data-information/digital-data

Donselaar, M.E., Cuevas Gozalo, M.C., Moyano, S., 2013. Avulsion processes at the terminus of low-gradient semi-arid fluvial systems: lessons from the Río Colorado, Altiplano endorheic basin, Bolivia. Sedimentary Geology 283, 1–14.

Drake, N.A., Bryant, R.G., Millington, A.C., Townshend, J.R.G., 1994. Playa sedimentology and geomorphology: Mixture modeling applied to Landsat thematic mapper data of Chott el Jerid, Tunisia. In: Sedimentology and Geochemistry of Modern and Ancient Saline Lakes, Tulsa, OK, SEPM Special Publication No. 50, pp. 125–131.

Fagan, S. D., And Nanson, G.C., 2004. The morphology and formation of floodplain-surface channels, Cooper Creek, Australia. Geomorphology, 60, 107–26.

Fisher, J.A., Krapf, C.B.E., Lang, S.C., Nichols, G., and Payenberg., T.H.D. 2008. Sedimentology and architecture of the Douglas Creek terminal splay, Lake Eyre, central Australia: Sedimentology, v. 55/6, pp 1915–1930.

Fitzsimmons, K.E. Magee J.W. & Amos K.J, 2009. Characterisation of aeolian sediments from the Strzelecki and Tirari Deserts, Australia: Implications for reconstructing palaeoenvironmental conditions. Sedimentary Geology, 218(1), pp.61–73.

Friend, P.F., 1978. Distinctive features of some ancient river systems in A.D.Miall (editor) Fluvial sedimentology, Canadian Society of Petroleum Geologists, Memoir 5: 531-542.

Frostick, L.E. and Reid I., 1986. Evolution and Sedimentary Character of Lake Deltas fed by Ephemeral Rivers in the Turkana basin, northern Kenya. In Sedimentation in the African RiftsL.E. Frostick, R. W. Renaut, I. Reid and J.J. Tiercelin (eds), 113-24. Geological Society of London Special Publication 25.

Gale S.J., Hoare P.G., 1991. The physical composition and analysis of regolith materials. Quaternary Sediments Petrographic Methods for the Study of Unlithified Rocks: 319.

Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: Deltas, Models for Exploration (Ed. M.L. Broussard), pp. 87–98. Houston Geological Society, Houston, TX.

George, G.T. Berry, J.K., 1993—A new lithostratigraphy and depositional model for the Upper Rotliegend of the UK Sector of the Southern North Sea. Geological Society. Special Publications, 73, 291–319.

Geoscience Australia, 2014. Maps of Australia, Commonwealth of Australia. URL: http://www.ga.gov.au/data-pubs/maps

Gilbert, G.K.,1885. The topographic features of lake shores.US Geol. Surv. Ann. Rep., 5,69–123.

Glennie K. W., 1987. Desert sedimentary environments, present and past: a summary. Sedimentary Geology 50, 135-165.

Gregory, C. M., Senior, B. R. and Galloway, M. C., 1967. The geology of the Connemara, Jundah, Canterbury, Windorah, and Adavale 1:250,000 Sheet areas. Bur. Miner. Resour. Geol. Geophys. Rec., 1967/16 (unpublished).

Habeck-Fardy, K., Nanson, G., 2014. Environmental character and history of the Lake Eyre Basin, one seventh of the Australian continent. Earth-Science Reviews, 132, 39–66

Hinds, D.J., Aliyeva, E., Allen, M.B., Davies, C.E., Kroonenberg, S.B., Simmons, M.D. And Vincent, S.J., 2004. Sedimentation in a discharge dominated fluvial-lacustrine system: the Neogene Productive Series of the South Caspian Basin, Azerbaijan. Marine and Petroleum Geology, 21 (5), 613–38.

Jansen, J.D., Nanson, G.C., Cohen, T.J., Fujioka, T., Fabel, D., Larsen, J.R., Codilean, A.T., Price, D.M., Bowman, H.H., May, J.-H., Gliganic, L.A., 2013. Lowland river responses to intra- plate tectonism and climate forcing quantified with luminescence and cosmogenic 10Be. Earth Planet. Sci. Lett. 366, 49-58.

Jorgensen, P.J., Fielding, C.R., 1996. Facies architecture of alluvial floodbasin deposits: three-dimensional data from the Upper Triassic Callide Coal Measures of east-central Queensland, Australia. Sedimentology 43, 479–497.

Kelly S.B. and Olsen, H. 1993. Terminal fans—a review with reference to Devonian examples. Sedimentary Geology, 85(1-4), pp.339–374.

Knighton, A.D., Nanson, G.C., 2000. Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. Geomorphology, 35(1), pp.101–117.

Knighton, A.D., Nanson, G.C., 1994. Waterholes and their significance in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 9, 311–324.

Lang, S. C., Payenberg, T.H.D., Reilly, M.R.W., Hicks, T., Benson, J., Kassan, J., 2004. Modern Fluvial Analogues for dryland sandy fluvial-lacustrine deltas and terminal splay reservoir. APPEA Journal, 2004, 329–56.

LEBARG, 2010. LEBARG Phase III Final Report to sponsors. Australian School of Petroleum, University of Adelaide.

Lewis, D.W., 1984. Practical Sedimentology. Hutchinson, Ross, Stroudsburg.

Li, J. and Bristow, C.S. 2015. Crevasse splay morphodynamics in a dryland river terminus: Río Colorado in Salar de Uyuni Bolivia. Quaternary International, 377, pp.71–82

Li, J., Donselaar, M.E., Aria, S.E.H., Koenders, R. and Oyen, A.M. 2014. Landsat imagery-based visualization of the geomorphological development at the terminus of a dryland river system. Quaternary International, 352, 100-110.

Magee, J.W., Bowler, J.M., Miller, G.H., Williams, D.L.G., 1995. Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan gulf, Lake Eyre, South Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 113, 3-42.

Maroulis, J.C. & Nanson, G.C., 1996. Bedload transport of aggregated muddy alluvium from Cooper Creek, central Australia: a flume study. Sedimentology, 43(5), pp.771–790.

Maroulis, Jerry C., Nanson, Gerald C., Price, David M., Pietsch, T., 2007. Aeolian-fluvial interaction and climate change: Source-bordering dune development over the past [approximately equal to 100ka on Cooper Creek, central Australia. Quaternary Science Reviews, 26(3 4), 386.

Nanson, G.C., Rust, B.R., Taylor, G., 1986. Coexistent mud braids and anastomosing channels in an arid-zone river: Cooper Creek, central Australia. Geology 14, 175–178.

Nanson, G.C., Tooth, S. and Knighton, A.D., 2002. A Global Perspective on Dryland Rivers: Perceptions, Misconceptions and Distinctions. Chapter In L.J. Bull and M.J. Kirkby (Eds), Dryland Rivers, Wiley, Chichester, p. 17-54.

Nanson, G.C., Tooth, S., 1999. Arid-zone rivers as indicators of climate change. In: Singhvi, A.K., Derbyshire, E. (Eds.), Palaeoenvironmental Reconstruction in Arid Lands. Oxford and IBH Press, New Dehli.

Nanson, G.C., Young, R.W., Price, D.M., Rust, B.R., 1988. Stratigraphy, sedimentology and Late Quaternary chronology of the Channel Country of western Queensland. In: Warner, R.F. (Ed.), Fluvial Geomorphology of Australia. Academic Press, Sydney.

Nanson, G.C., Young, R.W., Price, D.M., Rust, B.R., 1988. Stratigraphy, sedimentology and Late Quaternary chronology of the Channel Country of western Queensland. In: Warner, R.F. (Ed.), Fluvial

Geomorphology of Australia. Academic Press, Sydney.

Nichols G.J. and Fisher, J.A.. 2007. Processes, facies and architecture of fluvial distributary system deposits. Sedimentary Geology, 195(1), pp.75–90.

Nichols, G.J. & Hirst, J.P., 1998. Alluvial fans and fluvial distributary systems, Oligo-Miocene, northern Spain; contrasting processes and products. Journal of Sedimentary Research, 68(5), pp.879–889.

Nichols, G.J., 1987. Syntectonic alluvial fan sedimentation, southern Pyrenees. Geological Magazine, 124(2), pp.121–133.

North C. P., Warwick G. L., 2007. Fluvial fans: myths, misconceptions, and the end of the terminal-fan model. Journal of Sedimentary Research 77: 693-701.

Queensland Government, 2016. Wetland mapping — Lake Yamma Yamma 100K map tile — 7145, WetlandInfo, Department of Environment and Heritage Protection, Queensland, <https://wetlandinfo.ehp.qld.gov.au/wetlands/facts-maps/tile-100k-lake-yamma-yamma/>.

R Core Team, 2012. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/

Richards, K., Mudie, P., Rochon, A., Athersuch, J., Bolikhovskaya, N., Hoogendoorn, R., Verlinden, V., 2017. Late Pleistocene to Holocene evolution of the Emba Delta, Kazakhstan, and coastline of the north-eastern Caspian Sea: Sediment, ostracods, pollen and dinoflagellate cyst records. Palaeogeography, Palaeoclimatology, Palaeoecology, 468, pp.427–452.

Rust, B.R., Nanson, G.C., 1989. Bedload transport of mud as pedogenic aggregates in modern and ancient rivers. Sedimentology, 36(2), pp.291–306.

Rust, B.R., Nanson, G.C., 1986. Contemporary and palaeochannel patterns and the Late Quaternary stratigraphy of Cooper Creek, southwest Queensland, Australia. Earth Surf. Process. Landf. 11, 581–590.

Schenk, C.J., Fryberger, S.G., 1988. Early diagenesis of eolian dune and interdune sands at White Sands, New Mexico. Sed. Geol. 55, 109–120.

Scherer, C.M.S., Lavina, E.L.C, Filho, D.C.D., Oliveira, F.M., Bongiolo, D.E., Aguiar, E. S., 2007, Stratigraphy and facies architecture of the fluvial-aeolian-lacustrine Sergi Formation (Upper Jurassic), Reconcavo Basin, Brazil. Sedimentary Geology, 194 (3–4), 169–93.

Senior, B. R., 1970. Barrolka, Qld. Bur. Mineral Resources, Geol. Geophys., Explan. Notes, SG/54-11.

Shaw, P. Bateman, M. Thomas, D. Davies, F., 2003. Holocene fluctuations of Lake Ngami, Middle Kalahari: chronology and responses to climatic change. Quaternary International, 111(1), pp.23–35.

Stanistreet, I.G., Stollhofen, H., 2002. Hoanib River flood deposits of Namib Desert interdunes as analogues for thin permeability barrier mudstone layers in aeolianite reservoirs. Sedimentology 49, 719–736.

Taylor, C.F.H., 1999. The role of overbank flow in governing the form of an anabranching river: the Fitzroy River, northwestern Australia. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI. Special Publication of the International Association of Sedimentologists, vol. 28, pp. 77–92.

Tooth, S., Nanson, G., 1999. Anabranching rivers on the Northern Plains of arid central Australia. Geomorphology, 29(3), pp.211–233.

Tooth, S., 2000. Process, form and change in dryland rivers: a review of recent research. Earth Sci. Rev. 51, 67–107.

Tooth, S., 2005. Splay formation along the lower reaches of ephemeral rivers on the Northern Plains of arid central Australia. J. Sediment. Res. 75, 636–649.

Turner, B.R., 1986. Tectonic and climatic controls on continental depositional facies in the Karoo Basin of northern Natal, South Africa. Sedimentary Geology, 46(3), pp.231–257.

Turner, P., Pilling, D., Walker, D., Exton, J., Binnie, J. And Sabaou, N., 2001—Sequence stratigraphy and sedimentology of the late Triassic TAG-I (Blocks 401/402, Berkine Basin, Algeria). Marine and Petroleum Geology.

Chapter 5: A Complex Regressive-Transgressive Transition from Continental to Marine Strata: Sedimentology, Stratigraphy and Provenance of the Cretaceous Dakota Formation, south-west Colorado

5.1. Abstract

The classification of net transgressive strata can be complex. The thinly bedded nature and complex internal architecture of transgressive deposits makes interpretation difficult. This study investigates the sedimentology, sequence stratigraphy and provenance of a series of net transgressive clastic sediments deposited on the margin of an epicontinental seaway during the Cenomanian. Although extensive outcrop studies have been conducted on the Western Interior Seaway strata in Utah, New Mexico and Colorado, the interval presented in this study has not been investigated in detail at this field site, and this case study provides an important contribution with regard to the character and nature of the initial transgression. Over fifty-seven 17 to 32 m logged outcrop sections from the Dakota Formation reveal a series of coarsening-up and fining-up parasequences characterised by mudstone-rich bases coarsening-up into amalgamated ripple-laminated sand packages, and coarse-sandstone scoured cross-stratified bases, fining upward into shale strata. Seven distinct facies associations were observed; depositional environments from prodelta to upper delta plain were interpreted. Interpretation of these deposits, along with detailed photo-mosaic images, suggest that although the Dakota Formation is a net transgressive package, the transgression occurred in a complex fashion, with periods of regression where relatively small fluvial and tide dominated deltas deposited sand-rich sediment. Sediment body geometry is ultimately controlled by subtle allogenic changes in sediment supply and relative sea-level, which caused the flooding and abandonment of deltaic systems, as well as autocyclic delta lobe abandonment. Detrital zircon provenance suggests that sediment supply was ultimately from the Sevier fold-and thrust belt, changing to the Mogollon Highlands and the Cordilleran magmatic arc

higher in the strata, suggesting that Dakota detritus was increasingly sourced from the south. The youngest concordant zircon grain, with an age of 94.4 ± 3.1 Ma suggests that sedimentation in the Dakota Formation continued well into the late Cenomanian and potentially into the early Turonian. When taken together, the sedimentologic, stratigraphic and provenance data allow the depositional environments to be reconstructed and the palaeogeography of the region to be better understood. Results presented here provide valuable insights into the character and nature of the initial transgression and creation of the Cretaceous Western Interior Seaway and provide an analogue for sediments deposited elsewhere under similar conditions.

5.2. Introduction

Transgressive deposits accumulate during a relative rise in base level where the increase in accommodation space is larger than that of sediment supply. Although typically thinly bedded (e.g., Tye et al., 1993; Ravnas and Steel, 1998; Steel et al., 2000), transgressive sands are commonly more texturally and mineralogically mature than their regressive counterparts and can make excellent hydrocarbon reservoirs (e.g., Devine, 1991; Snedden and Dalrymple, 1999; Posamentier, 2002). Transgressive deposits can be marine dominated, estuarine/lagoonal or fluvial, and can include facies such as coal and aeolian deposits. Variability is driven by changes in rate of sea-level rise, textural character of the sediments, sediment supply, shelf gradient or basin physiography (Cattaneo and Steel, 2002). The relative strength and interplay of fluvial, tidal and wave-driven depositional processes exerts a primary control on the dimensions, geometry, orientation, preservation and distribution of these marginal marine element bodies and facies belts in the geological record (Ainsworth et al., 2011).

Two approaches are commonly used to describe transgressive deposits in the literature. One approach to interpret transgressive tidal and fluvially dominated relies heavily on sequence stratigraphic models. In these models sand deposits are interpreted to be preserved in incised valleys during transgressions (e.g. Dalrymple, 1992; Dalrymple et al., 1992; Posamentier & Allen, 1999), although some sequence stratigraphic models place less emphasis on incised valleys and more on the tectonic creation of accommodation space as a mechanism for sand preservation (Gilbert, 1885; Sanders and Kumar, 1975; Swift et al., 1991; Nummedal et al., 1993; Thorne and Swift, 1991). The second, and an alternative approach, is to base interpretation on modern settings. These studies tend to describe the sedimentology and stratigraphy of deposits in detail (Yoshida et al., 2001; Plink-Bjorklund, 2005; Dalrymple, 2006; Sixsmith et al., 2008; Ponten & Plink-Bjorklund, 2009), but base interpretation of sedimentology on a very limited range of well-studied high-latitude modern back barriers and estuary systems (e.g. Van Straaten & Kunen, 1957; Oomkes & Terwindt, 1960; Van Straaten, 1961; Evans, 1965; Reineck, 1967; Terwindt, 1971). A combination of both of these approaches is ideal if the volume of data allows.

Almost any effort at classifying transgressive deposits based on depositional controls and driving factors is likely to be over idealised, due to the variability in thickness, lateral dimensions, and internal architecture of transgressive deposits (Cattaneo and Steel, 2002). Modern examples of depositional processes of transgression are difficult to observe on a useful timescale. Also, transgressive processes and resultant deposits are difficult to observe in a modern setting as evidence is often obscured by encroaching waters. A lack of variability of studies detailing the sedimentology, stratigraphy and architecture transgressive deposits also adds to the difficulty of interpreting these types of deposits. In order to develop a sound understanding of the facies relationships and stratigraphic architectures resulting from the interaction of fluvial, wave and tidal processes during transgressive deposition, well-documented outcrop examples are needed in which vertical and lateral facies dimensions and spatial relationships can be measured.

One such outcrop is provided by the Cenomanian Dakota Formation. On a regional scale the Dakota Formation has been inferred as a mixed influence net transgressive deltaic succession, preserving the initial encroachment of marine waters onto the continental landmass during the Cenomanian (Young, 1960; Weimer, 1982; Serradji, 2007). This study aims to develop an improved understanding of the detailed local sedimentological processes, facies and stratigraphic architecture of the Dakota Formation, which is continually exposed for over 25km between the towns of Montrose and Ridgway. This aim is achieved by documenting facies characteristics within a framework of carefully interpreted stratigraphic surfaces and facies successions and provides more data, higher density data and more of a focus on stratigraphic architecture than previous investigations. This primary sedimentological study is supported by detrital zircon U-Pb geochronology in order to develop more of an understanding of sediment supply and basin palaeogeography and potential controls that these factors may play on the nature and character of the transgression and resultant deposits. The aim of this study was not to provide a detailed basin-wide correlation as that was beyond the scope of this thesis work. For a recent discussion of broad scale correlation of the Dakota Formation, including locations in the Henry Mountains and the Kaiparowits

Plateau the reader is referred to Antia and Fielding, 2011.

5.3. Geological Setting

In the Early Cretaceous, marine waters encroached on the North American Continent from the Arctic and the Tethys regions concurrently, converging in Colorado to form the Cretaceous Western Interior Seaway (WIS) (Figure 1). By the mid-Cretaceous, the WIS covered an area from the Arctic to the Gulf of Mexico and from central Utah to the western Appalachians (Blakey and Umhoefer, 2003; Miall et al. 2008). On a continental scale the mechanism responsible for the formation of the seaway is thought to be Sevier thrust (Jordan, 1981; Cross and Pilger, 1978; Cross, 1986; DeCelles, 1994) and mantle flow-induced dynamic subsidence associated with cold Farallon plate subduction (Liu et al., 2011). Second and third order controls include thrust-related foredeep rebound during periods of reduced tectonic activity between thrust movements, eustatic sea level change modulated by subsidence and by sediment supply related to climate (Gomez-Veroiza and Steel, 2010; Hampson et al., 2011; Aschoff and Steel, 2011; Liu, 2011).

During formation of the WIS, sediment was transported from the Sevier Orogen eastward, depositing a series of progradational and retrogradational coastal sediment wedges (Miall et al. 2008). The most basal of these coastal sediment wedges, the Dakota Formation, was deposited approximately 400 km east of the thrust front of the Sevier Orogenic belt (Figure 1) on the margin of the WIS (Ulincy, 1999; Valdez, 1993). In Western Colorado, the Dakota Formation has been interpreted to represent a transgressive event, preserving the initial encroachment of marine conditions and recording the initial transgression of the Cretaceous seaway

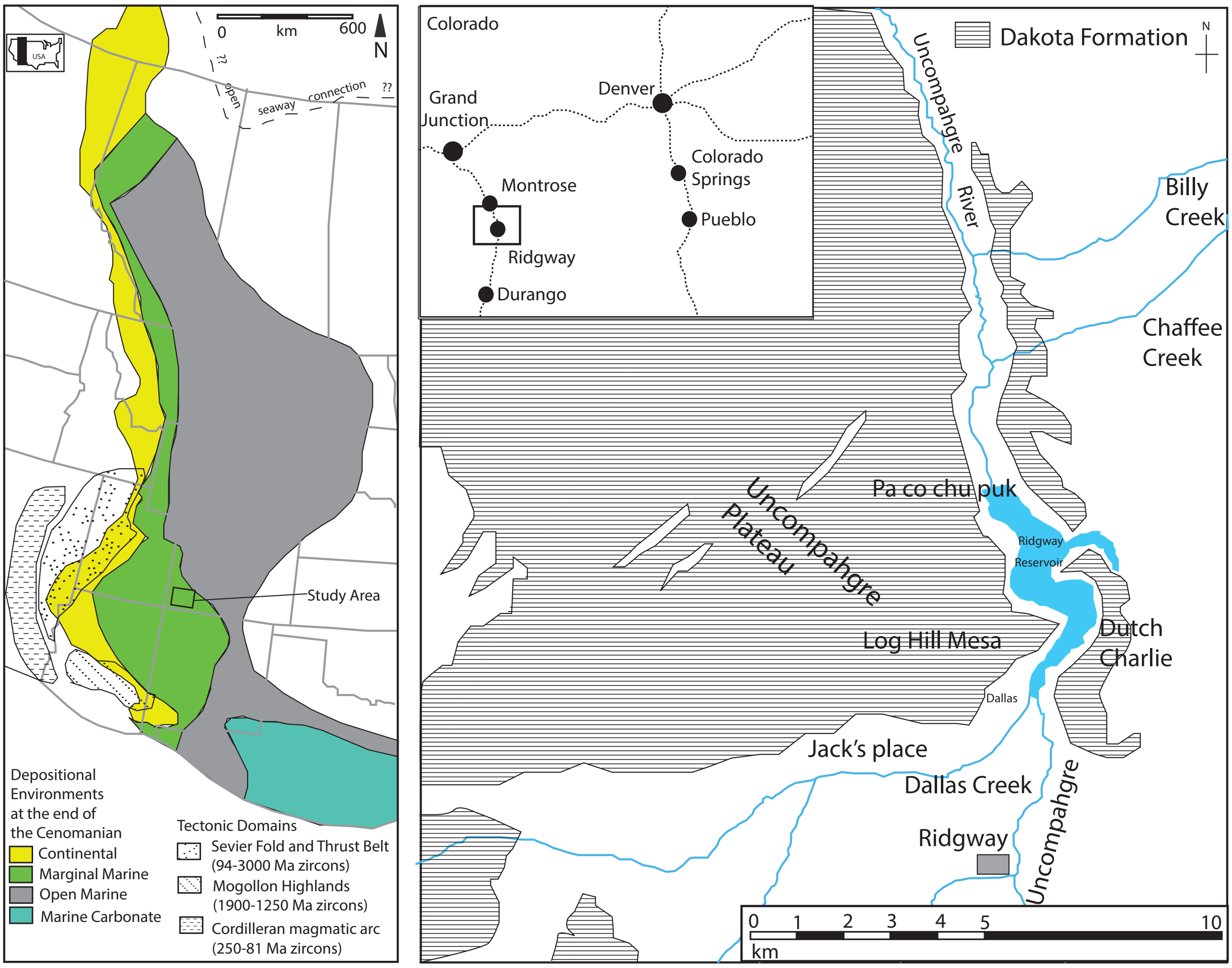


Figure 1: Left: Location map for this study showing palaeogeographic reconstruction (after Miall et al., 2008) and tectonic domains (after Szwarc et al., 2014) at the end of the Cenomanian. Right: Location map for this work, showing outcropping Dakota Formation and major morphological features (After Steven and Hail, 1989).

across South-western Colorado (Young, 1960). Due to a lack of detailed studies, the age of the formation is unknown in the Ridgway area. It is estimated to be Early Cretaceous (Cenomanian) based on regional studies (Weimer, 1982). The Dakota Sandstone is underlain by the Burro Canyon Formation and overlain by the Mancos Shale (Young, 1960) (Figure 2). The Lower Cretaceous (Aptian and Albian) Burro Canyon formation is composed of continental and fluvial sediments (Weimer, 1982).

The Mancos Shale is of Late Cretaceous (Turonian) age (Young, 1960). It consists of organic-rich black shale deposited in very low oxygen conditions and is interpreted to represent the offshore and open sea environment of the WIS (Weimer, 1982). This vertical stratigraphic pattern confirms the net transgressive nature of the Dakota Formation.

Stratigraphic nomenclature used to describe the Dakota Formation is complicated (Figure 2), perhaps because of the broad and variable extent of the formation along the margin of the WIS (Figure 1). Meek and Hayden (1861) first designated this unit “The Dakota” near the town of Dakota, north-eastern Nebraska. Many authors have used variations on the name: Dakota Sandstone, Dakota Group and Naturita Formation (Bartleson, 1994; Burbank, 1930; Carter, 1957; Fouch et al., 1983; Gustason, 1985; Gustason, 1989; Hail, 1989; McGookey, 1972; Meek and Hayden, 1861; Weimer, 1982; Young, 1960) in describing expressions of packages interpreted to be age equivalent. In this chapter, we use the term Dakota Formation. This study focuses on outcrop in the Ridgway area (Figure 1). Due to a lack of detailed study of this area, the age of the formation is unknown. This locality was chosen in part because of the laterally extensive exposure of the Dakota Formation on the cliff face, and because of the preservation and exposure of the full Dakota Formation package with interpreted continental strata below and marine strata above.

5.4. Data Set and Methods

This study focuses on the Dakota Formation exposed on the cliff face of the Uncompahgre Plateau between the towns of Montrose and Ridgway, south west Colorado. Previous fundamental but unpublished work (Young, 1960, Weimer, 1982 Serradji, 2007) was considered as a basic framework for observation and description and a guide to selecting study locations. The geomorphology of the Uncomprahange Plateau allows a three dimensional view of the formation. Exposures are relatively

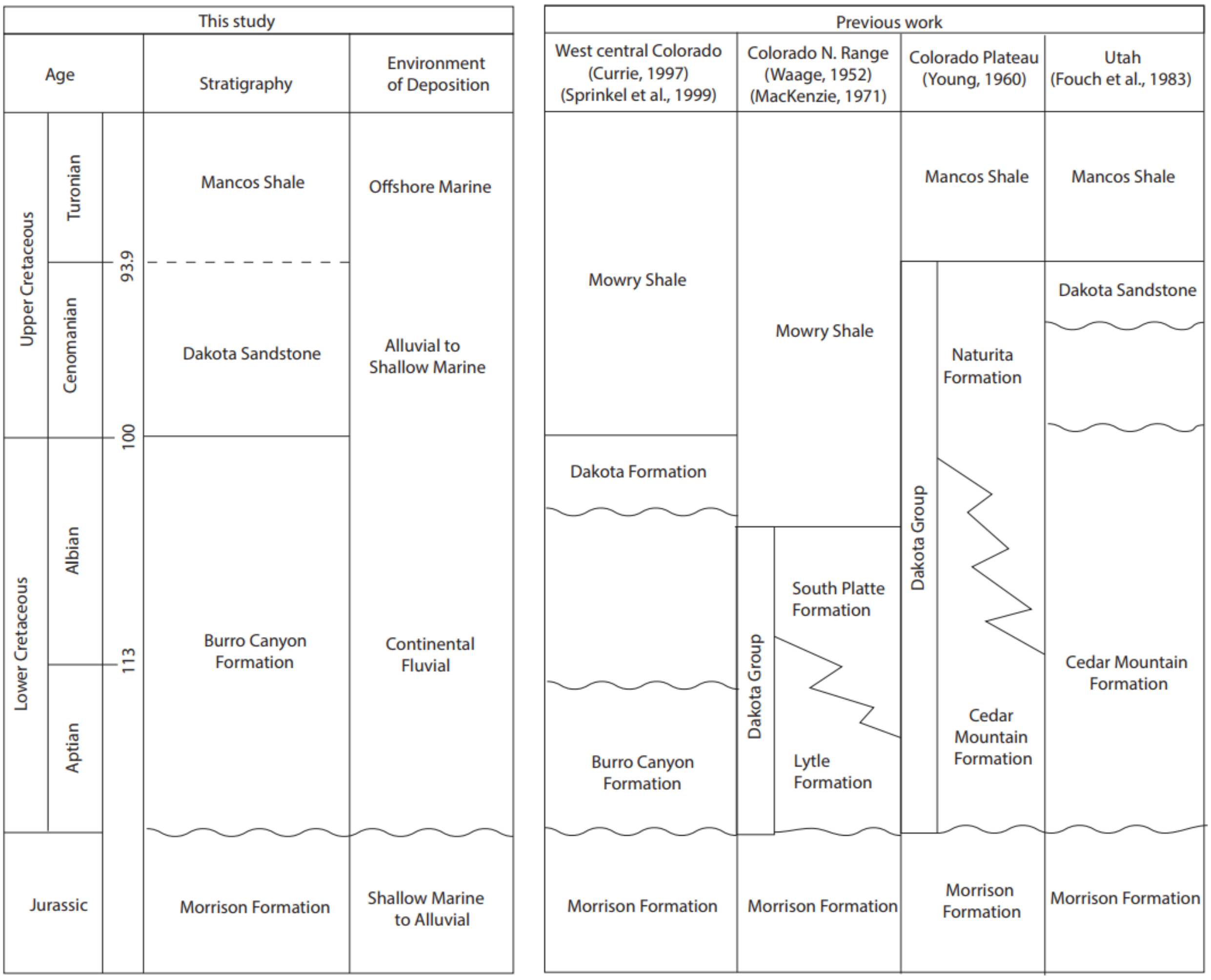


Figure 2: Stratigraphic nomenclature used to describe the Dakota Formation is not straightforward. Left: Summary of stratigraphy in and near the study area (after Steven and Hail, 1989 and Carter, 1957). Right: Summary of stratigraphy described by previous workers in West central Colorado (Currie, 1997 and Sprinkel et al., 1999), Colorado N. Range (Waage, 1952 and MacKenzie, 1971), Colorado Plateau (Young, 1960) and south-eastern Utah (Fouch et al., 1983).

continuous, with beds dipping approximately 3 to 5 degrees. Fifty-seven vertical sections were measured along the 25km length of the plateau and where canyons cut the cliff face (Figure 3). These sections are each between 17m and 32m vertical thickness. In each section lithologies were examined closely with regard to bed thickness, grain size, sorting, rounding, sedimentary structures, bed continuity and lateral characteristics. A GigaPan Epic Pro paired with an EOS 60D DSLR camera and 300mm zoom lens was used to capture over 40 high resolution panoramic images of exposed cliff faces (locations shown in Figure 3). The panoramas enabled tracing and interpretation of stratal units between measured sections.

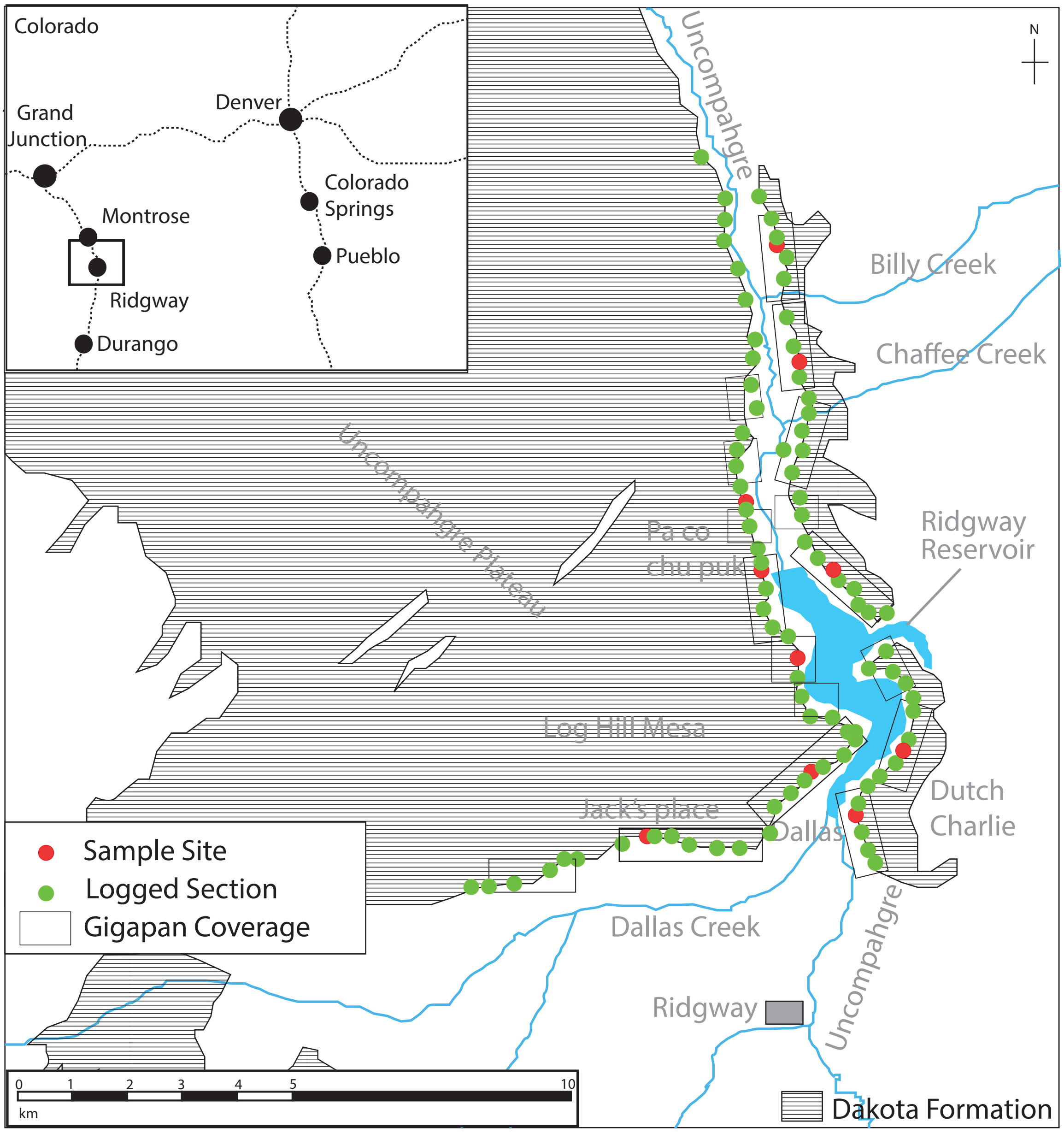


Figure 3: Map of the study area showing the spatial extent of the Dakota Formation, and the location of stratigraphic logs, sampled sections, and photo-panoramas used in this study.

Dakota Formation deposits were categorised based on lithology, sedimentary structures and ichnology, and depositional elements interpreted after grouping these into facies associations. Special focus was placed on interpreting data in a process-based framework. Dimensions, geometries and lateral distributions of facies associations are characterised within the context of sequence stratigraphic units. These are described in terms of facies successions, which allows for the description of stratigraphic architecture, correlation between logged sites and the development of a depositional model. To aid in correlation, a bentonite bed was used as a local chronostratigraphic marker and the Mancos Shale was used as a datum on which to hang the correlations. Fieldwork was completed in June and July of 2015 by the author of this thesis.

Rock samples representative of major stratigraphic units were taken (locations shown in Figure 3) with the objective of conducting Zircon U-Pb geochronology analysis. The samples underwent separation to isolate the zircon fraction through physical, magnetic and heavy liquids techniques. Individual grains were handpicked and mounted into epoxy resin blocks. Prior to analysis, zircon grains were analysed using CL imaging on a Phillips XL-30 SEM with attached Gatan Cathode Luminescence detector in order to identify domains within the grains and select ablation locations within a single domain. Data were obtained on a Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) using a New Wave UP-213 laser attached to an Agilent 7500cx Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at The University of Adelaide. A spot size of 30 μm and repetition rate of 5 Hz was used. Analysed grains were selected without using any particular criteria, to avoid undue bias, but some grains were excluded due to metamictisation and small grain size.

Age calculations were completed using Iolite v2.31 (Paton et al., 2011) with use of the primary zircon standard GJ-1, TIMS normalization data Pb^{207}/Pb^{206}= 608.3 Ma, Pb^{206}/U^{238} = 600.7 Ma and Pb^{207}/U^{235} = 602.2 Ma (Jackson et al., 2004). Instrument drift was corrected for via bracketing groups of unknowns of 15–20 with 8-10 standards and the application of a linear correction. Accuracy of the methodology was verified by repeated analyses of Plešovice zircon (Pb^{206}/U^{238} = 337.13 ± 0.37 Ma; Sláma et al., 2008). Concordia plots were generated using Isoplot v3.75 (Ludwig, 2012). Analyses with anomalously high concentrations of U and depleted concentrations of Th were discarded because grains of this type can be highly susceptible to Pb loss (Dickinson and Gehrels, 2009). Concordant grains were defined as those with Pb^{207}/Pb^{206} and Pb^{206}/U^{238} ratios within a 10% error threshold from a predetermined ideal relationship between the two ratios, and only concordant grains were used for interpretation. Pb^{207}/Pb^{206} ratios were used for age determination for grains older than 1 Ga, and Pb^{206}/U^{238} ratios were used for those younger. When ages split the 1 Ga boundary Pb^{207}/Pb^{206} ratios took precedence. Zircon age distributions were compared using the Kolmogorov-Smirnov (K-S) test (Press et al., 1986). High p values ($p > 0.05$) indicate a statistically significant likelihood that two samples may have been derived from sources with the same zircon age distributions. Low p values ($p < 0.05$) suggest the samples were sourced by statistically distinguishable distributions of zircon ages. All work described including sample preparation and analysis was done by the author of this thesis. The complete data set is provided in Chapter 8 as supplementary data.

5.5. Results and Interpretation

5.5.1. Facies Associations

Seven Facies Associations (FA) were recognised based on detailed observations of lithology, grain sorting and size, sedimentary structures, paleocurrent and trace fossils, a summary of which is shown in Figure 4. Bioturbation intensity (BI) was recorded according to the Taylor & Goldring (1993) scheme, with 0 representing no bioturbation and 4 representing extreme bioturbation. Trace fossil diversity and ichnofacies classification follows models presented by MacEachern and Bann (2008).

Facies Association 1: Bioturbated mudstones

Description

Facies Association 1 (FA 1) consists of thinly bedded (millimetre and sub millimetre scale) light grey to very dark grey claystone, mudstone and occasional siltstone beds (Figure 5A). In mudstone and siltstone beds planar lamination and low angle cross lamination was present. Mudstone and siltstone beds were separated from claystone beds by sharp lower boundaries. Millimetre scale lenticular bedding was present but rare in mudstone and siltstone beds and often graded laterally into finer claystone beds. Occasional thicker (centimetre scale) claystone beds were observed in thicker sections. Outcrop featuring this facies association was very weathered but occasionally exposures were observed in sheltered canyons and freshly excavated regions so observation of continuity of this facies was limited. This FA was often observed below FA2 (Figure 5B). Bioturbation was moderate to high (BI=3-4), but with low species diversity. The character and presence of *Palaeophycus, Thalassinoides, Skolithos* and *Arenicolites* suggest a distal *Cruziana* icnofacies assemblage (MacEachern & Bann, 2008).

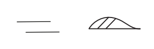
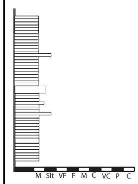
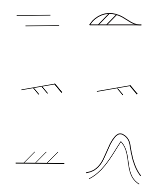
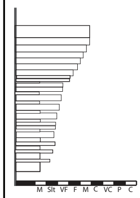
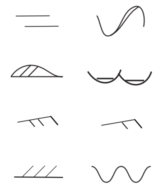
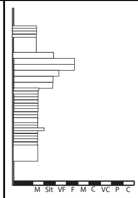
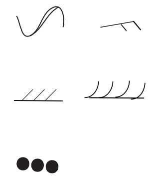
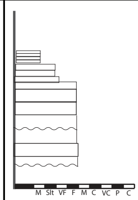
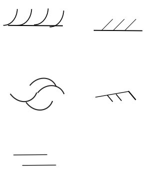
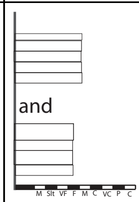
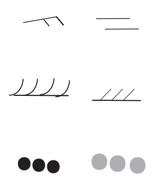
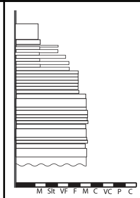
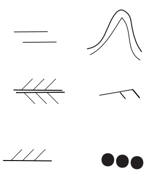
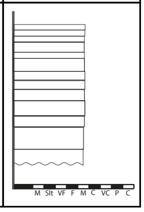
Label	Interpretation	Summary Lithology Description	Key Sedimentary Structures	Bioturbation	Stratigraphic Thickness Range	Shape	Vertical Motif
FA1	Prodelta	Millimetre to sub millimetre interbedded light grey to very dark grey claystone, mudstone and occasional siltstone beds		Palaeophycus, Thalassinoides, Skolithos, Arenicolites	0 m to 2 m	Continuous	
FA2	Delta Front	Upward coarsening package, gray silty shale interbedded with lower-medium beds at base, medium-upper grained cross bedded quartz arenite at top		Ophiomorpha, Thalassinoides, Planolites, Arenicolites, Skolithos, Diplocraterion	1 m to 3 m	Continuous	
FA3	Delta Plain	Centimetre scale dark grey silty shale irregularly interbedded with thick beds of fine to medium grainedquartz arenite, some carbonaceous and coal layers		Planolites, Skolithos, Rhizocorallium, Arenicolites, Diplocraterion	1 m to 5 m	Continuous	
FA4	Distributary channel	Sharp concave upward based, medium-grained quartz arenite occasionally topped by non-continuous coal, siltstone or claystone beds		Rare Arenicolites	0 m to 3 m	Lenticular	
FA5	Shoreface	Lower-fine grained well sorted quartz arenite and upper fine to medium grained sandstone sometimes overlain by planar-cross bedded sandstone and laminated fine sands		Palaeophycus, Ophiomorpha, Planolites, Arenicolites, Skolithos	1 m to 4 m	Continuous	
FA6	Sinuous fluvial channel	Sharp based, upward fining succession ranging from medium-upper sandstone with minor granules and pebbles at the base to alternating silt and sand at the top		Arenicolites, Planolites, Diplocraterion, Cochlichnus, small Scoyenia	0 m to 5 m	Lenticular	
FA7	High energy fluvial channel	Scoured base, upward thinning amalgamated beds of upper-medium to coarse moderately rounded quartz arenite		Small Planolites, Skolithos	0 m to 4 m	Lenticular	

Figure 4: Description and interpretation of the facies associations present in the studied interval of the Dakota Formation. For key to sedimentary structures see Figure 12. Grain size abbreviations: M=mud, Slt=silt, VF= very fine sand, F= fine sand, M= medium sand, C= course sand, VC= very coarse sand, P= pebbles, C= cobbles.

Interpretation

A predominantly distal *Cruziana* icnofacies assemblage, the fine grain size and abundance of planar lamination in Facies Association 1 suggests a low energy, distal marine environment away from fluvial and wave activity. Thicker claystone beds are interpreted to have been deposited from suspension fallout during very low energy periods. Coarser mudstone and siltstone beds are interpreted as preserved episodic storm or high river discharge events (Wright, 1977; Bhattacharya & MacEachern, 2009; Legler et al. 2014). This facies association is interpreted to have been deposited in a shallow prodeltaic environment.

Facies Association 2: Upward coarsening finer interbedded sands and muds

Description

Facies Association 2 (FA2) consists of an upward coarsening succession composed of laminated gray silty shale interbedded with centimetre scale sandstone beds at the base to medium-upper grained cross stratified locally carbonaceous quartz arenite (20-30 cm) at the top (Figure 5 C). Wave modified current ripple laminae (Figure 5D) and current ripple lamina alternating with planar laminated fine to lower medium sandstone beds (Figure 5E) become more dominant at the top of the unit, while planar laminated sands and silts with minor slumping and millimetre thick organic beds are present at the base. Beds generally become thicker and more laterally continuous toward the top of the section. This FA is generally highly burrowed with a high trace diversity and abundance (BI=3), particularly in heterolithic strata. The BI ranges from 2-4, with coarser beds toward the top of the succession likely to have a higher BI. *Ophiomorpha, Thalassinoides, Planolites, Arenicolites, Skolithos,* (Figure 5F) and *Diplocraterion* were observed; suggesting a potentially poorly populated mixed *Cruziana* and *Skolithos* ichnofacies (MacEachern & Bann, 2008). Traces were smooth walled, curved, lined and unlined, passively and actively filled, with a high variation of sizes of traces preserved. This facies association is laterally continuous in the study area and is spatially grades into Facies Association 1 and 3, and is associated with Facies Association 4.

Interpretation

The upward coarsening pattern, the dominance of current and wave-modified current ripple structures and the high intensity mixed *Cruziana* and *Skolithos* ichnofacies suggest an environment with low to moderate energy. Wave influence is limited, but recorded in wave modified current ripple lamina, suggesting the depositional environment is predominantly influenced by fluvial energy. Abundance and diversity of trace species also suggest a relatively sheltered, non-stressed setting. Similar depositional patterns have been interpreted as delta front depositional settings in fluvial dominated deltas (Hansen and MacEachern, 2005; Miall, 1984; Kamola and Van Wagoner, 1995). The upward coarsening succession is interpreted to reflect progradation of the delta front. Preservation of wave influenced structures could be due to isolated extreme weather events. This facies association stacking pattern is similar to a typical delta front from a digitate delta (Fisk, 1961) and a lobate river dominated delta (Barton 1994), which indicates that deltas depositing sediments in this FA could have displayed these morphologies. The typical total thickness of the Dakota package (6-8m) compared to the Wax Lake Delta, Atchafalaya (60-70 m) and Panther Tongue, Perrin Delta (15-20 m) (Olariu and Bhattacharya, 2006) is small. This could be due to the Dakota Formation containing less amalgamated sand deposits than other settings due to rapid sea level rise causing flooding of deltaic lobes during deposition and consequently a shorter depositional time. Mouth bar deposits are virtually inseparable from terminal distributary channel deposits as mouth bars infill the channels (van Heerden and Roberts, 1988) although a high bioturbation index suggests a higher concentration of mouth bars over terminal distributary channel deposits. Differentiation is not made in this case as both occur on the delta front depositional environment.

