Sedimentological Lithofacies, Internal Architecture and Evolution of Deep Marine Fans of the Tithonian Angel Formation, Northwestern Dampier Sub-basin, North West Shelf, Australia

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6 Lithofacies Associations and Related Depositional Elements

6.1 Introduction

The examination of cores in Chapter 5 resulted in the classification of eleven lithofacies based on lithology and sedimentological structure. This chapter groups the interpreted lithofacies into lithofacies associations indicative of particular depositional elements. These depositional elements are further classified into fourth, fifth and sixth order architectural units (Chapters 7 and 8).

A particular depositional element can be inferred by a distinctive association of lithofacies, however it is not solely the lithofacies varieties within the lithofacies association that determines a depositional element but also the location of the lithofacies association in relation to its neighbours. The eleven core lithofacies can be assembled into two primary classifications containing a total of seven lithofacies associations:

Table 6-1: Lithofacies associations and related lithofacies from Chapter 5.

Lithofacies Association (Chapter 6)			Lithofacies (Chapter 5)
Channelised Lithofacies Associations	FA1	Crevasse Splays	C, D, E and F
	FA2	Channel Axis Fill	A
	FA3	Channel Margins and Levees	A, B, D, G and H(?)
	FA4	Channel Abandonment	E and F
Unchannelised Lithofacies Associations	FA5	Sand-Dominated Frontal Splays	A, B, D, G, H and K
	FA6	Silt-Dominated Frontal Splays	D, E, F, G, H and K
	FA7	Splay Abandonment	F

The lithofacies associations and their related depositional elements are interpreted at a high resolution, i.e. frontal splays are interpreted to represent deposition from a distributary channel mouth and crevasse splays are dominantly unchannelised.

Prior to the classification and discussion of lithofacies associations, it is imperative to recognise that a preserved lithofacies association within core can be dependent on its depositional location basinward of the sediment source. Many features (i.e. channel dimensions) of a deep marine depositional system change with increasing distance downslope from the shelf. Understanding the downslope process variability of individual flow events and hence the lithofacies associations they create is important in order to correctly interpret and classify them.

6.2 Two-Dimensional Basinward Transition of Lithofacies Associations

Many process-related relationships are assumed when analysing the range of lithofacies associations present within the Angel sandstone (Figure 6-1 and 6-2).

i.   Sand-dominated weakly cohesive debris flows rapidly transform to high density turbidity flows and low density turbidity flows with increasing transport distance downslope (Figure 6-1).

ii.   An erosive channel system will transform downslope into a mixed erosive and depositional channel system and a depositional channel system respectively (Figure 6-1).

iii. Channel confinement is at a maximum in proximal settings (canyons and confined channel complexes). It decreases downslope as channel systems become less erosive and more depositional, resulting in the development of levees. The channel system will eventually become depositional and levees non-existent (Figures 6-1 and 6-2).

iv.   Due to the confinement relationship (iii), flow overspill outside channel systems will increase downslope as the degree of confinement decreases (Figures 6-1 and 6-2)

v.   As overspill outside of channel systems increases downslope, the ratio of preserved channel margin and levee deposits to the channel axis deposits increases downslope as a function of decreasing channel width/depth and increased accumulation of sediments on the margins (Figure 6-2). The highest ratios are concentrated around shallow distributary systems and pinch out regions of the depositional fan.

vi.   In relation to the flow transformation relationship (i), the ratio of mud to sand volume within a flow unit increases downslope. This results to an increased concentration of clay and silt in levees which will lead to a downslope increase in channel sinuosity (Figure 6-1).
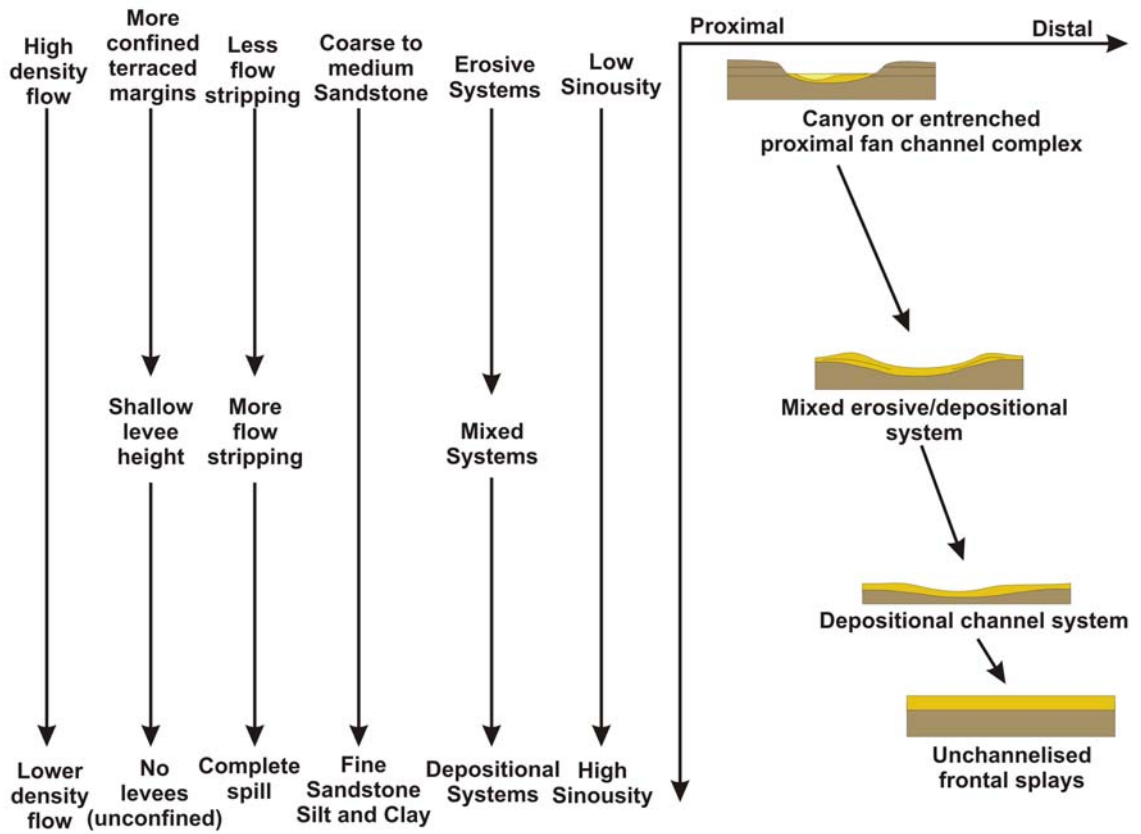
Figure 6-1: The downslope transition of parameters common in deep marine settings such as flow confinement, sinuousity, degree of overspill and sediment type. A simple downslope profile is assumed.
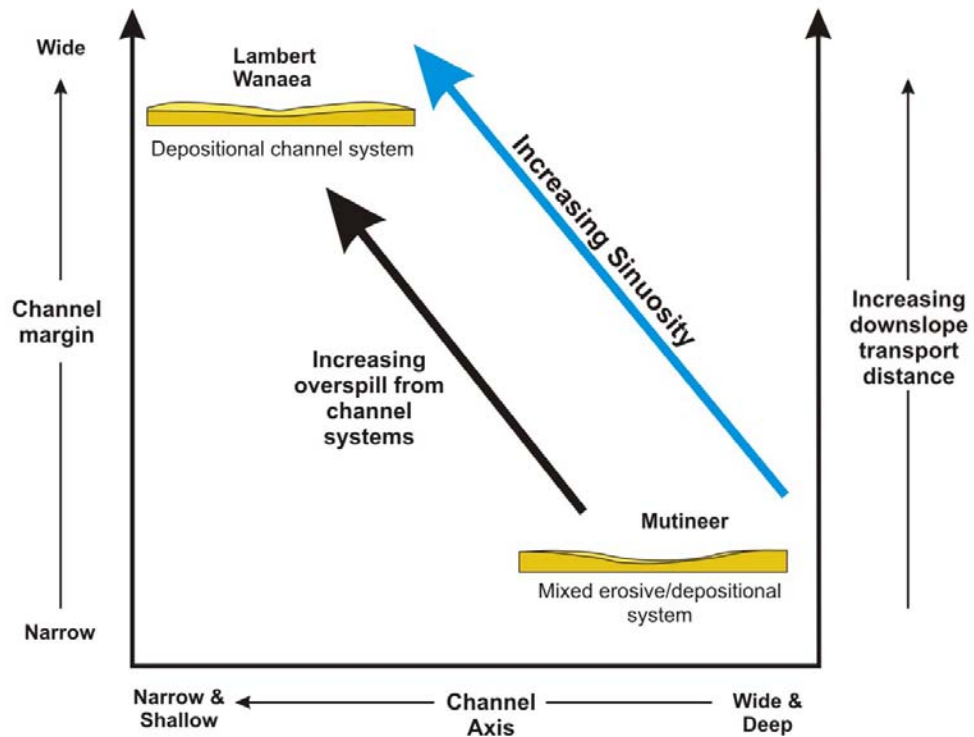

Figure 6-2: Relationship between channel axis and margin size with increasing downslope transport distance. As gravity flow events flow downslope, they become less erosive and more depositional, resulting in a decrease in channel axis width and depth. This results in an increase in flow overspill which forms the channel margin deposits.

6.3 Channelised Lithofacies Associations

Channelised lithofacies associations represent those associations that are related to submarine channel processes. This includes mixed depositional and erosional leveed channels together with leveed and non-leveed distributary channels and crevasse splays. Four channelised lithofacies associations are recognised. They are:

- crevasse splays and overbank sedimentation;

- channel axis (or thalweg) fills;

- channel margin and levee successions, and;

- channel abandonment successions.

These channelised lithofacies associations represent the building blocks that form the slope and distributary channel systems within the larger channelised frontal splays of Posamentier (2003).

6.3.1 Lithofacies Association 1: Crevasse Splays

This association comprises thin interbedded successions of laminated units of Lithofacies D with concentrations of carbonaceous material grading into the heterolithic and mudstone-dominated units of Lithofacies E and F (Figure 6-3).

Crevasse splays can (Figure 6-3):

- display a finer grain-size distribution than the dominant grain-size of channelised successions;

- display either a fining upward or a coarsening upward grain-size trend;

- share basal contacts with heterolithic, siltstone or mudstone-dominated beds or with channel fill or channel margin sandstones of lithofacies associations 2 and 3;

- have upper contacts that can be either erosional with the overlying structureless and structured sandstones of Lithofacies A and B or conformable with overlying thickly bedded frontal splay successions. They can grade into overlying bioturbated heterolithic units;

- range in thickness from a few centimetres to over two metres in thickness, and;

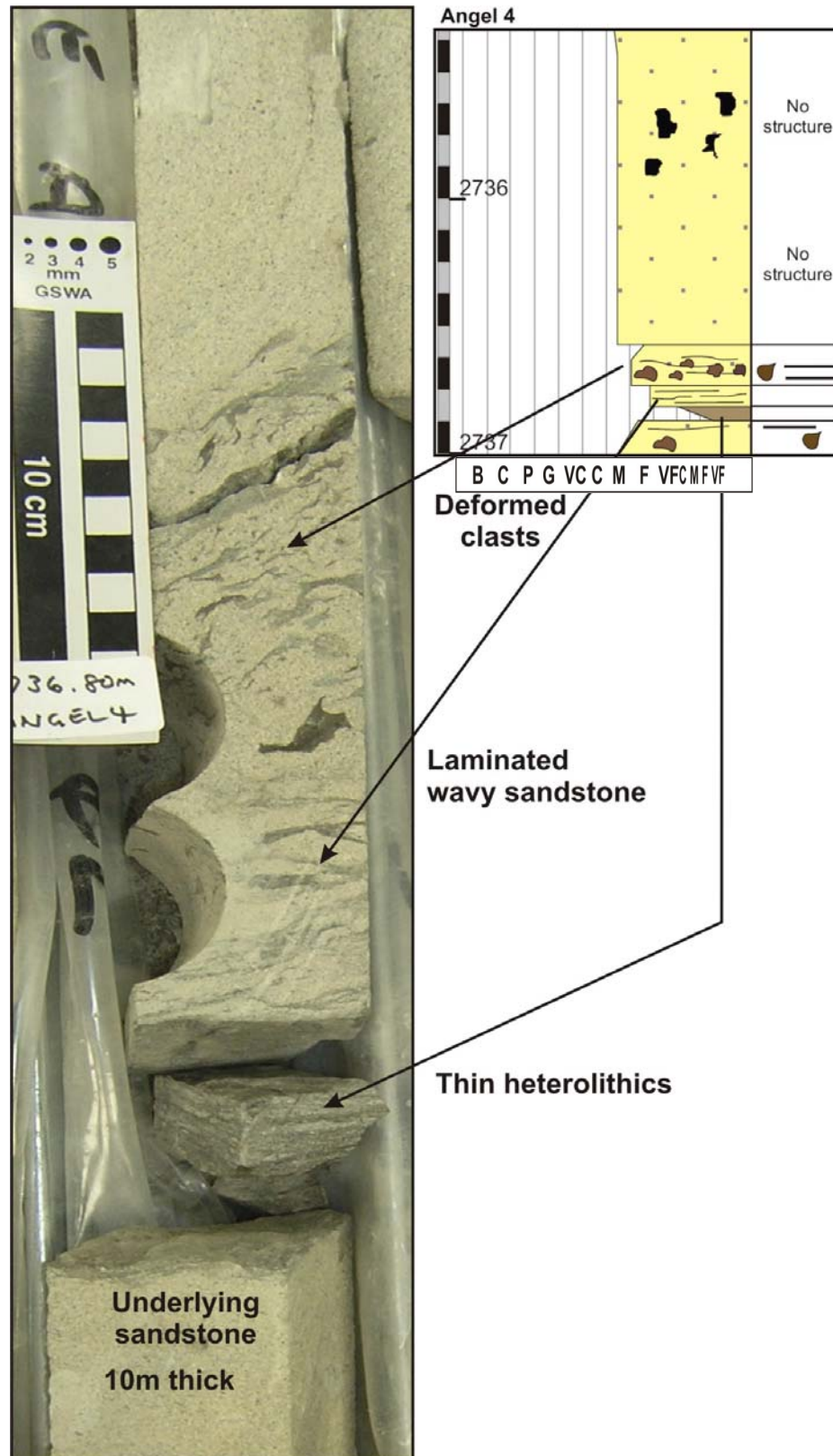- stack to form multi-storey splays.

Figure 6-3: Amalgamated crevasse splay units from Angel-4. Note the coarsening upward trend of the stacked unit in Angel-4. Deformed clasts could be interpreted as being created through fluidisation processes from adjacent overpressured channel forms. They may also represent a hybrid flow event. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.
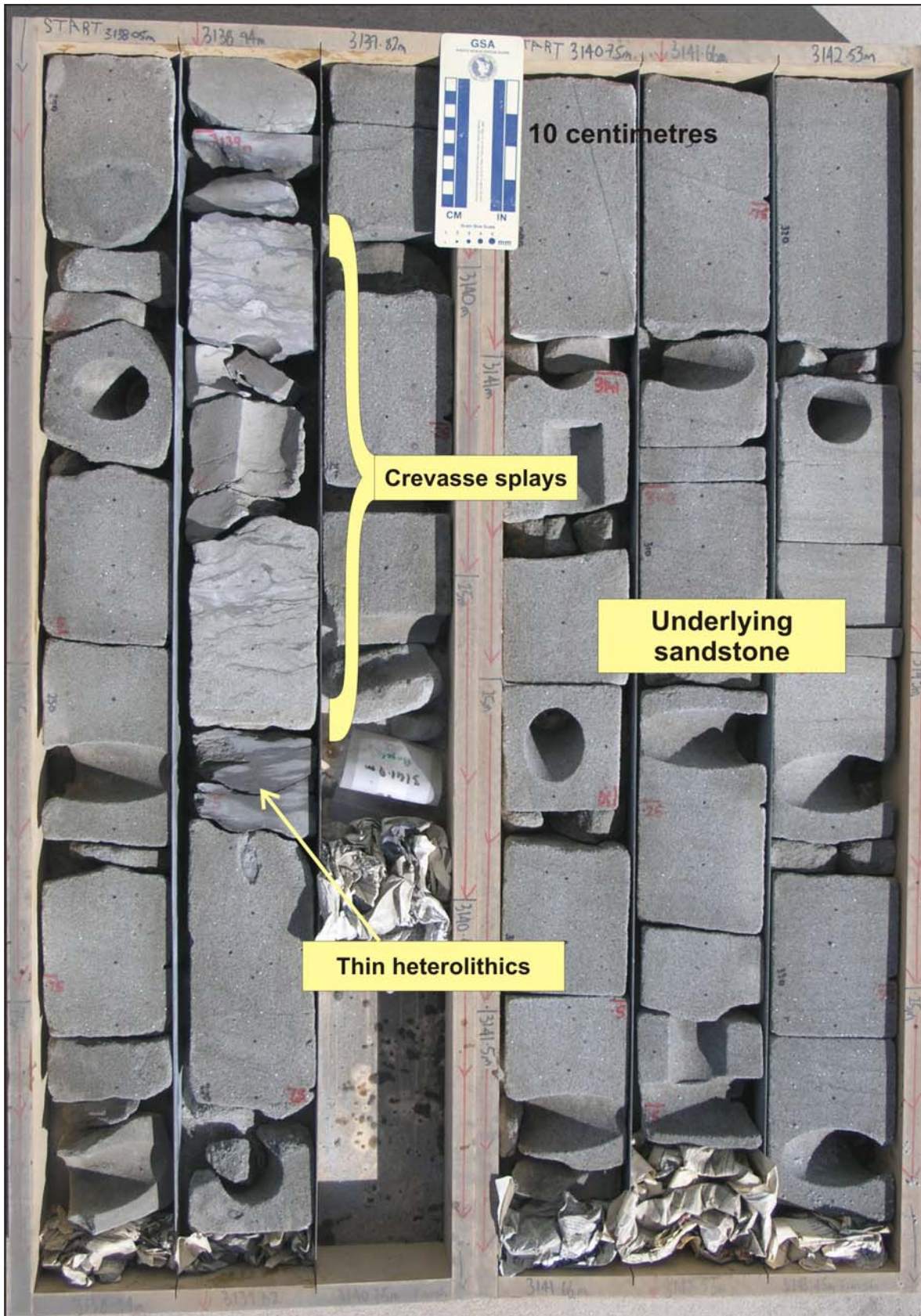
Figure 6-4: Crevasse splays from Mutineer-1B. They overlie a thin heterolithic section that overlies a thick sandstone approximately 12 metres thick.

Crevasse splays are thin-bedded turbidites deposited on overbank settings. They form through the process of flow stripping or overspill from an adjacent channel system (this would not apply if the deposit is a hybrid flow). Flow stripping is a sedimentological process where stratified turbulent flows are hydraulically separated at channel bends. The more turbulent component of the flow overtops the channel margin and levee, depositing onto overbank settings (Piper and Normark, 1983) (Figure 6-5 and 6-6). Flow stripping occurs either when turbidity currents are volumetrically large in relation to channel depth or when they flow within a sinuous channel with sharp bends. The rate of supply of turbiditic flow stripped events to overbank regions is interpreted to become enhanced downslope as channelised systems become increasingly less confined (refer Section 6.2).

Figure 6-5 (right): Process of flow stripping from channel systems (modified from Peakall *et al.,* 2000a;2000b; Piper and Normark, 1983; Timbrell, 1993)
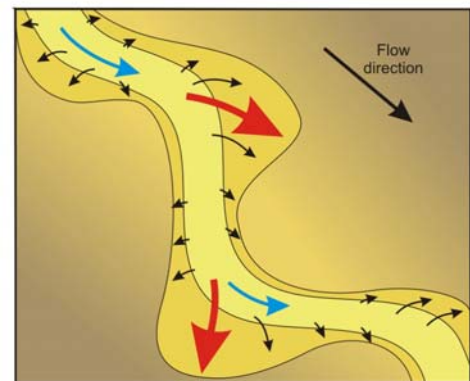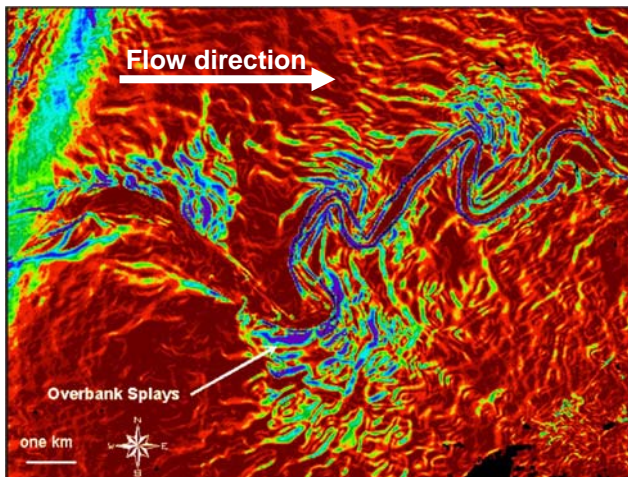

Figure 6-6 (left): Seismic example of splays formed as a result of active flow stripping concentrated around channel bends from the Makassar Strait, offshore eastern Kalimantan, Indonesia (Posamentier *et al.,* 2000a; 2000b).

