FLUVIAL ARCHITECTURE AND GEOMETRY OF THE MUNGAROO FORMATION ON THE RANKIN TREND OF THE NORTHWEST SHELF OF AUSTRALIA

by

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DEDICATION

I would like to dedicate this to my family Nora, Kimberly and Christina for being supportive of my efforts and for forgiving me for being away from home far more than a dad should while I was in school. I would also like to dedicate this to my mom who has always been supportive even though it took me almost thirty years to finally get my masters degree.

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ABSTRACT

FLUVIAL ARCHITECTURE AND GEOMETRY OF THE MUNGAROO FORMATION ON THE RANKIN TREND OF THE NORTHWEST SHELF OF AUSTRALIA

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The Northwest Shelf of Australia contains many producing world class gas reservoirs with large areas remaining unexplored. The fluvio-deltaic Mungaroo Formation of Rankin Trend on the Northwest Shelf is the site of many producing fields on the Northwest Shelf and data collected from these sites is invaluable in understanding the architecture and geometry of the fluvial strata that house these reservoirs.

The Mungaroo Formation contains alternating sections of low accommodation amalgamated sand bodies, and high accommodation shale prone sections that record architecturally complex floodplain deposits. The study sections were broken down into eight architectural elements; thalweg fill, unit bar, abandonment phase, floodplain mudflat, crevasse splay, splay delta, open lake, and swamp. This work presents architectural and geometrical interpretations of the high and low accommodation sections of the Mungaroo Formation on the Rankin Trend using core.

The low accommodation Lower E amalgamated sands are multiple channel belts thick and display internal architectural complexity that implies internal higher order surfaces up to the sequence boundary level and the buffers and buttresses model is employed to gain a better understanding of their regional context. The channel/channel belt geometries can be divided into three size populations that can be reconciled by using the modern Pilbara as an analog.

The Middle E and Upper F high accommodation sections are complex mud and silt dominated floodplain deposits. This study suggests that floodplain deposits may have a better reservoir potential than current thinking implies due the complexity of the sand bodies and the tendency of splay deltas to form ribbon channels, not lobes as current thinking implies, that connect channel belts, thus, creating larger reservoirs consisting of multiple channel belts.

A better understanding of the areas complicated sedimentology will enhance current fields production, and assist in ongoing exploration efforts.

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CHAPTER 1

INTRODUCTION

The Northwest Shelf of Australia contains world class gas reservoirs that are under production and large areas remain unexplored. There is a need for a greater understanding of the complicated sedimentology of the area to improve current reservoir characterization and future exploration efforts. This paper focuses on the architecture and geometry of the marginal, fluvio-deltaic Late Triassic Mungaroo Formation on the Rankin Tend of the Northwest Shelf of Australia and is limited to non-marine influenced deposits. The Mungaroo Formation hosts many of the large reservoirs of the Northwest Shelf.

The non-marine influenced portions of the Mungaroo Formation on the Rankin Trend consist of alternating sections of low accommodation amalgamated sand bodies, and high accommodation shale prone sections that record architecturally complex floodplain deposits. General models have been used to describe the nature of the deposits in these contrasting environments (Westcott, 1993; Wright and Marriott, 1993; Shanley and McCabe, 1994; Olsen et al., 1995; Van Wagoner et al., 1995; Currie, 1997; Dalrymple et al., 1998; Ethridge et al., 1998; Milana, 1998; Martinsen et al., 1999 and others), however, these models tend to over-simplify complexity of fluvial style (Mackey and Bridge 1995; Aslan and Autin, 1999; Bridge 2003; Strong et al. 2005; Miall, 2006; Holbrook et al., 2006; Strong and Paola, 2008) leading to less than ideal reservoir characterization and missed exploration opportunities. A robust architectural and geometrical analysis of the deposits along with the application of more realistic conceptional and analog models will lead to improved reservoir characterization and exploration.

The purposes of this paper are to 1) Categorize and describe the architectural elements that combine to form the high and low accommodation sections. 2) Evaluate the architecture and geometry of the various elements in these sections by comparison with previous research and, where appropriate, utilizing published empirical and quantitative methods. 3) Employ modern and ancient analogs to augment these findings. This study is being done in concert with accompanying Goodwyn seismic and regional well log studies with the overall goal of gaining a better understanding of the internal structure and regional spatial trends of the Mungaroo Formation in order to enhance current production and facilitate future exploration.

CHAPTER 2

GEOLOGIC SETTING

Regional Geology and Paleogeogaphy

The Northern Carnarvon Basin is the southernmost of four extensional basins that form the Northwest Shelf of Australia (Figure 2-1). These basins are in turn part of the "Westralian Superbasin" of Yeates et al., (1986) which is comprised of the Northern Bonaparte Basin, Browse Basin, Offshore Canning Basin Northern Carnarvon Basin, and the Perth Basin which lies further to the south. (AGSO (Australian Geological Survey Organization) Northwest Shelf Study Group, 1994; Exon and Colwell, 1994; Westphal and Aigner, 1997). The Northern Carnarvon Basin is bounded by the Precambrian Craton to the east and by the oceanic crust of the Argo, Gascoyne and Cuvier Abyssal Plains to the north, west and southeast respectively (Hocking et al., 1987) (Figure 2-1). The "Superbasin" was formed by a series of complex, sporadic pre-rift and rifting events related to the breakup of Gondwana that began in the Permian - Carboniferous and continued until the breakup of Australia and India in the Early Cretaceous (Yeates et al., 1986; Westphal and Aigner, 1997). After breakup the region developed as a passive continental margin and underwent a thermal subsidence sag phase. On the Northwest Shelf this was followed by a flexural subsidence phase periodically punctuated by compressive episodes as the Australian and Asian plates converged in the Tertiary (Westphal and Aigner, 1997).

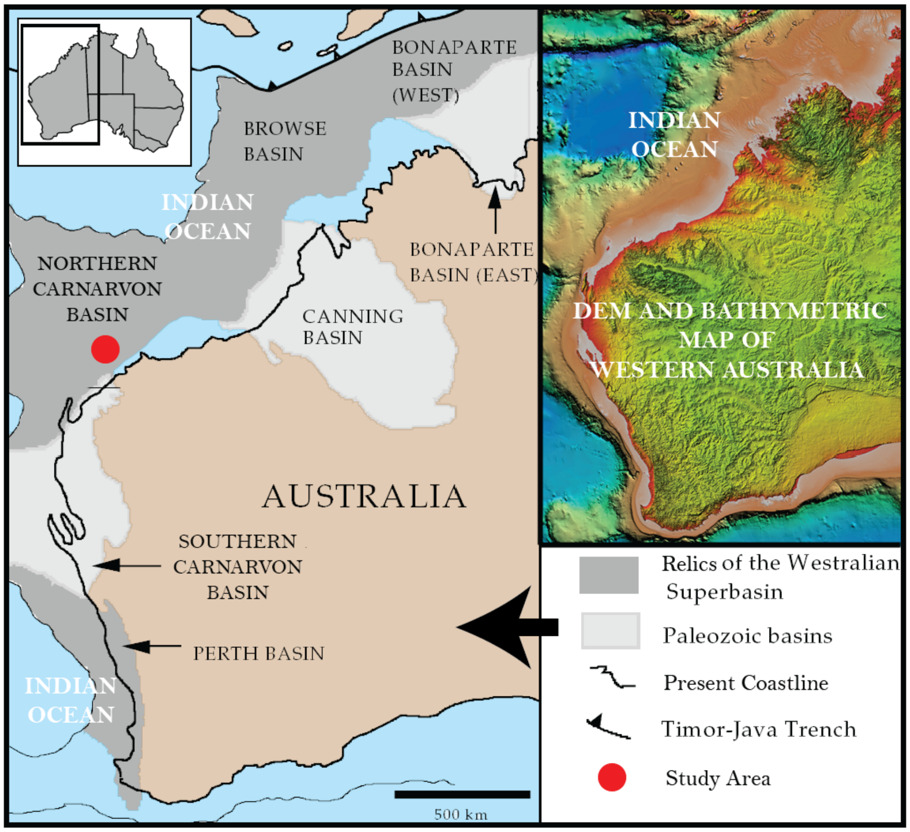


Figure 2-1: Basins of the Northwest Shelf of Australia and the "Westralian Superbasin". DEM and bathymetric map shown for comparison. (After Westphal and Aigner, 1997)

During the Late Triassic the Northwest Shelf was located on the eastern part of Gondwana forming part of the southern Tethyan continental margin (Exon and Colwell, 1994; Westphal and Aigner, 1997) (Figure 2-2). The climate in the Triassic was thought to be temperate to warm, humid and monsoonal, indicating wet and dry periods (Dickens, 1985; Bradshaw et al., 1994). The fluvio-deltaic sediments of the Mungaroo Formation originated in the Ross High in eastern Australia which were transported by a drainage system which may have rivaled the Mississippi's (Jablonski, 1997) and from a major uplift of the adjacent Pilbara Cratonic Block (Seggie et al., 2007). The rivers were interpreted to be of both high and low sinuosity and filled more than 2000m of accommodation space. (Seggie et al., 2007).

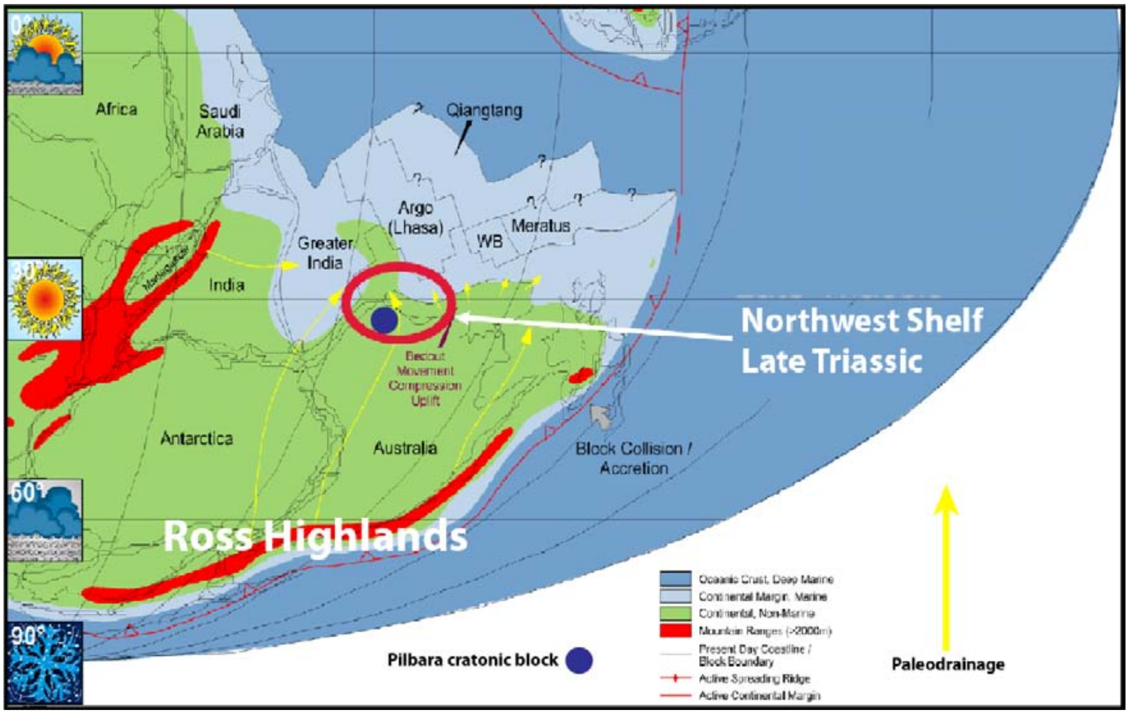


Figure 2-2: Location of the Northwest Shelf in the Late Triassic and paleo-drainage trends. The Northwest Shelf received sediments from the Ross Highlands via a drainage system that may have rivaled the Mississippi's as well as from the adjacent Pilbara Cratonic Block (After Longley et al., 2002).

Stratigraphy and Geology of the Study Area

The Late Triassic succession is divided into the Locker Shale, Mungaroo Formation and the Brigadier Formation (Figure 2-3). The Locker Shale overlies Permian sediments and represents an initial transgression into a northeasterly trending, large scale trough created by a pre-rift sag phase (Barber, 1982, Westphal and Aigner, 1997). The Mungaroo Formation overlies the Locker Shale and records the regression of a fluvio-deltaic system into the sag basin. This study concerns the E sub-section (Figure 2-3). It is comprised of primarily channel, floodplain and lacustrine deposits with local marine influence that increases outboard. (Barber 1982; Westphal and Aigner, 1997; Longley et al., 2002). The Mungaroo system prograded to the northwest covering most of the offshore parts of the Northern Carnarvon Basin to a depth of several kilometers (Vincent and Tilbury, 1988). The large scale pre-rift sag would have created a low slope "ramp" setting for the prograding fluvio-deltaic system. In the latest Triassic a transgression deposited the overlying marginal marine shales and sandstones of the Brigadier Formation.

A rifting episode beginning in the Latest Triassic to Early Jurassic created the Rankin Trend as an extended, northeasterly trending horst block which is broken up to form individual fault blocks that dip generally to the northwest (Barber, 1988; Boote and Kirk, 1989; Seggie et al., 2007) (Figure 2-4). During this period of extensional rift-faulting and warping Jurassic syn-rift sediments were deposited in grabens and low lying areas (Barber, 1988). When sea floor spreading commenced to the northwest in the Oxfordian a significant relative sea level fall led to a major unconformity (the "main unconformity" (MU) event of Veenstra, 1985) truncating uplifts, including the Rankin Trend, as deep as the Triassic (Vincent and Tilbury, 1988, Seggie et al., 2007).

Cretaceous transgression sealed these tilted and eroded Triassic and Early Jurassic sediments draping shales of the Forestier Claystone and the Muderong Shale (Barber, 1988; A.A. Bal et al., 2002) (Fig. 2-4). This forms the basis for the main trap style in the

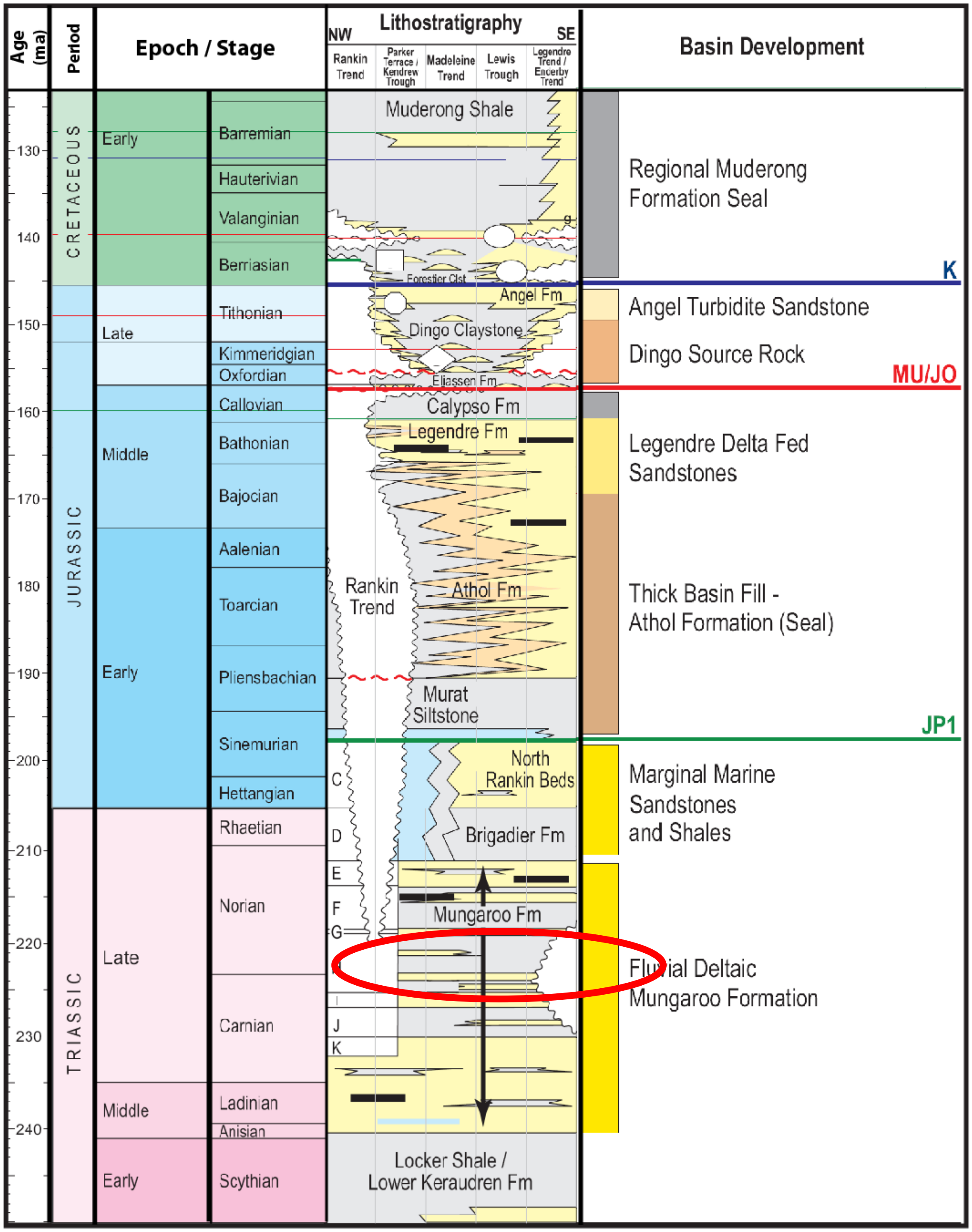


Figure 2-3: Stratigraghy of the Northwest Shelf with study section circled. (After Bennot and Bussel, 2006)

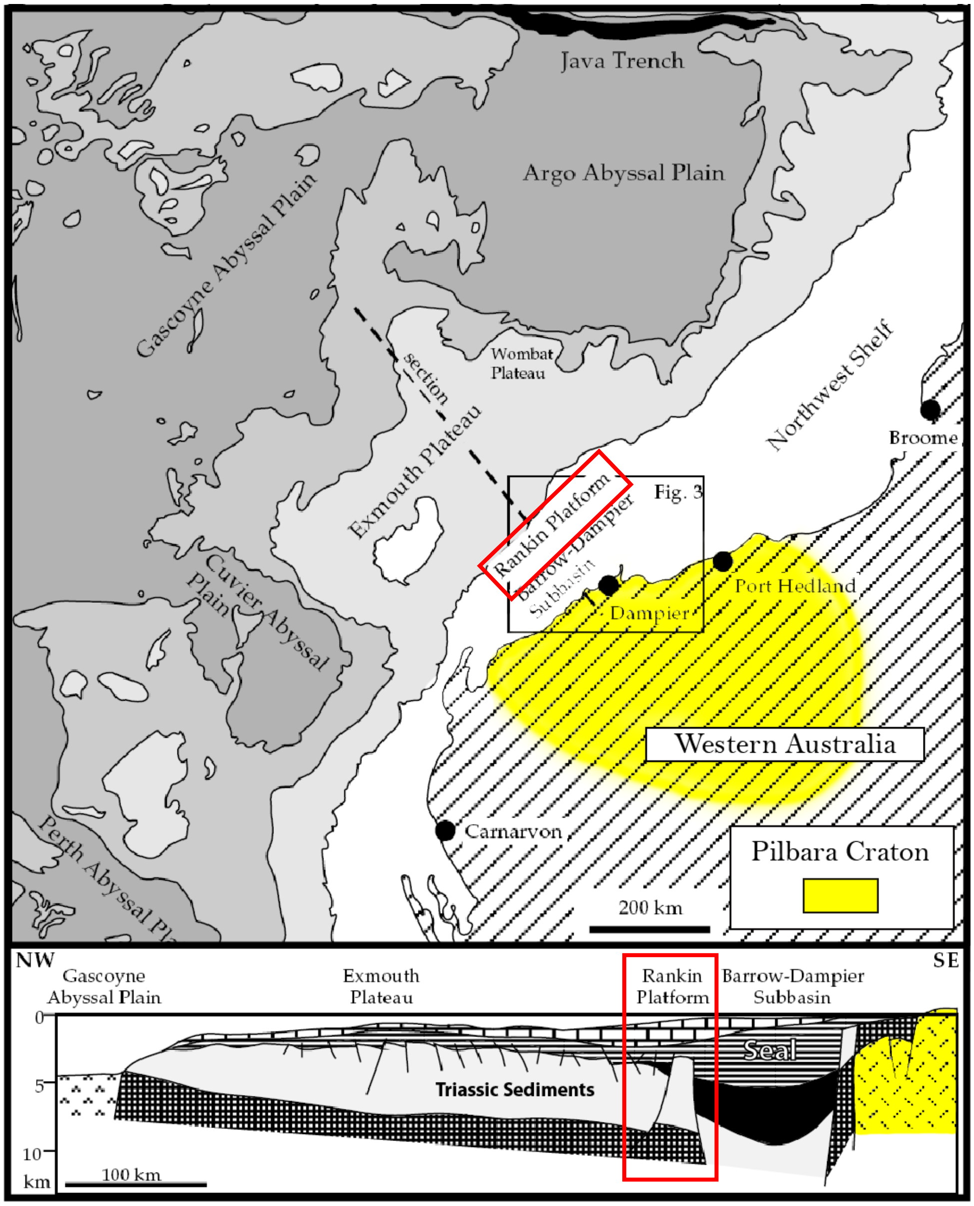


Figure 2-4: Plan view map and cross-section through the Northwest Shelf highlighting the Rankin Trend. Triassic sediments and the regional seal are labeled on the cross-section (After Westphal and Aigner, 1997) .

Mungaroo which is horst/tilted fault block structures sealed by the MU (Longley et al., 2002). Intra-formational seals and pinch- outs are also important traps.

The Late Jurassic Dingo Formation is thought to be the source of hydrocarbon accumulation in the Mungaroo Formation on the Rankin Trend (Longley et al., 2002).

These formations became connected during faulting in the Late Jurassic. The prevalence of gas (84% by boe) is due to the composition, and often high maturity, of the source rocks (Longley et al., 2002). Local oil-prone source rocks exist, but economic production is not common due to gas flushing and biodegradation. The sourcing process is not well understood and debate continues on the subject. There is isotope evidence that some Mungaroo Formation reservoirs are at least partially self-sourced by organic rich high accommodation sections (Edwards et al., 2005). Organic maturity of the hydrocarbons was achieved by burial under thick Cenozoic carbonates (Hocking, 1988).

Structural Development and Setting

Numerous theories are proposed to explain the complex pre-rift and rift events that occurred from the Permian - Carboniferous to the Cretaceous on the Northwest Shelf of Australia. One which appears to work well with the sediment distribution in the Northern Carnarvon Basin is the concept of an asymmetric breakup of a wide rift basin which was proposed by Bassi et al. (1993) and applied to the Northern Carnarvon Basin by Gartrell, (2000). This theory suggests the symmetrical growth of a wide rift basin followed by asymmetric breakup as deformation preferentially localizes in one of the bounding narrow rift basins (Bassi et al., 1993) (Figure 2-5). This concept was applied to the Northern Carnarvon Basin by Gartell, (2000) and appears to explain many of the features found there especially the wide, predominantly flat lying sediments observed on the Exmouth Plateau (Figure 2-6). Gartell suggests that extension of warm ductile

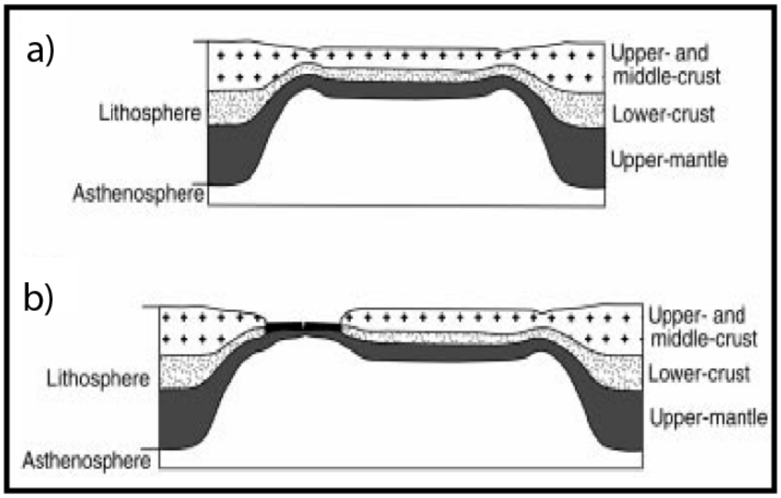


Figure 2-5: Asymmetric breakup of a wide rift basin. a) Symmetrical growth of a wide rift basin b) Asymmetric breakup as the central area cools and hardens and deformation preferentially localizes in the weaker of the bounding narrow rift basins causing it to rift.

lithosphere in the Permian-Carboniferous resulted in extensive wide rifting accompanied by low throw normal faults distributed over a wide region. This was followed by outward flow of ductile lower crustal material to the basin margins from the late Permian to the Late Triassic creating the pre-rift sag basin in which the Mungaroo Formation was deposited. As a result, crustal thinning and cooling occurred in the central areas of the basin making the lithosphere strong and brittle. Subsequent extension of the wide rift during the Latest Triassic to Cretaceous resulted in the formation of the narrow bounding rift basins and subsequent sea floor spreading in the weaker western narrow rift. The Argo Abyssal Plain to the northeast and the Cuvier Abyssal Plain the southwest can be explained by the theory that the active rift can relay from one side of the wide rift basin to the other if the narrow bounding rift basin is weaker on the other side in a given stretch (Gartell, 2000). Perhaps the eastern narrow rift was strengthened by the flanking Pilbara Cratonic Block, inducing the active rift to relay to the western side along this stretch leading to the creation of the Exmouth Plateau (Figure 2-4). This raises the possibility an Exmouth Plateau equivalent outcrop may be found in the sediments deposited above the Argo Abyssal Plain that detached and rifted away. Paleogeographic reconstructions suggest this outcrop would be located somewhere in the eastern Himalayas (Scotese, 1999). There are no known outcrops of the Mungaroo Formation, so finding one would be of great value in reconstructing its sedimentology.

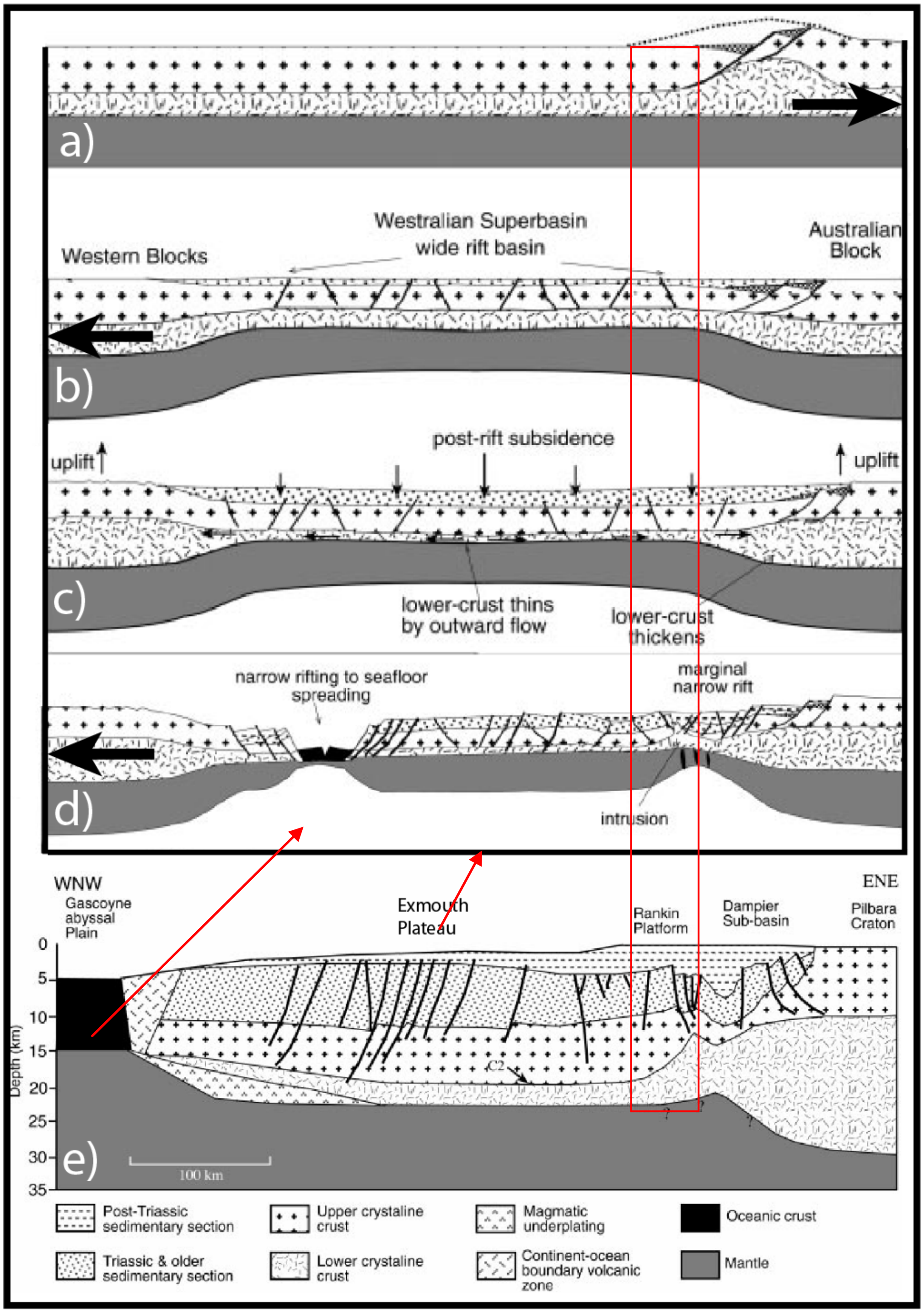


Figure 2-6: Asymmetric wide rift breakup model applied to the Northern Carnarvon Basin a) Proterozoic thin skinned extension. b) Permian - Carboniferous wide rifting c) Late Permian to Late Triassic sag phase resulting from outward flow of the lower crust d) Jurassic-Cretaceous extensional reactivation of more brittle cooled lithosphere results in bounding narrow rift basins and eventually sea floor spreading at the weaker western rift basin. e) Present day cross section. (After Gartell, 2000). Rankin Trend area highlighted.