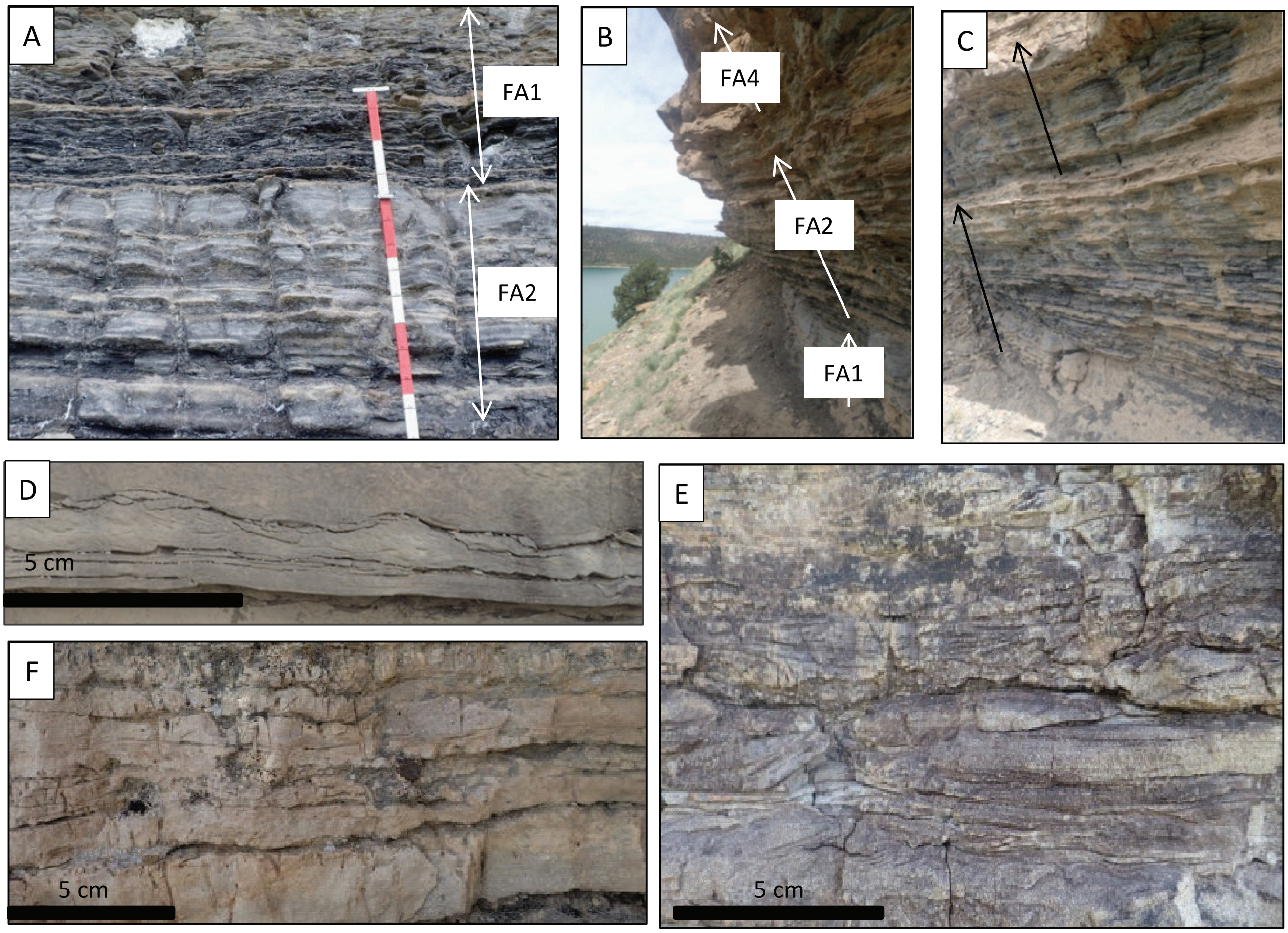


Figure 5: Representative field photos of FA1 Bioturbated mudstones (Prodelta) and FA2 Upward coarsening finer interbedded sands and muds (Delta Front). A- Interbedded FA1 and FA2 typical outcrop expression. Red and white intervals are 15 cm and black marks are 10 cm on the Jacob staff. B- A typical facies succession, FA1 grading into FA2 topped by FA4. FA1 is 1m thickness. C- Coarsening up sequences, a typical field expression of FA2. Beds are approximately 1 m thickness. D- Wave modified current ripple, a typical sedimentary structure in FA2. E- Typical Skolithos expression in FA2. F- Current ripples in silty fine sand in FA2. Typical expression of FA2.

Facies Association 3: Interbedded fine to medium sand, silts and muds with dominant fluvial and tidal structures

Description

Facies Association 3 (FA 3) consisted of centimetre scale planar laminated dark grey silty shale irregularly interbedded with 10 to 50 cm thick beds of fine to medium grained current and wave rippled quartz arenite. Sand beds were sharp based, preserved tabular cross stratification, inclined low angle cross stratification with mud draped foresets (Figure 6A), occasional coal beds (up to 50 cm thick) (Figure 6B) and current ripple lamina (Figure 6C). Flaser, lenticular and less commonly wavy bedding (Reineck & Wunderlich, 1968) were present, with lateral grading between the three types of heterolithic strata present. The lower contact of this facies association was characterised by a scoured base and rip-up clasts were locally dispersed. Occasional millimetre scale carbonaceous layers, coal wisps and woody fragments (Figure 6D) were observed in the upper section of this facies association. Synaeresis cracks were observed in sandier beds toward the top of the FA (Figure 6E). Although this FA was generally poorly exposed due to the mud rich nature of the facies association, it was present in all measured sections and relatively laterally continuous. Sparse *Planolites* and *Skolithos*, as well as rare *Rhizocorallium, Arenicolites* and *Diplocraterion* (Figure 6F) were observed in sand rich beds, with a BI of 1-2, although preserved trace fossils size within the same species was diverse. A poorly developed *Skolithos* ichnofacies is suggested, although elements of *Scoyenia* and *Glossifungites* Ichnofacies are preserved (MacEachern & Bann, 2008).

Interpretation

The presence of sand beds with sharp bases, tabular cross beds, low angle cross beds and current ripple lamina suggests small scale cut and fill structures, interpreted to be small channel fill deposits (Wescott and Ethridge, 1980; Holbrook, 2001; Olariu and Bhattacharya, 2006). Interbedded fine sand and mud beds with ripples could represent proximal overbank deposits as well as levees and potential crevasse splays, particularly where they pinch out and grade into other lithofacies laterally (Holbrook, 2001). The occurrence of lenticular and wavy bedding signifies intermittent tidal current activity through the environment (Van Straaten & Kuenen, 1957; Reineck & Wunderlich, 1968; Oomkes, 1974; Staub & Gastaldo, 2003; Legler et al., 2013). IHS indicates accretion of a mobile substrate within laterally migrating packages (Thomas et al., 1987; Choi et al., 2004), although in this setting, evidence of lateral migration is not strong, potentially due to the poor exposure of this FA. A coal horizon, as well as preserved woody, organic and carbonaceous material suggests a nearby source of abundant plant material. Mixed wave, tidal and fluvial action is preserved in this facies association, with both relatively high and low energy elements preserved. This facies association in interpreted to represent a delta plain setting due to the diverse range of sub-environments, mixed wave, tidal and fluvial influence, as well as the evidence for the *Skolithos* with elements of *Scoyenia* and potentially *Glossifungites* Ichnofacies (MacEachern & Bann, 2008).

Facies Association 4: Sharp based scoured concave upward based, medium-grained quartz arenite

Description

Facies Association 4 (FA 4) consisted of sharp concave upward based,

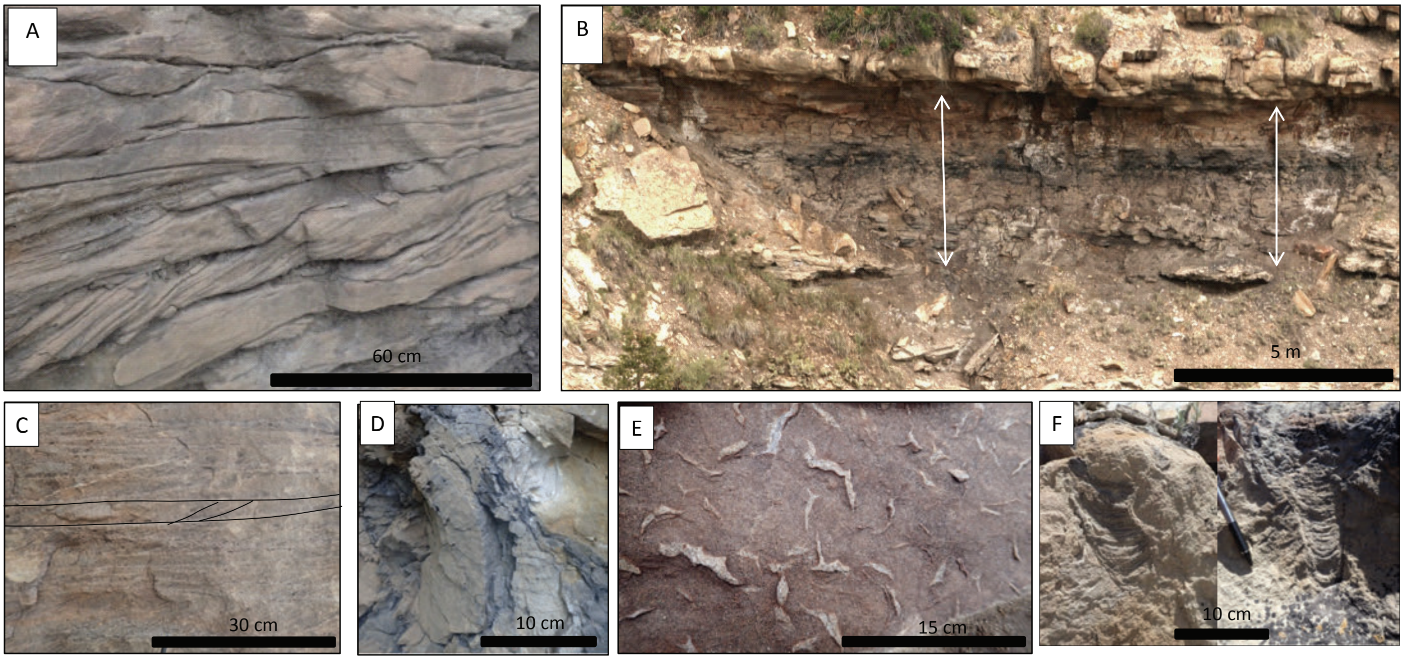


Figure 6: Representative field photos and specific structures of FA3. FA3 was highly variable in nature, so no typical outcrop expression photo is included. A- Planar tabular cross stratification, planar laminar stratification and current ripple stratification in FA3. Mud drapes were observed on foresets of the cross stratification. B- A sandier section of FA3 with a coal bed approximately 40 cm thick. C- Current ripple lamina. Some interpretation is included as a guide. D- Wood fragments preserved in FA3. E- Synaereses cracks in laminations between centimetre scale sand beds. F- Diplocraterion showing U shape laminae perpendicular to bedding. Entire burrows with detailed internal spreite were generally very well preserved.

medium-grained quartz arenite beds with centimetre to millimetre scale rip-up clasts and carbonaceous rich lag at the base of the FA (Figure 7A). This basal bed was overlain by planar tabular and trough cross stratification (Figure 7B), grading into current-rippled medium to fine sands and flaser beds, occasionally topped by non-continuous coal, siltstone or claystone beds (Figure 7C) up to 30 cm thick. Mud drapes were present on the foresets of current ripples. Where this was observed a fining up pattern was present although internal concave upward scours were common and full preservation of the fining up was rare (As in Figure 7D). This FA was lenticular and extended laterally 5-150m, and was often associated with FA2. Rare *Arenicolites*, *Skolithos* (Figure 7E) and millimetre scale horizontal burrows were present in mud-rich sections.

Interpretation

Scour and fill structures, sharp bases with lags and a fining upward pattern suggest an environment with decreasing energy. Relatively low thickness, a combination of fluvial and marine structures and the close association with FA2 delta front suggests an interpretation of amalgamated small distributary channels (Elliott 1978; Bhattacharya and Walker 1992; Reading and Collinson 1996; Olariu and Bhattacharya, 2006). Although scour and fill structures are present and there is evidence for incision within the beds and into FA2, this is interpreted to be a function of the depositional environment rather than a function of external change (DuMars 2002; Roberts 1998; Olariu and Bhattacharya, 2006). *Arenicolites* suggests brackish or marine environment, low species abundance and diversity suggests stressed environment (MacEachern & Bann, 2008). Due to the evidence for a change in fresh high energy to low energy brackish environment it is likely that these channels retained an open connection with the sea during abandonment, forming estuarine channels (Dalrymple et al., 1992).

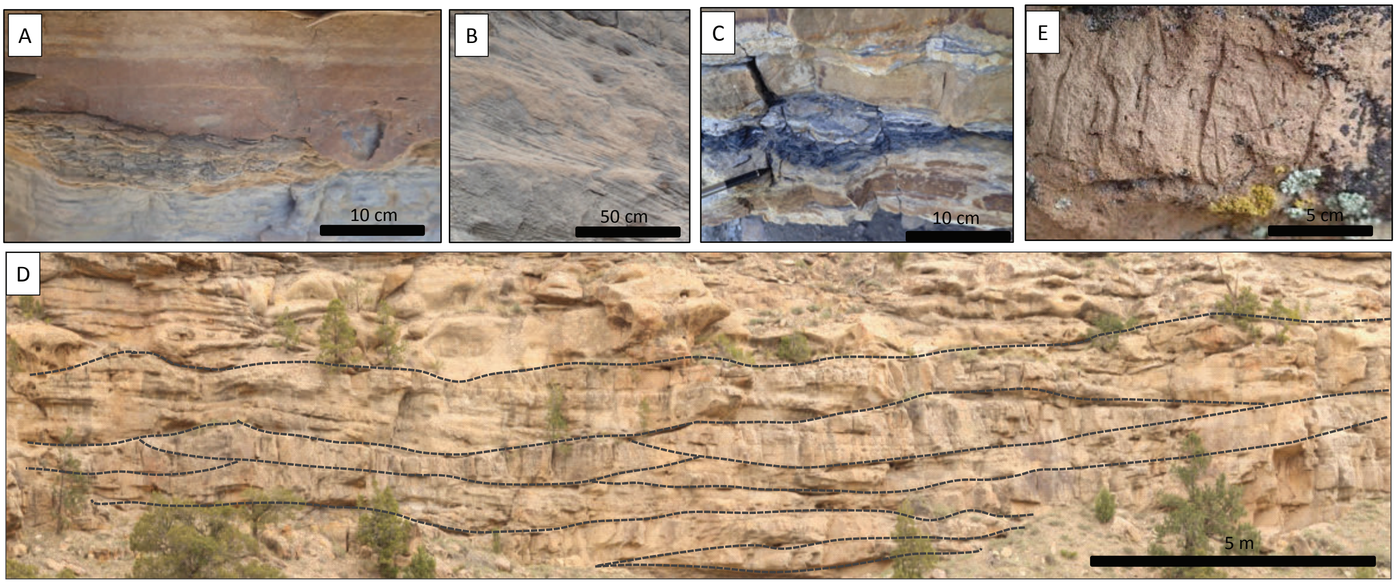


Figure 7: Field photos of FA 4 (Distributary channels): A- Carbonaceous lag and mud clasts at the base of the FA. B- Planar trough cross bedding near the middle of the FA. C- Non-continuous coal beds near the top of the FA. D- Internal concave upward scours were commonly preserved in the FA, particularly near the base. E- Rare Skolithos observed near the top of the FA.

Facies Association 5: Fine sand dominated by HCS and coarse trough- and planar- cross stratified sand

Description

Facies Association 5 (FA 5) consists of two genetically related interfingering and laterally grading facies: a lower-fine grained well sorted quartz arenite dominated by hummocky cross stratification (Figure 8A) and an upper fine to medium grained trough-cross stratified sandstone sometimes overlain by planar-cross stratified sandstone (Figure 8B) and planar laminated finer sands (Figure 8C). In beds with hummocky cross stratification, two types of hummocky cross stratification are present: isolated beds containing hummocks and swales (such as Figure 8D), usually in the lower part of the FA and amalgamated individual beds (such as Figure 8E) up to 40cm thick, capped by wave ripples, usually concentrated in the upper FA. Isolated beds generally have a larger wavelength (1-3 m) than amalgamated individual beds (0.2- 1 m). A sharp erosional lower boundary exists at the base of the FA and a gradational boundary is present between the two facies. This facies association shows strong lateral continuity throughout the region. Trace fossils included *Palaeophycus*, *Ophiomorpha*, *Planolites*, *Arenicolites* and *Skolithos*. A BI of 0-2 was recorded. Burrows were generally small and occasionally damaged or partially preserved (Figure 8 F). A *Skolithos* ichnofacies is interpreted based on the dominance of traces belonging to this group, although some elements of *Cruziana* are present (MacEachern & Bann, 2008).

Interpretation

Hummocky cross stratification indicates deposition by episodic storm events in water depths between the effective storm-wave base and fair-weather wave base

(Dott & Bourgeois, 1982; Duke, 1985; Keen et al., 2012). Individual HCS beds most likely formed in deeper conditions and as a result of larger storms and smaller amalgamated beds were a result of smaller, longer storms or water shallowing, most likely in the lower shoreface (Storms & Hampson, 2005). The intermittent preservation of trough-cross stratified, planar-cross stratified and laminated sands suggest that elements of the upper shoreface and nearshore bars are preserved. A wave dominated shoreline is interpreted for this FA. The occurrence of a *Skolithos* ichnofacies with some elements of *Cruziana* supports this interpretation (MacEachern & Bann, 2008). Deposition likely occurred in an open area where wave energy and storm intensity were high. Fluvial input was reduced or negligible at the time.

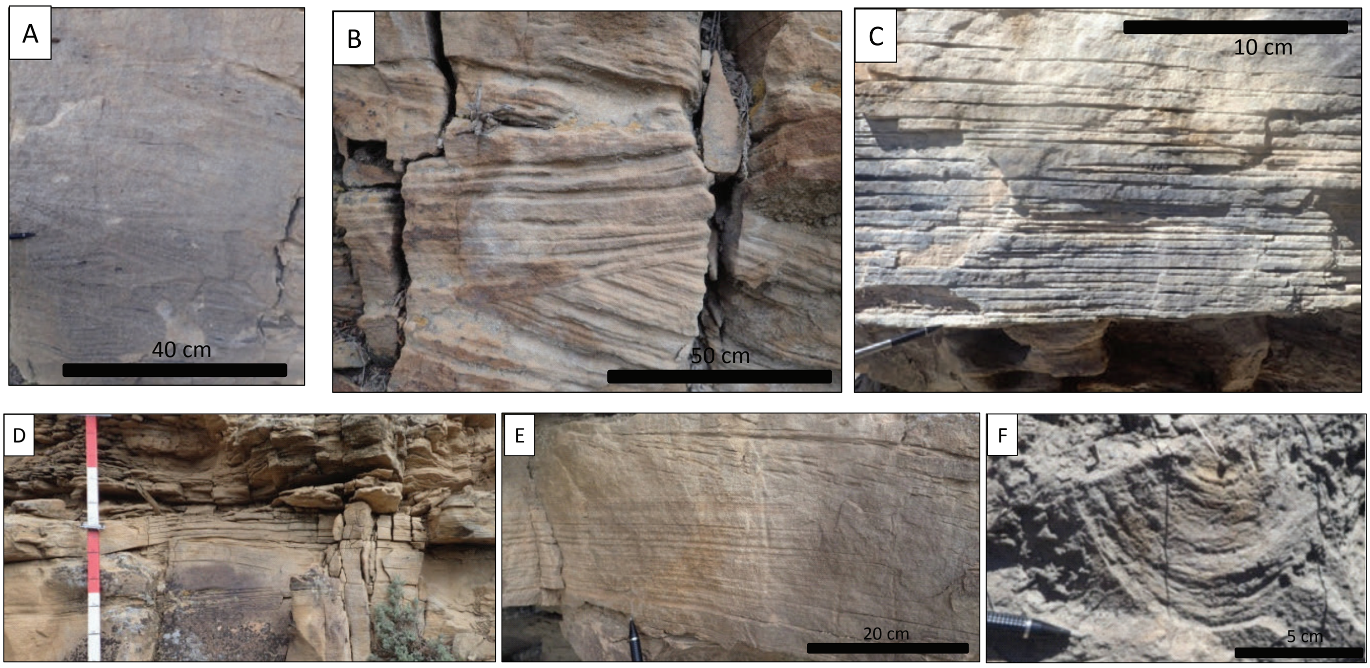


Figure 8: Field photos of Facies Association 5: Fine sand dominated by HCS and coarse trough- and planar-cross stratified sand (Lower shoreface and Upper shoreface) A- Pervasive hummocky cross stratification was observed throughout the FA. B- Trough-cross stratified coarse sandstone was preserved. C- Planar laminated fine sands. D- Isolated larger beds containing hummocks and swales. Red and white intervals are 15 cm and black marks are 10 cm on the Jacob staff. E- Amalgamated individual containing planar lamination overlain by hummocks and swales. F- Example of partially preserved Diplocraterion*. Other damaged and partially preserved burrows were observed also.*

Facies Association 6: Sharp scoured base upward fining sand

Description

Facies association 6 (FA 6) consists of a sharp or scoured based, upward fining succession ranging from medium-upper sandstone with minor granules and pebbles at the base to alternating silt and sand at the top. Rip-up clasts coupled with carbonaceous lag (Figure 9A) and compound cross stratification with granules and pebbles (Figure 9B) at the base of the FA are overlain by planar tabular cross-stratification (Figure 9C) and current ripple lamina (Figure 9D), topped by alternating siltstone and fine sand planar laminated stratification with current ripple lamina. Interbedded lenticular coal and mud strata of 1-5 cm (Figure 9E) with ripple structures and coal beds up to 10 cm are present at the top of the facies, along with interbedded planar laminated silt and mud. Mud draping on ripple forests is common higher in the FA, where occasional herringbone stratifications and synaereses cracks were also observed (Figure 9F). Scour surfaces are common within the facies and lateral accretion was observed. Lithofacies grade laterally and grain size is highly variable throughout the FA. Although the FA reaches a maximum of 6 m thickness, individual beds (0.5-2 m) are stacked and amalgamated (Holbrook, 2001) and preserved both with and without a full fining up sequence. The FA is laterally discontinuous and lenticular throughout the study area. Sparse *Arenicolites*, common *Planolites*, *Diplocraterion*, *Camborygma* (Figure 9G) and small *Scoyenia* (Figure 9H) were observed (BI=2-3), suggesting the occurrence of a *Scoyenia* and occasional proximal *Skolithos* Ichnofacies (MacEachern & Bann, 2008).

Interpretation

The dominantly upward fining nature, variation in structures and lateral accretion suggest an interpretation of meandering fluvial channel fill with minor tidal influence higher in the FA. Sparse evidence for tidal structures suggests no marine influence to only weak marine for the majority of deposition, which would occur on an upper delta plain to fully continental transitional setting. This interpretation is consistent with a *Scoyenia* and occasional proximal *Skolithos* ichnofacies (MacEachern & Bann, 2008). The presence of scour and fill structures suggest the incision of channels into a relatively immobile mud-rich substrate, while fining and thinning up patters suggest a progressive shallowing of water depth and decrease in depositional energy. Lateral accretion coupled with interbedded lenticular silts, muds and coals suggest the active formation of point bars and channel abandonment plugs. This FA shares some similarities with FA4, but cross-stratified beds within this facies were thicker, fining up patterns were more distinct, grain size was larger, trace fossils were different and lateral accretion was apparent (Figure 14B).

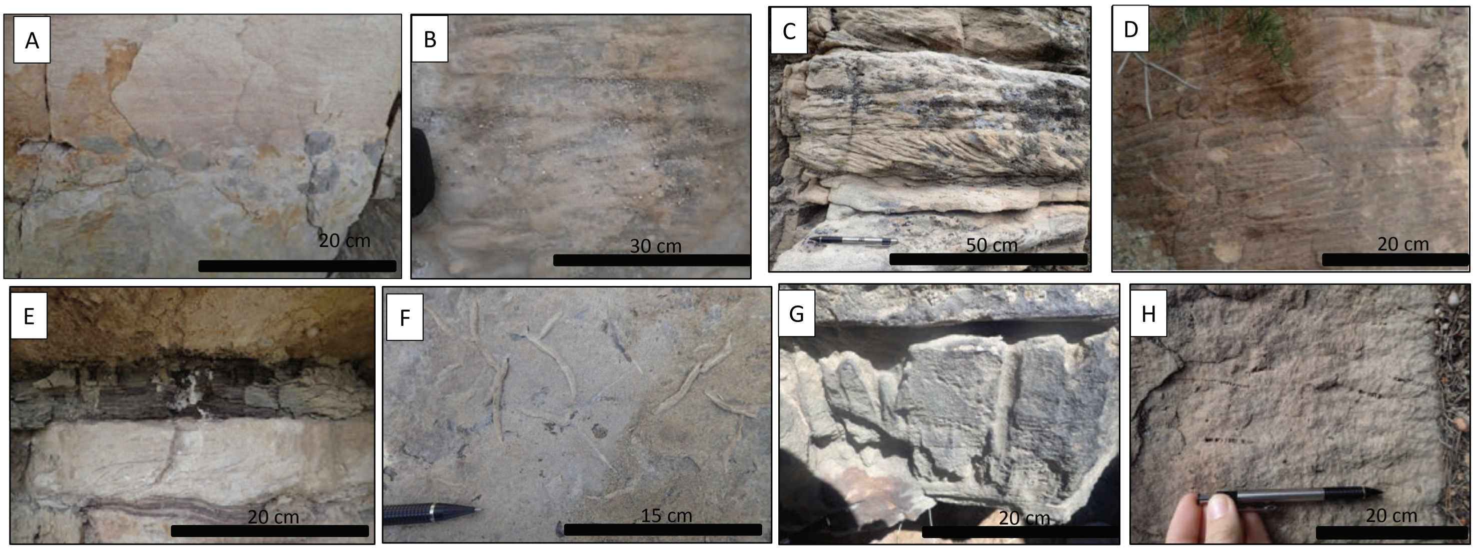


Figure 9: Field photos of Facies Association 6: Sharp based, upward fining heterolithic (Sinuous Fluvial Channel Upper delta plain to alluvial). A- Carbonaceous lag and rip-up clasts at the base of the succession. B- Granules and pebbles are present in cross-stratification at the base of the FA. C- Planar trough cross stratification. D- Current ripple stratification. E- Thin coal beds at the top of the FA. F- Synaereses cracks present between thin sand beds at the top of the FA. G- Interpreted Camborygma. *H- Interpreted Scoyenia. Also see Figure 14B for a larger scale snapshot.*

Facies Association 7: Upward thinning medium to coarse grained planar tabular sands

Description

Facies association 7 (FA 7) consists of a scoured base with rip up clasts and upward thinning amalgamated beds of upper-medium to coarse moderately rounded quartz arenite with abundant planar tabular cross stratification (Figure 10 A). Current ripple and wave modified current- ripple lamina exist right at the top of the FA. Asymmetric herringbone cross stratification is common toward the middle-top of the facies, with the alternate paleocurrent bed approximately half of less of the size of the dominant basal bed. Convolute bedding (Figure 10 B) and soft sediment deformation along foresets (Figure 10 C) was observed with discrete beds, often closer to the base of the FA. This FA is strongly bedded and grain size is relatively constant vertically and laterally throughout the facies, although grains become more well-rounded toward the top of the FA. The FA is up to 8 m thick, with beds of up to 120 cm at the base and as small as 20 cm at the top. This FA is lenticular and discontinuous in the region and incises into FA 2 and FA 3. Trace fossils are non-existent to rare (BI=0-0.5), with small isolated *Planolites* and *Skolithos* present in the very upper section of the FA.

Interpretation

The pervasiveness of highly structured planar tabular cross-stratification indicates deposition from subaqueous dunes that migrated as a result of strong currents. Although typical tidal indicators such as mudstone drapes, flaser and lenticular bedding and are absent, herringbone cross-stratification with bi-directional paleocurrents (Figure 14B) is a strong indicator of bi-directional currents most likely as a result of tidal action (Allen, 1980; Visser, 1980; Van den Berg et al., 2007). The uniform grain size, moderate degree of rounding and absence of mud may not have allowed for the development of heterolithic features and suggests a very high energy, clean source with rapid deposition. The absence of a well preserved trace fossil assemblage is consistent with deposition in a high-energy marine environment, potentially with brackish water conditions toward the top of the FA (MacEachern & Bann, 2008). FA7 was not present at all locations and was particularly thick (up to seven metres) in the southern section of the study area (Figure 11), with a more lenticular geometry than other FA's. This FA is interpreted to be amalgamated fluvial-dominated tidally influenced channel fill bars with minor wave reworking at the top of the FA. Amalgamation and internal scour has resulted in incomplete preservation of channel-fill, making assessment of true depositional channel dimensions difficult (Holbrook, 2001). A major drop in sea level followed by a rapid rise could be interpreted from this vertical stacking pattern (Shanely and McCabe, 1992; 1993; 1995; Blum and Törnqvist, 2001) given the proximity of the continent to the open ocean and interpreted multifaceted encroachment pattern of the seaway at the time of deposition.

5.5.2. Facies Successions, Key Surfaces and Stratigraphic Architecture

In the study area, key surfaces separate facies successions, which are composed of the previously described facies associations. Vertical facies successions can be traced laterally for kilometres throughout the study area (Figure 3). In some of the cliff-face exposures, three-dimensional reconstructions of stratigraphic architecture and facies-association distributions over several hundreds of metres have been interpreted (Figure 11, Figure 12; Figure 13). In this interpretation, facies associations are grouped into facies successions based on their separation by bounding surfaces. Figure 13 presents a simplified overview of the bounding surfaces and facies successions and facies associations present in each facies succession.

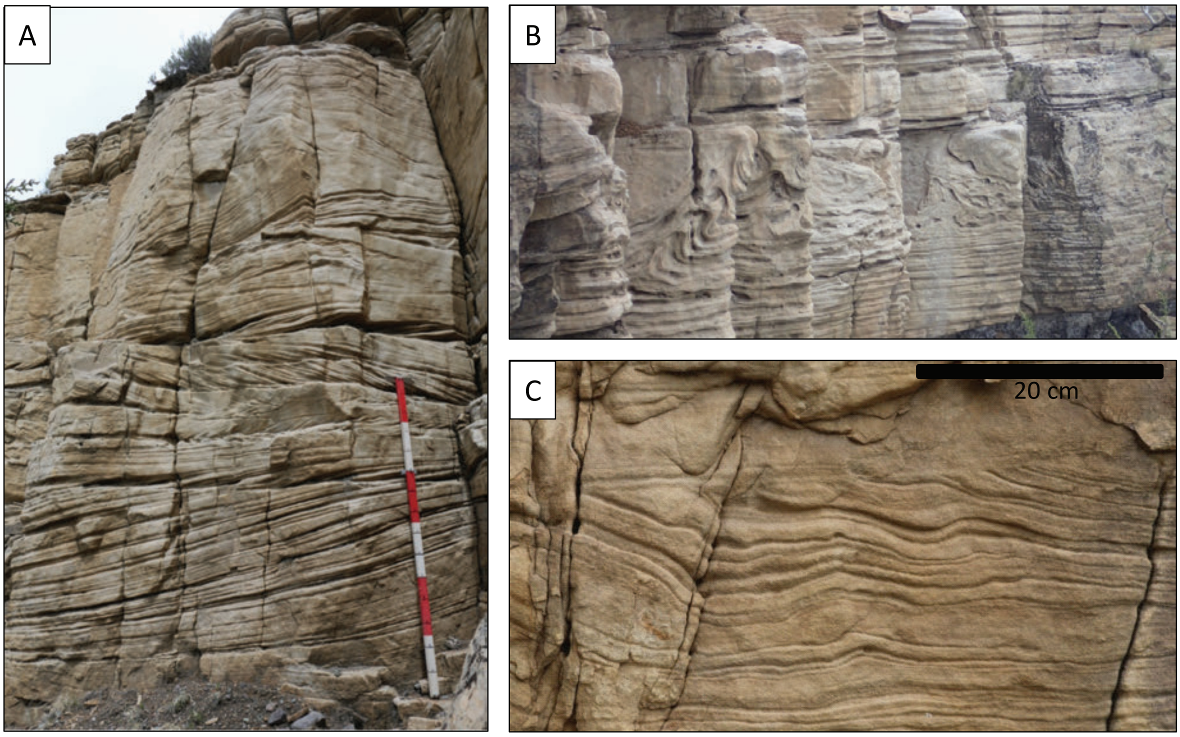


Figure 10: Field photos of Facies Association 7: Upward thinning medium to coarse grained planar tabular sands (High energy fluvial channel Incision of Upper delta plain). A- Typical field expression of FA7; amalgamated upper-medium to coarse sandstone with strong planar tabular stratification at the base and herringbone cross stratification toward the middle of the FA. Structures within this FA indicate potential deposition in a tidal setting. Red and white intervals are 15 cm and black marks are 10 cm on the Jacob staff. B- Convolute bedding within FA 7. Bed is 85 cm thick. C- Soft sediment deformation along foresets of cross-beds in FA7. Also see Figure 14B for a larger scale snapshot.

Facies Succession 0 (FS 0)

The base of this succession is in the Burro Canyon Formation. The transition between the Burro Canyon Formation and the Dakota Formation was gradual and not always clear, with the formations interbedded across the study area. Where observed, the transition was characterised by a change from fluvial coarse-grained green-tinted sands to FA3 and FA4 deposits. In some locations channels near the base of the Dakota Formation was erosional, as scour and rip up clasts were observed at the base of beds, but in others the transition was gradual, with interbeds from millimetre to centimetre scale observed. This facies succession was observed across the study area and had a thickness 2 m to 7 m with an average of 4 m. The boundary between the Dakota Formation and Burro Canyon Formation was clearer and the FA3 and FA4 deposits in this Facies succession were thicker in the northern section of the study area.

FS0 is interpreted to be dominated by fluvial and continental processes at the base. Non-deposition or erosion of transitional facies is inferred; however a clear ravinement or erosional surface was not observed. This may have been due to lack of exposure of this surface; mud from the overlying FA quite often washed down over this contact making it tough to trace laterally.

Facies Succession 1 (FS 1)

A series of upward thickening coarsening up successions characterise the lower part of the study interval, each comprising of FA 1, coupled with FA2 and FA4. The coarsening up successions are present above Facies Succession 0 in all sections across the study area. This facies succession has a maximum thickness of 18 m, a minimum thickness of 6 m and is typically between 10 to 12 m in thickness. Five coarsening up packages were recorded in the most northerly logged section of the study area, while three coarsening up sequences are preserved in the most southerly logged section. In the south, the final coarsening up section is incomplete and incised into, suggesting that the full section is not preserved in the area (Figure 14, Dutch Charlie B). FA1 typically grades horizontally into FA2 within this facies succession in the study area, and is sometimes capped by FA4.

FS1 is dominated by wave and tidal processes and is interpreted to have been deposited in a fully marine to marginal marine setting. The gradual transition from FA1 (prodelta) to FA2 (delta front) suggests gradual shallowing. The presence of FA4 suggests further shallowing as distributary channels generally mark the shallowest palaeowater depth in delta front successions (Li & Bhattacharya, 2014). A repeat of the cycle with a sharp based transition from FA4 back to FA1 suggests a sharp transition from delta front back to prodelta, which could indicate rapid flooding back of distributary channels. This back-flooding could be a result of sea-level rise and retrogradation, or of lobe avulsion and abandonment on a local scale. A detailed analysis of sediment supply and provenance may help to interpret controls on deposition.

Facies Succession 2 (FS 2)

The middle of the studied interval is comprised of FS 2 and is characterised by FA5 and FA6, sometimes topped with FA 3. This facies succession has a thickness between 12 m and 3 m with an average of 4-5 m. The facies succession is present in the majority of sections across the study area; it is relatively thin in the very north of the area and thickens toward the south. The base of the succession is interpreted to be a major sequence boundary. FS2 marks the start of fining up and blocky sequences, compared to FS1, where parasequences were generally coarsening up.

FS2 marks the beginning of fluvial dominated deltaic deposition within the formation, which grades up to wave and tide dominated deposition. The basal surface of FS2 is a likely candidate for an incised valley interpretation due to the rapid change in facies and the character of the incision surface at the base of the facies succession. However no other evidence for an incised valley was preserved and the incision depth is quite small compared to other systems. The sequence boundary may record erosion during lowering of relative sea-level and forced regression due to climate change.

Facies Succession 3 (FS 3)

The upper part of the interval is comprised primarily of FA 7. This facies succession has a thickness between 8 m and 0.5 m with an average of 2-3 m. It thickens toward the south and disappears toward the north, although the equivalent surface can be traced throughout the study area. The base of the succession is interpreted to be a sequence boundary. A sharp transition is observed between FA7 and the Mancos Shale.

Deposition of FS3 was dominated by fluvial and tidal processes. The nature of FA7 suggests rapid high energy deposition, making FS3 the most likely candidate for incised valley deposition. Deposits are also thicker than those of FS2. However, as with FS 2, within FS3 no other elements of incised valley deposition were observed.

Formation thickness and large scale trends

No significant change in thickness during the deposition of the Dakota Sandstone was observed in the study area (Figure 12). The small change that was observed (2-3 m) can be accounted for through depositional compaction. Although tectonic activity was widening and deepening the seaway, sea level was rising faster than sediment was depositing, resulting in a net transgression. Overall, four major regressive-transgressive packages are interpreted in a net transgressive setting (Figure 14). Regression and transgression was complex and most likely occurred on

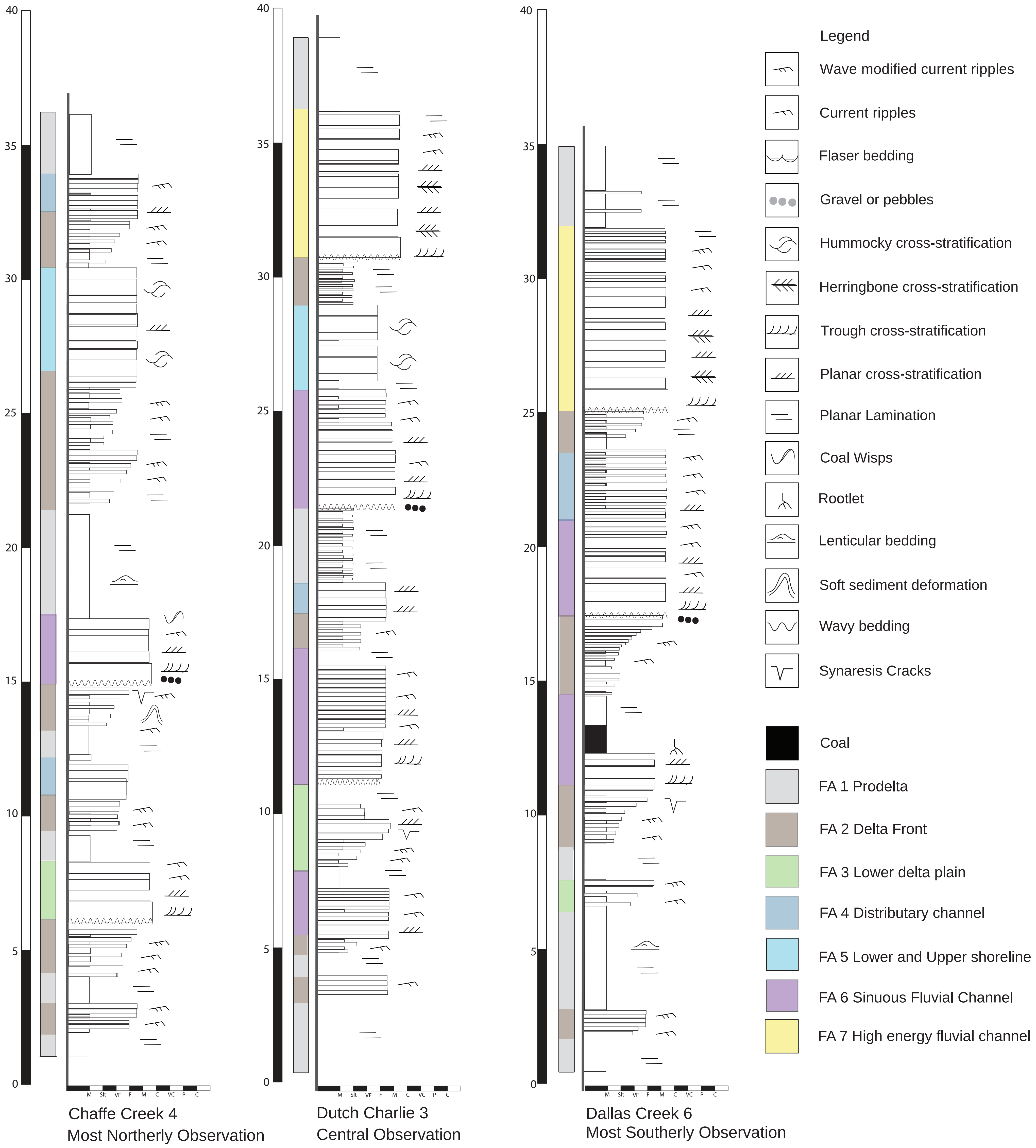


Figure 11: Three representative sedimentary logs depicting spatial facies variations for vertical successions observed in the Dakota Formation. Examples are taken from most northerly observation point, most southerly observation point and central observation point in order to get a representative spread of data. Legend contains facies associations and symbols used throughout this chapter. See Figure 3 for locations and Figure 4 for detailed facies associations data. Grain size abbreviations: M=mud, Slt=silt, VF= very fine sand, F= fine sand, M= medium sand, C= course sand, VC= very coarse sand, P= pebbles, C= cobbles.

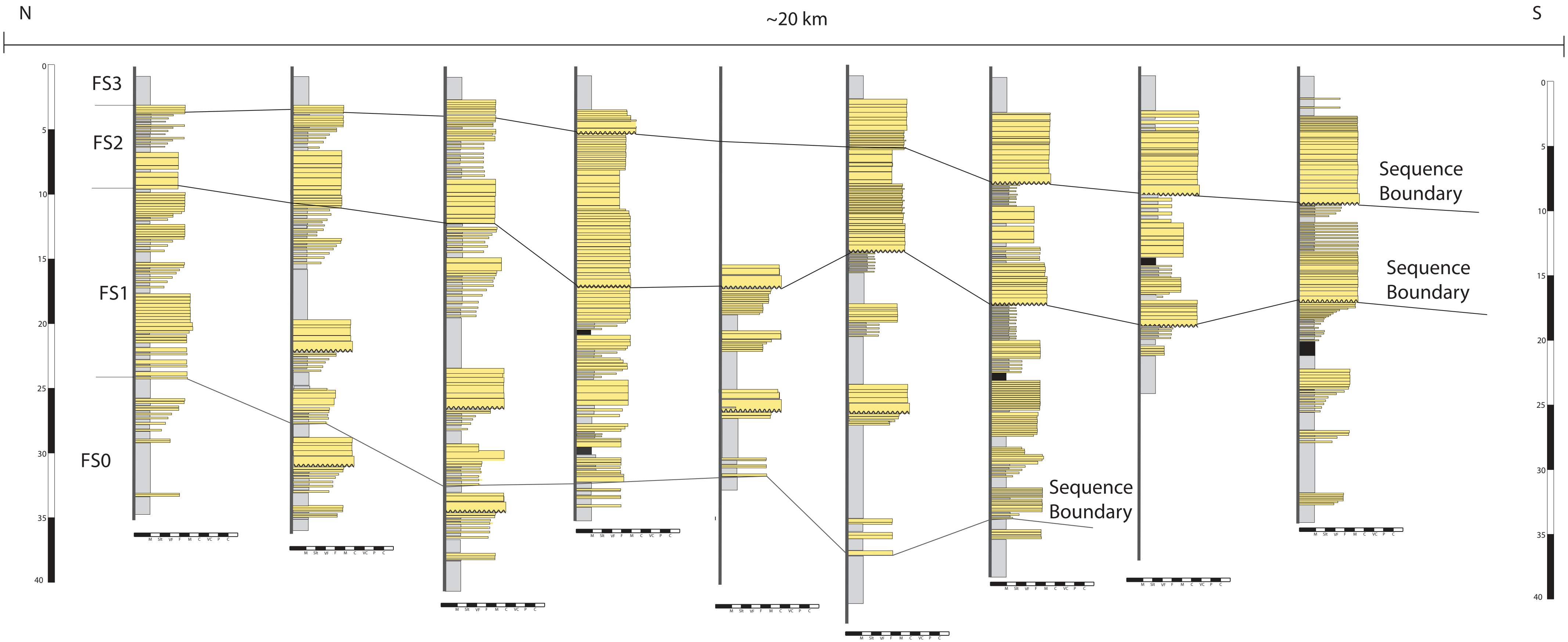


Figure 12: Correlation panel with representative stratigraphic logs from the north to the south or the study area. The base of the Mancos Shale and coincident top of the Dakota Formation (e.g. see Figure 2) is used as a datum. Key stratigraphic surfaces that have been mapped over the study area are shown. Yellow represents sands, grey represents muds and coals are shown in black. Grain size abbreviations: M=mud, Slt=silt, VF= very fine sand, F= fine sand, M= medium sand, C= course sand, VC= very coarse sand, P= pebbles, C= cobbles.

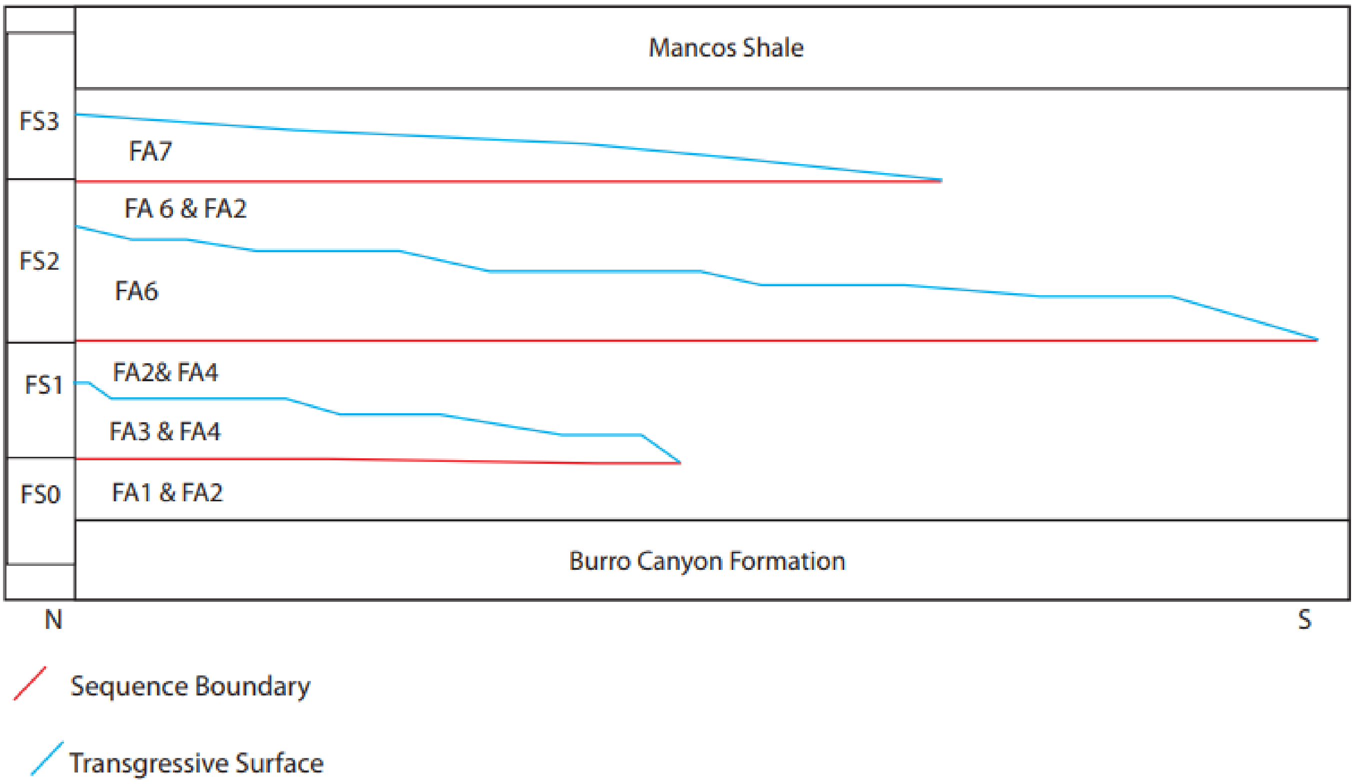


Figure 13: Simplified conceptual sequence stratigraphic sketch of the Dakota Formation approximately in a North-South orientation. Surfaces and facies successions correlate to those throughout Figure 14 and 15. FA is an abbreviation for Facies Association and FS is an abbreviation for Facies Succession. A Facies Association is made up of a grouping of several lithofacies and a Facies Succession comprises a grouping of Facies Associations.