Two varieties of splay were interpreted based on their vertical relationship with other associations. They are:

- progradational crevasse splays, and;
- retrogradational "overspill" splays.

Progradational crevasse splays develop during progradation in relation to channel avulsion. Flow stripping can lead to rapid deposition and infilling within the abandoned channel system near the avulsed knickpoint (Piper and Normark, 1983) which can lead to complete channel avulsion and the creation of a younger channel system. Channel compensational stacking is the key mechanism responsible for shifting the site of gravity flow pathways that cut and fill submarine channels (Gardner *et al.,* 2003) (Figure 6-7) (Section 8.3.1).
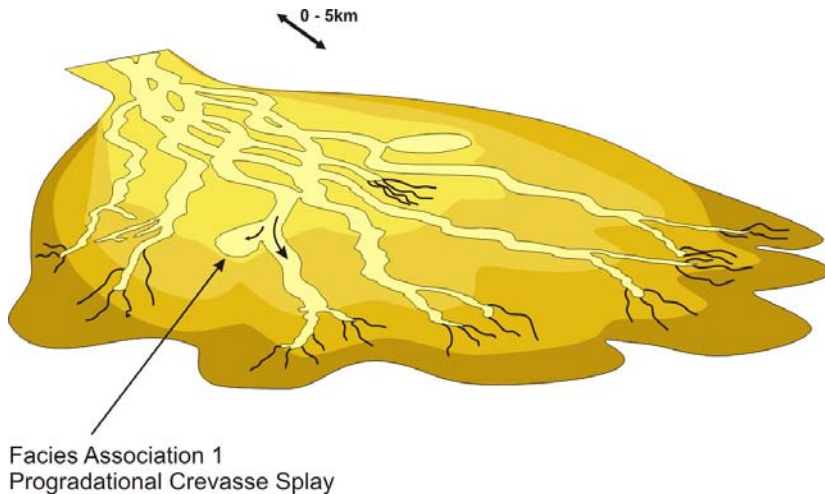
Figure 6-7: The depositional model of a progradational crevasse splay. Flow stripping processes at channel bends results in the formation of a crevasse splay. Channel avulsion has not occurred at this point in time (fan modified from Johnson *et al.,* 2001).

Facies Association 1
Progradational Crevasse Splay

Retrogradational overspill crevasse splays are created in relation to the infilling of depositional channel systems. The frequency of flow stripping processes and the rate of sediment supply to overbank regions are related to the depth of the channel system and the increased turbulent nature of the gravity flow (which increases over time from its initiation). Backfilling of channel systems occurs through transgression, resulting in a reduction in levee height which further results in an increase in sand-dominated overspill outside channel systems. These units are typically associated with unchannelised frontal splay successions as it is difficult to differentiate between them in the core. These units are commonly stacked and are more thickly-bedded than progradational crevasse splays. They are comparable to the spill-over lobes recognised in the Upper Carboniferous Ross Formation of Western Ireland (Elliot, 2000; Lien *et al.,* 2003).

Flow stripping and crevasse splay deposits have been documented by many researchers in the Navy Fan of California, the Palaeogene successions of the North Sea, the Annot sandstones of southeast France and deep marine systems offshore Indonesia (Piper and Normark, 1983; Sinclair and Tomasso, 2002; Fildani *et al.,* 2006; Peakall *et al.,* 1998; Posamentier *et al.,* 2000; Timbrell, 1993).

6.3.2 Lithofacies Association 2: Channel Axis (or Thalweg) Fill

These successions are represented by thick-bedded, unstructured to normally graded very coarse grained to medium-grained sandstone of Lithofacies A with or without lags (Figure 6-8 and 6-9). They can:

- appear ungraded but occasionally grade vertically from lag to unstructured sandstone;

- display a sharp basal bedding contact recognised by an abrupt vertical lithofacies change from bioturbated heterolithic or siltstone to medium- to coarse-grained well- to moderately-sorted sandstone;

- display the occasional consolidation lamination that represents a loaded contact between depositional flow events;

- be amalgamated or bedded with channel margin and levee sediments of Lithofacies Association 3;

- display a high sandstone net-to-gross (N:G);

- overlie all varieties of lithofacies, and;

- range from 50 centimetres to over 9 metres (amalgamated) in thickness.

These successions represent amalgamated channel fills deposited by high density sand-dominated turbidity flows. Basal channel lags are interpreted to be deposited by erosive sand-dominated high density turbulent flows that can cut and load channels with lags whilst continuing to transport the finer sediment constituent downslope (Figure 6-10). Deposition of homogenous unstructured channel fills is interpreted to represent the backfilling of the axial region of the channel system during late lowstand and transgressive periods of time (Figure 6-10). Sandstones with gradual upward gradients suggest conspicuous backfilling in relation to retrogradation of the depositional system. Stacked amalgamated successions of channel axis fills with associated lags are clearly recognised within Egret-2, Montague-1, Angel-4, Mutineer-1B and Mutineer-3. Amalgamated channel fill successions with no associated lags are identifiable within all wells.
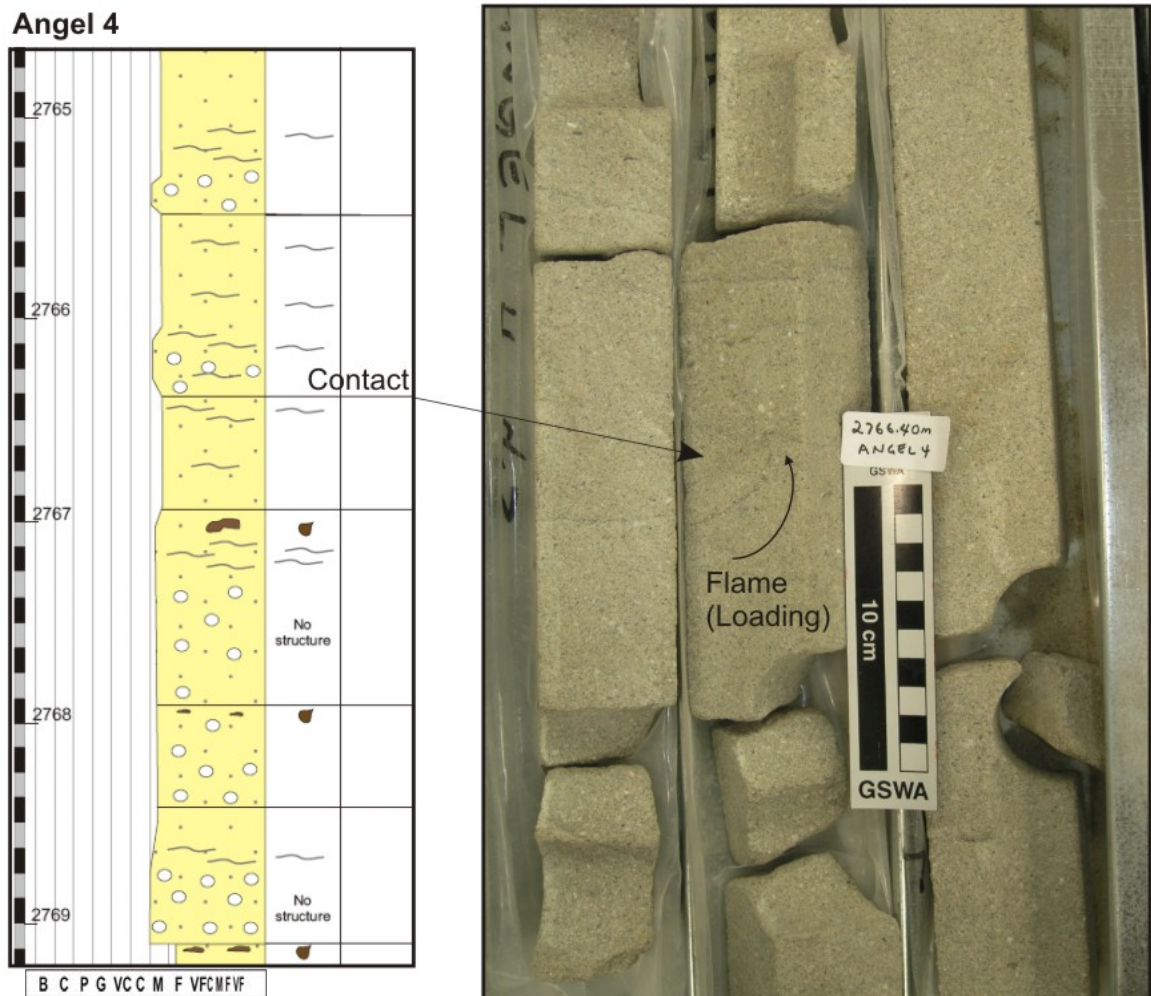

Figure 6-8: Channel fill succession with associated lags from Angel-4. Note that even though channel bases are considered erosive, this example shows density loading. This loading occurred with the non-turbulent base of a high density flow event waning and loaded both the erosive contact and the underlying unconsolidated sediments. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.
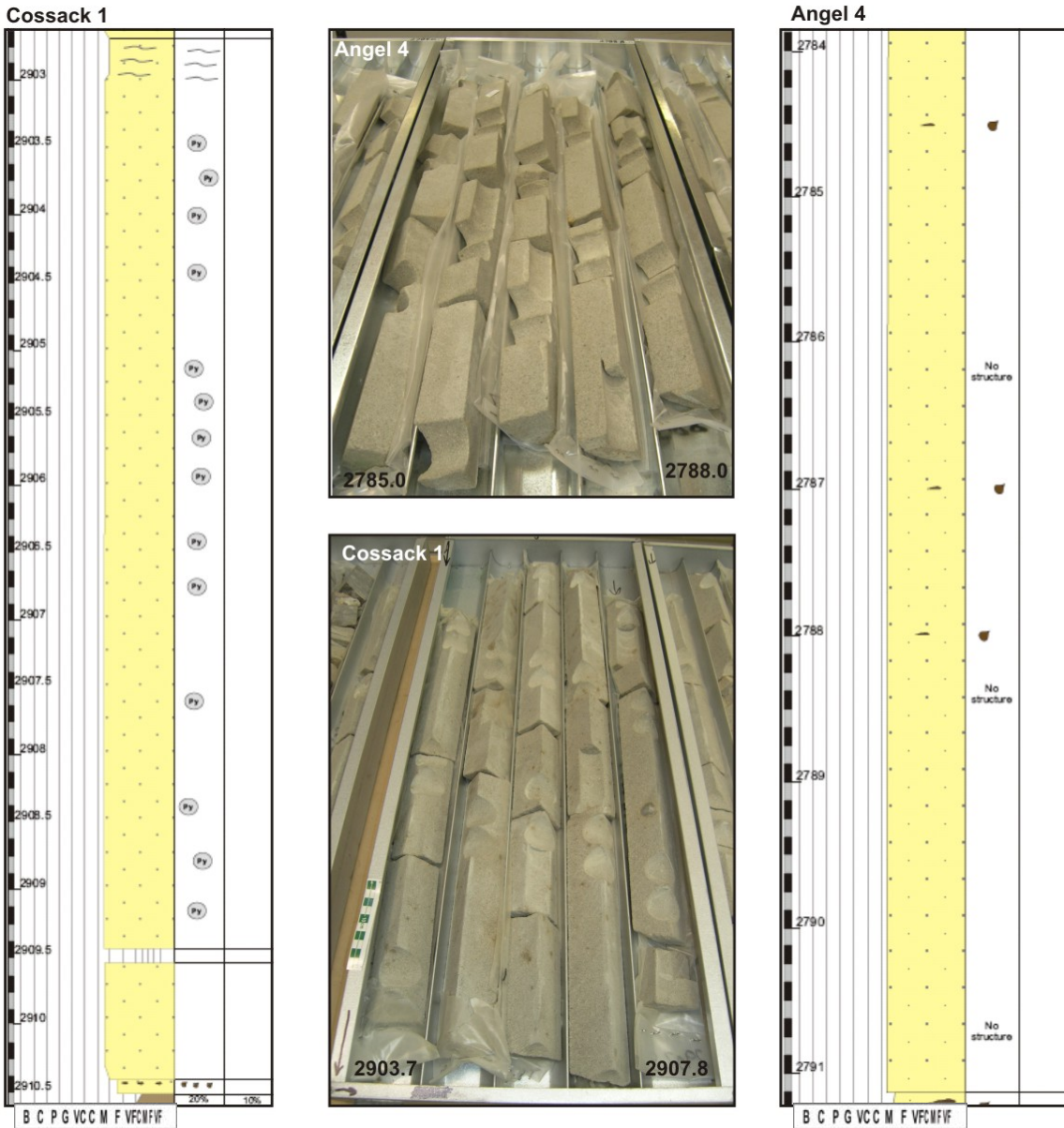
Figure 6-9: Amalgamated channel fills with no visible lag deposits from Angel-4 and Cossack-1. It represents a multistorey channel complex. Occasional faint stratification can be seen in the sandstones. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.

Channel fills with associated lags are interpreted to be either:

- more proximally located to the shelf than channel fills with no associated lags, or;

- deposited within an architecturally larger channel-levee system.

Channel fills with no associated lags are interpreted to be more representative of smaller, more distributary-like channel systems, which can be distributive or sinuous. Posamentier and Kolla (2003) proposed that a basinward transformation from distributive to sinuous channel patterns can occur in response to a decrease in the sand-to-mud ratio within turbulent flows, which is representative of the waning phase of turbidite flow channel evolution.

Individual channel fill units are interpreted to be single storey units. These units can stack to form multistorey or composite channel systems (Chapter 7). Amalgamated channel fill successions identified within Mutineer-1B, Mutineer-3 and Montague-1 clearly represent composite channel systems. The amalgamated channel fill successions recognised within Angel-4 and Cossack-1 represent stacked smaller-scaled individual channel fill successions with no preserved channel lag. They could represent channel systems that are more distributary-like than those identified within Mutineer-1B, Mutineer-3 and Montague-1.

Amalgamated sand-dominated successions mapped as channel fills formed through backfilling processes from outcrop and subsurface analogues are similar to those identified in cores from the Angel Formation. Comparable analogues include channel fills from the Issac Formation, Southern Canadian Cordillera (Schwarz and Arnott, 2007), the Ainsa systems of the Eocene Hecho Group in the Pyrenees (Clark and Pickering, 1996; Cronin *et al.,* 1998), the Tanqua Karoo Basin, South Africa (Van Der Werff and Johnson, 2003), the Brushy Canyon Complex, Texas (Gardner *et al.,* 2003) and Tertiary sediments along the West African margin (Mayall and Stewart, 2000).
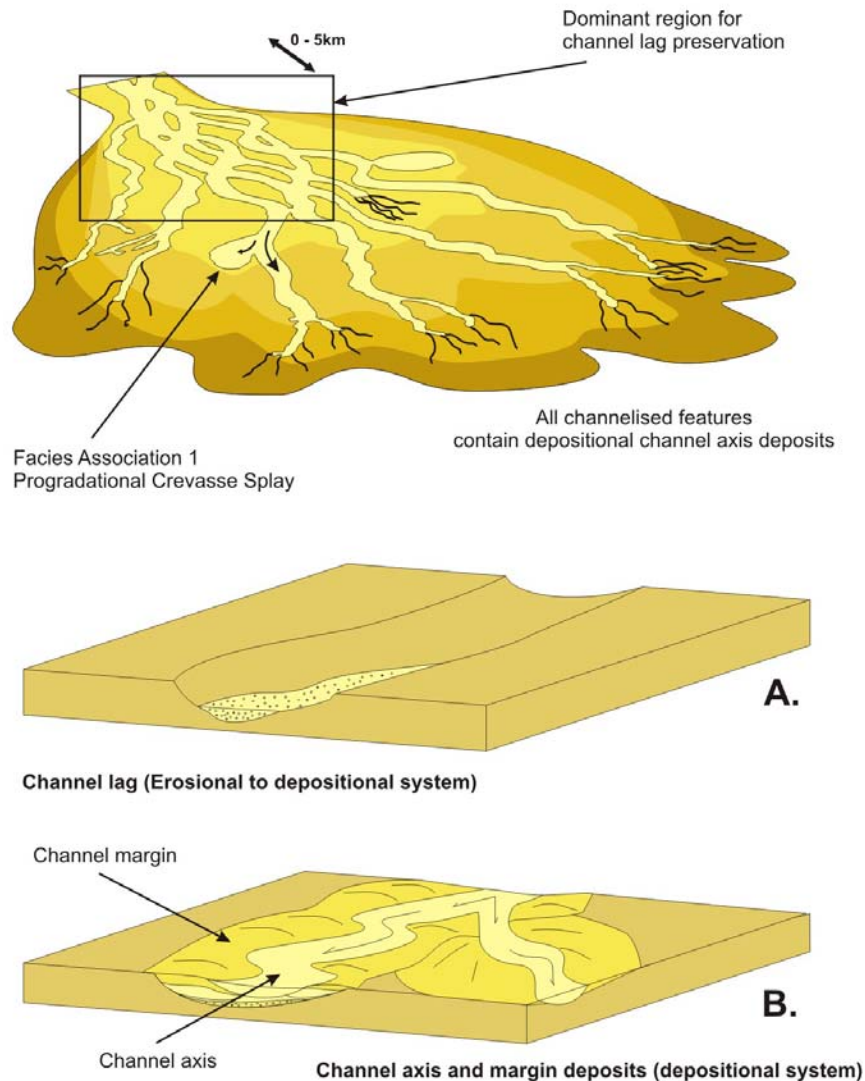

Figure 6-10: Depositional models for channel lag and axis deposits. Channel systems comprise of an erosive (A) and depositional and backfilling phase (B).

6.3.3 Lithofacies Association 3: Off-Axis Channel Successions

Off axis channel successions comprise successions of parallel stratified, dewatered, ripple/wavy laminated and silt-laminated sandstones of Lithofacies A, B and D in association with possible injected breccias of Lithofacies H (Figures 6-12, 6-13, 6-14, 6-15 and 6-16). It is important to remember that the injected breccia interpretation of Lithofacies H is one of two possible interpretations as it may also represent linked debrites which would not exist in an overbank setting. Linked debrites would differently placed in an overlying splay succession (refer Chapter 7).

These off axis channel successions can:

- overlie channel fill sandstones (Figure 6-12);

- be overlain by the erosional contacts of younger channel systems or by heterolithics and abandonment deposits (Figure 6-13);

- be interbedded with thin overbank successions which, with burial and overpressure, can possibly transform into injection breccia that is present within the margin and bar units (Figure 6-16), and;

- display dewatering features (dishes and pipes). The extent of dewatering (Lithofacies B1 to B4) is interpreted to be related to the increasing intensity of flow deposits stacking in marginal environments over time.

These successions represent overspill of turbulent flows from the main channel axis accumulating onto the channel margin and overbank environments. They are similar to crevasse splays of Lithofacies Association 1. They are often interbedded with channel fill successions, thus possibly recording their migrationary habits.

Two varieties of off-axis systems are interpreted within the Angel sandstones (Figure 6-11).

i. Channel margin units which are proximal to the axial channel system and are represented by parallel stratified and dewatered sandstones (Figure 6-12 and 6-13). They are comparable to proximal channel margin of Johnson *et al.,* (2001).

ii. Overbank units which are distal to the channel system and are represented by ripple or wavy laminated to silt-dominated laminated sandstones and siltstones (Figures 6-14 and 6-15) They can be possibly deformed into injected clasts (Lithofacies H) (Figure 6-16). If sandy, they could contain crevasse splay sediments. Ripple and wavy lamination, which is a structure commonly identified in overbank successions, was identified in several cores and ranged from tens of centimetres thick (Figure 5-25) to over one metre thick (Figure 5-32).