CHAPTER 3

METHODS AND DATA

The fluvial high and low accommodation settings of the Mungaroo Formation E and F units on the Rankin Trend were analyzed utilizing portions of core from Goodwyn GWA-02, Goodwyn GWA-03, Goodwyn 8, Yodel 2 and Pluto 2 CH1(Figure 3-1). This

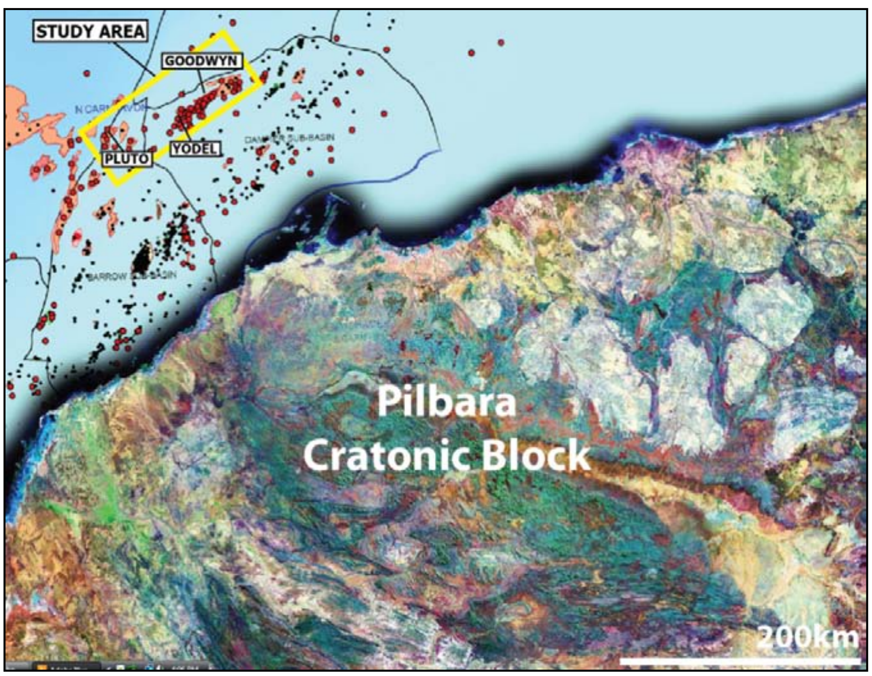


Figure 3-1: Location of Pluto, Yodel, and Goodwyn fields on the Rankin Trend. Core samples are from these three locations.

area was chosen because 3-d seismic is available in the Goodwyn Field for comparison of results, and the seismic is the subject of an accompanying study. The E unit can be divided into upper, middle and lower sections. Upper E and Lower E sections are generally low accommodation and sand dominated while the Middle E has more mud-dominated high accommodation sections (Figure 3-2). The Upper F is predominantly composed of high accommodation muddy sections. E and F units are separated at the top of the H. Balmei populated flooding surface. The H. Balmei biostratigraphic marker is interpreted to indicate a marine influence. Study sections of core from Goodwyn 8 and Yodel 2 lie in the low accommodation Lower E while the sections from Goodwyn GWA-02 and Pluto 2 CH1 are located in the higher accommodation Middle E. Goodwyn

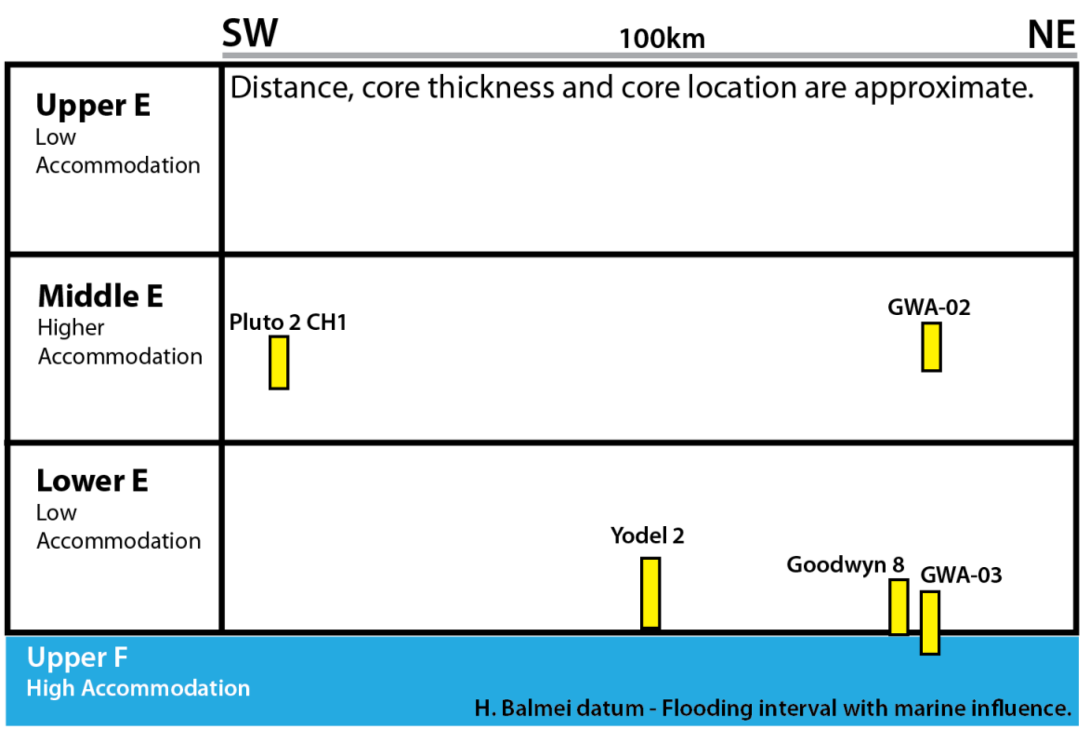


Figure 3-2: Location of core used in this study in relation to facies units and accommodation setting. E and F units are separated at the top of the H. Balmei flooding interval. The occurrence of H. Balmei is interpreted to indicate a marine influence.

GWA-03 core penetrates the Lower E and probably the Upper F. See Table 1 for core intervals and type of accommodation penetrated by the cores . Where there are two intervals given core is not available for the missing section.

Table 3-1: Study core intervals and accommodation associations.

	Sand Dominated Low-Accommodation	More Mud Sections Higher-Accommodation
Goodwyn 8	2844m-2848m and 2858m-2890m: Lower E	X
Yodel 2	2936m-2957m and 2979m-3035m: Lower E	X
Pluto 2 CH1	X	3199m-3212m: Middle E
Goodwyn GWA-02	X	3862m-3932m: Middle E
Goodwyn GWA-03	2967m-3005m: Lower E	3005m-3041m: Upper F?

Core from high accommodation Middle E and Upper F sections were examined directly in Perth, while low accommodation Lower E and sandy Middle E sections were analyzed using high resolution photos in the lab. The study consisted of a detailed facies and architectural element analysis of these sections. Modern and ancient analogs interpreted to approximate the high and low accommodation environments present in the Triassic on the Northwest Shelf were chosen to augment the study.

A detailed bedding diagram was constructed for the low accommodation Lower E and sandy Middle E sections, which are primarily amalgamated bar/channel deposits within higher order channel belts, with the goal of identifying higher order surfaces indicating the presence of multi-valleys and/or sequence boundaries and determining channel/channel belt dimensions. This was done by drawing lines on all cross-set and bedding surfaces and: 1) Interpreting higher order channel belt, valley and sequence bounding surfaces by facies and architectural associations. 2) Determining channel and channel belt dimensions using published numerical and graphical-empirical methods. Channel depth is considered to approximate the thickness of its associated channel belt due to the fact that channels migrate laterally as they create their associated belt. The core from Goodwyn 8 was degraded to the extent that a detailed bedding diagram could not be developed.

Architectural-element analysis techniques developed by Miall (1985,1988,1996) were employed as an aid in understanding bounding surface hierarchies and identifying higher order channel belt, valley and sequence bounding surfaces (Figure 3-3). A good example of its implementation is Holbrook's, (2001) effort in southeastern Colorado where it was used to identify higher order surfaces in middle Cretaceous outcrops (Figure 3-4). This technique is best used on outcrops where bounding surfaces can be walked out to determine their relationships. Up to tens of kilometers of outcrop may be necessary for accurate identification of higher order valley and sequence bounding surfaces. It can, however, be useful in borehole settings when combined with the other empirical and quantitative techniques described below. Furthermore, it is the concept of higher order surfaces and realizing where they are likely to be present that is important. Higher order valley bounding surfaces in amalgamated channel belts implying a multi-valley or sequence level of architectural complexity may be indicated in core by a fundamental change in depositional style and/or porosity. However, this bounding surface obviously cannot be walked out to discern its true bounding nature, so it is not a given. It is also possible for these surfaces to be present without displaying distinct changes in

Grp	Time scale of process (a)	Examples of processes	Instan-taneous sedimentation rate (m/ka)	Fluvial, deltaic depositional units	Rank and characteristics of bounding surfaces
1	10^{-6}	Burst-sweep cycle		Lamina	0th-order, lamination surface
2	10^{-5} -10^{-4}	Bedform migration	10^{5}	Ripple (microform)	1st-order, set bounding surface
3	10^{-3}	Bedform migration	10^{5}	Diurnal dune increment, reactivation surface	1st-order, set bounding surface
4	10^{-2} -10^{-1}	Bedform migration	10^{4}	Dune (mesoform)	2nd-order, coset bounding surface
5	10^{0} -10^{1}	Seasonal events, 10-year flood	10^{2-3}	Macroform growth increment	3rd-order, dipping 5–20° in direction of accretion
6	10^{2} -10^{3}	100-year flood, channel and bar migration	10^{2-3}	Macroform, e.g., point bar, levee, splay immature paleosol	4th-order, convex-up macroform top, minor channel scour, flat surface bounding floodplain elements
7	10^{3} -10^{4}	Long-term geomorphic processes, e.g. channel avulsion	10^{0}–10^{1}	Channel, delta lobe, mature paleosol	5th-order, flat to concave-up channel base
8	10^{4} -10^{5}	5th-order (Milankovitch) cycles, response to fault pulse	10^{-1}	Channel belt, alluvial fan, minor sequence	6th-order, flat, regionally extensive, or base of incised valley
9	10^{5} -10^{6}	4th-order (Milankovitch) cycles, response to fault pulse	10^{-1}–10^{-2}	Major dep. system, fan tract, sequence	7th-order, sequence boundary; flat, regionally extensive, or base of incised valley
10	10^{6} -10^{7}	3rd-order cycles. Tectonic and eustatic processes	10^{-1}–10^{-2}	Basin-fill complex	8th-order, regional disconformity

Figure 3-3: Miall's bounding surface hierarchies. Of particular interest to this study are 5th order channel bounding surfaces, 6th order valley bounding surfaces and 7th order sequence boundaries (Miall, 1985, 1988, 1996).

depositional style and/or porosity (Miall and Arush, 2001, Adams and Battacharya, 2005). Hence, bounding surface interpretations are made with the aid the other mentioned architectural analysis methods and an evaluation of thickness of the entire amalgamated sand body.

Estimates of channel and channel belt dimensions were made using published numerical and graphical-empirical methods. Bankfull channel depth was estimated first

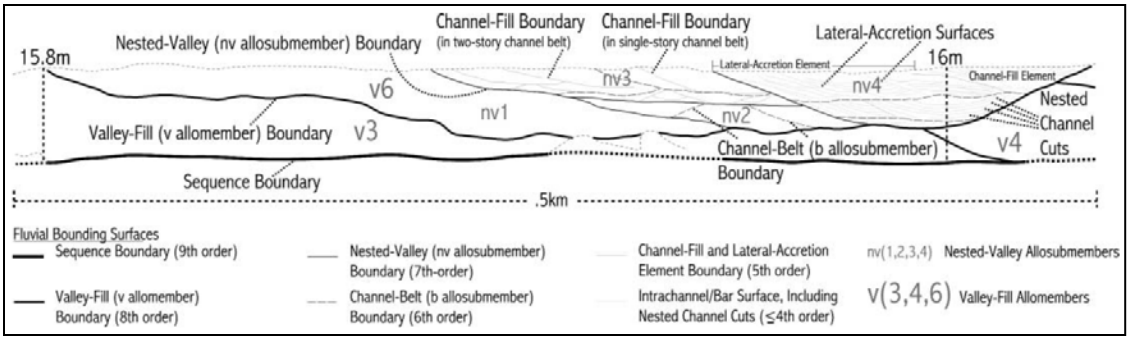


Figure 3-4: Holbrook's 2001 study of middle Cretaceous strata in southeastern Colorado in which higher order channel-belt, valley and sequence bounding surfaces are interpreted in outcrop using Miall's architectural-element analysis technique.

as the other dimensions are scaled to this parameter. Two methods were used to estimate bankfull channel depth.

1) An estimate of bankfull channel depths was made by using the techniques of Bridge and Tye, (2000) to pick out a succession of channel fill architectural elements that represent a reasonably complete channel fill. A relatively complete succession of: thalweg fill - unit bar - abandonment phase architectural elements or: unit bars-abandonment phase architectural elements represents a complete or mostly complete channel fill, and thus, a minimum channel depth for the system which produced the deposits (Figure 3-5).

2) A further evaluation of bankfull channel depth was obtained by using empirically derived equations based on flume experiments and modern/ancient observations. Cross-set thickness in fluvial deposits is controlled primarily by formative dune height and dune height is controlled primarily by bankfull channel depth (Yalin, 1964; Allen, 1984; Bridge, 1993; Leclair et al., 1997; Leclair and Bridge, 1999;

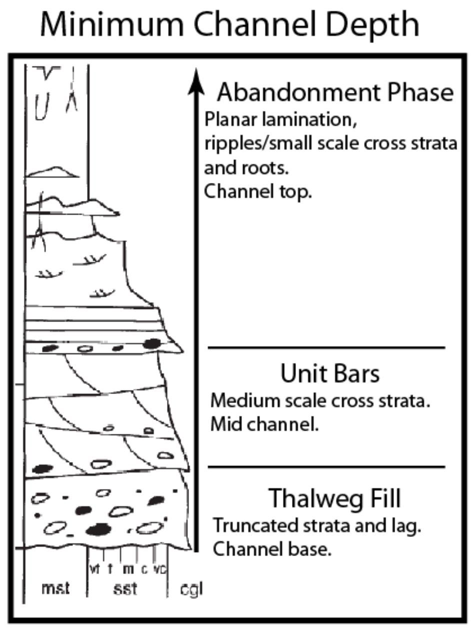


Figure 3-5: Minimum bankfull channel depth is interpreted architecturally from core by identifying a relatively complete succession of the channel fill architectural elements which make up a complete channel fill. An estimate may still be made with the thalweg fill element missing given a reasonable succession of unit bars, although such estimates should definitely be considered minimums. (After Bridge and Tye, 2000).

Bridge and Tye, 2000; Leclair and Bridge 2001; Bridge, 2003). Using these relationships dune height is considered to be approximately 2.9 times the mean cross-set thickness (Leclair et al., 1997; Leclair and Bridge, 1999; Leclair and Bridge 2001) and bankfull channel depth is six to ten times dune height (Yalin, 1964; Allen, 1984; Bridge and Tye, 2000). See Adams and Battacharya, 2005 and McClaurin and Steel, 2007 for examples of employment of these methods. The cross-sets in each sandy section were measured and channel depths were estimated using the procedures described above.

Once an estimate of bankfull channel depth was made an estimate of mean bankfull channel width was made by using the equation $Wc = 8.8dm^{1.82}$ where dm =

mean bankfull channel depth, which is approximately one half bankfull channel depth (Bridge and Mackey, 1993).

Channel belt width was estimated from bankfull channel depth using both numerical and graphical-empirical methods. Using the numerical method (Bridge and Mackey, 1993) channel belt width can range from $cbw = 59.9dm^{1.8}$ to $cbw = 192dm^{1.37}$ where dm = mean bankfull flow depth. Bankfull channel depth was also plugged into three graphical-empirical charts by Fielding and Crane, (1987); Strong et al.,(2002) and Gibling, (2006) to estimate channel belt width (Figure 3-6). Where incised valleys were suspected the total sand body thickness was plugged into a similar chart (Gibling, 2006) to estimate valley width.

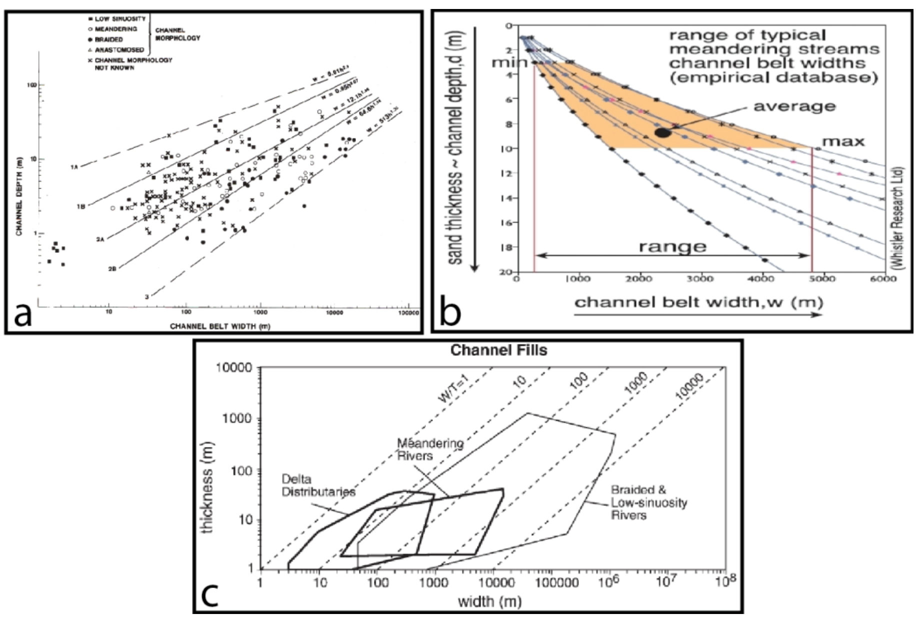


Figure 3-6: Quantitative methods for estimating channel belt width from channel depth. a) Fielding and Crane, 1987. b) Strong et al., 2002. c) Gibling, 2006.

An attempt was made to constrain the lateral dimensions of the architectural elements found in the high accommodation sections. Due to the relative lack of literature on the lateral dimensions of these elements only very broad estimates could be made. As a result the findings on geometries and dimensions of elements in these sections lean heavily on modern analog.

A modern geomorphic study using satellite photos from Google Earth was undertaken to try and relate the geometry of Open Lake Elements to their related fluvial system. Three high accommodation fluvial systems with abundant floodplain lakes were chosen from deltaic, coastal plain and interior basin settings. The lakes, channel belts, and interfluves were digitized to facilitate analysis using ArcGIS (See Supplement 4).

CHAPTER 4

ARCHITECTURAL ELEMENTS

The cores used in this study have eight associated architectural elements which are the building blocks of high and low accommodation fluvial deposits. This study is restricted to fluvial deposits with no marine influence. Architectural elements 1,2, and 3 are associated with channel-belt deposits, which prevail in low accommodation settings. Breaking channel-belt deposits into three elements allows a more detailed examination in these settings. All eight are typical of the high accommodation sections.

Architectural Element 1: Thalweg Fill

Figure 4-1*Characteristics:* (Figure 4-1) Planar-to-trough cross-bedded, rare planar laminated and rare ripple bed forms forming truncated bed sets up to 30cm thick of medium-to-granular poorly-to-moderately sorted sandstone with a sharp scour base and abundant internal scours. Scours locally lined by course sand, pebbles, mud chip rip-ups or concretionary rip-up lags. Local massive bedding. These sandstone elements average 1.8m thick and account for 10% of the total thickness of channel belt deposits. Thalweg fills typically display a basal scour surface which may or may not contain lag. Truncated bedforms are stacked above the basal scour and the top is nested against relatively untruncated bed-sets of unit bars or, less commonly, the low flow regime bedforms of abandonment phase deposits.

Interpretation: These strata record deposition in the basal, highest energy portion of the river by migrating sand waves, dunes and ripple bed forms. They represent the bottom portion of a complete channel-belt fill. Scours are cut during high flow events and then the section fills with bed forms as flow wanes. Successive pulses of energy lead to frequent truncation, leaving scraps and remnants of the bedforms to be preserved in the sedimentary record. Scour lag was eroded as the thalweg cut through underlying sediments and entrained particles too large to carry effectively. Massive bedding reflects slumping of the sides of the channel into the thalweg as it undercut bank deposits. Deposits similar to thalweg fill units have been observed by other researchers (Puigdefabregas and Van Vilet, 1978; Bluck, 1980, Smith, 1987) and described as thalweg fill units by McLaurin and Steel (2007). This element is known as the "coarse members" (Smith, 1987), "in channel deposits" (Bluck, 1980) and basal section of "lower bars" (Bridge, 1995).

Architectural Element 2: Unit Bars

Characteristics: (Figure 4-1) Small-to-medium scale planar cross-bedded, planer-laminated, rare rippled and rare trough cross-bedded fine-to-course moderately-to-well sorted well winnowed sandstone with rare pebble intraclasts. Fining up is common in the individual beds and bed-sets. Local mud drapes. Deposited as sets of distinct units reflecting upward loss of flow regime (Figure 4-2). Basal scour may or may not be

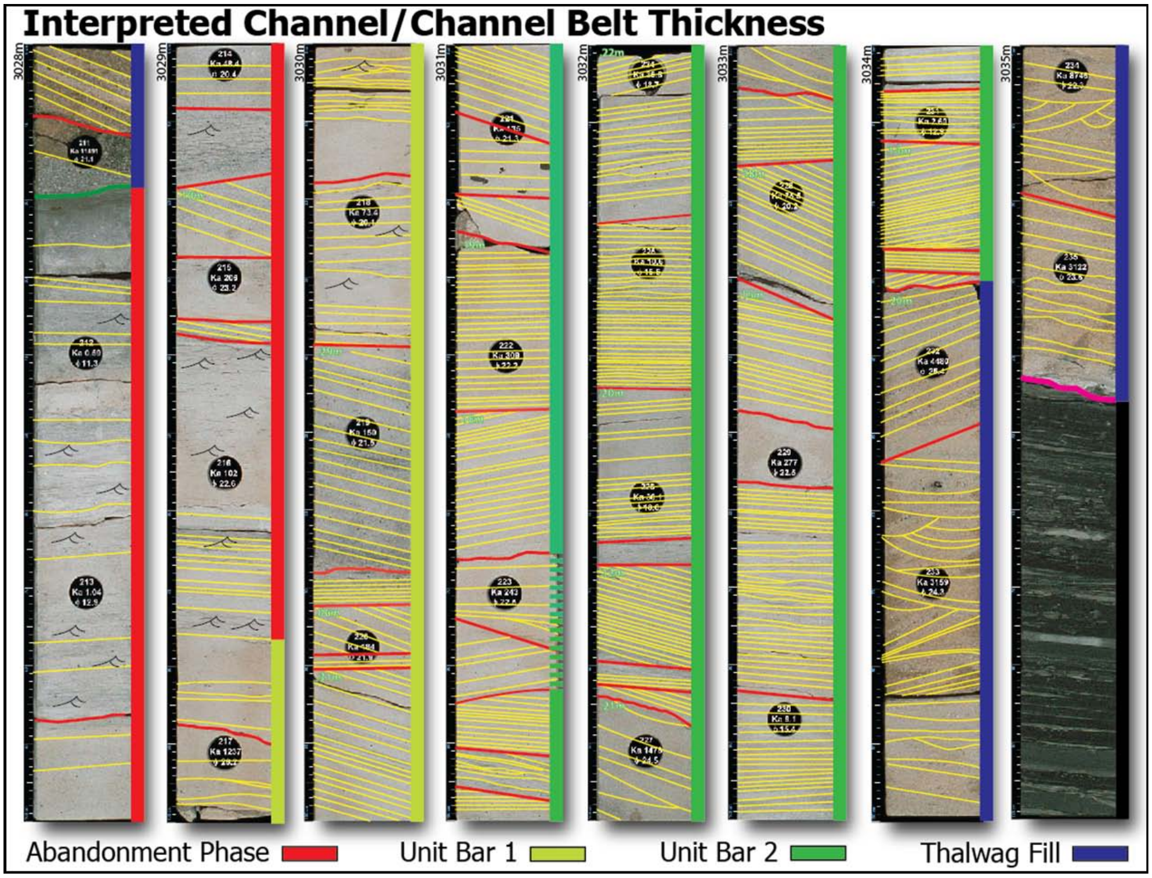


Figure 4-1: Channel fill representing its three compositional elements. Thalweg Fill Element (in blue) note sharp scour base, rip-ups and truncation of bed sets in the upper portion. This strata represents the basal high energy section of a channel which scours into underlying sediment during high flow events and fills with bedforms as flow wanes. Repeated high flow events scour into the basal bedforms truncating them and leaving fragments. Unit Bar Elements (in green). Two unit bars composed of planar cross-bedding and planar lamination. These strata were formed during waxing and waning high flow events. Abandonment Phase Element (in red). This represents beginning of an abandonment phase with unwashed sand, ripples, and rooting. Abandonment phase may grade upward into an oxbow type Open Lake Element, but they are often truncated by overlying channel fill. Basel thalweg fill truncates this abandonment phase at the top of the core. Example is from Yodel 2 core.

present. Unit Bar Elements average 9.9m thick and account for 70% of the total thickness of channel/channel-belt deposits. A typical unit begins at the base with relatively complete medium scale planar cross-beds and/or trough cross-beds which tend to decrease in bed thickness upwards. These grade into planar laminations and/or ripple beds with local mud drapes. The top of the unit often contains rooting emanating from a distinct horizon which was the bar top. These sections are commonly bounded at the base by Thalweg Fill Elements, although they may overlie floodplain deposits, other unit bar, or Abandonment Phase Elements. They commonly grade upwards into an Abandonment Phase Element or they may be truncated by a Thalweg Fill Element. *Interpretation:* Unit bars represent the components of compound point, alternate and midstream bars, which migrate in and alongside the channel over the channel thalweg. The bars are formed as dunes, bedload sheets and ripples migrate downstream during waxing and waning high energy flow events or seasons "smearing" the unit bar onto its associated compound bar (Collinson,1970; Nanson, 1980; Bridge et al., 1986, 1995, 1998, 2000; Bridge, 2003; Best et al., 2003) (Figure 4-2). Unit bars generally grow in height by the accretion

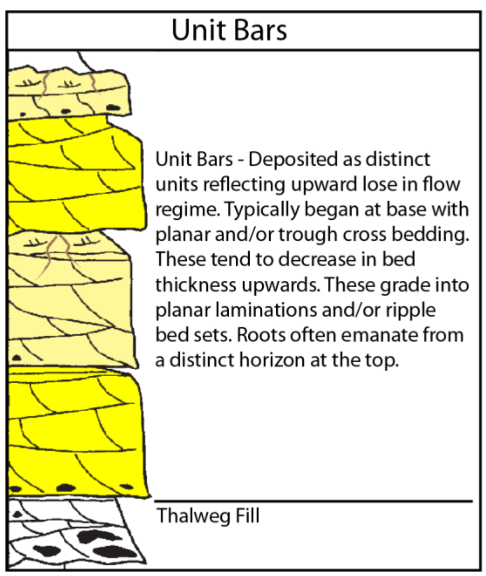


Figure 4-2: Four distinct unit bars reflecting construction of a compound bar by successive flood events or flood seasons. (After Bridge, 2003).

of the smaller scale bedforms over them and these bedforms reflect the loss of flow regime upwards (Bridge, 2003). When the flood event or flood season is over the bar tops may become colonized by plants. The unit bars stack reflecting multiple high flow events as the bar migrated and grew by accretion..

Architectural Element 3: Abandonment Phase

Characteristics: (Figure 4-1) A complete section of this element begins with small scale planar laminated, planar cross-bedded, massive and rippled fine-to- medium well-to-moderately sorted sandstone. This grades to similar, but heterolithic, strata containing common mud drapes. Abandonment Phase Elements average 6.4m thick and account for 20% of the total thickness of low accommodation channel/channel-belt deposits. These deposits are commonly not well washed with mud apparent in the sandstone. Root bioturbation is common at several levels in these sections, emanating from discrete horizons near the top. The uppermost strata give way to oxbow type lake deposits which then grade to composite soil. Often this element is truncated by a thalweg fill scour surface or unit bar deposits, so complete sections are rare. They typically overlie Unit Bar Elements or, less commonly, Thalweg Fill Elements.

Interpretation: These strata record gradual abandonment of the channel through upstream avulsion of the river or loop cutoff, and the deposition of primarily low flow regime bedforms. They form the uppermost progression of a ideal complete channel fill overlying a succession of thalweg fill and unit bars. During flooding events slugs of sand are washed through the channel as small scale sand waves, dunes, and ripple bedforms, especially in the lower sections while the channel is still relatively deep (Bridge, 2003).

As the flow wanes sluggish flow leads to suspended load muds being deposited with the sand and/or as drapes (Miall, 2006). Planar laminations are likely from the lower plain flow regime. Continued shallowing of the channel allows plants to colonize the river leading to frequent rooting in the upper levels from discrete horizons that are commonly bar tops or shallow lake bottoms (Bridge, 2003). Oxbow type lakes may form when a more rapid avulsion event occurs (Fisk, 1944). The preservation potential of these lake deposits is low in low accommodation deposits due to the fact that channel reoccupation and scour truncation is common. In this study lakes are associated with channels only in the high accommodation sections.

Architectural Element 4: Floodplain Mudflat

Characteristics: (Figure 4-3a) Dominantly mudstone to claystone with silty intervals. Thoroughly bioturbated to the extent that primary sedimentary structures are destroyed. Abundant root traces and local burrows that lack marine characteristics. Local adhesive meniscate burrows indicative of non-marine floodplain composite soils or paleosols (Hasiotis and Dubiel, 1994). Rooting is dispersed throughout and cannot be traced to distinct horizons. Local well developed peds with slickensides, but no significant mature soil development. Common local FeO and some possible siderite nodules but otherwise lack of discrete soil horizons. These sections average 3.2m thick and compose 26.4% of the high accommodation floodplain deposits. Floodplain mudflats most commonly associated with crevasse splay, splay delta, open lake and swamp elements. They may be bound by any of these. Less commonly they may be truncated by thalweg fill, or unit bars.

Interpretation: These strata record deposition onto a floodplain emergent enough to sustain significant plant growth. Deposits are generally assumed to be subaerial, although some plants can flourish in water up to a few decimeters (Hasiotis, 2004) . True subaerial deposition can only be confirmed when the facies are associated with pedogenic features (Hasiotis, 2004) . These sections lack sandy material and record deposition of suspended clay and silt during flooding events. As these emergent overbank floodplain deposits aggraded, plants destroyed the primary fabric through constant root bioturbation. Aggradation was sufficient to prevent the formation of mature soil horizons most commonly allowing development of weakly developed orders such as Entisols and Inceptisols (Aslan and Autin, 1998). Locally sufficient stability and shrink-swell conditions allowed the formation of Vertisols. These aggrading deposits of immature floodplain soils with weak indications of prolonged stability are the "Composite" soils of Aslan and Autin, (1998).