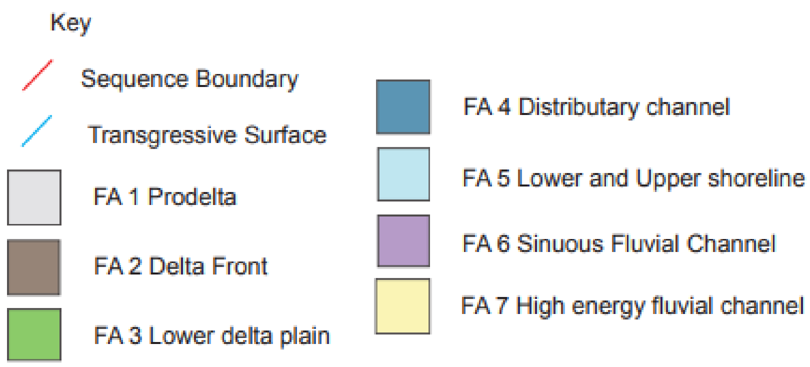
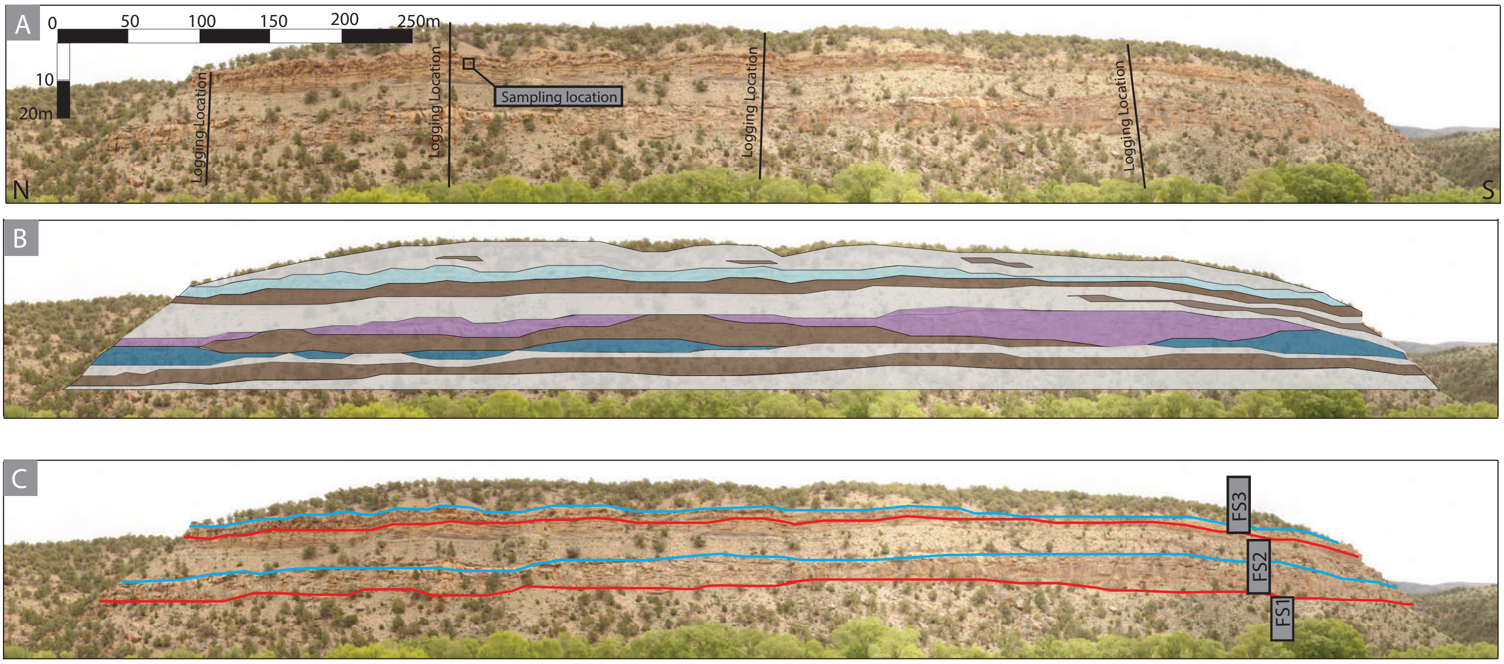
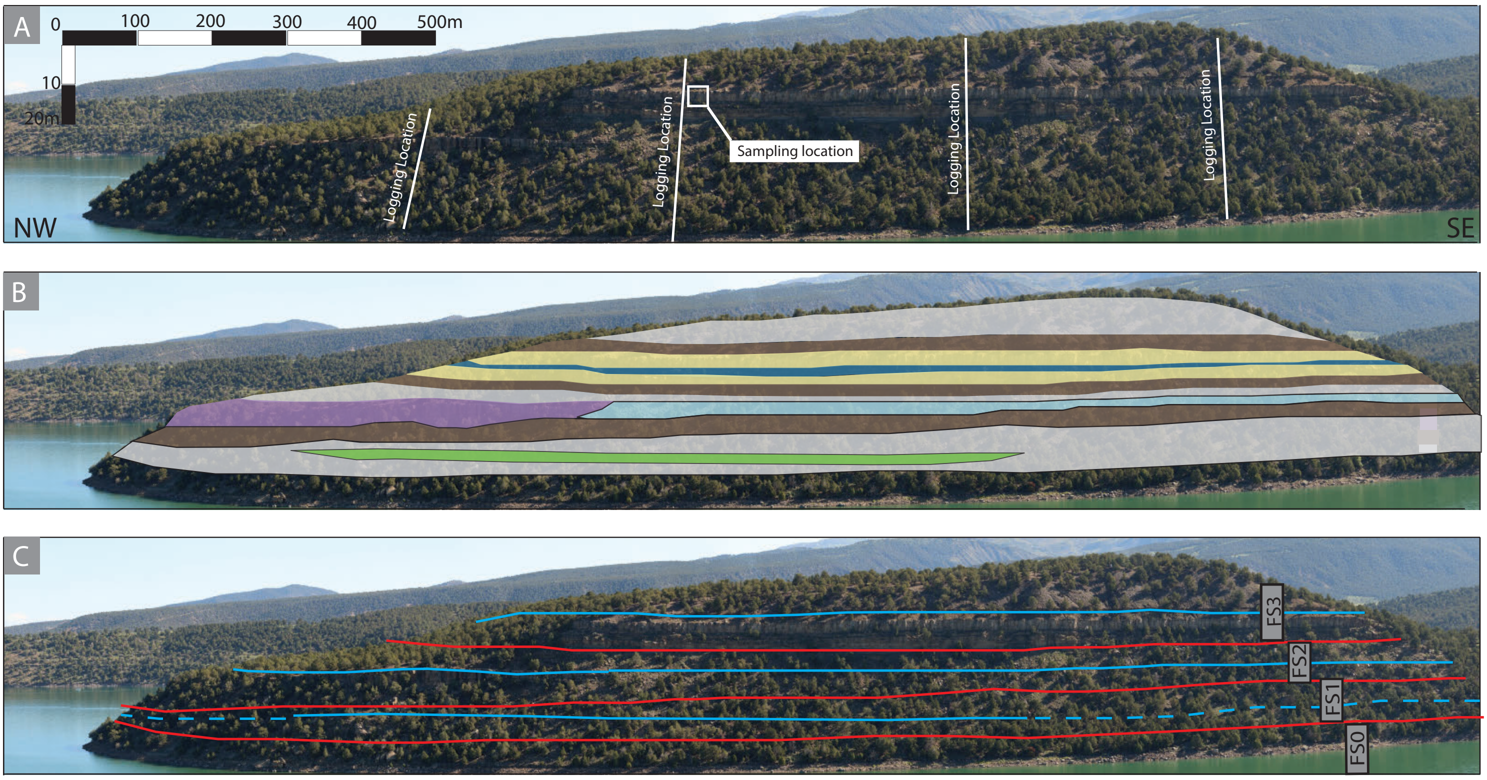


Figure 14A: Above and next page. For two locations: (A) High resolution photomosaic (Gigapan) of at selected sites with the locations of the measured sections marked. Additional observations were taken between logging locations. Sampling locations for detrital zircon analyses are marked. (B) Interpreted photomosaic with main facies highlighted. Facies correspond and use the same colour scheme as those described in Figures 4 to 11. (C) Overlain lines showing facies successions, sequence boundaries and transgressive surfaces.

Billy Creek #13



Dutch Charlie #40



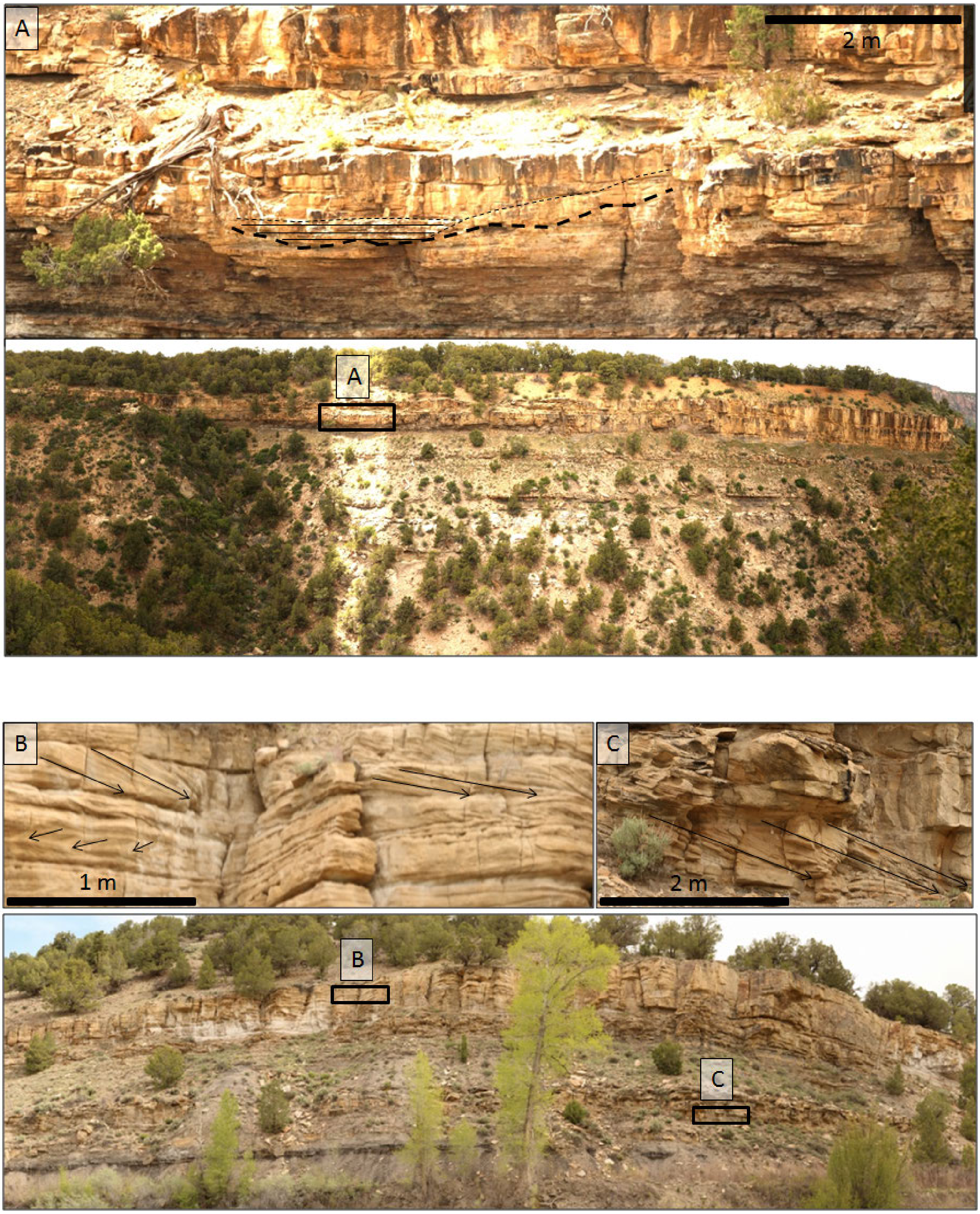


Figure 14B: Zoomed in snapshots of Gigapan photomosaics. A- Potential channel body feature. Bold dashed lines represent the base of the channel. Thin solid lines represent the basal sediments and the thin dashed line represents potential accretion and top of the basal sediments (FA 6). B- Bi-directional flow structures, indicating a potential tidal depositional environment. Arrows show the direction of the foresets (FA 7). C- Large scale cross bedding with arrows indicating direction of foresets (FA 6).

a number of scales. FS 2 is interpreted to preserve the broadest ranging regressive-transgressive event due to the depositional environment shift from delta front/prodelta to upper delta plain above tidal reach.

5.5.3. Sediment Provenance

Of 14 collected samples, seven yielded zircon grains. When considered together, grains yielded a small population of Mesoarchaean to Neoarchaean ages, some Paleoproterozoic detritus, Paleoproterozoic to Cambrian ages, a minor concentration in the Neoproterozoic, major detrital peaks in the Ediacaran to Cambrian and Carboniferous to Triassic and a final concentration of Triassic to Cretaceous-aged detritus (Figure 15A). The aggregate of all results can be separated into a series of populations based on major concentrations (Figure 15A).

Population A: Paleoproterozoic, Neoarchean and Mesoarchean Ages (3100–2100 Ma)

Paleoproterozoic, Neoarchean and Mesoarchean Ages age populations are represented by approximately 7% of the Dakota Formation zircons. These ages form peaks at 2650 Ma, 2645 Ma and 2440 Ma and have the highest relative concentration in samples Kd011, Kd010 and Kd004. These grains are most likely sourced from units of Precambrian, Paleozoic and Mesozoic age in the Sevier fold-and-thrust belt (Figure 1; Dickinson and Gehrels, 2009; Lawton et al., 2010).

Population B: Mesoproterozoic and Paleoproterozoic Ages (2100- 1500 Ma)

26% of the Dakota Formation zircons are represented by Mesoproterozoic and Paleoproterozoic Ages. Ages in this population form a major concentrated peak at 1660 Ma and a minor peak at 1890 Ma. A small group of older grains have ages of 2100-1900 Ma. Age peaks for the population are relatively highly concentrated in all samples except Kd001 and Kd004, where they are almost absent. In Kd001 the 1890 Ma peak is more prominent than in other samples.

Population B zircons are interpreted to have been predominately derived from the Mogollon Highlands in central Arizona (Figure 1). The 1890 Ma and 1660 Ma age peaks identified in most Dakota Formation samples are correlative with Mogollon Highlands Yavapai- Mazatzal basement rocks in central Arizona (Wasserburg and Lanphere, 1965; Lanphere, 1968; Anderson and Bender, 1989; Gleason et al., 1994; Hawkins et al., 1996; Spencer and Pecha, 2012) as well as potentially many less-exposed sedimentary units in the Sevier fold-and-thrust belt and throughout the southwestern United States (Dickinson and Gehrels, 2008; Laskowski et al., 2013). The smaller group of older grains (2100-1900 Ma) is most likely Sevier fold-and-thrust belt units, which contain grains of similar ages (Dickinson and Gehrels, 2009; Lawton et al., 2010), but the original source of the 1800-1600 Ma zircons is primarily interpreted to be an extensive metamorphosed magmatic belt that developed as a result of plate convergence during the Paleoproterozoic Mazatzal orogeny (Amato et al., 2008). The expansive distribution of this magmatic belt resulted in widespread exposures of 1800-1600 Ma in the Mogollon Highlands during the time of Deposition of the Dakota Formation.

Population C: Paleozoic through Neoproterozoic Ages (1500–800 Ma)

Paleozoic through Neoproterozoic Ages represent 45.6% of the Dakota Formation zircons. Ages in this population for a major peak around 1040 Ma as well as minor peaks around 900, 1180 and 1365 Ma. Large age peaks for this population are present in all of the samples, but particularly prominent in Kd001 and Kd004 and very small in Kd013.

Grenville ages (900–1250 Ma) are prominent in many units within the Sevier fold-and-thrust belt (Dickinson and Gehrels, 2008a, 2008b, 2009; Lawton et al., 2010; Lawton and Bradford, 2011). Peaks at 1180, 1040 and 900 most likely represent the recycling of Grenville orogenic detritus originally derived from eastern Laurentia. Additionally, Paleoproterozoic and Neoproterozoic ages originally derived from remnant magmatic arc sources in eastern Laurentia and Mexico are common in the Sevier fold-and-thrust belt (Dickinson and Gehrels, 2008b), so this is considered to be the most likely source for this sediment.

Population D: Neoproterozoic to Permian Ages (800-252 Ma)

Neoproterozoic to Permian Ages comprise 18.8% of the analysed Dakota Formation zircons. This age population is dominated by two age peaks. A major age peak for this population exists at 600 Ma. A relatively smaller peak occurs around 400 Ma. The 600 Ma peak is particularly prominent in Kd013 Kd010 and Kd007. The 400 Ma peak is particularly prominent in Kd004, Kd009 and Kd011. Where the 600 Ma peak is prominent, the 400 Ma peak is generally small or absent, and the opposite is true, with the exception of Kd004, where both peaks are equally prominent.

Potential sources for the 600 and 400 Ma sediment are to the southeast, lying in the same direction from the depositional sites as the East Mexico magmatic arc. These include both Laurentian and Oaxaquian Grenville provinces, the intervening

Ouachita Paleozoic orogen, and the more distant Yucatãn–Campeche block, where both Paleozoic and Neoproterozoic bedrock of these ages exists (Krogh et al. 1993; Steiner and Walker 1996).

Population E: Triassic to Cretaceous Ages (252-94 Ma)

Triassic to Cretaceous ages comprise 2.6% of the analysed Dakota Formation zircons. Three peaks occur. A major peak occurs at 96 Ma and two minor peaks occur at 147 and 235 Ma. These peaks are particularly prominent in Kd004, Kd011 and Kd013, but absent in Kd010. This could be due to the small concordant sample size in Kd010 (n=32), although KD013 had a similar amount of concordant grains (n=41), but this population was still present in that sample.

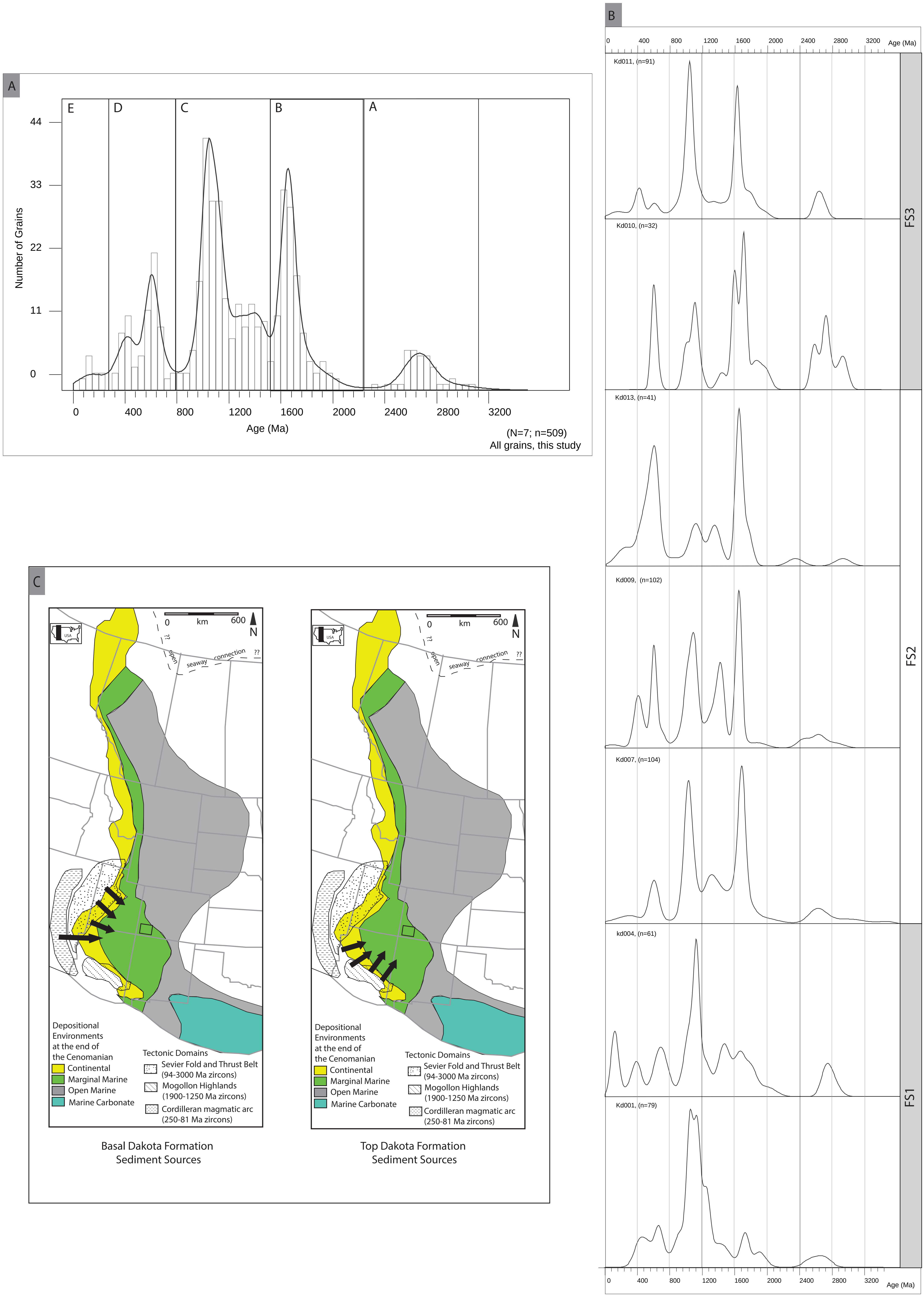
The youngest concordant age is 94.4 ± 3.1 Ma (1σ error youngest single grain method, 95% confidence interval, as in Dickinson and Gehrels, 2009) was obtained from a volcanic grain in Kd011. This is slightly older than the maximum depositional age of 93.9 Ma reported, consistent with the Dakota Formation being of Late Cenomanian age (Figure 14). This grain was from a fluvial sample taken in the middle of the Formation, so it is likely that at least half of the deposition for the formation occurred after 94.4 ± 3.1 Ma. This age is quite close to the Cenomanian/Turonian age boundary, 93.9 Ma, so deposition of the Dakota Formation at this location could have potentially at least partially occurred in the Turonian.

A potential source for the 235 Ma age peak is Mesozoic foreland basin strata containing arc-derived zircons (Dickinson and Gehrels, 2009). Grains composing the 147 Ma peak were likely derived from 147 Ma intrusions in the Mojave Desert region of southern California (Schermer and Busby, 1994; Gerber et al., 1995; Walker et al., 2002). Late Cretaceous ages forming the 96 Ma peak were most likely originally derived from the Sierra Nevada batholiths (Coleman and Glazner, 1997).

Temporal Age Variation

Based on provenance data from this study the Dakota Formation appears to have undergone a substantial provenance change during deposition (Figure 15 B). Facies Succession 1 samples are dominated by a population of zircons at 1040 to 1080 Ma. Other smaller populations exist, but these peaks are minor. These Grenvillian ages (900–1250 Ma) are interpreted to have been sourced from the Sevier fold-and-thrust belt, so it is most likely that this was the primary source for deposition during this time (Figure 15 C). In the younger FS3, and to some degree in FS2, a peak around 1660 Ma becomes prominent and population D zircons become more common (Figure 15 B). These 1660 Ma zircons are interpreted to have been predominately derived from the Mogollon Highlands in central Arizona, whilepotential sources for the 600 and 400 Ma sediment are within the Cordilleran magmatic arc to

Figure 15: A. Relative probability plot containing ages from all detrital zircons in this study (N=7 samples, n=509 concordant grains). Left vertical axis corresponds to number of grains in each age bin (age bins span 100 m.y.) Age populations are denoted by white shaded bars. Chart is annotated with populations A-E as discussed in the text. B. Relative probability plots for all detrital zircons samples analysed in this study (N=7). Left vertical axis corresponds to number of grains in each age bin (age bins span 100 m.y.). Horizontal axis corresponds to age of samples. Number of analyses (n) and sample number is shown for each sample. All data is available in supplementary data files. C. Dakota Formation sediment input sources based on interpreted detrital zircon data.


A
E
D
C
B
A
Number of Grains
44
33
22
11
0
0
400
800
1200
1600
2000
2400
2800
3200
Age (Ma)
(N=7; n=509)
All grains, this study
B
Age (Ma)
Kd011, (n=91)
Kd010, (n=32)
Kd013, (n=41)
Kd009, (n=102)
Kd007, (n=104)
kd004, (n=61)
Kd001, (n=79)
FS3
FS2
FS1
C
km
600
N
open
seaway
connection
??
USA
Depositional Environments at the end of the Cenomanian
Continental
Marginal Marine
Open Marine
Marine Carbonate
Tectonic Domains
Sevier Fold and Thrust Belt (94-3000 Ma zircons)
Mogollon Highlands (1900-1250 Ma zircons)
Cordilleran magmatic arc (250-81 Ma zircons)
Basal Dakota Formation Sediment Sources
Top Dakota Formation Sediment Sources

the southeast (Figure 15 C). This change in provenance suggests that changes related to upstream fluvial dynamics could have had an effect on the sedimentology, stratigraphy and depositional architecture of the Dakota Formation.

5.6. Discussion

The Cenomanian Dakota Formation exposed between Ridgway and Montrose (Figure 1) was deposited in a net transgressive mixed influence continental to marine environment. In this study seven facies associations, grouped into four facies successions, are described (see Figure 4 for summary). These facies successions represent progradational and retrogradational sediment packages deposited during the initial net transgression of marine waters on to the North American Continent to form the Western Interior Seaway (WIS). The preserved sediment pattern indicates that the transgression was most likely complex and occurred in at least four stages (Figure 14), with a change in sediment provenance throughout the transgression event (Figure 15).

The Dakota Formation gives an example of a complex multi-stage initial transgression where marine waters encroach onto a content to form an epicontinental or epeiric seaway. Epicontinental or epeiric seaways have been interpreted to have existed throughout geological time. These seaways are thought to have been present during the Late Ordovician, late Silurian to Early Devonian, the late Devonian to mid Pensylvanian, the mid- Jurassic, the Cretaceous and the Carboniferous-Permian glacial intervals mainly as a result of high sea level and low tectonic relief (Miall et al., 2008). The Dakota Formation is a good example of the initial transgression phases and would be a useful analogue for interpreting similar deposits in the subsurface.

Within separate facies successions, the Dakota Formation is comparable to all of five types of transgressive facies patterns commonly recognised (Cattaneo and Steel, 2002) but most likely represents a stepped transgression surface (Swift et al., 1991). In this case sediment supply, probably initially from the tectonically active Sevier thrust, temporarily overbalances the relative rate of sea level rise, resulting in an a preserved upward offset series of transgressive surfaces, each separated by brief progradational pulses of sediment. The resultant deposits are a succession of interfingering of marine and continental deposits, organised as a series of backstepping series (e.g. Siggerud and Steel, 1999). In this case, the slightly offset (landwards) stacking of successive transgressive surfaces results in aggradation of the net transgressive formation (Olsen et al., 1995; Siggerud and Steel, 1999; Cattaneo and Steel, 2002).

The four stages of transgression within the Dakota Formation at the study site (Figure 14) are characterised by transitions from fluvial to distal marine, marginal marine to distal marine, upper delta plain (above tidal influence) to distal marine and upper delta plain to offshore depositional settings. Sequence stratigraphic models proposing sand deposits preserved in incised valleys during transgressions (e.g. Dalrymple, 1992; Dalrymple et al., 1992; Posamentier & Allen, 1999) are not ideal for describing the Dakota Formation, as other elements of incised valleys (interfluves etc) are not observed. Sequence stratigraphic models and interpretations with less influence on incised valleys as a mechanism for sand preservation (Gilbert, 1885; Sanders and Kumar, 1975, Swift et al., 1991, Nummedal et al., 1993, Swift and Thorne, 1991) are a better fit for the Dakota Formation, potentially due to the relatively low basin gradient and piecewise nature of the transgression at the time of deposition.

Some features of the Dakota Formation are comparable with modern deposits, however the range of high-latitude well studied transgressive modern back barriers and estuary systems (e.g. Van Straaten & Kunen, 1957; Oomkes & Terwindt, 1960; Van Straaten, 1961; Evans, 1965; Reineck, 1967; Terwindt, 1971) do not fully capture the smaller scale or complexity of transgressions in epicontinental or epeiric seaways. Compared to these well-studied settings the Dakota Formation preserves thinner and more fluvially-influenced deposits. The modern Mississippi Delta, which is similar to the Dakota Formation in terms of fluvial and tidal controls (Coleman and Prior, 1981) preserves fluvial-deltaic sequences between 10 to 50 m thick (Penland et al, 1988). Fluvial-deltaic facies sequences of deltaic deposits within the Dakota Sandstone are approximately 5 m thick. The Dakota Formation sands were deposited on an epicontinental or epeiric seaway as opposed to a true continental shelf. The continental shelf has more accommodation space compared to an epicontinental or epeiric seaway shelf, and this distinction would be particularly notable early in the life of the epicontinental or epeiric seaway formation.

The Mississippi Delta (Coleman and Prior, 1981) as well as the commonly studied modern back barriers and estuary systems (e.g. Van Straaten & Kunen, 1957; Oomkes & Terwindt, 1960; Van Straaten, 1961; Evans, 1965; Reineck, 1967; Terwindt, 1971) have a large, stable source river with consistent provenance. The Dakota Formation sands had a changing sediment source during deposition. Irregular discharge as the catchment areas transitioned may have resulted in periods of non-deposition and lobe flooding within the Dakota Formation. This suggests localized, autocyclic abandonment of parts of the delta as an important local control on deposition.

5.7. Conclusion

The Dakota Formation is a net transgressive deltaic unit that preserves the complex Early Cretaceous initial transgression of marine waters which form the Western Interior Seaway (WIS). Deposits of the Dakota Formation exposed on the cliff face of the Uncompahgre Plateau between the town of Montrose and Ridgway, south west Colorado have not previously been described and interpreted in detail. In this study, seven facies associations are interpreted to have been preserved in the Dakota Formation in the study area. Four regressive-transgressive sequences are interpreted. These sequences are described in terms of facies successions.

A millimetre to sub millimetre interbedded light grey to very dark grey claystone package with mudstone and occasional siltstone beds was interpreted as prodelta deposits. Together with an upward coarsening package with gray silty shale and lower-medium sand beds at base, as well as medium-upper grained cross bedded quartz arenite at top, interpreted as delta front deposits, this facies association forms facies succession zero, at the base of the Dakota Formation. Centimetre scale dark grey silty shale irregularly interbedded with thick beds of fine to medium grained quartz arenite, some carbonaceous and coal layers were interpreted as delta plain deposits. These and delta front deposits were the primary facies associations in facies succession one. Sharp concave upward based, medium-grained quartz arenite occasionally topped by non-continuous coal, siltstone or claystone beds, interpreted as distributary channels were common throughout the two basal facies successions. A sharp based, upward fining succession ranging from with minor granules and pebbles at the base to alternating silt and sand at the top graded into a lower-fine grained arenite and upper fine to medium grained sandstone overlain by planar-cross bedded sandstone and laminated fine sands with pervasive hummocky cross stratification. These facies, along with some delta front deposits are interpreted as the second facies succession in the study area. A high energy fluvial dominated channel, consisting of a scoured base, upward thinning amalgamated beds of upper-medium to coarse moderately rounded quartz arenite was interpreted as a third and final facies succession in the study area.

A marked change in provenance is evident from the base to the top of the Dakota Formation. The transition between catchment areas may have resulted in periods of non-deposition and localised, autocyclic abandonment of parts of the delta, which was an important local control on deposition. Wave, tidal and fluvial influences were evident, with the dominant process changing between facies associations as the depositional system evolved. Changes in rate of sediment supply, initially from the tectonically active Sevier thrust, and the encroachment of marine waters onto the continent are recorded in this complex multi-stage initial transgressive package, which records the beginning of the formation of the epicontinental Western Interior Seaway.

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5.9. References

Ainsworth, R.B., Vakarelov, B.K., Nanson, R.A., 2011. Dynamic Spatial and Temporal Prediction of Changes in Depositional Processes on Clastic Shorelines: Toward Improved Subsurface Uncertainty Reduction and Management. AAPG Bulletin, v. 95, p. 267-297.

Allen, J.R.L., 1980. Sand waves: a model of origin and internal structure. Sed. Geol., 26, 281–328.

Amato, J.M., Boullion, A.O., Serna, A.M., Sanders, A.E., Farmer, G.L., Gehrels, G.E., Wooden, J.L., 2008. Evolution of the Mazatzal Province and the timing of the Mazatzal Orogeny: Insights from U-Pb geochronology and geochemistry of igneous and metasedimentary rocks in southern New Mexico. Geological Society of America Bulletin, v. 120, p. 328–346.

Anderson, J.L., Bender, E.E., 1989. Nature and origin of Proterozoic A-type granitic magmatism in the south-western United States of America. Lithos, v. 23, p. 19–52.

Aschoff, J.L. Steel, R.J., 2011, Anatomy and development of a low-accommodation clastic wedge, upper Cretaceous, Cordilleran Foreland Basin, USA. Sed. Geol., 236, 1–24.

Bartleson, B., 1994. Dakota Sandstone and associated rocks near Gunnison, Colorado: Geological Society of America, Rocky Mountain Section, 46th annual meeting. Abstracts with Programs Geological Society of America, v. 26, p. 3.

Barton, M.D., 1994. Outcrop characterization of architecture and permeability structure in fluvial–deltaic sandstones, Cretaceous Ferron Sandstone, Utah [Ph.D. thesis]: University of Texas: Austin, 259 p.

Bhattacharya, J.P. and J.A. MacEachern, 2009. Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: JSR, v. 79/4, p. 184-209.

Bhattacharya, J.P., and Walker, R.G., 1992. Deltas, in Walker, R.G., and James, N.P., eds., Facies Models: Response to Sea Level Change: Geological Association of Canada, p. 195–218.

Blakey, R. C., and P. J. Umhoefer, 2003. Jurassic-Cretaceous paleogeography, terrane accretion, and tectonic evolution of western North America: Geological Society of America, 2003 annual meeting. Abstracts with Programs Geological Society of America, v. 35, p. 558.

Blum, M. D., and T. E. Törnqvist, 2000. Fluvial responses to climate and sea-level change: A review and look forward: Sedimentology, v. 47, p. 2–48.

Burbank, W. S., 1930. Revision of geologic structure and stratigraphy in the Ouray District of Colorado, and its bearing on ore deposition: Proceedings of the Colorado Scientific Society, v. 12, p. 151-232.

Carter, W. D., 1957. Disconformity between lower and upper Cretaceous in western Colorado and eastern Utah: Geological Society of America Bulletin, v. 68, p. 307-314.

Cattaneo, A. and R. J. Steel., 2002. Transgressive deposits: a review of their variability. Earth Science Reviews, 1277, 1-43.

Choi, K.S., Dalrymple, R.W., Chun, S.S. and Kim, S., 2004. Sedimentology of Modern, Inclined Heterolithic Stratification (IHS) in the Macrotidal Han River Delta, Korea. J. Sed. Res., 74, 677–689.

Coleman, D.S., and Glazner, A.F., 1997. The Sierra Crest magmatic event: Rapid formation of juvenile crust during the Late Cretaceous in California. International Geology Review, v. 39, p. 768–787

Coleman, J. M., and D. B. Prior, 1981. Deltaic Environments of Deposition: The American Association of Petroleum Geologists, v. 31, p. 139-178.

Cross, T. A., and R. H. Pilger Jr., 1978. Tectonic controls of late Cretaceous sedimentation, western interior, USA, Nature, 274, 653 – 657, 1978.

Dalrymple R. W., 2006. Incised valleys in space and time: an introduction to the volume and an examination of the controls on valley formation and filling. In: Dalrymple RW. Leckie DA, Tillman RW (eds) Incised valleys in space and time. SEPM special publications 85. Society for Sedimentary Geology, Tulsa, pp 5-12.

Dalrymple, R.W., 1992. Tidal depositional systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models—Response to Sea Level Change. Geological Association of Canada Publications, pp. 195 – 218.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology 62, 1130 – 1146.

DeCelles, P. G., 1994. Late Cretaceous–Paleocene synorogenic sedimentation and kinematic history of the Sevier thrust belt, northeast Utah and southwest Wyoming: Geological Society of America Bulletin, v. 106, p. 32–56.

Devine, P.E., 1991. Transgressive origin of channelled estuarine deposits in the Point Lookout Sandstone, North-western New Mexico: a model for Upper Cretaceous, cyclic regressive parasequences of the U.S. Western Interior. American Association of Petroleum Geologists Bulletin 75, 1039 – 1063.

Dickinson, W.R., and Gehrels, G.E., 2008a. Sediment delivery to the Cordilleran foreland basin: Insights from U-Pb ages of detrital zircons in Upper Jurassic and Cretaceous strata of the Colorado Plateau. American Journal of Science, v. 308, p. 1041–1082.

Dickinson, W.R., and Gehrels, G.E., 2008b. U-Pb ages of detrital zircons in relation to paleogeography: Triassic paleodrainage networks and sediment dispersal across southwest Laurentia. Journal of Sedimentary Research, v. 78, p. 745–764.

Dickinson W.R., Gehrels G.E., 2009. Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database. Earth and Planetary Science Letters, v. 288, p. 115–125.

Dott, R.H. and Bourgeois, J., 1982. Hummocky stratification: significance of its variable bedding sequences. Geol. Soc. Am. Bull., 93, 663–680.

Duke, W.L. 1985. Hummocky cross-stratification, tropical hurricanes, and intense winter storms. Sedimentology, 32, 167–194.

DuMars, A.J. 2002. Distributary mouth bar formation and channel bifurcation in the Wax Lake Delta, Atchafalaya Bay, Louisiana. M.S. thesis, Louisiana State University, 88 p.

Elliott, T., 1978. Deltas, in Reading, H.G., ed., Sedimentary Environments and Facies: New York, Elsevier, p. 97–142.

Evans, G. 1965. Intertidal flat sediments and their environments of deposition in the Wash. J. Geol. Soc., 121, 209-240.

Fisk, H.N., 1961. Bar-finger sands of the Mississippi delta, in Geometry of Sandstone Bodies: American Association of Petroleum Geologists, 45th Annual Meeting: Atlantic City, New Jersey, April 25–28, 1960, p. 29–52.

Fouch, T.D., Lawton, T.F., Nichols, D.J., Cashion, W.B. and Cobban, W.A.. 1983. Patterns and timing of synorogenic sedimentation in Upper Cretaceous rocks of central and northeast Utah. In: Mesozoic Palaeogeography of West-Central United States (Eds M.W. Reynolds and E.D. Dolly), pp. 305–336. Rocky Mountain Section, SEPM Denver, Colorado.

Gerber, M.E., Miller, C.F., and Wooden, J.L., 1995. Plutonism at the interior margin of the Jurassic magmatic arc, Mojave Desert, California, in Miller, D.M., and Busby, C., eds., Jurassic Magmatism and Tectonics of the North American Cordillera. Geological Society of America Special Paper 299, p. 351–374.

Gilbert, 1885. Gilbert's Topographic Features of Lake Shores. The American Naturalist, 20(7), 626-628.

Gleason, J.D., Miller, C.F., Wooden, J.L., and Bennett, V.C., 1994, Petrogenesis of the highly potassic 1.42 Ga Barrel Spring pluton, southeastern California, with implications for mid-Proterozoic magma genesis in the south-western USA. Contributions to Mineralogy and Petrology, v. 118, p. 182–197.

Gomez-Veroiza, C.A., Steel, R.J. 2010. Iles clastic wedge development and sediment partitioning within a 300-kmfluvial to marine Campanian transect (3 m.y.), Western Interior seaway, south-western Wyoming and northern Colorado. AAPG Bull., 94, 1349–1377.

Gustason, E. R. 1989. Stratigraphy and sedimentology of the middle Cretaceous (Albian Cenomanian) Dakota Formation, south-western Utah. Ph.D. dissertation, University of Colorado, Boulder, Colorado, 376 pp.

Gustason, E. R., and E. G. Kauffman, 1985. The Dakota Group and the Kiowa- Skull Creek Cyclothem in the Canon City-Pueblo area, Colorado. In L. M. Pratt, E. G. Kauffman, and F. Zelt (ed.), Soc. Econ. Palaeontologists, Mineralogists, Field Trip Guidebook No. 4; 1985 Midyear Meeting, Golden, CO. p. 72-89.

Hail, W. J., Jr., 1989. Reconnaissance geologic map of the Ridgway quadrangle, Ouray County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2100.

Hampson, G.J., Gani, M.R., Sharman, K.E., Irfan, N., Bracken, B., 2011. Alongstrike and down-dip variations in shallow-marine sequence stratigraphic architecture: Upper Cretaceous Star Point Sandstone, Wasatch Plateau, Central Utah, USA: Journal of Sedimentary Research, v. 81, p. 159–184.

Hansen, C. D., J. A. MacEachern, 2005. Along-strike ichnological and sedimentological variations in a mixed wave- and river-influenced delta lobe, Upper Cretaceous Basal Belly River Formation, Central Alberta.: MacEachern, J. A., Bann, K. L., Gingras, M. K., and Pemberton, S. G., eds., Applied Ichnology Short Course #11 Notes, AAPG and SEPM Conference, Calgary, Alberta, 16 p.

Hawkins, D.P., Bowring, S.A., Ilg, B.R., Karlstrom, K.E., Williams, M.L., 1996. U-Pb geochronologic constraints on the Paleoproterozoic crustal evolution of the Upper Granite Gorge, Grand Canyon, Arizona. Geological Society of America Bulletin, v. 108, p. 1167–1181.

Holbrook, J.M., 2001. Origin, genetic interrelationships, and stratigraphy over the continuum of fluvial channel-form bounding surfaces: An illustration from middle Cretaceous strata, south-eastern Colorado: Sedimentary Geology, v. 124, p. 202–246.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology, 211, 47–69

Jordan, T.E., 1981. Thrust loads and foreland basin evolution, Cretaceous, western United-States. Am. Assoc. Petrol. Geol., 65, 2506–2520.

Kamola, D. L., and J. C. Van Wagoner, 1995. Stratigraphy and facies architecture of parasequences with examples from the Spring Canyon Member, Blackhawk Formation, Utah.;

Sequence stratigraphy of foreland basin deposits; outcrop and subsurface examples from the Cretaceous of North America: AAPG Memoir, v. 64, p. 27-54.

Keen, T.R., Slingerland, R.L., Bentley, S.J., Furukawa, Y., Teague, W.J., Dykes, J.D. 2012. Sediment Transport on Continental Shelves: Storm Bed Formation and Preservation in Heterogeneous Sediments. In: Sediments, Morphology and Sedimentary Processes on Continental Shelves: Advances in Technologies, Research, and Applications (Eds M.Z. Li, C.R. Sherwood and P.R. Hill), IAS Spec. Publ., 44, 295–310.

Krogh, T. 1993. High precision U-Pb ages for granulite metamorphism and deformation in the Archean Kapuskasing structural zone, Ontario: Implications for structure and development of the lower crust. Earth and Planetary Science Letters, 119(1), 1-18.

Lanphere, M.A., 1968. Geochronology of the Yavapai Series of central Arizona. Canadian Journal of Earth Sciences, v. 5, p. 757–762.

Laskowski, A.K., DeCelles, P.G., and Gehrels, G.E., 2013. Detrital zircon geochronology of Cordilleran retroarc foreland basin strata, western North America. Tectonics, v. 32, p. 1027–1048.

Lawton, T.F., and Bradford, B.A., 2011. Correlation and provenance of Upper Cretaceous (Campanian) fluvial strata, Utah, USA, from zircon U-Pb geochronology and petrography. Journal of Sedimentary Research, v. 81, p. 495–512.

Lawton, T.F., Hunt, G.J., and Gehrels, G.E., 2010. Detrital zircon record of thrust belt unroofing in Lower Cretaceous synorogenic conglomerates, central Utah. Geology, v. 38, p. 463–466.

Legler, B., Hampson, G.J., Jackson, C.A., Johnson, H.D., Massart, B.Y.G., Sarginson, M. and Ravnås, R. 2014. Facies Relationships and Stratigraphic Architecture of Distal, Mixed Tide- and Wave-Influenced Deltaic Deposits: Lower Sego Sandstone, Western Colorado, U.S.A. J. Sed. Res., 84, 605–625.

Legler, B., Johnson, H.D., Hampson, G.J., Massart, B.Y.G., Jackson, C.A., Jackson, M.D., El-Barkooky, A. and Ravnås, R. 2013. Facies model of a fine-grained, tide-dominated delta: Lower Dir Abu Lifa Member (Eocene), Western Desert, Egypt. Sedimentology, 60, 1313–1356.

Li, Y. and Bhattacharya, J., 2014. Facies architecture of asymmetrical branching distributary channels: Cretaceous Ferron Sandstone, Utah, USA. Sedimentology, 61, 1452-1483.

Liu, S.F., Nummedal, D. and Liu, L., 2011. Migration of dynamic subsidence across the Late Cretaceous United States Western Interior Basin in response to Farallon plate subduction. Geology, 39, 555–558

MacEachern, J.A. and Bann, K.L., 2008. The Role of Ichnology in Refining Shallow Marine Facies Models. In: Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy (Eds G.J.

Hampson, R.J. Steel, P.M. Burgess and R.W. Dalrymple), SEPM Spec. Publ., 90, 73–116.

McGookey, D. P., J. D. Haum, L. A. Hale, H. G. Goodell, D. G. McCubbin, R. J. Weimer, and G. R. Walf, 1972. Geological Atlas of The Rocky Mountain Region, Rocky Mountain Association of Geologists, 331 p.

Meek, F. B., and F. V. Hayden, 1861. Description of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska, by the exploring expedition under the command of Capt. Wm. F. Reynolds, U. S. Top. Engineers; with some remarks on the rocks from which they were obtained: Phila. Acad. Nat. Sci. Proc, v. 13, p. 415-447.

Miall, A. D., 1984. Deltas, in Walker, R. G., ed., Facies models, 2nd Ed: Geoscience Canada Reprint Ser. 1, p. 105-118.

Miall, A.D., Catuneanu, O., Vakarelov, B., Post, R., 2008. The Western Interior Basin, in Miall, A.D., ed., The Sedimentary Basins of the United States and Canada: Sedimentary basins of the World, v. 5 (K.J. Hsü, Series Editor): Amsterdam, Elsevier Science, p. 329–362.

Nummedal, D., Riley, G.W., Templet, P.L., 1993. High-resolution sequence architecture: a chronostratigraphic model based on equilibrium profile studies. In: Posamentier, H.W., Summerhayes, C.P., Haq, B.U., Allen, G.P. (Eds.), sequence stratigraphy and Facies Associations, vol. 18. International Association of Sedimentologists Special Publication, pp. 55–68.

Olariu, C., Bhattacharya, J.P., 2006. Terminal Distributary Channels and Delta Front Architecture of River-dominated delta systems. Journal of Sedimentary Research, Perspectives, v. 76, p.212-233.

Olsen, T., Steel, R., Hogseth, K., Skar, T., Roe, S.L., 1995. Sequential architecture in a fluvial succession: Sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah. Journal of Sedimentary Research, v. 65, p. 265–280.

Oomkes, E. and Terwindt, J.H.J., 1960. Inshore estuarine sediments in the Haringvliet (Netherlands). Geol. Mijnbouw, 39, 701-710.

Oomkes, E. 1974. Lithofacies relations in the Late Quaternary Niger Delta complex. Sedimentology, 21, 195–222.

Paton C., Hellstrom J.C., Paul B., Woodhead J.D., Hergt J.M., 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. Journal of Analytical Atomic Spectrometry, v. 26, p. 2508–2518.

Penland, S., R. Boyd, and J. R. Suter, 1988. The transgressive depositional systems of the Mississippi delta plain: A model for barrier shoreline and shelf sand development: Jour. Sed. Petrology, v. 58, p. 932-949.

Plink-Björklund, P., 2005. Stacked fluvial and estuarine deposits in high-frequency (4th-order) sequences of the Eocene Central Basin, Spitsbergen, Sedimentology, 52, 391-428.