Figure 6-11: Cartoon illustrating the location of channel axis, channel margin and overbank settings on a mixed erosive and depositional channel system from a mid-fan setting (adapted from Johnson *et al.,* 2001 from the Karoo Sub-basin). Lateral scale is a few hundred metres to over one kilometre in width.

Channel margin units are identifiable within Egret-2, Montague-1, Lambert-2 (Figure 6-12), Mutineer-1B (Figure 6-13), Mutineer-3, Spica-1, Wanaea-2A, Wanaea-3 and Wanaea-5. They are less common within Cossack-1. Thick stacked successions of channel margin units are identifiable in Angel-4 and Egret-2 (Figures 6-14 and 6-15). Thinner silt-dominated overbank sediments are recognisable in Lambert-2, Spica-1, Exeter-5ST1, Wanaea-2A, Wanaea-3 and Wanaea-5 (Figure 6-16).
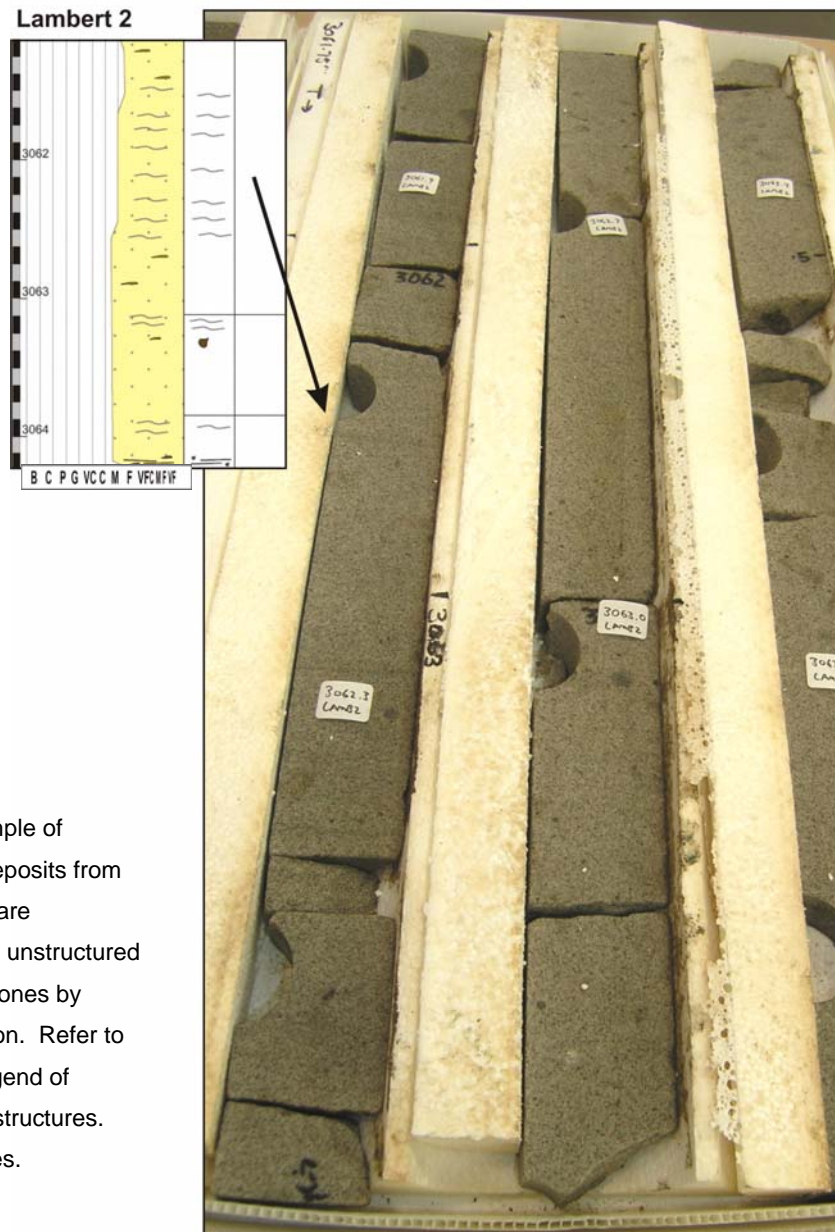

Figure 6-12: Example of channel margin deposits from Lambert-2. They are differentiated from unstructured channel fill sandstones by parallel stratification. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.

Figure 6-13: Example of channel margin deposits from Mutineer-1B. They are differentiated from unstructured channel fill sandstones by wavy parallel stratification and often dewatering. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.
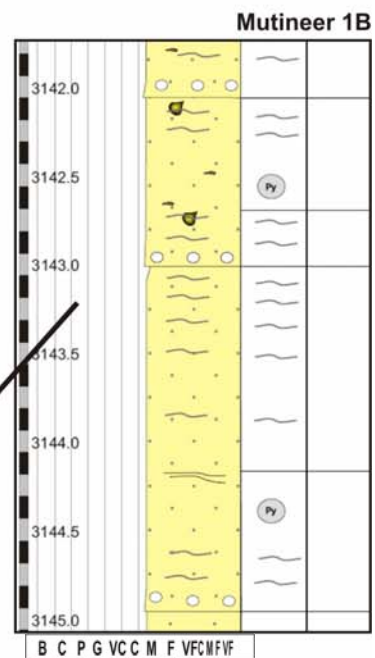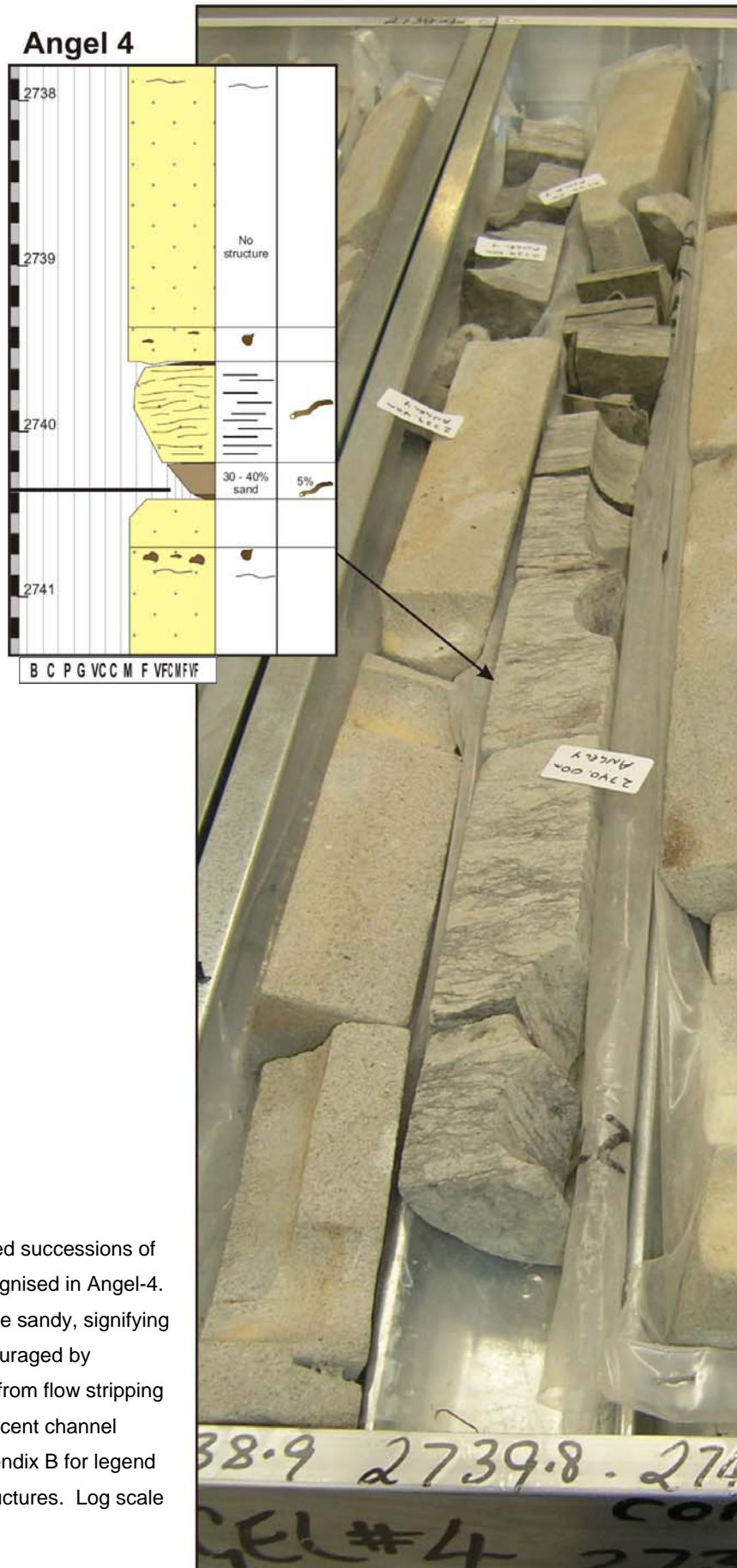
Figure 6-14: The stacked successions of overbank deposits recognised in Angel-4. These deposits are quite sandy, signifying that they could be encouraged by crevasse splay activity from flow stripping processes from an adjacent channel system.   Refer to Appendix B for legend of sedimentological structures. Log scale in metres.
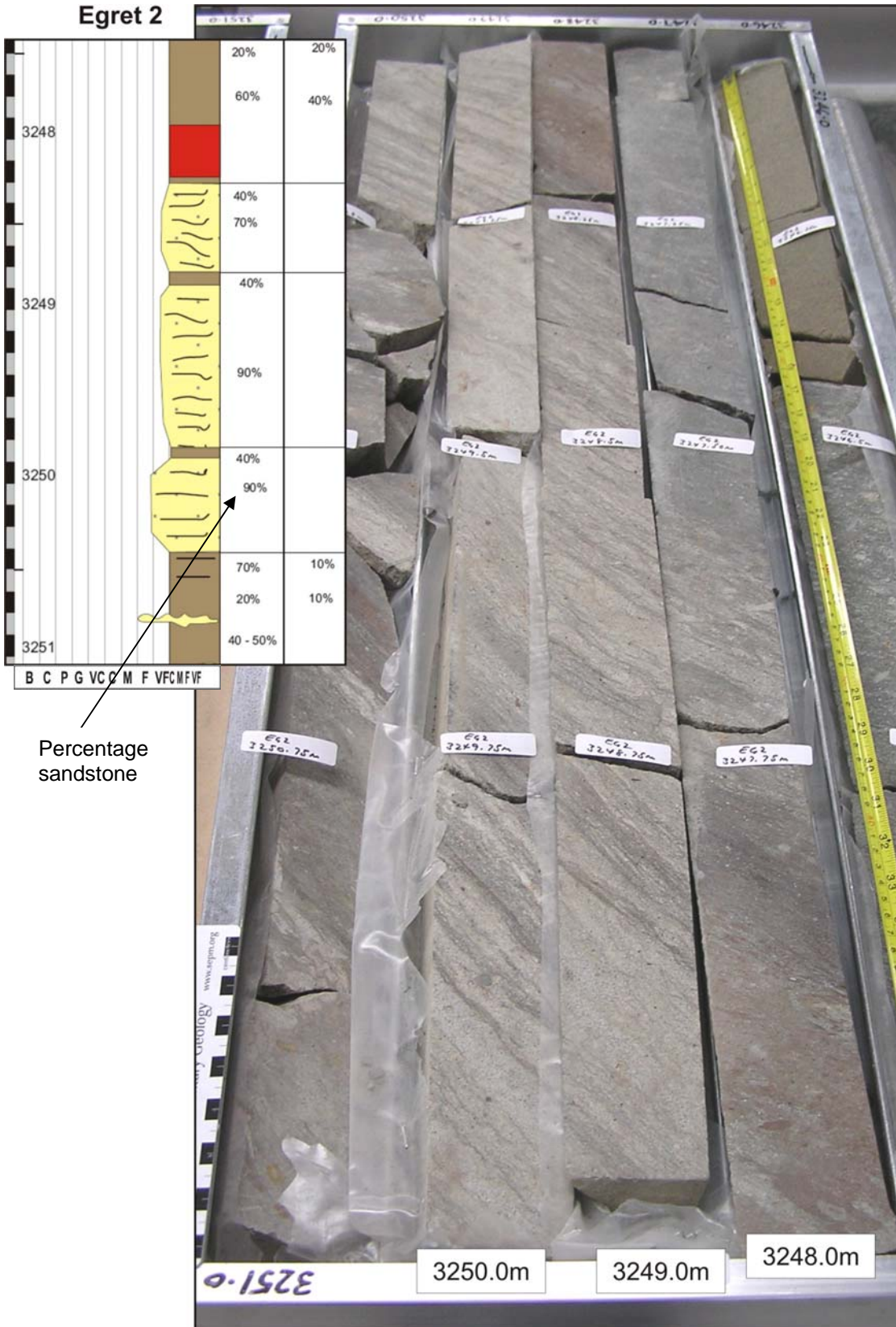
Figure 6-15: Stacked successions of overbank deposits recognised in Egret-2. Like Angel-4 (Figure 6-14), they are sandy in places suggesting that these deposits are thin crevasse splays formed from flow stripping processes from an adjacent channel system. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.
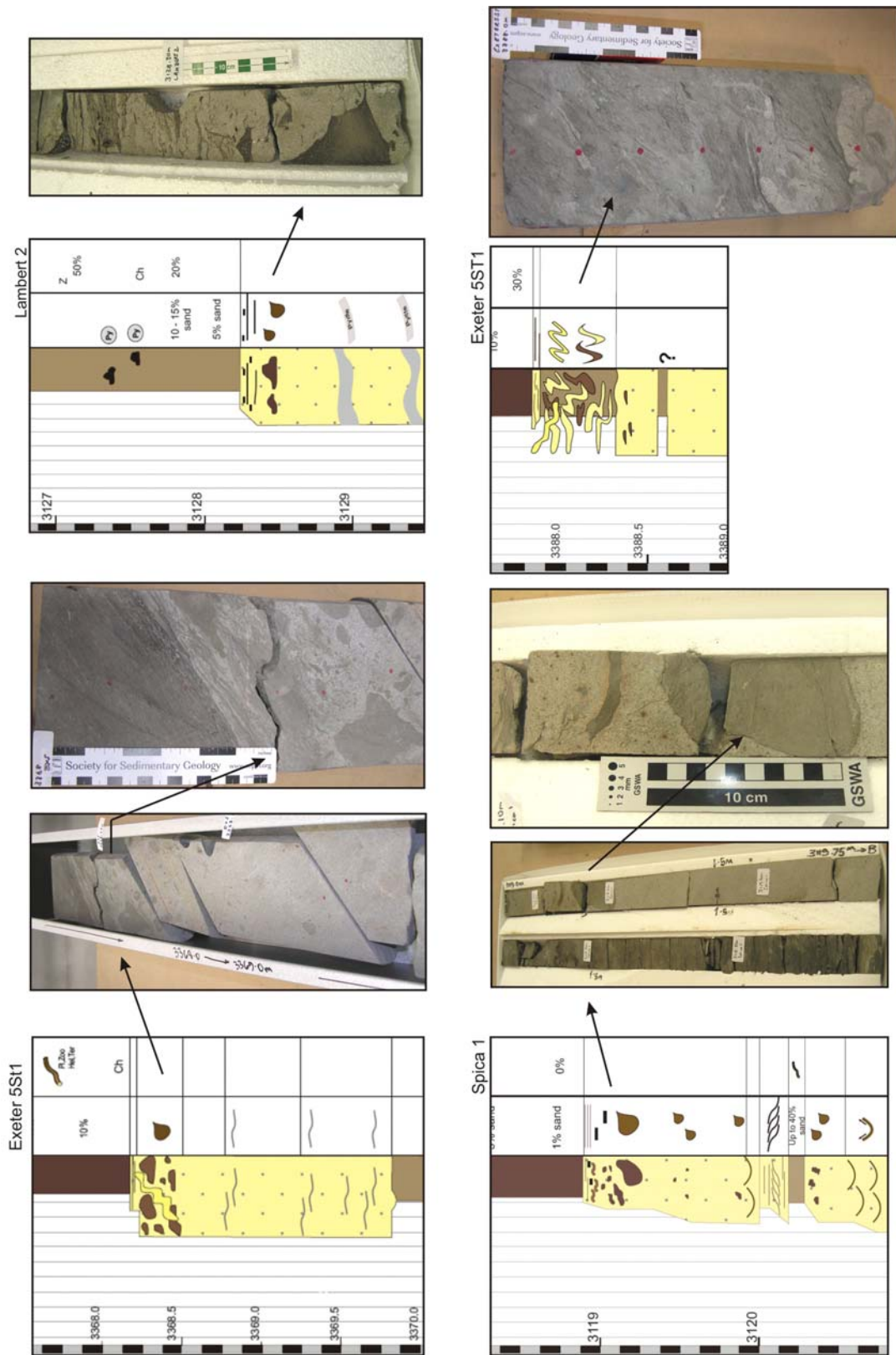
Figure 6-16: Examples of possible injected overbank successions within shallow distributary channels. The overbank units can be interbedded with retrogradational frontal splays (section 6.4.1). These units may also be differently interpreted as linked debrites with thin waning flow deposits overlying them to which they would not rest within an overbank environment but within a channel or splay setting. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.

It is interpreted that the concentration of laminae and dewatering is related to the depositional frequency of flows continuously being stacked upon each other. Dewatering in these channel margin and levee systems may also be laterally sourced from the channel axis through the loading action of new flow events and through early burial and injection from the channel axis.

It is further interpreted that the lateral extent of channel margins and levees depends on the degree of confinement acting upon the channel system. If a single storey channel system is confined within an entrenched erosive system, its related channel margin and levee units would build within the confined space (Figure 6-17). If a single storey channel system exists within an unconfined and dominantly aggradational setting, its related channel margin and levee units would stack from the overspill of turbulent flows to build raised margins and low angle channel levees (Peakall *et al.,* 2000a; 2000b) (Figure 6-17). A dominantly erosive system is expected during the early stages of channel infilling. An aggradational and depositional system is expected during middle to late stages of channel infilling when the confines of the initial erosive cut are overcome by aggrading channel fill.
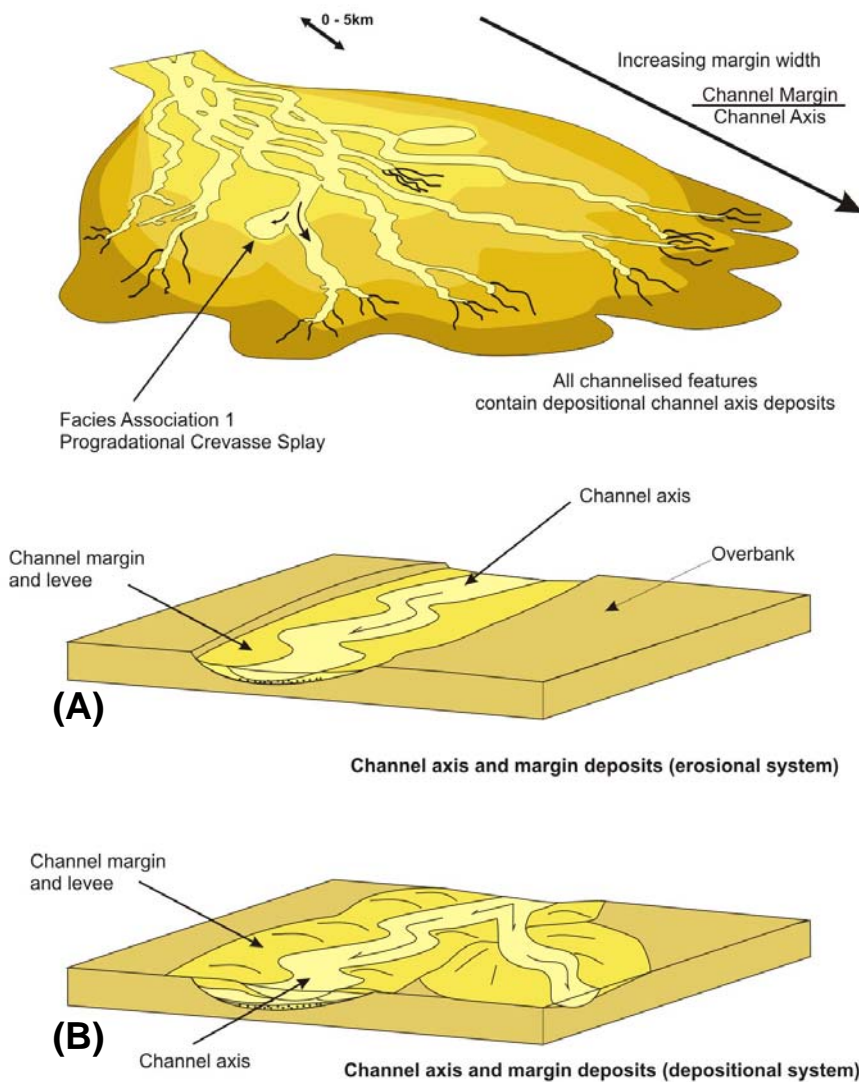
Figure 6-17: Depositional model for channel margin and levee successions within an erosional confined system (A) and an aggradational depositional levee-confined system (B). Within the aggradational system, the channel margin and levee deposits are similar as the levees are built up from aggrading margin deposits.