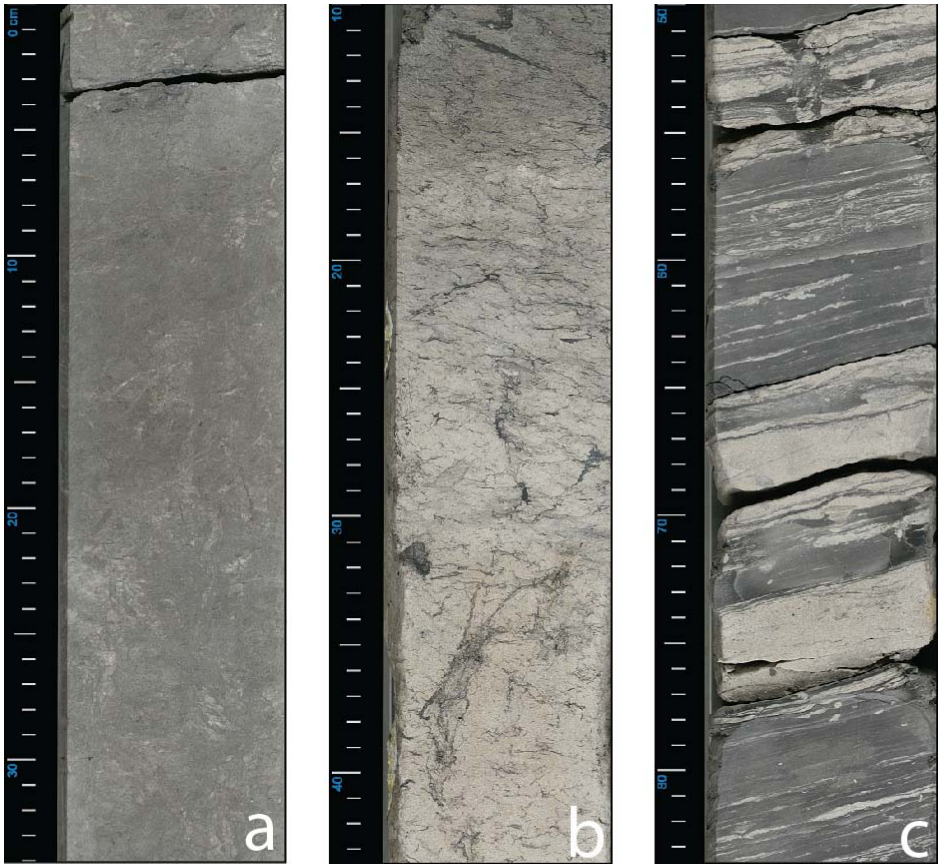


Figure 4-3: a) Floodplain mudflat element; note abundant bioturbation which churns the sediment, destroying primary sedimentary structure. b) Crevasse splay element; similar to floodplain mudflat lithofacies, but with coarser sediment. c) Splay delta element - this example is from the proximal portion of the splay delta; note lack of rooting, planar laminations and current rippled small scale bedding. Examples from Pluto 2 CH1.

Architectural Element 5: Crevasse Splay

Characteristics: (Figure 4-3b) Heterolithic mix of profusely bioturbated mudstone, siltstone and sandstone with primary structure rarely preserved. Fining upward, coarsening upward and sections with no evident organization are all present. Local channel fill elements. Abundant rooting some of which extends from discrete horizons. Local FeO concretions and rooting horizons are the only hint of soil development. This section is very similar to the “Floodplain Mudflat” facies except for the inclusion of abundant siltstone and sandstone intervals and almost complete lack of soil development. These sections average 1.6m thick and compose 4.6% of the high accommodation floodplain deposits. Crevasse splays are typically based by floodplain mudflat deposits and are identified by an increase in siltstone and sandstone. They may include small channel fill sections (Figure 4-4).

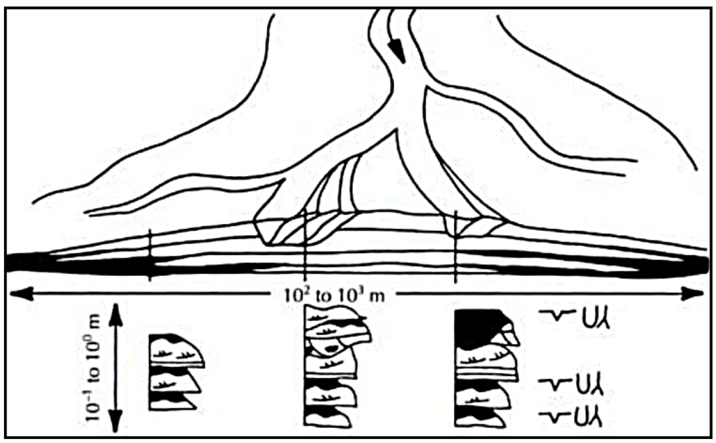


Figure 4-4: Cross section of typical lobate crevasse splay with feeder channels. Note the heterolithic nature of the deposits. These primary bedding features are normally destroyed by rooting shortly after deposition (Bridge, 2003).

Interpretation: These deposits were formed by deposition of overbank sediments onto emergent floodplains by feeder channels breaching the levee during flood stage. The channels on crevasse splays would be expected to be smaller on average than those in trunk channels and show signs of periodic abandonment (cracked mud layers, rooting, and burrows) (Bridge, 2003). Because they are deposited similarly to deltas, crevasse splays are typically very heterogeneous in nature. The channels and terminal mouth bars of splays are usually sandy, but interdistributary areas may be silty or sandy. Flood generated deposits in the unchannelized portions of crevasse splays are inclined at a low angle in the direction of splay progradation (Bridge, 2003). Progradation of the edge of a crevasse splay that is at the angle of repose results in a set of cross strata analogous to Gilbert-type deltas (O'Brien and Wells, 1986; Bristow et al., 1999). Crevasse splays are lobate in shape and appear lenticular in sections normal and oblique to flow direction, but triangular in sections parallel to flow direction (Bridge, 2003). Splays are usually rapidly deposited onto the floodplain and thus experience little bioturbation during deposition, but are rapidly colonized by plants soon thereafter and the churning of root bioturbation incorporates them into the overall aggrading composite floodplain soil. They are typically thin enough for rooting to penetrate the entire section amalgamating them with underlying deposits. They document a rapid introduction of coarse material onto the emergent floodplain setting, but otherwise represent no change in depositional environment compared to the floodplain mudflat environment.

Architectural Element 6: Splay Deltas

Characteristics: (Figure 4-3c) Heterolithic to sandy sections with no evidence of considerable root bioturbation and lack of trace fossils with marine characteristics. These deposits contain lithofacies assemblages with coarser grained and finer grained end members. The finer grained range contains parallel-laminated mudstone inter-laminated with thick siltstone and/or fine sandstone lamina that make up 20% or more of the section. The coarser grained range of this lithofacies contains parallel-laminated, current-rippled and small-scale cross-laminated thin-to-medium bedded sandstone. May contain cross-bedded sands of feeder channels. These sections average 2.6m thick and compose 29% of the high accommodation floodplain deposits. These strata range between these coarse and fine end members, and are usually arranged into moderately to well-developed coarsening-upward sections. Lamina are well preserved throughout the splay delta sections with the exception of common rooting within and extending down from the uppermost part of discrete coarsening up intervals. Coarsening up sections are commonly stacked into repetitive successions forming multiple stacked elements.

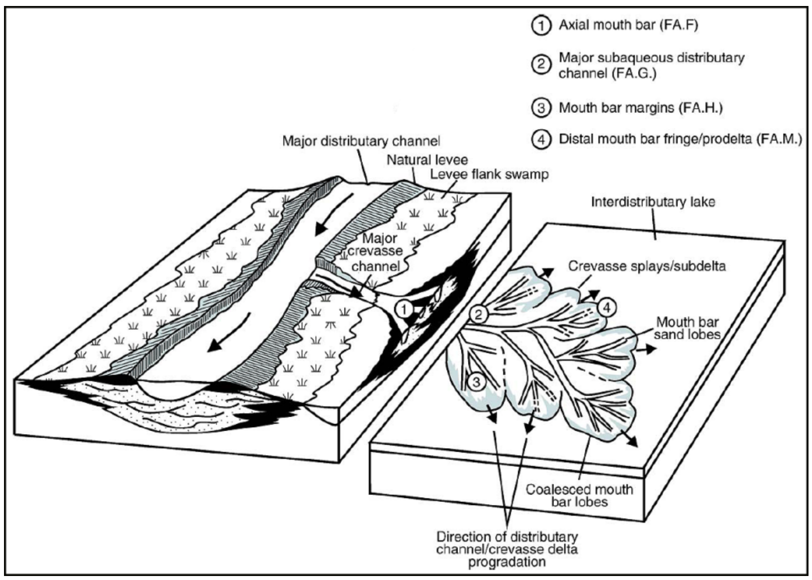


Figure 4-5: Classic spay delta prograding into a floodplain open lake. These elements are interpreted to be primarily lobate in form. Proximal splay delta deposits display thicker lamina of coarser silt and sand inter-laminated with mud, while distal deltas have thinner lamina of silt interlaminated with mud. Feeder channels decrease in size and sediment caliber as they become distal (Tester and Turner, 2006).

Interpretation: The finer-grained end member of this lithofacies is formed with the introduction of the distal splay delta toe as it first begins to introduce coarser grained material into a suspension dominated lake setting (Figure 4-5). As progradation continues progressively coarser deposits are introduced as the higher energy component of the proximal splay delta build out over the distal splay delta. As progradation reaches completion the coarser end member of these lithofacies is deposited. Rooting does not occur in the finer end member of these deposits because water depth was such that plant growth was rare. Continued progradation often leads to emergence which often leads to the rooting of the upper coarse sections. Progradation is responsible for the coarsening-up nature of the profile. Individual coarsening-up intervals commonly terminate abruptly which records delta abandonment and flooding. These deposits were formed by deposition of deltas prograding into floodplain lakes. They were fed by channels splayed off main trunk channels just like crevasse splays with the difference being they were splayed into lakes instead of emergent floodplains. These elements are interpreted to be primarily lobate in form, but a modern geomorphic analysis done for this study found they often form elongate channels that partition the floodplain lakes and connect trunk channel belts (Stoner and Holbrook, 2008). This will be discussed in more detail below.

Architectural Element 7: Open Lake

Characteristics: (Figure 4-6a) Sections of consistent shale with rare rooting and lack of marine or terrestrial burrows. Deposits are thick-to-medium-laminated thin-to-thick dark grey mudshale beds with little or no interbedding of silty material. These strata contain local siderite and rare pyrite nodules. These sections average 2.8m thick and compose 33.6% of the high accommodation floodplain deposits. Open lakes are commonly associated with, and bound by floodplain mudflat and swamp deposits.

Interpretation: These lakes formed adjacent to and between rapidly aggrading channel belts when the rate of channel belt aggradation exceeded the rate of floodplain aggradation in amounts sufficient to result in significant drowning of the floodplain as water tables attached to the aggrading river level were raised well above the floodplain

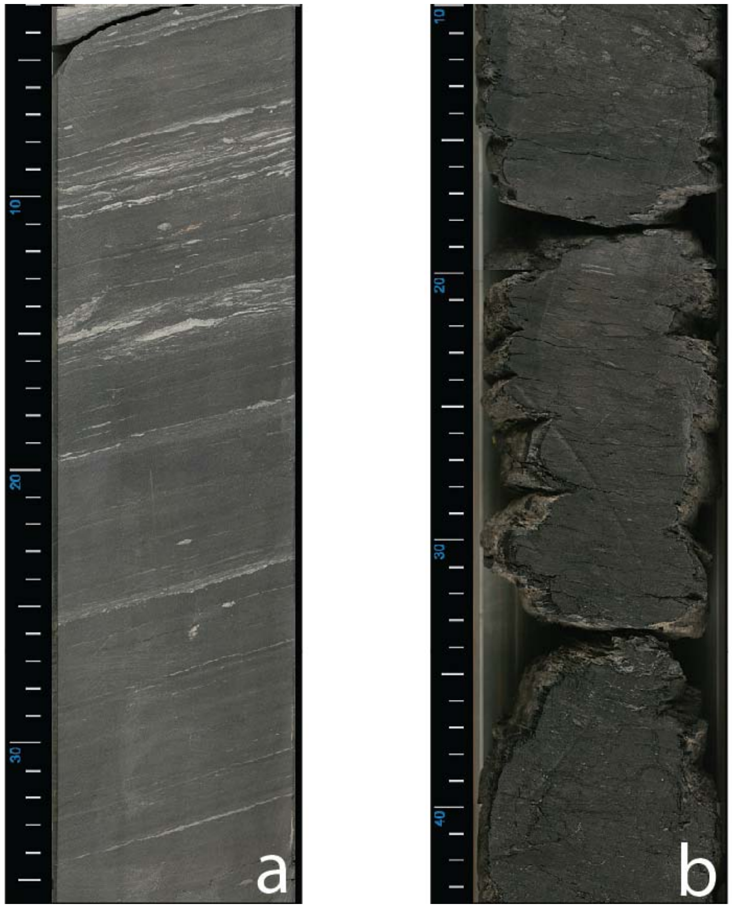


Figure 4-6: a) Open lake element - consistent mudstone with minor silty laminations. b) Swamp element - composed of coaly organic material. Examples from Pluto 2 CH1.

surface (Bridge and Leeder, 1979; Wright and Marriott, 1993; Shanley and McCabe, 1994) (Figure 4-7). They differ from oxbow lakes in that they form on the floodplain and not in abandoned river channels. The water depth was raised enough above the floodplain surface to render the bottom of the lakes inhospitable to all but lake marginal, sparse plant growth due to the decrease of oxygen, high levels of carbon dioxide and possible high sedimentation rates (Hasiotis, 2004). The same factors apply to burrowing organisms. Deposition is primarily from suspended mud during flooding events and by mud plumbs forming at the most distal portion of splay deltas. Where these deposits

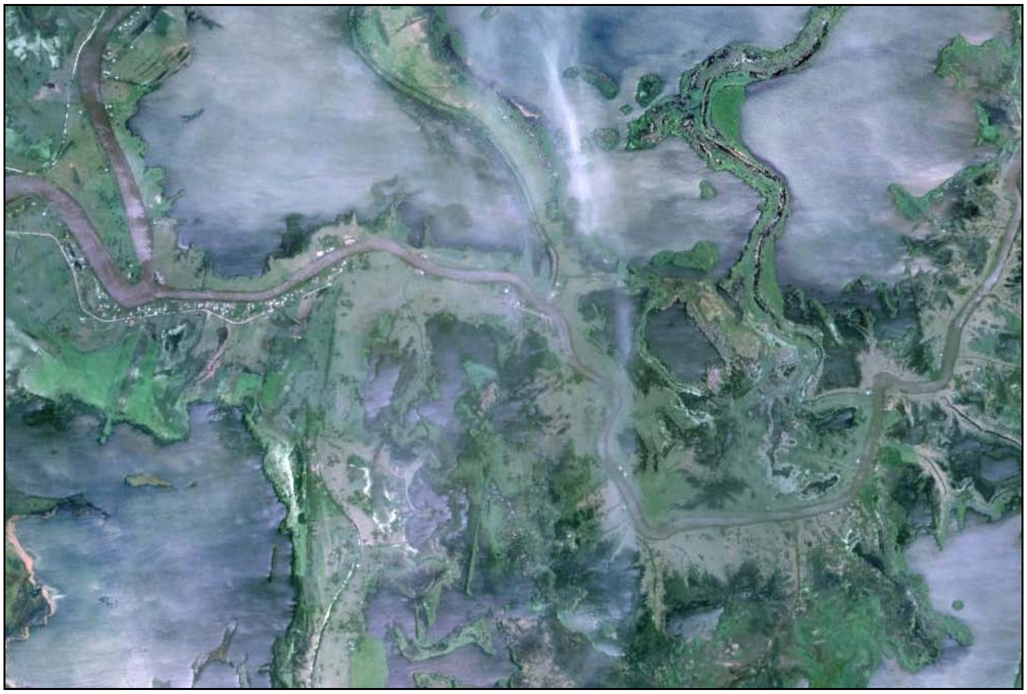


Figure 4-7: Abundant floodplain lakes in a high accommodation floodplain setting. This example is from the Grijalva River coastal plain in Tabasco, Mexico (Google Earth, 2010).

exist directly above active channel deposits (e.g., Pluto 2 3185.2-3183.25m), they could be interpreted as the abandonment phase of channel filling following the active channel filling phase below, i.e. oxbow lakes.

Architectural Element 8: Swamp

Characteristics: (Figure 4-6b) These deposits are primarily dark grey to black coaly organic-rich material with common rooting. They may range from highly carbonaceous shale to true coal. Sections locally include small to large (rarely up to 3cm) siderite and/or pyrite concretions. They are commonly associated vertically with open lake deposits. These sections average 1.4m thick and compose 6.4% of the high accommodation floodplain deposits. Swamp deposits typically are basal to and/or top lake deposits. They may also have no lake association in core. They are identified by the transition to coaly organic rich material.

Interpretation: As with the open lake lithofacies rates of channel belt aggradation exceeded the rate of adjacent floodplain aggradation in amounts sufficient to result in significant drowning of the adjacent floodplain as the water table was drawn up. In areas where this draw up was not too rapid or deep, and which were protected from significant siliciclastic input, plants were able to generate enough organic accumulation to keep up with the rise of water leading to peat accumulation (Berendsen and Stouthamer, 2001). Peat is highly compactable (peat:coal = 10:1, Ward, 1984), therefore coaly sections could represent considerable floodplain aggradation. Floating peat bogs are common and the possibility of deposition in deeper water cannot be ruled out without knowledge of biota type in the coals.

CHAPTER 5

ARCHITECTURAL GEOMETRY

Geometries of Low Accommodation Amalgamated Sands

Yodel 2

A low accommodation section of the Yodel 2 core composed primarily of thalweg fill, unit bar and channel abandonment phase elements was used in this study. This section ranges from the MU at 2937.50m to the E unit - F unit transition at 3035.45m.

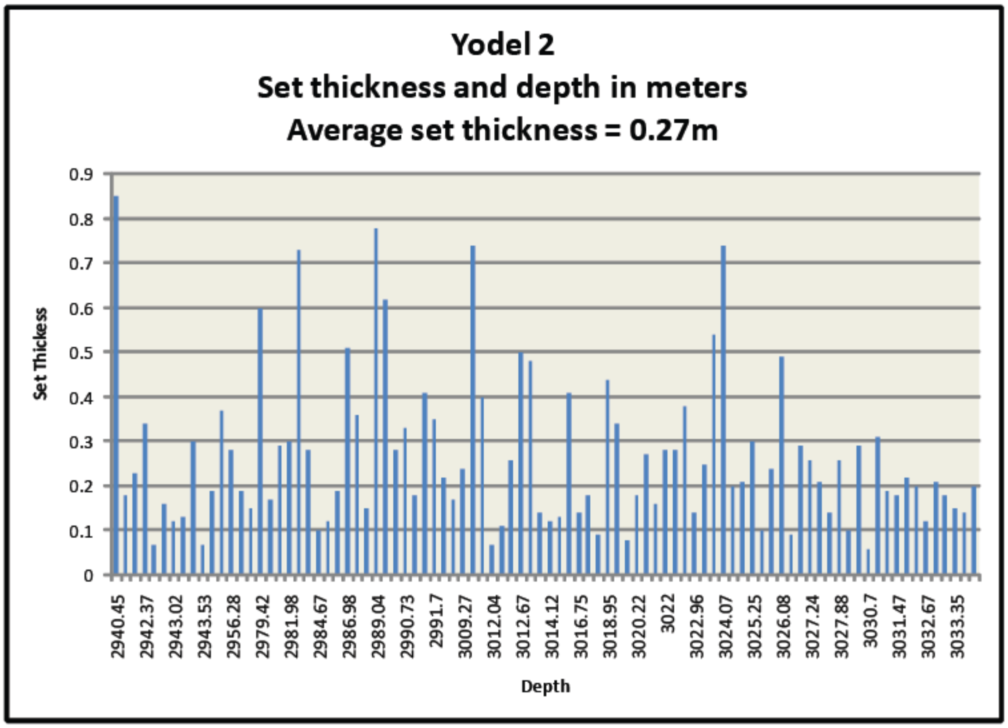
I constructed a detailed bedding diagram (Supplement 1) and identified five to seven channel/channel belt successions using the architectural approach of Bridge and Tye, 2000 (Table 5-1). A potential 6th order valley bounding surface is identified at 3028.20m where there is a fundamental change in depositional style and a significant increase in porosity. This surface coincides with the base of interpreted Channel 4. The interpreted channel depths range from 7.4m - 15.6m or 5.5m - 15.6m if Channel 2 is considered two separate channels.

I also employed Published numerical and graphical-empirical methods to estimate channel depth, channel width and channel belt width as described in the methods section (Figure 5-2). Channel depths, and thus channel belt thickness, calculated from average cross-set thickness range from 9.4m - 15.7m which correlates well with the depths

Table 5-1: Channels/channel belts identified by architectural analysis in Yodel 2 as discussed in the methods section. All estimates record the preserved thickness and should be considered minimum estimates of the original channel thickness due to potential truncation and compaction. Core is not available adjacent to two sections as noted, thus, these are definitely minimums.

Yodel 2 Channels/Channel Belts Identified by Bridge and Tye's (2000) Architectural Approach	
Identified Channels/Channel Belts	**Thickness of Identified Channels/Channel Belts**
Channel 1	**12.6m**: 2944.4m - 2957.0m. This is a minimum due a missing section of core below 2957.0m.
Channel 2	**13.9m**: 2979.0m - 2992.9m. This is a minimum due to missing section of core above 2979.0m.
Or alternatively this may be two separate channels: 2a and 2b.	
Channel 2a	**5.5m**: 2979.0m - 2984.5m. This is a minimum due to missing section of core above 2979.0m.
Channel 2b	**8.4m**: 2984.5m - 2992.9m.
Channel 3	**15.6m**: 2992.9m - 3008.5m.
Or alternatively this may be two separate channels: 3a and 3b. If unit bars below unit are included it may potentially be up to 26m thick.	
Channel 3a	**9.7m**: 2992.9m - 3002.6m.
Channel 3b	**5.9m**: 3002.6m - 3008.5m.
Channel 4	**8.2m**: 3020.0m - 3028.2m.
Channel 5	**7.4m**: 3028.2m - 3035.6m

estimated by architectural analysis and suggests that Channels 2 and 3 are each best interpreted as one channel/channel belt. Alternatively this may suggest this method overestimates the lower end of the range. Channel width is estimated to range from 147m - 373m using Bridge and Mackey's (1993) method. Channel belt width estimates range widely between the four methods used ranging from 14m to 250km. It was decided that the Strong et al., 2002 graph produces the most reasonable results and it is the one used in this study. This estimate results in a channel belt range of 1.4k to a maximum of 6.0k. The Gibling, 2006 graph has too many outliers and the range is so wide as to render it not useful.



Empirical attributes (Bridge and Mackey, 1993, LeClair and Bridge, 2001)		
Average set thickness	0.27	
Mean dune height	0.78	
Channel bank full depth range	9.40	meters to
	15.66	meters
Mean bank full depth range	4.70	meters to
	7.83	meters
Channel width range	147.02	meters to
	372.50	meters
Channel belt width range	970.22	meters to
	3219.25	meters
Channel belt width/Thickness	20.73	

Figure 5-1: Yodel 2 cross-set measurements, channel depth, channel width and channel-belt width estimates from numerical methods (Bridge and Mackey, 1993, Leclair and Bridge, 2001). These methods relates average cross set thickness to average dune height and average dune height to channel depth. Channel and channel-belt width are numerically related to channel depth. Results are an average for the sandy interval as a whole.

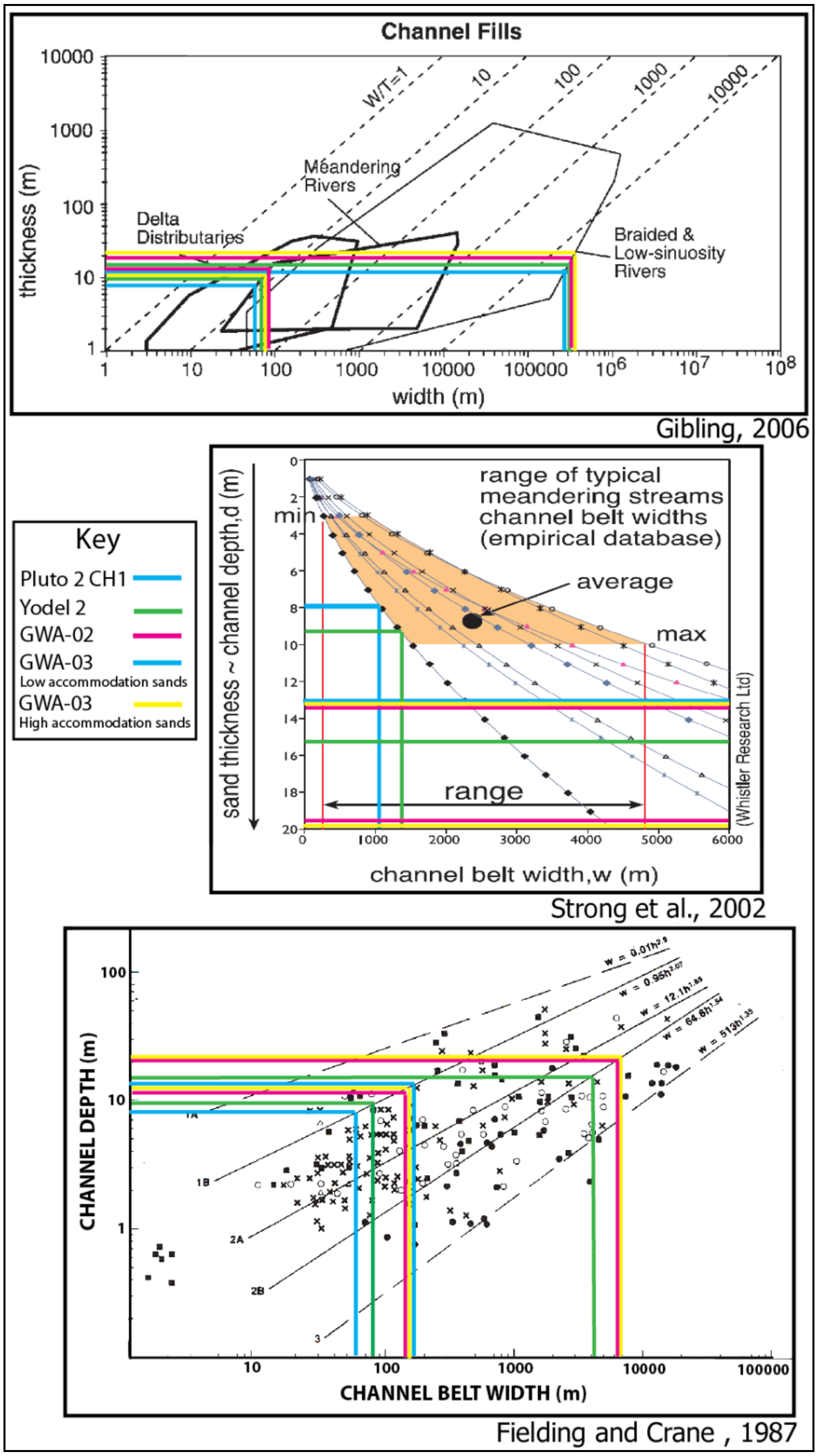


Figure 5-2: Estimated channel-belt widths from channel depths using graphical empirical charts (Fielding and Crane, 1987; Strong et al., 2002; Gibling, 2006). The chart by Strong, et al., 2002 is considered to be a good average between the viable methods and it is used here. The Gibling (2006) chart has too many outliers and included multi-valleys with the channel belts, thus, it is considered inaccurate and greatly overestimates channel belt width.

This portion of core from Yodel 2 represents a thick section of amalgamated sands. Channels 1 through 5 represent 84.6m of uninterrupted sand from the base of the sharp, scoured F unit to E unit transition at 3035.6m (the base of Channel 5) until the upper portion of the Channel 1 abandonment phase element begins to display occasional mud drapes at 2953.0m. This abandonment phase gives way to oxbow type lake deposits at 2949.1m and culminates with 0.8m of composite soil ending at 2944.3m. The remaining 6.5m of interpreted core is a thalweg fill element which is truncated by the MU at 2937.8m.

Channel 5 is predominantly fine-to-medium sand while Channels 1 - 4 are predominantly medium to coarse sand. Channel 4 scours into Channel 5 at 3028.2m were there is also significant change in porosity. The bedding style changes from mainly small scale planar laminated sets in Channel 5 to mostly medium scale planar cross-bedded sets in Channel 4. This boundary is interpreted to represent a 7th or higher order valley or sequence bounding surface due to the significant and enduring change and its association with an interpreted channel base. The interpreted high order valley or sequence bounding surface raises the architectural complexity of this section of amalgamated channel belts to the multi-valley scale. This is important because it raises the potential lateral scale of this sand section significantly. These surfaces are often indistinguishable even at outcrops due to tendency of channel belt in stacked successions to have similar characteristics (Miall and Arush, 2001). Estimates of multi-valley widths are given below. The muddy section at the top of Channel 1 is interpreted to represent the transition from the low accommodation Lower E to the higher accommodation Middle E.

Goodwyn GWA-03

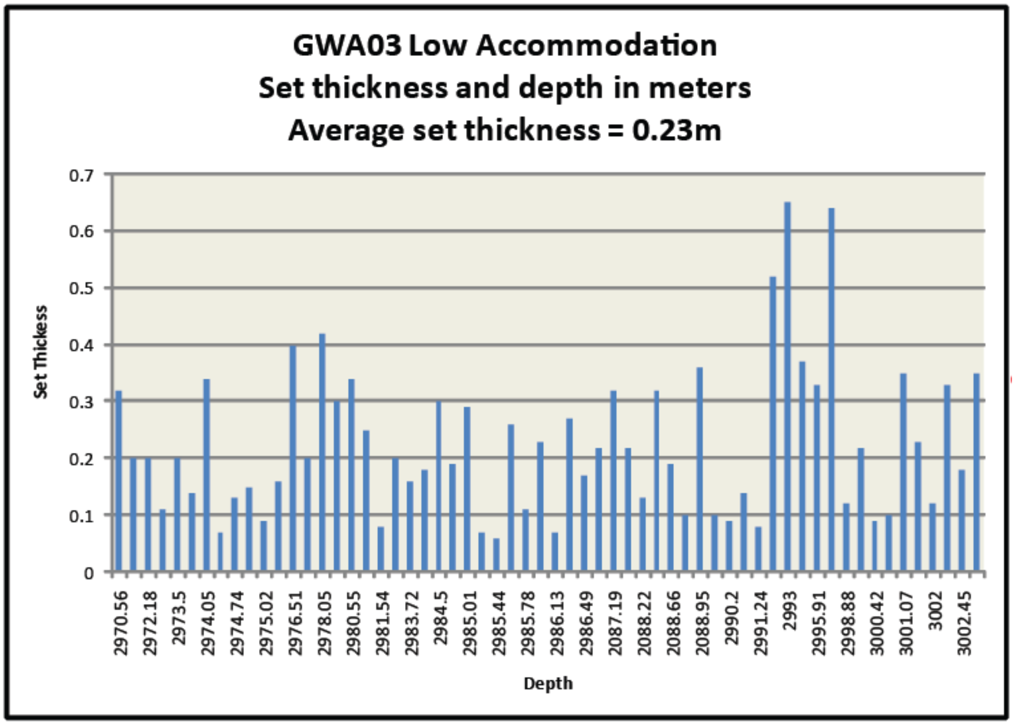
The core from Goodwyn GWA-03 is from the Lower E Unit and probably penetrates the Upper F at the base. It represents a sandy low accommodation Lower E section from 2967.0m - 3005.0m and a muddy high accommodation section which is probably Upper F from 3005.0m - 3041.0m which are addressed separately.

Goodwyn GWA-03 Low Accommodation Section

A detailed bedding diagram was made for the low accommodation section (Supplement 2). It was not possible to identify any complete channel/channel belt successions using the architectural approach of Bridge and Tye, 2000 (Figure 5-3). Numerical (Figure 5-4) and graphical-empirical (Figure 5-2) methods were employed to estimate channel depth, channel width and channel belt width. Channel depth is estimated to range from 8.0m - 13.3m and Channel width is estimated to range from 110m to 278m. The quantitative method of Strong et al., 2002 was used again to estimate channel belt width at 1.1km to a maximum of 6km.