Pontén, A. and Plink-Björklund, P., 2009. Process Regime Changes Across a Regressive to Transgressive Turnaround in a Shelf–Slope Basin, Eocene Central Basin of Spitsbergen. J. Sed. Res., 79, 2-23.

Posamentier, H.W., 2002. Ancient shelf ridges—a potentially significant component of the transgressive systems tract: case study from offshore northwest Java. American Association of Petroleum Geologist Bulletin 86, 75 – 106.

Posamentier, H.W., Allen, G.P., 1999. Siliciclastic Sequence Stratigraphy—Concepts and Applications. SEPM Concepts in Sedimentology and Paleontology, vol. 7. 216 pp.

Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., 1986. Numerical Recipes, The Art of Scientific Computing. Cambridge, UK, Cambridge University Press, 186 p.

Ravnas, R., Steel, R.J., 1998. Architecture of marine rift-basin successions. American Association of Petroleum Geologist Bulletin 82, 110 – 146.

Reading, H. G., & Collinson, J. D., 1996. Clastic coasts. In: Sedimentary environments: Processes, facies and stratigraphy, London: Blackwell, pp. 154–231.

Reineck, H.E., 1967. Layered Sediments of Tidal Flats, Beaches, and Shelf Bottoms of the North Sea. In: Estuaries (Ed. G.H. Lauff), Am. Assoc. Adv. Sci. Spec. Publ. 83, 191-206, Stoudsburg.

Reineck, H.E. and Wunderlich, F., 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, 11, 99–104.

Roberts, H.H., 1998. Delta switching, early responses to the Atchafalaya River diversion: Journal of Coastal Research, v. 14, p. 882–899.

Sanders, J., & Kumar, N. 1975. Evidence of Shoreface Retreat and In-Place 'Drowning' During Holocene Submergence of Barriers, Shelf off Fire Island, New York. Geological Society of America Bulletin, 86(1), 65-7606-86-1-65-16836.

Schermer, E.R., and Busby, C., 1994. Jurassic magmatism in the central Mojave Desert; implications for arc paleogeography and preservation of continental volcanic sequences. Geological Society of America Bulletin, v. 106, p. 767–790.

Serradji, H., 2007. Depositional Environments and Sequence Stratigraphy of the Lower Cretaceous Dakota Sandstone in South-western Colorado, Unpublished, unreviewed Masters thesis, University of Kansas.

Shanley, K.W., and McCabe, P.J., 1993. Alluvial architecture in a sequence stratigraphic framework: A case history from the Upper Cretaceous of southern Utah, USA, in Flint, S., and Bryant, I., eds., Quantitative Modelling of Clastic Hydrocarbon Reservoirs and Outcrop Analogues. International Association of Sedimentologists Special Publication 15, p. 21–56.

Shanley, K.W., and McCabe, P.J., 1995. Sequence stratigraphy of Turonian–Santonian strata, Kaiparowits Plateau, southern Utah, USA: Implications for regional correlation and foreland basin evolution, in Van Wagoner, J.C., and Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits; Outcrop and Subsurface Examples from the Cretaceous of North America. American Association of Petroleum Geologists Memoir 64, p. 103–136.

Shanley, K.W., McCabe, P.J., and Hettinger, R.D., 1992. Tidal influence in Cretaceous fluvial strata from Utah, U.S.A.: A key sequence stratigraphic interpretation. Sedimentology, v. 39, p. 905–930.

Siggerud, I.H. E. & Steel, R.J., 1999. Architecture and trace fossil characteristics of a 10.000-20.000 year, fluvial-marine sequence, SE Ebro Basin, Spain. Journal Sedimentary Research, 69, 365-387.

Sixsmith, P.J., Hampson, G.J., Gupta, S., Johnson, H.D. and Fofana, J.F., 2008. Facies architecture of a net transgressive sandstone reservoir analog: The Cretaceous Hosta Tongue, New Mexico. AAPG Bull., 92, 513-547.

Slama J., Kosler J., Condon D.J., Crowley J.L., Gerdes A., Hanchar J.M., Horstwood M.S.A., Morris G.A., Nasdala L., Norberg N., Schaltegger U., Schoene B., Tubrett M.N. and Whitehouse M.J., 2008. Plesovice zircon - A new natural reference material for U-Pb and Hf isotopic microanalysis. Chemical Geology, 249, 1–35.

Snedden, J.W., Dalrymple, R.W., 1999. Modern shelf sand ridges: from historical perspective to a unified hydrodynamic and evolutionary model. In: Bergman, K.M., Snedden, J.W. (Eds.), Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentological Interpretation. SEPM Special Publication, vol. 64, pp. 13 – 28.

Spencer, J.E., and Pecha, M., 2012. U-Pb Zircon Geochronologic Investigation of Granitoids and Sandstones in the Jerome Canyon and Chino Valley North 7 ½′ Quadrangles, Prescott Area, Central Arizona. Arizona Geological Survey Open-File Report 12-02, 8 p.

Staub, J.R. and Gastaldo, R.A., 2003. Late Quaternary sedimentation and peat development in the Rajang river delta, Sarawak, east Malaysia. In: Tropical Deltas of Southeast Asia- Sedimentology, Stratigraphy, and Petroleum Geology (Eds F. Hasan Sidi, D. Nummedal, P. Imbert, H. Darman and H. Posamentier), SEPM Spec. Publ., 76, 71–78.

Steel, R.J., Rasmussen, H., Eide, S., Neuman, B., Siggerud, E.I.H., 2000. Anatomy of high-sediment-supply, transgressive tracts in the Vilomara composite sequence, Sant Llorenc del Munt, Ebro basin, NE Spain. Sedimentary Geology 138, 125 – 142.

Steiner, M. B., and J. D. Walker. 1996. Late Silurian plutons in Yucatan, J. Geophys. Res., 101(B8), 727–735.

Storms, J.E.A. and Hampson, G.J. 2005. Mechanisms for Forming Discontinuity Surfaces Within Shoreface–shelf Parasequences: Sea Level, Sediment Supply, or Wave Regime. J. Sed. Res., 75, 67–81.

Swift, D.J.P., Phillips, S., and Thorne, J.A., 1991. Sedimentation on continental margins, VI: lithofacies and depositional systems, in Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies, IAS Special Publication, v. 14, p. 89-152.

Szwarc, T.S., Johnson, C.L., Stright, L.E., McFarlane, C.M., 2014. Interactions between axial and transverse drainage systems in the Late Cretaceous Cordilleran foreland basin: Evidence from detrital zircons in the Straight Cliffs Formation, southern Utah, USA, Geological Society of America Bulletin, v. 127, n. 3-4, p. 372-392.

Taylor, A.M. and Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. J. Geol. Soc., 150, 141–148.

Terwindt, J.H.J., 1971. Litho-facies of inshore estuarine and tidal-inlet deposits. Geol. Mijnbouw, 50, 515-526.

Thomas, R.G., Smith, D.G., Wood, J.M., Visser, J., Calverley-Range, E.A. and Koster, E.H. 1987. Inclined heterolithic stratification—terminology, description, interpretation and significance. Sed. Geol., 53, 123–179.

Swift, D.J.P., and Thorne, J.A., 1991. Sedimentation on continental margins, I: a general model for shelf sedimentation, in Swift, D.J.P., Oertel, G.F, Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies, International Association of Sedimentologists Special Publication, No. 14, p. 3-31.

Tye, R.S., Hewlett, J.S., Thompson, P.R., Goodman, D.K., 1993. Integrated stratigraphic and depositional-facies analysis of parasequences in a transgressive systems tract, San Joaquin Basin, California. In: Weimer, P., Posamentier, H.W. (Eds.), Siliciclastic Sequence Stratigraphy: Recent Developments and Applications. American Association of Petroleum Geologists Memoir, vol. 58, pp. 99 – 133.

Ulicny, D., 1999. Sequence stratigraphy of the Dakota Formation (Cenomanian), southern Utah: interplay of eustasy and tectonics in a foreland basin: Sedimentology, v. 46, p. 807-836.

Valdes, P. J., 1993. The influence to the Western Interior Seaway on climate modelling of the

Cretaceous.; 1993 SEPM meeting abstracts with program, stratigraphic record of global change, 69 p.

Van den Berg, J.H., Boersma, J.R. and Van Gelder, A., 2007. Diagnostic sedimentary structures of the fluvial-tidal transition zone – evidence from deposits of the Rhine and Meuse. Neth. J. Geosci., 86, 287–306.

Van Heerden, I.L., And Roberts, H.H., 1988. Facies development of Atchafalaya Delta, Louisiana: a modern bayhead delta: American Association of Petroleum Geologists, Bulletin, v. 72, p. 439–453.

Van Straaten, L.M., Kuenen, R., 1957. Accumulation of fine grained sediments in the Dutch Wadden Sea Geologie en Mijnbouw, 19, pp. 329–354

Van Straaten, L.M. 1961. Sedimentation in tidal flat areas. J. Alberta Soc. Petrol. Geol., 9, 213-46.

Visser, M.J. 1980. Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: A preliminary note. Geology, 8, 543-546.

Walker, J.D., Martin, M.W., Glazner, A.F., 2002. Late Paleozoic to Mesozoic development of the Mojave Desert and environs, in Glazner, A.F., Walker, J.D., and Bartley J.M., eds., Geologic Evolution of the Mojave Desert and South-western Basin and Range. Geological Society of America Memoir 195, p. 1–18.

Wasserburg, G.J., and Lanphere, M.A., 1965. Age determinations in the Precambrian of Arizona and Nevada. Geological Society of America Bulletin, v. 76, p. 735–758.

Weimer, P. C., 1982. Upper Cretaceous stratigraphy and tectonic history of the Ridgway area, north-western San Juan Mountains, Colorado: The Mountain Geologist, v. 19, p. 91-104.

Wescott, W. A., and F. G. Ethridge, 1980. Fan-delta sedimentology and tectonic setting; Yallahs fan delta, Southeast Jamaica: AAPG Bulletin, v. 64, p. 374-399.

Wright, D.L., 1977. Sediment transport and deposition at river mouths: a synthesis: Geological Society of America, Bulletin, v. 88, p. 857–868.

Yoshida, S., Jackson, M.D., Johnson, H.D., Muggeridge, A.H. and Martinius, A.W. 2001. Outcrop studies of tidal sandstones for reservoir characterization (Lower Cretaceous Vectis Formation, Isle of Wight, Southern England). In: Sedimentary Environments Offshore Norway - Palaeozoic to Recent (Eds. O.J. Martinsen and T. Dreyer), Norwegian Petroleum Society Spec. Publ. 10, 233-257.

Young, R. G., 1960. Dakota Group of Colorado Plateau: AAPG Bulletin, v. 44, p. 156-194.

Chapter 6: A Lacustrine Continental to Epicontinental Seaway transition: The Early Cretaceous Murta Formation of the Eromanga Basin

6.1. Abstract

A fundamental understanding of the characteristics of marine incursions and the formation of epicontinental seaways is important for forecasting potential future impacts of climate change and reconstructing Earth history. Few studies focus on the sedimentology of initial stages of transgression, where the depositional environment transitions from continental to marginal marine. As a result, these environments are poorly understood and are difficult to interpret in the subsurface. Here, a facies model is presented for the basal transgressive Early Cretaceous Murta Formation of the Eromanga Basin. Previous depositional models for the Murta Formation are inconsistent and have failed to predict or account for lithologies observed. The Murta Formation has been interpreted as both marginal marine to lacustrine within the same study areas. This study utilises data from core, wireline log and detrital zircon analyses. Six distinct facies associations are described, interpreted to be from environments ranging from deep marine to upper delta plain. A process-based depositional interpretation is provided. Sediment transport pathways are interpreted based upon detrital zircon data. Conceptual paleogeographic reconstructions are presented. The lower Murta Formation is dominated by lacustrine deposits whereas the upper Murta Formation includes more evidence for marine influence, including higher magnitude correlatable regressions and transgressions. This study provides an opportunity to better understand the sedimentological character of the transition from a continental to marine depositional environment at a variety of scales.

6.2. Introduction

Understanding the character and timing of marine incursions is important for reconstructing earth history and forecasting future impacts of climate change. Information about past marine incursions is obtained from stratigraphic analysis of deposits. However, marine and continental environments do not always have unambiguously distinctive deposits (for further discussion see the Chapter 2 Section 2 of this thesis). In the case of a succession recording a marine incursion, distinguishing between such depositional settings can thus be difficult, and potential mis-interpretation may have a substantial impact on palaeogeographic reconstructions and stratigraphic correlations. A detailed analysis of early-stage transgressive deposits is thus required, in order for these interpretations to produce robust basin-wide stratigraphic models. This is of direct relevance to the oil and gas industry, for which such models are an important tool in exploration and development.

Marine water bodies and resultant depositional systems may inundate large previously non-marine areas of continents. When these areas are bordered by land masses and connected to the ocean they form epicontinental seas. Similarities and differences between depositional processes on continental shelves, very large lakes and epicontinental seaways are not well understood (Allison and Wells, 2006; Miall, 2008). The transition from continental systems to epicontinental seaways has been documented in the Cretaceous and is interpreted to be mostly controlled by significant eustatic fluctuations (Haq et al., 1987; Miller et al., 2005), high-frequency tectonism (Catuneanu et al., 1999; Catuneanu et al., 2000; Vakarelov et al., 2006) and orbital forcing (Elder et al., 1994; Sageman et al., 1997; Plint and Kreitner, 2007).

Despite having many similarities in depositional processes, elements and morphologies, the behaviour and characteristics of lakes can differ considerably from marine systems (Gierlowski-Kordesch & Kelts, 1994; Bagnaz et al., 2012). Their behaviour and characteristics are not controlled by marine base level. The character of depositional systems in lakes is controlled not only by sediment supply, but also pre-existing topography or bathymetry and the timing of peak clastic influx relative to lake level. Peak clastic influx and lake level may or may not be related (Bohacs, 2012). Challenges in prediction of marginal lacustrine depositional patterns arise from the non-unique relations of lake character to tectonics and climate, responses of lakes to climate change and variety of relationships between lake level, sediment supply and water supply (Gierlowski-Kordesch & Kelts, 1994; Bagnaz et al., 2012). Wireline log expression of lacustrine strata varies widely among lacustrine facies associations and can differ greatly from similar facies associations commonly observed in marginal marine strata (Bohacs and Miskell-Gerhardt, 1998; Bagnaz et al., 2012) making interpretation and correlation difficult.

This chapter focuses on the Murta Formation which preserves a lacustrine to marginal marine transgression within the Eromanga Basin in Australia (Figure 1A). In previous studies the Murta Formation has been interpreted as lacustrine to marginal marine (Ambrose et al, 1982 and 1986; Gorter 1994; Bradley, 1993; Mount, 1981, 1982; Newton, 1986; Zoellner, 1988; Lennox, 1986; Hill, 1999). Specific objectives of this basin-wide study were to (i) Develop a consistent understanding of facies and depositional environments, (ii) Improve the basin-wide understanding of sediment provenance and paleogeography, and (iii) Provide a holistic sequence stratigraphic model for the Murta Formation across the basin.

6.3. Geological Background

In the Eromanga Basin (Figure 1) unequivocal evidence of marine

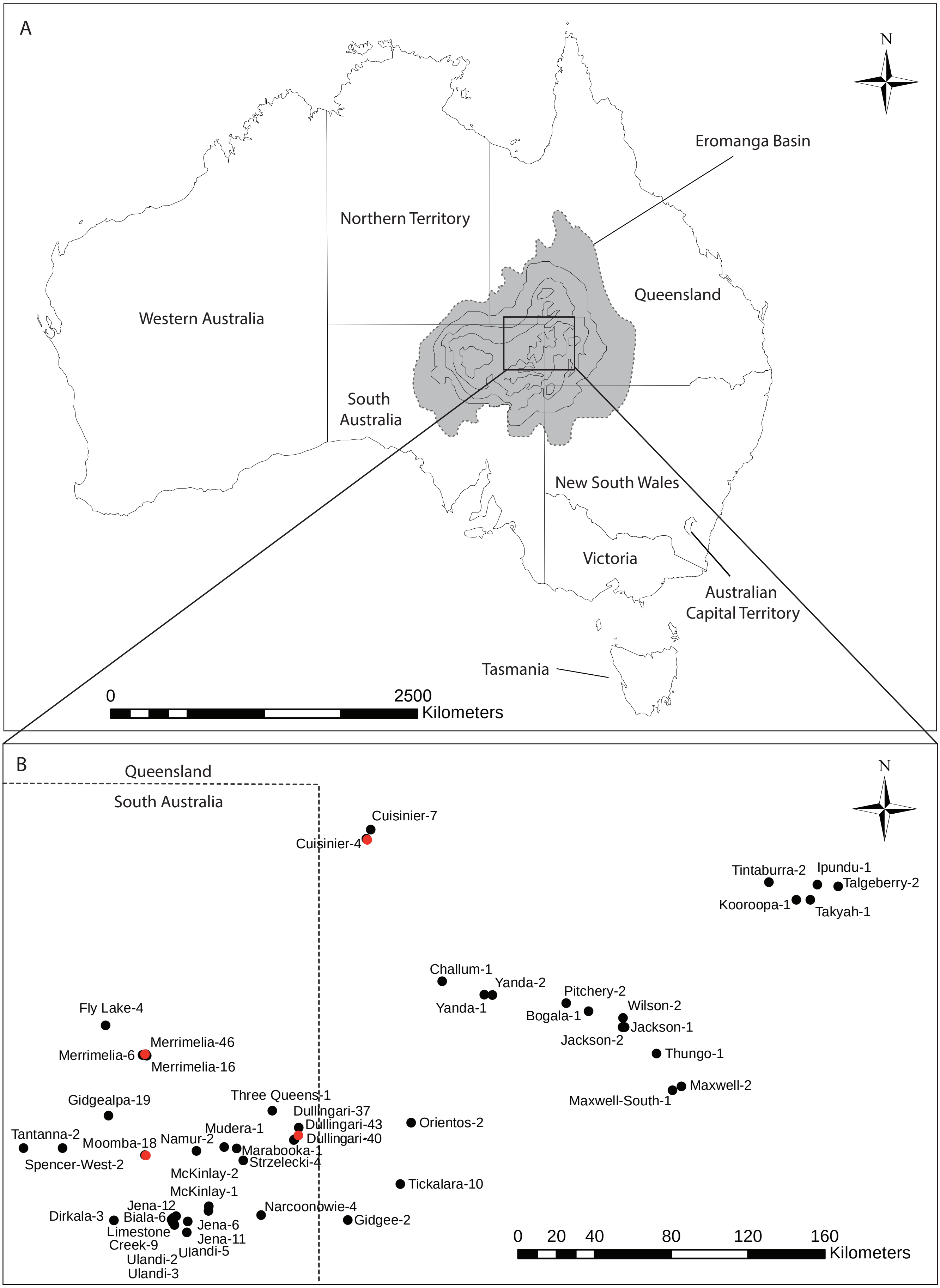

Figure 1: Location Map. A: The Eromanga Basin in the context of the Australian continent. Structure contours represent isopachs lines for the (in gradations of 500 metres below sea-level) on the top of the Cadna-owie formation which lies just above the Murta Formation. Adapted from Gallagher and Lambeck, 1989. B: Wells logged and referred to in this study. Wells which are also sample locations are indicated in red. Compiled and adapted from location data in well completion reports. This map does not represent all of the wells that intersect the Murta Formation, just ones that were selected for this study (for more information on the dataset see Methods).

sedimentation is recognised in the sediments of the Neocomian Cadna-owie Formation (see Figure 2 for stratigraphic context). By the Aptian, a Cretaceous sea covered approximately 60% of the Australian continent. On a continental scale, mechanisms responsible for the basin subsidence, which allowed for the formation of the continental seaway, have been interpreted by different workers to be: intracratonic sag resulting from thermal contraction (Gallagher and Lambeck, 1989; Gray et al., 2002), dynamic topographic changes induced by a subducted lithospheric slab (Russell and Gurnis, 1994; Matthews et al., 2011) and foreland basin dynamics (Jones and Veevers, 1983; Gallagher and Lambeck, 1989; Gallagher, 1990; Draper, 2002). Timing of the initiation of the seaway is also uncertain.

Lower order controls on sedimentation including sediment supply related to climate, subsidence and local tectonic activity impacted Cretaceous sedimentation in the Eromanga Basin (Gostin and Therriault, 1997). Eustatic sea level change during the Cretaceous is well documented (most recently by Laurin and Sageman, 2007; Wendler et al., 2010; Boulila et al., 2011; Wendler et al., 2014; Laurin et al., 2015) and is likely to have been influenced by the breakup of Gondwana in the southern hemisphere. Sediment supply was influenced by major climatic changes, from uniformly warm and wet in the Jurassic period to an interpreted cool temperate climate in the Cretaceous (McKellar, 1996; Gorter, 1994). During the Early Cretaceous, paleolatitudinal positioning of the basin was comparable to the present day latitudes of Norway and Alaska (Figure 3A). The climate at these present-day latitudes is cold temperate to sub-arctic and subject to seasonality (Gorter, 1994), but this may have differed in the Early Cretaceous. The role of tectonics at the local level (e.g. Gostin and Therriault, 1997) is important, as low-gradient basins such as the Eromanga Basin are sensitive to subtle tectonic movements, the effects of which on sedimentation patterns can be substantial (Jansen, 2013).

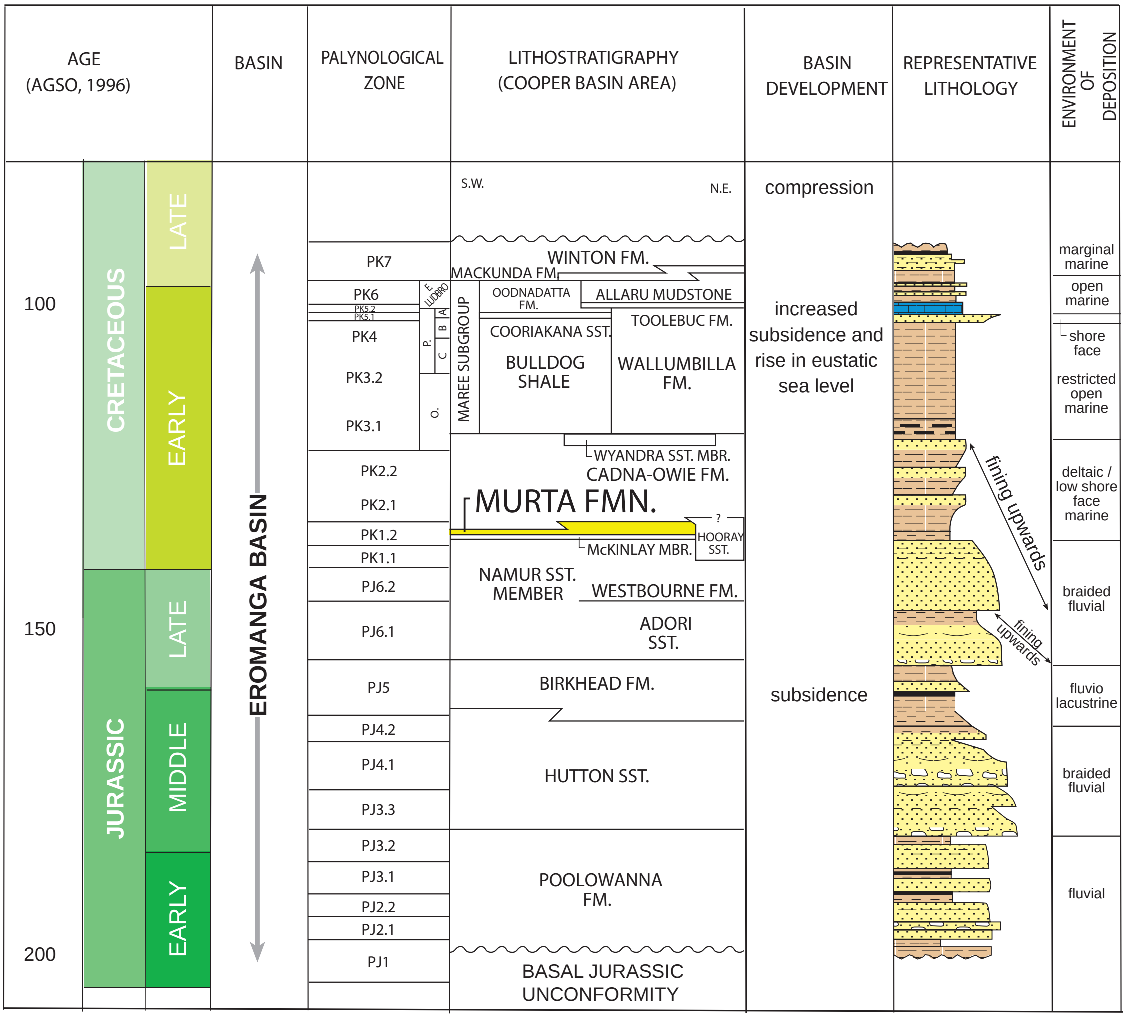

Figure 2: Stratigraphic table showing the age, palynological zone, lithology, interpreted environment of deposition and basin development for the Murta Formation, as highlighted in yellow (After Santos Ltd, 2014).

The Berrasian to Valanginian (145-134 Ma) Murta Formation is underlain by the continental sand-rich Oxfordian to Berriasian Namur Formation and McKinlay Formation and overlain by the Valanginian to Berrasian Cadna-owie Formation, which is composed of thick marine mudstones interbedded with siltstone and sandstone (Figure 2; Gravestock et al., 1995). This vertical stratigraphic placement suggests that the Murta Formation is an overall net transgressive package. Sediment infill of the basin during the Cretaceous at the time of deposition of the Murta Formation is interpreted to have been derived from younger volcanogenic sediments to the east of the basin (Hoffmann, 1989; Allen et al, 1996) (Figure 4). Fundamental

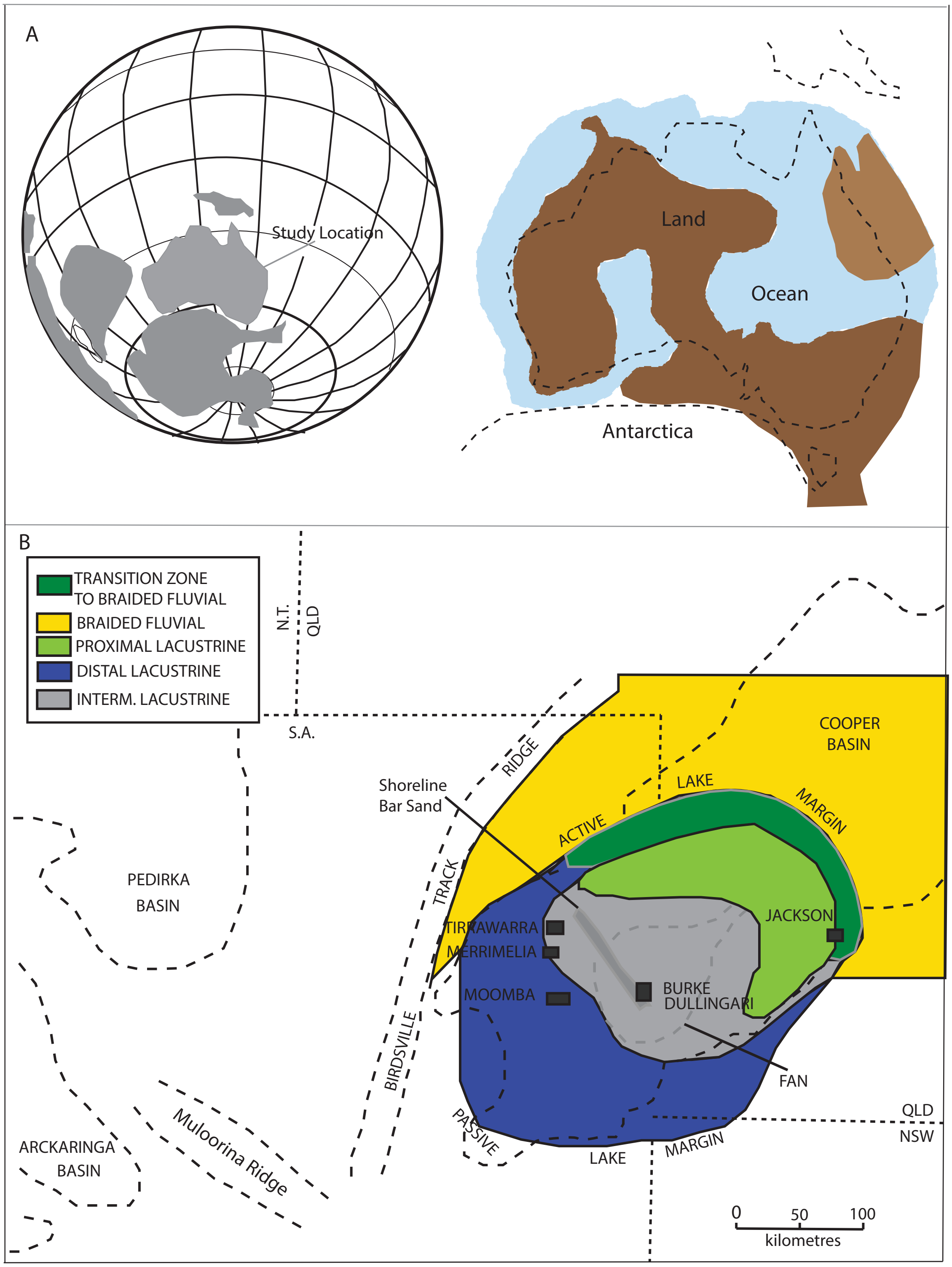

Figure 3: A. Paleogeography for the Australian continent in the Middle Cretaceous, after deposition of the Murta Formation. No specific age is given, but Albian to Aptian age is inferred (After Frakes and Francis, 1988 and Gorter, 1994). B. Paleogeography during the time of deposition for the Murta Formation, based mainly on work done in the Dullingari area (Redrawn from Ambrose et al., 1986).

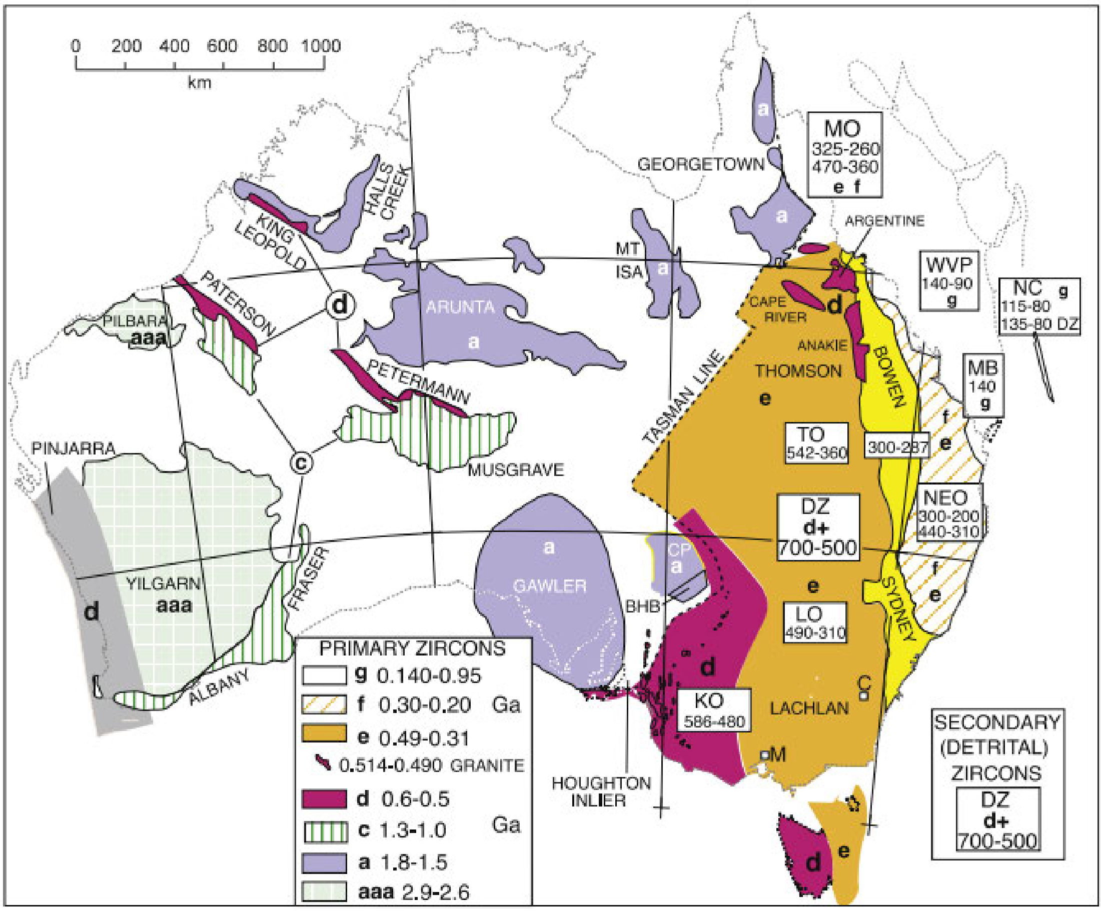

Figure 4: Likely source terrains and ages A: Principal bedrock-age provinces of Australia. BHB = Broken Hill Block; C=Canberra; CP=Curnamona Province; DZ=Secondary Detrital Grains; KO=Kanmantoo Orogen; LO=Lachlan Orogen; M=Melbourne; MB=Maryborough Basin; MO=Mossman Orogen; NC=New Caledonia; NEO= New England Orogen; TO = Thomson Orogen; WVP=Whitsunday Volcanic Province (After Veevers, 2016).

bedrock-age provinces of Australia are divided by the Tasman Line with the Phanerozoic to the east and the Precambrian to the west (Figure 4).

Existing regional and semi-regional models for the Murta Formation (Ambrose et al, 1982 and 1986; Gorter 1994; Bradley, 1993; Mount, 1981, 1982; Newton, 1986; Zoellner, 1988; Lennox, 1986; Hill, 1999) show inconsistencies, however all authors describe the Murta Member as lacustrine to marginal marine. The Murta Formation was first defined as a fine-grained lacustrine sequence intervening between braided-fluvial sediments of the Namur Sandstone and the overlying, marginal to fully marine Cadna-owie Formation (Ambrose et al. 1982; 1986), mainly from work completed in the South Australian sector. A regional reduction in thickness and sand content from the north-northeast to the southwest was interpreted to reflect a depositional pattern where the main source of sediment into the "Murta Lake" was a delta building from the north and east (Figure 3B; Ambrose et al. 1982; 1986). A similar lacustrine delta model, sourced from the north, providing sediment to the Nockatunga, Thungo, Winna and Dilkera Fields was interpreted for reservoir facies in the Murta Formation in the south east of the basin in the Queensland sector (Lennox, 1986).

Apatite nodules, glauconite pellets and calcisphere microfossils together with geochemical trace element data were used to infer a brackish to marine environment in the upper Murta Formation (Naylor et al., 1988; Zoellner, 1988; Powell et al., 1989). Hill (1999) analysed facies of the cored intervals of the Murta Formation within a specific field in the Southern Queensland area and interpreted that the reservoir system represents a progradational lacustrine shoreface sandstone succession. In the southeast of the basin a lacustrine system with vegetated islands, followed by a rapid drop in base level causing channel incision is interpreted during the mid Murta time (Gorter, 1994). Subsequently, slow base level rise and infill of channels by sediment reworking and transgression was interpreted to form estuarine deposits, although no evidence of marine influence is directly mentioned. Continued transgression is interpreted to form basin-wide shoaling cycles and maximum transgression results in a mud-rich condensed section (Gorter, 1994).

The McKinlay Member and Murta Formation have previously been considered as a genetic package (Theologou, 1995). A drowned river valley was used as a depositional model for the basal McKinlay Member and a transgressive lake barrier-bar system for the Upper Murta Member. The drowned valley was interpreted to form part of a lacustrine transgressive systems tract (e.g. Reinsen, 1992; Dalrymple et al., 1992). The upper part of the McKinlay Member is interpreted by Theologou (1995) to have been deposited as part of a transgressive lake barrier-bar system which transgressed rapidly over the lake (e.g. Reinsen, 1992; Galloway, 1986; Kraft and John, 1978). Sand packages are either designated as prograding lacustrine deltas or a prograding wave dominated shoreline facies. As the formation is interpreted as lacustrine, the absence of tides is often implied (Theologou, 1995) and hence the flood tidal delta and tidal flat components of this facies models are ignored, however lithologies similar to these facies exist. Rapid transgression is implied to reduce preservation potential.

Stratigraphic nomenclature used to describe the Murta Formation (Figure 2) can be complicated. The Murta Formation was previously referred to as the Murta Member, but was promoted to Formation status (Gravestock et al., 1995). The Murta Formation grades laterally into the Hooray Sandstone. Although horizontal grading of the (South-Australian type) Murta Formation into the Hooray Sandstone in Queensland represents a major facies change, deposition is time-equivalent and hence for the purpose of this study the Hooray Sandstone will be incorporated into the Murta Formation. In this chapter, the term Murta Formation will be used to describe the formation studied throughout the Basin, including the Hooray Sandstone.

6.4. Methods and Dataset

This study focuses on the Murta Formation throughout the Eromanga Basin, integrating dataset of wireline logs, core descriptions and geochronology to improve the conceptual geological model for the formation and develop paleogeographic reconstructions. It will also enable better understanding of the transgression from lacustrine to marine on a basin scale. Palynological, geochemical and petrographical data from previous studies or other workers are incorporated into this work.

A total of forty-five representative cores intersecting the Murta Formation were logged in South Australia and Queensland, with the aim of obtaining geographically representative coverage for the entire Eromanga Basin (just over 1,000,000 km^2; Gravestock et al., 1995). Lithofacies, facies and facies associations were identified based on lithology, grain size, sedimentary structures and ichnology. Special focus was placed on interpreting data in a process-based framework. Process-based depositional settings were interpreted from facies associations. Results from core analysis were integrated with wireline logs. Ninety-two representative wireline logs were selected for the study, mainly on the basis of data quality and with the aim of obtaining a representative geographically representative coverage. Gamma ray and sonic logs were primarily used to construct regional cross sections and determine facies continuity. The sandstone upper limit was set as 100 API and a velocity cut off of 100 µs per foot was used to determine carbonate cement zones. Stacking patterns and stratigraphic trends were used to determine local depositional architecture and regional basin scale trends. This context allowed for regional correlation across the basin. Marine and non-marine correlation techniques were considered. Subdivision of the Murta Formation was based upon sequence stratigraphic analysis. All of this work was completed by the author of this thesis.

Twelve rock samples representative of major stratigraphic units were taken (locations shown in Figure 1*;* depths shown in Figure 7) with the objective of conducting Zircon U-Pb geochronology analysis. The samples underwent separation to isolate the zircon fraction through physical, magnetic and heavy liquids techniques. Individual grains were handpicked and mounted into epoxy resin blocks at the University of Adelaide. Prior to analysis, zircon grains were analysed in order to identify domains within the grains. Data were obtained on a Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) using a New Wave UP-213 laser attached to an Agilent 7500cx Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at Adelaide Microscopy, The University of Adelaide. A spot size of 30 μm and repetition rate of 5 Hz was used. Analysed grains were selected without using any particular criteria, to avoid undue bias.

Age calculations were completed using Iolite v2.31 (Paton et al., 2011) with use of the primary zircon standard GJ-1, TIMS normalization data Pb^{207}/Pb^{206}= 608.3 Ma, Pb^{206}/U^{238} = 600.7 Ma and Pb^{207}/U^{235} = 602.2 Ma (Jackson et al., 2004). Instrument drift was corrected for via bracketing groups of unknowns of 15–20 with 8-10 standards and the application of a linear correction. Accuracy of the methodology was verified by repeated analyses of Plešovice zircon (Pb^{206}/U^{238} = 337.13 ± 0.37 Ma; Sláma et al., 2008). Isotope ratios are presented uncorrected for common lead, with Concordia plots generated using Isoplot v3.75.

Data ±10% concordant were retained, with the exception of grains younger than 500 Ma, where a concordance of ±15% was accepted. Analyses with anomalously high concentrations of U and depleted concentrations of Th were discarded because grains of this type can be highly susceptible to Pb loss (Dickinson and Gehrels, 2009). Pb^{207}/Pb^{206} ratios were used for age determination for grains older than 1 Ga, and Pb^{206}/U^{238} ratios were used for those younger. When ages split the 1 Ga boundary Pb^{207}/Pb^{206} ratios took precedence. Zircon age distributions were compared using the Kolmogorov-Smirnov (K-S) test (Press et al., 1986). High p values ($p > 0.05$) indicate a statistically significant likelihood that two samples may have been derived from sources with the same zircon age distributions. Low p values ($p < 0.05$) suggest the samples were sourced by statistically distinguishable distributions of zircon ages. All of this analysis was completed by the author of this thesis at the University of Adelaide and the complete data set is provided as a supplementary data set in Chapter 8.

Geochronology data were integrated with core data and wireline log analysis to develop paleogeographic reconstructions for the Eromanga Basin during the Early Cretaceous (Berriasian to Valanginian, 145-134 Ma). Reconstructions focus on likely sediment transport pathways and paleoenvironmental conditions. Sparse data coverage gives rise to uncertainty, and as such reconstructions should be considered as a single realisation of many potential scenarios and updated as new information is obtained. Furthermore, the majority of data in this study is concentrated in closer to the centre of the basin (Figure 1). The basin margins are under-represented as very few data are available there.

6.5. Results

Twenty-six lithofacies and six distinct facies associations were recognised based on detailed observations of lithology, grain sorting and size, sedimentary

Figure 5: Next page. Photographs of representative lithologies for Facies 1 through 6, potential tidal structures and ichnofabrics. See Figure 1B for locations of wells. A: FA 1 Offshore (L-R: Cuisinier 4, 1622-1621 m, Merrimelia 16, 5248-5248.10 ft, Three Queens 1, 4784-4783 m, Gidgealpa 24, 5182-5184 ft). B: FA 2 Prodelta (L-R: Cuisinier 4 1625-1626 m, Merrimelia 46, 5081-5080 ft, Jena-12, 3629-3636 ft, Tantanna-2 4453-4451 ft) C: FA 3 Delta Front (L-R: Jackson 1, 4388.5 -4387 ft, Narcoonowie 4, 4388.5 -4387 ft, Tantanna 2, 4449 -4447 ft, Cuisinier 4, 1660.55 -1660.30 m) D: FA 4 Lower Delta Plain (L-R Jena 12, 4040- 4041 ft, Biala 6 3935.9-3936.9 ft, Dullingari 37 5585- 5584 ft, Orientos 2 4291-4292 ft, Dirkala 3 4509-4507 ft), E: FA 5 Shorelines (Jena 3 3988.10-3989.10 ft, Dirkala 3 4620.5- 4621.5 ft, Mudera 2 6720.1- 6720.11 ft, Jena 12 4205-4206 ft, Cuisinier 4 1632.0- 1631.0 m, Jackson 4365- 4364 ft, Jena 3 3990-3991 ft), F: FA 6 Fluvial dominated upper delta plain (Jena 11 3895.6-3896.1 ft, Spencer West 2 5398.3-5369.3 ft, Spencer West 2 5365.7-5366.5 ft, Spencer West 2 4493.9- 4494.9 ft, Dirkala 2 6222.1- 6223 ft, Jena 3 3716- 3716.5 ft, Cuisinier 4 1639.0- 1638.0 m). G: Potential structures indicating tidal influence- Tantanna 2 4479-4480, Gidgealpa 19, 5089.9-5089.5, Narcoonowie 4 4355-4356 ft, Above Dullingari 37 4338 ft , Below Jena 12 5324 ft, Above Cuisinier 4 1645.2 m Below Cuisinier 4 1639.73- 1369.38 m). H: Variation in ichnofabrics (Mudera 5 7059-7058.1 ft, Mudera 2 4956.4-6957.2 ft, Narcoonowie 4 4367.4-4368.4 ft, Merrimelia 46 5129.4-5130.4 ft, Merrimelia 46 5100-5101 ft, Cuisininier 4 1668-1667.8 m, Gidgealpa 24 5187.6- 5187.5 ft, Jackson 2 4065, 4067, 4066, Cuisinier 4 1654, 1659.

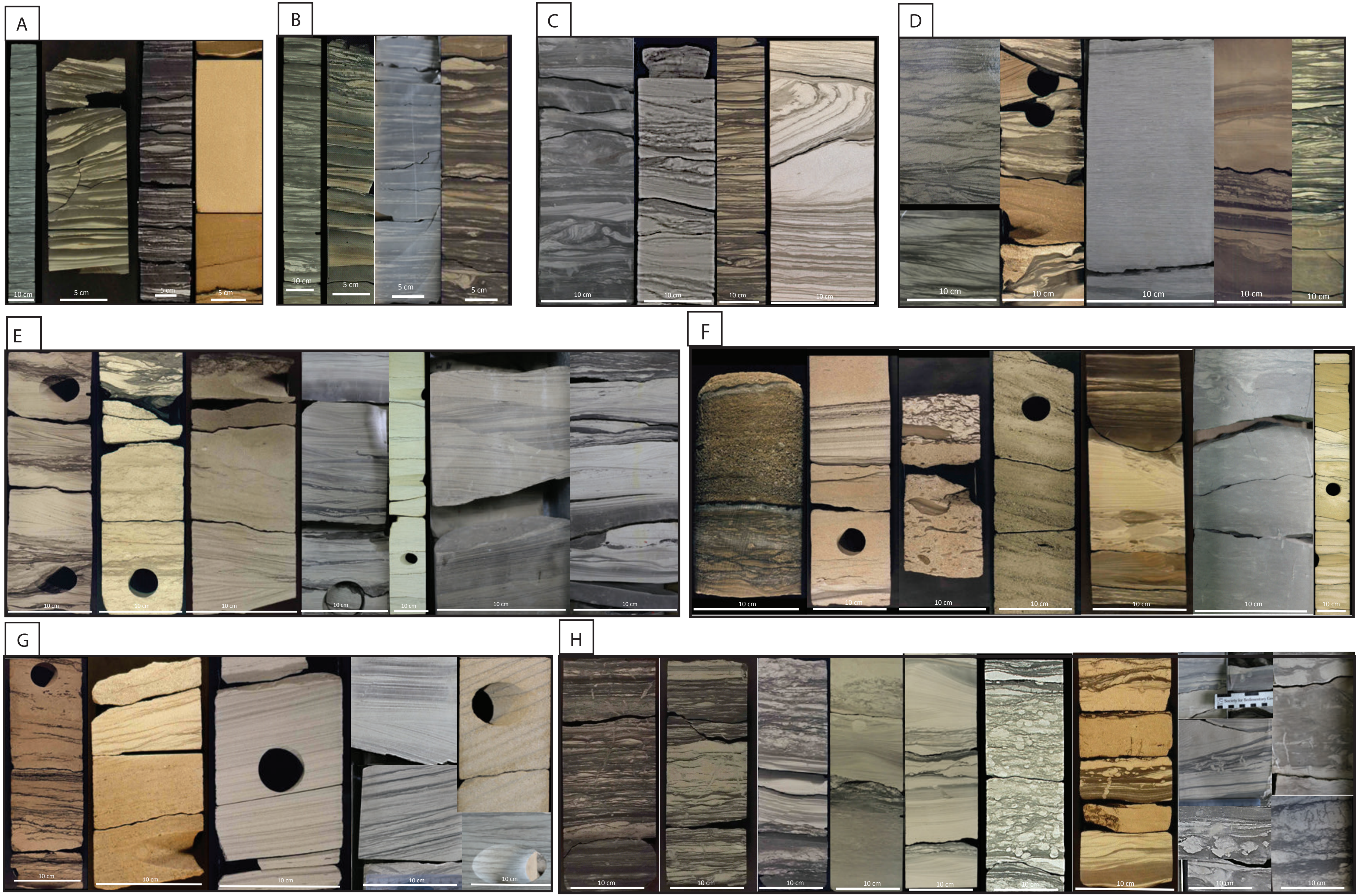
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Figure 6: Table of lithofacies, facies and descriptions. Characteristics are also discussed in the text. Continued over the following two pages.