Lateral migration of a channel system can result in the deposition of accretionary packages along the inner side of the channel with erosion on the outer side. Lateral migration of individual sinuous

channels can produce laterally amalgamated channel complexes that have varying degrees of internal amalgamation depending on the nature of the channel fill (Abreu *et al.,* 2003) (Figure 6-18). Large-scaled accretionary packages can not be resolved within the cored successions from the Angel Formation as they are features that are interpreted to be outsized in relation to the scale of core. They are features that are more commonly seismically resolvable.

Lateral migration is related to channel sinuousity. The sinuousity of the channel systems increases with retrogradation in relation to a decrease in sand net to gross and are interpreted to be most sinuous towards the distal regions of the fan (Posamentier and Kolla, 2003). Evidence of lateral migration and channel sinuosity from the Angel Formation is preserved in the upper bed sections of many single and multistorey channel systems as a result of increased sinuosity with decreasing net to gross with retrogradation (Figure 6-1 and 6-19). Thin single storey crevasse splay units that overlie channel fill, margin or leveed sandstones within progradational and aggradational successions can also be interpreted to have been deposited through lateral migration. These units could also be differently interpreted to be fining-upward channel abandonment successions (Lithofacies Association 4). Lateral migration within progradational to aggradational successions is not commonly identified throughout core (Figure 6-19).

Analogous examples of channel margin sediments similar to those identified within the Angel sandstone include channel margins from the Skeiding channel-overbank complex of the Laingsburg Karoo (Grecula *et al.,* 2003) (Figure 6-20).

Figure 6-18: Block model depicting laterally migrational channel systems that compensationally stack.
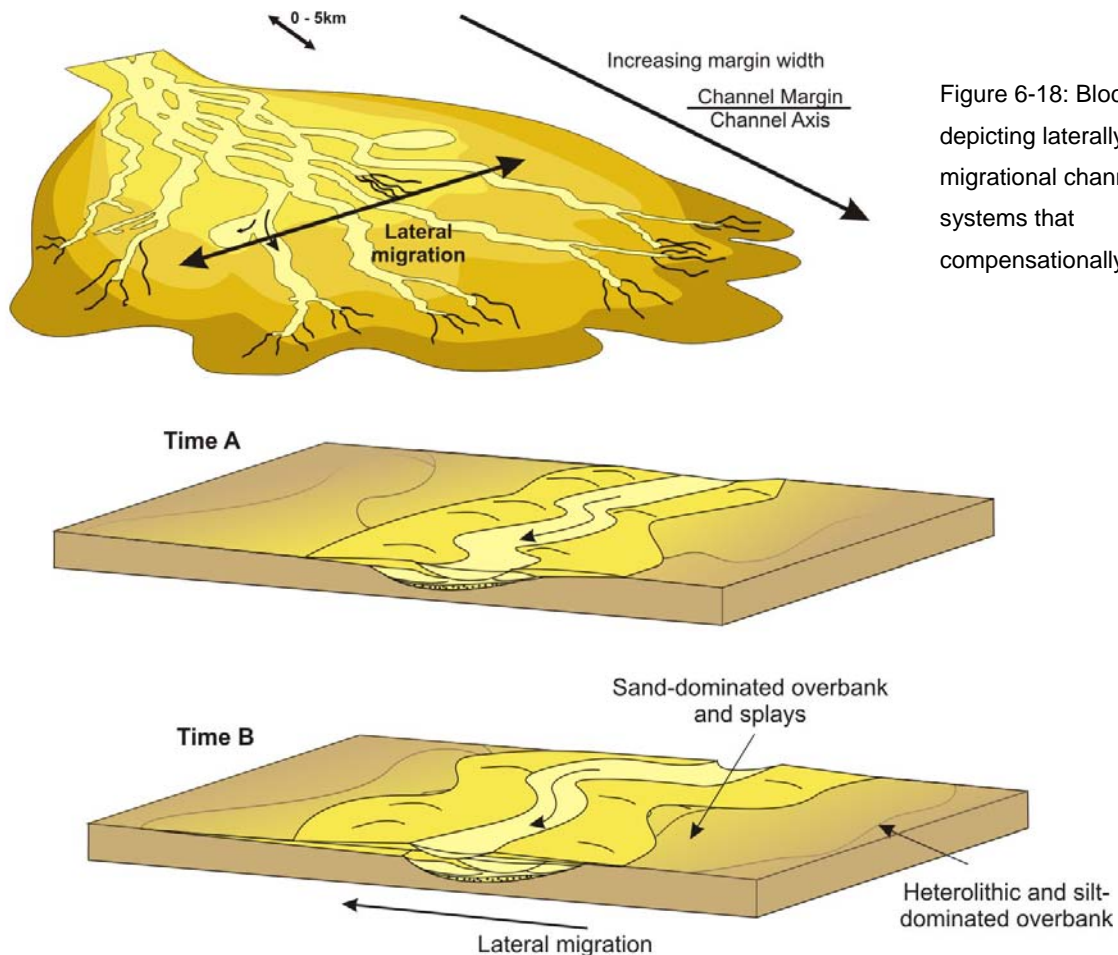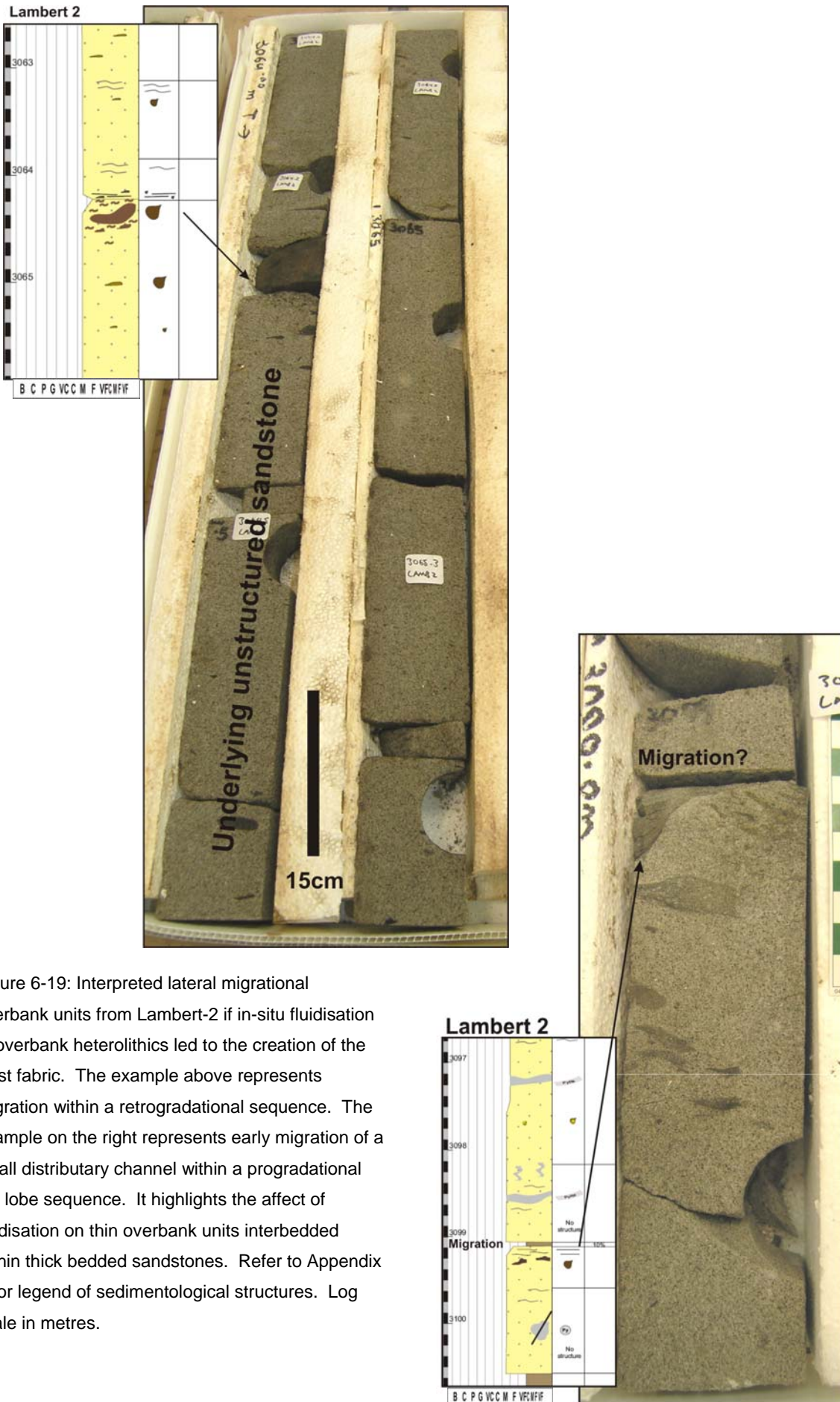
Figure 6-19: Interpreted lateral migrational overbank units from Lambert-2 if in-situ fluidisation of overbank heterolithics led to the creation of the clast fabric. The example above represents migration within a retrogradational sequence. The example on the right represents early migration of a small distributary channel within a progradational fan lobe sequence. It highlights the affect of fluidisation on thin overbank units interbedded within thick bedded sandstones. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.

Figure 6-20: The Skeiding channel axis and margin system, Laingsburg Karoo, South Africa. It is an analogue to the channel axis and margin systems present within the Angel sandstone. Lateral thinning of the thick axial sandstones is seen to occur towards the margin resulting in increased stratification. This analogous channel system is closely scaled to the proximal fan channel system identified with the Angel and Egret fields (Chapter 8). Outcrop is 40 to 50 metres high (Grecula *et al.,* 2003).
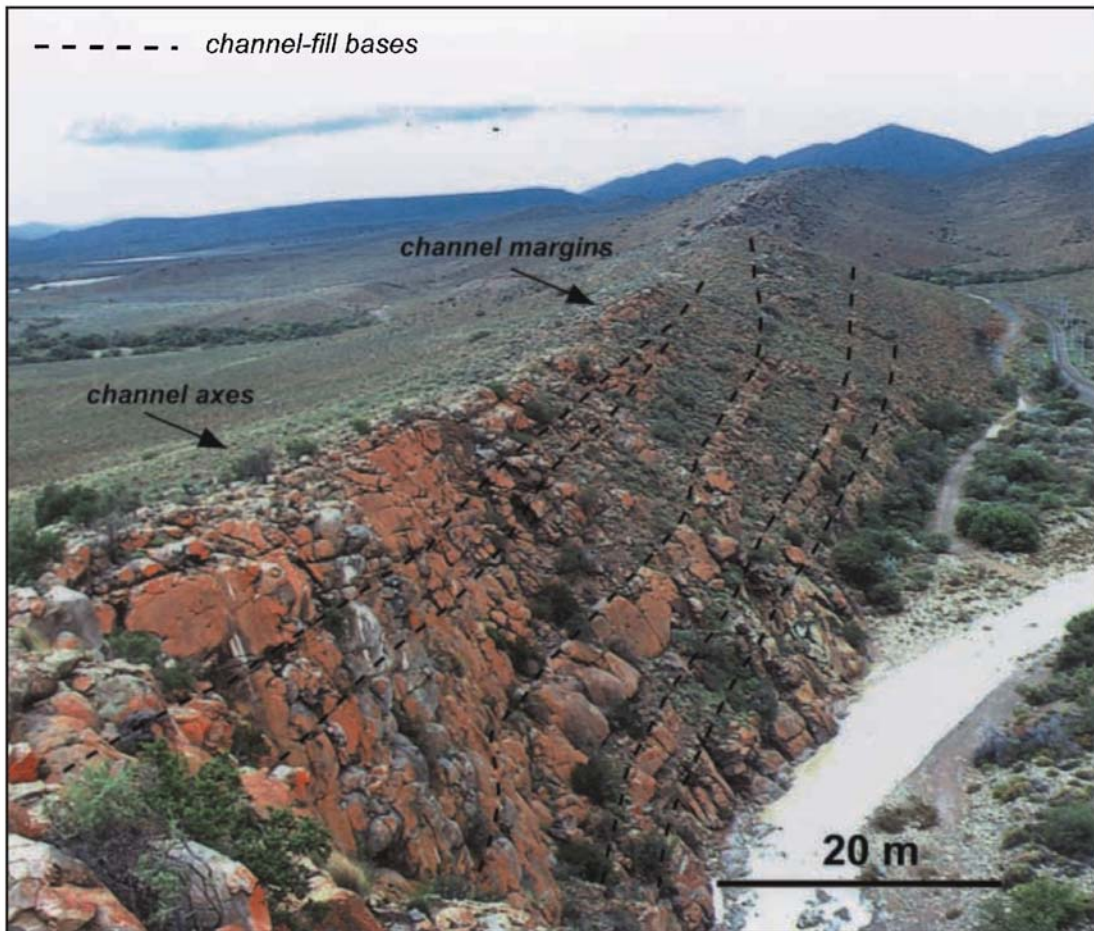
6.3.4 Lithofacies Association 4: Channel Abandonment Successions

These successions are represented by the abrupt and sharp transition from homogenous channel axis sandstones to heterolithic and silt-dominated sediments. The transition displays little to no fining upward grain-size trends. The upper bed contact is often affected by injection processes either displaying rip-down clasts created through injection, inclined upper contacts or ptygmatic injectites. There is no preserved laminated lithofacies of crevasse and retrogradational frontal splays (Figure 6-21).

This lithofacies association is produced through one of two processes. They are:

- channel abandonment, or
- complete sandstone fluidisation at the upper bed contact.

It is difficult to differentiate between the two processes as the channel abandonment successions in core are thin and post-depositional fluidisation could be an active process of abandonment-related upper bed sandstone contacts.

Channel abandonment is a common characteristic of sinuous deep water channels (Weimer and Slatt, 2004). It can occur through three processes.

i. Up-slope avulsion of distributary and mid-fan channel levee systems (Bruhn and Walker, 1997) as a result of autocyclic switching. Rapid termination of sediment fed down the abandoned channel results in underfilling and the accumulation of silt- and mud-dominated intervals within the channel feature.

ii. Changes in the rate of sediment supply (Clark and Pickering, 1996) in relation to fluctuating relative sea level (McCaffery *et al.,* 2002).

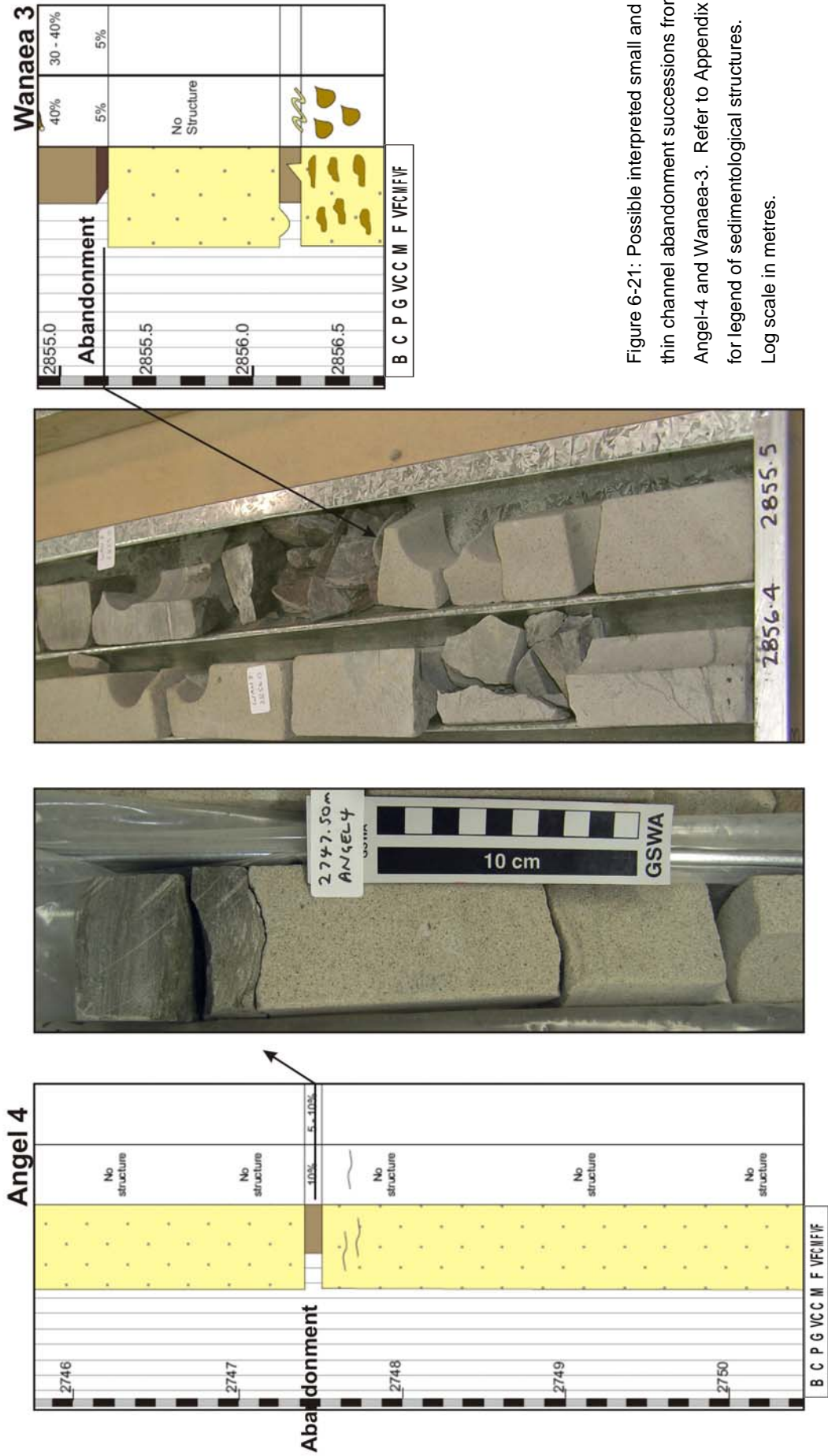iii. Lateral movement of channel systems (Kolla *et al.,* 2001).

Figure 6-21: Possible interpreted small and thin channel abandonment successions from Angel-4 and Wanaea-3. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.

Peakall *et al.,* (2000a; 2000b) suggested channel abandonment successions can be identified by either fining upward successions as a result of decreasing flow magnitudes into the channel or by hemipelagic material that draped the abandoned channel.

It is interpreted that the abandonment deposits recognised within this study were deposited within channels that were dominantly left open and filled with hemipelagic material (Figure 6-22). They were located distally from the avulsion point. Fining-upward channel abandonment successions may be located proximally to the point of avulsion, however, it is difficult from a core perspective to differentiate these units from unconfined frontal splays. These units can be interpreted when larger order architecture is considered (Chapter 7).
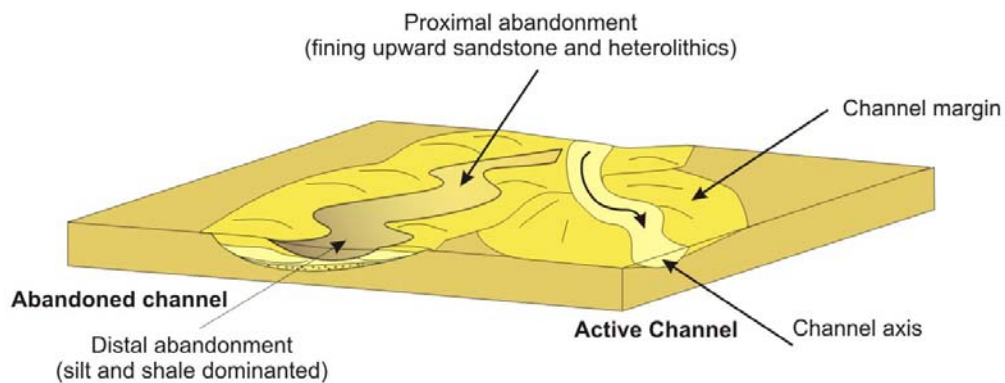
Figure 6-22: Model of channel abandonment. Distal abandonment deposits are dominated by siltstones and mudstones. Proximal abandonment deposits comprise of fining upward sandstones and heterolithics deposited by waning turbidity flows.