The base of this section begins with .6m of composite soil grading to coal which is truncated at 3005.4m by a 1.4m scour based thalweg fill element composed of pebble conglomerate grading to a granular conglomerate. This is followed by 33.5m of up to nine unit bar elements. This sections records 38.6m of continuous sand which is enough to contain almost five channels, and thus channel belts, the size of the minimum interpreted channel depth. This suggests 6th order valley bounding surfaces are present, but cannot be identified in the core (Miall and Arush, 2001), thus, this section is interpreted as a multi-valley.

Figure 5-3: GWA-03 identification of channel/channel belt successions using the architectural approach of Bridge and Tye, 2000. No discrete channel/channel belts were distinguished using this method.



Empirical attributes (Bridge and Mackey, 1993, LeClair and Bridge, 2001)		
Average set thickness	0.23	
Mean dune height	0.67	
Channel bank full depth range	8.00	meters to
	13.34	meters
Mean bank full depth range	4.00	meters to
	6.67	meters
Channel width range	109.81	meters to
	278.22	meters
Channel belt width range	726.99	meters to
	2584.36	meters
Channel belt width/Thickness	18.18	

Figure 5-4: Goodwyn GWA-03 cross-set measurements, channel depth, channel width and channel-belt width estimates from numerical methods (Bridge and Mackey, 1993, Leclair and Bridge, 2001). Results are an average for the sandy interval as a whole.

Goodwyn GWA-03 High Accommodation Section

The Goodwyn GWA-03 high accommodation section records a complex set of architectural elements typical of emergent and submergent floodplain environments

(Appendix 1). The lower portion of the strata begins with a channel abandonment element which is followed by a succession of open lake, splay delta, floodplain mudflat and crevasse splay elements. A 14.4m fluvial section composed of thalweg fill, unit bar and abandonment phase elements and topped by an oxbow lake begins at 3028.0m. The succession of thalweg fill, unit bar, abandonment phase and oxbow lake suggest one complete channel fill. Numerical (Figure 5-2) and graphical-empirical methods estimate a channel depth range of 13m to 21m and a channel belt width range of 2.2k to 6.0k reinforcing the conclusion above. This channel is interpreted to be a 14.4m trunk channel traversing the high accommodation floodplain.

The top portion of the core is composed primarily of the floodplain mudflat element with two small open lake elements. It grades at the top to a swamp element which is primarily coal. This is truncated by the low accommodation section described above at 3005.0m. Bioturbation in the form of adhesive meniscate borrows is common in the floodplain mudflat element section which has been interpreted here as indicating subaqueous conditions and perhaps a marine influence (Figure 5-5). However, Hasiotis, (2002), Hasiotis et al., (1994) and Smith et al., (2008) have shown that adhesive meniscate burrows are common during periods of better drainage in imperfectly drained floodplain mudflat elements and their presence is not a sure indication of a marine influence. As a result this floodplain mudflat element is interpreted as subaerial with no marine influence.

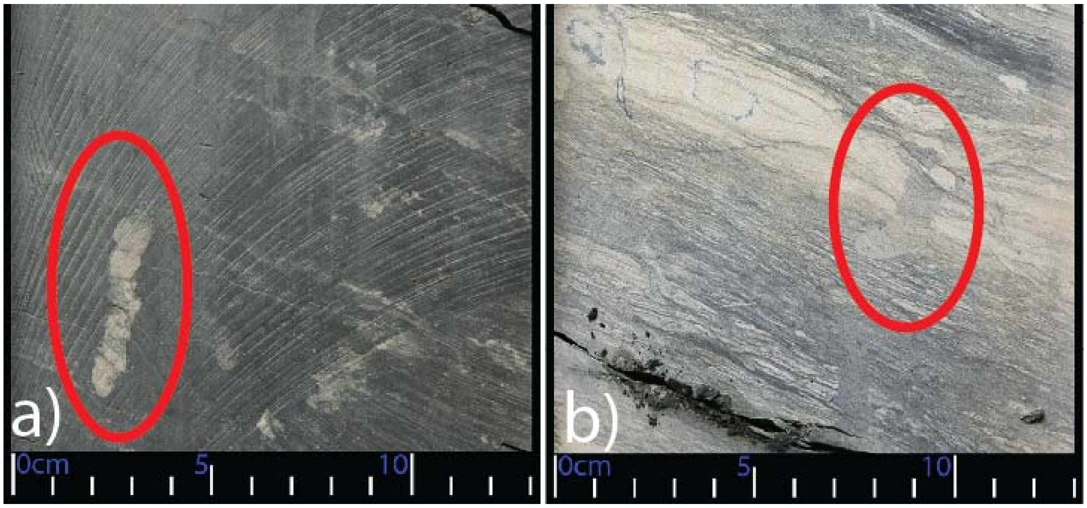


Figure 5-5: a) Adhesive meniscate burrow at 3008.9m. b) Adhesive meniscate burrow at 3015.2m. These types of burrows have been shown to be common in floodplain mudflat elements and are not necessarily an indication a marine influenced environment (Hasiotis, 2002; Hasiotis et al., 1994; Smith et al., 2008) .

Pluto 2 CH1

A thorough core review of the middle E Pluto 2 CH1 core was performed in Perth. It is representative of a complex floodplain environment. A 13.6m sandy section of the core composed of unit bar elements was chosen to perform a more thorough examination of this sand unit using the architectural approach of Bridge and Tye, 2000 (Supplement 3). One 5m complete bar element was identified which is equivalent to approximately one channel depth (Figure 5-6). Another 3m complete channel fill encased in floodplain deposits was identified by the Bridge and Tye, 2000 architectural approach during the core review (Table 5-2).

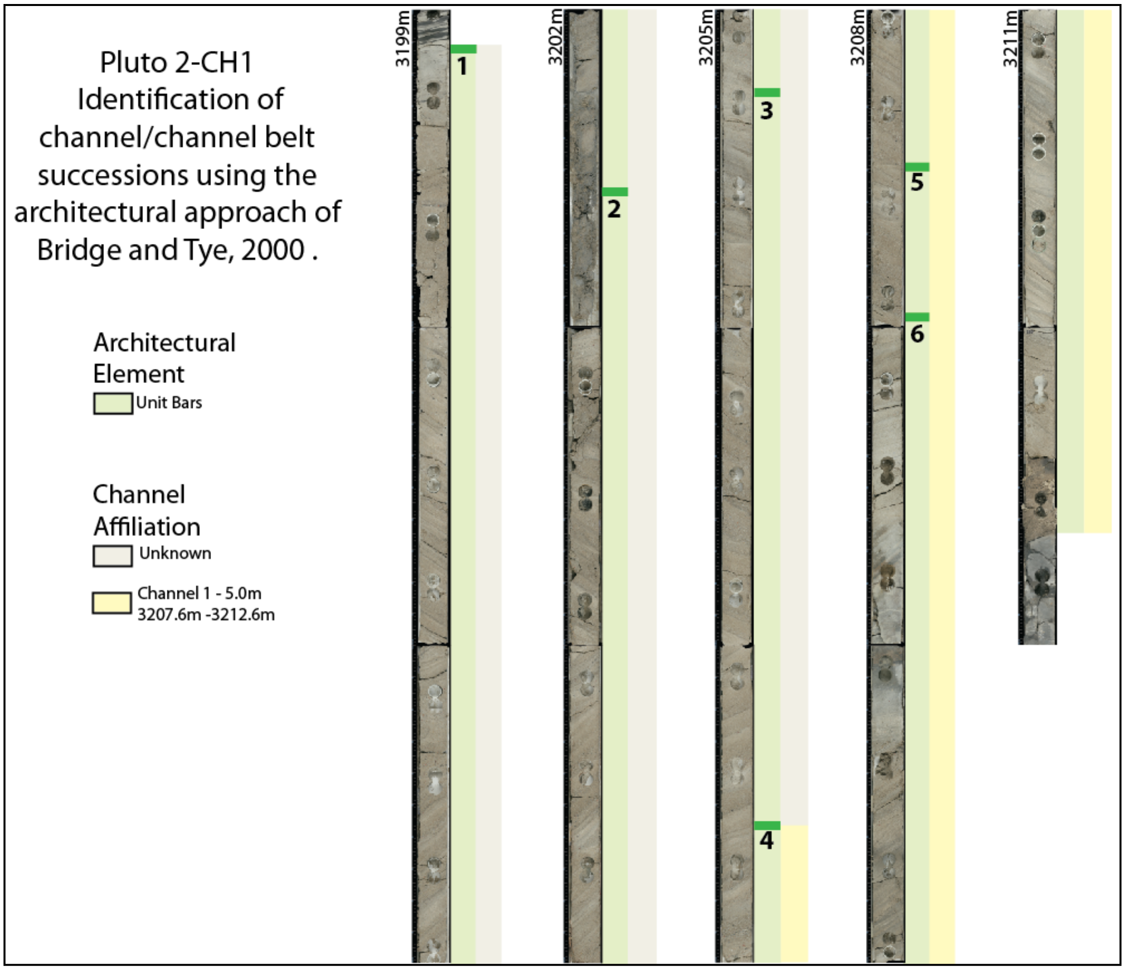
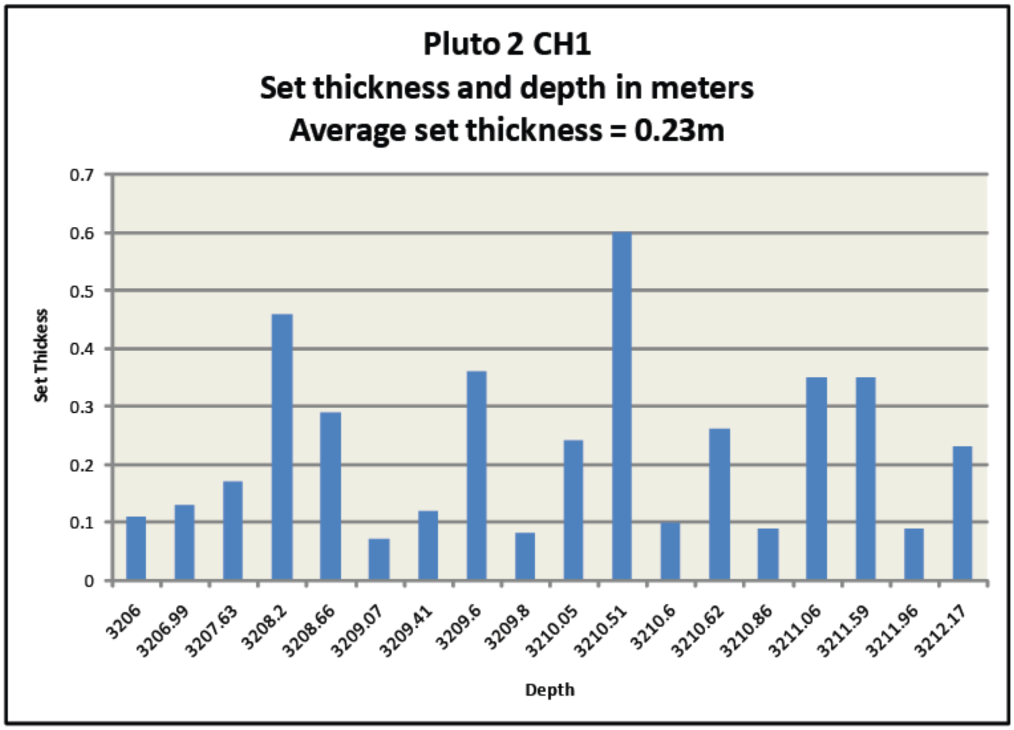


Figure 5-6: Pluto 2 CH1 identification of channel/channel belt successions using the architectural approach of Bridge and Tye, 2000. One 5.0m channel/channel belt was identified using this method.

Table 5-2: Pluto 2 CH1 Channels/Channel Belts

Pluto 2 CH1 Channels/Channel Belts Identified by Bridge and Tye's (2000) Architectural Approach	
Identified Channels/Channel Belts	**Thickness of Identified Channels/Channel Belts**
Channel 1	**3.0m**: 3186.0m - 3189.0m.
Channel 2	**5.0m**: 3207.6m - 3212.6m.

Numerical (Figure 5-2) and graphical-empirical (Figure 5-7) methods were also employed to estimate channel depth, channel width and channel belt width as described in the methods section (Figure 5-7:). Channel depths are estimated to be 8.0m to 13.3m and channel width is estimated to range from 109.8m to 279.22m. Using Strong et al, 2002 channel belt width is estimated at 1.1k to 5.6k. These estimates are higher than the 5.0m estimate above, however, it was a minimum based on a bar element. This channel is interpreted to be one approximately 13.6m trunk channel/channel belt crossing the floodplain or a smaller 8.0m to 9.0m trunk channel which experienced a degree of vertical stacking as accommodation increased. The 3.0m channel encased in floodplain deposits is interpreted to be a secondary bypass channel.



Empirical attributes (Bridge and Mackey, 1993, LeClair and Bridge, 2001)		
Average set thickness	0.23	
Mean dune height	0.67	
Channel bank full depth range	8.00	meters to
	13.34	meters
Mean bank full depth range	4.00	meters to
	6.67	meters
Channel width range	109.81	meters to
	278.22	meters
Channel belt width range	726.99	meters to
	2584.36	meters
Channel belt width/Thickness	18.18	

Figure 5-7: Pluto 2 CH1 cross-set measurements, channel depth, channel width and channel-belt width estimates from numerical methods (Bridge and Mackey, 1993, Leclair and Bridge, 2001). Results are an average for the sandy interval as a whole.

Goodwyn GWA-02

This section is from the relatively high accommodation Middle E Unit and ranges from 3862.0m to 3932.0m. A thorough core review was performed (Appendix 2). The basal 19.2m of the core records a complex mosaic of deposits from submergent floodplain and contains splay delta, swamp, open lake, crevasse splay and floodplain mudflat architectural elements. A well drained section from 3921.2m - 3922.0m displays a good vertisol, which indicates thousands of years of emergence (Seggie et al., 2007). Above this is a 10.6m section of channel deposits. Interpretation based on the architectural approach of Bridge and Tye, 2000 indicates this is either one 10.6m channel or two channels of 4.0m and 6.6m (Table 5-3). Numerical (Figure 5-2) and graphical-empirical methods estimate a channel depth range of 13.0m - 22.0m, however only six cross-set measurements. were obtained and this small data set very likely skews the

Table 5-3: Goodwyn GWA-02 Channels/Channel Belts

Goodwyn GWA-02 Channels/Channel Belts Identified by Bridge and Tye's (2000) Architectural Approach	
Identified Channels/Channel Belts	**Thickness of Identified Channels/Channel Belts**
Channel 1	**10.6**: 3902.6 - 3913.2m.
Or alternatively this may be two separate channels: 1a and 1b.	
Channel 1a	**4.0m**: 3902.6 m - 3906.6m.
Channel 1b	**6.6m**: 3906.6m - 3913.2.0m.

results. This section is interpreted as one 10.6 floodplain trunk channel or, alternatively, a 6.6m trunk channel that stacked vertically during increasing accommodation. Above the channel the core again records a primarily submerged floodplain setting until 3892.5m were a scour records the base of a 6.6m channel sequence. This channel is interpreted as estuary fill due to the presence of couplets and potential flaser bedding. The top 4.0m of the core are channel strata.

Goodwyn 8

These two cores range from 2844m-2848m and 2858m-2890m. They are from the low accommodation Lower E Unit. Due to extensive fragmentation of the core and the poor quality of the core photos it was not possible to construct a detailed bedding diagram, however, thorough core description was made (Appendix 3). The lower portion of the core records primarily unit bar elements composed of planar cross-beds and planar lamination. Scour surfaces are abundant and the cross-beds are small, ranging to 30cm, although 10cm and 20cm cross-sets are the norm. It was possible to identify one complete channel fill of 3.8m from 2884.2m - 2888.0m composed of thalweg fill, unit bars and abandonment phase elements (Table 5-4) using Bridge and Tye's architectural approach. There is a 10cm dark mud drape at the top of the lower core.

Table 5-4: Goodwyn 8 Channels/Channel Belts

Goodwyn 8 Channels/Channel Belts Identified by Bridge and Tye's (2000) Architectural Approach	
Channel 1	**3.8m**: 2884.2m - 2888.0m.

The upper portion of the core is highly fragmented. It is possible to identify one planar cross-set that measures 1.0m. Bed-sets composed of planar cross-bedding up to 1.0m can be identified. The channels that created these cross-sets and bed-sets would be much larger than the 3.8m channel in the lower core. The well log shows about .75m of shale above the bottom core with the rest of the missing section being sand. The upper section represents a major change in depositional style and the boundary between the upper and lower sand section may represent a 6th order valley boundary.

Valley Geometry

The interpreted valley widths can be estimated using a quantitative chart produced by Gibling, 2006 and plugging in the overall thickness of the amalgamated sand, which represents the total valleys thickness (Figure 5-8). Seismic evidence indicates the valleys are probably stacked multi-valleys (Kliem, personal communication) meaning these width estimates are probably high for individual valleys, however, the possibility the valleys are part of a more laterally extensive multi-valley sheet is high, therefore, the estimates are most likely less than the width of the entire sand sheet. This chart produces a wide range of interpreted widths so in this study the outliers are discarded to narrow the range. The amalgamated sands of Goodwyn GWA-03 and Goodwyn 8 are similar, 39m thick and 46m thick respectively. The width range for valleys this thick is between 4.2km and 45km. Yodel 2 sands are 90m thick. The estimated width range for these valleys of this thickness is 9km to 79km.

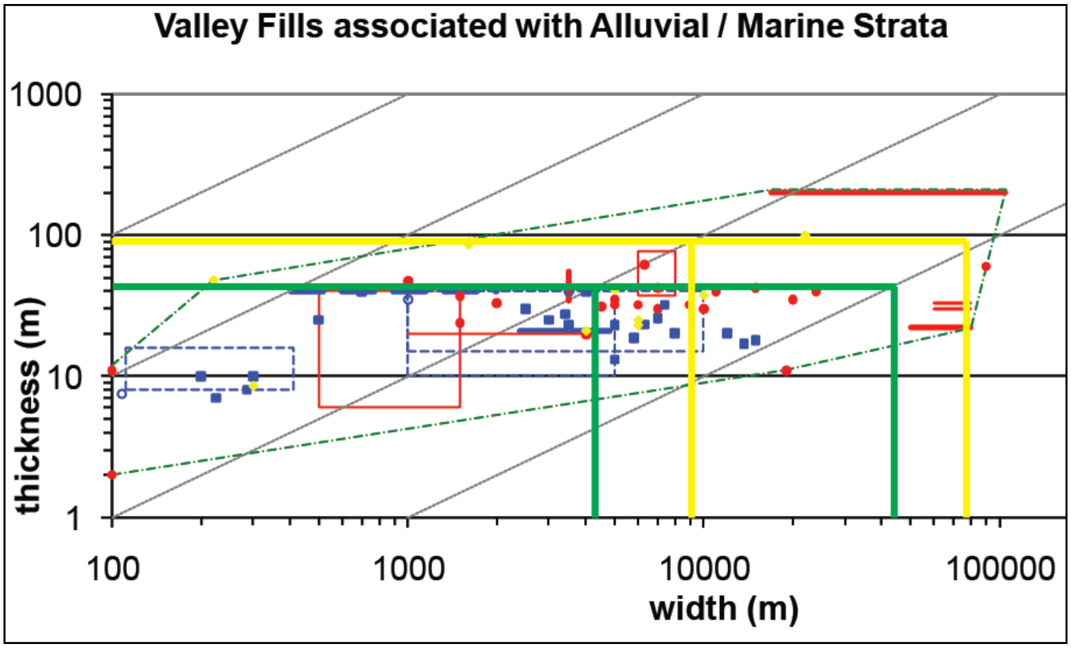


Figure 5-8: Valley width estimates from valley thickness. The Goodwyn GWA-03 and Goodwyn 8 amalgamated sands (in green) are estimated to produce valleys 4.2km to 45km wide. The Yodel 2 sands (in yellow) are estimated to produce valleys 9km to 79km wide (Gibling, 2006). These are probably multi-valleys making the width estimates for individual valleys on the high side, however, they are likely part of a laterally extensive multi-valley sheet, therefore, the estimates are most likely less than the width of the entire sand sheet.

Geometries of High Accommodation Architectural Elements

Floodplain Mudflats

In contrast to abundant research done on channel fill sediments, floodplain deposits have received much less attention (Miall, 1996). As a result less data is available on the dimensions of these strata and the data that is available in much more general in nature. Floodplain width can vary in range from channel belt width to many tens of channel belt widths (Mackey and Bridge, 1995; Bridge, 2003).

Crevasse Splays

Miall (1996) states that crevasse splays are lens-shaped bodies, typically 2-6 m thick, that range up to 10km long (the long portion is oriented parallel with the rivers axis) and 5km wide. This is in agreement with Bridge (2003) assessment that crevasse splays on major rivers are commonly hundreds of meters to kilometers long and wide. Bristow (1999) described a splay deposited on the aggrading Niobrara River floodplain in Nebraska during the winter of 1994/1995 that was 200 m by 1000 m, with sediment up to 2 to5 m thick.

Splay Deltas

Tye and Coleman (1989) describe fluvial dominated lacustrine deltas on the modern Mississippi delta plain as being 3 to 5m thick on average, and covering tens to hundreds of square kilometers. A geomorphic study found that splay deltas are rare in the modern and that splays into lakes more commonly form elongate splay channels which dissect the lakes (Stoner and Holbrook, 2008) (Supplement 4). This will be discussed in more depth below.

Swamps

Estimates of the lateral extent of swamps are rare in the public record. It is reasonable to assume they would be similar to the scale of the floodplain lake deposits (see below), but probably smaller because they are limited to areas free of abundant siliciclastic accumulation.

Swamps

Information of open lakes in the ancient record is lacking, but measurement of modern floodplain lakes on satellite images shows that they tend to be up to several kilometers in diameter and in some instances much larger. They are limited in area by the distance between contemporary channel belts or a channel belt and the edge of the floodplain.

A modern geomorphic study was done to try and relate the size of an floodplain lake to its related fluvial system (Stoner and Holbrook, 2008) (Supplement 4). This was done by choosing three high accommodation fluvial settings with abundant floodplain lakes the Kobuk River Delta in Alaska, the Magdalena River interior river basin in Colombia and the Grijalva River coastal plains in Mexico. Raster data of the rivers, lakes, and interfluves were drawn over satellite images and converted to geo-referenced vector data. ArcGIS was employed to explore relationships (Figure 5-9). The best relationship found was that a larger interfluve relates to more lakes (Figure 5-10). Weaker relationships indicate that a higher channel density relates to smaller lakes and less total lake area. No good relationships could be found between channel or channel-belt size and lake area.

It was observed that the lakes were dissected by the splay channels discussed above. This had the tendency to destroy the relationships between floodplain lakes and their bounding channel belts. The implications of this observation will be discussed in more detail below.

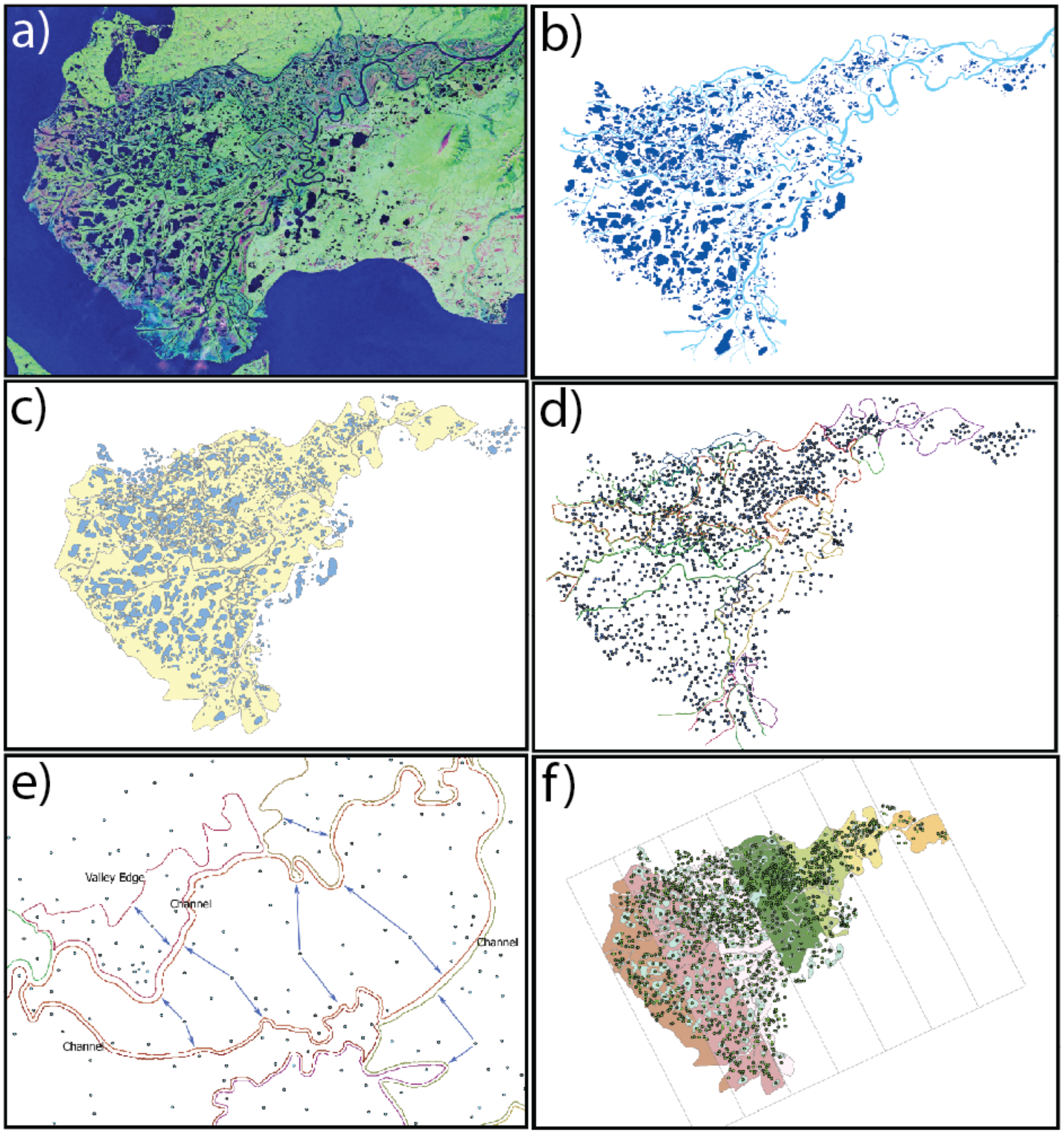


Figure 5-9: Example from the Kobuk River, Alaska of methods used for exploring geometric trends in floodplain lakes. a) Obtained Landsat 5 and Google Earth satellite images of the study areas. b) Drew lakes, interfluves, and rivers as rasters over satellite images. c) Converted rasters to geo-ref erenced vector features and calculated geometries. d) Lake centroids calculated with ArcGIS. e) Calculated distance from the lakes centroids to the two closest channels and added the results together to find the width between the channels from the lakes centroid. f) Divided study areas into zones to explore relationships between channel size, channel density, lake density, lake area, and interfluve area.

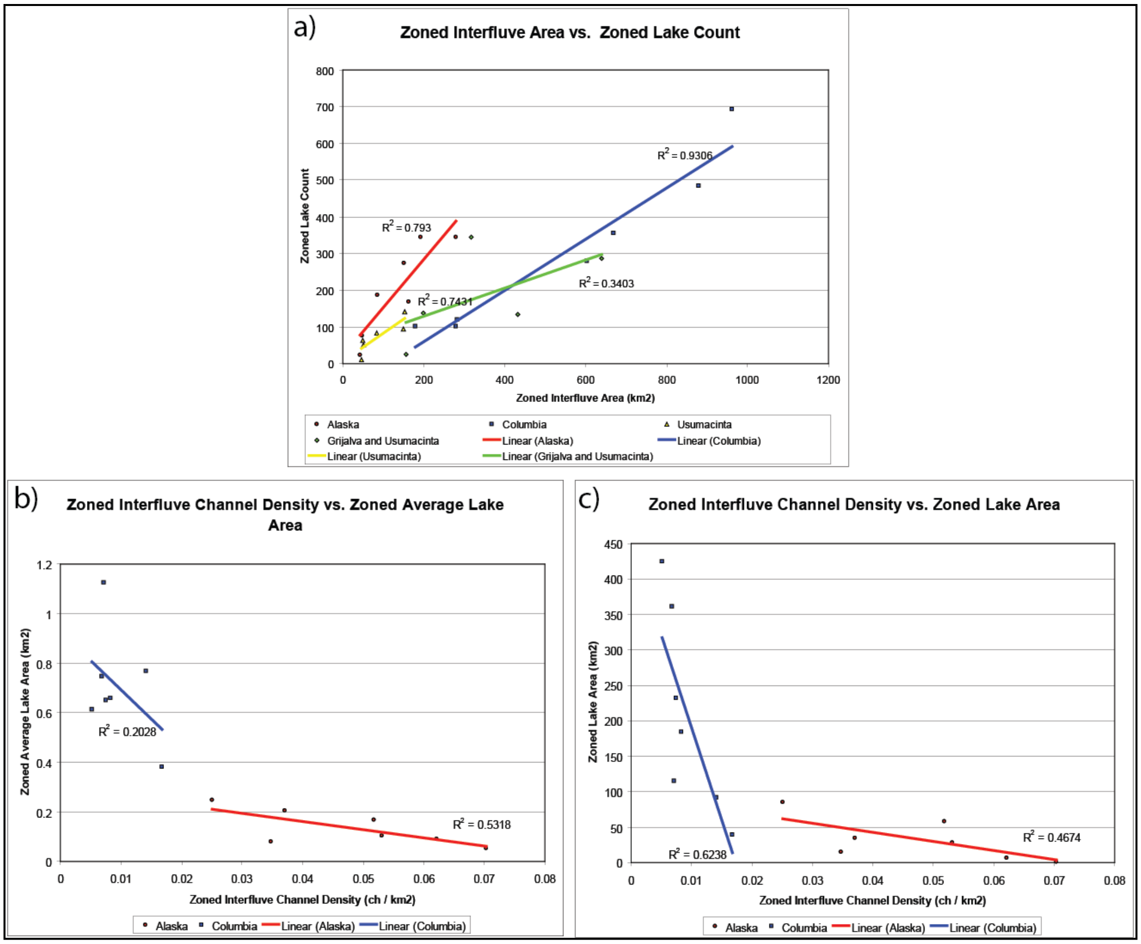


Figure 5-10: Relationships between floodplain lakes and their related fluvial system. a) The best relationship is that between interfluve area and the number of lakes. b) and c) Weaker relationships indicate that the more channels that cut an interfluve area the less the total lake area and the smaller the lake size. No good relationships could be found between lake size and channel/channel-belt size.