<table>
<tr><th>Code</th><th>Facies</th><th>Description</th><th>Process Interpretation</th><th colspan="4">Interpretation</th></tr>
<tr><td>St, Sp</td><td>Trough cross and planar cross bedding</td><td>Fine-grained to very coarse-grained, sub-angular to sub-rounded clasts showing poor to moderate sorting. Course grained lag, bioturbation common.</td><td>Migration of sand bar forms within a fluvial channel.</td><td rowspan="8"></td><td rowspan="4">Channelized elements</td><td rowspan="4">FA6</td><td rowspan="8">Upper and Lower Delta Plain</td></tr>
<tr><td>Sm</td><td>Massive sand</td><td>Very fine to medium-grained poor to well sorted structureless sandstone</td><td>Rapid deposition or destruction of structure due to bioturbation or other event.</td></tr>
<tr><td>Fldb</td><td>Deformed and bioturbated mud</td><td>Distorted, disorganised, sub-horizontal laminations. Intense bioturbation common.</td><td>Channel abandonment deposition</td></tr>
<tr><td>G</td><td>Gravel</td><td>Fine to coarse gravel, quartz arenite rich</td><td>Basal lag of fluvial systems</td></tr>
<tr><td>Sb</td><td>Bioturbated sand</td><td rowspan="2">Clay, silt and fine sand with remnant ripple and planar lamination structures mostly destroyed by bioturbation.</td><td rowspan="2">Overbank deposits, levees and splays in location conductive to faunal activity</td><td rowspan="4">Unchannelised elements</td><td rowspan="4">FA4</td></tr>
<tr><td>Fb</td><td>Bioturbated mud</td></tr>
<tr><td>Sbr</td><td>Bioturbated and rippled sand</td><td>Fine sand reworked</td><td>Overbank deposition forms levees and splays</td></tr>
<tr><td>C</td><td>Coal</td><td>Dark brown to black discrete clasts or beds less than 30 cm</td><td>Peat forming swamp-like environments</td></tr>
<tr><td>Frw</td><td>Wave ripple laminated sandstone</td><td>Very fine-grained to medium grained wave ripple lamination, sometimes mud draped</td><td>Reworked sand due to wave action. Mud settles on face of foresets during low energy times.</td><td></td><td>Shorelines</td><td>FA5</td><td></td></tr>
</table>

Sh	Planar horizontal stratification	Very fine-grained to medium-grained, moderately sorted. Laminations average 5 to 10 mm thick and show normal grading.	Deposition under upper-flow regime, high energy				Delta Front and Shorelines
Sbr	Bioturbated and rippled sand	Very fine to lower-medium sandstone	Wave rippled sand effected by burrowing behind berm				
Sr	Rippled sand	Small scale starved quartz rich with dominant current and occasional wave rippled sand	Reworking of sand mostly due to currents but occasionally due to wave action		Delta Front	FA3	
Ss	Storm influenced sand	Fine to very fine sand with small and large scale high and low wavelength hummock and swale structures	Unidirectional, oscillatory flow that is generated by storm waves below normal fair weather wave base				
Sbr	Bioturbated and rippled sand	Sand beds with remnants of ripple structures mostly destroyed by burrowing and faunal activity	Sand deposited with ripple structure which has been destroyed by faunal burrowing				
Fb	Bioturbated sand	Sand beds with horizontal and vertical burrows, structures mainly destroyed by burrowing	Damp or wet, probably rippled or laminated sand, which was subject to intense bioturbation and soft sediment deformation				
Sd	Sand deformed	Well rounded quartz rich sand with evidence for soft sedimentation including sheared ripples, slumping and dewatering	Slope failure and loading onto wet and unlithified sediment, also potential tectonic influence				
Sr	Rippled sand	Small scale starved quartz rich current ripples	Currents transporting sand out into the basin		Prodelta	FA2	

Sbr	Bioturbated and rippled sand	Very fine to lower-medium sandstone and clay to silt with current ripple structures sometimes destroyed by bioturbation	Sand originally reworked by currents, but structure destroyed by burrowing of fauna				
Fb	Bioturbated mud						
Fl	Laminated mud	Clay to fine silt with planar laminations on a millimetre and sub-millimetre scale, little organic matter	Deposition in a low energy environment through suspension fallout				Prodelta and Offshore
Fl	Laminated mud	Clay to fine silt with planar laminations	Deposition under low energy regime through suspension fallout. May or may not be associated with mass flow deposits		Deepwater	FA1	
Ss	Rippled sand	Well rounded fining upward ripple laminated sand	Mass flow deposition including debris and turbidite flows				
Sm	Massive, graded sand	Sharp based, well rounded quartz rich fining up sand					
Sc	Sand with suspended clasts	Well rounded fining up sand with suspended mud or lithic fragment clasts.					
Sd	Sand deformed	Well rounded quartz rich sand with deformation which may include dewatering structures					

structures, paleocurrent and trace fossils, a summary of which is shown in Figure 5 and Figure 6. Facies Associations described in detail in the following section. Bioturbation intensity (BI) was recorded according to the Taylor & Goldring (1993) scheme, with 0 representing no bioturbation and 4 representing extreme bioturbation. Trace fossil diversity and ichnofacies classification follows models presented by MacEachern and Bann (2008).

6.5.1. Facies Description and Interpretation

This facies association scheme is designed such that the interpreted deeper facies are designated as lower numbers (e.g. Facies Association 1) and the interpreted shallower facies are interpreted designated as lower numbers (e.g. Facies Association 6).

Facies Association 1

Description

Facies Association 1 (FA1) consists of thinly bedded (centimetre to millimetre scale) and laminated mudstone-dominated beds, as well as massive and deformed sand beds (Figure 5 A). Linsen lamination, parallel lamination and flaser bedding were common. Quartz-rich well-sorted sandstone beds up to 1 cm thick were present but rare. These minor very thin hummocky and ripple-laminated sandstones have a sharp base, preserve very small dewatering structures and show a general fining-upward pattern. FA1 showed no overall grading. Soft sediment deformation including dewatering and slump structures, as well as microfaults and siderite concretions were present in this facies association. Beds consisting of massive graded sand, deformed sand and sand with isolates pebble-sized clasts topped with laminated mud were also observed. This FA was often observed in association with FA2. Very minor burrowing (BI=0-1) was present in thin silt and rare sand layers. The character and presence of small *Cruziana, Zoophycos, Teichichnus, Planolites, Helminthodia, Chondrites* and *Skolithos* suggest *Zoophycos* icnofacies assemblage with elements of distal *Cruziana* (MacEachern & Bann, 2008).

Interpretation

The abundance of fine-grained material coupled with planar lamination suggests deposition in a low energy environment below wave base away from fluvial activity. Mudstone beds are interpreted to have been deposited due to suspension fallout during very low energy periods, with laminations and the amalgamation of mud layers indicating long periods of low energy. Minor, thin clean ripple-laminated sands with sharp bases, fining up profiles, slumps and dewatering structures within beds are interpreted to be event beds deposited as a result of gravity flows. In this case density flows are interpreted to form as a result of slope failure events and/or hyperpycnal currents from rivers (Wright, 1977; Bhattacharya & MacEachern, 2009; Legler et al., 2014). Due to the combination of low energy deposition, density flows and a distal *Cruziana* to *Zoophycos* icnofacies assemblage, FA1 is interpreted to have been deposited in a deep water environment. No diagnostic species or elements of *Nerites* ichnofacies (MacEachern & Bann, 2008) were identified, although many species identified are common to *Cruziana* and *Zoophycos* as well as *Nerites*. Sand-rich event beds may carry species from shallower *Cruziana* to *Zoophycos* ichnofacies to deeper water environments, explaining the small burrow size, as these organisms failed to thrive in a deeper water environment. With more data to assess species diversity, the designation of the *Nerites* ichnofacies to this facies association is plausible, although the likely shallow nature of the basin may have allowed for *Cruziana* to *Zoophycos* ichnofacies to in a more distal setting than conventionally interpreted.

Facies Association 2

Description

Facies Association 2 (FA2) consists of thinly bedded (millimetre and sub millimetre scale) light grey to very dark grey claystone, siltstone and occasional 5-10 cm quartz arenite sandstone beds. Individual sand beds exhibited a fining up structure, with sharp bases, a lower fine to very fine sand package and an upper gradual transition to silty mud tops (Figure 5 B). Lenticular and wavy stratification, clean sand ripples, mud draped ripples, starved ripples, climbing ripples and planar stratification structures were common. Sand beds also occasionally preserved hummocks, swales and hummocky laminae. Planar lamination was abundant in mudstone beds. Soft sediment deformation was present, with slumps, load casts and dish structures common in mudstones and microfaults present in sandstones. Dewatering structures were common at the interface between sand and mud layers. Siderite concretions occurred in all lithologies throughout FA2. FA2 exhibited a generally subtle coarsening-up pattern, and a general upward increase in sand content. Bioturbation overprints original sedimentary structures. Thicker sand beds are generally less bioturbated, and more likely to have vertical burrows. Bioturbation is common in siltstones and sandier layers with a BI of 1 to 2. The presence of *Arenicolites*, *Thalassinoides*, *Teichichnus*, *Rhizocorallium*, *Rosselia, Planolites* and *Skolithos* suggest a dominantly *Cruziana* ichnofacies (MacEachern & Bann, 2008).

Interpretation

Abundant millimetre and sub millimetre scale claystone, siltstone and occasional sandstone beds with a dominantly *Cruziana* ichnofacies suggest a low energy environment distal to sediment source, fluvial activity and wave activity. Thin ripple-laminated sands with sharp bases, fining up profiles, slumps and dewatering structures are interpreted to be event beds deposited as a result of density flows, potentially as a result of slope failure events, higher river discharge and hyperpycnal plumes from rivers. Interpreted density flow deposits in FA2 are over 50% thicker and show a more defined fining up trends than in FA 1; they are interpreted to be the proximal equivalent of the density flow deposits in FA1. Hummocks and swales most likely record extreme weather events, while slumping and soft sediment deformation suggest gravity-induced mass movements were occurring in the depositional environment. Siderite concretions are most likely to have formed post deposition, most likely early in diagenisis, and are related to the chemical conditions in the depositional environment and pore waters during diagenisis (Schulz-Rojahn, 1993). FA2 is interpreted to have been deposited in a prodeltaic setting.

Facies Association 3

Description

Facies Association 3 (FA3) consists of upward-coarsening predominantly ripple-laminated quartz-rich moderately to well sorted fine-grained sandstone interbedded with planar laminated mica-rich siltstone and mudstone (Figure 5 C). Sand bed thicknesses ranged from approximately 10 to 30 cm. Centimetre-scale hummocks and swales, wave modified current ripple lamina, massive sandstone beds, starved ripples and dewatering structures were present. Slump-folding and flame structures were common in mudstones. Capping the sand-rich section were mud-rich strata with planar laminations and small scale ripples. Synaereses cracks were observed throughout the FA. Microfaults were present in sandstone strata. Centimetre-scale coal clasts, wood clasts, well-rounded isolated pebbles and siderite concretions were preserved in rare cases in sand beds. High concentrations of micaceous minerals, as well as isolated potential glauconitic grains were observed. Traces were small, rare (BI=1) and most commonly observed in siltstones and claystones. The presence of *Planolites, Skolithos, Ophiomorpha, Thalassinoides, Arenicolites* and *Rosselia* indicate a mixed *Skolithos* and potentially proximal *Cruziana* ichnofacies (MacEachern & Bann, 2008).

Interpretation

The upward-coarsening depositional trend, predominantly ripple-laminated sands interbedded with siltstone and mudstone and a mixed *Cruziana* and *Skolithos* ichnofacies suggest a depositional environment of low to moderate energy. Diverse ripple structures together with wave-modified strata suggest a fluvial dominated, wave influenced (c.f. Ainsworth et al., 2011) depositional setting. Similar patterns have been interpreted as delta front depositional settings in fluvial dominated deltas (Hansen and MacEachern, 2005; Miall, 1984; Kamola and Van Wagoner, 1995). Sand rich sections represent distributary-channel mouthbars, which are interbedded with overbank splays and shallow-bay deposits. An upward-coarsening pattern is interpreted to be a sign of progradation of the delta front. Soft sediment deformation and massive sandstones suggest rapid or event-based deposition. The presence of synaereses cracks, which form as a result of subaqueous shrinkage of clay which has flocculated rapidly due to a rapid change in chemistry, or salinity, causing shrinkage in montmorillonitic clay (Pratt, 1998), implies deposition in sub-aqueous conditions and may indicate variations in salinity in a low energy sub-aqueous environment. A variation in salinity, or brackish conditions, is also suggested by the low diversity and abundance of traces. Sparse organic matter suggests a nearby plant source. Isolated pebbles could be interpreted as glacial erratics, but could have been rafted to the location along with the organic matter, or potentially by

Cretaceous fauna. Glauconitic material is most likely a result of alteration of micaceous minerals or degraded organic material. In delta front settings, mouth bar deposits are difficult to distinguish from terminal distributary channel deposits, as mouth bars infill the channels (van Heerden and Roberts, 1988).

Facies Association 4

Description

Facies Association 4 (FA4) consists of a wide variety of lithofacies, but mostly centimetre-scale planar laminated dark grey silty shale, irregularly interbedded with 1 to 10 cm thick beds of fine to medium grained current- and wave-rippled quartz arenite (Figure 5 D). Carbonate cementation was pervasive in sand beds. Sand beds were sharp and sometimes erosionally based. These beds preserved inclined low-angle cross-stratification, planar tabular stratification and planar lamination as well as current ripples and, less commonly, wave ripples. Flaser, linsen and lenticular stratification (Reineck & Wunderlich, 1968) were present, with gradual transitions between these patterns common. Centimetre scale dewatering structures were observed. Coal wisps and woody fragments were present. Synaereses cracks were common in the upper section of FA4, most often present in clay-rich sections. Oxidised horizons, siderite cementation, carbonate cementation and millimetre-scale rootlets were occasionally observed in mud strata. *Planolites* and *Skolithos*, as well as rare *Camborygma, Rhizocorallium, Diplocraterion* (*habichi*) and *Arenicolites* were observed in sand rich beds, with a BI of 2 to 4. Preserved trace fossils size within the same species was diverse. A *Skolithos* ichnofacies is suggested, although potentially some elements of *Scoyenia* are preserved (MacEachern & Bann, 2008).

Interpretation

The abundance of planar lamination and the occurrence of flaser, linsen and lenticular stratification suggest a depositional environment of fluctuating energy. Current ripples, planar lamination and inclined low-angle cross-stratification could indicate splays, levees and proximal overbank deposits (Holbrook, 2001). Preserved coal wisps and woody fragments suggest a nearby source of plant material. Synaereses cracks indicate sub-aqueous conditions and a potential variation in salinity. Minor oxidised horizons and rootlets suggest relatively short times of sub-areal exposure. FA4 is interpreted to represent a delta plain environment due to the diverse range of sub-environments and the evidence for a *Skolithos* ichnofacies (MacEachern & Bann, 2008).

Facies Association 5

Description

Facies Association 5 (FA 5) consisted primarily of a coarsening-up package of wave ripple-laminated, hummocky cross-stratified, occasional planar cross stratified and planar laminated well-sorted, clean, fine-grained quartz arenites, often with high mica content (Figure 5 E). FA5 generally has a sharp and erosional boundary at the base and a gradual boundary into the overlying FA. Very thin millimetre-scale laminated silt and claystone beds are interbedded with sandstones. This FA often occurs with relatively low bioturbation (BI = 0 to 1) and well preserved sedimentary structures and sometimes occurred with major bioturbation (BI = 2 to 3), particularly around siltstone and claystone layers. Depositional sedimentary structures were partially deformed and sometimes destroyed by burrowing. Burrows were occasionally damaged or partially preserved. *Rhizocorallium, Macaronichnus* and *Skolithos*, as well as rare *Diplocraterion habichi, Psilonichnus, Scoyenia* were observed. A *Skolithos* Ichnofacies is interpreted based on the dominance of traces belonging to this group, but elements of *Psilonichnus* and to a lesser extent

Scoyenia exist (MacEachern & Bann, 2008).

Interpretation

Hummocky cross stratification (HCS) indicates deposition by episodic storm events in water depths between the effective storm wave-base and fair-weather wave base (Dott & Bourgeois, 1982; Duke, 1985; Keen et al., 2012). Individual HCS beds most likely formed in deeper conditions and as a result of larger storms and smaller amalgamated beds a result of smaller, longer-duration storms or water shallowing, most likely in a shoreface setting (Storms & Hampson, 2005). This is consistent with a coarsening-up depositional pattern and the interpreted ichnofacies. The intermittent presence of planar tabular cross stratification and planar stratification suggests elements of the upper shoreface, backshore and nearshore bars are preserved. Highly bioturbated occurrences of this FA were most likely deposited during storm events, and then densely inhabited by organisms during calmer conditions. Damaged or partially preserved burrows are probably due to storm activity on the shoreface.

Facies Association 6

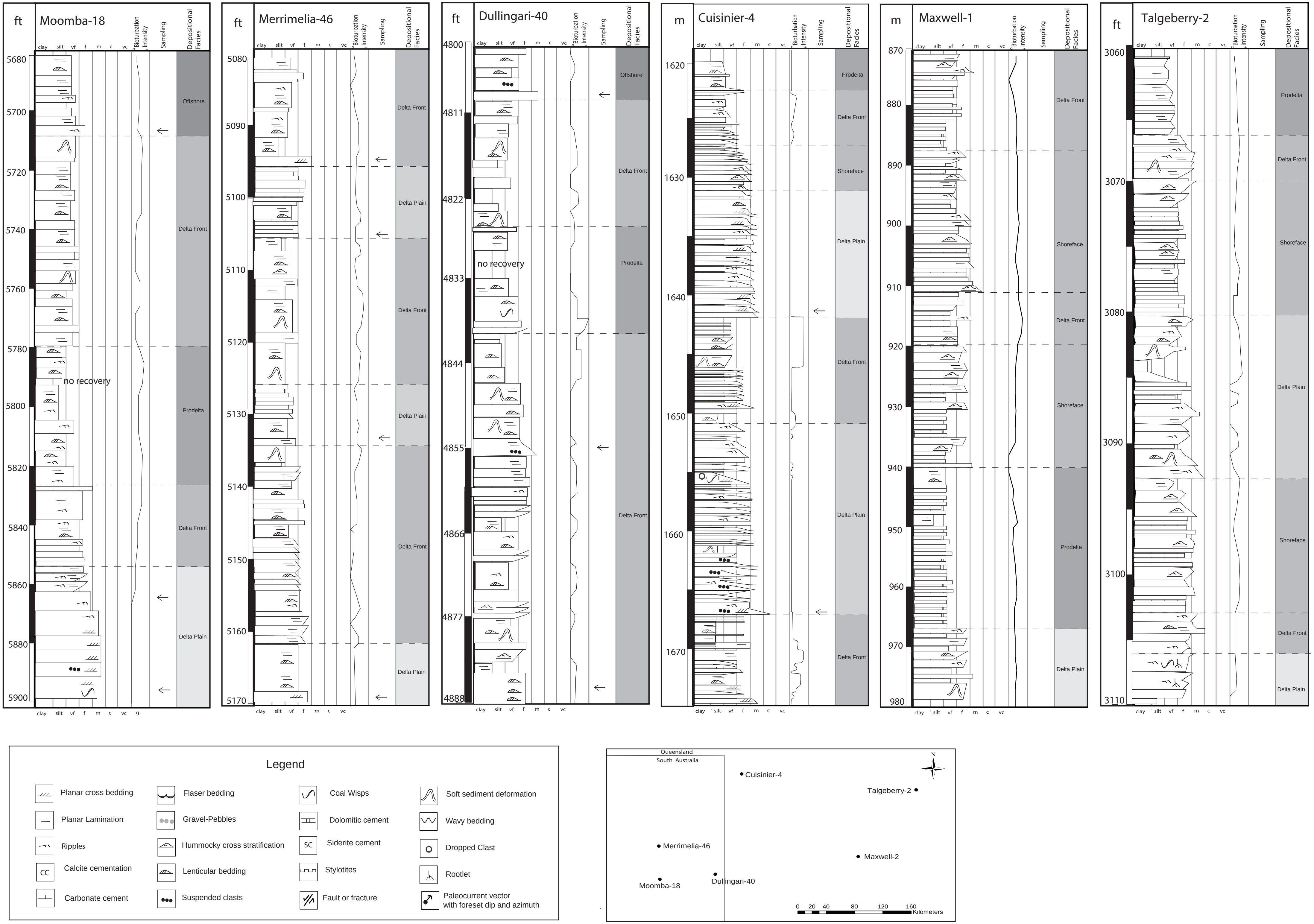
Description

Facies Association 6 (FA6) is a well-sorted, medium-sand sized, quartz arenite, with trough cross-stratified, planar tabular cross-stratified, massive, current-rippled and planar-laminated structures, and occasional isolated granule to pebble clasts (Figure 5 F). The basal bed of most packages in this FA consists of sharp- to erosionally-based cross-stratified fine- to medium-quartz arenite with sparse quartz and lithic pebbles, mud rip-up clasts, coal chips and plant detritus. Internal scours were present. This basal package was overlain by planar tabular cross-stratified, massive and planar laminated relatively quartz-rich sands. Mud was present on the foresets of trough and planar tabular cross-stratified sands. A fining-up trend was observed in FA6. Siltstone or claystone beds with planar lamination topped the package. Carbonate cement, oxidisation and millimetre-scale rootlets were occasionally observed in the mud strata. Bioturbation is rare lower in the FA (BI = 0 to 1) but becomes relatively more abundant (BI = 1 to 2) at the mud-rich top of the package. *Skolithos, Scoyenia*, and *Planolites* were present. A poorly developed *Skolithos* ichnofacies is suggested, although elements of *Scoyenia* are preserved (MacEachern & Bann, 2008).

Interpretation

Scour and fill structures, sharp bases with trough and planar tabular cross-stratification and coarse lags, fining–up to current rippled and planar-laminated sands and muds, suggest an environment with decreasing energy. Trough cross-stratification is formed by the migration of three-dimensional bedforms with bedload transport and indicates the presence of a relatively strong current, while massive bedding with little structure could indicate rapid deposition. Relatively low thickness, a combination of unidirectional flow indicators and a close association with FA3, FA4 and FA5 infers that this facies represents fluvial- dominated distributary channels (Elliott 1978; Bhattacharya and Walker 1992; Reading and Collinson 1996; Olariu and Bhattacharya, 2006). Meandering fluvial and braided streams also exhibit many of the characteristics of FA6 (Galloway, 1975; Miall, 1978) so these environments should not be discounted entirely, but the vertical thickness of this facies (0.5- 4 m) and association with FA3 and FA4 are more suggestive of a distributary channel environment. A change from a high energy to low energy brackish environment up

Figure 7: Next page. Detailed logging across a variety of lithofacies. Detailed core log and interpretation for 6 of 45 wells logged for this study; Moomba-18, Merrimelia-46, Dullingari-40, Cuisinier-4, Maxwell-1 and Talgeberry-2. Wells were selected to show the variation in depositional environments. Overall deepening patter is present.


Moomba-18
Merrimelia-46
Dullingari-40
Cuisinier-4
Maxwell-1
Talgeberry-2
ft
m
Bioturbation Intensity
Sampling
Depositional Facies
clay silt vf f m c vc g
Offshore
Delta Front
Delta Plain
Prodelta
Shoreface
no recovery
Legend
Planar cross bedding
Planar Lamination
Ripples
Calcite cementation
Carbonate cement
Flaser bedding
Gravel-Pebbles
Hummocky cross stratification
Lenticular bedding
Suspended clasts
Coal Wisps
Dolomitic cement
Siderite cement
Stylotites
Fault or fracture
Soft sediment deformation
Wavy bedding
Dropped Clast
Rootlet
Paleocurrent vector with foreset dip and azimuth
Queensland
South Australia
Cuisinier-4
Talgeberry-2
Merrimelia-46
Maxwell-2
Moomba-18
Dullingari-40
N
0 20 40 80 120 160 Kilometers

facies is inferred from changes in sedimentation and bioturbation. It is possible that these channels retained an open connection with a marine environment during abandonment, forming estuarine channels (e.g. Dalrymple et al., 1992). The presence of mud drapes and cyclic planar laminated sands and muds may also indicate a tidal environment, supporting the interpretation of an estuarine environment.

Low-gradient basins, such as the Eromanga Basin, are sensitive to subtle tectonic movements, the effects of which on sedimentation patterns can be substantial (Habeck-Fardy and Nanson, 2014). Small tectonic movement can greatly affect channel position.

6.5.7. Carbonate cemented horizons

Diagenetic overprinting of various sedimentary facies by carbonate (mainly siderite) cementation is common throughout the Murta Formation. These horizons vary in thickness from 30cm to 1m. They are generally pervasive, have sharp tops and gradational bases, and are often fractured.

Cementation in the Murta Formation occurred in a number of ways, with a number of different mechanisms responsible (Schulz-Rojahn, 1993). The two most cited mechanisms in the Eromanga Basin literature are described here. Cooper Basin carbon dioxide migrated vertically into the calcium-bearing aquifers of the Eromanga Basin. Mixing of migrating carbon dioxide with calcium-rich waters could have led to the formation of intensely carbonate-cemented zones (Schulz-Rojahn, 1993). Many of the calcite-cemented zones occur near the top of coarsening-up cycles, together with synaresis cracks. In this case calcite cemented beds could have originated from precipitation near the boundaries of fresh and salt-water phreatic zones due to a chemical reaction from the change in salinity (Schulz-Rojahn, 1993).

6.5.8.Palynology

Description

Biostratigraphic data from the Murta Formation were generally taken within the first few metres of the top of the formation. Samples were interpreted on the wellsite while drilling. Data was available for twelve wells, with one or two samples available near the top of the well, mainly from sections classified as FA2 (Prodelta), FA3 (Delta Front) or FA4 (Delta Plain). A lack of abundant and diverse dinoflagellate flora is characteristic of the Murta Formation (Price, 1997). Araucarean/ Podocarpacean conifers, seed ferns and tree ferns are common. Brackish water algae, such as *Botryococcus Pediastrum*; acritarchs, such as *Microfasta* and *Schizospora,* and rare dinoflaggelates such as *Baticashpaera Fusiformacysta* and *Nummus* are present.

Interpretation

A lack of abundant and diverse dinoflagellate flora suggests a stressed brackish environment where salinity changes were common, or a continental environment of deposition. The abundance of spores and pollens suggest a continental deposition setting, however spores and pollens can be transported in fluvial systems to marginal marine depositional environments (De Vernal, 2009). High levels of fresh-water runoff, rich in traces of continental flora and deposited into shallow, semi-enclosed bodies of water may explain the high abundance of pollens and spores together with the presence of algae and acritarchs. A further detailed study which re-samples wells in the Murta Formation and describes the palynology is likely to yield further depositional setting information, however the very low range of data currently available only adds to the interpretation uncertainty.

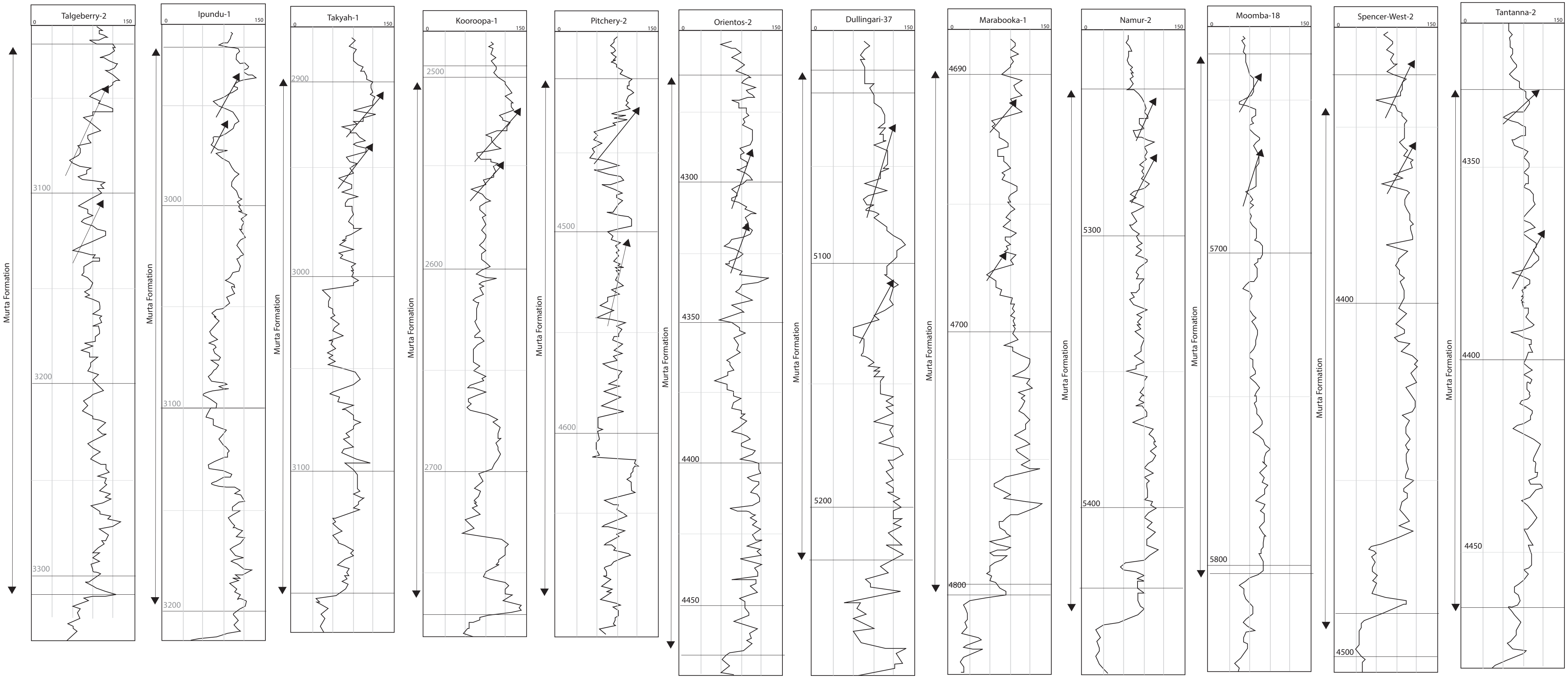
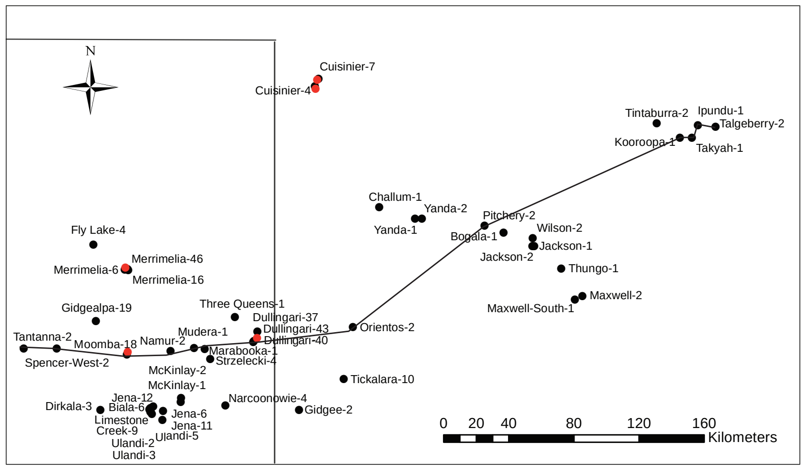
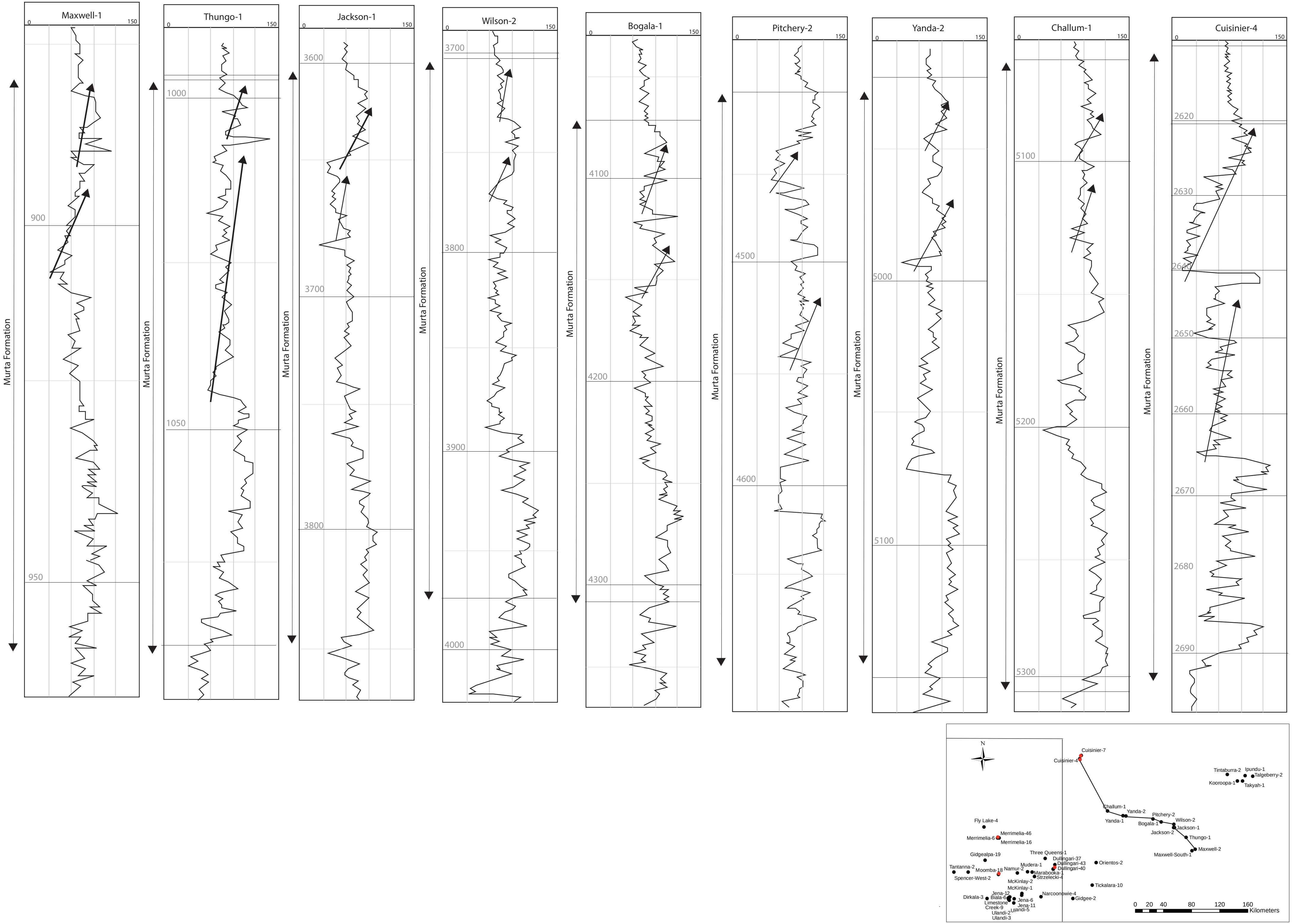


Figure 8: Two pages. Correlations across the basin. Two wireline log-based figures are presented. Wireline gamma signatures are only presented. (A) North- East South West wireline log signature for the Murta Formation. (B) North-West South-East wireline log signature patterns for the Murta Formation.





Maxwell-1
Thungo-1
Jackson-1
Wilson-2
Bogala-1
Pitchery-2
Yanda-2
Challum-1
Cuisinier-4
0
150
900
950
1000
1050
3600
3700
3800
3900
4000
4100
4200
4300
4500
4600
5000
5100
5200
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2620
2630
2640
2650
2660
2670
2680
2690
Murta Formation
N
Cuisinier-7
Cuisinier-4
Challum-1
Yanda-2
Yanda-1
Pitchery-2
Bogala-1
Wilson-2
Jackson-1
Jackson-2
Thungo-1
Maxwell-2
Maxwell-South-1
Tintaburra-2
Ipundu-1
Talgeberry-2
Kooroopa-1
Takyah-1
Fly Lake-4
Merrimelia-46
Merrimelia-6
Merrimelia-16
Gidgealpa-19
Three Queens-1
Dullingari-37
Dullingari-43
Dullingari-40
Orientos-2
Tantanna-2
Moomba-18
Namur-2
Mudera-1
Marabooka-1
Strzelecki-4
Spencer-West-2
McKinlay-2
McKinlay-1
Tickalara-10
Narcoonowie-4
Gidgee-2
Dirkala-3
Jena-12
Biala-6
Jena-6
Limestone
Creek-9
Jena-11
Ulandi-5
Ulandi-2
Ulandi-3
0 20 40 80 120 160
Kilometers

6.5.2. Regional Variation in Sedimentary Architecture

Wireline log observations and interpretations show that the Murta Formation tends to exhibit more of a coarsening/ cleaning upward signature on the Queensland side of the state border (see Figure 1 for state locations). Here the Murta Formation is generally thinner and more sand-rich. The transition from the McKinlay Formation to the Murta Formation is subtle in this region. The Murta Formation thickens over the Cooper Basin region, suggesting that the depocentre of the basin was in this location at the time of deposition of the Murta Formation. The Murta Formation becomes more mud-rich and sand beds become thinner on the South Australian side of the state border (see Figure 1 for state locations). Coarsening-up intervals are less pronounced, meaning that there are still coarsening up sections, but the magnitude of change in the grain size (or at least the wireline log response) is smaller. Most of the wells studied on the South Australian side of the state border (see Figure 1 for state locations) are interpreted to be close to the depocentre of the basin. Throughout the Eromanga Basin, the basal part of the Murta Formation is most likely to contain fining-up distributary-channel fill or prograding lacustrine sequences, whereas the upper section is more likely to contain coarsening-up estuarine, shoreface and distributary channel type patterns.

Two potential sequence boundaries could be interpreted within the Murta Formation on most logs (Figure 7 A, B). An abrupt change in facies from a deeper to a shallower water depositional setting was interpreted to indicate a sequence boundary. Lower order localised sequence boundaries occur on a more regional scale and are particularly common in the lower Murta Formation. Often they do not correlate outside of specific field areas or between Queensland and South Australian sides of the basin. Potentially, the two areas were controlled by different factors during this time, or were controlled by autogenetic processes. Flooding surfaces are generally distinct. Transgressive surfaces were difficult to pick and transgressions were most likely complex, piecewise events. These surfaces sometimes could be interpreted to be erosive in nature, such as at Dullingari where transgressive lags were present in many wells (Figure 7 A, B). Lower-order parasequences may be present within the interpreted sequences, although distinguishing basin-wide events from localised processes was difficult. While these factors must be carefully considered, over-interpretation or correlation of autogenetic processes will not result in a predictive sequence stratigraphic model.

Comparable log character changes between closely spaced wells in the Murta Formation within the same field. For example, at the Dullingari Field, an upward coarsening pattern is present at Dullingari-11, and within the interpreted time equivalent unit, an upward fining pattern is present at Dullingari-5. A similar patent is present at Thungo-3 where a distinctive fining up gamma ray log response is in contrast to coarsening upward sequences in other Thungo wells. While this may be indicative of, and has been interpreted as, an erosional boundary or sequence boundary, this could also be due to the scale of such features and the limited sampling. Reservoir sands in the Murta Formation are on average less than 4 m thick and heterolithic in nature, making seismic mapping difficult. Compared to the estimated lateral extent of these features (tens of metres), well spacing is relatively sparse as it is usually in the order of kilometres. If these features are not targeted specifically, well intersections with sandbodies are random. No verification or further indication of a sequence or erosional boundary, such as subarial exposure indicators, paleosols or erosional surfaces, are seen in core in adjacent wells where sands are not present. At this scale, autogenetic processes such as avulsion of distributary channels may be a reasonable explanation rather than incised valley formation due to the size and scale of the features. Furthermore, simple lobe switching due to the changes in sediment flux or sediment loading can give the impression of a regional flooding surface, but it is most likely a local flooding surface.

tectonic uplift and subsidence, on a reservoir scale, may have caused localised incision and fill structures, similar to those in low-gradient basins today (Kati Thanda-Lake Eyre Basin, Habeck-Fardy and Nanson, 2014; This thesis, Chapter 4 and the references within). Localised sediment re-routing may have resulted in sediment bypass and sediment sumps above the ultimate base level of the basin. This could explain incised-valley-like features at Dullingari and Thungo. These features are more common along the margins of the basin.

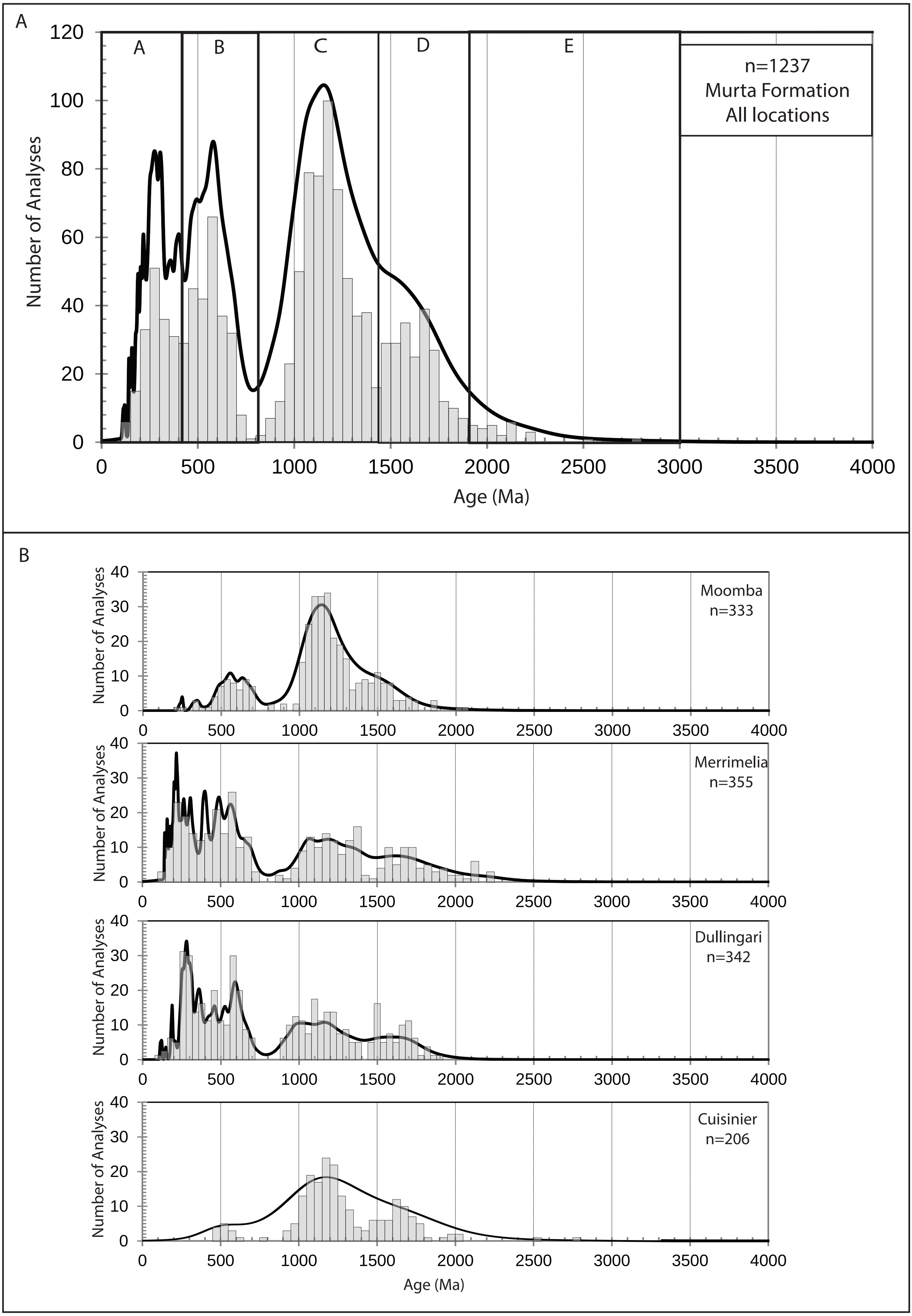
Subtle thickening is observed over major structures in the Eromanga Basin (see Figure 3 for location of major structures), indicating that an increase in accommodation space occurred, most likely due to low-magnitude tectonic activity and base level rise. Sediment supply in the eastern part of the basin was most likely steady to increasing, resulting in the progradational and aggradational parasequence patterns observed (Figure 7 A, B). Sediment supply in the western part of the basin was most likely lower, with older, more mature quartz rich cratons with less relief providing a lower rate of sediment supply. This could be the reason that we see more retrogradational patterns on this side of the basin (Figure 7 A, B). This further complicates stratigraphic correlations across the basin and the determination of allogenic compared to autogenic events, as they may be expressed differently on the eastern and western sides of the basin.

6.5.3. Provenance and Paleogeography

Results

At the time of deposition of the Murta Formation, basin fill was most likely sourced from (1) mature quartzose continental cratonic sources primarily to the south and west and (2) younger volcanogenic sediments derived mainly from the east (Hoffmann, 1989; Allen et al, 1996; Figure 4). Evidence for younger volcanogenic sediments was clear in sands in wells to the east and south of the basin during core logging. In that area (e.g. Talgeberry-2, Takyah-1, Maxwell-2, Pitchery-2) sediments were generally fine grained, relatively angular, more felspathic, relatively rich in micas and more clay-rich (authigenic kaolinite) than comparable depositional environments in other locationsin the south and west of the Eromanga Basin. This is supported by petrographic studies in these areas (Hill, 1999; Martin, 1983), which suggest a proximal metamorphic and igneous source. In the south west and north of the basin, sediment provenance has not been investigated as thoroughly and is difficult to infer from petrographic observation.