Similar channel abandonment successions to those identified within the study have been recognised in potentially analogous systems including the Brushy Canyon, West Texas (Gardner *et al.,* 2003), the Dalradian turbidites of the Southern Highland Group, MacDuff (Campbell and MacDonald, 2006), the Pab Range outcrops in Pakistan (Eschard *et al.,* 2003) and the Golo turbidite system located along the eastern margin of Corsica (Gervais *et al.,* 2004).

These units could be differently interpreted as being the product of complete fluidisation of the sandstone at the upper bed contact. Laminae and fining trends would be destroyed resulting in a sharp upper bed contact. Evidence for this interpretation includes the presence of injection features and inclined bedding at many interpreted abandonment successions (Figure 6-23). These contacts could also be differently interpreted as being debritic as well.

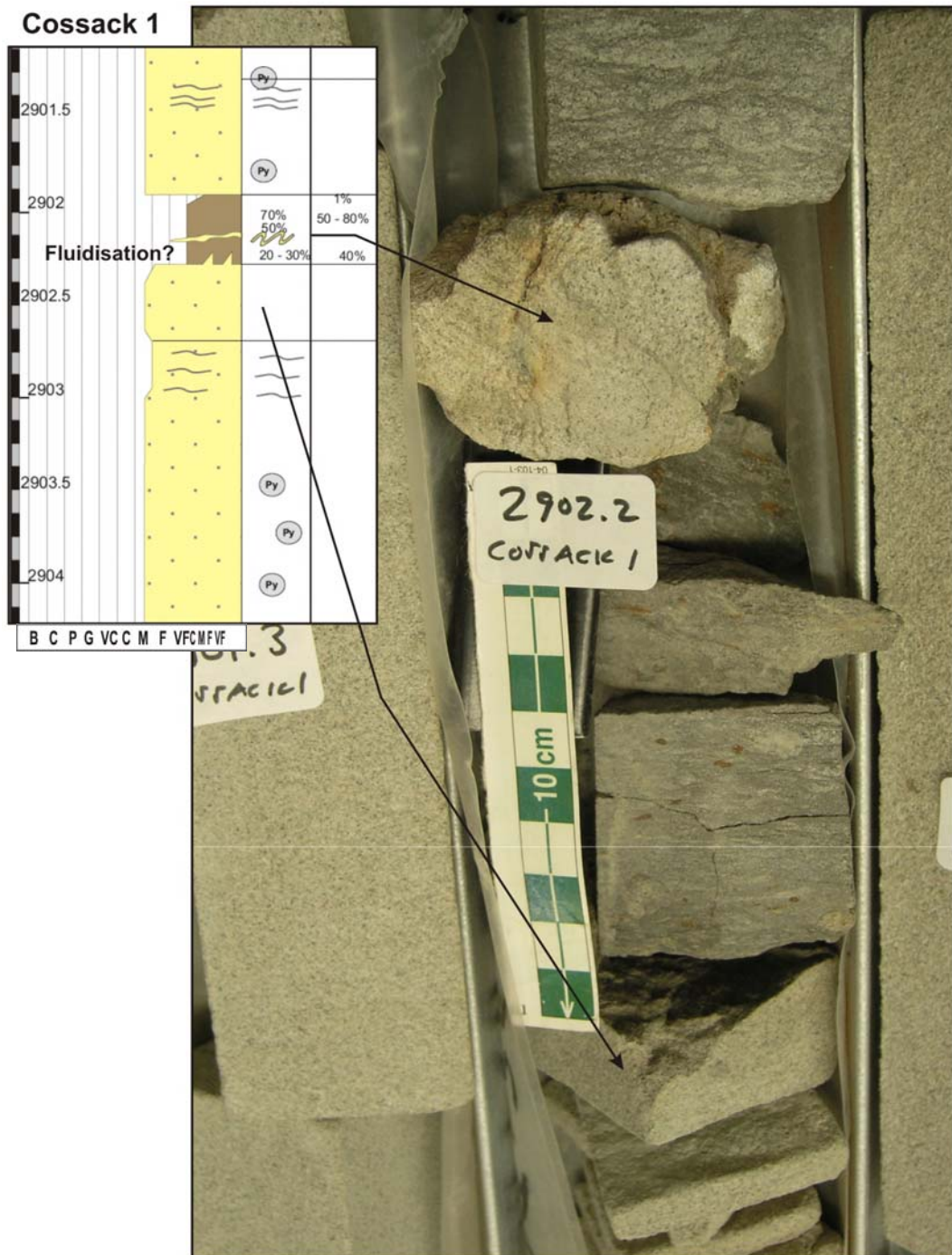Figure 6-23: Fluidised upper bed contact from Cossack-1. Primary structures such as laminae were destroyed. This is supported by the presence of both ptygmatic injectites out of the bed contact and within the heterolithic unit. Refer to Appendix B for legend of sedimentological structures. Log scale in metres.

6.4 Unchannelised Lithofacies Associations (Sheet Systems)

Unchannelised lithofacies associations represent associations that are related to unconfined and unchannelised depositional systems. They stack to form sheet complexes. The three lithofacies associations are:

- proximal sand-dominated unchannelised frontal splays;

- distal silt-dominated unchannelised frontal splays, and;

- splay abandonment units.

6.4.1 Lithofacies Association 5: Unchannelised Sand-Dominated Frontal Splays

These successions are best represented by interbedded successions of parallel stratified, dewatered and laminated sandstones of Lithofacies A, B and D with breccia/linked debrites of Lithofacies H and K and ptygmatic injectites of Lithofacies G (Figure 6-24). They can:

- grade upwards into laminated and bioturbated heterolithics of Lithofacies Association 7 through retrogradation or migration (distal silt-dominated splay) (Figure 6-24);

- be truncated by channel systems through active progradation of the depositional system;

- be interbedded with small distributary channel fills;

- range from a few centimetres to over 10 metres thick (sheet complex), and;

- can contain breccia or linked debrites and hybrid flow deposits.

These units are interpreted to be proximal deposits comprising the coarser and sandier fraction of waning, laterally spreading and unconfined flow events from distributary channel system mouths (Figure 6-25). Unchannelised frontal splays occur in the outer regions of a fan system where distributary systems cease to exist at a particular point in time. Small unchannelised splays are also interpreted to form off newly created channel avulsion events within mid-fan settings.

Thin successions of unchannelised frontal splay deposits are identified within all wells. Many intervals are interpreted to be single storey non-amalgamated frontal splay events deposited through retrogradation of a fan lobe or depositional fan system with transgression (Figure 6-26). Amalgamated aggradational frontal splays (sheet complexes) are identified in Lambert-2, Wanaea-2A and Wanaea-3 (Figure 6-27).
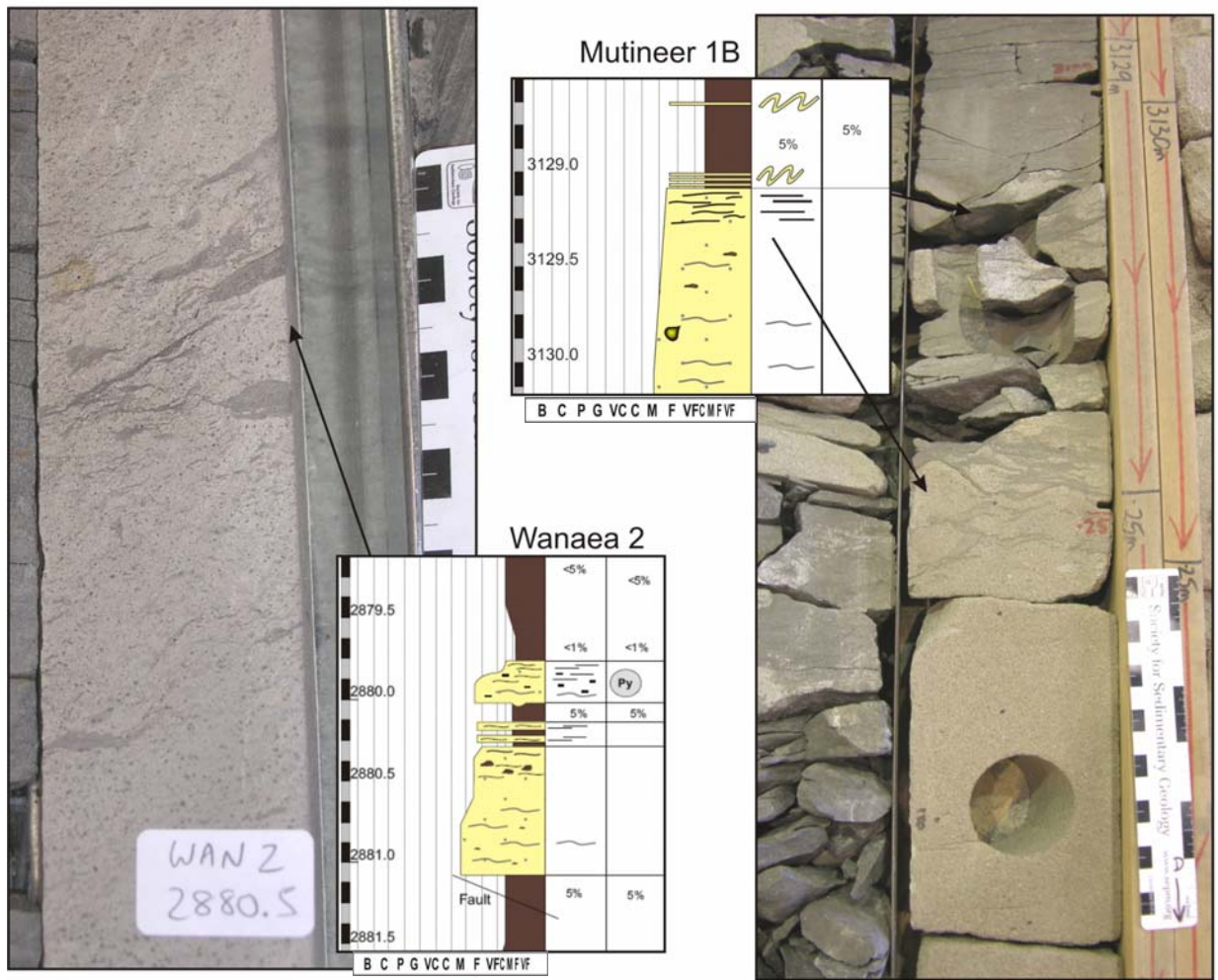
Figure 6-24: Interpreted frontal splays from Wanaea-2A and Mutineer-1B deposited through retrogradation. They are represented by wavy and laminated sandstones. Refer to Appendix B for core log legend. Depth in metres.
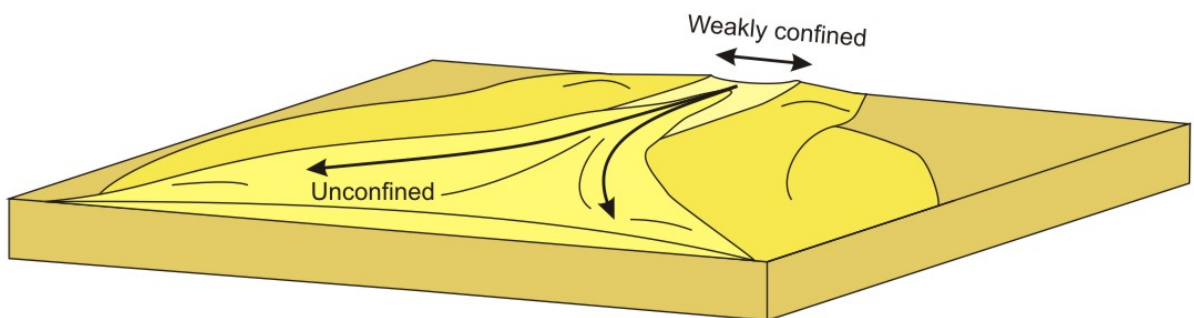
Figure 6-25: Model of a sand-dominated unchannelised frontal splay.
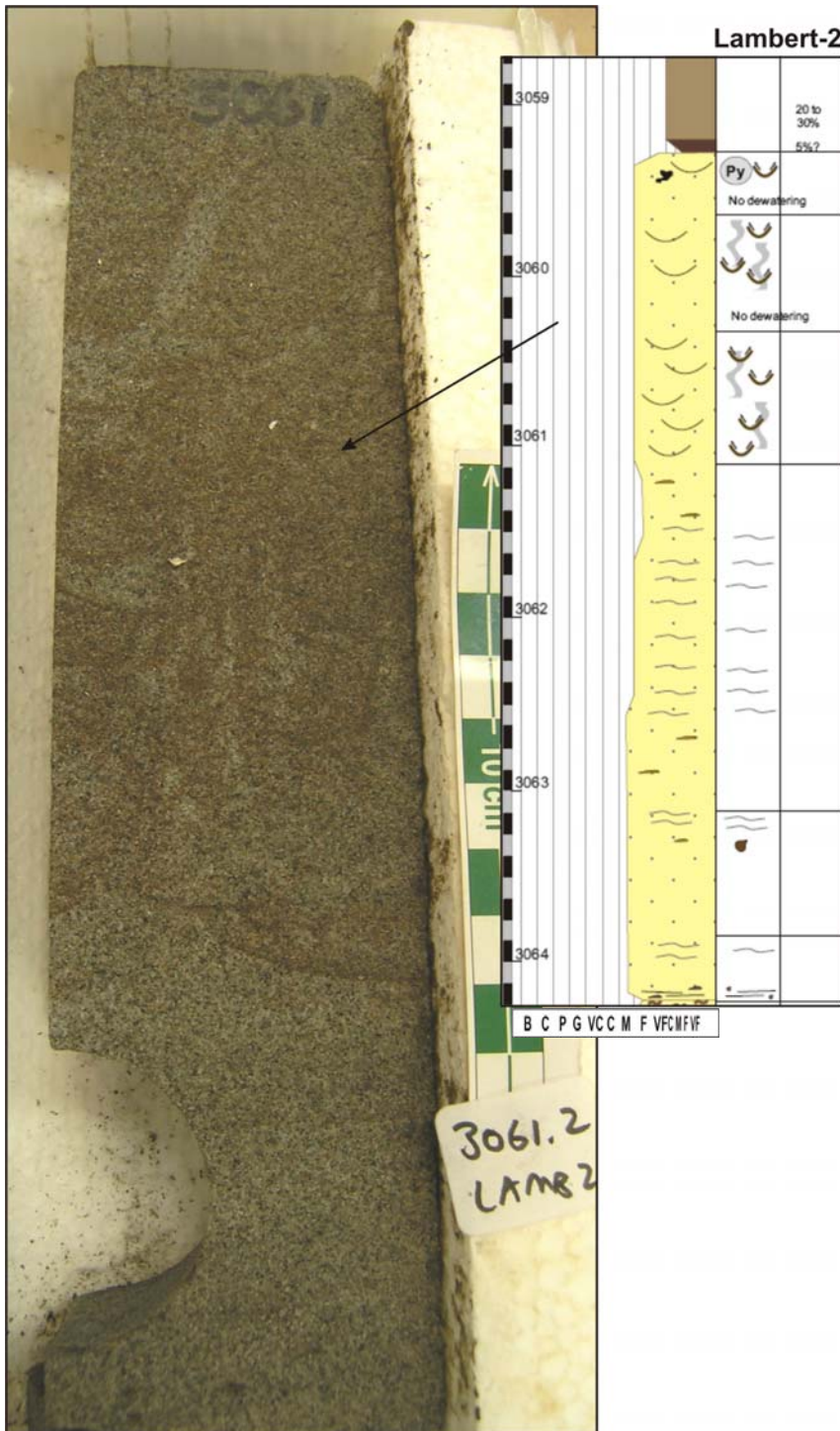
Figure 6-26: Sand-dominated stacked (three storey) frontal splay deposit interpreted from Lambert-2. It contains dish and pipe structures. The entire splay overlies channel margin deposits and grades upward into siltstones and heterolithics. Refer to Appendix B for core log legend. Core depth is in metres.
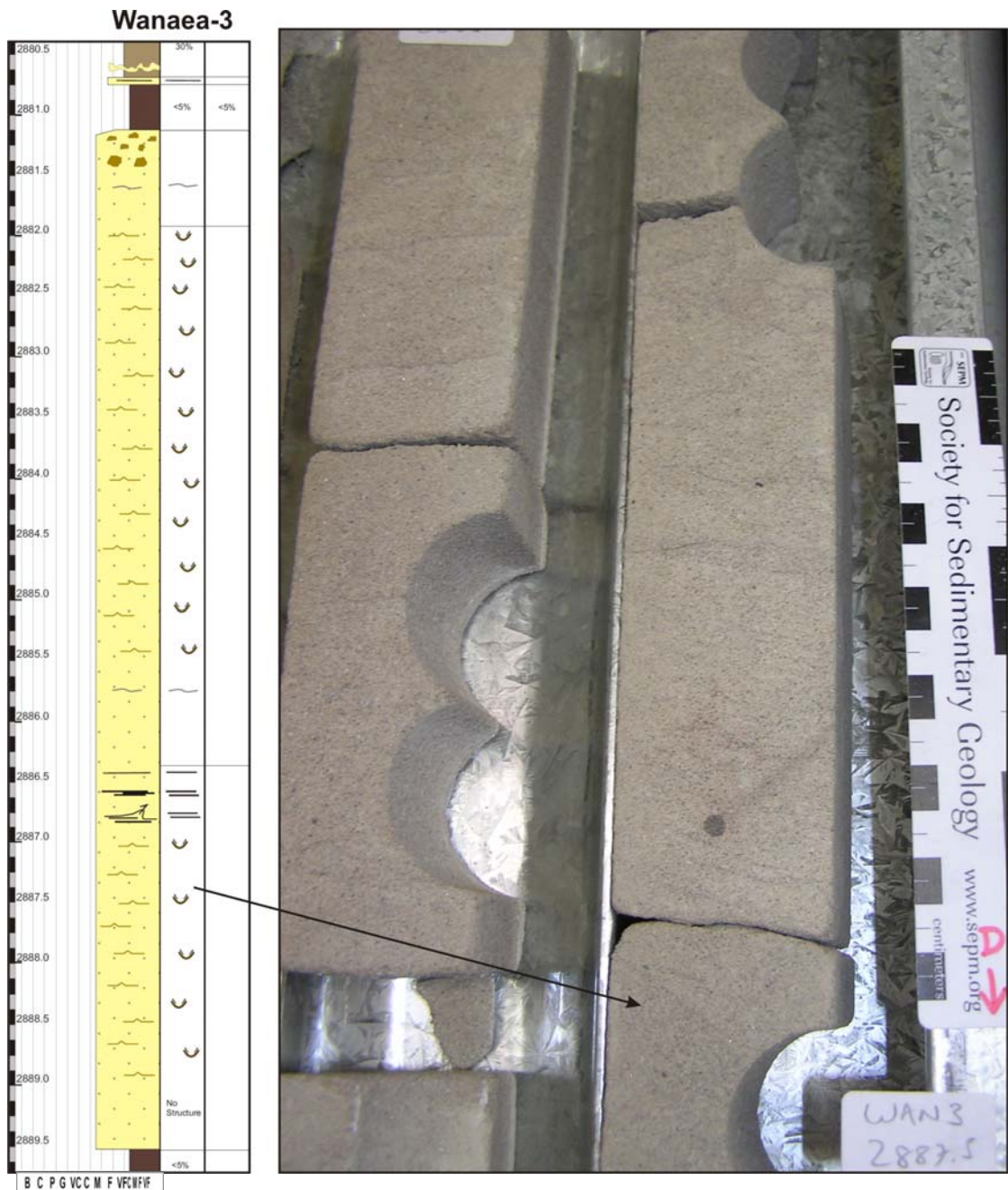
Figure 6-27: Sand-dominated amalgamated frontal splay deposit (sheet complex) interpreted from Wanaea-3. It contains dish and pipe structures and is approximately 8 metres thick. Refer to Appendix B for core log legend. Core depth is in metres.