CHAPTER 6

DISCUSSION

Fluvial Sequence Stratigraphic Models

Sequence stratigraphic methods have been applied to marginal and continental fluvial deposits resulting in models that generally relate fluctuating amounts of sandbody amalgamation to changes in downstream base-level (Wright and Marriot, 1993; Legarreta et al., 1993; Shanley and McCabe, 1994; Olsen et al., 1995; Martinson et al., 1999; Atchley, et al., 2004) (Figure 6-1). In these models a sequence is typically based by an sequence boundary (SB) erosional unconformity developed by incision during base level fall (i.e. sea level in marginal settings) followed by amalgamated channel belts which represent low rates of aggradation associated with low levels of base-level rise and fall. These deposits are considered the lowstand system tract (LST). Base-level rise triggers increasing accommodation resulting in channels and channel belts become much less connected and separated by prevalent floodplain deposits. This transgressive system tract (TST) portion of the sequence is culminated by the maximum flooding surface (MFS) which represents the maximum extent of the transgression. In marginal fluvial systems this may be represented by marine deposits, a marine influence or swamps and coals depending on the dip location. After base-level reaches its peak the highstand system

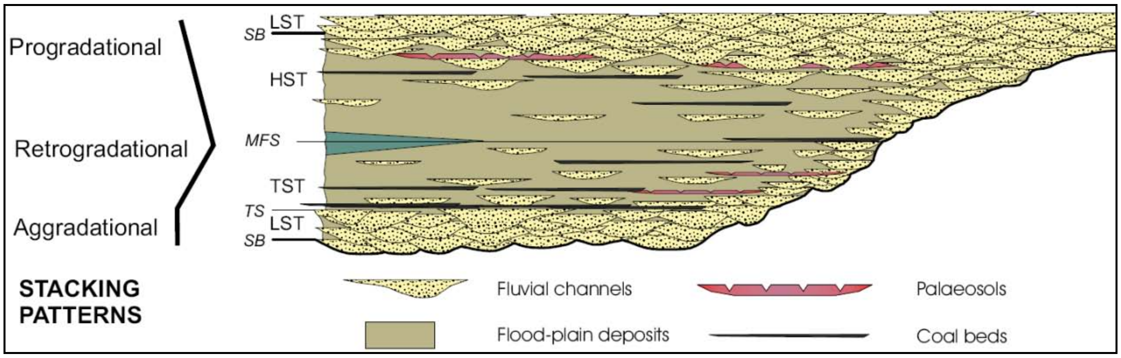


Figure 6-1: General fluvial sequence stratigraphic model showing the relationships between the lowstand LST), transgressive (TST) and highstand (HST) systems tracts. Thick amalgamated channel belts are associated with the LST and the upper HST which represent low levels of aggradation associated with low levels of base-level rise and fall. The TST and lower HST are associated with low net-to-gross sections of isolated channel-belts encased in abundant floodplain sediments. (Allen et al, 1996; Allen and Posamentier, 1999; Grech and Lemon, 2000; Legarreta and Uliana, 1998).

tract (HST) begins to fill the accommodation space and, if base-level is stable at this point, the channel belts began to become increasingly amalgamated towards the top of the sequence. Subsequent base-level fall triggers incision and the start of the next sequence.

Several workers noted problems with this downstream base-level controlled model. Notably 1) In a low-slope ramp setting transgression and regression do not necessarily cause an aggradational or degradational response (Schumm, 1993; Wescott, 1993). 2) Influence of sea level on river grade decreases with distance up dip and after a few tens to two hundred kilometers rarely has any influence, at which point upstream controls such as climate and tectonics take over (Blum 1993; Shanley and McCabe 1994; Guccione 1994; Tornqvist 1998; Blum and Tornqvist 2000). 3) The autocyclic and allocyclic erosional and depositional processes that form incisional valleys include terraces and the sequence boundaries themselves may be composed of diachronous composite surfaces (Schumm 1977; Blum and Price, 1998; Catuneanu et al. 1998; Blum and Tornqvist 2000; Weissmann et al. 2002; Ethridge et al. 2005, Strong and Paola, 2008) (Figure 6-2). This creates amalgamated sand bodies that are much more complex than the general model implies.

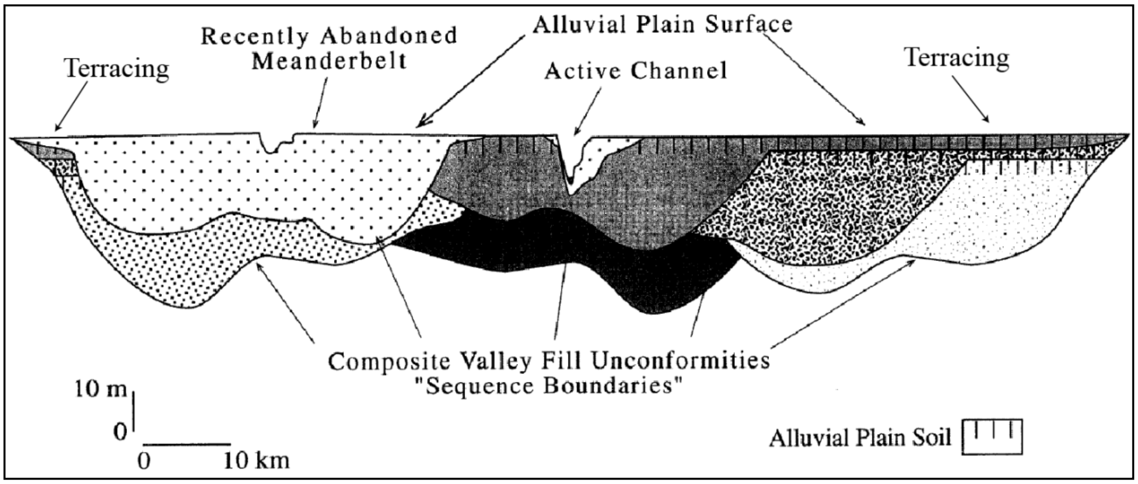


Figure 6-2: Complex amalgamated sand body including terracing and a basal composite sequence boundary created by diachronous valley scours (Blum and Price, 1998).

Buffer and Buttresses Model

The buffers and buttresses model (Holbrook et al., 2006) provides a general model that addresses the problems with the earlier models and allows the prediction of fluvial sandbody geometry and architecture in the context of both upstream and downstream base-level controls (Figure 6-3). Downstream base-level is considered to be the "buttress" which streams cannot incise below or aggrade appreciably above. This results in wide laterally amalgamated sands that are about one channel thick during periods of buttress stability. The maximum upper and lower upstream profiles are considered to be the "buffers" and the space between by upstream them is controlled primarily controls such as climate and tectonics as they introduce profile variability.

There is a transition zone were both upstream and downstream controls have an effect. The upper and lower buffers are anchored to the buttress and move and/or alter shape when the downstream base-level shifts. Thick, wide sandbody amalgamation between the buffers relies on a relatively long period of buttress stability which allows the fluvial system to incise and aggrade repeatedly between the buffers vertically and laterally due to varying upstream controls. This is relatively common because downstream base-level controls generally operate on the time scale of 10^4 to 10^7 years while upstream controls generally operate on the 10^1 to 10^4 years. This creates the complex fluvial architecture not accounted for by the earlier models and it does so with minimal change in base-level. Rapid base level rise floods the system and the TST's and HST's are similar those of the earlier models described above with the exception that amalgamated sands in the upper HST's are the result of the buffers becoming reestablished.

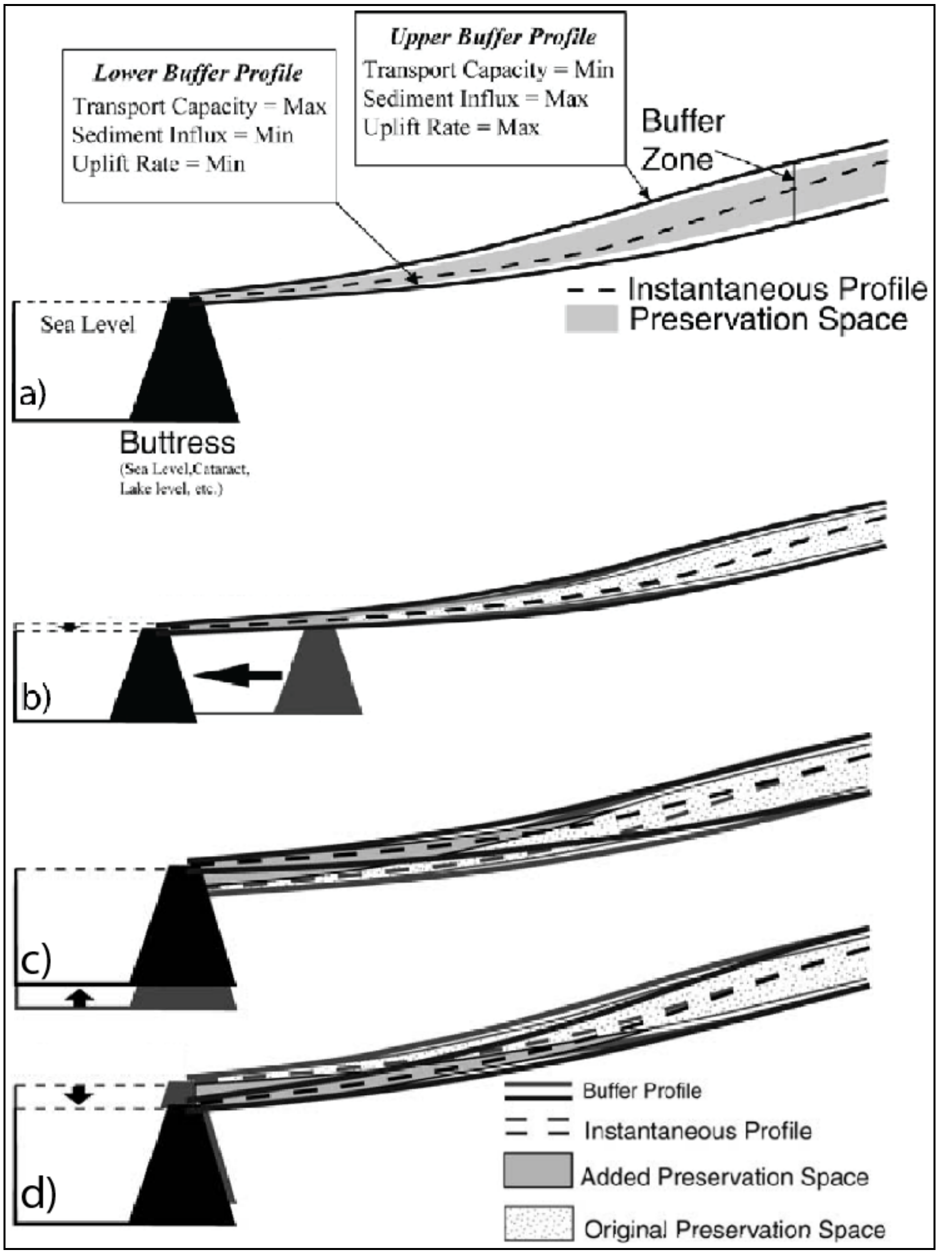


Figure 6-3: a) Buffers and buttresses model. Rivers cannot incise below or aggrade appreciably above sea level (the "buttress"). Consequently sandbody thickness is not appreciably thicker than one channel depth here. The buffer zone is controlled by upstream controls and the fluvial system incises and aggrades repeatedly between them during buttress stability creating thick amalgamated sands with a complex internal architecture . b) Shifting of the buttress along the profile, as would occur in a low slope ramp setting, lengthens or shortens the preservation space, but ads little additional accommodation space. c) Buttress rise adds some accommodation space and shifts the buttress profile up. d) Buttress fall adds some accommodation space and shifts the buttress profile down (After Holbrook et al., 2006).

Low Accommodation Sections

Paleodrainage and Channel/Channel Belt Size

The Rankin Trend was sourced by sediments from the adjacent Pilbara Block (Seggie et al., 2007) and most likely from an extensive depositional system that traversed the entire Australian Continent from the Late Permian to the Early Jurassic (Jablonski, 2000) (Figure 6-4). A foreland basin formed in the Late Permian behind the Ross High Upland magmatic arc and continued to develop into the Late Triassic (Baille, et al., 1994). This formed a large outwash fluvial plain that that extended as far as Greater India and northeastern Australia (Jablonski, 2000). Remnants of Phanerozoic continental sediments preserved in central-eastern Australia and the onshore Canning Basin support the existence of this major drainage system which may have approached the size of the present day Amazon or Mississippi systems (Jablonski, 2000). The intracratonic Australian Phanerozoic basins were probably bypassed and acted as conduits due to a lack of accommodation space (Jablonski, 2000). Permian sediments of intracratonic basins have a consistent north-northwesterly paleodrainage pattern similar to that inferred for the Late Triassic (Wilson, 1990). The Cratonic Pilbara and Kimberly Blocks would have funneled portions of this paleodrainage to the Rankin Trend area (Figure 6-4).

The channel sizes and related channel belt widths on the Rankin Trend can be divided into three populations; small 4-7m deep channels, medium 8-10m channels and large 14-16+m channels (Table 6-1). This is interpreted to express deposition from three distinct river systems traversing the section. A modern satellite image of Northwest Australia provides a good analog for the paleodrainage system of the Triassic Northwest Shelf because the Pilbara Cratonic Block was present in the Triassic and the remnants of

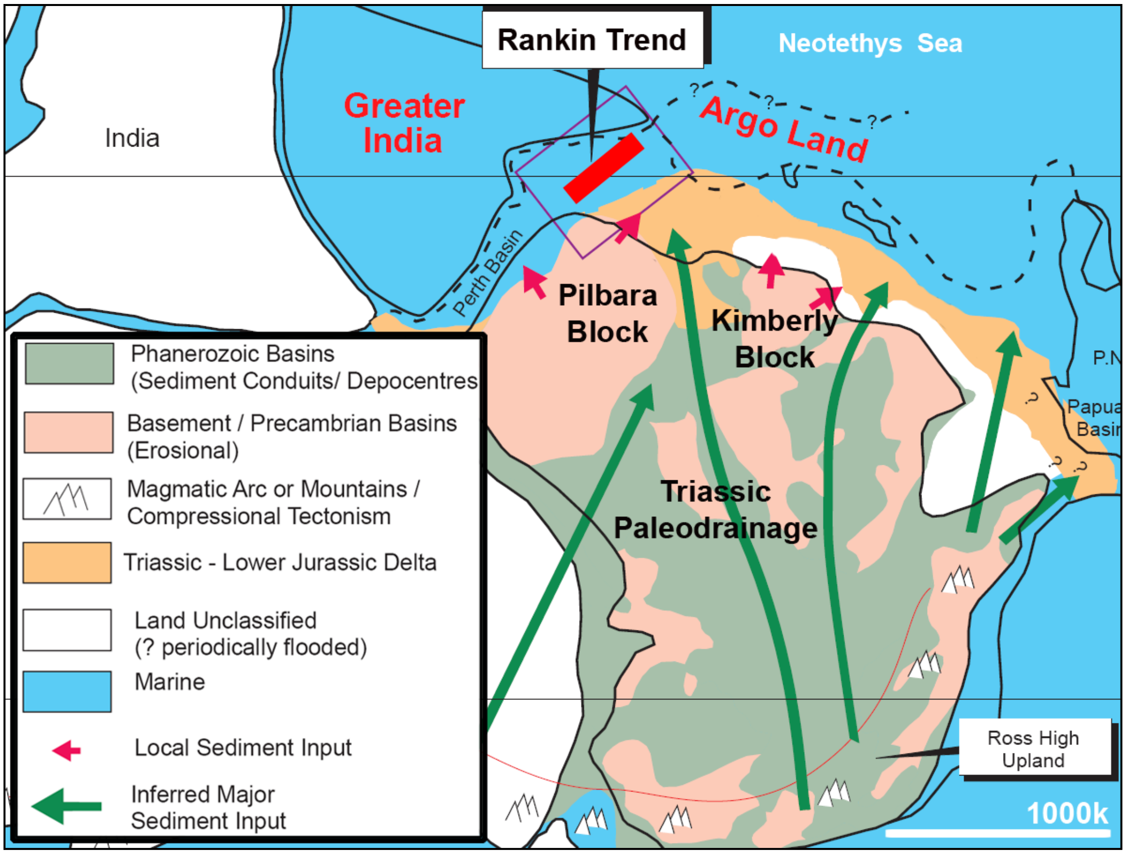


Figure 6-4: Interpreted paleodrainage for Australia during the Triassic. The Rankin Trend was sourced from the adjacent Pilbara Block and from a continental scale drainage system that originated in the Ross High Upland on the southern edge of the continent (After Jablonski, 2000).

Table 6-1: Three channel size populations with related channel widths and channel belt widths determined from core analysis on the Rankin Trend. The Strong et al., 2002 channel belt widths are considered here to be the best of the three techniques employed.

Channel and Channel Belt Dimensions of the Mungaroo on the Rankin Trend			
	Small - 4m to 7m Channel Depth	Medium - 8m to 10m Channel Depth	Large - 14m to 16m+ Channel Depth
Channel Width Range			
(Bridge and Mackey, 1993)	47m-86m	110m-115m	344m-530m
Channel Belt Width Range			
(Bridge and Mackey, 1993)	312m-1068m	726m-1741m	2252m-4195m
(Fielding and Crane, 1993)	30m-1300m	60m-2000m	150m-5000m
(Strong et al., 2003)	550m-2800m	3400m-6000m	6000m
(Gibling, 2006)	45m-200,000m	60m-250,000m	100m-300,000m

the Triassic continental drainage system are still expressed at the surface (Figure 6-5). Conditions in the Triassic were different so the size and pattern of the rivers would have varied, however, the origin and scale distribution would have been similar. Small channels flowed directly off the western side of the Pilbara Cratonic Block. Medium channels represent coalescing small channels of the Pilbara flowing off the southwest, middle and northeast portions of the block. The large channels represent the continental drainage system flowing around the northern side of the Pilbara Block. The Pilbara appears to block the large continental system creating a "shadow" to the northwest of the block making it harder for the large system to reach the southwestern portions of the Rankin Trend. It should be noted that thinner amalgamated sands on the southwest Rankin Trend (Pluto area) may be a result of its being at the edge of the strike portion of the large fluvial systems rather than down dip.

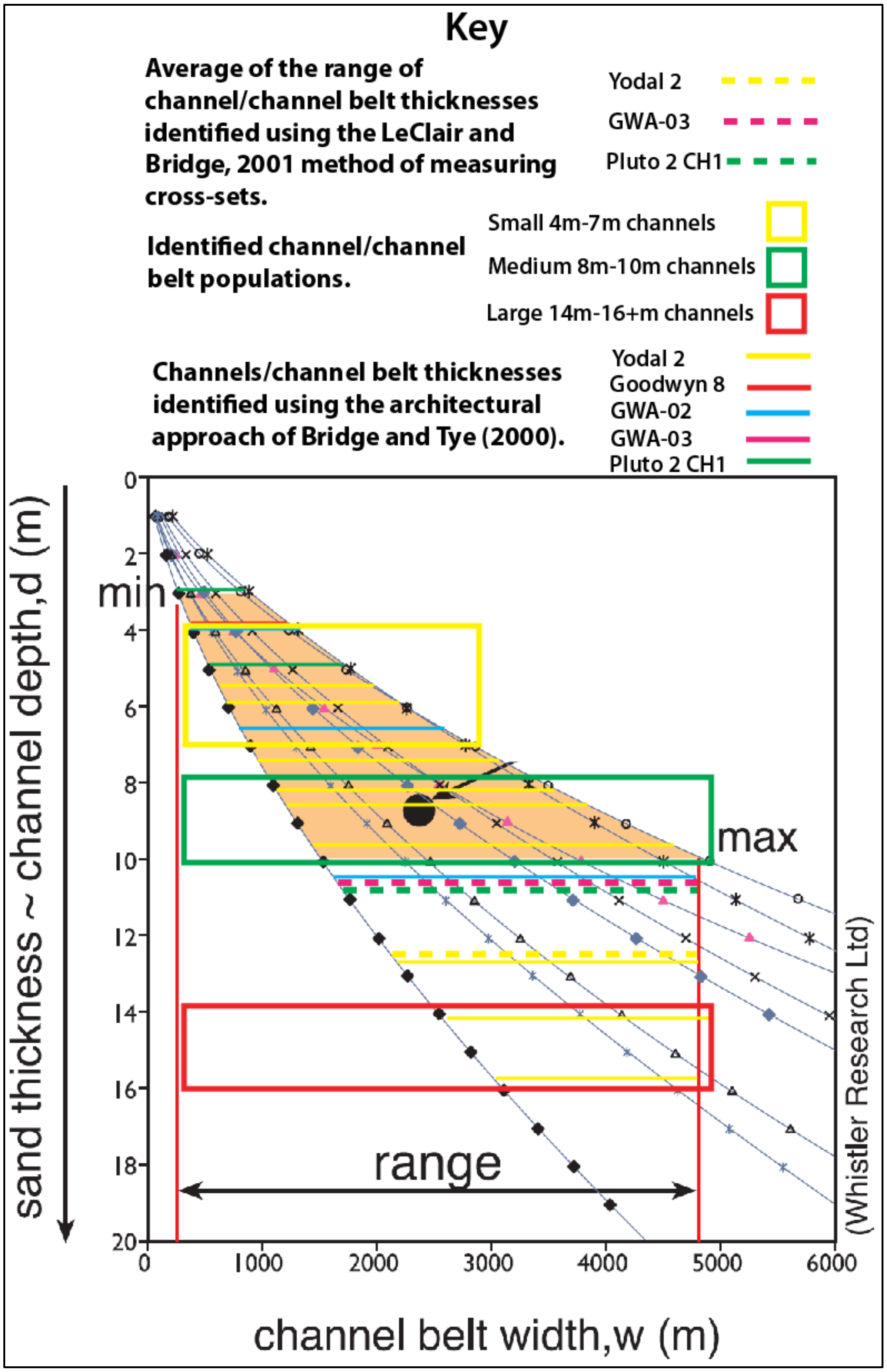


Figure 6-5: Channels measured by Bridge and Tye's (2000) architectural method and LeClair and Bridge's, (2001) cross-set measurement method plotted together. The heavy dashed lines are an average of the range calculated using the LeClair and Bridge, 2001 method. Small 4m-7m, medium 8m-10m, and large 14m-16m+ populations are noted.

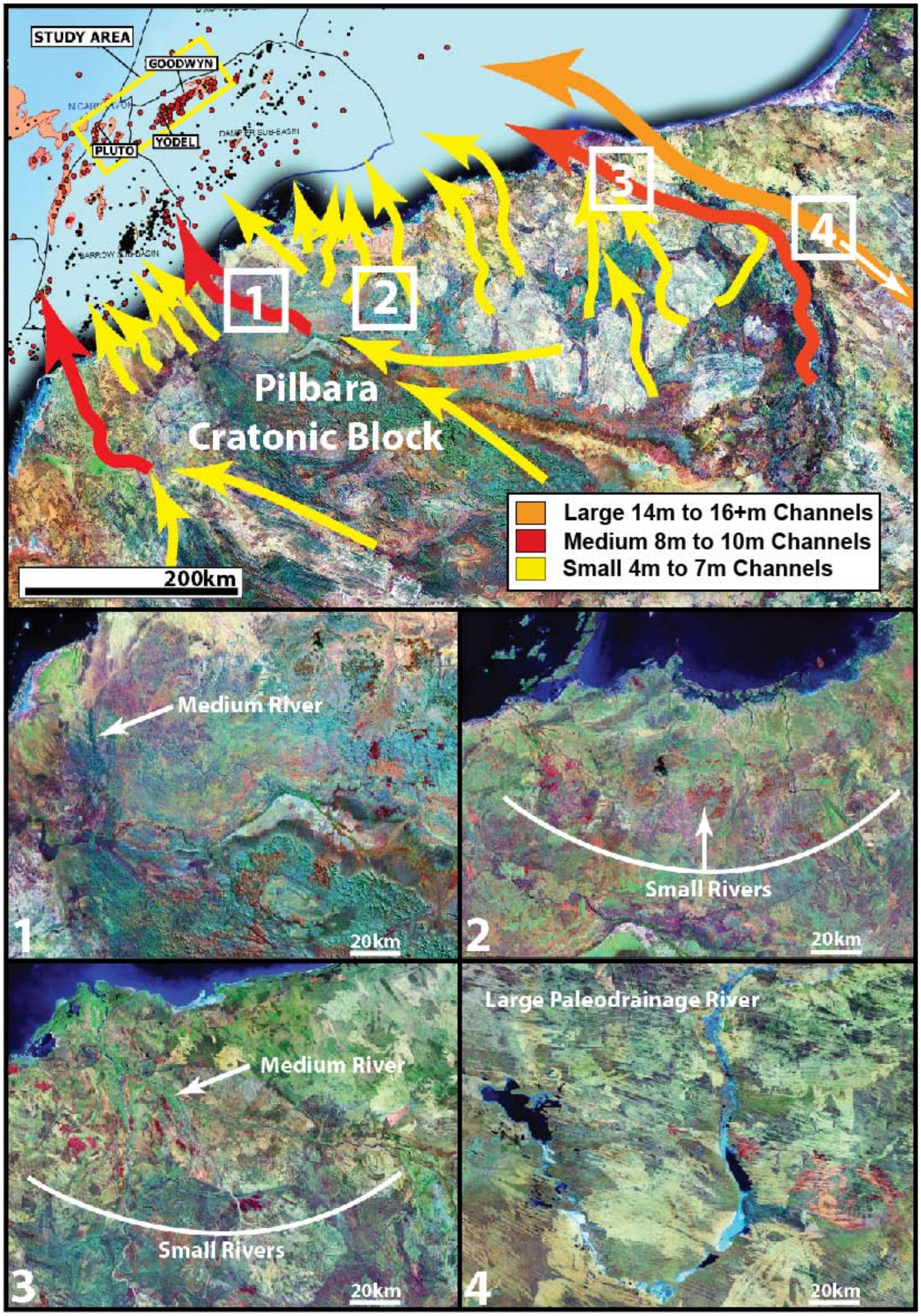


Figure 6-6: Channel size populations on the Rankin Trend.

The three channel size populations are interpreted as being a result of three distinct river systems. Small systems drained directly off the Western Pilbara. Medium systems are a result of coalescing small systems flowing off the Pilbara and The large systems are a result of the continental drainage system present in the Late Triassic. 1) Medium river formed by smaller rivers coalescing down the central Pilbara. 2) Small river flowing directly off the Pilbara. 3) Smaller rivers join on the northern flank of the Pilbara to form a medium size river. 4) Remnants of large continental scale paleo-river that was active in the Triassic.

A recent approach for estimating catchment size based on channel depth suggests that the 15m channels interpreted on the Rankin Trend in this study cannot have been sourced by the adjacent Pilbara Block (Davidson and North, 2009). This method uses climate appropriate modern geomorphological regional curves to relate drainage area to channel dimensions. and valley width to the length of the system. Wet climates need less catchment area to produce a system of a given size. These serve as analogs to ancient fluvial systems. The Early Jurassic Kayenta Formation of Utah and southwest Colorado has interpreted channel depths of 12m, close to large 15m channels found on the Rankin Trend. The climate was likely drier during deposition of the Kayenta, however, regional curves from the Pacific Maritime Mountains of the northwest coast of the U.S.A., which are interpreted to be represent to the regional curves produced by the Triassic Ross High Uplands (Davidson and North, 2009) were chosen. Using Davidson and North's (2009) data and choosing a valley widths of 25km to 75km, similar to valley widths interpreted in this study, it is estimated the system that produced these channel

and valley geometries was 2800km to 8500km long (Table 6-2). 2800km is similar to the distance from the Ross High Uplands to the Rankin Trend (Figure 6-4). This suggests the large systems found on the Rankin Trend were sourced from a large continental-scale

Table 6-2: Interpreted drainage lengths for the Early Jurassic Kayenta Formation of Utah and southwest Colorado using modern geomorphological regional curves. The Kayenta channel depths are estimated to be 12m, similar to the larger channels in the Mungaroo. Valley widths of 25km to 75km, similar to valley widths interpreted in this study, were chosen. Regional curves from the Pacific Maritime Mountains of the northwest coast of the U.S.A., which are interpreted to represent the regional curves produced by the Triassic Ross High Uplands, were used to make the interpretation (after Davidson and North, 2009).

	Kayenta Formation		
	Case 5a-min 213,210 km^2	Case 5a-max 789,980 km^2	Case 5c 2,118 km^2
Width km	*Length km*	*Length km*	*Length km*
25	8,528	31,599	85
50	4,264	15,800	42
75	2,843	10,533	28
100	2,132	7,900	21
125	1,706	6,320	17
150	1,421	5,267	14

drainage and they most likely did not originate on the adjacent Pilbara Block, which is only 200km away.

Architecture of Low Accommodation Amalgamated Sands

The low accommodation sections of core analyzed in this study from Goodwyn GWA-03, Goodwyn 8, and Yodel 2 record thick successions of sand 39m, 46m and 90m respectively. Goodwyn 8 sands are truncated by the MU and their original total thickness was likely to approach that of the 90m found in Yodel 2. The lower E sands can be correlated the 22k from Goodwyn 8 to Yodel 2, and with less confidence throughout the Rankin Trend which is approximately 100km along interpreted strike, although the thickness varies with the thinner sections generally lying to the southwest. These sands are composed of stacked channel belts at least three to six times thinner than the total sand body and there are indications of higher order surfaces in Yodel 2 and Goodwyn 8 that argue for presence of more complex architecture such as multiple valleys. Miall and Arush, (2001) suggest that even in outcrops it can be very difficult to distinguish regionally significant bounding surfaces from autogenic scour surfaces in thick successions of sand, and that they are not necessarily characterized by erosional relief and draped by lag deposits. This indicates there may be more indistinguishable 6th and higher order valley bounding surfaces present in these cores and it is suggested here that this is probable. Bal et al. (2002) found evidence of higher order surfaces in an FMI analysis of Yodel 2, although there are differences with the interpretations presented here (Figure 6-6). These amalgamated sand deposits have been interpreted as LST's related a downward adjustment in the rivers longitudinal profile during base level fall as discussed above in the downstream base-level controlled models (Bal et al., 2002), and as LST's in which much of the sediment bypassed via incised valleys or multi-valleys leading to the deposition of well drained vertisols on the higher bypassed areas (Seggie et al., 2007). Presumably these valleys filled by aggradation during late lowstand and transgression. It seems highly unlikely that base level would rise at the slow and constant rate necessary to produce these thick, extensive sheets of clean sand primarily through progressive aggradational processes. The higher order surfaces, thickness and wide extent of these amalgamated sand bodies suggests they were formed as multi-valleys by multiple episodes of incision and aggradation between buffers as predicted by the buffers and buttresses model. An ancient outcrop analog can be found in the Mesa Rica and Romeroville sandstones of the Cretaceous Dakota Group in Southeast Colorado

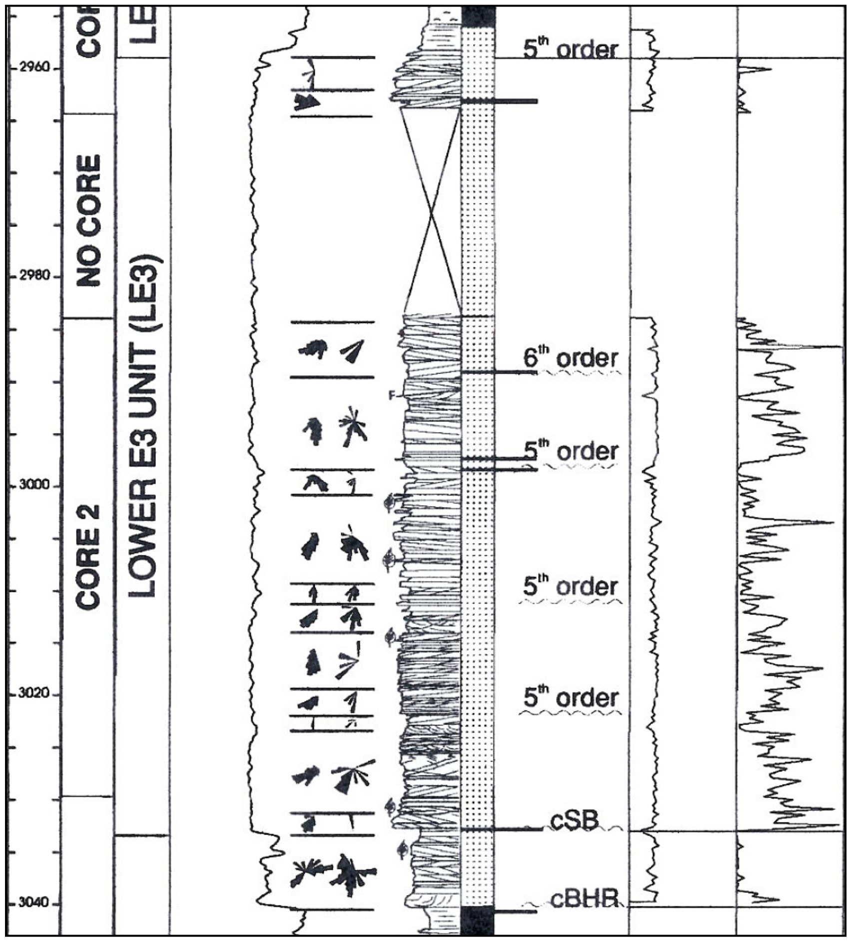


Figure 6-7: FMI based interpretations of higher order surfaces in the Yodel 2 core. 6th order surfaces represent valley boundaries while 7th order surface represent sequence boundaries. The 7th order surface is labeled cSB. (Bal et al., 2002).