In order to further investigate sediment provenance 1237 zircon U-Pb data were acquired from 12 samples from interpreted fluvial-dominated sandstone units for four well locations in the Murta Formation (see Figure 1 and Figure 7 for locations). Analysed grains were selected without using any particular criteria, to avoid undue bias in the data collection. Data are within 10% concordance and retained due to acceptable concentrations of U and Th. Data are presented using age histograms superimposed on relative probability plots (Figure 10). Data from samples taken at each horizon within a particular well are identical, therefore results have been combined for each well location (e.g. Figure 10). This result suggests that the sediment source did not change substantially throughout deposition of the Murta


A
A
B
C
D
E
n=1237
Murta Formation
All locations
Number of Analyses
Age (Ma)
B
Moomba
n=333
Merrimelia
n=355
Dullingari
n=342
Cuisinier
n=206
Number of Analyses
Age (Ma)

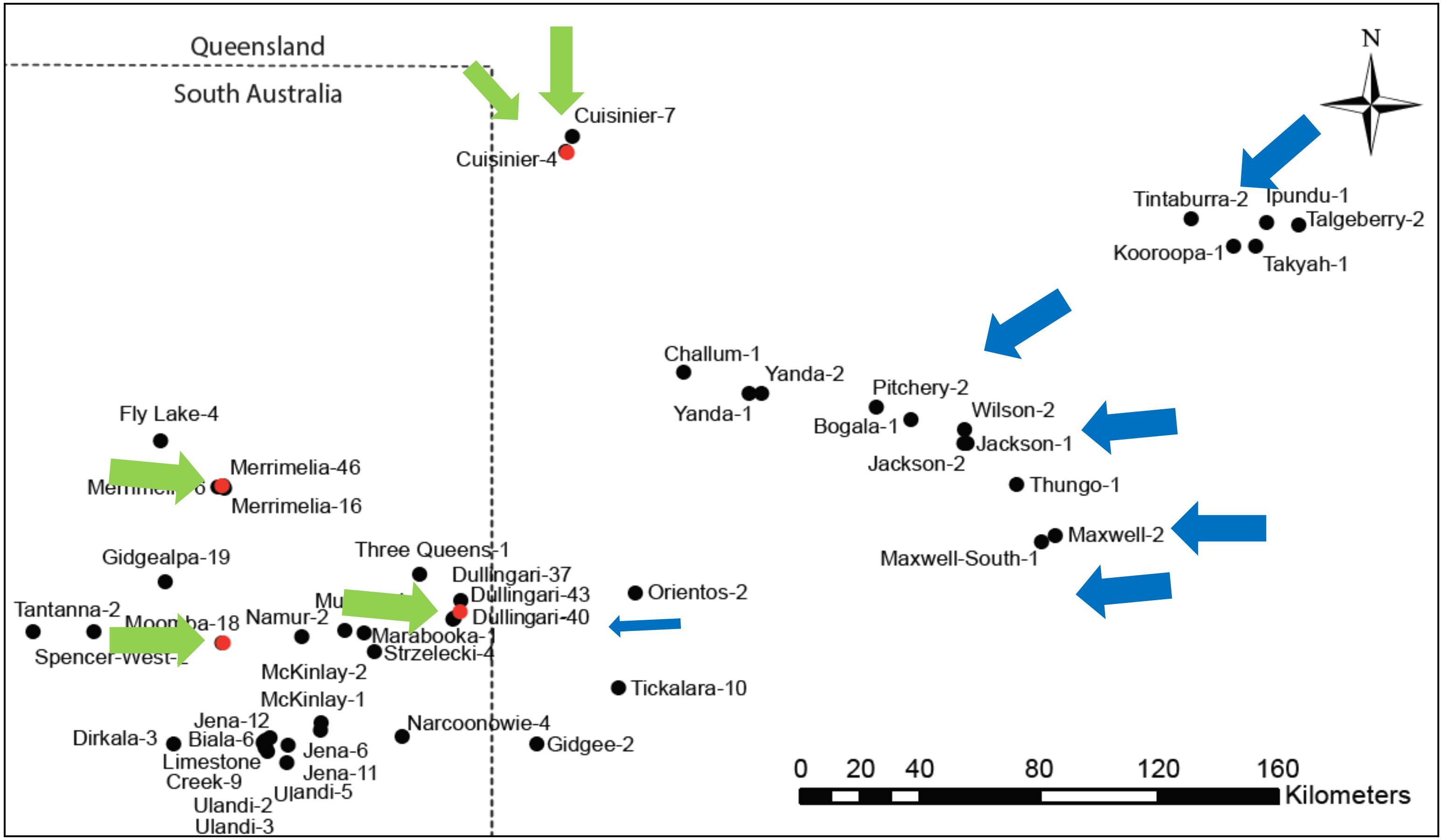

Queensland
South Australia
N
Cuisinier-7
Cuisinier-4
Tintaburra-2
Ipundu-1
Talgeberry-2
Kooroopa-1
Takyah-1
Challum-1
Yanda-2
Yanda-1
Pitchery-2
Bogala-1
Wilson-2
Jackson-1
Jackson-2
Thungo-1
Maxwell-2
Maxwell-South-1
Fly Lake-4
Merrimelia-46
Merrimelia-16
Gidgealpa-19
Three Queens-1
Dullingari-37
Dullingari-43
Dullingari-40
Orientos-2
Tantanna-2
Namur-2
Marabooka-1
Strzelecki-4
McKinlay-2
McKinlay-1
Tickalara-10
Jena-12
Narcoonowie-4
Dirkala-3
Biala-6
Jena-6
Gidgee-2
Limestone
Creek-9
Jena-11
Ulandi-2
Ulandi-5
Ulandi-3
0 20 40 80 120 160
Kilometers

Figure 10: Previous Two Pages.

A. Relative probability plot containing ages from all detrital zircons in this study (n = 1237 grains). Left vertical axis corresponds to number of grains in each age bin (age bins span 50 m.y.). Age populations are denoted by grey shaded bars. Population C constitutes the largest percentage of all ages from the Murta Formation (44.5% of all grains), followed by population D (20.4%), then population B (17.5%), population E (15.3%), and population A (2.2%).
B. Relative probability histograms for each detrital zircon sample location from the Murta Formation. The name and number of grains corresponding to each sample are labelled. For locations of samples see Figure 1B.C: Over page. Likely sediment transport pathways. Green represents older, more stable cratons. Blue represents younger cratons. Size of transport direction arrow indicates confidence in interpretation.

Formation. Results have been subdivided into five age populations (A–E; Figure 10). Each population may be linked with one or more potential source regions exposed on the Eromanga Basin margins during the Cretaceous. The characteristics of each age population are outlined in this section with an interpretation of spatial and temporal trends observed in the data set.

6.7.1. Population A: Archean to Paleoproterozoic ages (3000–1900 Ma)

Paleoproterozoic to Archean age zircons make up 2.2% grains analysed. Small peaks exist around 2100 and 1800 Ma. The primary source for these grains was most likely the Gawler, Curnamona, Arunta and Mt. Isa cratonic provinces (Veevers, 2000). A few older grains (2900–2600Ma) are most likely to be inherited and recycled from ancient terrains, such as the Yilgarn and/or Pilbara regions (Veevers, 2000). These older populations are present at Cuisinier, Merrimelia and Moomba, but absent at Dullingari.

6.7.2. Population B: Paleoproterozoic to Mesoproterozoic (1900–1425 Ma)

Population B, Paleoproterozoic to Mesoproterozoic age zircons account for 17.5% of Murta Formation zircons analysed. Four major peaks exist at 1720 Ma, 1670 Ma, 1580 Ma, and 1500 Ma, with a few grains of 1900-1750 Ma present. Zircons most likely originated from the Gawler, Curnamona, Arunta, Mt. Isa cratonic provinces (Howard et al., 2011; Veevers, 2000). The 1500 Ma population is pronounced at Moomba and Dullingari, but minor at Cuisinier and Merrimelia. Likely sources are intrusive igneous lithologies of the Gawler Craton and Arunta Region (Howard et al., 2008). Merrimelia and Dullingari share peaks at 1670 Ma and 1580 Ma, which could have been derived from igneous sources such as the Middlecamp, Moody and Tunkilla suites on the Gawler Craton (Howard et al., 2008). The main peak at Cuisinier is at 1620 Ma, which could have been sourced from the Mt Isa province, particularly the Mt Isa Eastern succession and the intrusive igneous Soldiers Cap group (Howard et al., 2008). This peak could have also been sourced from the Gawler Craton or Arunta Region, as these regions share similar aged events (Howard et al., 2011, Veevers et al., 2000); however the closest terrain to each well respectively is the most likely source. The presence of these peaks suggests that older, more stable Southern Australia and Northern Australian cratons were emergent at this time. Alternatively this sediment could have been recycled from older underlying formations, particularly at the basin margins.

6.7.3. Population C: Mesoproterozoic to Neoproterozoic Ages (1425-900 Ma)

Mesoproterozoic to Neoproterozoic grains consist of 44.5% of Murta Formation zircons analysed in this study. Major peaks exist at 1308 Ma, 1166 Ma and 1034 Ma. 1425-900 Ma grains dominate Moomba and Cuisinier samples and are less prominent in others. Peaks at 1308 Ma, 1166 Ma and 1034 Ma correlate with events in the Musgrave, Albany-Fraser and Patterson Blocks which exist to the south and west of the basin (Wade, 2008). These grains were most likely sourced from the south and west of the basin. These provinces would have represented the basin margins at the time of deposition of the Murta Formation. These ages, particularly 1308 Ma, which is prominent in the Cuisinier samples, also correspond with igneous events in the Mt Isa inlier, suggesting that sediment at Cuisinier may have also been locally sourced from the Mt Isa inlier to the North-East.

6.7.4. Population D: Neoproterozoic to Silurian Ages (900-420 Ma)

Neoproterozoic to Silurian ages account for 20.4% of Murta Formation zircons analysed. Major peaks exist at 678 Ma, 640 Ma, 578 Ma, 510 Ma and 460 Ma. The population at 678 Ma is small, but is coincident with detrital zircons originating from East Africa/ice-covered Antarctica and Lachlan Orogen and in derived sands (Veevers and Saeed, 2011). This material was most likely sourced from the south of the basin. The peak at 578 Ma is coincident with the Mt. Arrowsmith volcanic event and detrital material of this age was most likely sourced from material from this event. The peak at 460 Ma is minor and likely again represents material sourced from East Africa/ice-covered Antarctica and Lachlan Orogen and in derived sands (Veevers and Saeed, 2008)

6.7.5. Population E: Silurian through Cretaceous Ages (420-140 Ma)

Population E, 420 to 140 Ma, contains 15.3% of Murta Formation zircons analysed. Within this population peaks exist at 380 Ma, 310 Ma, 256 Ma, 205 Ma, and 152 Ma. Peaks at 380 Ma and 310 Ma correspond to igneous activity relating to the Tabberabberan Cycle and the Benambran Cycle as a part of the Lachlan Orogen to the west of the basin (Veevers et al., 2011; Veevers, 2013). New England Late Triassic magmatic activity in the New England Orogen coincides with the peak at

205 Ma (Veevers, 2013). The population centred on 152 Ma is most likely due to Jurassic volcanism, which was widespread throughout the western margin of the basin during the Jurassic. This is further supported by the visual appearance of these younger grains, as they were more likely to exhibit angular edges and fewer domains.

The youngest analysis is 141.6 ± 2.4 Ma (Merrimelia) and hence deposition of the Murta Formation occurred after this time. This is in agreement with an Early Cretaceous Berriasian to Valanginian (145-134 Ma) depositional age for the Formation, although the depositional age could be younger than this.

6.5.4. Interpretation

Results indicate that material was sourced from all around the basin margins during deposition of the Murta Formation (Figure 10C). There was no noticeable shift in provenance between samples from different stratigraphic layers at individual locations, indicating no major shift in source during deposition, even over interpreted sequence boundaries. Although the Neoproterozoic to Cretaceous age peaks are present (35.7%), Paleoproterozoic to Neoproterozoic ages (62%) dominate the population.

Samples from Dullingari and Merrimelia share a similar detrital signature (Figure 10), indicating that they could be supplied by a similar sediment source. Fluvial systems originating in the east and west of the basin could have deposited sediments in deltaic systems which then fed into deeper water sediments at Merrimelia and Dullingari, which are interpreted to have been deposited close to the depocentre of the basin. Surprisingly, Cuisinier and Moomba share a similar detrital signature, as it is unlikely that Cuisinier and Moomba share a common detrital source. This is interpreted to be because the Gawler Craton, Arunta Block and Mt Isa block share a similar evolutionary history, which is reflected in correlatable events and a similar detrital signature.

Although it is not unexpected that material was sourced from all around the basin margins during deposition of the Murta Formation, previous interpretations have

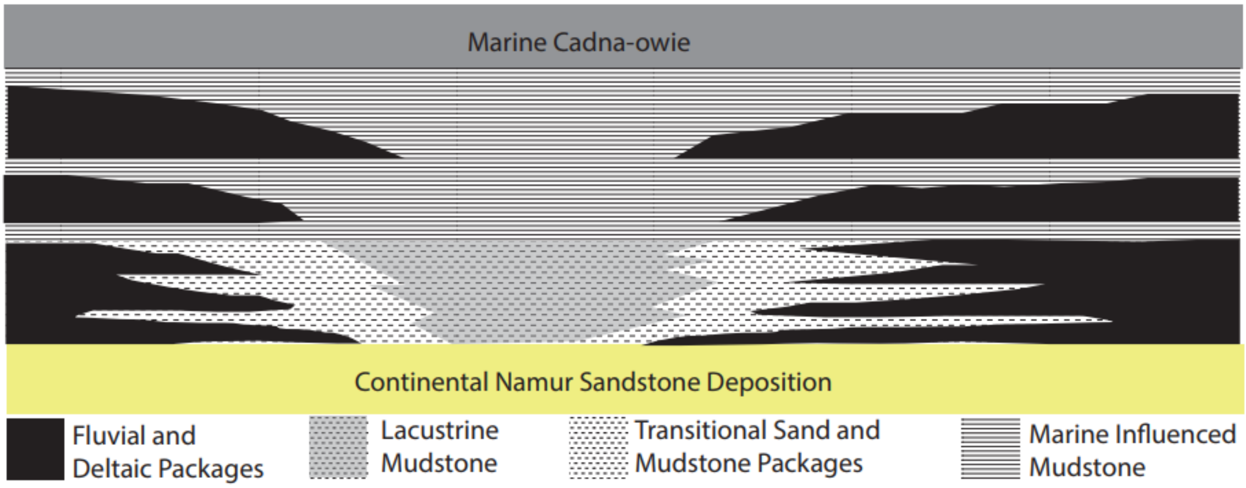
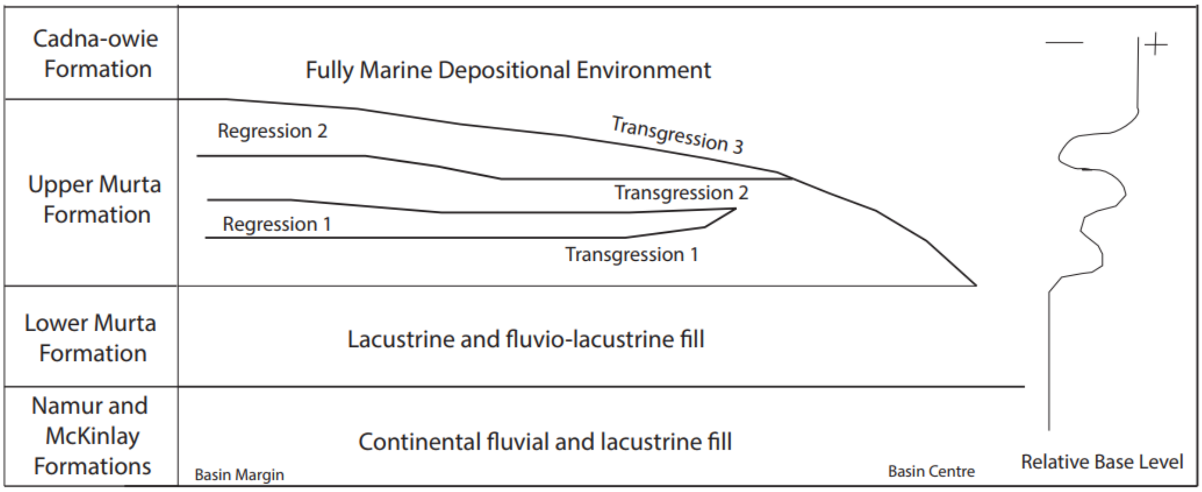
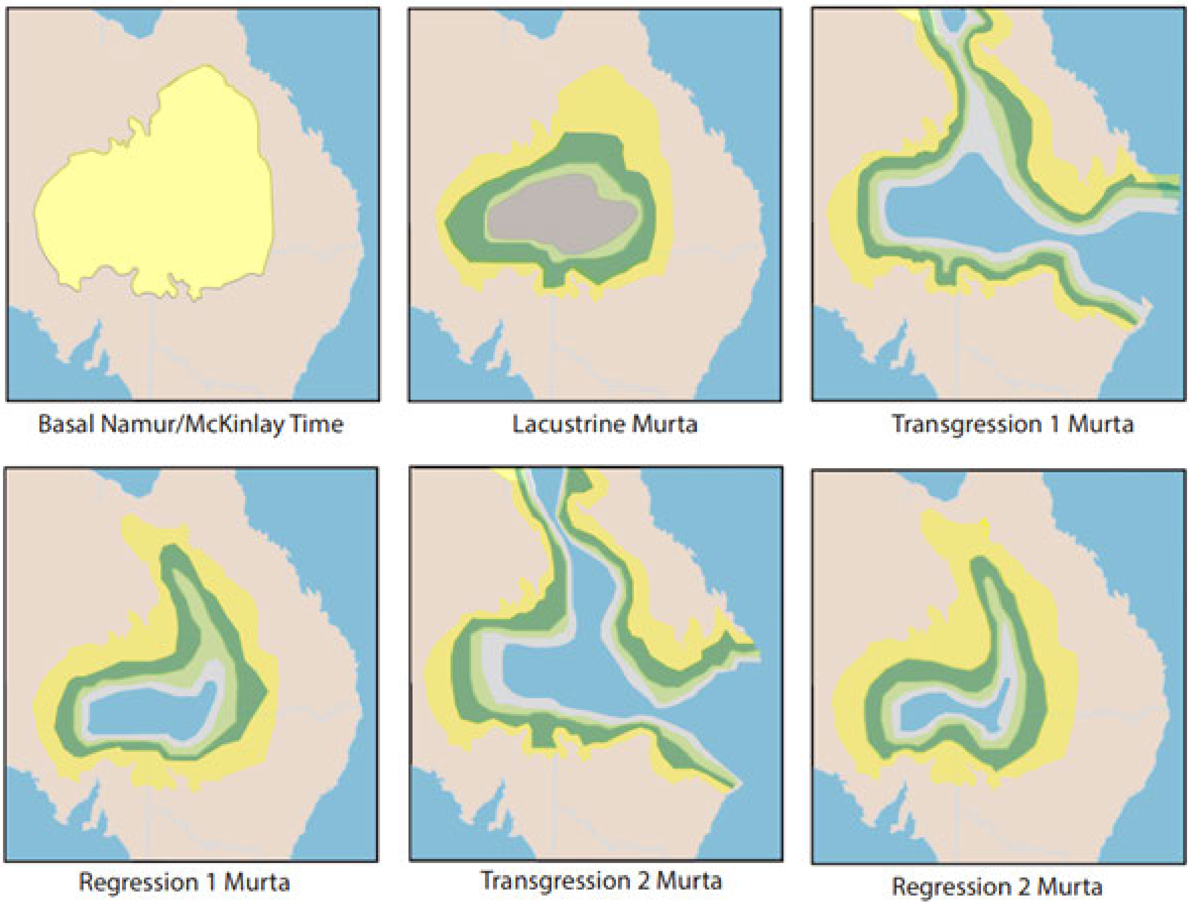


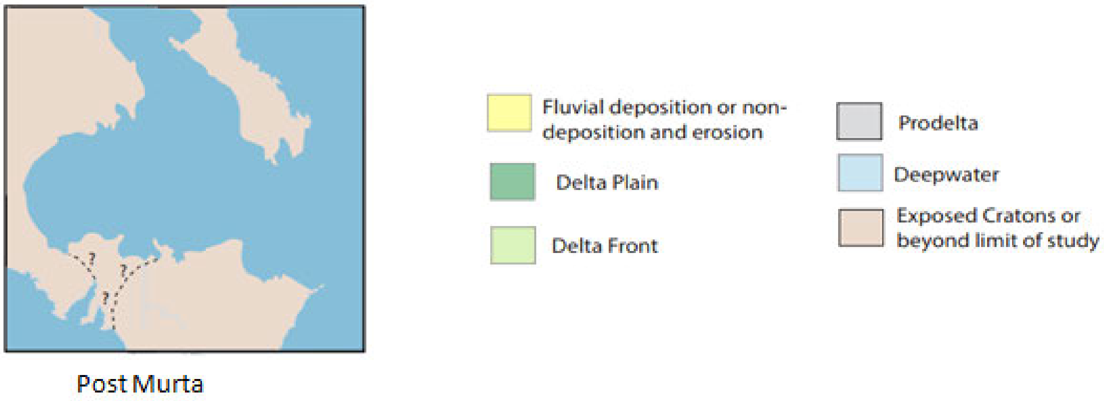
Figure 11: Overall model for deposition in the basin during deposition of the Murta Formation.

suggested that deltas sourced from the eastern margins prograded across the entire basin. Sampling of facies within the basin is likely affected by biases, as more wells on the Queensland side of the border (See Figure 1 for state locations) sample proximal, shallow water regions, while South Australian wells sample the depocentre of the basin. Considering that wells on the South Australia side of the basin sample deepwater facies in the Murta Formation, it is likely that delta plain and delta front facies exist to further to the west in the basin and they have most likely have not been penetrated to date.

Figure 12: Stratigraphic notation and paleogeography. Top: Simplified generalised stratigraphic model for the Murta Formation across the Eromanga Basin. Base: Paleogeography and generalised depositional environment maps of the Murta Formation over a series of time slices, showing continued transgression over the course of the formation. Time between time slices is not equal. Transgression and regression maps show maxima of these potential events. Intervals are approximate. Environments are generalised and represent one realisation of what the basin may have looked like at the time of deposition. *Continued on the next page.*







6.6. Discussion

Depositional Setting and Provenance

The Murta Formation was deposited as the Eromanga Basin was transitioning from a continental lacustrine to marine setting (Figure 11; Figure 12), and is interpreted as a net-transgressive fluvio-deltaic unit. Facies associations have been described, ranging from delta plain, with fluvially-dominated delta plain, to wave-dominated estuary and shoreline deposits, to offshore density flow deposits (Figure 6). In a complete idealised transgressive sequence, mudstone-dominated beds of FA1 offshore deposits are overlain by thin (millimetre and sub millimetre scale) light grey to very dark grey claystone, siltstone and occasional 5-10 cm quartz arenite sandstone beds of FA2 prodelta deposits. In turn these are overlain by upward coarsening ripple laminated quartz rich fine grained sandstones interbedded with planar laminated mica rich siltstone and mudstones of FA 3, the delta front. This facies association may or may not be overlain by a wave ripple-laminated, hummocky cross stratified, occasional planar cross stratified and planar laminated well sorted, clean, fine grained quartz arenite, which makes up FA5, a shoreline deposit which is generally overlain by centimetre scale planar laminated dark grey silty shale irregularly interbedded with fine to medium grained current and wave rippled quartz arenite of FA4, the lower delta plain. Trough cross-stratified, planar–tabular cross-stratified, massive, current-rippled and planar-laminated well-sorted fine- to medium-sand grained quartz arenites, with occasional discrete granules to pebbles, are the final FA6, distributary channels, interpreted to have been deposited on the upper and lower delta plain. Two marine-linked regional regression and subsequent transgression events preserving parts of this idealised facies sequence most likely occurred (Figure 12). A regional reduction in sand bed thickness and sand content from the north-northeast to the southwest, observed in core probably reflects data bias and to some degree sediment provenance (Figure 10).

Data to the east of the basin from the Queensland area (see Figure 1 for state locations) represents more proximal facies and depositional environments. Data from the central section of the Eromanga Basin in the SA sector represents deeper water settings. Few data exist from the western side of the basin, which could potentially contain proximal facies and depositional environments, based on simple basin symmetry and evidence that cratons to the west (Figure 10) were shedding sediment. During deposition of the Murta Formation the eastern highlands of the Eromanga Basin were probably more prominent than the older, stable and more mature cratons to the south and west (Figure 10); however these are still likely to have produced sediment and resulted in deposition of associated continental and marginal-lacustrine/marine facies. Further exploration to the west of the basin may yield clean sand deposits sourced from these mature cratons.

Evidence for Continental and Marginal Marine Deposition

Distinguishing between marginal marine and lacustrine depositional environments in the ancient record can be difficult and careful interpretation needs to be made in the case of the Murta Formation. It has been long-noted that sedimentary structures often attributed to marine tidal processes can occur in fluvual and lacustrine settings (Fraser and Hester, 1977; Alam et al., 1985; Ainsworth et al., 2012). Interpretation of marine tidal processes should thus be based on a careful interpretation of diagnostic and supporting (non-diagnostic) indicators of tidal activity (e.g. Ainsworth et al., 2012) as well as other indicators of depositional environment. In the text following, the evidence available in this context is discussed, and it is concluded that the facies described represent a transition from lacustrine to marine. First, a case for marine influence is presented, followed by a case for a lacustrine environment, then a model which best fits all of the evidence.

Evidence for marine influence within the Murta Formation is substantial. Sedimentary features such as pervasive hummocky-cross stratification, reversal of current ripple directions verging on herringbone cross stratification, synaereses cracks and upper flow regime planar stratification (Figure 5 G) are consistent with a brackish to marine depositional environment. It is important to note that these are not diagnostic of a marginal marine environment (e.g Ainsworth et al., 2011) and could all occur in a lacustrine setting, however, it is one of many lines of evidence that suggest a marine environment. The presence of *Zoophycos, Cruziana* and *Skolithos* ichnofacies (Figure 5H) are consistent with a marginal marine to moderately-deep marine environment. We suggest that difference in abundance and diversity compared to other marginal marine environments may be explained by low temperatures (considering the global positioning of the Murta Formation during the Cretaceous) and regional evolution of species between different continents. Vertical stacking patterns including coarsening-up cycles and coarsening-up topped with fining-up cycles are consistent with those of coastal barrier island systems, migrating barrier bar and barrier islands in a transgressive marine environment (Theologou, 1995). The overall deltaic and estuarine sedimentary nature of the facies, as well as the overall transgressive nature of the formation, in the context of the low-gradient basin setting, is consistent with a large influx of water. A potential explanation for this is the influx of water is from the ocean through the formation of an interior seaway. An alternative explanation could be rapid and large lake expansion, or a rapid change in climate.

Geochemical findings from previous studies (Naylor et al., 1988; Zoellner, 1988; Powell et al., 1989) suggest that the Murta Formation was deposited in a brackish to marine environment. The presence of apatite nodules, glauconite pellets and calcisphere microfossils suggest marine influences on the depositional environment. Elevated trace element Boron levels also provide evidence for a marine influence, as modern seawater shares a similar chemical signature (Zoellner, 1988). The presence of *Botryococcus Pediastrum* (a planktonic cyanobacterium) (Michaelsen and McKirdy, 1989) acritarchs, such as *Microfasta* and *Schizospora* and rare dinoflaggelates such as *Baticashpaera Fusiformacysta* and *Nummus*, together with land plant spores and pollen could be considered as evidence for freshwater runoff into a brackish or marine influenced body of water. It should be noted that the sample size for palynology is small and further work would improve this interpretation.

Evidence for marginal marine influence is particularly strong for the Upper Murta formation, in which the Murta Formation grades into the fully marine overlying Cadna-owie Formation. A marginal marine interpretation of the Murta Formation allows for the application of classical sequence stratigraphic methods (e.g. Mitchum et al., 1977; Vail et al., 1977; Posamentier et al., 1988; Van Wagoner et al. 1988;

Catuneanu et al., 2009). This interpretation (Figure 13) fits well with global eustatic fluctuations (Haq et al., 1987; Miller et al., 2005) and tectonic reconstructions for the Australian continent at the time of deposition (Veevers et al., 2007; Baillie et al., 1994; Alexander et al., 1998).

Evidence for a lacustrine depositional setting is also strong. Sedimentary features such as wave ripples and very fine planar lamination contained in moderately well sorted thinly bedded strata are generally consistent with lacustrine and marginal lacustrine facies. A scarcity of tidal indicators such as herringbone stratification or tidal rythmites could be an indication that tidal activity was not present. Shorelines can occur in both marginal marine and marginal lacustrine settings, but shorelines in lacustrine settings are generally thinner and more unpredictable than those in marine settings (Talbot & Allen, 1996; Bagnaz et al., 2012). Shorelines in the Murta Formation, particularly in the lower section, are more consistent with those in marginal lacustrine settings.

The presence of a *Scoyenia* ichnofacies potentially suggests a freshwater firmground (continental) depositional environment. A lack of abundant and diverse dinoflagellate flora is observed. Continental pollens such as Araucarean/ podocarpacean conifers, seed ferns and tree ferns are common. These, along with a lack of coral, echinoid, brachiopod or cephalopod species may indicate a freshwater depositional environment. The fact that sediment was most likely sourced from around the margins of the basin and does not show signs of being transported along an interior corridor (e.g. Gorter, 1994; Theologou, 1995) could indicate that the basin was not receiving a large influx of water from outside the basin.

Evidence for continental and lacustrine deposition is particularly strong in the lower Murta Formation. Lakes are complex non-linear dynamic systems and behaviour and characteristics differs considerably from marine systems in that clastic influx and base level may or may not be related (Gierlowski-Kordesch & Kelts, 1994). The role of tectonics at the local level is important in controlling topography or bathymetry as low-gradient basins are sensitive to subtle tectonic movements (Chapter 4, this thesis and references within). Wireline expression of lacustrine strata varies widely among lacustrine facies associations and can differ greatly from that commonly observed in marginal marine strata (Bohacs and Miskell-Gerhardt, 1998), which places more uncertainty on the patterns interpreted in this study. There have been tentative links between sea level and stratigraphic base level fluctuations in interior lacustrine basins (Bagnaz, 2012; Street-Perrot & Harrison, 1985). These links have been made on the assumption that there are links between global eustacy and global climate, and that climate can has a large impact on the base levels of intracratonic basins. Inverse or more complex relationships have also been identified in lakes during eustatic highstands (Street-Perrot & Harrison, 1985; Allison and Wells, 2006).

Depositional Analogues and Model

In terms of basin gradient, the Murta Formation is comparable to the modern Kati Thanda- Lake Eyre depositional Basin. Fluvio-lacustrine systems in the Kati Thanda-Lake Eyre catchment have wide, long, floodplains and the basin base level is below sea level. Sediment accretion and incision is controlled by tectonics at the local level, such as domal uplift of the Tookoonooka igneous body (Gostin and Therriault, 1997). These local events are important as low-gradient basins, such as the Eromanga Basin and modern Kati Thanda- Lake Eyre (depositional) Basin, are sensitive to subtle tectonic movements, which cause incision and sediment accretion in upstream mini-basins. The effects on sedimentation patterns are important (Jansen, 2013), but difficult to reconstruct precisely. Drainage diversion as a result of localised tectonic activity probably controlled incision and deposition within the Murta Formation. An improved understanding of the localised tectonics of Eromanga Basin will lead to a better understanding of sedimentation patterns in the Murta Formation.

The Cretaceous Dakota Formation, (Chapter 5, this thesis), is similar to the Murta Formation in that it represents the encroachment the ocean onto a continental landmass during the formation of the Western Interior Seaway (cite your previous chapter). Transgression in the Dakota Formation is complex and piecewise. Facies interpreted in the Dakota Formation are similar to those in the Murta Formation, except in the Dakota Formation the upper delta plain and lower delta plain are more clearly defined. The Murta channel bar facies are generally in the range of 15-20 m thick, but they are composed of smaller scale depositional bedsets in the order of 2-5 m thick. The relatively small size of the fluvial dominated, tide influenced deltas responsible for the deposition of the Dakota Formation is most likely similar to that of the Murta Formation.

A broadly similar transition to that of the Namur-Murta-Cadna-owie depositional system is that of the Triassic Mungaroo-Brigadier-Murat system in the Northern Carnarvon Basin, North West Shelf of Australia (Adamson et al., 2013). The transition from the Mungaroo to the Brigadier Formation represents a transgressive sequence set with the fluvially dominated Mungaroo units passing gradationally upwards into the dominantly deltaic Brigadier reservoirs (Longley, 2002; Adamson et al., 2013; Marshall & Lang, 2013). The Northern Carnarvon Basin most likely had much more accommodation space than the Eromanga Basin. Sediments in the Carnarvon Basin were depositing on an open shelf from a stable, mature craton, rather than in an intercontinental setting between a relatively mature, stable source and an immature, volcanic arc. This would have influenced preserved sediment thickness and composition; however analogous facies were observed in the Brigadier Formation (e.g. Adamson et al., 2013) to those present in the Murta Formation (this chapter).

In the Brigadier Formation the general absence of interpreted LST deposits is thought to be a function of elevated/rising relative sea level in response to the transgressive nature of the sea-level cycle (Marshall and Lang, 2013). A similar process can be interpreted for the Murta Formation. The locally progradational nature of the fluvial dominated deltas in the Brigadier Formation contrasts with the long-lived phase of transgression which continues and accelerates upwards, with an overall transition into delta plain, delta front and finally pro-delta settings (Adamson et al., 2013). The major transgression is piecewise and complex, reflecting incremental sea level rise and fall within the overall rising pattern. The same is true for deposits in the Murta Formation, where piecewise transgressions were punctuated with locally progradational shoreline and deltaic processes. Minor transgressive reworking in both the Brigadier and Murta Formations is interpreted in tidal inlet/shoreface deposits at the top of individual sequences (TST conditions), although these dominantly appear to have been deposited during HST conditions. The lack of a continuous *Glossifungites* horizon, commonly observed in transgressive systems such as the Brigadier Formation (Adamson et al., 2013) but not observed in the Murta Formation, could be explained by the cooler climate and hence lower species abundance and diversity during the time of Murta deposition.

Figure 11 presents a likely depositional model for the Murta Formation, which represents the transition from fluvial depositional environments in the underlying

Namur Sandstone to the overlying fully Marine Cadna-owie Formation. Due to the low gradient of the Eromanga Basin, the transgression was complex and piecewise. The exact point that the net transgression occurs cannot be precisely defined, however the occurrence of two basin-wide correlatable transgressive events in the Upper Murta Formation, along with a wide range of marine indicators (discussed above), suggest that base level was uniformly rising and falling and most likely connected to a marine source. This in interpreted to be due to the basin being connected to the open ocean and subject to eustatic rise and fall.

When viewed as a whole, the data in this chapter come together to enable a logical geological interpretation for the Murta Formation. Detailed sedimentology work was useful in determining depositional processes. In-depth stratigraphic analysis helped to describe depositional stacking patterns and basin-wide trends. Detrital zircon geochronology gave an improved understanding of sediment input and transport pathways, and proved valuable in predicting facies on the western side of the basin. Although beyond the scope of this study, further palynology work could prove useful in determining between different depositional environments. The limited amount of palynology data available and the fact that it was sampled in order to confirm formation depths, as opposed to being sampled for the purpose of a depositional environment interpretation limits the usefulness of the data. In a similar respect borehole data is also limited to locations where petroleum exploration and development targets are located. Biases inherent in this type of sampling should be considered. The area of the Eromanga Basin is over 1,000,000 km^2. Detailed maps of depositional elements are not likely to be accurate given the skewed distribution of data over the basin. Further application of analogues and conceptual geological models to the Murta Formation should be considered.

6.7. Conclusion

The Murta Formation is interpreted as a net-transgressive fluvio-deltaic unit. Deposits can be characterised into six facies associations. In an complete idealised transgressive sequence, thinly bedded (centimetre to millimetre scale) and laminated mudstone-dominated beds of FA1 offshore deposits are overlain by thin (millimetre and sub millimetre scale) light grey to very dark grey claystone, siltstone and occasional 5-10 cm quartz arenite sandstone beds of FA2 prodelta deposits. These in turn are overlain by of upward coarsening ripple laminated quartz rich fine grained sandstones interbedded with planar laminated mica rich siltstone and mudstones of FA 3 delta front. This may or may not be overlain by a wave ripple-laminated, hummocky cross stratified, occasional planar cross stratified and planar laminated well sorted, clean, fine grained quartz arenite, which makes up FA5, a shoreline deposit which is generally overlain by centimetre scale planar laminated dark grey silty shale irregularly interbedded with fine to medium grained current and wave rippled quartz arenite of FA4, the lower delta plain. Trough cross-stratified, planar–tabular cross-stratified, massive, current-rippled and planar-laminated well-sorted fine- to medium-sand grained quartz arenites, with occasional discrete granules to pebbles, are the final FA6, distributary channels, interpreted to have been deposited on the upper and lower delta plain.

Understanding the character and timing of marine incursions such as those that occurred during the Cretaceous in the Murta Formation is essential in reconstructing and interpreting Earth history. Two basin-wide, most likely marine influenced, regressive and transgressive events are interpreted to have occurred and these are located in the in the Upper Murta Formation. The transgression was most likely complex and occurred in a piecewise fashion. Basin fill was most likely sourced from proximal cratons from all sides of the basin during deposition. Other smaller events likely occurred on a local scale but these were concentrated in the Lower Murta Formation and most likely reflect a rise and fall in sea level. Strata in the Lower Murta Formation were most likely deposited in a marginal lacustrine environment. Sediments in the Upper Murta Formation were most likely influenced by marine conditions as a Cretaceous seaway developed. Evidence for both depositional settings is substantial in respective intervals.

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6.9. References

Adamson, K.R., Lang, S.M., Marshall, N.G., Seggie, R., Adamson, N.J., Bann, K.L., 2013. Understanding the Late Triassic Mungaroo and Brigadier Deltas of the Northern Carnarvon Basin, North West Shelf. In: Keep, M. and Moss, S.J. (eds) The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 2013.

Ainsworth, R.B. 2010. Prediction of Stratigraphic Compartmentalization in Marginal Marine Reservoirs. In: Jolley, S.J, Fisher, Q.J., Ainsworth, R.B., Vrolijk, P. and Delisle, S. (eds.), Reservoir Compartmentalization. Geological Society of London Special Publication No. 347, p. 199–218.

Ainsworth, R.B., Hasiotis, S.T., Amos, K.J., Krapf, C.B.E., Payenberg, T.H.D., Vakarelov, B.K., Sandstrom, M.L. Lang, S.C. 2012. Tidal signatures in an intracratonic playa lake. Geology, v. 40, p.607-610.

Ainsworth, R.B., Vakarelov, B.V., and Nanson, R.A. 2011. Dynamic Spatial and Temporal Prediction of Changes in Depositional Processes on Clastic Shorelines: Toward Improved Subsurface Uncertainty Reduction and Management. American Association of Petroleum Geologists Bulletin, v. 95, p. 267-297.

Alam, M.M., Crook, K.A.W., and Taylor, G., 1985, Fluvial herring-bone cross-stratification in a modern tributary mouth bar, Coonambele, New South Wales, Australia: Sedimentology, v. 32, p. 235–244.

Alexander, E.M., Gravestock, D.I., Cubitt, C. And Chaney, A. 1998. Lithostratigraphy and environments of deposition. In: Gravestock, D.I., Hibburt, J.E. & Drexel, J.F. (eds), The petroleum geology of South Australia, vol. 4, Cooper Basin. Primary Industries and Resources SA, Report Book 98/9, p. 69-115.

Allen G., Lang S., Musakti O. & Chirinos A. 1996. Application of Sequence Stratigraphy to Continental Successions: Implications for Mesozoic Cratonic Interior Basins of Eastern Australia. In Mesozoic Geology of the Eastern Australia Plate Conference, pp. 22-26. Geological Society of Australia Inc. Extended Abstracts No. 43, Queensland, Australia.

Allen J.R. 1982. Sedimentary Structures – Their Character and Physical Basis, Volume 2. Elsevier Scientific Publishing Company, New York.

Allison, P.A., and Wells, M.R., 2006. Circulation in large ancient epicontinental seas: What was different and why? Palaios, v. 21, p. 513–515.

Ambrose G., Suttill R. & Lavering I. 1982. A Review of the Early Cretaceous Murta Member in the Southern Eromanga Basin. In Moore, P.S. & Mount T.J. eds. Eromanga Basin Symposium, Summary

Papers, pp 92-109. Geological Society of Australia & Petroleum Exploration Society of Australia, Adelaide.

Ambrose G., Suttill R. & Lavering I. 1986. The Geology and Hydrocarbon Potential of the Murta Member (Mooga Formation). In the Southern Eromanga Basin. In Gravestock D.I., Moore P.S. & Pitt G.M. eds. Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin. GSA, Special Publication No. 12, 71-84.

Baganz, O.W. Baganz, O., Bartov, Y., Bohacs, K. M., Nummedal, D. 2012. Lacustrine sandstone reservoirs and hydrocarbon systems American Association of Petroleum Geologists, AAPG Hedberg Research Conference. AAPG Memoir ; 95.

Baillie, P.W., Powell, M.C.A., Li, Z.X. And Ryall, A.M., 1994. The tectonic framework of Western Australia's Neoproterozoic to Recent sedimentary basins. In: Purcell, P.G. and R.R. (eds) The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 1994.

Bhattacharya, J.P. and J.A. MacEachern, 2009. Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: JSR, v. 79/4, p. 184-209.

Bhattacharya, J.P., and Walker, R.G., 1992. Deltas, in Walker, R.G., and James, N.P., eds., Facies Models: Response to Sea Level Change: Geological Association of Canada, p. 195–218.

Bloch S. 1994. Effect of Detrital Mineral Composition on Reservoir Quality. In Wilson M.D. eds. Reservoir Quality Assessment and Prediction in Clastic Rocks SEPM Short Course 30.

Boggs Jr S., 1995. Principles of Sedimentology and Stratigraphy – Second Edition. Prentice-Hall, Upper Saddle River, New Jersey.

Bohacs, K. M., 2012. Relation of hydrocarbon reservoir potential to lake-basin type: an integrated approach to unravelling complex genetic relations among fluvial, lake-plain, lake margin, and lake centre strata. in O. W. Baganz, Y. Bartov, K. Bohacs, and D. Nummedal, eds., Lacustrine sandstone reservoirs and hydrocarbon systems: AAPG Memoir 95, p. 417 – 431.

Bohacs, K.M., Miskell-Gerhardt, K., 1998. Well-logexpression of lake strata; controls of lake-basin type and provenance, contrasts with marine strata. AAPG Annual Meeting Expanded Abstracts, Tulsa, Oklahoma, p. A78.

Bradley G. 1993. Depositional Facies and Reservoir Analysis of the Murta Member – Thungo and Maxwell Fields. Report Prepared for Minora Resources NL. (Unpublished)

Brinkley, K.L., Wilkinson, B.H., and Owen, R.M., 1980. Vadose beachrock cementation along a southeastern Michigan marl lake: Journal of Sedimentary Petrology, v. 50, p. 953–962.

Campbell I.B. & O'driscoll E.S.T. 1989. Lineament-Hydrocarbon Associations in the Cooper and Eromanga Basins. In O'Neil B.J. ed. The Cooper & Eromanga Basins, Australia. Proceedings of the Cooper and Eromanga Basins Conference, Adelaide. pp300-313.

Carter, W. D., 1957. Disconformity between lower and upper Cretaceous in western Colorado and eastern Utah: Geological Society of America Bulletin, v. 68, p. 307-314.

Catuneanu, O. , Abreu, V. , Bhattacharya, J.P. , Blum, M.D. , Dalrymple, R.W. , Eriksson, P.G. , Fielding, C.R. , Fisher, W.L. , Galloway, W.E. , Gibling, M.R. , Giles, K.A. , Holbrook, J.M. , Jordan, R., Kendall, C.G.St.C. , Macurda, B. , Martinsen, O.J. , Miall, A.D. , Neal, J.E. , Nummedal, D. , Pomar, L., Posamentier, H.W. , Pratt, B.R. , Sarg, J.F. , Shanley, K.W. , Steel, R.J. , Strasser, A., Tucker, M.E. , Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth Science Reviews, 92(1), pp.1–33.

Catuneanu, O., Sweet, A., and Miall, A. D., 1999. Concept and styles of reciprocal stratigraphies: Western Canada foreland system. Terra Nova, v. 11, pp. 1–8.

Catuneanu, O., Sweet, A., and Miall, A. D., 2000, Reciprocal stratigraphy of the Campanian–Paleocene Western Interior of North America. Sedimentary Geology, v. 134, pp. 235–255.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology 62, 1130 – 1146.

Dam G. & Surlyk F. 1993. Cyclic Sedimentation in a Large Wave- and Storm-Dominated Anoxic Lake; Kap Stewart Formation (Rhaetian-Sinemurian), Jameson Land, East Greenland. In Posamentier H.W., Summerhayes C.P., Haq B.U., & Allen G.P. eds. Sequence Stratigraphy and Facies Associations, pp.419-448. Special Publication Number 18 of the International Association of Sedimentologists, Blackwell Scientific Publications, Oxford.

De Vernal, A., 2009. Marine palynology and its use for studying nearshore environments. IOP Conference Series: Earth and Environmental Science, 5(1), p.13.

Dickinson, W.R., and Gehrels, G.E., 2008. Sediment delivery to the Cordilleran foreland basin: Insights from U-Pb ages of detrital zircons in Upper Jurassic and Cretaceous strata of the Colorado Plateau. American Journal of Science, v. 308, p. 1041–1082.

Dott, R.H. and Bourgeois, J., 1982. Hummocky stratification: significance of its variable bedding sequences. Geol. Soc. Am. Bull., 93, 663–680.

Draper J.J., 2002. Geological setting: in Draper JJ (editor) 'Geology of the Cooper and Eromanga basins, Queensland'. Queensland Government, Natural Resources and Mines, Queensland Mineral and Energy Review Series, DVD, 57–59.

Duke, W.L., 1985. Hummocky cross-stratification, tropical hurricanes, and intense winter storms.

Sedimentology, 32, pp 167–194.

Elder, W. P., Gustason, E. R., and Sageman, B. B., 1994. Correlation of basinal carbonate cycles to nearshore parasequences in the Late Cretaceous Greenhorn seaway, Western Interior, U.S.A. Geological Society of America Bulletin, v. 106, pp. 892–902.

Fraser and Hester, 1977, Sediments and sedimentary structures of a beach-ridge complex, southwestern shore of Lake Michigan: Journal of Sedimentary Petrology, v. 47, p. 1187–1200.

Gallagher, K. & Lambeck, K., 1989. Subsidence, sedimentation and sea-level changes in the Eromanga Basin, Australia. Basin Research, 2(2), pp.115–131.

Gallagher, K., 1990. Permian to Cretaceous subsidence history along the Eromanga-Brisbane Geoscience Transect; In Finlayson D.M. (ed) The Eromanga-Brisbane Geoscience Transect: A guide to basin development across Phanerozoic Australia in Southern Qld Bureau of Mineral Resources, Australia. Bulletin 232 p133-151.

Galloway W.E., 1986. Genetic Stratigraphic Sequences in Basin Analysis 1: Architecture and Genesis of Flooding-Surface Bounded Depositional Units. The American Association of Petroleum Geologists Bulletin 73, No. 2, 125-142.

Galloway W.E., 1989. Genetic Stratigraphic Sequences in Basin Analysis 1: Architecture and Genesis of Flooding-Surface Bounded Depositional Units. The American Association of Petroleum Geologists Bulletin 73, No. 2, 125-142.

Gierlowski-Kordesch, E., and Kelts K., 1994. Introduction In Gierlowski-Kordesch E. & Kelts K. Global Geological Record of Lake Basins, Volume 1. Cambridge University Press, Cambridge.

Gorter J.D. 1994. Sequence Stratigraphy and the Depositional History of the Murta Member (Upper Hooray Sandstone), Southeastern Eromanga Basin, Australia: Implications for the Development of Source and Reservoir Facies. APEA Journal, 644-673.

Gorter J.D., 1989. Depositional Models for the Murta Member, Westbourne and Birkhead Formations, ATP 267P, Queensland – Implications for Prediction for Reservoir Sandstones. Report for Command Petroleum N.L. (Unpublished)

Gostin, V. A.; Therriault, A. M., 1997. Tookoonooka, a large buried Early Cretaceous impact structure in the Eromanga Basin of southwestern Queensland, Australia. Meteoritics, vol. 32, pages 593-599.

Gravestock D.I., Benbow M.C., Gatehouse C.G., Krieg G.W., 1995. Eromanga Basin. In JF Drexel and WV Preiss eds, The geology of South Australia, Volume 2, The Phanerozoic, Bulletin 54. Geological Survey of South Australia, pp. 35–41.

Gravestock D.I., Benbow M.C., Gatehouse C.G., Krieg G.W., 1995. Eromanga Basin. In JF Drexel and WV Preiss eds, The geology of South Australia, Volume 2, The Phanerozoic, Bulletin 54. Geological Survey of South Australia, pp. 35–41.

Gray A.R.G., McKillop M., and McKellar J.L., 2002. Eromanga Basin Stratigraphy: in Draper JJ (editor) 'Geology of the Cooper and Eromanga basins, Queensland'. Queensland Government, Natural Resources and Mines, Queensland Mineral and Energy Review Series, 30–56.

Habeck-Fardy and Nanson, 2014. Environmental character and history of the Lake Eyre Basin, one seventh of the Australian continent. Earth-Science Reviews, 132 (2014) 39–66.