6.4.2 Lithofacies Association 6: Unchannelised Silt-Dominated Splays

These units are represented by thin laminated units of Lithofacies D, heterolithic intervals of Lithofacies E and injected and debritic lithofacies of G and H. They can:

- be interbedded with or grade upwards into sand-dominated frontal splays, crevasse splays and channelised systems (progradational) or into splay abandonment deposits (retrogradational);

- overlie either sand-dominated unchannelised frontal splays (retrogradational) or splay abandonment deposits (progradational);

- range from a few centimetres to tens of metres in thickness, and;

- be highly bioturbated.

These units are interpreted to be distal deposits comprising the siltier fraction of waning, unconfined and laterally spreading turbulent flow events erupting from distributary channel systems (Figure 6-28). They represent the background lithofacies which is present in all wells.
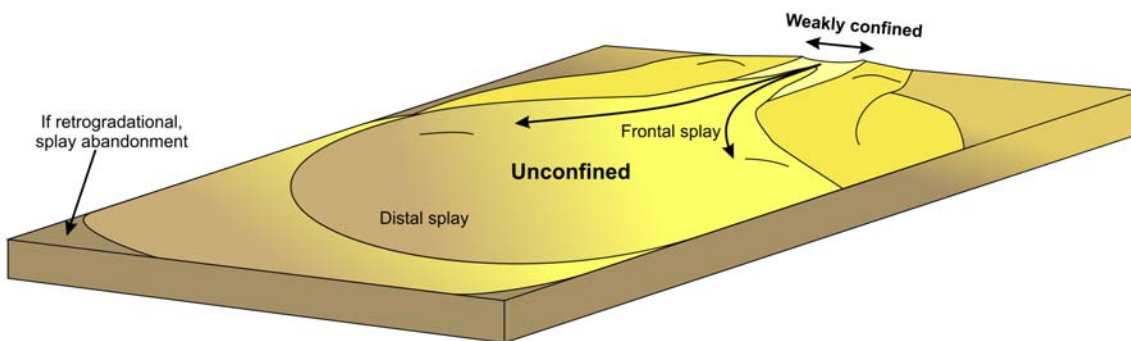

Figure 6-28: Cartoon illustrating a distal silt-dominated frontal splay located downslope of a proximal sand-dominated frontal splay.

6.4.3 Lithofacies Association 7: Splay Abandonment Unit

These units are represented by the siltstone- and mudstone-dominated sediments of Lithofacies F with a visible decrease in sandstone content and bioturbation. They are interpreted to represent quiescent depositional conditions where hemipelagic sedimentation dominated.

Turbulent flows transport not only sediment to the deep marine, but also organic matter and oxygen-rich water. Organisms rely on this organic material and oxygen to survive. Within abandonment deposits, little to no bioturbation is recognised as these requirements for organism survival are not met.

It is interpreted that overbank sediments located within a confined and proximal channelised system lacking sufficient channel bends to promote flow stripping and avulsion may contain more finer-grained

hemipelagic material than their downslope equivalent overbank sediments that are located within more sinuous and less confined channelised systems.

6.5 Summary

Seven lithofacies associations and their related depositional elements were classified from particular associations of core lithofacies and their relationships with neighbouring associations. It was determined that the Tithonian succession of the Angel sandstone contains both channelised (i.e. single and multistorey channel fills and margins) and unchannelised elements (i.e. frontal splays) (Table 6-2 next page). This does not correlate to the Mutti (1985) Type 1 classification made by Barber (1994a; 1994b) for this unit. This discrepancy in interpretation is discussed further in Section 9.2.

Chapter 7 will examine stacking relationships between individual lithofacies associations and combine them into fourth and fifth order architectural elements.

Table 6-2: Table of lithofacies associations interpreted from the Angel Formation with related lithofacies types, relationships with other associations and phases (progradational/aggradational/retrogradational).

Lithofacies Association		Lithofacies	Commonly associated with	Stacking pattern
1	Crevasse splays	Lithofacies C, D, E and F	Overlain by channel axis fill / Overlies splay abandonment units	Progradational
			Overlain by sand-dominated, silt-dominated and splay abandonment units / Overlies channel axis fill and margin deposits	Retrogradational (overspill splays)
2	Channel axis fill	Lithofacies A	Overlies crevasse splays, splay abandonment units, or sand- and silt-dominated unchannelised splays. Overlain by channel margin or abandonment units	Aggradational to retrogradational (lags can be progradational)
3	Channel margin and levee	Lithofacies A, B, D, G and H (injection breccia interpretation)	Overlies channel axis fill. Rarely overlies splays adjacent to channel system. Can be interbedded with overbank (abandonment)	Aggradational or retrogradational
4	Channel abandonment	Lithofacies E and F	Overlies channel axis fill and channel margin deposits	All phases (Autocyclic process)
5	Unchannelised sand-dominated frontal splays	Lithofacies A (thin), B, D, G and H (linked debrite interpretation) and K	Overlies silt-dominated splays/abandonment units / Overlain by channel axis and margin deposits	Progradational
			Overlies channel axis and margin deposits / Overlain by silt-dominated splays and abandonment units	Retrogradational
6	Unchannelised silt-dominated splays	Lithofacies D, E, F, H (linked debrite interpretation) and G	Overlies abandonment units	Progradational
			Overlies sand-dominated splays	Retrogradational
7	Splay abandonment	Lithofacies F	Overlies silt-dominated splays / Overlain by silt-dominated splays	Maximum flood (allocyclic) or maximum abandonment (autocyclic)

7 Fourth and Fifth Order Architectural and Stratigraphic Models

The first and second order architectural elements (core lithofacies) and the third order architectural elements (lithofacies associations) were examined in Chapters 5 and 6 respectively. This chapter will:

- set the depositional scene for the fourth, fifth and sixth order architectural analysis by determining the general depositional system of the Angel Formation (Reading and Richards, 1994);

- combine the third order architectural elements (lithofacies associations) into fourth and fifth order architectural units that represent the development of a composite channel-splay and sheet system;

- analyse different varieties of fifth order models that represent downslope and lateral transitions of composite channel-splay and sheet complexes, and;

- discuss the variety of fifth order composite channel-splay and sheet complexes interpreted in all cored wells.

7.1 Generalised Depositional Setting of Tithonian Angel Formation

A critical step in analysing the architecture and stratigraphy of a sedimentary unit is to determine the general physiographic setting of the region under investigation (Posamentier and Allen, 1993). This is important as the scale and variety of architectural elements can vary significantly in accordance to the type of dominant grain-size and feeder system (Reading and Richards, 1994; Richards and Bowman, 1998).

The generalised depositional setting of the Tithonian Angel Formation along the northwestern margin of the Dampier Sub-basin is best represented by the mixed sand- and mud-rich ramp setting of Reading and Richards (1994) (Figure 7-1). Reasoning behind adopting this model includes:

- the existence of multiple fault-controlled feeder complexes that existed along the edge of the Rankin Platform (Stein, 1994, Wulff and Barber, 1994 and Jablonski, 1997);

- the presence of significant quantities of mudstone-dominated successions between depositional fan units as identified from core and wireline logs (Chapters 5, 6, 7 and 8), and;

- the retrogradational nature of the Late Tithonian succession. Renewed sea floor spreading between Western Australia and Greater India resulted in basin subsidence and transgression (Jablonski, 1997).

NOTE:
This figure is included on page 148 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 7-1: Combination mud- and sand-dominated submarine ramp system as interpreted for the Tithonian interval of the Angel Formation (Reading and Richards, 1994). The Angel system is interpreted to contain more sandstone than the above model, which would result in the formation of channelised fan lobes and decreased levee height. Even though it is interpreted to be sandier, it is not interpreted to be wholly represented by the sand-rich ramp model of Reading and Richards (1994) (Figure 2-9). It is interpreted to exist between the two models.

7.2 Fourth Order Channel Architectural Element and Model

Third order lithofacies associations determined from Chapter 5 can be stacked to form a fourth order architectural model. A fourth order architectural element is represented by a single storey elementary channel fill unit. It comprises channel lags and fills of lithofacies association 2 that can grade migrationally into channel margin and overbank successions of Lithofacies Association 3 (Figure 7-2).
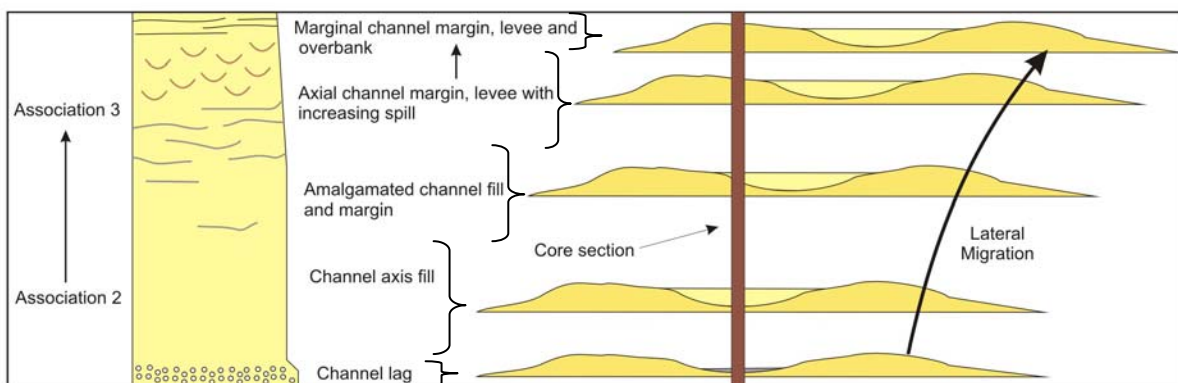

Figure 7-2 Fourth order channel architectural element formed through cut and fill lateral migration.

Fourth order architectural elements are interpreted to range from approximately one metre and can amalgamate into units over 10 metres thick (Angel-4 and Montague-1). They form multistorey or composite channel complexes that represent fifth order models (Section 7.3.1). They are assumed to decrease in width and depth from proximal to distal fan settings. Lateral migration and sinuousity is also interpreted to be greater within distal fan distributary systems due to a possible increase of clay within flows and a decreased slope gradient.

7.2.1 Channel Aspect Ratios from Literature

Published research on deep marine fan systems have noted a lack of channel systems that exist within distal fan regions dominated by sheet complexes This is thought to be related to the resolution of datasets used to investigate deep marine systems (i.e. seismic, multibeam bathymetry) (Figure 7-3).

Outcrop research from regions such as the Ross Formation, Western Ireland, demonstrate that small-scale distributary channel systems and scours can develop within sheet complexes (Elliot, 2000). Quantitative research conducted by Clark and Pickering (1996) on submarine channel dimensions calculated that lower fan distributary channel systems can range from three to twelve metres in depth and can have aspect ratios ranging from 4:1 to 100:1 (Figure 7-3). Elliot (2000) determined that distributary channel systems of the Ross Formation displayed a channel width to meander belt ratio of 1:3.

NOTE:
This figure is included on page 149 of the print copy of the thesis held in the University of Adelaide Library.

Figure 7-3: Plot of submarine channel width and depth data from ancient, modern and subsurface channels. This plot covers several orders of architectural elements. There is a resolution bias on the recognition of these systems (from Clark and Pickering, 1996).

NOTE:
This figure is included on page 150 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 7-4: Graph highlighting the range of aspect ratios for lower and middle fan submarine channels (graph and data modified from Clark and Pickering, 1996). The range of aspect ratios is interpreted to be related to features such as grain size population of flows and the slope gradient (and related slope equilibrium profile).

Small and often single storey distributary channel systems have been identified from the following ancient outcrops and modern fan systems (Table 7-1):

Table 7-1: Range of distributary channel geometries from ancient and modern analogues.

Analogue	Model Type	Description and Geometries
The Spitsbergen slope and basin floor system (Plink-Bjorklund *et al.,* 2001)	Ancient	Sand- and heterolithic-dominated sheet systems are dissected by channels 50 to 100 metres wide and 2 to 4 metres deep on the lower slope and base of slope setting. Minor distributary channels between 3 to 5 metres wide and 0.4 to 1.0 metres thick were interpreted on the upper slope setting downslope of a deltaic system.
Brushy Canyon, West Texas (Gardner *et al.,* 2003).	Ancient	Geometries of distributary channel systems mapped from Fan 4 are approximately 30 metres wide and 2 to 5 metres deep.
Loskop South (Fan 2) south-western Karoo Basin, South Africa (Rozman, 2000 (as discussed by De Ville Wickens, 2007)).	Ancient	A mapped shallow channel fill displayed a maximum thickness of 4 metres and a width of 200 metres. The upper section of the channel fill continued out of the channel system, becoming part of the sheet system that has an average thickness of approximately 1 metre.
The Ross Formation, Western Ireland (Elliot, 2000)	Ancient	Single storey distributary channels around 7.5 metres deep and 130 metres wide. They migrate laterally to produce a meander belt 380 metres wide.
The eastern margin of Corsica (Gervais *et al.,* 2004)	Modern	High resolution seismic reflection data demonstrates the relationship of sheet sands with small, infilled channels that are less than 10 metres deep and approximately 100 metres wide.
The Navy submarine fan, California (Piper and Normark, 2001)	Modern	Distributary channel systems range up to 500 metres wide and are 5 to 15 metres deep.

It is deemed acceptable based on the review of available literature to state that individual distributary channel systems in the Tithonian Angel Formation can be no less than 1 metre thick, however the thickness of a channel unit in core often represents the marginal component and not the central axis of the channel, resulting in the interpretation of a thin channel axis unit (Section 7.3.3.2). All channel

geometries within this research are considered to rest within the aspect ratios of 4:1 to 100:1 as determined by Clark and Pickering (1996) (Figure 7-4).

7.3 Fifth Order Architectural Models: The Composite Channel-Splay and Sheet Complex

There are two varieties of fifth order architectural units.

i. A sheet unit comprising progradational and retrogradational frontal splays.

ii. A composite channel system comprising amalgamated multiple storey channel units (fourth order architectural elements) overlain by a spill phase of unconfined splays (Figure 7-5). This system overlies a progradational frontal/crevasse splay or sheet complex and can be overlain by retrogradational splays.

These architectural units produce autocyclic fan lobe deposits and related upslope mixed erosive and depositional channel systems (Figure 2.14).
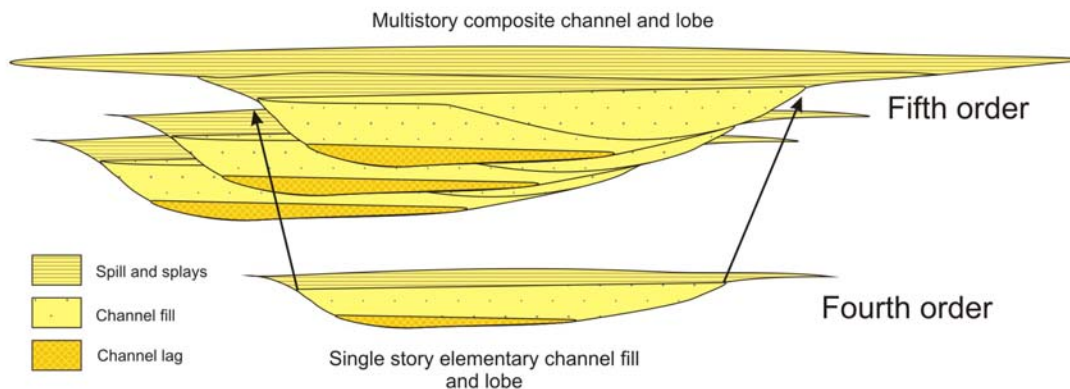
Figure 7-5: Relationship of fourth order elementary channel forms to fifth order composite channel complexes (adapted from Gardner *et al.,* 2003).

Fifth order models are adapted on the 'build-cut-fill-spill' model from the Permian Brushy Canyon Formation (Gardner *et al.,* 2003; Gardner and Borer, 2000) and the channel complex development model from the Klein Hangklip region in the Tanqua depocentre, Karoo Basin (Wild *et al.,* 2005). This variety of architectural model has also been noted in outcrop localities including the Upper Cretaceous Juniper Ridge Conglomerate near Coalinga in California (Hickson and Lowe, 2002).

7.3.1 The Standard Model

The standard model represents the concept of a fifth order channel-splay element overlying a progradational frontal or crevasse splay succession, which represents the commencement of a fifth order sheet system. The model relates lithofacies patterns in channel, margin and splay deposits to their position on a slope to basin profile (Gardner and Borer, 2000). Variation in preserved fifth order units in cores from the Tithonian succession of the Angel Formation can be used to infer slope location and stratigraphic setting.

It is important to recognise that the standard model represents a whole basinward model where infilling of the channel complex is related to retrogradation. Fifth order channel splay systems within the middle to upper successions of a sixth order depositional fan unit would preserve these successions. Lateral models, where the infilling and abandonment of the channel is related to autocyclic processes and upslope channel avulsion, are interpreted to exist within lower successions of a sixth order depositional fan unit when fan lobes are prograding (refer Chapter 7).

Sheet complexes represent the downslope derivative of composite channel-splay complexes and comprise progradational and retrogradational splay deposits (build and retrogradational build phase of Gardner *et al.,* 2003).

Composite channel-splay systems overlie progradational splay deposits (build phase of Gardner *et al.,* 2003) and are formed through the following succession (Figure 7-6).

    i.   Cut and bypass phase.

   ii.   Fill phase.

  iii.   Late fill and overspill phase.

  iv.   Retrogradational build phase.
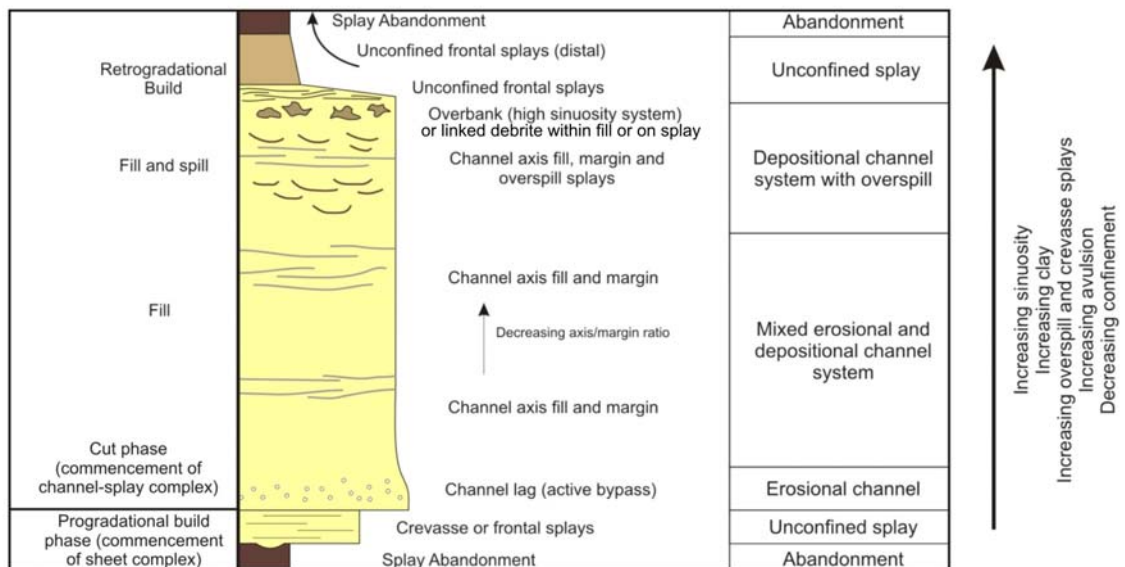
Figure 7-6: Standard fifth order composite channel-splay model overlying progradational splays of a sheet complex. The existence of particular features within the model is dependent on the slope location of the preserved succession. A standard fifth order model starts at the erosive cut of the first fourth order channel form.

7.3.1.1 Progradational Build Phase (Commencement of a Fifth Order Sheet Complex)

The progradational build phase represents progradational unconfined frontal splays that underlie the channel body. It is the downslope derivative of an upslope fifth order channel-splay complex. Splays

are deposited from the mouth of prograding distributary channel systems, which are controlled by either a relative fall in sea-level or a new channel avulsion event (Figure 7-7).