(Holbrook, 2001; Holbrook, 2008) (Figure 6-7). These sands were interpreted as being deposited between buffers and display the complex architecture interpreted in the Mungaroo Formation in this study. The multiple episodes of incision and aggradation between buffers would wash the sands of floodplain muds and account for their thick,

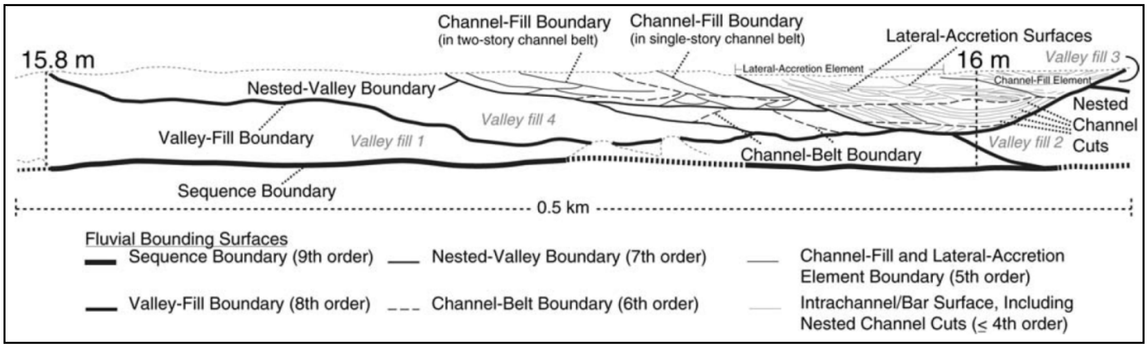


Figure 6-8: Simplified strike section of the Romeroville Sandstone representing the complex architecture of multi-valley sheets deposited between buffers with incision and aggradation controlled by upstream climatic and/or tectonic changes. The architectural complexity makes it necessary to bump up the bounding surface order making valley fill boundaries 7th and 8th order while sequence boundaries are 9th order. This section is composed of four valleys each containing multiple channel belts and valley four contains nested valleys in which valleys re-incise into the original valley. Once a valley fills it the system is free to avulse to a new location which accounts for the wide lateral strike extent of the sheet. The outcrop used in this study was 14k along strike (Holbrook, 2001).

widespread occurrence. A dip section through these same strata provide an analog for the alternating low, high, low accommodation sections of Upper, Middle and Lower E of the Mungaroo Formation (Holbrook et al, 2006) (Figure 6-8). The muddy high accommodation Pajarito Formation between the buffer confined Upper Mesa Rica and Romeroville low accommodation sands resulting from a rapid transgression flooding. the system. This is confirmed by a marine influence in the down dip portions of these sandwiched Dakota Group strata. These buffer sand encased muddy floodplain deposits are analogous to the Middle E while the sands represent the Upper and Lower E. Lower E strata differs from the Dakota Group analog in that it is much thicker. A related seismic study indicates the Lower E likely records stacked or composite buffers in the Goodwyn

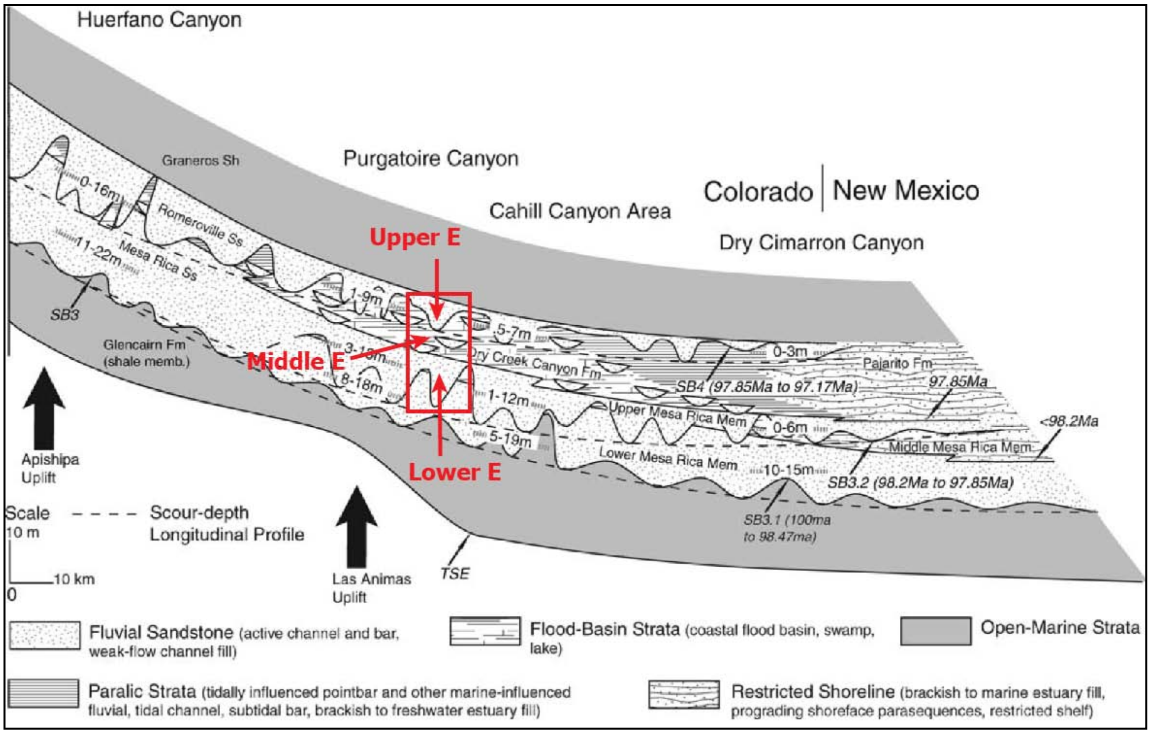


Figure 6-9: Dip section through the Dakota Group. This section is analogous to the Lower, Middle and Upper E with the transgressive, muddy Pajarito Formation, representing the Middle E, sandwiched between two buffer confined amalgamated sands which represent the Lower and Upper E of the Mungaroo Formation.

field (Kliem, personal communication). This, and the fact that the fluvial systems were larger in the Lower E than in the Dakota Group, helps explain their greater thickness. In the buffers and buttresses model the most mature soils would be found up-dip between valleys as they narrow towards there source leaving inter-valley areas to undergo soil development for the entire length of the related buffer systems stability.

Gulf of Carpentaria Modern Analog for Highstand Buffer System

Fluvial deposits on the west side of the Gulf of Carpentaria located in Northern Australia provide a good potential modern analog of a HST low accommodation buffer and buttress system in the Mungaroo (Figure 6-9). Two main fluvial systems feed the western side of the gulf creating a buffer system that merges down-dip. They have up-dip nodal avulsion points that feed predominantly low-sinuosity rivers which rake across the down-dip areas as they avulse. These rivers become sinuous as they adjust to the lower gradient coastal plain. The up-dip portion of the fluvial deposits are creating thick amalgamated buffer deposits as they cut, fill and avulse in response to autogenic and upstream allogenic changes in climate and tectonics. They are analogous to the Upper and Lower E Units of the Mungaroo Formation on the Rankin Trend. The down-dip fluvial coastal plain deposits gradually become controlled by the sea level buttress which they cannot incise appreciably below or aggrade appreciably above. As a result these deposits fan out and thin to approximately one channel depth. Correlating these deposits, as is being done in the related seismic and regional studies, should allow fluvial system and sand thickness trends to be mapped on the Northwest Shelf.

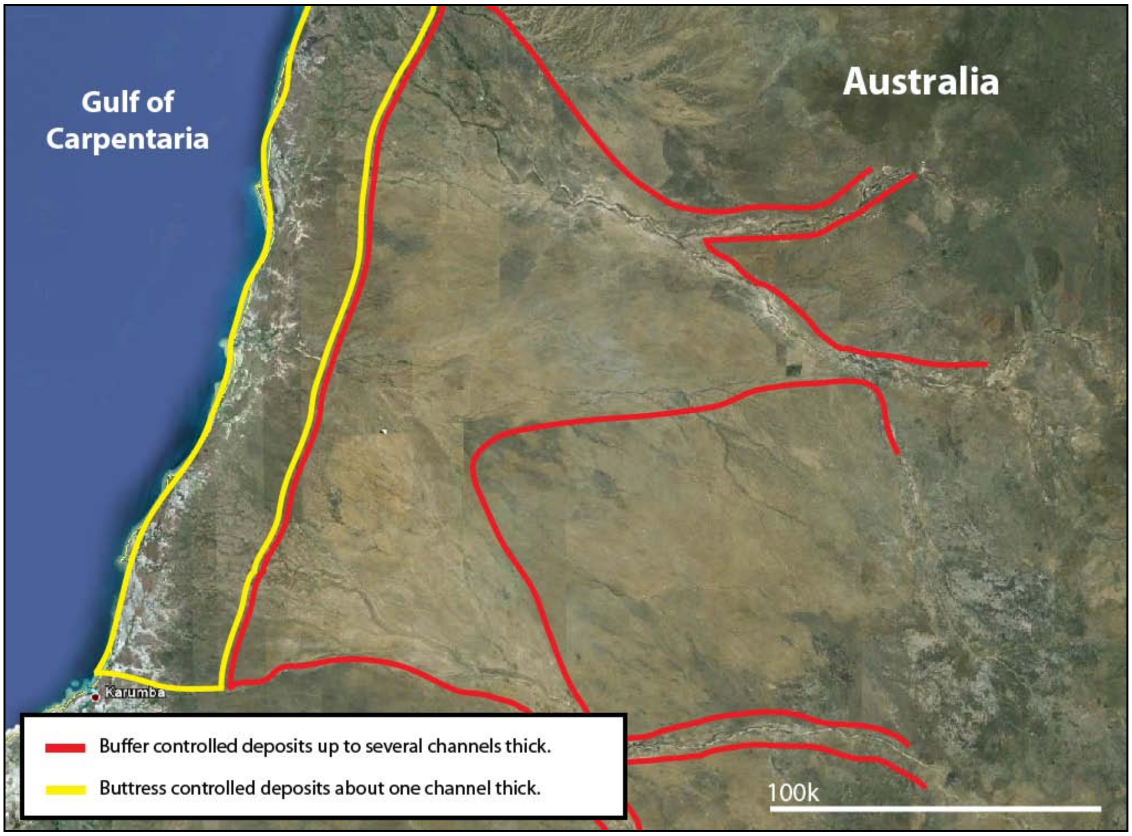


Figure 6-10: Modern interpreted buffer and buttress system on the west side of the Gulf of Carpentaria. According to this model up-dip deposits, outlined in red, can become up to several channels thick as they cut, fill and avulse between the buffers in response to autogenic and upstream allogenic climatic and tectonic changes. The down-dip buttress controlled deposits, outlined in yellow, are interpreted to be approximately one channel thick because they cannot incise appreciably below, or aggrade appreciably above, the sea level buttress. The change between the two is gradational and not sharp as may be assumed by the picture (Google Earth, 2010) .

High Accommodation Sections

High Accommodation Architecture

Complex high accommodation fluvial deposits are a common component of the Triassic Mungaroo on the Rankin Trend. All of the architectural elements interpreted in this study can be found in these strata. They represent the condition when a relatively rapid rise in base level floods the buffer system and accommodation is created at the limit of sediment input (Bridge and Leeder, 1979; Wright and Marriot, 1993; Shanley and McCabe, 1994). They have been modeled as having abundant muddy floodplain deposits which contain disconnected, dispersed channel belts (Allen, 1978, Wright and Marriott, 1993, Shanley and McCabe, 1994). As such their reservoir potential is generally considered low. These deposits are best divided into sections that reflect well drained and poorly drained floodplain environments. Climatic cycles in the Triassic of the Northwest Shelf likely produced wet and dry cycles and changes in relative sea level also control how well drained the floodplain is at a given time. When the sea encroaches a coastal plain it pushes up the water table creating more swamps and lakes. This effect can extend a considerable distance in interpreted Rankin Trend Mungaroo Formation low slope ramp settings. In marginal fluvial systems poorly drained floodplain environments can be an indicator for the maximum flooding surface. Generally marginal fluvial strata grade from a poorly depositional environment on the coastal plain to a well drained environment at some point up-dip. This point depends on relative sea level, climate, local tectonic and drainage factors.

High Accommodation Architecture Element Occurrence

The occurrence of high accommodation floodplain architectural elements is given in (Figure 6-10). The three elements that comprise channel fills (thalweg fill, unit bars, and abandonment phase) account for 37% of the total. Channel fill occurs in both well and poorly drained floodplains, although one might expect slightly less channel fill in

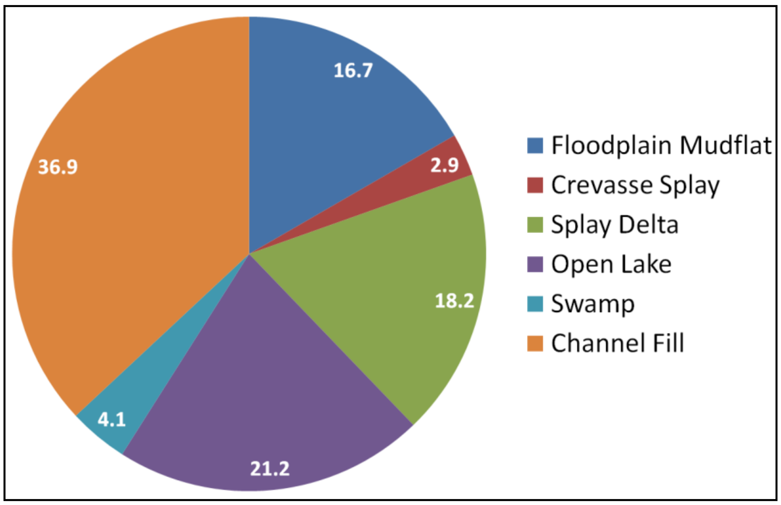


Figure 6-11: High accommodation architectural element occurrence. The preponderance of poorly drained non-channel strata suggests the Middle E Mungaroo floodplains were generally poorly drained.

poorly drained floodplains because they likely represent higher accommodation and, thus, more floodplain fines in relation to channel deposits (Wright and Marriot, 1993, Shanley and McCabe, 1994). However, open lake, splay delta, and swamp deposits that represent poorly drained floodplains make up 69% of the total deposits that are not channel fill, with well drained floodplain mudflat and crevasse splay deposits making up the remaining 31%. This overwhelming presence of poorly drained strata deposits reflect a wet climate or a low slope on the floodplain leading to wet conditions.

Well Drained Floodplain Architecture

The well drained floodplain environment is composed primarily of floodplain mudflat deposits which consists of bioturbated, churned silts and muds, the immature "composite soils" of Aslan and Autin, (1999). These were deposited during overbank flooding events. Isolated trunk channel-belts composed of thalweg fill deposits and stacks of unit bars are dispersed throughout these overbank deposits. These strata provide the best reservoir potential. Gradual avulsion results in the channel filling with primarily lower flow regime Abandonment Phase Elements. These deposits have fair reservoir potential. The muds of oxbow lake type Open Lake Elements may be deposited when a trunk channel experiences a relatively rapid avulsion leaving a depression filled by the high water table found on floodplains. Secondary channels branch from, and coalesce with, the trunk channel depositing similar, but smaller scale deposits across the floodplain. Crevasse Splay Elements are formed when a trunk channel breaches its levee and spills suspended and bed load onto the emergent floodplain. These deposits form a fairway of relatively coarse silty deposits next to the trunk channel belts and have limited reservoir potential.

Gulf of Carpentaria Modern Analog for Well Drained Floodplains

Fluvial deposits on the west side of the Gulf of Carpentaria located in Northern Australia also provide a good modern analog for the well drained floodplain environment of the Mungaroo. A few elements of poorly drained floodplain deposition are present, but during the current sea level highstand and dry environment found in the Gulf of Carpentaria region it is a better analog for well drained floodplains. This area contains abundant floodplain mudflat deposits and both low sinuosity and high sinuosity rivers

(Figure 6-11: a,b,c). The rivers are flanked by local crevasse splays (Figure 6-11 a,c). In general the rivers are low sinuosity up-dip with the sinuosity increasing as they adjust

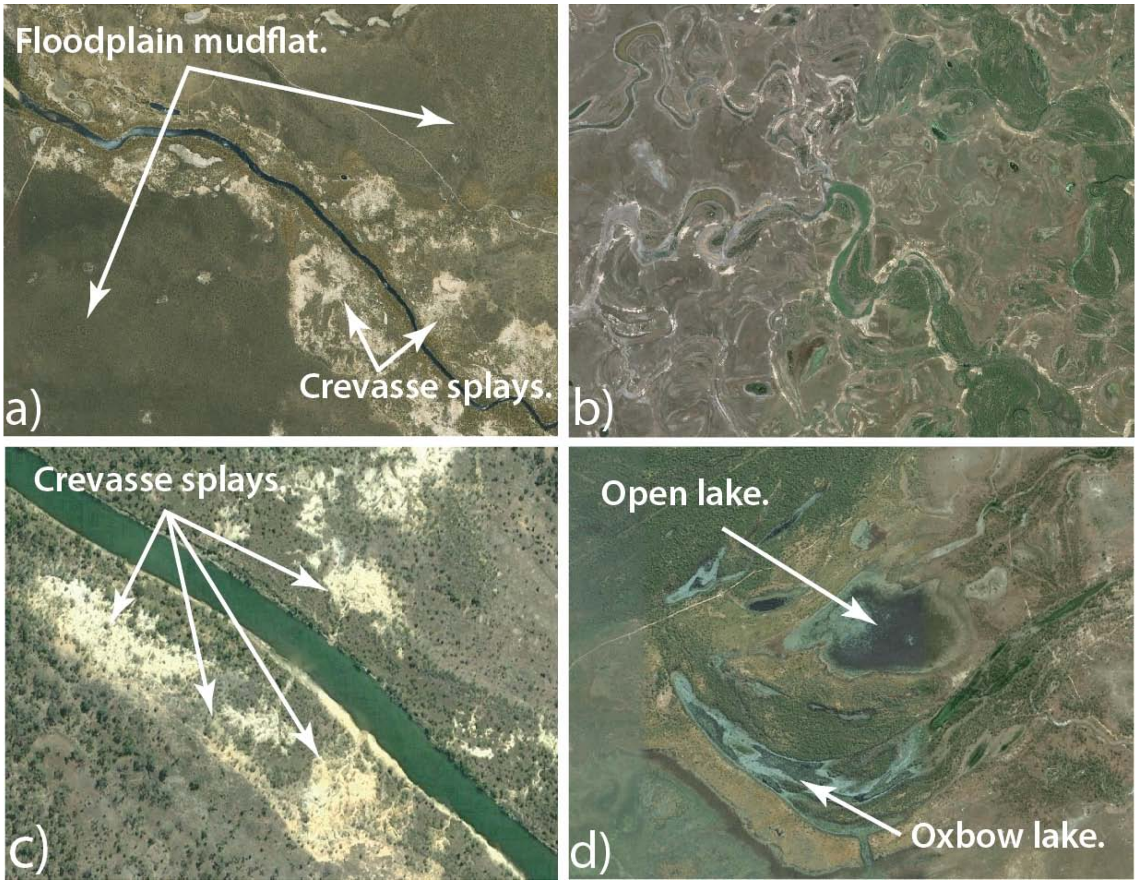


Figure 6-12: Western Gulf of Carpentaria analog for well drained floodplain deposits. a) Low sinuosity channel flanked by crevasse splays and floodplain mudflat deposits. b) High sinuosity rivers on the coastal plain. c) Low sinuosity river flanked by crevasse splays. d) Open lake and oxbow lake deposits (Google Earth, 2010).

to the lower slope of the coastal plains. The relatively high water table of the coastal plains allows the formation of oxbow lakes in abandoned channels and open lakes between the channel belts (Figure 6-11 d).

Poorly Drained Floodplain Architecture

The poorly drained floodplain environment is composed primarily of Swamp Elements and Open Lake Elements leaving coaly mudstone, coal, and mudstone with minor silty intervals. Some drier areas produce the composite soils of the Floodplain Mudflat Element. Trunk channels and secondary channels are generally assumed to be dispersed through these strata in a manner similar to the dry floodplain environment. Crevasse splays may form if the area adjacent to the river is relatively dry. Splays into lakes are generally assumed to form lobate Splay Delta Elements as sediment pours through the breached levee and creates a delta, based on an analogy with marine lobate deltas (Fisk, 1944), next to the trunk or secondary channel. A modern geomorphalogic study based on observations using satellite images from Google Earth (Supplement 4) found that these lobate splay deltas are relatively rare. Instead they commonly form linear channels that propagate across the lake forming a ribbon of splay delta deposits bisected by a central channel (Stoner and Holbrook, 2008). These "propagating channels" continue to propagate until they intersect another channel or until they become abandoned. At least one other study has noted the linear nature of splay deltas. Jorgensen and Fielding, 1996 concluded during a study of the high accommodation Upper Triassic Callide Coal Measures of Queensland Australia that *"Perhaps the most important outcome of this work...... is the recognition that splay geometries in alluvial floodbasin deposits are not necessarily lobate, as has been commonly assumed."*

This inclination of splay deltas to form propagating linear channels could have important connotations for reservoir characterization. 1) Splay deltas found in association with abundant lake deposits should be modeled as linear channels instead of lobes. 2) If the caliber of sand is sufficient for gas migration these channels would provide conduits between large trunk channel belts allowing multiple belts to be drained through one reservoir. 3) There is evidence as discussed above that the Mungaroo is at least partially self-sourced. These conduits would enhance the migration of gas formed in organic rich, but relatively impermeable, lake and associated swamp deposits to trunk channels. These factors suggest that sands encountered in appropriate high accommodation settings may have better production potential than previously realized. At the present these splay channels are not well studied and it is not known if the lithologic and geometric properties of these channels are adequate to facilitate the mechanisms discussed above. Further research is warranted.

Grijalva River Coastal Floodplain Modern Analog for Poorly Drained Floodplains

The Grijalva River coastal floodplain of Tabasco State Mexico is an excellent analog for poorly drained floodplain deposits in the Mungaroo Formation (Figure 6-12). Due to the current highstand there few high accommodation marginal fluvial systems in the world today. This area is experiencing active subsidence (Burkart and Scotese, 1990; Ambrose et al., 2003) and a result relative sea level is continuously rising providing abundant accommodation. In addition it is in a tropical to subtropical area like the Northwest shelf in the Triassic and there is relatively little human modification. There are abundant floodplain lakes and swampy areas. Scattered trunk channel belts and secondary belts connected by propagating splay channels as discussed above are scattered through the area(Figure 6-13a). Several areas appear to contain raised mires, which will form coals if preserved and lithified (Figure 6-13b). The organic rich sections would also provide good source rock for gas generation. Abandoned propagating splay channels are apparent in these raised mires (Figure 6-13 b) and they may provide a connection between these organic rich areas and the trunk channels. This modern analog suggests poorly drained high accommodation floodplains may produce better reservoirs than current thinking suggests.

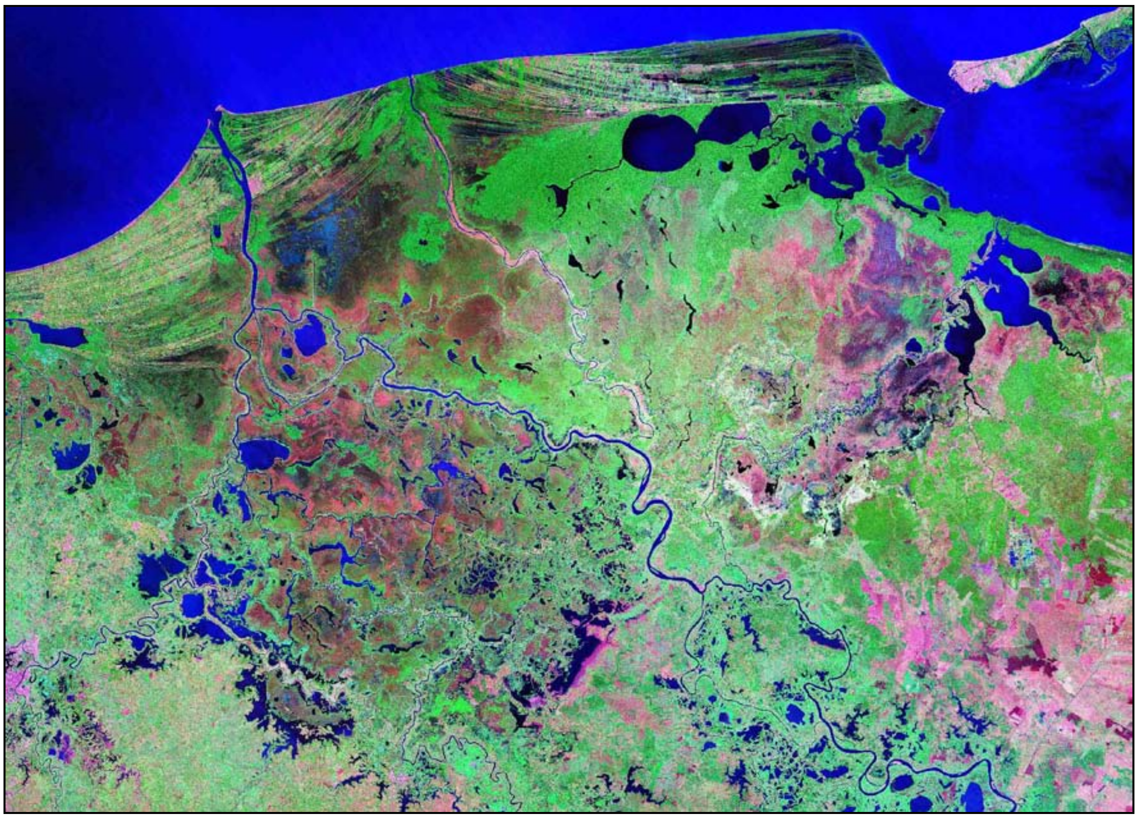


Figure 6-13: Overview of the Grijalva coastal floodplain. This area is undergoing active subsidence creating a relative sea level rise and the creation of ample accommodation as the water table is pushed up. There are numerous floodplain lakes and swampy areas as a result. Scattered trunk and secondary channel belts connected by propagating splay channels traverse the floodplain. Several areas contain raised mires conducive to coal formation (NASA).

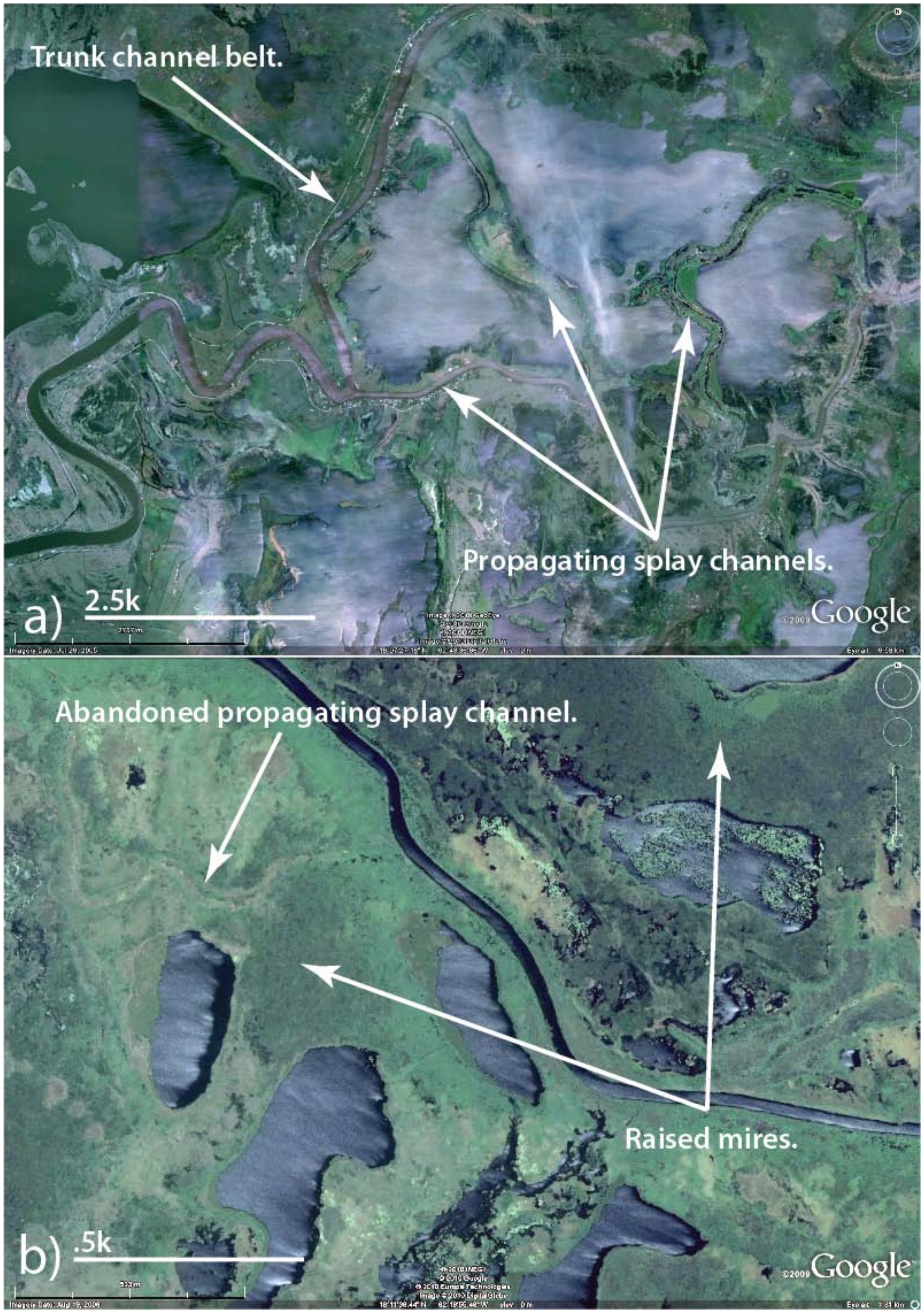


Figure 6-14: a) Close-up of trunk channel with propagating splay channels. b) Raised mires with abandoned propagating splay channel running through the mire. These channels could link channel belts together and link channel belts to organic rich source rock after lithification (Google Earth, 2010) .