Hansen, C. D., and J. A. MacEachern, 2005. Along-strike ichnological and sedimentological variations in a mixed wave- and river-influenced delta lobe, Upper Cretaceous Basal Belly River Formation, Central Alberta.: MacEachern, J. A., Bann, K. L., Gingras, M. K., and Pemberton, S. G., eds., Applied Ichnology Short Course #11 Notes, AAPG and SEPM Conference, Calgary, Alberta, 16 p.

Haq, Bilal U., Hardenbol, Jan & Vail, Peter R., 1987. Chronology of fluctuating sea levels since the Triassic. (Vail sea level curves). Science, 235, p.1156.

Hardy R., Tucker M. 1988. X-ray powder diffraction of sediments. Techniques in sedimentology p. 191-228

Helland-Hansen W., Martinsen O.J. 1996. Shoreline Trajectories and Sequences: Description of Variable Depositional-Dip Scenarios. Journal of Sedimentary Research. V 66, No. 4, pp 670-688.

Heslop K. 1997. Methodology of Shaly Sand Interpretation. Reservoir, v. 24, n. 10, p. 26-27

Hill A.J. 1999. Yanda Field Probe Permeameter Study. Report Prepared for Santos Ltd. (Unpublished)

Hoffmann K.L. 1989. The Influence of pre-Jurassic Tectonic Regimes on the Structural Development of the Southern Eromanga Basin, Queensland. In O'Neil B.J. ed. The Cooper & Eromanga Basins Australia. pp.315-328. Proceedings of the Cooper and Eromanga Basins Conference, Adelaide, 1989.

Holbrook, J.M., 2001. Origin, genetic interrelationships, and stratigraphy over the continuum of fluvial channel-form bounding surfaces: An illustration from middle Cretaceous strata, south-eastern Colorado: Sedimentary Geology, v. 124, p. 202–246.

Howard, K., Hand, M., Barovich, K., & Belousova, E. 2011. Provenance of late Paleoproterozoic cover sequences in the central Gawler Craton: Exploring stratigraphic correlations in eastern Proterozoic Australia using detrital zircon ages, Hf and Nd isotopic data. Australian Journal of Earth Sciences, 58(5), 475-500.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology, 211, 47–69

Jansen, J.D., Nanson, G.C., Cohen, T.J., Fujioka, T., Fabel, D., Larsen, J.R., Codilean, A.T., Price, D.M., Bowman, H.H., May, J.-H., Gliganic, L.A., 2013. Lowland river responses to intra- plate tectonism and climate forcing quantified with luminescence and cosmogenic 10Be. Earth Planet. Sci. Lett. 366, 49-58.

Jones J G and Veevers, J. J. 1983. Mesozoic origins and antecedents of Australia's Eastern Highlands. Journal of the Geological Society of Australia. 30, 305-322.

Kamola, D. L., and J. C. Van Wagoner, 1995. Stratigraphy and facies architecture of parasequences with examples from the Spring Canyon Member, Blackhawk Formation, Utah.; Sequence stratigraphy of foreland basin deposits; outcrop and subsurface examples from the Cretaceous of North America: AAPG Memoir, v. 64, p. 27-54.

Keen, T.R., Slingerland, R.L., Bentley, S.J., Furukawa, Y., Teague, W.J. and Dykes, J.D. 2012. Sediment Transport on Continental Shelves: Storm Bed Formation and Preservation in Heterogeneous Sediments. In: Sediments, Morphology and Sedimentary Processes on Continental Shelves: Advances in Technologies, Research, and Applications (Eds M.Z. Li, C.R. Sherwood and P.R. Hill), IAS Spec. Publ., 44, 295–310.

Kraft J.C. & John C.J., 1979. Lateral and vertical facies relations of transgressive barrier. AAPG Bulletin Vol. 63 No. 12; pp 2145-2163.

Laurin and Sageman, 2007; Boulila, S., Galbrun, B., Miller, K.G., Pekar, S.F., Browning, J.V., Laskar, J., Wright, J.D., 2011. On the origin of Cenozoic and Mesozoic “third-order” eustatic sequences. Earth Sci. Rev. 109, 94–112.

Laurin, J., Meyers, S.R., Uličný, D., Jarvis, I., Sageman, B.B., 2015. Axial obliquity control on the greenhouse carbon budget through middle to high latitude reservoirs. Paleoceanography

Legler, B., Hampson, G.J., Jackson, C.A., Johnson, H.D., Massart, B.Y.G., Sarginson, M. and Ravnås, R. 2014. Facies Relationships and Stratigraphic Architecture of Distal, Mixed Tide- and Wave-Influenced Deltaic Deposits: Lower Sego Sandstone, Western Colorado, U.S.A. J. Sed. Res., 84, 605–625.

Lennox C.L. 1986. Early Cretaceous Sedimentology and Depositional Facies at Nockatunga Oilfield, Cooper-Eromanga Basin, Queensland. Unpublished B.Sc. Honours Thesis, University of New South Wales.

Longley, I.M., Buessenschuett, C., Clydsdale, L., Cubitt, C.J., Davis, R.C., Johnson, M.K., Marshall, N.M., Murray, A.P., Somerville, R., Spry, T.B. & Thompson, N.B., 2002. The North West Shelf Of Australia – A Woodside Perspective, In Keep, M. & Moss, S.J. (Eds), The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 2002, 27–88.

MacEachern, J.A. and Bann, K.L., 2008. The Role of Ichnology in Refining Shallow Marine Facies Models. In: Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy (Eds G.J. Hampson, R.J. Steel, P.M. Burgess and R.W. Dalrymple), SEPM Spec. Publ., 90, 73–116.

Marshall, N.G., Lang, S.C., 2013. A new stratigraphic framework for the North West Shelf, Australia. In: Keep, M. and Moss, S.J. (eds) The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 2013.

Martin K.R. 1983. Petrology of the Murta Member, Westbourne Formation and Hutton Sandstone in the Jackson No. 1 and Jackson South No. 1, Eromanga Basin, Southwest Queensland. Report to Delhi Petroleum Pty. Ltd. (Unpublished)

Martin K.R. 1984. Petrology and Reservoir Quality of the Murta Member and the Namur Sandstone Member in Sigma No.1, Eromanga Basin, Southwestern Queensland. Report to Delhi Petroleum Pty. Ltd. (Unpublished)

Martin K.R. 1985. Petrology of the Murta Member of the Mooga Formation in Challum #1 and Yanda #1, Cooper-Eromanga Basin, Southwest Queensland. Report to Delhi Petroleum Pty. Ltd. (Unpublished)

Matthews, K.J., Hale, A.J., Gurnis, M., Müller, R.D., and DiCaprio, L., 2011. Dynamic subsidence of eastern Australia during the Cretaceous: Gondwana Research, v. 19, no. 2, p. 372–383.

McKellar J.L. 1996. Palynofloral and Megafloral Indications of Palaeoclimate in the Late Triassic, Jurassic, and Early Cretaceous of Southeastern Queensland. In Mesozoic Geology of the Eastern Australia Plate Conference, pp. 336-371. Geological Society of Australia Inc. Extended Abstracts No. 43, Queensland, Australia.

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Fluvial Sedimentology (Ed. A.D. Miall). Can. Soc. Petrol. Geol. Mem., 5, 597-604.

Miall, A.D., Catuneanu, O., Vakarelov, B., and Post, R., 2008. The Western Interior Basin, in Miall, A.D., ed., The Sedimentary Basins of the United States and Canada: Sedimentary basins of the World, v. 5 (K.J. Hsü, Series Editor): Amsterdam, Elsevier Science, p. 329–362.

Michaelsen B.H. & Mckirdy D.M., 1989. Organic facies and petroleum geochemistry of the lacustrine Murta Member (Mooga Formation) in the Eromanga Basin, Australia. in: ONeil, B.J., (ed.), The Cooper and Eromanga Basins, Australia. Proceedings of Petroleum Exploration Society of

Australia, Society of Petroleum Engineers, Australian Society of Exploration Geophysicists (SA Branches), Adelaide, pp 541-558.

Miller, G.H., Mangan, J., Pollard, D., Thompson, S., Felzer, B., Magee, J., 2005. Sensitivity of the Australian Monsoon to insolation and vegetation: implications for human impact on continental moisture balance. Geology 33, 65-68.

Mitchum Jr.R.M., Vail P.R. & Thompson Iii S. 1977. Seismic Stratigraphy and Global Changes in Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis, In Payton C.E. ed. Seismic Stratigraphy – Applications to Hydrocarbon Exploration: AAPG Memoir 26, p. 53-62.

Mount T.J., 1982. Geology of the Dullingari Murta Oilfield. In Moore P.S. & Mount T.J. eds. Eromanga Basin Symposium. Summary Papers. GSA and PESA, Adelaide. Australian Sedimentologists Special Group, Wollongong, 307-337.

Mount, T.J., 1981. Dullingari North 1, an oil discovery in the Murta Member of the Eromanga Basin. APEA Journal 21(1) p71-77.

Neal, J. Abreu, V., 2009. Sequence stratigraphy hierarchy and the accommodation succession method, Geology, v. 37, p. 779-782.

Newton C.B. 1986. The Tintaburra Oilfield. APEA Journal, 26(1), pp 334-352.

Olariu, C., and Bhattacharya, J.P., 2006. Terminal Distributary Channels and Delta Front Architecture of River-dominated delta systems. Journal of Sedimentary Research, Perspectives, v. 76, p.212-233.

Overeem, I., Groenensteijn, K. Veldkamp, T., van Dijke, J.J., Kroonenberg, S.B., 1998. Holocene erosion and sedimentation history of the Volga delta related to sea-level changes. Annual Meeting International Association of Sedimentologists, April 1998, Alicante, Spain.

Oviatt C.G., Mccoy W.D. & Nash W.P. 1994. Sequence Stratigraphy of Lacustrine Deposits: A Quaternary Example for the Bonneville Basin, Utah. Geological Society of America Bulletin 106, 133-144.

Passmore V. & Pain L. 1996. Australia's Premier Onshore Oil Province – the Eromanga Basin. In Mesozoic Geology of the Eastern Australia Plate Conference, pp. 433-441. Geological Society of Australia Inc. Extended Abstracts No. 43, Queensland, Australia.

Payton, C.E., 1977. Seismic stratigraphy – application to hydrocarbon exploration. Am Assoc Petrol Geol Mem 26.

Plint, A. G., Kreitner, M. A., 2007. Extensive, thin sequence spanning Cretaceous foredeep suggest high-frequency eustatic control: Late Cenomanian, Western Canada foreland basin. Geology,

v. 35, pp. 735–738.

Posamentier HW, Vail PR. 1988. Eustatic controls on clastic deposition, II. Sequence and systems tract models C.K. Wilgus, B.S. Hastings, H.W. Posamentier, C.A. Ross, J.C. Van Wagoner (Eds.), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral. Spec. Publ., 42 (1988), pp. 71-108.

Powell T.G., Boreham C.J., McKirdy D.M., Michaelsen B.H., Summons R.E., 1989. Petroleum Geochemistry of the Murta Member, Mooga Formation, and Associated Oils, Eromanga Basin. The APPEA Journal 29, 114-129.

Pratt, B. 1998. Syneresis cracks: subaqueous shrinkage in argillaceous sediments caused by earthquake-induced dewatering. Sedimentary Geology. 117: 1–10

Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., 1986. Numerical Recipes, The Art of Scientific Computing. Cambridge, UK, Cambridge University Press, 186 p.

Price P.L., 1997. Permian to Jurassic palynostratigraphic nomenclature of the Bowen and Surat Basins: in Green PM (editor) The Surat and Bowen Basins, south-east Queensland. Queensland Minerals and Energy Review Series, 137–178

Reading, H. G., Collinson, J. D., 1996. Clastic coasts. In: Sedimentary environments: Processes, facies and stratigraphy, London: Blackwell, pp. 154–231.

Reineck, H.E. and Singh, I. B., 1973. Depositional sedimentary environments with reference to terrigenous clastics, Berlin ; New York: Springer-Verlag.

Reinsen, G.E., 1992. Transgressive barrier island and estuarine systems. In: Walker R.G. & Plint A.G. (ed) Fades models, Geological association of Canada; pp 179- 194.

Russell, M., Gurnis, M., 1994. The planform of epeirogeny: vertical motions of Australia during the Cretaceous. Basin Research 6, 63–76.

Sageman, B. B., Rich, J., Arthur, M. A., Birchfield, G. E., and Dean, W. E., 1997. Evidence for Milankovitch periodicities in Cenomanian–Turonian lithologic and geochemical cycles, western interior, U.S.A. Journal of Sedimentary Research, v. 67, pp. 286–302.

Schulz-Rojahn J.P. 1993. Calcite Cemented Zones in the Eromanga Basin: Clues to Petroleum Migration and Entrapment? APEA Journal, pp 63-76

Storms, J.E.A. and Hampson, G.J., 2005. Mechanisms for Forming Discontinuity Surfaces Within Shoreface–shelf Parasequences: Sea Level, Sediment Supply, or Wave Regime. J. Sed. Res., 75, 67–81.

Street-Perrot F.A., Harrison S.P., 1985. Lake Levels and Climate Reconstruction, In Hecht A.D. ed. Paleoclimate Analysis and Modelling, New York, John Wiley, p. 291-340.

Talbot M.R. & Allen P.A.,1996. Lakes. In Reading H.G. ed. Sedimentary Environments: Processes, Facies, and Stratigraphy, pp. 83-124. Blackwell Science ,Oxford.

Taylor, A.M. and Goldring, R., 1993. Description and analysis of bioturbation and ichnofabric. J. Geol. Soc., 150, 141–148.

Theologou, P., 1995. Murta Formation/McKinlay Member of the Murteree Ridge Nappacoongee-Murteree Block Improved Oil recovery project. Unpublished PhD thesis, University of South Australia.

Vail, P. R.; Mitchum Jr., R. M.; Todd, R. G.; Widmier, J. M.; Thompson, S.; Sangree, J. B., 1977. "Seismic stratigraphy and global changes in sea level". In Payton, C. E. Seismic Stratigraphy–Applications to hydrocarbon exploration, AAPG Memoir. 26. Tulsa: American Association of Petroleum Geologists. pp. 49–205.

Vakarelov, B. K., Bhattacharya, J. P., and Nebrigic, D. D., 2006. Importance of high-frequency tectonic sequences during greenhouse times of earth history. Geology, v. 34, pp. 797–800.

Van Heerden, I.L., And Roberts, H.H., 1988. Facies development of Atchafalaya Delta, Louisiana: a modern bayhead delta: American Association of Petroleum Geologists, Bulletin, v. 72, p. 439–453.

Van Wagoner J.C., Posamentier H.W., Mitchum Jr. R.M., Vail P.R., Sarg J.F., Loutit T.S. & Hardenbol J. 1988. An Overview of the Fundamentals of Sequence Stratigraphy and Key Definitions. In Wilgus C.K., Hastings B.S., Kendall C.G.St.C., Posamentier H.W., Ross C.A. & Van Wagoner J.C. eds. Sea Level Changes: an Integrated Approach. SEPM Special Publication 42, pp. 39-45.

Veevers, J.J., Walter, M.R. & Scheibner, E., 1997. Neoproterozoic Tectonics of AustraliaAntarctica and Laurentia and the 560 Ma Birth of the Pacific Ocean Reflect the 400 M.Y. Pangean Supercycle. The Journal of Geology, 105(2), pp.225–242.

Veevers J.J., Belousova E. A. & Saeed A., 2016. Zircons traced from the 700–500 Ma Transgondwanan Supermountains and the Gamburtsev Subglacial Mountains to the Ordovician Lachlan Orogen, Cretaceous Ceduna Delta, and modern Channel Country, central-southern Australia. Sedimentary Geology, 334, pp.115–141.

Veevers JJ, 1984. Phanerozoic Earth history of Australia. Clarendon Press Oxford.

Veevers, J.J., 2000. Billion-Year Earth History of Australia & Neighbours in Gondwanaland. GEMOC Press, Sydney. 400 pp.

Veevers, J.J., Saeed, A., 2011. Age and composition of Antarctic bedrock reflected by detrital zircons, erratics, and recycled microfossils in the Wilkes Land–Ross Sea– Marie Byrd Land sector

(100°–240° E). Gondwana Research 20, 710–738.

Wade, B., 2008. Detrital Zircon Geochronology of the Musgrave Province. Unpublished PhD thesis. University of Adelaide.

Wendler, J.E., Lehmann, J., Kuss, J., 2010. Orbital time scale, intra-platform basin correlation, carbon isotope stratigraphy, and sea level history of the Cenomanian/Turonian Eastern Levant platform, Jordan. Geol. Soc. Lond. Spec. Publ. 341, 171–186.

Wendler, J.E., Meyers, S.R., Wendler, I., Kuss, J., 2014. A million-year-scale astronomical control on Late Cretaceous sea-level. Newsl. Stratigr. 47, 1–19.

Wright, D.L., 1977. Sediment transport and deposition at river mouths: a synthesis: Geological Society of America, Bulletin, v. 88, pp 857–868.

Zoellner E., 1988. Geology of the Early Cretaceous Murta Member, Mooga Formation, in the Cooper Basin Area, South Australia and Queensland. Flinders University PhD Thesis (Unpublished).

Chapter 7: Conclusions

7.1 Summary and Implications

The chapters of this thesis combine to enable the depositional setting of the early Cretaceous net transgressive Murta Formation in the Eromanga Basin to be interpreted, both directly and through analogue studies. Each chapter of this thesis contributes to the understanding of the sedimentology and stratigraphy of the Murta Formation as a whole. Chapter 3 provides an integrated study of the Cuisinier Field. From this study it was clear that investigations needed to focus on sedimentation in low-gradient basins, the initial stages of transgression onto a continental landmass and the development of a coherent depositional model for the Murta Formation. Chapter 4 provides insight into fluvial termination facies and incision dynamics in a low-gradient basin at Lake Yamma Yamma in central Australia. Chapter 5 provides insight into facies and controls on deposition during encroachment of a marine system onto a continent. Chapter 6 provides an integrated depositional model for the Murta Formation, and discusses ways that the Murta Formation is similar and different to the analogues presented.

The initial study of the Cuisinier Field (Chapter 3) raised important research questions that were explored throughout the thesis. Key research questions were:

- What is the nature of fluvial terminations in low accommodation basins? How can we classify and compare these? What are the key sedimentary characteristics, depositional settings and sand-body geometries in these settings?

These questions were considered in Chapter 4, where a new way of classifying and comparing modern fluvial terminations in dryland settings was presented. A new case study was provided and key sedimentary characteristics, depositional settings and sand-body geometries were discussed.

- What is the nature of marine transgressions in epicontinental seaways? Particularly as the transgression commences; what are the sedimentary features, depositional processes and preserved geometries?

These questions were considered in Chapter 5, where the Dakota Formation was described in detail at a study site in South-West Colorado. Sedimentary features, depositional processes and preserved geometries are presented for this site.

- What was the depositional setting and paleogeography of the Murta Formation? Was deposition dominated by marginal marine or lacustrine conditions? What was the depositional nature of the formation across the basin and what are the key controls on deposition?

Chapter 3 and Chapter 6 covered these research questions. Chapter 3 provided an in-depth study of the Cuisinier Field within the Murta Formation. The sedimentology and stratigraphy is described in detail. The depositional setting and controls are discussed. Chapter 6 describes the entire Murta Formation across the Eromanga Basin. Core data and laboratory results to investigate the sedimentology, provenance and paleogeography of the Murta Formation, as well as knowledge gained from studying two depositional analogues, allows for the presentation of a new depositional model for the Murta Formation, with marginal marine and lacustrine conditions considered. Given the sparse nature of this type of research in the Eromanga Basin, this contribution is a very useful one for future seismic geomorphology, sedimentology, stratigraphy and provenance research in the region.

Results from facies analysis show that previous classification of the Murta Formation as either purely marine or continental lacustrine is likely over simplified, as sediments show characteristics of both depositional environments (as discussed in detail in Chapter 4). The Murta Formation represents the transition from a fluvial depositional environment in the underlying Namur Sandstone to the overlying fully Marine Cadna-owie Formation. In a low gradient basin such as the Eromanga, the transgression was most likely complex and piecewise. The most likely geological model for the Murta Formation separates the formation into two categories. The Lower Murta Formation is dominated by sedimentary features such as wave ripples and very fine planar lamination contained in moderately well sorted thinly bedded strata. These facies are generally consistent with lacustrine and marginal lacustrine depositional environments. Palynological, geochemical and trace fossil evidence support this interpretation. Sediments in the Lower Murta Formation are unlikely to preserve correlatable sequences (highstands and lowstands). The Upper Murta Formation exhibits sedimentary features such as pervasive hummocky-cross stratification, near herringbone cross stratification, synaereses cracks and upper flow regime planar stratification, which could all be could be consistent with marginal marine depositional environment. Palynological, geochemical and trace fossil evidence support the interpretation of a marginal marine environment and although no feature taken in isolation can be considered as a conclusive depositional environment indicator, the cumulative evidence suggests that this is the best possible interpretation. Sequences in the Upper Murta Formation are more easily correlated with two large transgressive cycles most readily identified on most well logs near the top of the Formation. This is consistent with the interpretation of the Cuisinier Field (Chapter 3), where two transgressive cycles, most likely in a deltaic depositional environment were interpreted. The introduction of marine influence into the Murta Formation most likely represents the first marine incursion into the Eromanga Basin.

U/Pb ages from over 1200 individual detrital zircon grains for twelve samples in the Murta Formation show similar spectrums of ages within different stratigraphic levels at the same location. However at different locations around the Eromanga Basin, very different age spectrums were observed (Chapter 6). Paleoproterozoic to Neoproterozoic ages (62%) dominate all populations, but Neoproterozoic to Cretaceous age peaks are present in some samples. Sediments in the Eromanga Basin are considered to have originated from the margins of the basin, contrary to previous interpretation that sediments were mostly sourced from the north-eastern margin of the basin. This suggests that the basin was inwardly draining and that no circulatory current or drainage pathways to the open ocean were well established. This is contrary to results from U/Pb ages from over 1400 individual detrital zircon grains from the Dakota Formation, which suggest that an axial depositional system transporting sediment from the south influenced deposition at this site (Chapter 5). A similar trend for the Murta Formation and development of the Eromanga Basin in the Early Cretaceous cannot be inferred.

In addition to the specific relevance to Australia, chapters within this thesis, particularly Chapter 4 and Chapter 5, can also be viewed as examples for similar types of deposits existing in the subsurface. The results presented here serve as a useful analogue for similar sediments in other localities and time periods, especially where data are sparse or of low quality. Analogue studies have proved popular and effective in the past. For example, studies from the Jurassic and Cretaceous Book Cliffs, central USA, have heavily shaped our understanding of sedimentology and stratigraphy in the subsurface. Many models for hydrocarbon exploration and development are derived from data from this location. While these outcrop studies provide excellent vertical data, critical lateral and process-based information cannot be observed. A large volume of interpretation is based on a small volume of well-known, well-studied examples, which do not capture the variability, heterogeneities and uncertainty in real-world environments. An interpretation utilising a mixture of modern and ancient outcrop analogues from a variety of analogous settings is optimal.

This thesis provides never-before studied data-rich examples of both a modern process-based analogue and an outcrop analogue, and integrates these with a detailed field scale stratigraphic study for a new discovery, to develop a new depositional model for important oil-bearing strata on a basin scale. The integrated and novel nature of the methods used in this study provide a model for future studies in the basin.

7.2. Further Work and Recommendations

All work for this thesis was carried out as planned, however several areas of study beyond the scope of this project could prove interesting and important. Proposed below are some recommendations for future work, organised into the following themes:

- *Cuisinier Field exploration and development,*
- *stratigraphic models for the Eromanga Basin,*
- *provenance of Eromanga Basin sediments,*
- *Quaternary paleoclimate at Lake Yamma Yamma,(and)*
- *broadening the availability of data from a range of depositional settings.*

7.2.1. Cuisinier Field Exploration and Development

In order to further understand the Cuisinier Field (discussed in Chapter 3) within the Murta Formation (discussed in Chapter 6), it would be greatly beneficial if better seismic could be acquired. Although the sandbodies are below the current seismic resolution, seismic technology is increasing at a rapid pace and new technologies may help with increasing the resolution of the data. It is possible that conditioning and tuning of the current data may provide more insight. The current seismic dataset suffers from a variety of artefacts and is not focussed on the reservoir interval. Analogue work, such as the work presented in this thesis can forecast likely trends and help with interpretation but cannot define the precise size or geometry of the reservoir. It would likely be misleading if relied on too heavily. Ultimately the reservoir will be precisely defined by higher-resolution seismic data.

In terms of practical field development, technologies such as fractured horizontal wells would provide more access to reservoir surface area. Existing producing wells with good reservoir which develop a high water cut could be re-entered and the reservoir drilled out laterally to avoid the risk of not encountering high quality reservoir. Drilling could be guided up into the oil-rich sections and the lower water bearing sections could be cased off. Investment in tracer experiments to determine connectivity of compartments may provide important information and prevent bypassed oil. Depending on the overall development strategy of the field, hydraulic fracturing and pressure support may provide production gains.

It is likely that the Cuisinier Field is not a unique feature with the Murta Formation. A series of similar depositional structures are likely to exist around the margins of the Eromanga Basin. As the features cannot be targeted on seismic, exploration strategies must draw upon the geological model. An exploration strategy to reduce risk could be selecting a well location where Early Cretaceous targets could be combined with Jurassic and Permian targets in a series of stacked plays.

Further near-field exploration upstream from the Cuisinier Field should also be considered. As deltaic facies exist in the Cuisinier region it is likely that fluvially-dominated sediments were deposited further upstream, which if preserved could provide reservoir facies.

7.2.2. Stratigraphic models for the Eromanga Basin

As mentioned in Chapter 3 and Chapter 6, stratigraphic models for the Eromanga Basin are not always consistent. Calibrating biostratigraphy with chronostratigraphy would be a good first step in providing a robust correlation framework for the basin. A better understanding of marine incursions throughout the history of the basin is needed. Many of the depositional models for the Eromanga Basin are based on a specific study area and not integrated across the basin. Big data analytics and machine learning may have a role to play in collating and integrating all of the data from wells drilled in the basin. With the assistance of these tools, workers may be able to spot trends and synthesise data in a more objective way. A project focussed on understanding how the Queensland, New South Wales and South Australian stratigraphy correlate and developing a robust correlative stratigraphic table for the entire Eromanga Basin would greatly improve our understanding of basin development.

7.2.3. Provenance of Sediments in the Murta Formation

No provenance studies had been conducted for the Murta Formation prior to this work. The provenance data reported here (Chapter 6) provides a starting point from which to conduct future studies. Detrital zircon grains are interpreted to have been sourced from all around the margins of the basin, rather than just from the north-east as prior literature has suggested. An increased sample density and the use of additional geochemical and isotopic fingerprinting techniques can provide a more detailed picture of the provenance of the Murta Formation. Other age-dating techniques such as Rubidium-Strontium or Potassium-Argon age-dating could potentially be more useful or could provide another source of data. Hafnium isotopes could also be used in conjunction with Uranium-Lead detrital zircon age-dating in order to further determine cratonic provenance. Uranium-lead detrital zircon age-dating combined with biostratigraphic methods could be used in order to better constrain the age of the Murta Formation and assist in detailed stratigraphic correlation.

Difficulties in determining the provenance for the Murta Formation (Chapter 6) were in part due to the relative lack of studies which provide age-data for the Australian continent. This became particularly apparent through the process of analysing Uranium-lead detrital zircon ages from the Dakota Formation (Chapter 5) compared to those for the Murta Formation (Chapter 6). For the Dakota Formation many comprehensive sources of data were available on the age of potential source terrains, compared to the few that were available for the Murta Formation. As the data available for Australian cratons increases, the determination of provenance for sedimentary rocks in Australian Basins will become more robust.

7.2.4. Quaternary Paleoclimate at Lake Yamma Yamma

The borehole drilled at Lake Yamma Yamma in 1967 showed that beneath the surface sediments studied in this thesis (Chapter 4) 103 m of mud, evaporitic gypsum and sands are preserved. Further drilling and OSL dating of sediments at Lake Yamma Yamma could provide insight into the larger vertical stacking patterns and preservation of sediments. A correlation of strata with other Quaternary lakes such as Lake Buchannan and Lake Frome could provide new insights into Australian Quaternary climate change. Given the remote location of these sites (over 200 km from the nearest small town) and the desert climate, drilling at this location would be challenging, risky and expensive.

7.2.5. Broadening the availability of data from a range of depositional settings

Sedimentology and stratigraphy research is biased toward particular depositional environments and study locations. A feature or location close to a large population or with excellent exposure will generally be studied more than it's remote or poorly exposed counterpart. If we are to understand the range of potential interpretations for depositional processes and environments occurring through the Earth's history, we need to have more case studies and more examples from a wide range of depositional settings to draw upon. This is true for modern and ancient deposits. The variability, heterogeneity and uncertainty in depositional settings in the subsurface will not be well represented or understood through analogy with one example. This is particularly true for transgressive systems in low accommodation basins. Transgressive systems are complex with variable controls including local tectonics, rate of sea level rise and local climate change, as discussed throughout this thesis. Autocyclic controls such as avulsion and bifurcation also play an important role in the distribution and deposition of sands within the system. Additionally time scales and magnitudes of transgression events are not well understood and may have been different in the Cretaceous to what they are today. Further research into the sedimentology and stratigraphy of a diverse range of settings will improve our ability to interpret deposition, with application to both modern environments and interpretation of the ancient record.

Chapter 8: Appendices

Data Sets for Chapter 4 (Laser Particle Grain Size data for all of the samples described in this study), **Chapter 5** (LAICPMS Data for each of the standard and unknown grains analyzed in this study) and **Chapter 6** (LAICPMS Data for each of the standard and unknown grains analyzed in this study) are available electronically from the copy of this thesis stored in the ASP Library. This data is also available from the author upon request.

Supplementary Data Set, Chapter 5: All Gigapan images from fieldwork.

Go to http://gigapan.com/

Log In with username Kendall55 and password dakota1

View all Gigapans taken for this research by selecting Portfolio in the My Gigapan drop down menu on the drop down menu on the top right hand corner of the page.

Supplementary Literature Review is included on the following pages.

Fundamental Literature

The aim of this section is to make this thesis more accessible to the non-specialist geoscientist or engineer and to provide the reader with an overview of the fundamental literature behind this work.

1. Interpretation of Depositional Environments

Facies analysis provides a rigorous scientific approach to the interpretation of strata, based on their composition and vertical sucession (Gressly, 1838; Anderton 1985; Collinson, 1969) and is undertaken in order to interpret and reconstruct paleoenvironments (Anderton 1985; Reading and Levell 1996; Walker 1992). However, depositional settings can often be difficult to interpret from the ancient record, particularly where data are sparse, such as when conducting an interpretation of subsurface data. This increases the uncertainty in interpretation and requires interpretation to draw on established depositional models and analogues. Depositional processes are not characteristic of a unique depositional environment, a factor which introduces further uncertainty into interpretation.

The following section provides an overview of the nature and controls on fluvial termination deposits in the range of environments in which they occur, from marginal marine to lacustrine and continental dryland. Common depositional processes between deposition in marginal marine and marginal lacustrine deltas are then explored, followed by a focus on lacustrine sedimentation. Epicontinental seaway settings are introduced, and then the application of sequence stratigraphy in marginal marine and lacustrine settings is discussed. These are very broad topics, thus only material relevant and important to the context of the original research presented in this thesis is reviewed. Facies interpretation in this thesis follows the commonly adopted scheme of Miall (1978), and the reader is referred to this resource for further information on the topic.

2. Marginal Marine Deltaic Settings

The description of deltaic depositional systems has been well documented. Historically description has focussed depositional environment interpretation and lithostratigraphy (Coleman and Wright, 1975; Galloway, 1975; Hayes, 1975, Hayes, 1979; Boyd et al., 1992; 2006). More recently, stratigraphic correlation and identification of key surfaces which helps place marginal-marine intervals into distinct categories (e.g. systems tracts or shoreline trajectory classes) (Posamentier et al., 1988; van Wagoner et al., 1990; Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009) has become standard practice. Marginal marine deltas are influenced by three main depositional processes: wave, tidal and fluvial. A process-based system of interpretation provides a scheme for the description of deltas and deltaic deposits (Ainsworth et al., 2011; Vakarelov and Ainsworth, 2013; Figure 2). Delta deposits in high accommodation settings, for example at continental rift margins, exhibit different depositional styles and geometries to those in low accommodation settings, for example interior basins or sag basins. Deposits in high accommodation settings will likely be thicker, and preserve highstand sediments, compared to low accommodation settings, where deposits are thinner reworking is more likely (Galloway, 1975; Hayes, 1975).

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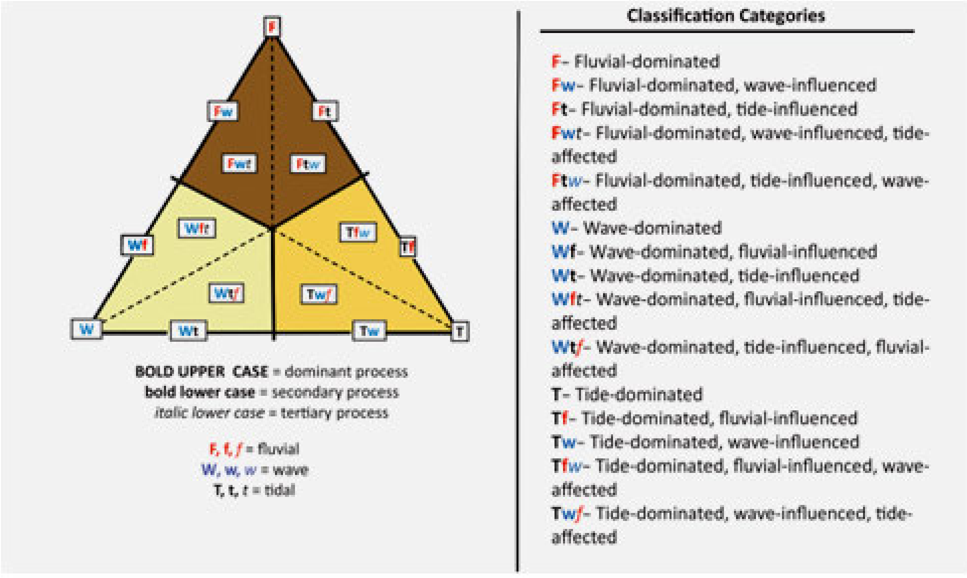

Figure 1: Process classification categories of the simple classification of Ainsworth et al. (2011). Letter codes refer to the dominant, secondary, and tertiary processes (fluvial, wave, and tide) that influence marginal marine systems. A Wft category, for example, refers to a wave-dominated, fluvial-influenced, tide-affected system, where the influence of waves, fluvial input, and tides decreases in that order. Single-letter codes refer to systems affected by a single process, two-letter codes refer to systems affected by two processes, and three-letter codes refer to systems affected by three processes. The classification thus effectively describes mixed influence systems. The process categories have no spatial component and can be applied to the different hierarchy levels of architecture (From Ainsworth et al., 2013).

3. Marginal Lacustrine Deltaic Settings

Descriptions of lacustrine deltas which terminate into perennial lakes are well documented. Well studied examples include the Volga delta (Overeem et al., 2002; Figure 2), Atchafalaya lacustrine deltas (Fisk, 1961; Tye and Coleman, 1989), the Breggia–Greggio river deltas in Italy (Fanetti and Vezzoli, 2007) and the Ural and Emba rivers, which terminate into the Caspian Sea (Richards et al., 2017). Lacustrine deltas share many depositional characteristics to comparatively well-studied marine deltas (Galloway, 1975; Ainsworth et al., 2011), except lack tidal influence (T, Tf and Tw elements of Ainsworth et al, 2011). They tend to be relatively thinly-bedded, with stacking patterns controlled by the base level of the lake and local tectonics (Bohacs, 2012).

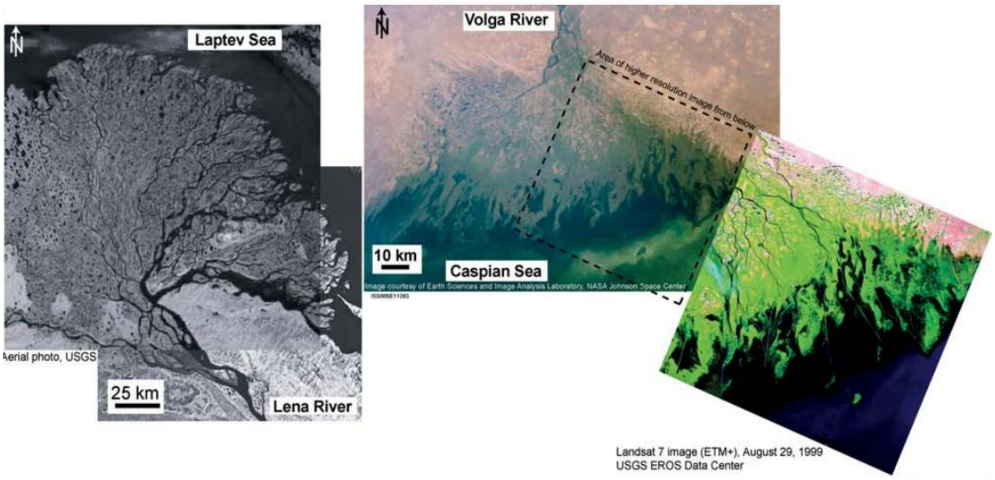

Figure 2: Modern delta examples from the Lena Delta and Volga Delta (from Olariu and Bhattacharya, 2006)

Within lacustrine deltas, simple lobe switching due to the changes in sediment flux can give the impression of a regional change in depositional setting. This is important in marine settings, but more difficult to distinguish in lacustrine settings, due to the often thinly bedded nature of the deposits and the unpredictable character of lakes (Bohacs et al., 2000a, Bohacs et al., 2000c). Such a characteristic is likely to also be true of terminal splay deposits in playas, but perhaps even more unpredictable due to the greater variability in environmental conditions and depositional processes. Distinguishing between autogenetic, as opposed to allogenic cycles is important when interpreting stratigraphic packages and surfaces. Regional studies focused on the determination of the provenance of sediments may aid in the discrimination between localised and sequence scale changes (Bagnaz et al., 2012).

4. Fluvial Termination Deposits

Fluvial systems which terminate in/on landforms which are not a body of water have been described as terminal fans (Friend, 1978; Kelly and Olsen, 1993; North and Warwick, 2007), floodouts (Tooth, 1999; Tooth, 2000), ephemeral mud-prone interdune fluvial terminations (e.g. Stanistreet and Stollhofen, 2002), distributive fluvial systems (Nichols 1987; Nichols and Hirst 1998; Nichols and Fisher, 2007) and ephemeral stream terminal distributary systems (Billi, 2007). The depositional character of these systems is highly varied; there is no distinct morphology or sedimentary succession, and no single facies model can predict depositional character (North and Warwick, 2007). These deposits share process-based characteristics with crevasse splays, deposits that form downstream of beaches in levees and other ephemeral floodplain features formed by overland flow (Jorgensen and Fielding, 1996; Taylor, 1999). An example of a fluvial termination deposit, a floodout in central Australia, is shown in Figure 3 (Tooth, 1999; Tooth, 2000).

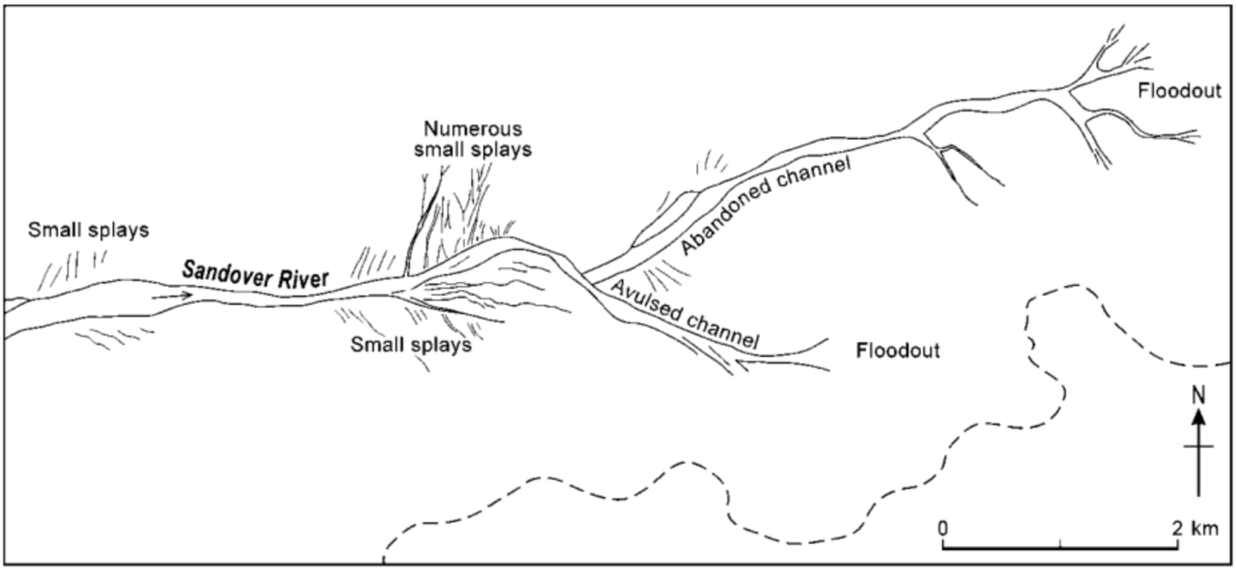

Figure 3: Floodouts of the Sandover River illustrating the main channel and floodplain features (Tooth, 2000).

Rivers that terminate into ephemeral lakes show a different depositional character to other dryland fluvial terminations, and have different depositional processes and temporal variability to rivers that terminate into a body of water and form a delta. Deposition can be subaqueous, similar to that which occurs in deltas, but can also be influenced by wetting and drying processes, aeolian reworking and subaerial flow. Examples of fluvial termination deposits in ephemeral lakes include those fed by ephemeral rivers in the Turkana basin, northern Kenya (Frostick and Reid, 1986), the Chott Rharsa system, southern Tunisia (Blum et al., 1998) and Kati Thanda- Lake Eyre margin terminal splays in the Kati Thanda- Lake Eyre Basin (Lang et al., 2004; Fisher et al., 2008).

5. Common Depositional Elements of Marginal Lacustrine and Marginal Marine Deposition

Modern lakes have similar depositional features to marginal marine settings, though usually at a smaller scale (Fraser et al., 2012; Bartov et al., 2012; Nichols, 2009). Two main processes affect depositional character in marginal lacustrine systems: wave and fluvial. Lunar and wind tides may be present in larger lakes (Ainsworth et al., 2012), but the effects of such are negligible on sediment reworking compared to tides in marginal marine environments. The occurrence of some similarities allows a large part of our understanding of marginal marine processes and depositional environments to be transferred to marginal lacustrine depositional environments. The processes that control sedimentation in lakes are similar to those affecting marine coasts, but lacking major tides (Nichols, 2009).

For example, Lake Michigan, a large-area freshwater lake in a overfilled lake basin features: beaches, barrier spits and islands, deltas, strand plains, upper delta plain fluvial and flood-plain systems, estuaries, a shelf-slope system with coastwise rectification of currents, a benthic nepheloid layer, density currents, mass flow deposits, coastal downwelling jets and Coriolis veering of lake currents (Fraser et al., 2012). These elements are also observed in modern marginal marine and oceanic settings. However Lake Michigan does differ from a marginal marine setting in that it has: a principally mild wave climate, a very small lunar tide and a spillpoint which places an upper limit on accommodation (Fraser et al., 2012).

Beaches can form virtually any place where the land and a body of water meet, including in lacustrine settings. Beaches can form in lakes covering less than a square kilometre, and apart from the obvious differences in fetch and tides, beach sedimentation in lakes is similar to that in the ocean (Davis, 1978). A beach is defined as the zone of unconsolidated sediment that extends from the uppermost limit of wave action to the low-tide mark (Davis, 1978; Timms, 1992). Because lake levels and wave activity are often highly variable, beach profiles are highly variable. In lakes with stable shorelines and low energy, beaches can be very narrow. However, near oceans and lakes with variable levels and high wave energy, beaches can become wide sand sheets extending vast distances.

Lake Michigan shows an example of a modern well developed beach system formed by dynamic wave energy on coastlines with high sand content. Beaches with widths of up to 300 m and effective depths of 7 m are recorded. If abundant sediment is supplied to the zone of shoaling and to the beaches along the lake shore, the shore progrades lakeward (Fraser et al., 2012). This forms a sheet of sand as thick as the depth of shoaling, coarsening upward from fine sediments to beach sands. The amount wave energy, and associated depth of shoaling, will govern the thickness of the sand sheet formed by beach progradation (Friedman and Sanders, 1978). The lateral extent of prograding beaches will be controlled by the morphology of the shoreline, the supply of sediment and the wave energy of the lake. Beaches can also be formed preferentially at one end of a lake if prevailing winds produce waves in a single uniform direction.

6. Characteristics of Lacustrine Sedimentation

A succinct definition of a lake is difficult to quote. Many of the elements observed in modern systems are not directly seen or measured in outcrops of ancient lakes (Gierlowski-Kordesch and Kelts, 1994). Less is known about preservation potential in lake systems than in marginal marine settings. Varying morphologies, tectonic settings, sizes, chemistries and degrees of permanency make classification attempts and fixed sedimentary models overly detailed, unscaleable, unwieldy, and geologically problematic (Timms, 1992; Gierlowski-Kordesch and Kelts, 1994). Authors have proposed many definitions with various classification schemes to define particular lake types (Oxford, 2016; Timms, 1992; Gierlowski-Kordesch and Kelts, 1994; Bayly and Williams, 1973; Reineck and Singh, 1980; Fouch and Dean, 1983, Selley, 1985; Bohacs et al., 2002).

In this thesis, for a water body to be defined as a lake: (1) the water body must fill or partially fill a basin, (2) the water body should have the same water level in all parts, except for relatively short events dominated by wind, thick ice cover or large inflows (3) The water body should not have an intrusion of seawater or communication with the ocean; however it may be located in the immediate vicinity of the coast, and (4) the surface area of the water body should exceed 1 km^2.

Allen and Collinson (1986) proposed that lakes be classified as either hydrologically open or hydrologically closed on the basis of input versus evaporation. Hydrologically open lakes are dominated by sedimentation from clastic input and have an outlet. Shorelines in hydrologically open lakes are generally more fixed and stable as input and precipitation is balanced by output and evaporation. Lakes which are classified as hydrologically closed lack an outlet and are dominated by biochemical and chemical sedimentation and experience rapid changes in their shorelines. All lakes could potentially pass through both of these hydrological settings throughout from genesis through evolution until their demise.

Gierlowski-Kordesch and Kelts (1994) further refined the classification of lake basins, defining three categories: event basins, paralic basins and tectonic basins. Event lake basins are created by short-term processes and are less likely to preserve thick lacustrine deposits in the geological record. Paralic lake basins include cut-off marine embayments and shoreline depressions controlled by sea level fluctuations. Tectonic lake basins are most commonly preserved in the geological rec ord. These generally occur in broad regional sags, orogenic-collapse basins, foreland deeps, or rifts and strike slip basins. In a shallow basin setting small volume changes will result in large changes in shoreline and rapid vertical facies changes. Paralic lake basins and tectonic lake basins will at some stage in their evolution connect with the open ocean to form eperic or epicontinental seaways.

7. Characteristics of Sedimentation in Epicontinental Seaways

Throughout geological history continents were flooded forming vast broad, shallow epicontinental seas (Shaw, 1964; Figure 4; Figure 5). These depositional settings are important as much of the marine stratigraphic record and details of climate change, evolution and extinction are preserved in such environments (Hallam, 1981; Allison and Briggs, 1993; Allison and Wells, 2006). Epicontinental seas lack appropriately scaled modern counterparts (Allison and Wells, 2006). They were typically shallow, on the order of 10 to 200 m deep, but of vast extent, covering areas of up to 1,000,000 km^2 (Wells et al., 2005; Allison and Wells, 2006). Depositional character within these basins would have been similar to that in modern low-accommodation basins; however without suitably scaled modern analogues our understanding of these depositional settings is hindered. Wave, tidal and fluvial processes effected deposition in epicontinental sea settings.