The build phase within a proximal location is typically recorded as an erosive surface of sediment bypass. Frontal splay units further downslope are primarily preserved within middle to distal settings as they are often thicker bedded and hence protected from being completely removed by severe channel incision. Crevasse splay units are primarily preserved within fifth order systems that exist within sixth order retrogradational settings (Section 8.3.2.2).

7.3.1.2 Erosion and Bypass Phase (Commencement of a Fifth Order Channel-Splay Complex)

The erosion and bypass phase represents the commencement of channelised systems across the progradational splay complex (Figure 7-7). This phase represents channel incision and flow bypass with flow stripped sediments accumulating on overbank settings. This phase is more frequently preserved with more proximal successions where entrenchment of channel systems can occur. The presence of lag successions within core can indicate this phase.

7.3.1.3 Channel Fill Phase

The fill phase represents the backfilling of channel systems onto the basal erosional surface that was incised into the progradational component of the sheet complex (Figure 7-7). Amalgamated channel fill units dominate this phase. The cut and fill phase can commonly repeat within a fifth order architectural element through fourth order migration and reincision. This repetitive cycle of infill and reincision results in the formation of a multi-storey composite channel system.

7.3.1.4 Late Fill and Overspill Phase

The late fill and overspill phase relates to the final stages of channel filling. A decrease in channel depth in combination with an increase in clay within the flow events (in relation to retrogradation and early transgression) results in a weakly confined and sinuous depositional channel system. Overspill is common as channel margins and levees are breached easily (Figure 7-7).

7.3.1.5 Retrogradational Build Phase (Termination of Sheet and Channel-Splay Complex)

The retrogradational build phase relates to the change from a weakly confined channelised system to an unconfined splay system with retrogradation. Like the progradational phase of a sheet complex, flows are deposited from the mouth of retrograding distributary channel systems, overlying the weakly confined channelised system (Figure 7-7). Unconfined splays become more silt-dominated as retrogradation leads to a system shutdown and splay abandonment.

If progradation of the fan system is not effective enough to produce channel forms in a particular location on a slope, the progradational build phase is overlain by the retrogradational build phase, resulting in the formation of a fifth order sheet complex (Figure 7-8).

NOTE:
This figure is included on page 155 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 7-7: Model highlighting the development of a basinward fifth order composite sheet and channel complex interpreted for the Dampier Sub-basin. Model is based on the build-cut-fill-spill model of Gardner *et al.,* (2003) and the channel complex development model of Wild *et al.,* (2005). Image modified from Wild *et al.,* (2005).

7.3.2 Variability of Fifth Order Models

The variability of fifth order composite channel-splay complexes and their preservation differs in accordance to their position on the slope to basin depositional profile or position within a depositional cycle that records migration of a profile (Gardner and Borer, 2000). Five basinward and lateral transitional fifth order architectural models are interpreted from core and lithofacies association analysis. They were interpreted in the core successions primarily through the identification of bounding surfaces and argillaceous units such as Facies E and F. The depositional style of stacking described in this chapter was also used to identify differing fifth order systems. Naturally there is always significant uncertainty involved when attempting to apply stratigraphic architecture to core.

The five basinward and lateral transitional fifth order architectural models are:

Model A: Proximal composite channel – splay model (Highly amalgamated sand-dominated).

Model B: Proximal to medial composite channel – splay model.

Model C: Medial composite channel – splay model.

Model D: Medial to distal composite channel – splay model.

Model E: Distal unconfined sheet complex model (unchannelised).

Downslope and/or lateral transition
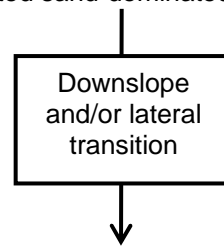
Basinward and lateral transitions are further discussed in Section 7.3.3.

7.3.2.1 Model A: The Proximal Channel-Splay Model

Model A represents a fifth order composite channel-splay system that is interpreted to exist within a proximal setting either on the slope or within the central region of a large mixed erosive and depositional channel system in a proximal fan setting. There are five characteristics indicative of this model (Figure 7-8).

i. Rare or thin progradational build phases. They are often cut down or removed by severe channelisation.

ii. Significant erosion and flow bypass.

iii. Unstructured channel fill with minor channel margin and levee development.

iv. Multiple amalgamated fourth order architectural elements (elementary channel fills).

v. Common sand-dominated retrogradational spill and overbank splays.

vi. Rare thin abandonment, overbank and retrogradational silt-dominated splays.

Model A fifth order units are interpreted to represent amalgamated successions of mixed erosive and depositional channel complexes of Mutti and Normark (1987) with minimal silt-dominated margin and levee development.   In sixth order retrogradational settings, they are overlain by sand-dominated retrogradational splays.

Individual 4th order elementary channel systems could be largely confined to incisional depressions formed during fifth order cut and bypass periods of time. Poor preservation of channel margin and levee sediments with little to no visible fining of individual channel systems suggests that a channel complex is being continuously infilled and reincised by younger channels (Figure 7-8). Both temporary and permanent channel abandonment can result in the formation of small splay-like successions above the channel fills. Channel lag is identifiable in these units (Figure 7-8).

This model is identified in cored intervals from Angel-4, Cossack-1, Exeter-5ST1, Spica-1, Montague-1 and Wanaea-3 (Appendix B).
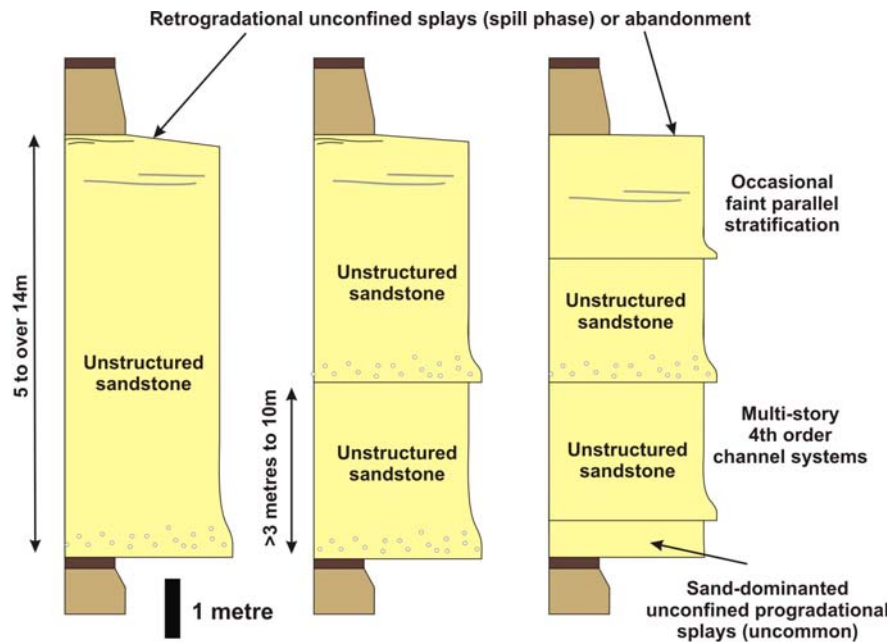
Figure 7-8: Model A comprising amalgamated 4th order elementary channel systems. Individual channel systems can range up to 10 metres thick. Channel lags are common. The succession can be overlain by unconfined retrogradational splays or abandonment units.

7.3.2.2 Model B: Proximal to Medial Composite Channel-Splay Model

The proximal to medial composite channel-splay system is a downslope or lateral transition of Model A. There are six characteristics of this model (Figure 7-9).

  i. Rare or thin progradational build phase. Like Model A, they are often cut down or removed by severe channelisation.

  ii. Significant cut phase.

  iii. Amalgamated unstructured and parallel stratified channel fill.

  iv. Multiple amalgamated fourth order architectural elements (elementary channel fills) which are thinner and less numerous than Model A.

  v. Overspill common. Channel margin overspill from individual 4th order channel features more obvious.

  vi. Thin retrogradational or abandonment splays.

Cut and fill phases with no build phase are commonly identified within these successions. The late fill, overspill and retrogradational build phase in relation with transgression can be thickly bedded. The unit contains an increased number of fourth order channel architectural elements that are thinner than those present within Model A. Common presence of interbedded channel margin and levee successions with the channel axis fills suggests that channel systems are less erosive and more depositional with increased lateral migration (Figure 7-9). A gradual upward fining of fills towards the top of each fourth order channel unit suggests the preservation of a small late fill and overspill phase or overbank/abandonment unit. Preservation of lag units may or may not occur. Rare presence of overbank injected clasts may suggest either a slight increase in channel sinuosity and clay content in flow events when compared with Model A or it may suggest deposition of linked debrite successions in the rare retrogradational splays. Units are interpreted to be amalgamated successions of more depositional mixed erosional and depositional channel systems with associated margin/levee units and lateral migration. They are identified in Angel-4, Cossack-1, Egret-2, Exeter-5ST1, Lambert-2, Mutineer-3, Mutineer-1B, Spica-1 and Wanaea-3 (Appendix B).
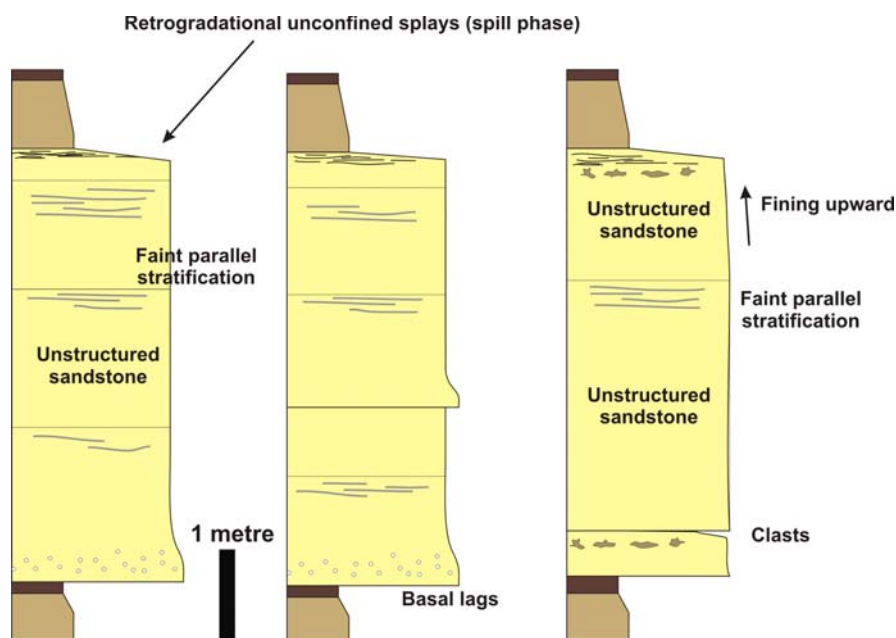
Figure 7-9: Variations of Model B. They can be preserved with or without a progradational splay succession. The units comprise multi-storey channel systems formed through repetitive cycles of incision and fill which are topped by either retrogradational splays or overbank successions. Individual fourth order channel elements as well as the overall fifth order succession are thinner than Model A.

7.3.2.3 Model C: Medial to Distal Composite Channel – Splay Model

The medial composite channel-splay model is a downbasinal and lateral transition of Model B. There are five characteristics of this model (Figure 7-10).

i. Common preserved progradational build phase of the older sheet complex (although it can still be missing in core as it may be removed through younger channelisation).

ii. Thin cut phase. Channel lags are rare.

iii. Amalgamated unstructured, parallel stratified and dewatered channel fill units representing the widening of channel margins and levees as the system becomes increasingly unconfined downslope or laterally.

iv. Common overspill, which is the result of decreasing channel depth due to aggradational infilling.

v. Thick-bedded (up to one metre) and often multiple stacked retrogradational splays or overbank units with increasing siltstone content.

Downslope thickening of the overspill phase is recognisable with the presence of dewatering features. They represent frequent overspilling of flow events onto channel margin and levee settings leading to an increased widening of the margins towards the late fill and overspill phase. Injected overbank clasts or linked debrites along with subtle to obvious fining upward grainsize trends may or may not be present (Figure 7-10). The degree of fining is related to the location of the overspill and retrogradational splay units to the channel axis. Both progradational and retrogradational splays of the associated sheet complex can display stacking patterns.

This model is identified in Egret-2, Exeter-5ST1, Lambert-2, Mutineer-1B, Spica-1, Montague-1, Wanaea-2A and Wanaea-3 (Appendix B).
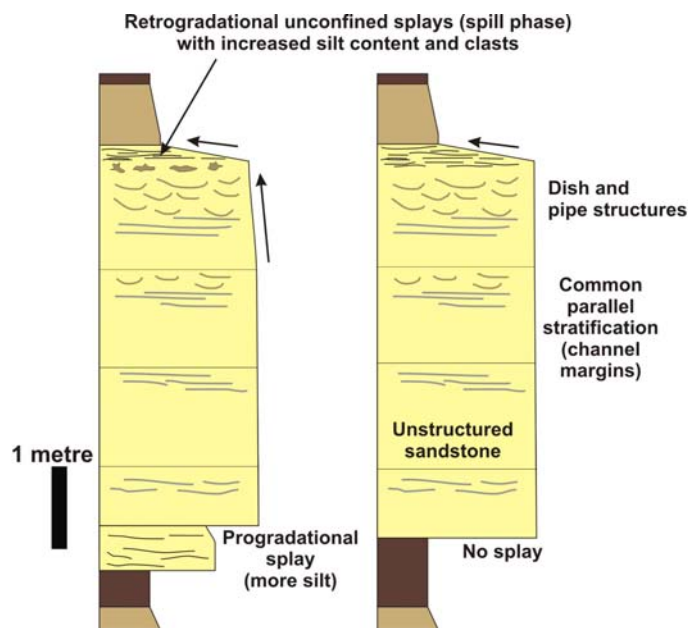
Figure 7-10: Variations of Model C. They can be preserved with or without a sheet complex progradational splay. Individual fourth order channel elements are thinner than the equivalent in Model B. They display a strong degree of dewatering and lamination indicative of increased channel migration and margin development.

7.3.2.4 Model D: Distal Mixed Composite Channel-Splay Model

The medial composite channel-splay model is a downbasinal and lateral transition of Model C. There are five characteristics of this model (Figure 7-11).

i. Thin to thick progradational build phase that commonly grades upward into overlying channel systems which are infilled by a similar grainsize. In rare cases, no build phase is present as it is removed by younger channelisation.

ii. Small to no cut phase. Channel lags are rare.

iii.   Amalgamated unstructured (rare), parallel stratified and dewatered channel fill (common). They represent increased downslope widening of the channel margins and levees.

iv.   Very common overspill signifying further decrease in channel depth with relation to infilling.

v.   Thick-bedded and often stacked retrogradational and overbank splays.

Increased amounts of late fill and overspill processes within an overall thin depositional sequence suggest the dominance of narrow distributary channel systems interpreted to be shallow (up to 5 metres) and narrow (<500 metres at 100:1). Associated margin and levee units are wide especially towards the overspill phase (Figure 7-11). Increased concentrations of siltstone and mudstone within the distal flow events in combination with the low slope gradient lead to an increase in channel sinuosity and lateral migration. Many submarine fans comprise metre scale distributary channel patterns in distal locations, often closely associated with the depositional lobe and sheet systems (Baas *et al.,* 2005).
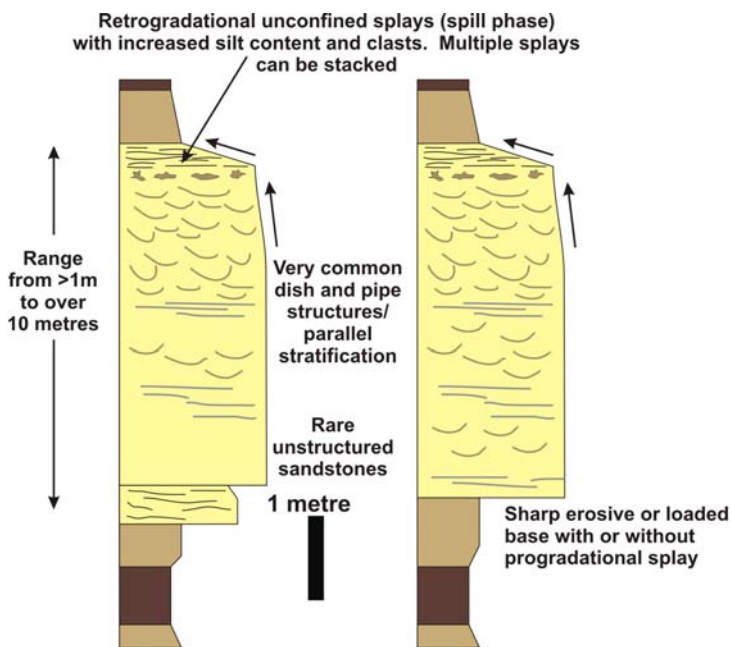
Figure 7-11: Variations of Model D. They are usually preserved with a progradational splay succession and small distributary-sized channel forms. It displays a very strong degree of dewatering and lamination.

7.3.2.5 Model E: Distal Frontal Splay Sheet Complex Model (Unchannelised)

Model E represents the basinward or lateral transition of Model D. It comprises a progradational sheet build phase which grades upward into overlying retrogradational build phase (Figure 7-12). Both phases contain stacked sand- and silt-dominated splays. Channelisation does not exist within this model as it is interpreted to rest within the unchannelised region of the fan model or laterally of a channel system.

Figure 7-12: Distal splay fifth order Model E comprising parallel stratified and dewatered sandstone with injection breccia/linked debrites. Successions are usually less than a metre thick and comprise of stacked splays.

7.3.3 Fifth Order Model Transitions

Fifth order architectural elements recognised in core and discussed above vary through a combination of lateral and basinward transformations.

7.3.3.1 Basinward Transitions

A basic basinward transition of the fifth order models demonstrates that:

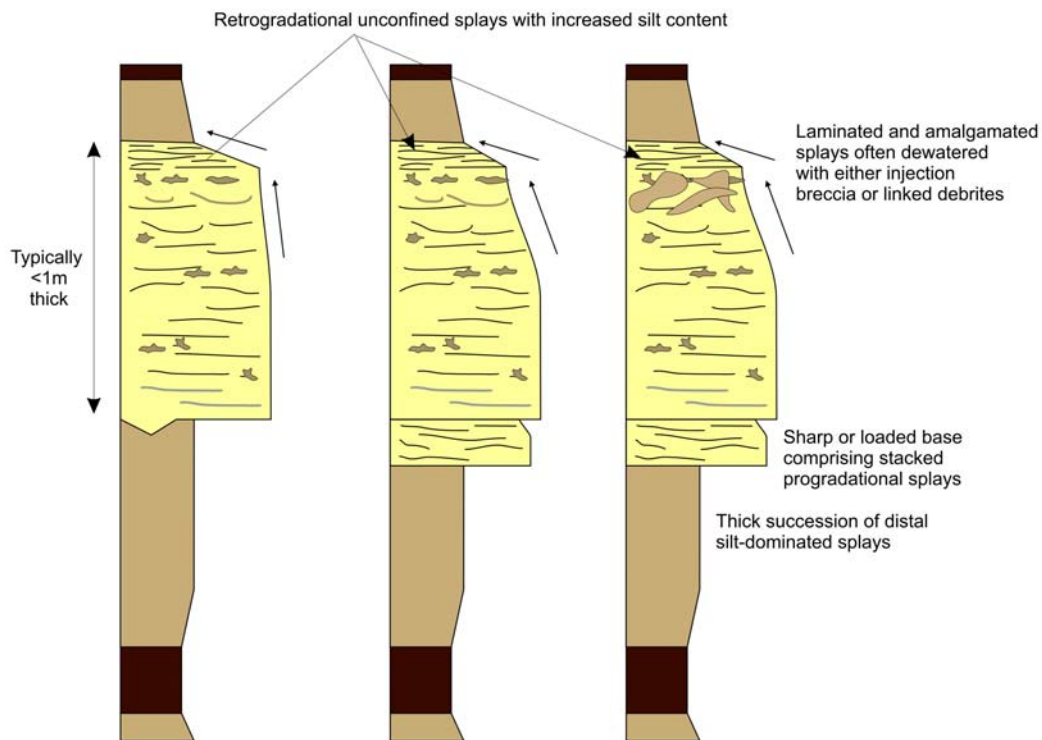- fourth order elementary channels thin and become less amalgamated basinward (Figures 7-13 and 7-14), and;

- channel margin and levee preservation increases downslope as the percentage of fine-grained material to coarser grained material increases (Figures 7-13 and 7-14). Channels become more depositional resulting in the narrowing and shallowing of single storey elements.