CHAPTER 7

CONCLUSIONS

This work presents an architectural breakdown of the high and low accommodation sections of the Mungaroo Formation on the Rankin Trend using core from the Lower and Middle E units of Goodwyn, Yodel and Pluto fields and provides estimates for the architecture and geometry of these deposits based on numerical and graphical empirical methods. These strata can be broken down into eight distinct architectural elements. Thalweg Fill Elements, Unit Bar Elements and Abandonment Phase Elements comprise channel deposits and make up the majority of the low accommodation sections. High accommodation floodplain strata contain the channel deposit elements plus Floodplain Mudflat Elements, Crevasse Splay Elements, Splay Delta Elements, Open Lake Elements and Swamp Elements. Modern and ancient analogs are chosen to provide additional information about how these architectural elements are distributed in these environments and to rationalize the findings. This effort is being done in collaboration with a seismic study of the Goodwyn Field and a regional well log study of the Northwest Shelf with the goal of placing the Mungaroo Formation in a buffer and buttresses model in order to determine regional trends.

The Middle E high accommodation sections are complex mud and silt dominated deposits composed of all the architectural elements. They can be divided into poorly drained floodplain deposits and well drained floodplain deposits. The poorly drained floodplain deposits are dominated by Open Lake and Swamp Elements while the well drained floodplain deposits are primarily composed of Floodplain Mudflat and Crevasse Splay Elements. These strata are generally assigned a low reservoir potential because they are low net-to-gross and have been interpreted to contain poorly connected channel belts scattered through the mud and silt. This study suggests that these poorly drained floodplain deposits may have a better reservoir potential than current thinking implies due to the tendency of splay deltas to form ribbon channels that connect the channel belts, thus creating larger reservoirs consisting of multiple channel belts connected by propagating splay channels. They would also provide a conduit for self sourced gas from the organic rich swampy areas to the channel belt reservoirs.

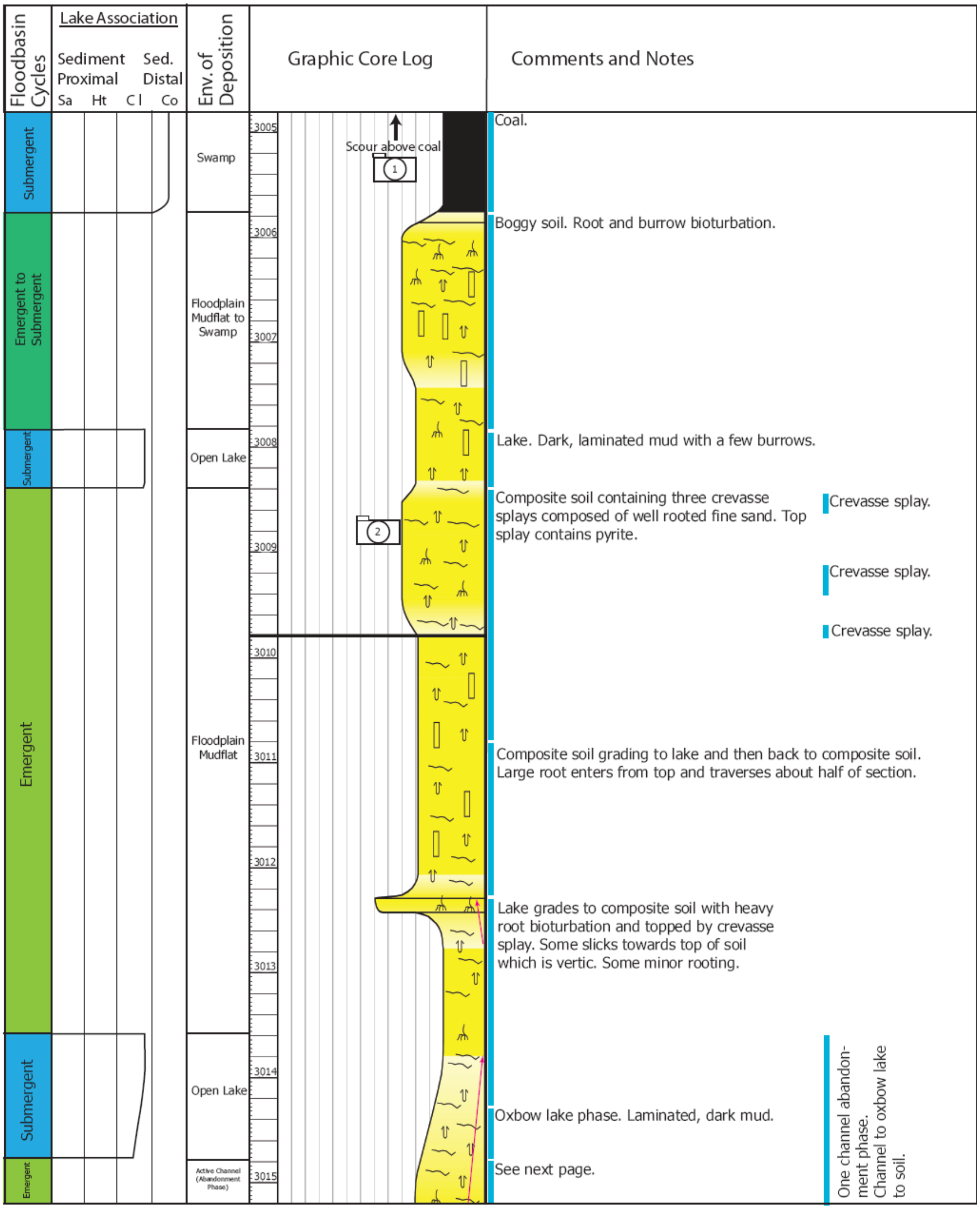
Modern satellite images of Northwest Australia provide a good analog for the paleodrainage system of the Triassic Northwest Shelf, although climatic conditions in the Triassic were different so size and pattern of the rivers would have varied. The channel/channel belt dimensions found in the E sands of the Mungaroo can be divided into three populations that relate to this analog. Small 4m to 7m channel systems are represented by channels flowing directly off the western side of the Pilbara Cratonic Block. Medium 8m to 10m channels represent coalescing small channels originating in the Pilbara Block. Large 14m to 16+m channels represent the continental drainage system flowing around the northern side of the Pilbara.

The low accommodation Lower E amalgamated sands are multiple channel belts thick and show indications of internal architectural complexity that imply internal higher order surfaces up to the sequence boundary level. The thickness of these sands also implies more of these higher order surfaces that cannot be identified in the core are present. This justifies placing these sections in a buffers and buttresses model in the regional and seismic studies in order to facilitate placing the Mungaroo Formation in a regional context.

APPENDIX A

GWA-03 CORE REVIEW

GWA-03 Core Review
3005 - 3015m



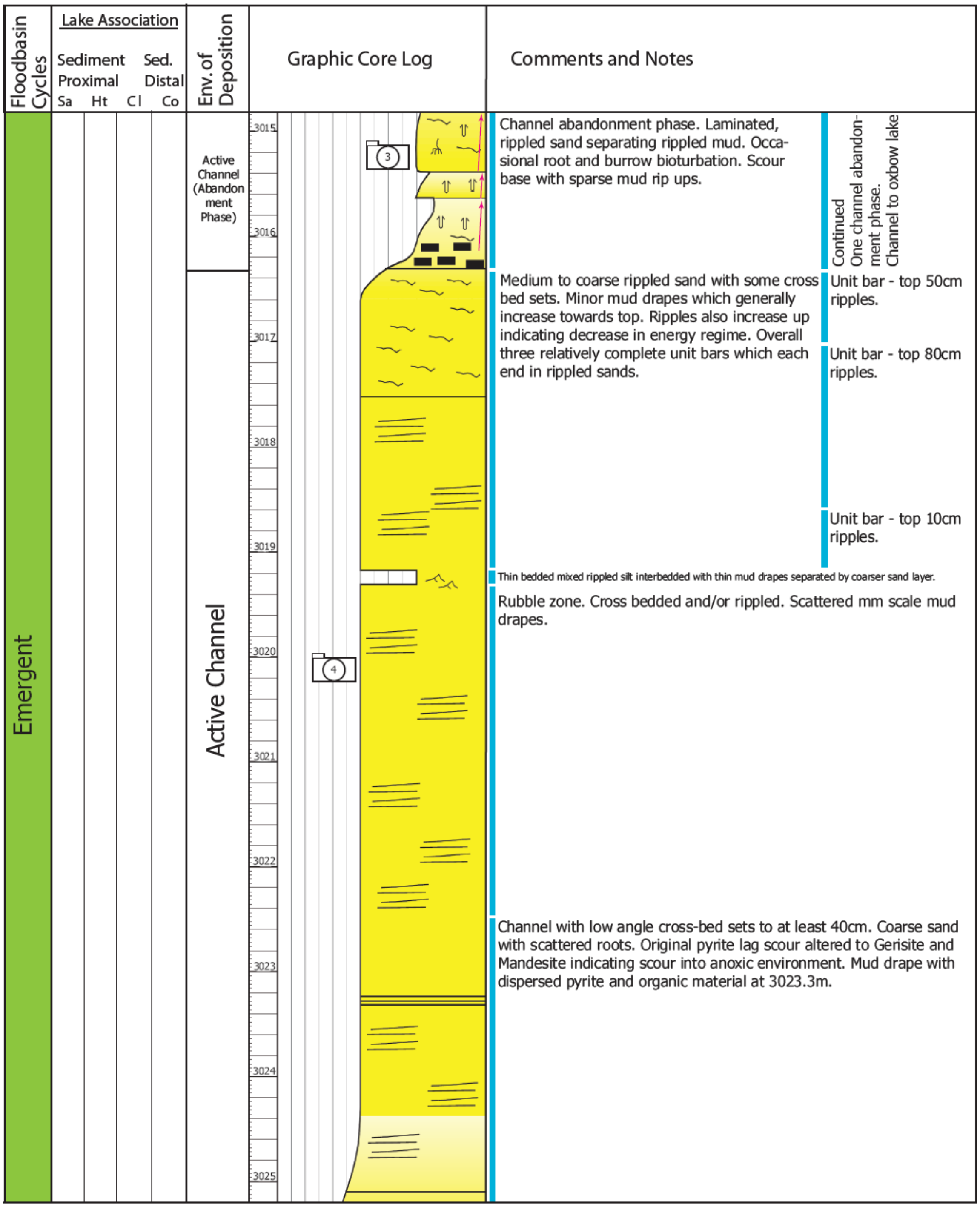
Core Photos GWA03 - Panel 1

3004m-3006m - Coal topped by gravel scour.

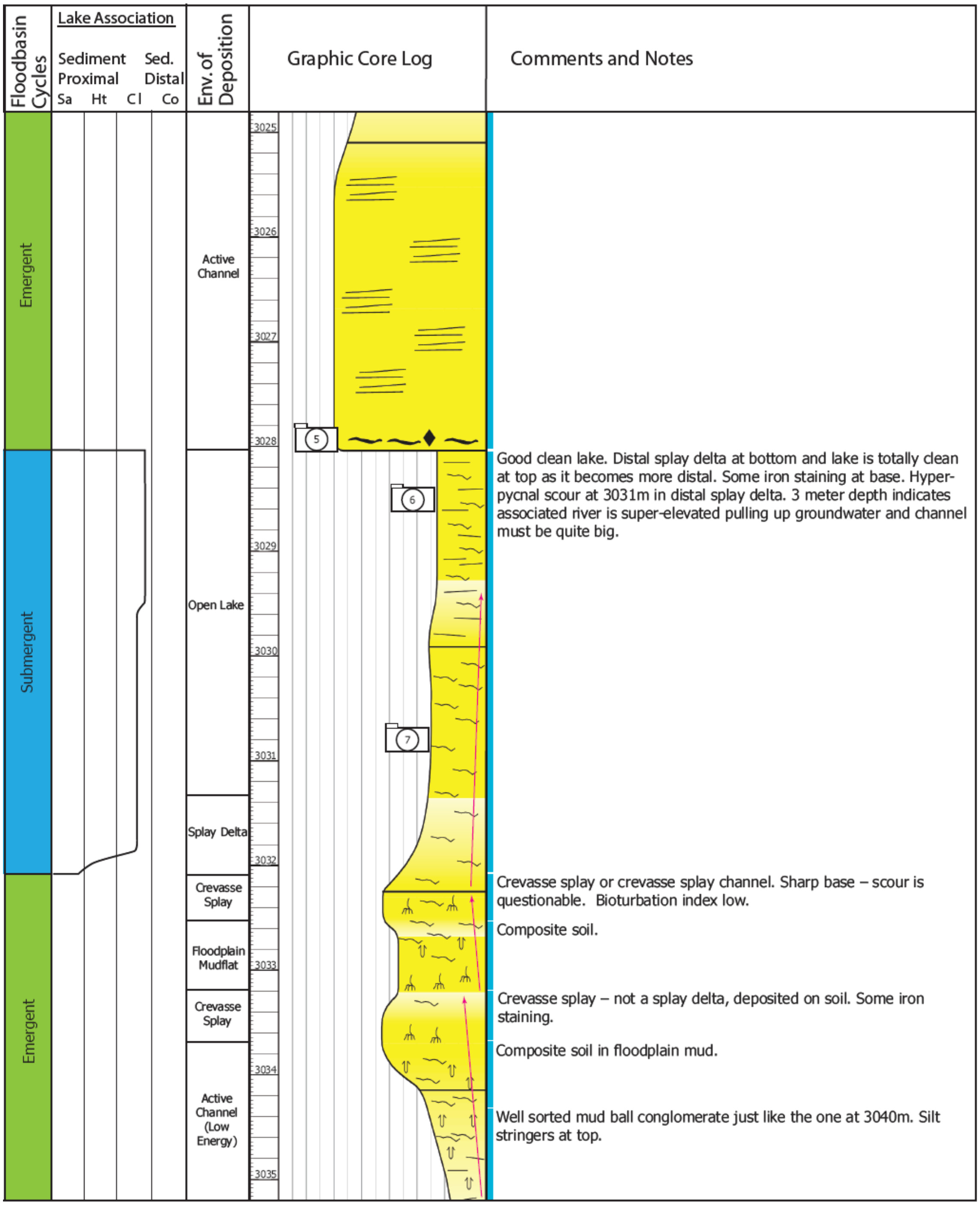
3008.9m - Bioturbation in floodplain mudflat.

3015.25m - Bioturbation in channel abandonment phase..

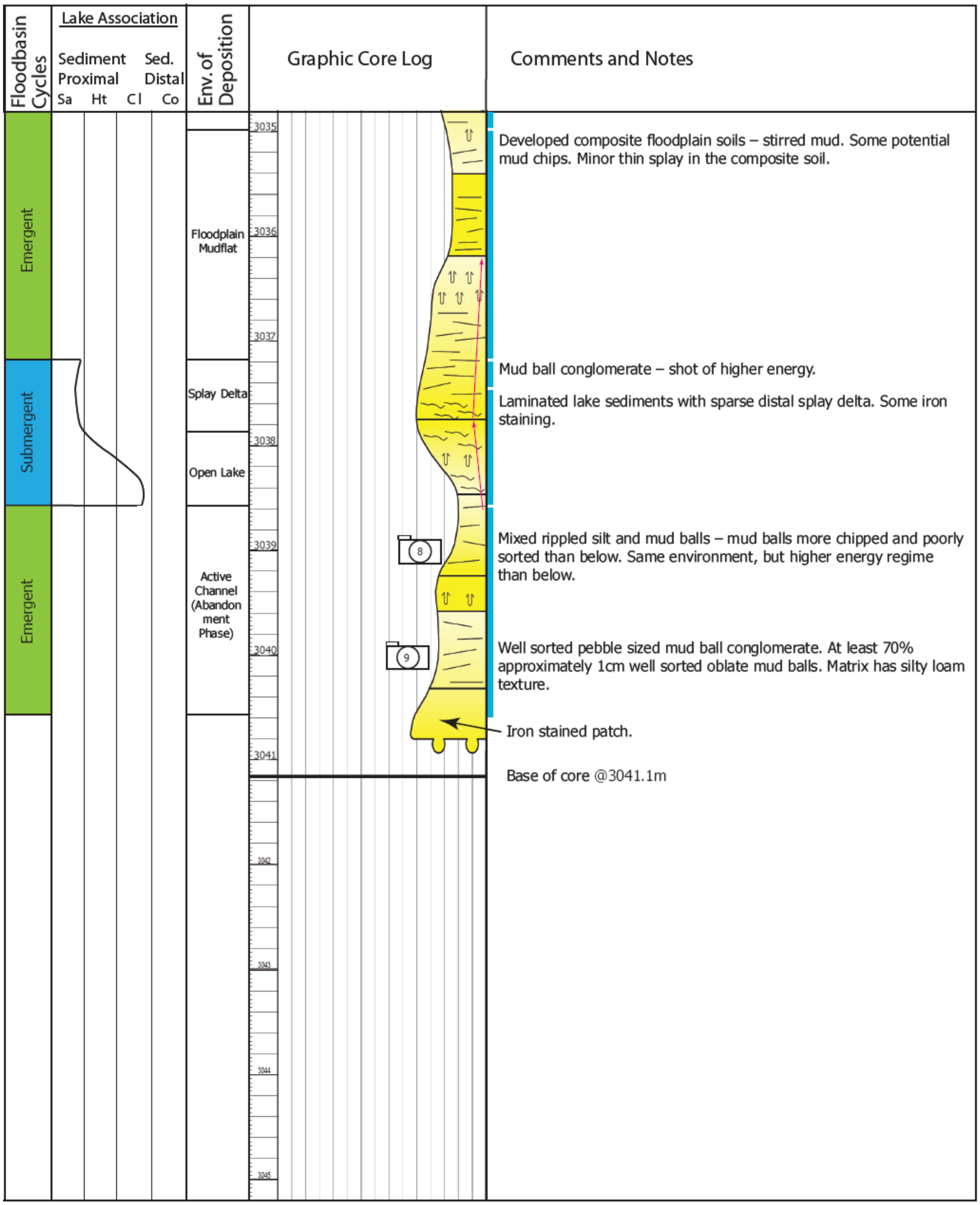
GWA-03 Core Review
3015 - 3025 m



GWA-03 Core Review
3025 - 3035 m



GWA-03 Core Review
3035 - 3041 m



Core Photos GWA03 - Panel 2

~3020.2m - Ripple scale mud drapes in active channel.

3027.9 - Scour with pyrite lag into clean lake.

~3028.5m - Open lake with minor rooting.

~3030.8m - Hyperpycnal scour with ripple scale bed forms into open lake.

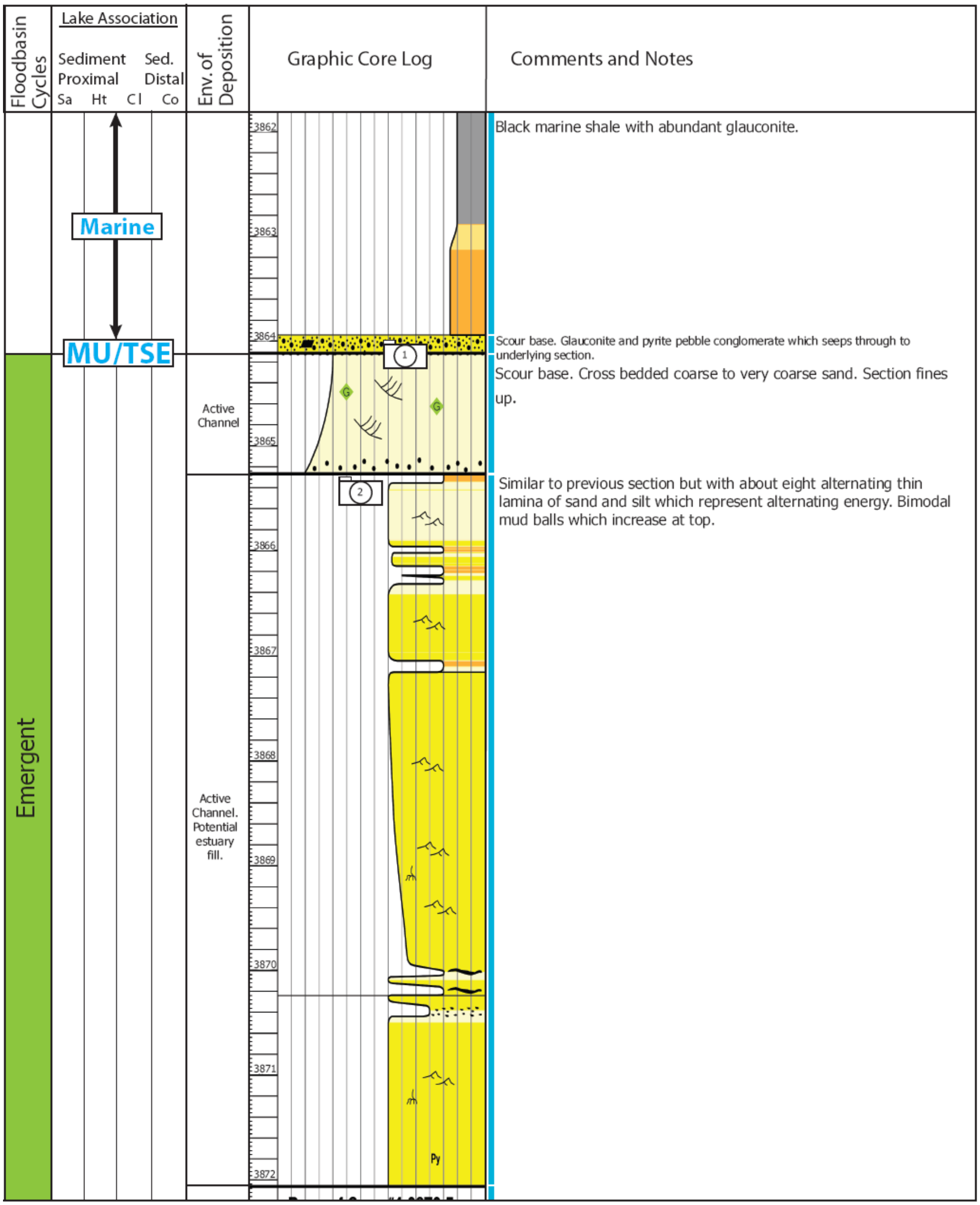
~3039m - Mudchips in abandonment phase of active channel (lazy river).

~3040m - Round mudballs in abandonment phase of active channel (lazy river).

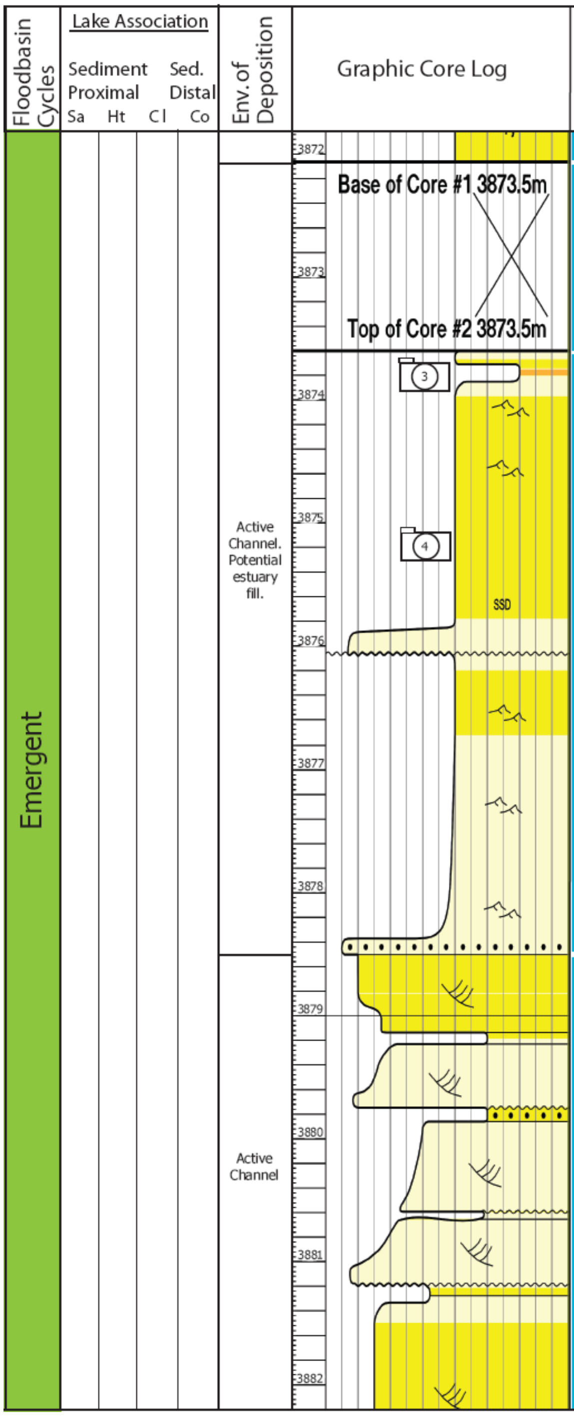
APPENDIX B

GWA-02 CORE REVIEW

GWA-02 Core Review
3862 - 3872 m



GWA-02 Core Review
3872 - 3882 m



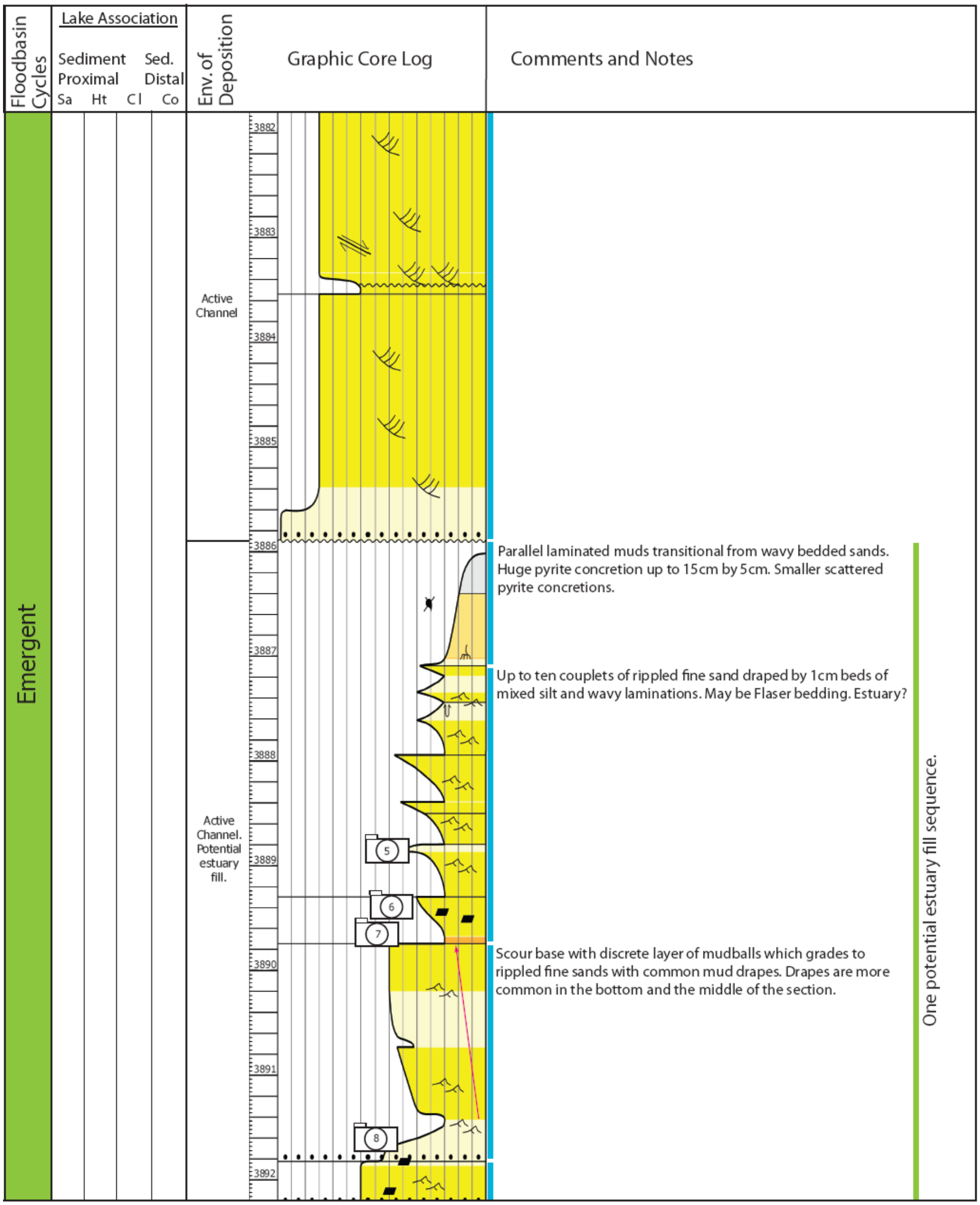
Comments and Notes

Rubble with desernable couplets similiar to previous section.

Scour base. Granular-sand conglomerate grading to small scale rippled fine sand with minor scattered drapes. Scattered mud balls in two distinct sizes. 25cm dots and large ones up to 4.0cm. Approximately bimodal. Possible couplet sets of sand and mud balls at 3874.3m and 3873.5m. Estuary?

Scour base. Planar laminations grading up to cross bedded coarse sand. Granular mm scale foreset drapes – 2 to 3 per meter.

GWA-02 Core Review
3882 - 3892 m



Core Photos GWA02 - Panel 1

3864.1m - JO/MU.

3865.3m - Bi-modal mud balls in wavy discontinuous laminated sand. Abandonment phase.