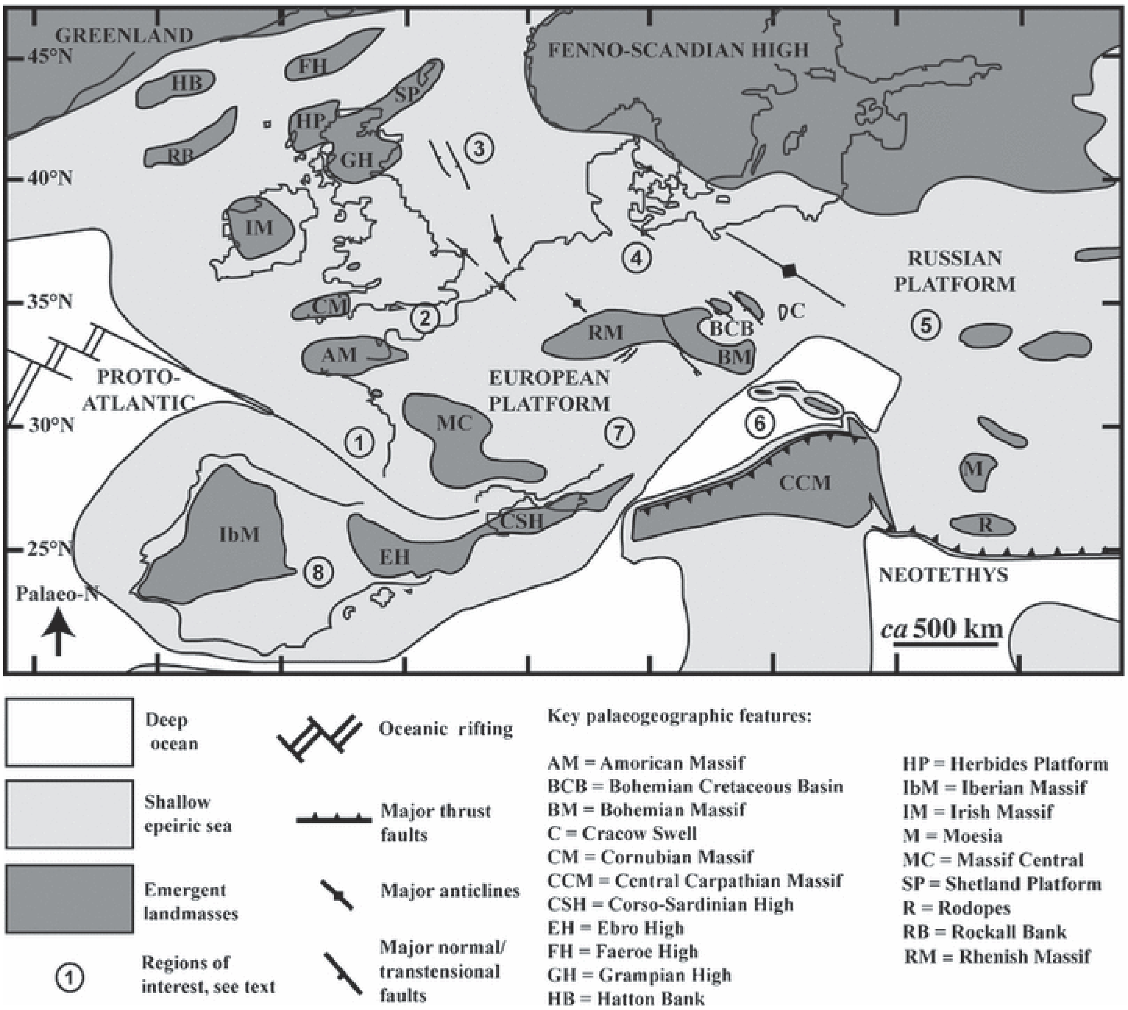

Figure 4: Regional palaeogeography for the Cretaceous European Epicontinental Sea compiled from Ziegler (1990), Dercourt et al. (2000), Golonka (2004, 2007), Gil et al. (2006), and Golonka et al. (2006). Eight regions of interest are summarized in the text: (1) Bay of Biscay Rift; (2) Anglo-Paris Basin; (3) North Sea Basin; (4) North to Central European Basins; (5) Russian Platform; (6) Outer Carpathian Foreland Basin; (7) Vocontian Basin; and (8) Iberian Microplate. From Mitchell et al., 2009.

Figure 5: Regional palaeogeography for the Cretaceous North American Western Interior Basin. Modern state and country borders are overlain (Blakely, 2016).

Tidal action in ancient epicontinental seas has been interpreted diversely as being either enhanced because of resonance and shoaling, or reduced because of frictional damping (e.g. Shaw, 1964; Klein and Ryer, 1978). Numerical modelling studies have shown that at least some epicontinental seas were regionally microtidal, with a tidal range of less than 2 metres (Ericksen and Slingerland, 1990; Wells et al., 2005, Wells et al., 2007). Conversely, there is geological evidence of widespread tidal influence that indicates the presence of tidal currents capable of transporting coarse grained clastics considerable distances from the paleocontinental margin in Proterozoic deposits (Sonnet et al., 1996). Tide-influenced conditions have been documented in Cenomanian estuarine deposits and proposed also for Turonian to Coniacian deltaic strata of the Cretaceous Bohemian Basin, Central Europe (Valečka, 1979; Uličný and Špičáková, 1996; Voigt, 1996; Uličný, 2001). Additionally, some workers suggest that tidal amplification may have occurred as a result of resonance and funnelling in embayments (Wells et al., 2007).

Wave action in ancient epicontinental seas has been suggested to have been attenuated by the large surface areas of the seas and hence large distances travelled by waves (Keulegan and Krumbein, 1949; Shaw, 1964; Irwin, 1965). Wind waves are affected by fetch, duration, and intensity of wind (Jonsson et al., 2002; Jonsson et al., 2005). Substantial waves are regularly documented in even the small semi-restricted seas of today. Wave heights (crest-to-trough height) of larger than 6 m are documented in the Baltic Sea (300,000 km^2 surface area, 55 m depth) annually (Allison and Wells, 2006). Models suggest that wavelengths of 200 metres are theoretically possible during large storms (Jonsson et al., 2002; Jonsson et al., 2005).

Fluvial action generally dominates deltaic deposition in epicontinental seas. Examples of fluvio-deltaic settings in epicontinental seas exist in Devonian (Slingerland, 1986), Carboniferous (Wells et al., 2005a, Wells et al., 2005b), and Cretaceous (Ericksen and Slingerland, 1990) deposits. Deltaic deposits are generally thinly bedded, due to the comparatively low amount of accommodation space in epicontinental seaways, compared to oceanic margins. Delta morphology in epicontinental seas is primarily fluvial-dominated, although estuarine-type settings deposits are proposed also for Turonian to Coniacian deltaic strata of the Bohemian Cretaceous Basin, Central Europe (Valečka, 1979; Uličný and Špičáková, 1996; Voigt, 1996; Uličný, 2001).

Depositional processes within epicontinental seas are diverse and complex (Allison and Wells, 2006). It is likely that no two epicontinental sea depositional settings are the same. Epicontinental seaways share characteristics with both lakes and oceans. In order to better understand the depositional character and architecture of these depositional settings, sequence stratigraphy can be used. As epicontinental seaway settings share characteristics of marine and lacustrine depositional environments, an understanding of the application of sequence stratigraphic methods to both of these depositional settings is important.

8. Sequence Stratigraphy in Marine and Lacustrine Settings

The fundamental sequence stratigraphic model (Mitchum et al., 1977, Payton et al., 1977; Vail et al., 1977; Vail 1987, Posamentier et al. 1988; Figure 6) was based on two assumptions: depositional sequences were controlled primarily by sea-level cycles, and sea level cycles were driven by eustacy (Mitchum et al., 1977). This implied that sequences from different continental margins would reflect the same global sea level curve (Vail et al. 1977) and that global correlation of sequences was possible on the basis of one Meso-Cenozoic sea level curve (Haq et al., 1987).

Sequence stratigraphy was originally developed as a seismic method in marine settings rather than processes at the scale of single depositional systems (Brown and Fischer 1977). Recent developments in sequence stratigraphy include efforts to define, delineate and standardise nomenclature, as well as developing ways to make objective observations, independent of model assumptions (Xue and Galloway, 1993, Catuneanu, 2006; Catuneanu et al., 2009; Neal and Abreu, 2009). The popularity of the model has greatly increased and it has been applied at different scales and settings. The latest models in sequence stratigraphy exclude explicit reference to sea-level as a primary influence in shaping sequences (Catuneanu et al. 2009; Neal and Abreu 2009), however sequence stratigraphy originated in the marine realm, and the influence that sea level had and still has on shaping the model should not be ignored (Burgess, 2016; Ridente et al., 2016).

Although sequence stratigraphic methods are conceptually different compared to traditional lithostratigraphic facies-analysis type methods, in that identification of genetic packages and surfaces within a chronostratigraphic framework is encouraged, the two can be used as complementary tools in suitable circumstances (Figure 7).

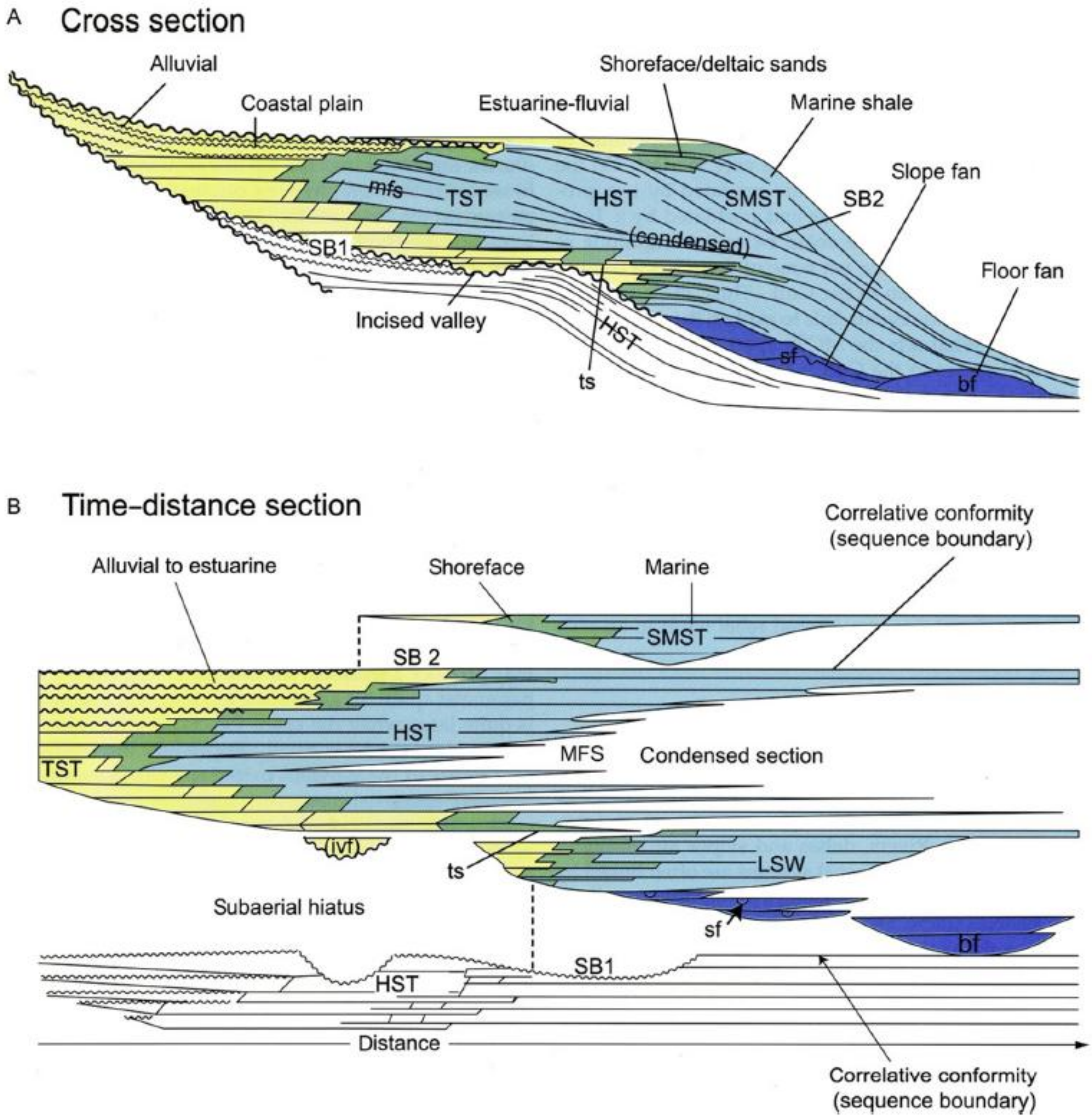

Figure 6: Vail (1987) standard sequence stratigraphic model. (A) Schematic cross section of the standard model. (B) Chronostratigraphic chart with distance on the horizontal axis (same scale as A) and time on the vertical axis (also termed a Wheeler diagram). Abbreviations: bf basin floor fan; HST highstand systems tract; LSW lowstand wedge; MFS maximum flooding surface; SB1 type 1 sequence boundary; SB2 type 2 sequence boundary; sf slope fan; SMST shelf-margin systems tract; ts transgressive surface; TST transgressive systems tract. Originally from Vail (1987). Modified by Schlager (2005).

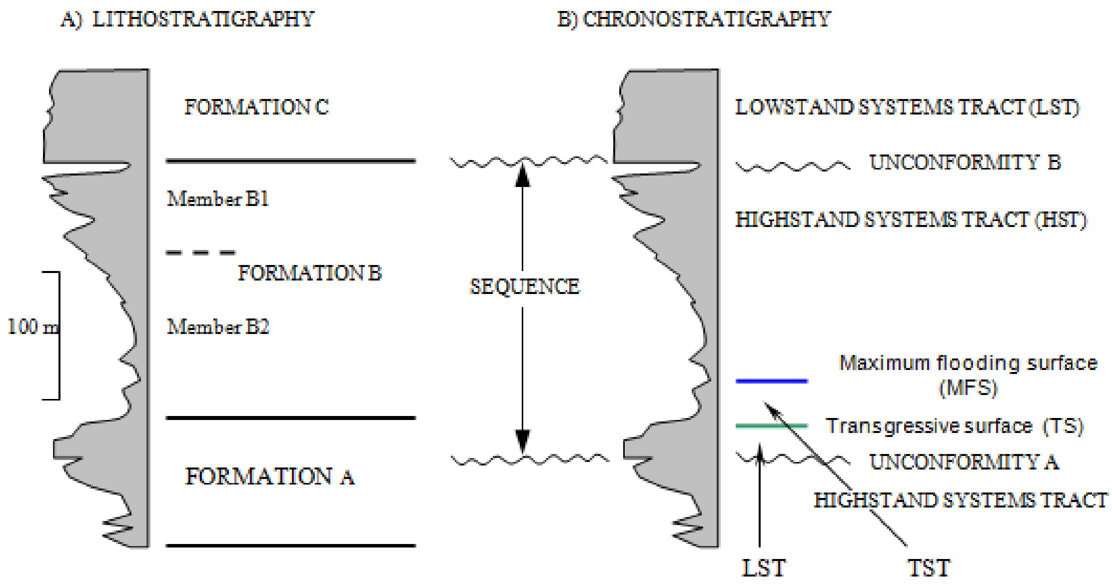

Figure 7: Diagram of the different approaches of interpretation, A) lithostratigraphy, and B) sequence stratigraphy or chronostratigraphy. (After Posamentier and Allen, 1999).

Concepts of sequences, systems tracts and discontinuities can be aplied in the non-marine realm based on work in marine settings (Posamentier and Weimer, 1993; Shanley and McCabe, 1994). Non-marine sequence stratigraphy provides a different method of classifying and interpreting the stratigraphic record of lacustrine basins than the traditional lithostratigraphic methods, as it provides a framework for prediction rather than being a purely descriptive tool (Oviatt et al, 1994).

Lakes are complex, non-linear and dynamic systems. Their behaviour and characteristics can differ considerably from marine systems (Figure 8, Gierlowski-Kordesch and Kelts, 1994). The character of lacustrine depositional systems is controlled by not only sediment supply, but also pre-existing topography or bathymetry and the timing of peak clastic influx relative to lake level (Bohacs et al., 2000b). Peak clastic influx and lake level may or may not be related (Bohacs, 2012). The applications of sequence stratigraphy, as well as prediction of depositional patterns, controlling factors and preserved geometries pose distinct challenges

(Bagnaz et al., 2012; example of depositional patterns shown in Figure 9). These challenges arise from the non-unique relations of lake character to tectonics and climate, contingent responses of lakes to climate change, variable ties among lake level, sediment supply and water supply (Bohacs et al., 2000b, Bohacs, 2012). Lake shoreline shapes vary widely at relatively short temporal and spatial scales and change fundamentally between different lake types. Wireline log expression of lacustrine strata varies widely among lacustrine facies associations and can differ greatly from that commonly observed in marginal marine strata (Bohacs and Miskell-Gerhardt, 1998).

Attribute	Lacustrine	Marine
Size	Highly variable, 1 up to 80,000km^2 today	Immense
Chemistry	Highly variable, ionic species function of drainage basin geology and climate	Uniform Na-Cl
Geodynamics	Altitude variations, drainage capture, sudden changes	Sea level, epeirogeny: slower changes
Climate change	Immediate, drastic response, level changes, composition: tens of years	Long term response: 100s of years
Cycles	Annual, sun-spot, short term climate, Milankovitch	Long-term climate, Milankovitch
Tide	No tides, seasonal level variations	Tidal dominated
Organic matter	Algae/bacteria: land plants. Type I common	Marine algae or land plant. Type II and III
Deltas	Short-term, rapid variance response to level changes	Long-term stability
Turbidites	Common in dilute waters	Rare events
Transgression / Regression	Very short period	Long period phenomena
Stratigraphy	Rapid facies change laterally and vertically	Walthers' law, transitional
Life span	Up to ~30 Ma	1-100 Ma

Figure 8: A comparison of attributes for lacustrine versus marine environments of deposition (after Gierlowski-Kordesch and Kelts, 1994).

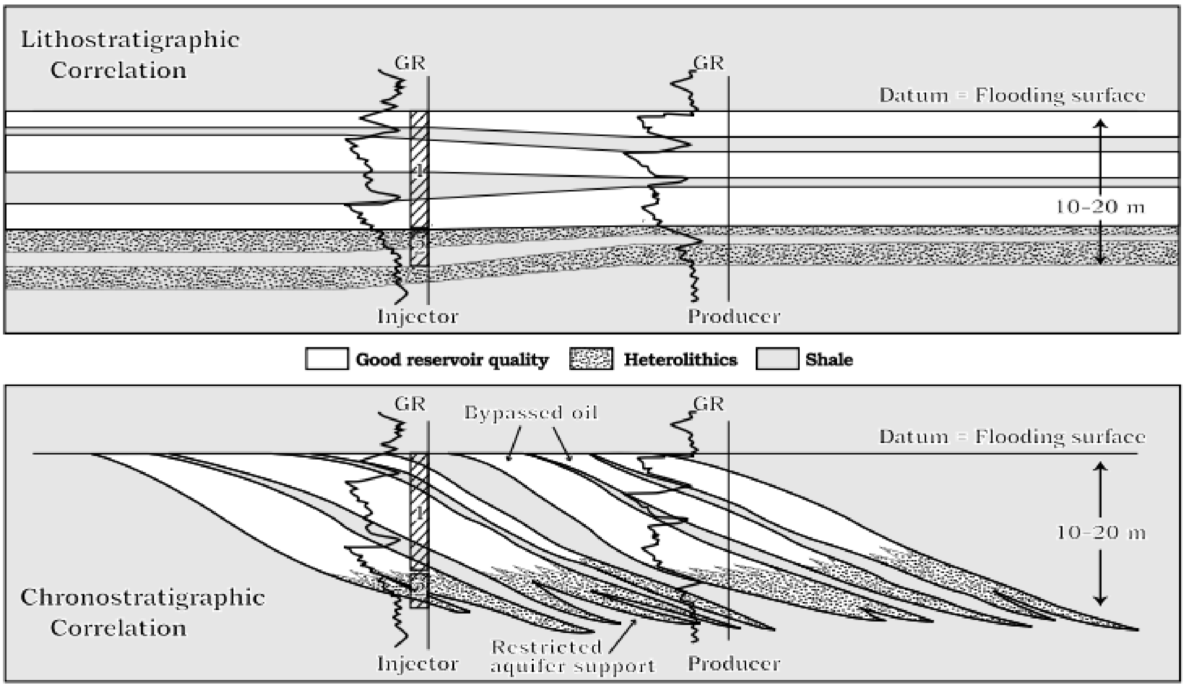

Figure 9: Distribution of connectivity in the Lan Krabu Formation (Miocene), Sirikit Field, Thailand. Delta-front and stream – mouth bar facies are well connected obliquely across the field but poorly connected vertically in any one well bore. Recognition of this characteristic pattern and reservoir modelling using a more accurate and appropriate correlation strategy increased reserve estimates by 43% in this lacustrine environment. (From Bohacs, 2012, originally modified from Ainsworth et al., 1999).

As epicontinental seaway settings share characteristics of both marine and lacustrine depositional environments, an understanding of the application of sequence stratigraphic methods to both of these depositional settings is important (Allison and Wells, 2006). When the seaway is open to the ocean, regular classical sequence stratigraphic principles apply, but if the seaway becomes closed to the ocean and transitions back to a lacustrine depositional setting, depositional architecture and geometries will be more difficult to predict. The inherent uncertainty in interpretation can be decreased through the use of existing depositional models and analogies with modern and ancient depositional systems that share sufficient similarity to provide useful insights.

9. Reservoir Analogue Studies

Since the first statement of the three fundamental laws of geology: the principle of original horizontality, the law of superposition and the principle of cross cutting relationships (Steno, 1669), sedimentology and sedimentary geology has played an important role in our description and understanding of the world around us. The recognition of deep time, that rocks record the evidence of the past action of processes which operate today, and the assumption that the same natural laws and processes that operate in the universe now have always operated in the past and apply everywhere in the universe is derived from fundamental process-based sedimentological observations (Hutton, 1788; Playfair, 1802). These ideas were developed into the concepts of uniformitarianism, (frequently cited by fundamental workers such as Charles Darwin) through close and careful sedimentological observations (Lyell, 1830).

The disciplines of sedimentology and stratigraphy rely heavily on comparisons and analogues since the development of rocks and structures, especially those in the subsurface, can rarely be observed directly. It may be relatively straightforward to describe and quantify a sedimentary succession from core, but using these data to predict sedimentary facies in unsampled areas requires datasets to be supplemented by analogue data (Alexander, 1992). Analogues studied in this thesis comprise of comparisons with modern depositional processes and ancient outcrop rock record examples.

Modern depositional analogues are used to increase the understanding of the reservoir rocks and the processes which operated during their deposition (Harris et al., 2004; Alexander, 1992). The consideration of modern processes and their products as analogues for reservoir rocks assumes that the present is the key to the past and that modern natural processes have been in effect throughout geological time (Alexander, 1992). Studying modern deposits allows the worker to provide a detailed description of the deposits, determine the processes operating during deposition, and to define the controls on those processes, which can allow for the construction of a process-based facies model (e.g. Bhattacharya et al., 2003; Fisher et al., 2008). Modern depositional analogues provide excellent lateral resolution but relatively poor vertical resolution (Harris et al., 2004).

Ancient outcrop analogues are used as a comparison tool with rocks or structures observed in the subsurface with descriptions of facies which appear to be similar (Harris et al., 2004; Alexander, 1992). Direct comparison of subsurface data with well-exposed similar rock units can lead to major advances in the understanding of the reservoir characteristics (e.g. Burton et al., 2014; Fischer et al., 2007). Data from outcrop can be used to model facies geometry, size and distribution, in order to give an indication of facies stacking patterns and architecture (e.g. Koehrer et al., 2011; Eltom et al., 2012). Ancient outcrop analogues provide excellent vertical resolution but cannot provide three dimensional lateral horizontal data (Harris et al., 2004).

10. References

Ainsworth, R.B. 2010. Prediction of Stratigraphic Compartmentalization in Marginal Marine Reservoirs. In: Jolley, S.J, Fisher, Q.J., Ainsworth, R.B., Vrolijk, P. and Delisle, S. (eds.), Reservoir Compartmentalization. Geological Society of London Special Publication No. 347, pp 199–218.

Ainsworth, R.B., Hasiotis, S.T., Amos, K.J., Krapf, C.B.E., Payenberg, T.H.D., Vakarelov, B.K., Sandstrom, M.L. and Lang, S.C. 2012. Tidal signatures in an intracratonic playa lake. Geology, v. 40, pp 607-610.

Ainsworth, R.B., Vakarelov, B.V., and Nanson, R.A. 2011. Dynamic Spatial and Temporal Prediction of Changes in Depositional Processes on Clastic Shorelines: Toward Improved Subsurface Uncertainty Reduction and Management. American Association of Petroleum Geologists Bulletin, v. 95, pp 267-297.

Alexander, J. 1992. A discussion on the use of analogues for reservoir geology. Geological Society Special Publication, 69, pp.175–194.

Allen P.A., Collinson J.D. 1986. Lakes. In: Reading, H.G. (ed) Sedimentary environments and facies. Blackwell, Oxford, pp 63-94

Alley N.F. 1998. Cainozoic stratigraphy, palaeoenvironments and geological evolution of the Lake Eyre Basin. Palaeogeography, Palaeoclimatology, Palaeoecology 144 pp 239-263.

Allison, P.A., and Briggs, D.E.G. 1993. Palaeolatitudinal sampling bias; species diversity and the end-Permian extinction event: Geology, v. 21, pp 65–68.

Allison, P.A., and Wells, M.R. 2006. Circulation in large ancient epicontinental seas: What was different and why? Palaios, v. 21, pp 513–515.

Anderton, R. 1985. Clastic facies models and facies analysis. Geological Society, London, Special Publications, 18(1), pp 31–47.

Baganz, O.W. Baganz, O., Bartov, Y., Bohacs, K. M., Nummedal, D. 2012. Lacustrine sandstone reservoirs and hydrocarbon systems American Association of Petroleum Geologists, AAPG Hedberg Research Conference. AAPG Memoir ; 95.

Barrell, J. 1917. Rhythms and the measurements of geologic time. Geological Society of America Bulletin, 28(1), pp 745–904.

Bartov, Y., Mordechai, S, Enzel, Y., Kendell, C., and Moore, P. 2012. Modeling the sensitivity to environmental controls of the Late Pleistocene Lacustrine Delta sequences in the Dead Sea Basin, in O. W. Baganz, Y. Bartov, K. Bohacs, and D. Nummedal, eds., Lacustrine sandstone reservoirs and hydrocarbon systems: AAPG Memoir 95, pp 417 – 431.

Bayly, I.A.E. and Williams, W. D. 1973. Inland waters and their ecology / I.A.E. Bayly, W.D. Williams., Camberwell, Vic: Longman Australia.

Bhattacharya, J.P., Giosan, L. 2003. Wave-influenced deltas: geomorphological implications for facies reconstruction. Sedimentology, 50, pp 187–210.

Billi P. 2007. Morphology and sediment dynamics of ephemeral streams terminal reaches in the Kobo basin (northern Welo, Ethiopia). Geomorphology, 85 pp 98–113

Blakey, R.C. 2016. North American Paleogeographic Maps. Colorado Plateau Geosystems.

Blum, M., Kocurek, G., Swezey, C., Deynoux, M., Lancaster, N., Price, D., Pion, J.C.1998. Quaternary wadi, lacustrine, aeolian depositional cycles and sequences, Chott Rharsa Basin, southern Tunisia. In: Alsharhan, A., Glennie, K., Whittle, G., Kendall, C. (Eds.), Quat. Deserts Climatic Change. Balkema, Rotterdam, pp 539–552.

Bohacs, K. M. 2012. Relation of hydrocarbon reservoir potential to lake-basin type: an integrated approach to unravelling complex genetic relations among fluvial, lake-plain, lake margin, and lake centre strata. in O. W. Baganz, Y. Bartov, K. Bohacs, and D. Nummedal, eds., Lacustrine sandstone reservoirs and hydrocarbon systems: AAPG Memoir 95, pp 417 – 431.

Bohacs, K.M., Carroll, A.R., and Neal, J.E. 2000a. Lessons from large lake systems- Thresholds, nonlinearity, and strange attractors: Geological Society of America Abstracts with Programs, v. 32, no. 7, pp A-312.

Bohacs, K.M., Carroll, A.R., Neal, J.E., and Mankiewicz, P.J. 2000b. Lake-basin type, source potential, and hydrocarbon character: An integrated sequencestratigraphic–geochemical framework, in Gierlowski-Kordesch, E., and Kelts, K., eds., Lake basins through space and time: American Association of Petroleum Geologists Studies in Geology v. 46, pp 3–37.

Bohacs, K.M., Miskell-Gerhardt, K. 1998. Well-logexpression of lake strata; controls of lake-basin type and provenance, contrasts with marine strata. AAPG Annual Meeting Expanded Abstracts, Tulsa, Oklahoma, pp A78.

Bohacs, K.M., Neal, J.E., Carroll, A.R., Reynolds. D.J. 2000c. Lakes are not small oceans! Sequence stratigraphy in lacustrine basins [abs.]: American Association of Petroleum Geologists Annual Meeting Expanded Abstracts, v. 9, pp 14.

Boyd, R., Dalrymple, R.W., Zaitlin, B.A. 2006. Estuary and incised valley facies models. In: Posamentier, H.W., Walker, R.G. (Eds.), Facies Models Revisited. SEPM Special Publication, vol. 84, pp 171–234.

Boyd, R., Dalrymple, R.W., Zaitlin, B.A., 1992. Classification of coastal sedimentary environments. Sedimentary Geology 80, pp 139–150.

Brown L.F., Fischer W.L. 1977. Seismic stratigraphic interpretation of depositional systems: examples from the Brazilian rift and pull-apart basins. See Payton 1977, pp 213- 48.

Burgess, P.M., Allen, P. A., Steel, R.J. 2016. Introduction to the Future of Sequence Stratigraphy: Evolution or Revolution? Journal of the Geological Society 173, 5, pp 801-02.

Burton, D., Woolf, K. & Sullivan, B. 2014. Lacustrine depositional environments in the Green River Formation, Uinta Basin: Expression in outcrop and wireline logs. AAPG Bulletin, 98(9), pp 1699–1715.

Catuneanu, O. , Abreu, V. , Bhattacharya, J.P. , Blum, M.D. , Dalrymple, R.W. , Eriksson, P.G. , Fielding, C.R. , Fisher, W.L. , Galloway, W.E. , Gibling, M.R. , Giles, K.A. , Holbrook, J.M. , Jordan, R., Kendall, C.G.St.C. , Macurda, B. , Martinsen, O.J. , Miall, A.D. , Neal, J.E. , Nummedal, D. , Pomar, L., Posamentier, H.W. , Pratt, B.R. , Sarg, J.F. , Shanley, K.W. , Steel, R.J. , Strasser, A., Tucker, M.E. , Winker, C. 2009. Towards the standardization of sequence stratigraphy. Earth Science Reviews, 92(1), pp1–33.

Catuneanu, O., Sweet, A., and Miall, A. D. 1999. Concept and styles of reciprocal stratigraphies: Western Canada foreland system. Terra Nova, v. 11, pp 1–8.

Catuneanu, O., Sweet, A., and Miall, A. D. 2000. Reciprocal stratigraphy of the Campanian–Paleocene Western Interior of North America. Sedimentary Geology, v. 134, pp 235–255.

Coleman, J.M., and L.D. Wright. 1975. Modern river deltas; variability of processes and sand bodies, in M.L. Broussard, (ed.), Deltas, models for exploration: Houston Geological Society, pp 99-149.

Collinson, D.W. 1969. The earth; its origin, history and physical constitution. Earth Science Reviews, (6), pp A251.

Davis R.A. Jr. 1978. Beach and Nearshore Zone. In Davis R.A. Jr. eds Coastal Sedimentary Environments, pp 237-286. Springer-Verlag New York.

Eltom, H., Makkawi, M., Abdullatif, O., & Alramadan, K. 2012. High-resolution facies and porosity models of the upper Jurassic Arab-D carbonate reservoir using an outcrop analogue, central Saudi Arabia. Arabian Journal of Geosciences, 6(11), pp 1-13.

Ericksen, M. C. and Slingerland, R. 1990. Numerical simulations of tidal and wind-driven circulation in the Cretaceous Interior Seaway of North America. The Geological Society of America Bulletin, 102(11), pp 54–62.

Fanetti, D. and Vezzoli, L. 2007. Sediment input and evolution of lacustrine deltas: The Breggia and Greggio rivers case study (Lake Como, Italy). Quaternary International, 173, pp 113.

Fischer, C., Gaupp, R., Dimke, M., & Sill, O. 2007. A 3D High Resolution Model of Bounding Surfaces in Aeolian-Fluvial Deposits: An Outcrop Analogue Study from the Permian Rotliegend, Northern Germany.(Author abstract). Journal of Petroleum Geology, 30(3), pp 257-274.

Fisher, J.A., Krapf, C.B.E., Lang, S.C., Nichols, G., and Payenberg., T.H.D. 2008. Sedimentology and architecture of the Douglas Creek terminal splay, Lake Eyre, central Australia: Sedimentology, v. 55/6, pp 1915–1930.

Fisk, H.N. 1961. Bar-finger sands of the Mississippi delta, in Geometry of Sandstone Bodies: American Association of Petroleum Geologists, 45th Annual Meeting: Atlantic City, New Jersey, April 25–28, 1960, pp 29–52.

Fraser, G. S., Thompson, T. A., and Atkinson, J. C. 2012. Sedimentary processes and sequence stratigraphy of Lake Michigan, United States. Relation of hydrocarbon reservoir potential to lake-basin type: an integrated approach to unravelling complex genetic relations among fluvial, lake-plain, lake margin, and lake centre strata. in O. W. Baganz, Y. Bartov, K. Bohacs, and D. Nummedal, eds., Lacustrine sandstone reservoirs and hydrocarbon systems: AAPG Memoir 95, pp 417 – 431.

Friedman G.M., Sanders J.E. 1978. Principles of Sedimentology. John Wiley & Sons, New York.

Friend, P.F. 1978. Distinctive features of some ancient river systems in A.D.Miall, Fluvial sedimentology, Canadian Society of Petroleum Geologists, Memoir 5: pp 531-542.

Frostick, L.E. and Reid I. 1986. Evolution and Sedimentary Character of Lake Deltas fed by Ephemeral Rivers in the Turkana basin, northern Kenya. In Sedimentation in the African RiftsL.E. Frostick, R. W. Renaut, I. Reid and J.J. Tiercelin (eds), pp 113-24. Geological Society of London Special Publication 25.

Galloway, W.E. 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, in M.L. Broussard (ed.) Deltas, Models for Exploration: Houston Geological Society, Houston, Texas, pp 87-98.

Gierlowski-Kordesch, E., and Kelts K. 1994. Chapter 1, in Gierlowski-Kordesch E. & Kelts K. Global Geological Record of Lake Basins, Volume 1. Cambridge University Press, Cambridge.

Gressly, A.1838. Observations géologiques sur le Jura soleurois. Nouveaux mémoires de la Société Helvetique des Sciences Naturelles. Neuchatel, 2, pp 349.

Hallam, A. 1981. Facies interpretation and the stratigraphic record / A. Hallam, Oxford ; San Francisco: W. H. Freeman.

Haq, Bilal U., Hardenbol, Jan & Vail, Peter, R. 1987. Chronology of fluctuating sea levels since the Triassic. (Vail sea level curves). Science, 235, pp 1156.

Harris, P., Grammer, G. Michael, E, Gregor, P. 2004. Integration of outcrop and modern analogs in reservoir modeling / edited by G. Michael Grammer, Paul M. "Mitch" Harris, Gregor P. Eberli. (AAPG memoir 80). Tulsa, Oklahoma, American Association of Petroleum Geologists.

Hayes M.O. 1975. Morphology of sand accumulations in estuaries: an introduction to the symposium. In: Cronin LE (ed) Estuarine research, vol 2. Academic Press, New York.

Hayes M.O. 1979. Barrier island morphology as a function of tidal and wave regime. In: Leatherman SP (ed) Barrier Islands: from the Gulf of St. Lawrence to the Gulf of Mexico. Academic, New York.

Helland-Hansen W., Martinsen O.J. 1996. Shoreline Trajectories and Sequences: Description of Variable Depositional-Dip Scenarios. Journal of Sedimentary Research. V 66, No. 4, pp 670-688.

Helland-Hansen, W. & Hampson, G.J. 2009. Trajectory analysis: concepts and applications. Basin Research, 21(5), pp 454–483.

Hutton, J. 1788. "Theory of the Earth; or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe". Transactions of the Royal Society of Edinburgh. 2 pp 209–304.

Irwin, M. L. 1965. General theory of epeiric clear water sedimentation: American Association of Petroleum Geologists Bulletin, v. 49, n 4, pp 445-459.

Jonsson, A., Broman, B., Rahm, L. 2002. Variations in the Baltic Sea wave fields: Ocean Engineering, v. 30, pp 107–126.

Jonsson, A., Danielsson, A ., Rahm, L. 2005. Bottom type distribution based on wave friction velocity in the Baltic Sea: Continental Shelf Research, v. 25, pp 419–435.

Kauffmann, E. G. 1977. Evolutionary rates and biostratigraphy, in Kauffman, E. G. and Hazel, J. E. eds., Concepts and methods of biostratigraphy, Dowden, Hutchinson and Ross Inc., Stroudsburg, PA, pp 109–142.

Kelly,S.B. and Olsen, H. 1993. Terminal fans—a review with reference to Devonian examples. Sedimentary Geology, 85(1-4), pp 339–374.

Keulegan G. H. Krumbein W. C. 1949. Stable configuration of bottom slope in a shallow sea and its bearing on geological processes. Eos, Transactions American Geophysical Union, 30(6), pp855–861.

Klein, G. de V., Ryer, T. A. 1978. Tidal circulation patterns in Precambrian, Paleozoic and Cretaceous epeiric and mioclinal shelf seas. Geol Soc Am Bull 89: pp 1050-1058.

Koehrer, B., Aigner, T. & Pöppelreiter, M. 2011. Field-Scale Geometries of Upper Khuff Reservoir Geobodies in an Outcrop Analogue (Oman Mountains, Sultanate of Oman). Petroleum Geoscience, 17(1), pp 3–16.

Lang, S. C., Payenberg, T.H.D., Reilly, M.R.W., Hicks, T., Benson, J. And Kassan, J. 2004. Modern Fluvial Analogues for dryland sandy fluvial-lacustrine deltas and terminal splay reservoir. APPEA Journal, 2004, pp 329–56.

Lyell, C. 1830. Principles of Geology: being an attempt to explain the former changes of the Earth's surface, by reference to causes now in operation. 1. London: John Murray.

Miall, A.D. 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Fluvial Sedimentology (Ed. A.D. Miall). Can. Soc. Petrol. Geol. Mem., 5, pp 597-604.

Mitchum Jr.R.M., Vail P.R., Thompson S. 1977. Seismic Stratigraphy and Global Changes in Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis, In Payton C.E. ed. Seismic Stratigraphy – Applications to Hydrocarbon Exploration: AAPG Memoir 26, pp 53-62.

Neal, J., and Abreu, V. 2009, sequence stratigraphy hierarchy and the accommodation succession method, Geology, v. 37, pp 779-782.

Nichols G.J., Fisher, J.A. 2007. Processes, facies and architecture of fluvial distributary system deposits. Sedimentary Geology, 195(1), pp 75–90.

Nichols, G. 2009. Sedimentology and stratigraphy / Gary Nichols. 2nd ed., Hoboken, NJ: Wiley.

Nichols, G.J. & Hirst, J.P. 1998. Alluvial fans and fluvial distributary systems, Oligo-Miocene, northern Spain; contrasting processes and products. Journal of Sedimentary Research, 68(5), pp 879–889.

Nichols, G.J. 1987. Syntectonic alluvial fan sedimentation, southern Pyrenees. Geological Magazine, 124(2), pp 121–133.

North C. P., Warwick G. L. 2007 Fluvial fans: myths, misconceptions, and the end ofthe terminal-fan model. Journal of Sedimentary Research 77: pp 693-701.

Olariu and Bhattacharya, 2006

Olariu, C., Bhattacharya, J.P. 2006. Terminal Distributary Channels and Delta Front Architecture of River-dominated delta systems. Journal of Sedimentary Research, Perspectives, v. 76, p.212-233.

Overeem, I., Groenensteijn, K. , Veldkamp, T., van Dijke, J.J., Kroonenberg, S.B. 1998. Holocene erosion and sedimentation history of the Volga delta related to sea-level changes. Annual Meeting International Association of Sedimentologists, April 1998, Alicante, Spain.

Oviatt C.G., Mccoy W.D. & Nash W.P. 1994. Sequence Stratigraphy of Lacustrine Deposits: A Quaternary Example for the Bonneville Basin, Utah. Geological Society of America Bulletin 106, pp 133-144.

Oxford Dictionary. 2016. In: Oxford Dictionary, Online Edition: http://www.oxforddictionaries.com/

Payton, C.E. 1977. Seismic stratigraphy – application to hydrocarbon exploration. Am Assoc Petrol Geol Mem 26.

Playfair, J. 1802. Illustrations of the Huttonian theory of the Earth. London: Cadell and Davies.

Plint, A. G., and Kreitner, M. A. 2007. Extensive, thin sequence spanning Cretaceous foredeep suggest high-frequency eustatic control: Late Cenomanian, Western Canada foreland basin. Geology, v. 35, pp 735–738.

Posamentier H.W. and Weimer P. 1993. Siliciclastic Sequence Stratigraphy and Petroleum Geology – Where to From Here? AAPG Bulletin 77, No. 5, pp 731-742.

Posamentier HW, Vail PR. 1988. Eustatic controls on clastic deposition, II. Sequence and systems tract models C.K. Wilgus, B.S. Hastings, H.W. Posamentier, C.A. Ross, J.C. Van Wagoner (Eds.), Sea-Level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral. Spec. Publ., 42 (1988), pp 71-108.

Reading H.G., Levell B.K. 1996. Controls on the Sedimentary Rock Record. In Reading H.G. ed. Sedimentary Environments: Processes, Facies and Stratigraphy, pp 5-36. Blackwell Science Ltd, Oxford.

Reading, H. G., Collinson, J. D. 1996. Clastic coasts. In: Sedimentary environments: Processes, facies and stratigraphy, London: Blackwell, pp 154–231.

Reineck, H.E., Singh, I. B. 1973. Depositional sedimentary environments with reference to terrigenous clastics, Berlin ; New York: Springer-Verlag.

Richards, K., Mudie, P., Rochon, A., Athersuch, J., Bolikhovskaya, N., Hoogendoorn, R., Verlinden, V. 2017. Late Pleistocene to Holocene evolution of the Emba Delta, Kazakhstan, and coastline of the north-eastern Caspian Sea: Sediment, ostracods, pollen and dinoflagellate cyst records. Palaeogeography, Palaeoclimatology, Palaeoecology, 468, pp 427–452.

Ridente, D. 2016. Releasing the sequence stratigraphy paradigm. Overview and perspectives. Journal of the Geological Society, London, 173, pp 845–853.

Selley, R.C. 1985. Petroleum Geology, Harcourt Brace Jovanovich, Sydney.

Shanley K.W., McCabe P.J.1994. Perspectives on the Sequence Stratigraphy of Continental Strata. The American Association of Petroleum Geologists Bulletin 78, No. 4, pp 544-568.

Shaw, A.B. 1964. Time in stratigraphy, New York: McGraw-Hill.

Sonnet, C.P., Kvale, E.P., Zakharian, A., Chan, M.A., and Demko, T.M. 1996. Late Proterozoic and Paleozoic tides, retreat of the Moon, and rotation of the Earth: Science, v. 273, pp 100–104.

Stanistreet, I.G., Stollhofen, H. 2002. Hoanib River flood deposits of Namib Desert interdunes as analogues for thin permeability barrier mudstone layers in aeolianite reservoirs. Sedimentology 49, pp 719–736.

Steno, N. 1669. De solido intra solidum naturaliter contento dissertationis prodromus [Of Solids Naturally Contained Within Solids]. Firenze Publishing.

Timms B.V. 1992. Lake Geomorphology. Gleneagles Publishing, Adelaide.

Tooth, S. 1999. Downstream changes in floodplain character on the Northern Plains of arid central Australia. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI, International Association of Sedimentologists, Special Publication No. 28. Blackwell Scientific Publications, Oxford.

Tooth, S. 2000. Process, form and change in dryland rivers: a review of recent research. Earth Sci. Rev. 51, pp 67–107.

Tye, R.S., Coleman, J.M. 1989. Evolution of Atchafalaya lacustrine deltas, south-central Louisiana. Sediment. Geol., 65, pp 95-112.

Uličný, D. 2001. Depositional systems and sequence stratigraphy of coarse-grained deltas in a shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic. Sedimentology 48, pp 599–628.

Uličný, D., Špičáková, L., 1996. Response to high frequency sea-level change in a fluvial to estuarine succession: Cenomanian palaeovalley fill, Bohemian Cretaceous Basin. Geological Society Special Publication, 104(1), pp 247–268.

Vail, P. R., Mitchum Jr., R. M., Todd, R. G., Widmier, J. M., Thompson, S., Sangree, J. B., 1977. Seismic stratigraphy and global changes in sea level. In Payton, C. E. Seismic Stratigraphy–Applications to hydrocarbon exploration, AAPG Memoir. 26. Tulsa: American Association of Petroleum Geologists. pp 49–205.

Vakarelov, B. K. and Ainsworth, R. B. 2013. A hierarchical approach to architectural classification in marginal marine systems – bridging the gap between sedimentology and sequence stratigraphy. AAPG Bulletin, v. 97, pp 1121-1161.

Valečka, V. 1979. Paleogeografie a litofaciální vývoj severozápadní části české pánve. Sbornik geologickich ved, (English translation- Cretaceous lithoevents in the Bohemian Cretaceous Basin, Czechoslovakia) 33, pp 48–81

Van Wagoner J.C., Mitchum Jr. R.M., Champion K.M., Rahmanaian V.D. 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High Resolution Correlation of Time and Facies. AAPG Methods in Exploration Series, No. 7. The American Association of Petroleum Geologists, Tulsa, Okalahoma.

Voigt, S. 1996. Cenomanian–Turonian composite δ13C curve for Western and Central Europe: the role of organic and inorganic carbon fluxes. Palaeogeography, Palaeoclimatology, Palaeoecology, 160 (2000), pp 91-104.

Walker R.G. 1992. Facies, fades models and modern stratigraphic concepts. In: Walker R.G. & Plint NP. (ed) Facies models, Geological association of Canada; pp 1-14.

Walther, J. 1893. Einleitung in die Geologie als historische Wissenschaft [Introduction to geology as a historical science] 3 volumes.

Wells, M.R., Allison, P.A., Hampson, G.J., Piggott, M.D., Pain, C.C. 2005b. Modelling ancient tides: The Upper Carboniferous epieric seaway of Northwest Europe: Sedimentology, v. 52, p. 715–735.

Wells, M.R., Allison, P.A., Piggott, M.D., Pain, C.C., Hampson, G.J., and De Oliveira, C. 2005a. Large sea, small tides: The Upper Carboniferous seaway of Northwest Europe: Geological Society of London, Journal, v. 162, p. 1–5.