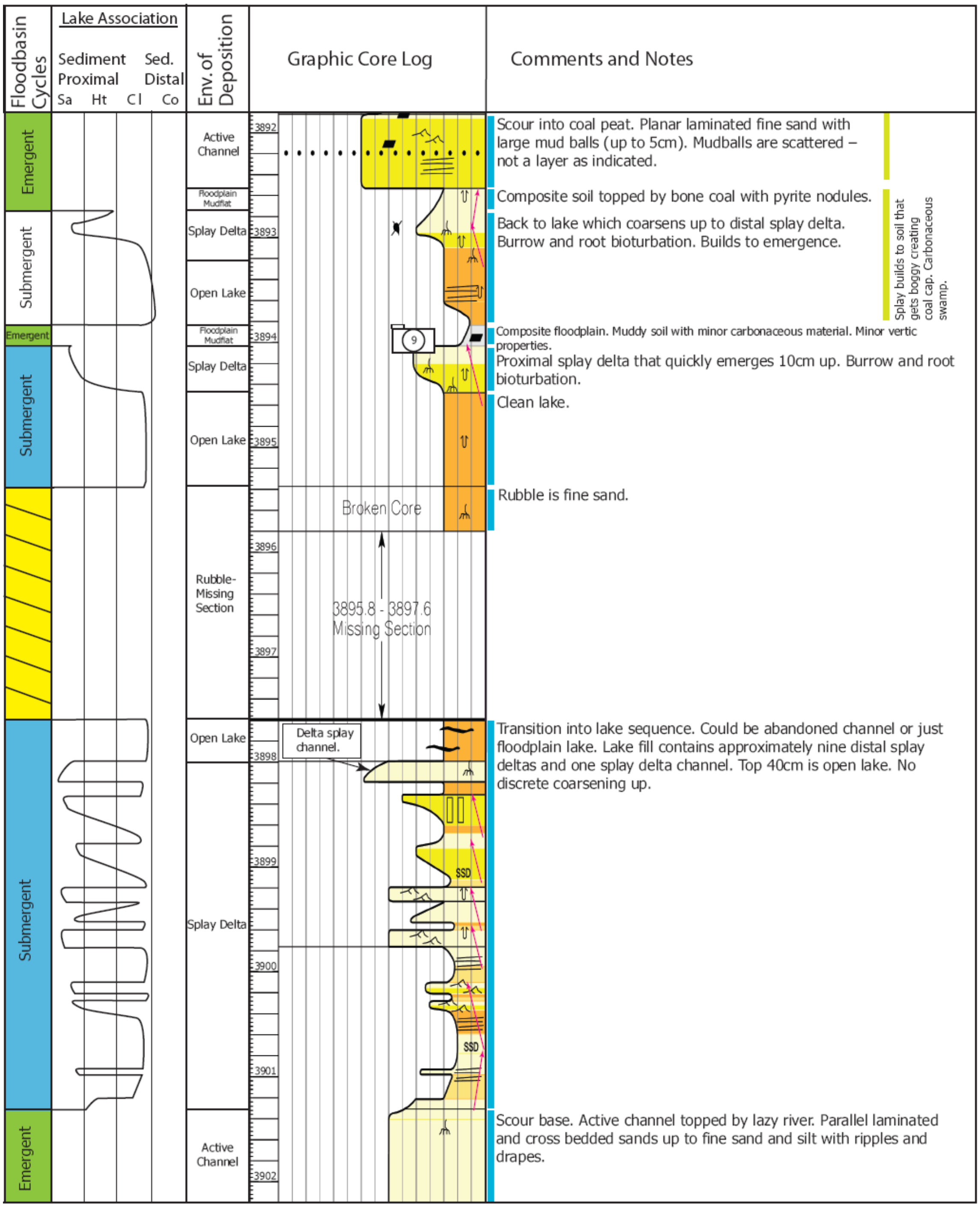
3873.8m - Couplet set with rippled sand and mud drapes. Another couplet set at 3874.3m.

3875.2m - Mud balls in wavy laminated sand.

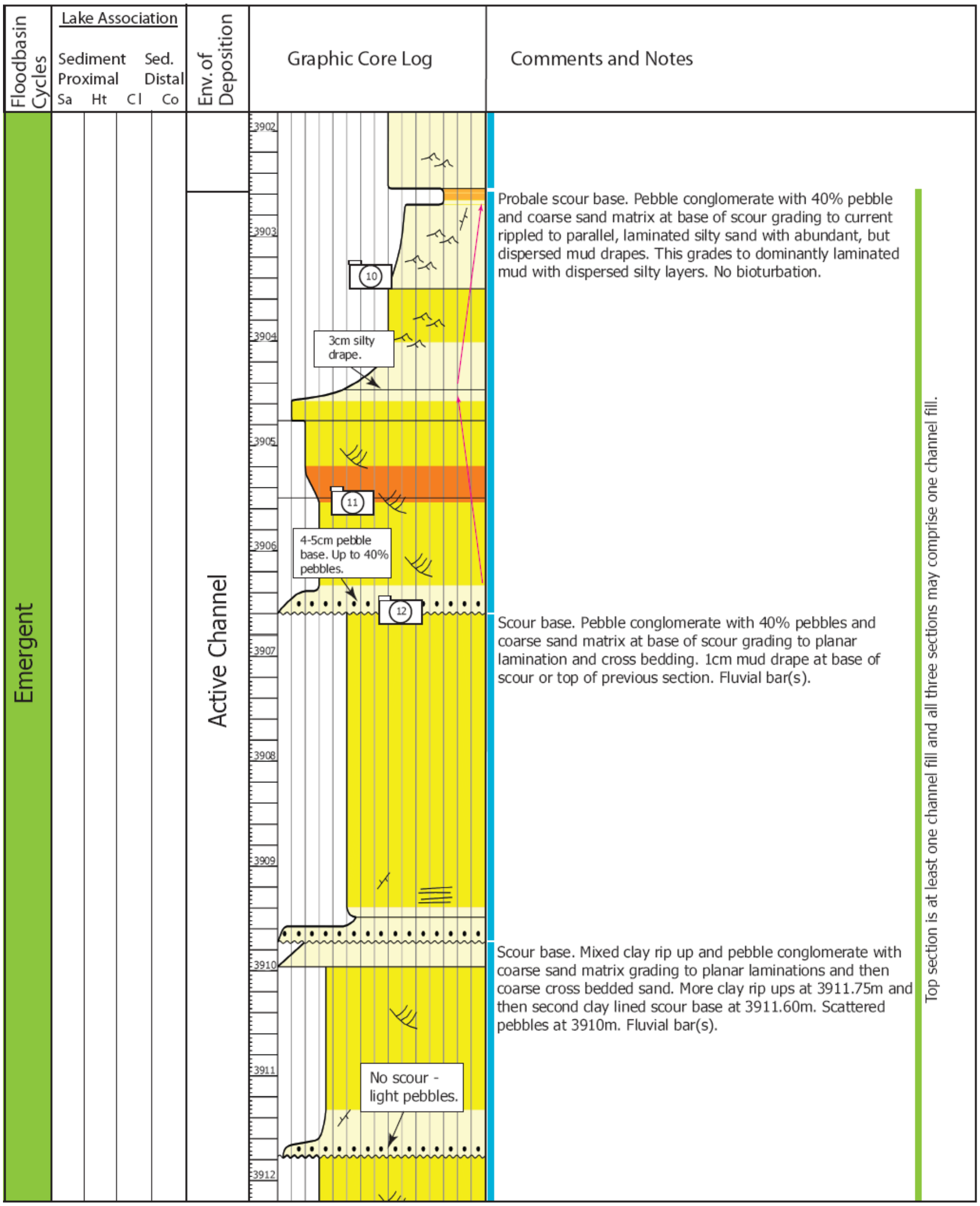
3888.8m - Couplet set in possible estuary fill.

3889.5m - Base of couplet set in possible estuary fill.

GWA-02 Core Review
3892 - 3902 m



GWA-02 Core Review
3902 - 3912 m



Core Photos GWA02 - Panel 2

3889.7m - Scour surface in rippled sand.

3891.7m - Mud rip up layers in cross-bedded sand.

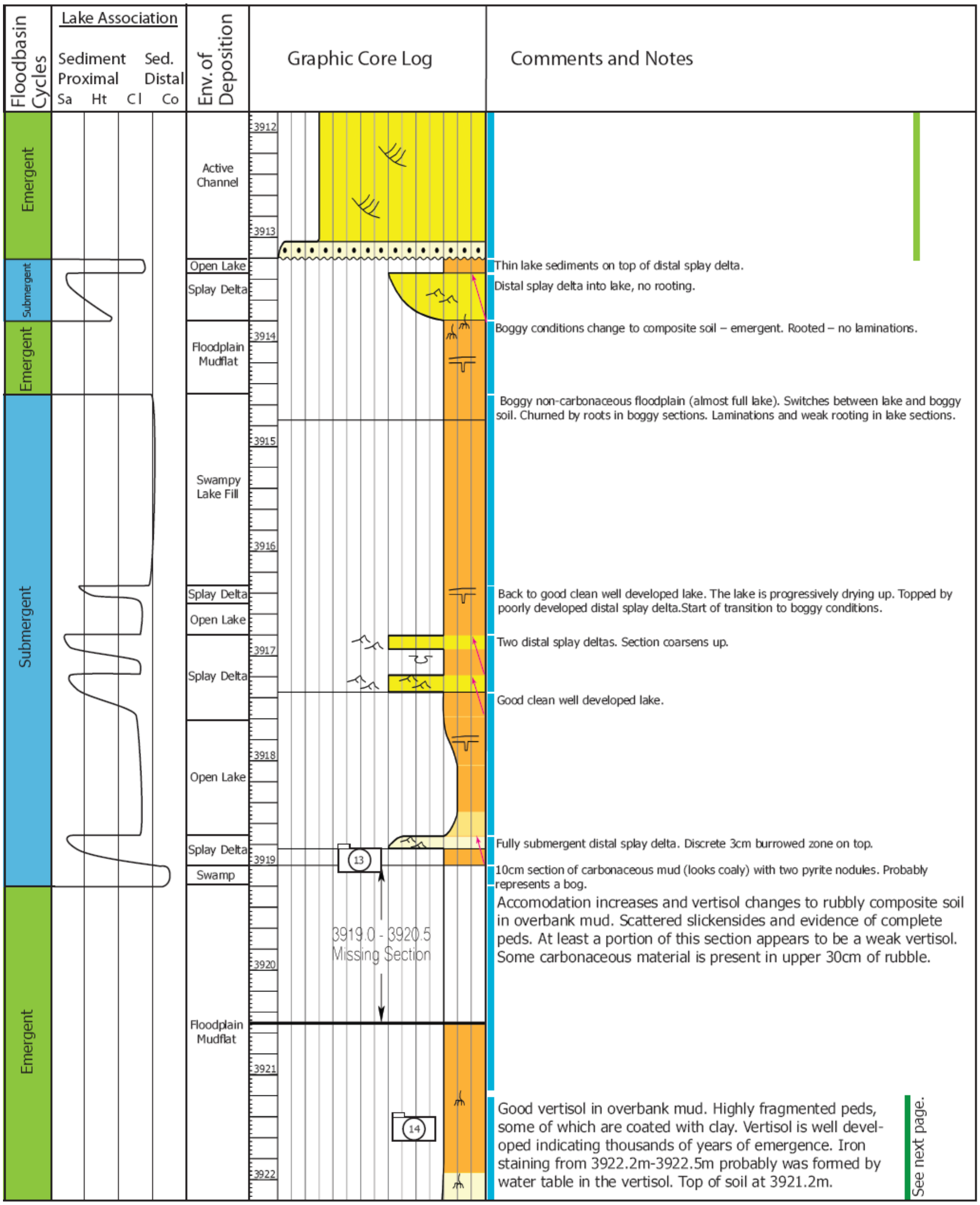
3893.9m - Isolated mud ball in cross-bedded sand.

3903.4m - Planar to wavy laminated fine to medium sandstone with a few ripples. Abundant clay drapes Abandoned river fill.

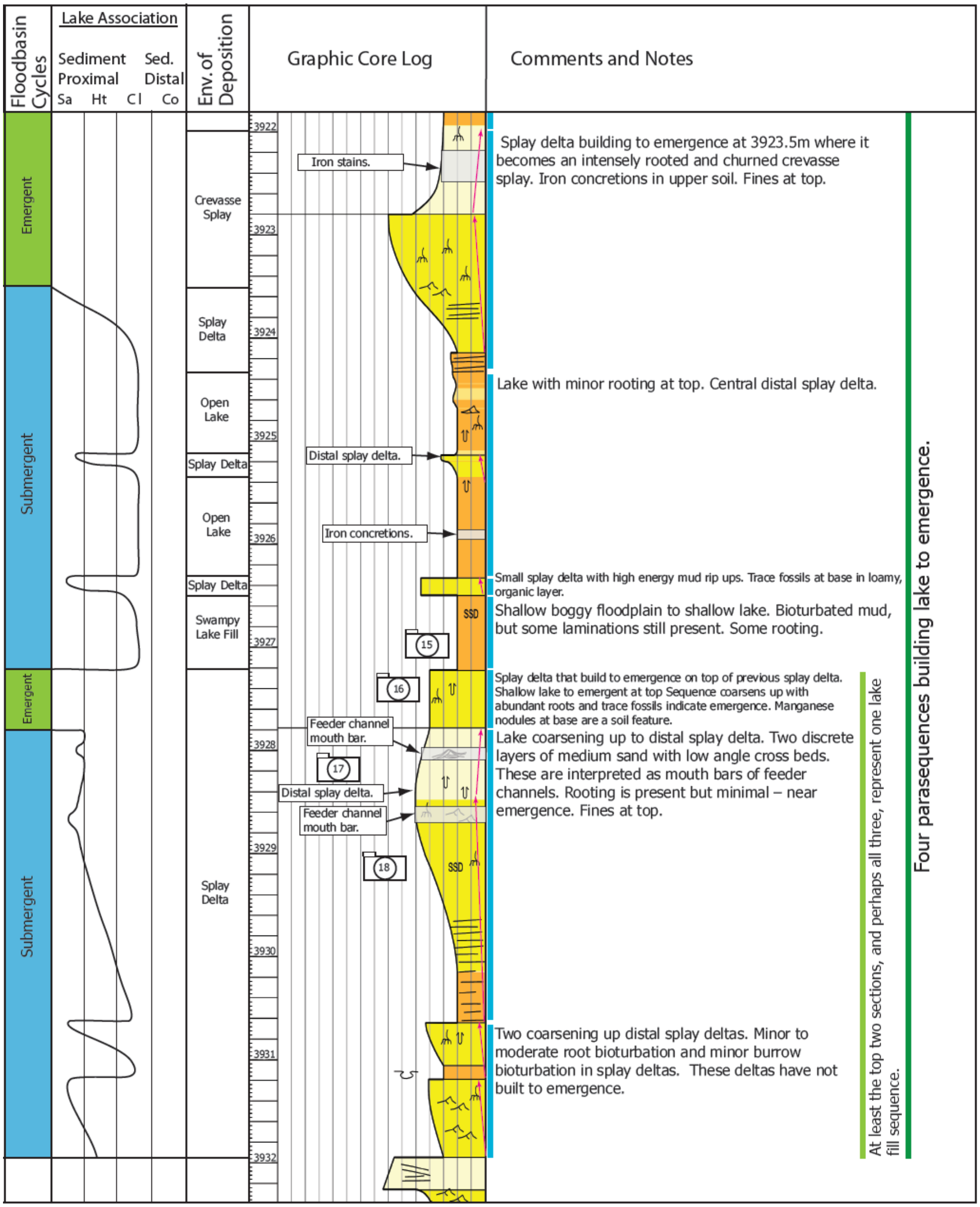
3905.5m - Cross-bedded coarse sand. Active channel fill..

3906.5m - Scour base with gravel lag.

GWA-02 Core Review
3912 - 3922 m



GWA-02 Core Review
3922 - 3932.4 m



Core Photos GWA02 - Panel 3

3919.3m - Bioturbation in distal splay delta.

3921m - 3922m - Vertisol with iron stain. iron stain represents top of water table.

3927m - Small splay delta within boggy to lake transition. Bioturbation at base of splay and thin coaly lamina at top.

3927.5m - Root developed in boggy floodplain above emergent splay.

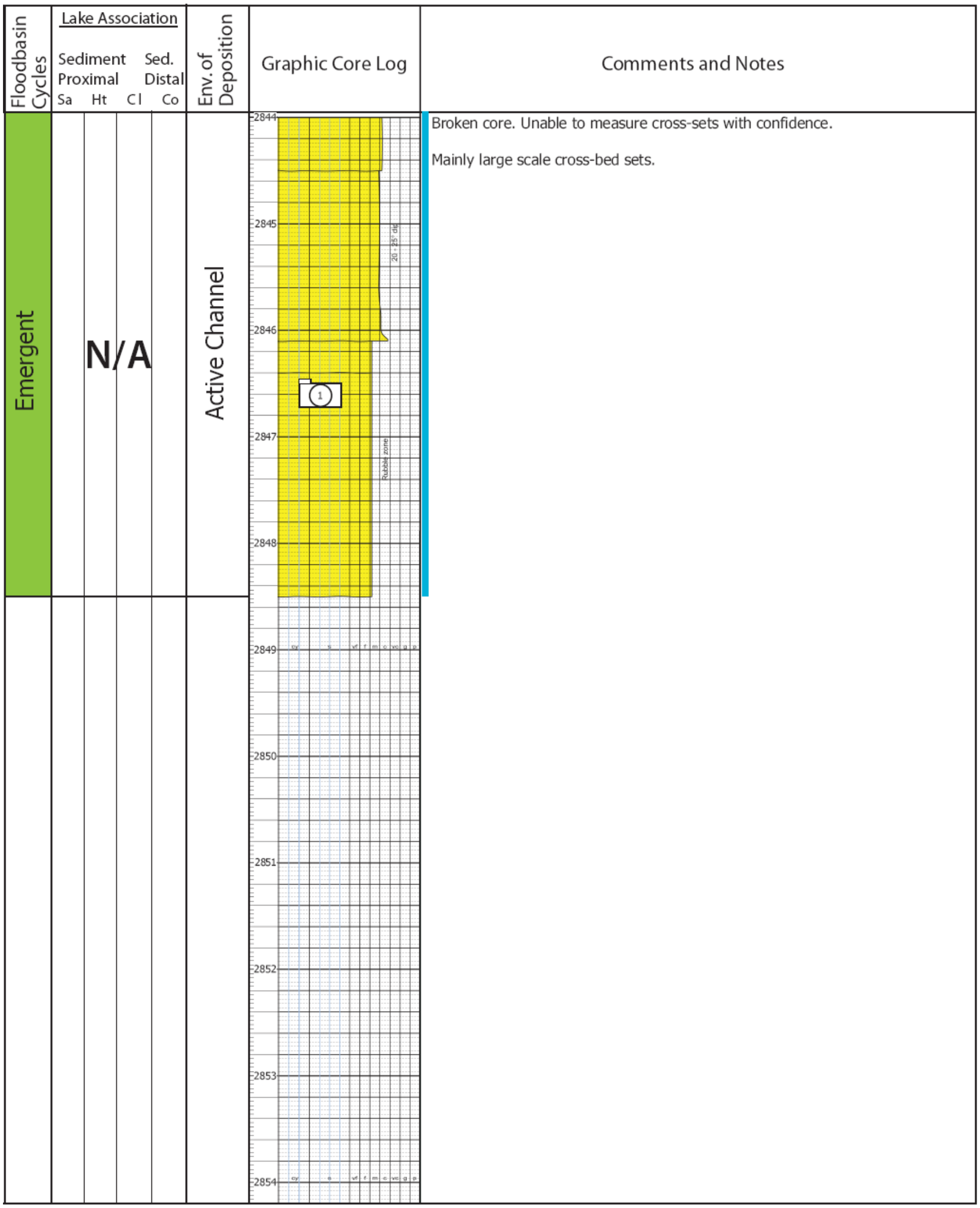
3928m - Bioturbated splay delta which has become emergent. Magnanese nodules present which are soil feature.

3929m - Sedimentary structures with minor rooting in distal splay delta. Thick central sand is likely a feeder channel.

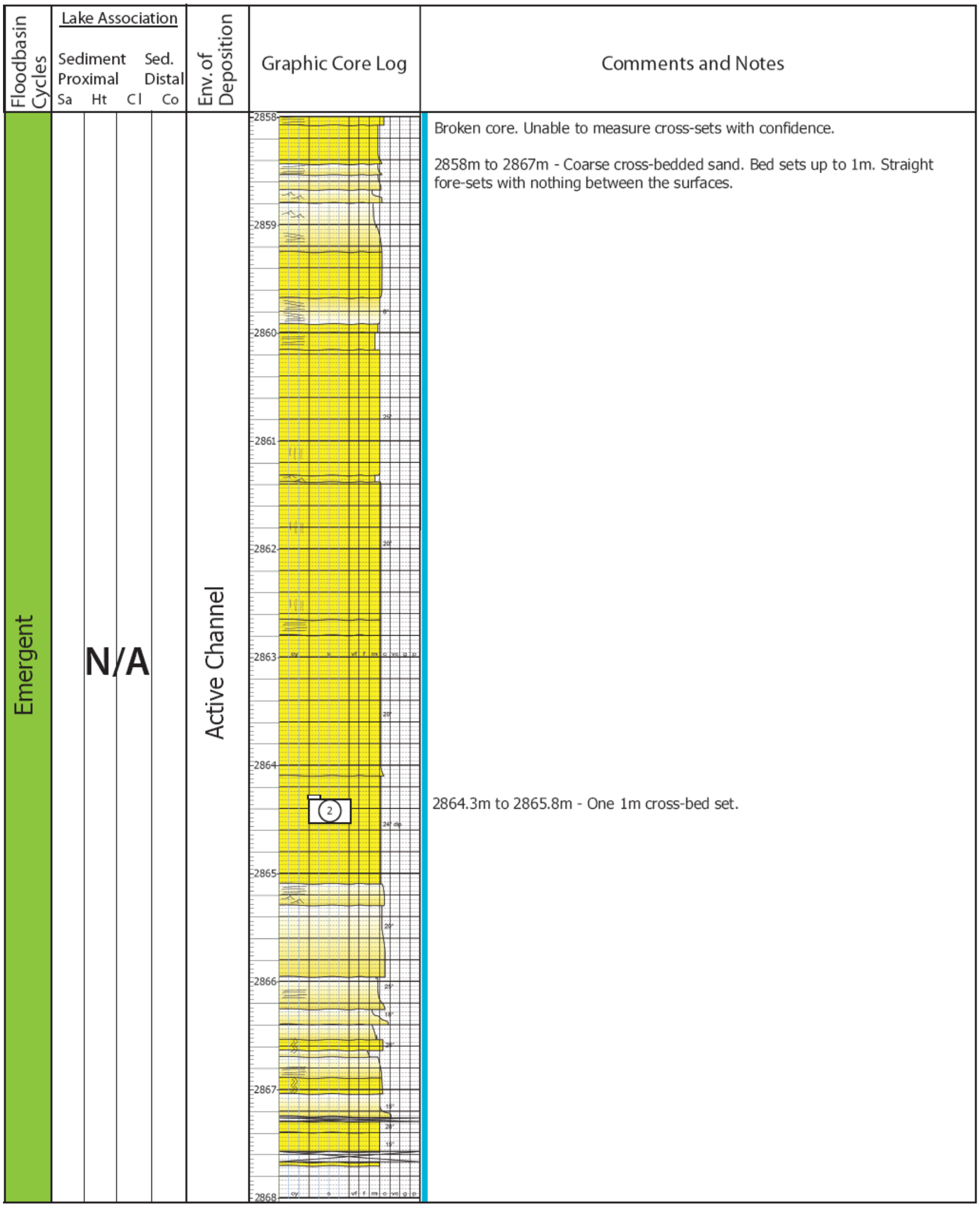
APPENDIX C

GOODWYN 8 CORE REVIEW

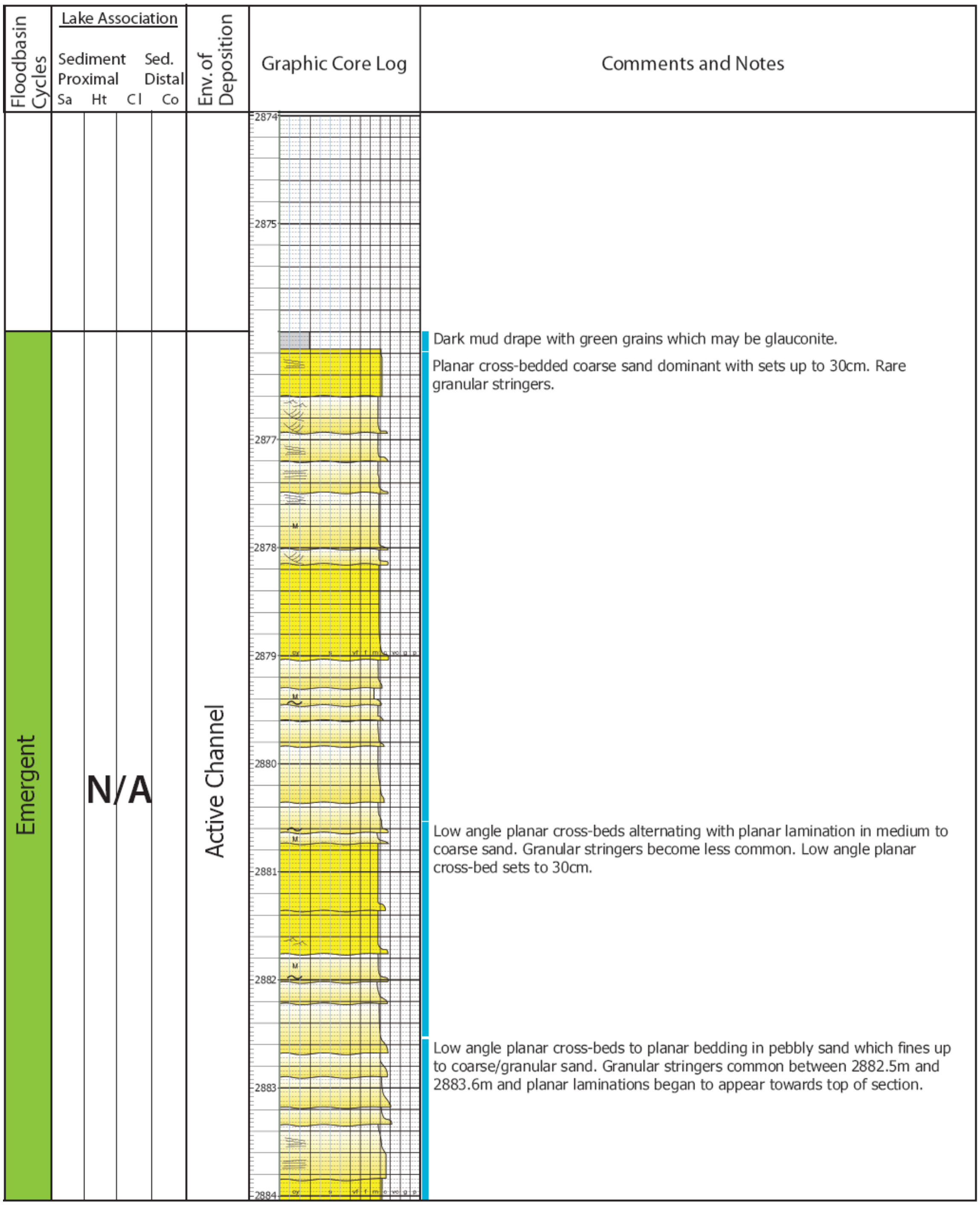
Goodwyn-8 Core 1 Core Review
2844 - 2848.5 m



Goodwyn-8 Core 2 Core Review
2858 - 2867.71 m



Goodwyn-8 Core 3 Core Review
2876 - 2884 m



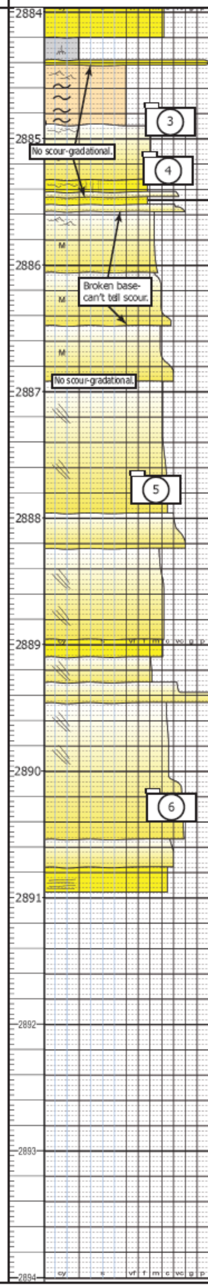
Goodwyn-8 Core 3 Core Review
2884 - 2890.97 m

Floodbasin Cycles | Lake Association: Sediment Proximal – Sed. Distal (Sa, Ht, Cl, Co) | Env. of Deposition | Graphic Core Log | Comments and Notes

Floodbasin Cycles: Emergent

Lake Association: N/A

Env. of Deposition: Active Channel



Mud dominated with minor rooting. Oxbow lake fill.

Rippled silt in center of section sandwiched by two mud rip-up conglomerates and topped by granular burst which is gradational from mud rip-up.

Missing core.

Small scale ripples with scattered mud drapes and mud chip rip-up clasts.

Parallel laminated with mm scale mud drapes

Pebbly planar cross-bedded sand grading into parallel laminated sands and washed out dunes at @ 2886m. Granular stringers at 2886.8m, 2886.6m and 2885.5m.

Some mud rip-ups and external chert pebbles, but no discrete scour.

Pebbly sand conglomerate at base grading up to pebbly planar cross-bedded sand.

3.8m channel fill and abandonment. Extremely variable flow conditions in a coarse system with abandonment resulting in mud deposition. Granular bursts may be significant breaks or just part of the flow.

Gravel scour base grading up to low angle cross beds in very pebbly sand. Continues grading up into low angle cross beds in slightly less pebbly sand. Grain size variation, but no noticeable breaks representing one unit with variable energy. Capped with 10cm muddy drape. Possible break at 2888.25m as gravel is picked up in new cross bed set. This is not necessarily a new bar scour, but probably represents variable energy. Overall represents sandy bar unit with muddy cap.

Base is 5.0cm thick pebble conglomerate lag. Pebbles up to 2.0cm – 3.0cm. Grades up to planar cross-bedded medium sand. Two 10cm cross bed sets. Sandy unit bar.

Parallel laminated to low angle cross-bedded pebbly conglomerate composed of up to 20% pebbles. Pebbles up to 2.0cm to 3.0cm. Poorly sorted and poorly consolidated. Abundant shrinkage cracks. Fines up to coarse planar cross-bedded sand with a few granule sized mm scale stringers. Truncated gravely unit bar.

Pebble conglomerate grading up to pebbly sand. Planar laminated to thinly bedded. Interpreted as one truncated gravely unit bar.

Core Photos Goodwyn 8

2846.6m - Granular cross-bed between two slighty less granular parallel laminated sets.

2864.4m - Meter scale cross-beds.

2884.9m - Rippled sand with mud drapes and mud rip-ups.

2885.3m - Mud rip-up conglomerate and silty ripples.

~2887.8m - Muddy sand cap or drilling Mud?

2890.3m - Muddy conglomerate.

APPENDIX D

YODAL 2 ARCHITECTURAL ANALYSIS

"See Supplemental File"

APPENDIX E

GWA-03 ARCHITECTURAL ANALYSIS

"See Supplemental File"

APPENDIX F

PLUTO 2 CH1 ARCHITECTURAL ANALYSIS

"See Supplemental File"

APPENDIX G

FLOODPLAIN LAKE STUDY

"See Supplemental File"

APPENDIX H

CHANNEL/CHANNEL BELT ATTRIBUTES

"See Supplemental File"

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