Sediments situated on a slope and upper basin floor setting tend to stack and promote flow bypass resulting in the preservation of a cut-fill-overspill motif. It displays little to no progradational phase due to severe channel incision. Fifth order composite channel-splay complexes are larger in proximal regions due to continuous localised channel infill and reincision by younger channels. These complexes can also incise into each other. Build and overspill phase deposits become more common downslope as the individual third order architectural elements (such as channel axis deposits) thin downslope. Lack of progradational splays beneath a fifth order channel-splay complex can indicate

that a cut phase existed within the model and that the model is not a purely lateral transitional variation (refer Section 7.3.3.2).

Varieties of fifth order composite channel-splay models transform basinward from a complex cut-fill-spill-build succession to a fill-spill-build succession to a spill-build succession that forms unchannelised sheet complexes in distal settings (Figure 7-13 and 7-14). This transition is recognised in outcrop from the Brushy Canyon Formation (Gardner and Borer, 2000) and the Klein Hangklip region of the Tanqua depocentre (Wild *et al.,* 2005).

Figure 7-13: Basinward model locations of the five variations in fifth order architectural elements (composite channels and sheet complexes). Model A is interpreted to rest within a proximal fan region whereas Model D rests within a medial to distal setting. Distal lobes are represented by Model E.

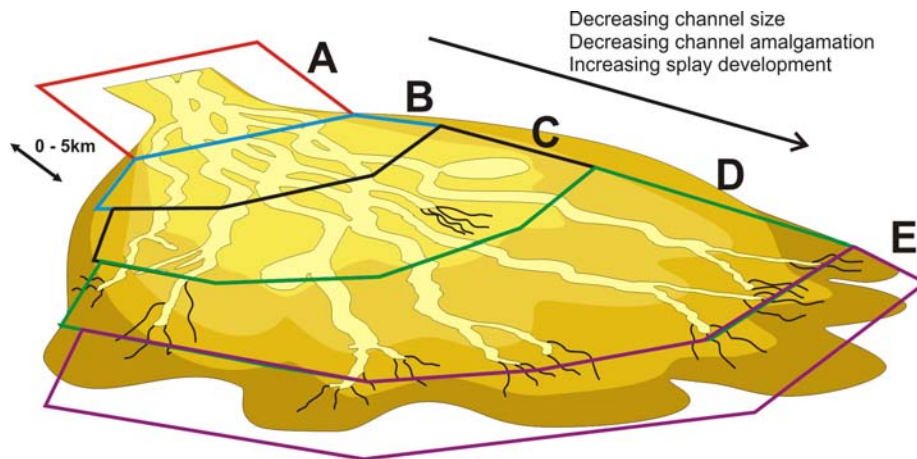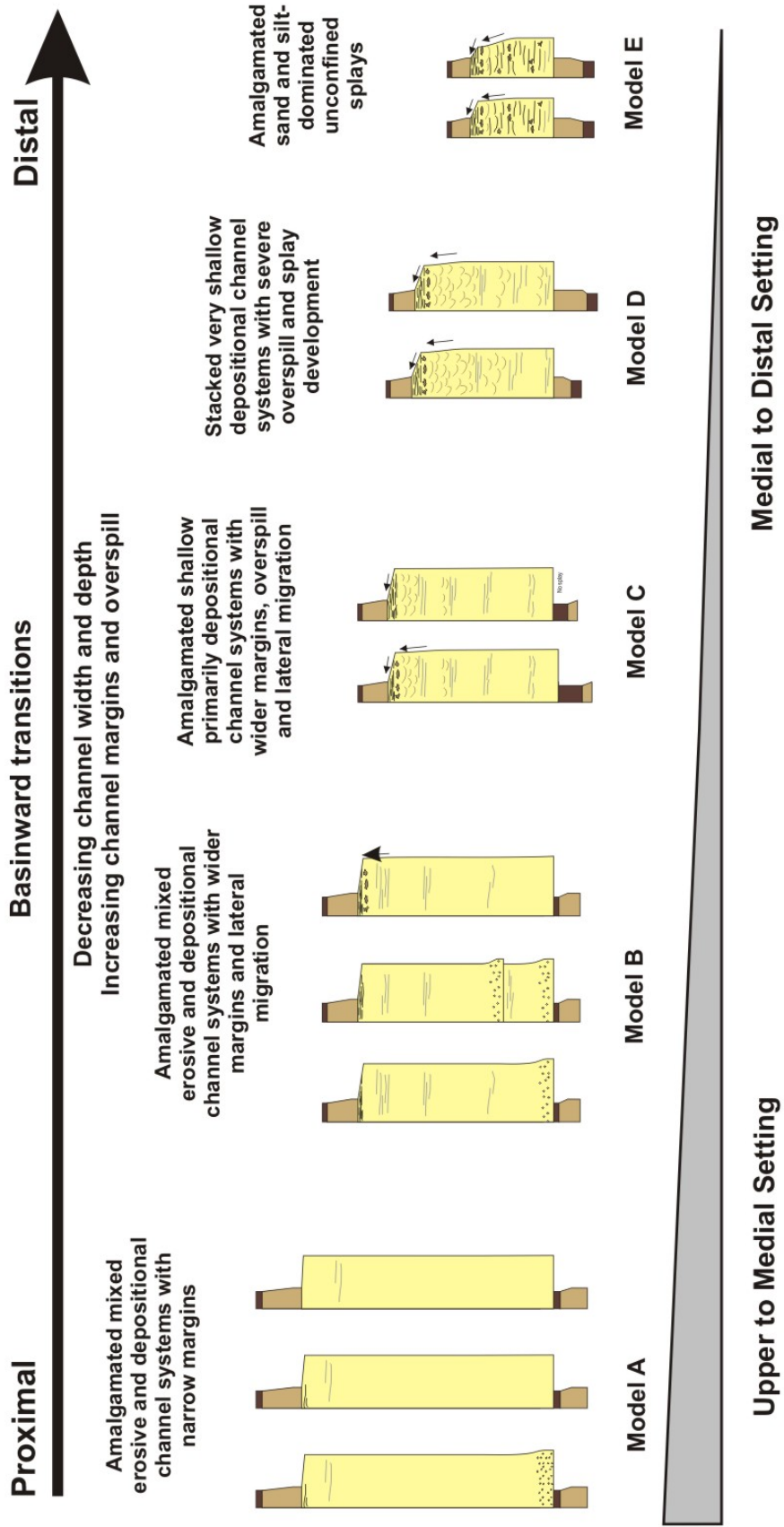Figure 7-14: Basinward transition (through the axis of the fan model) of the five variations in fifth order architectural elements (composite channels and sheet complexes).

7.3.3.2 Lateral Transitions

Basinward transitions of fifth order co-exist with a lateral transitional aspect. This is due to the fact that::

- these channel-splay systems can be migrational, and;

- wells may only intersect the margin of a channel-splay system and not the central axis.

Composite channel systems can display migrational stacking patterns of individual channel forms through compensational stacking, resulting in a vertical decrease in channel thickness and introduction of more channel margin lithofacies (parallel stratification and dewatering) in core (Figure 7-15). Sedimentary structure interpretation, model thickness and the presence of progradational splays beneath the fifth order model can assist in the identification of beds that may represent lateral variation of an adjacent channel complex. It is interpreted that the increasing presence of dewatering structures represents a basinward transition rather than lateral transition due to the downslope increasing channel and margin size as described in Section 7.3.3.1.

Figure 7-15: Lateral transitions of fifth order channel-splay models. Model A rests within a channel axis whereas Models B and C represent a lateral change in bed thickness with increased stratification and dewatering towards the margins. The preservation of underlying splay deposits in Model D and E could indicate lateral transition. Dewatering structures could also be emphasised by lateral dewatering.
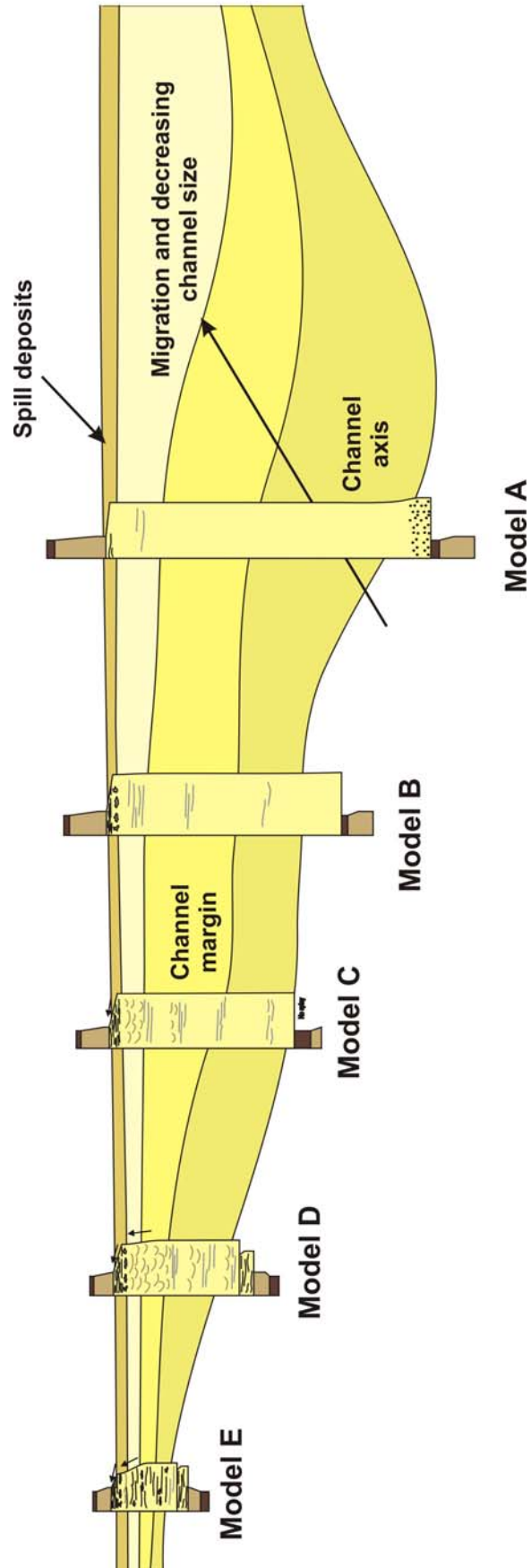
7.4 Fifth Order Architectural Systems of the Dampier Sub-basin

Analysis of fifth order channel-splay and sheet complexes was completed on all core logs (Appendix B). All wells are interpreted to contain a combination of lateral and basinward model variations (Table 7.2). Fifth order composite log plots were created for some wells to best illustrate the interpreted stacking behaviour of fourth and fifth order architectural elements and hence fan lobe development.

Table 7-2: Examination of interpreted fifth order channel-splay and sheet complexes in the Dampier Sub-basin. Aspect ratios of 4:1 to 100:1 for individual channels and 3:1 for channel belt to channel widths are used from Section 7.2.1.

Well	Models	Discussion
Angel-4	A, B overlain by E	Fifth order composite channel-splay systems in this well are multi-storey. They represent a strong history of channel infill and reincision. It contains the most evidence of multiple channel infill and reincision events where a minimum of five to six individual migrational channel forms are interpreted to exist within the one fifth order composite channel complex (2758.5 to 2769.0 metres). These units are best represented by a mixture of Model A and B overlain by spill deposits of Model E, which were deposited through retrogradation of the system.
Cossack-1	A and B overlain by E	Fifth order composite channel-splay complexes in this well are a combination of Models A and B overlain by spill deposits of Model E (Figure 7-16). This suggests that a strongly channelised system with minor splays existed during upper Tithonian time in the region. Individual fourth order channel systems are interpreted to be less than five to six metres in thickness. This signifies channelisation by distributary channels up to approximately 200 metres wide across a fairway 600 metres wide (Figure 7-16).
Montague-1	A and C	Fifth order composite channel-splay complexes in this well are represented by Model A and C. The complexes are interpreted to be greater than 5 metres thick but this value is speculated due to the short cored unit (18 metres).
Exeter 5-ST1	A, B, C and E.	Fifth order composite channel-splay complexes in this well are a combination of Models A, B, C and E. The well is interpreted to have intersected the central axis of one large composite channel system up to 20 metres thick (11 metres in core with marginal deposits) which could contain more than one fifth order system through amalgamation. Other channel composites could be interpreted to be marginal systems to the main channel axis. They contain hybrid flows and injection features (Figure 7-17).

Egret-2	B,C,D overlain by E	Fifth order composite channel-splay complexes in this well are a combination of Models B, C, and D overlain by retrogradational splay deposits of Model E. This range of fifth order systems suggests high variability of channel migration around the well. Fifth order systems of Models B and C are thin (between 3274 and 3295 metres) suggesting that the well did not intersect the axis of the composite channel system. This could further be supported by the existence of post-depositional injected zones (Section 9.5).
Mutineer-3	B, D and E	Fifth order composite channel-splay complexes in this well are a combination of Models B, D and E. Model B represents the most channelised component. Model D represents a time of distributary channel networks that were highly migrational. Fourth order individual channel systems are distributary-sized and interpreted to range up to 5 metres thick forming fifth order systems up to 15 metres thick. This correlates to individual channels up to 500 metres wide (Figure 7-18). Figure 7.22 highlights a section from Mutineer-3 to Mutineer-1B highlighting how overall packages could comprise laterally amalgamated channelised systems.
Mutineer-1B	B,C,D and E	Fifth order composite channel-splay complexes in this well are a combination of Models B, C, D and E. It is interpreted to contain two thick fifth order channel complexes separated by thin distributary- and splay-dominated complexes. The individual fourth order channel systems are dominantly distributary-sized ranging up to five metres thick and interpreted to be up to 500 metres wide. The channel systems could be interpreted to be migrational (Figure 7-19)
Spica-1	A, B, C, D and E	Spica-1 contains all fifth order model types from A to E. The lack of structures in the Model A fifth order channel-splay complex (3154 – 3149 metres) suggests that it did not undergo much migration. This could represent fault control. Models C and D are interpreted to represent central and marginal deposits of distributary-sized channel systems. There is an increased amount of migration of the fifth order channel-splay complexes towards the top of the cored section which suggests decreasing channel size and increased sinuousity in relation to retrogradation of the entire succession (Figure 7-20).

Lambert-2	B, C, D and E.	Fifth order composite channel-splay complexes in this well are a combination of Models B, C, D and E. Model B is not common throughout the core. Fourth order individual channel systems are interpreted to be distributary-sized with well developed margins displaying strong stratification and dewatering structures. Individual channels are interpreted to be three to five metres deep, up to 500 metres wide and highly migrational. They form multistorey composites up to 13 metres thick within a channelised fairway up to 1500 metres wide (aspect ratio 10:1 to 100:1)
Wanaea-3	A, B, C, D and E	Wanaea-3 contains all fifth order model types from A to E suggesting varying amounts of channel migration and sediment flux. The well is five kilometres from Cossack-1 which is interpreted to contain a more channelised system. Wanaea-3 is dominated by fifth order channel-splay complexes and sheet complexes. A large composite channel-splay system between 2908m and 2915m overlies progradational splays. It is interpreted to range from 7 to up to 15 metres thick (if marginal sediments were intersected) and contain individual channel systems up to 3 to 4 metres thick. This correlates to an individual channel width of up to 400 metres and a channelised fairway up to 1200 metres wide.
Wanaea-2A	C, D and E	Fifth order composite channel-splay and sheet complexes are a combination of Models C, D and E. The well is dominated by migrational distributary channel complexes and sheet complexes comprising stacked sand and silt-dominated frontal splays. An amalgamated and migrational distributary-sized composite channel-splay complex is interpreted at the base of the cored unit (2916m to 2930m), which migrates away from the borehole (Figure 7-21). Individual channel systems are up to two metres thick. This would suggest that individual channels could range up to 200 metres wide and form a channelised belt over 600 metres wide.

Figure 7-16: Fifth order channel-splay composite log highlighting interpreted stacking of channel forms and splays throughout the Cossack-1 log. The fifth order channel-splay complexes are interpreted to be distributary-sized with individual channels up to 5 metres thick and up to 500 metres wide.

Figure 7-17: Fifth order channel-splay composite log highlighting interpreted stacking of channel forms and splays throughout the Exeter-5ST1. The well is interpreted to have intersected the central axis of one large channel composite system up to 20 metres thick.

Figure 7-18: Fifth order channel-splay composite log highlighting interpreted stacking of channel forms and splays throughout the Mutineer-3 log. Individual fourth order channel forms are interpreted to range up to 5 metres thick and 500 metres wide forming amalgamated successions of fifth order complexes up to 15 metres thick and 1500 metres wide. The complexes are interpreted to be migrational.
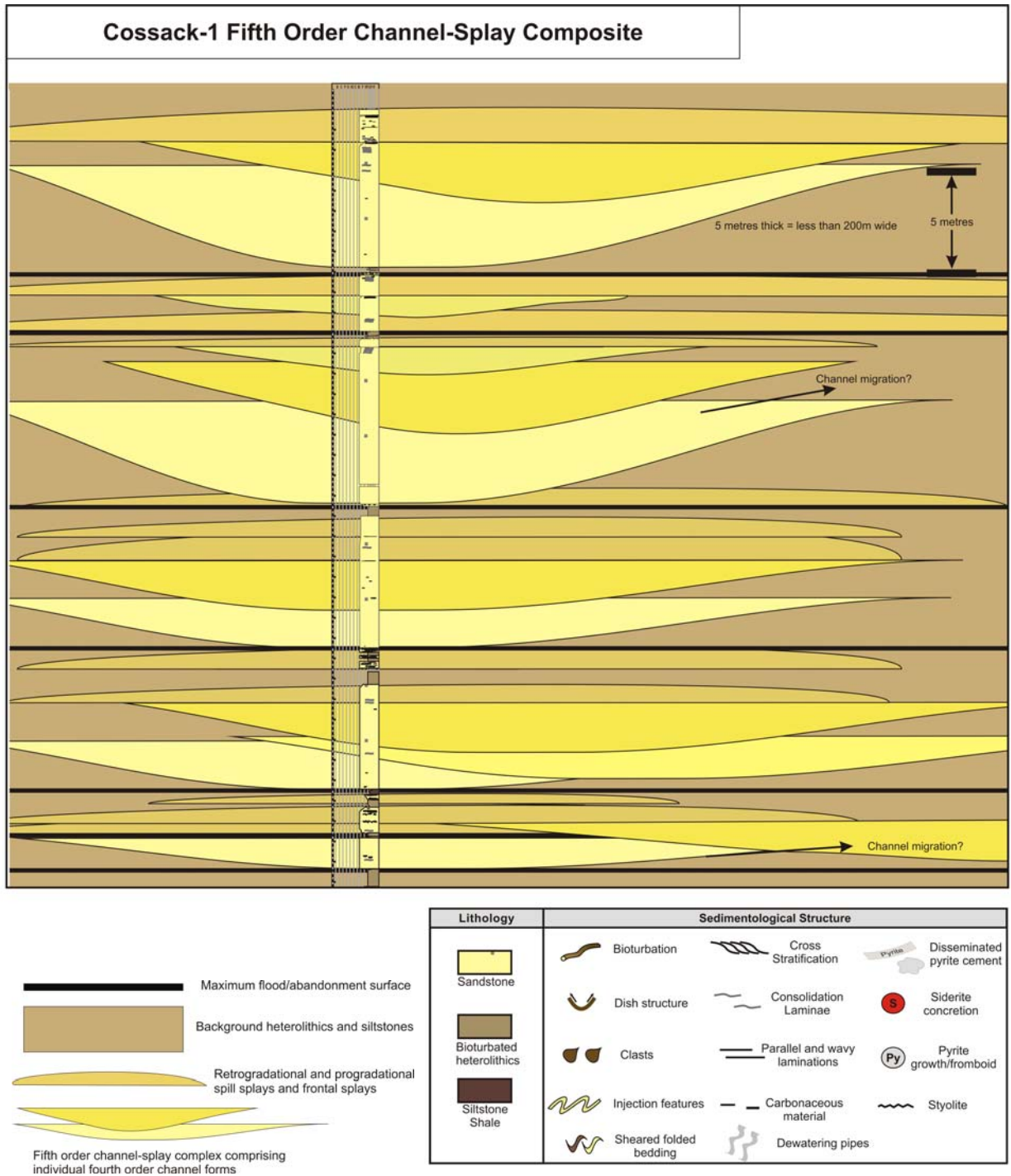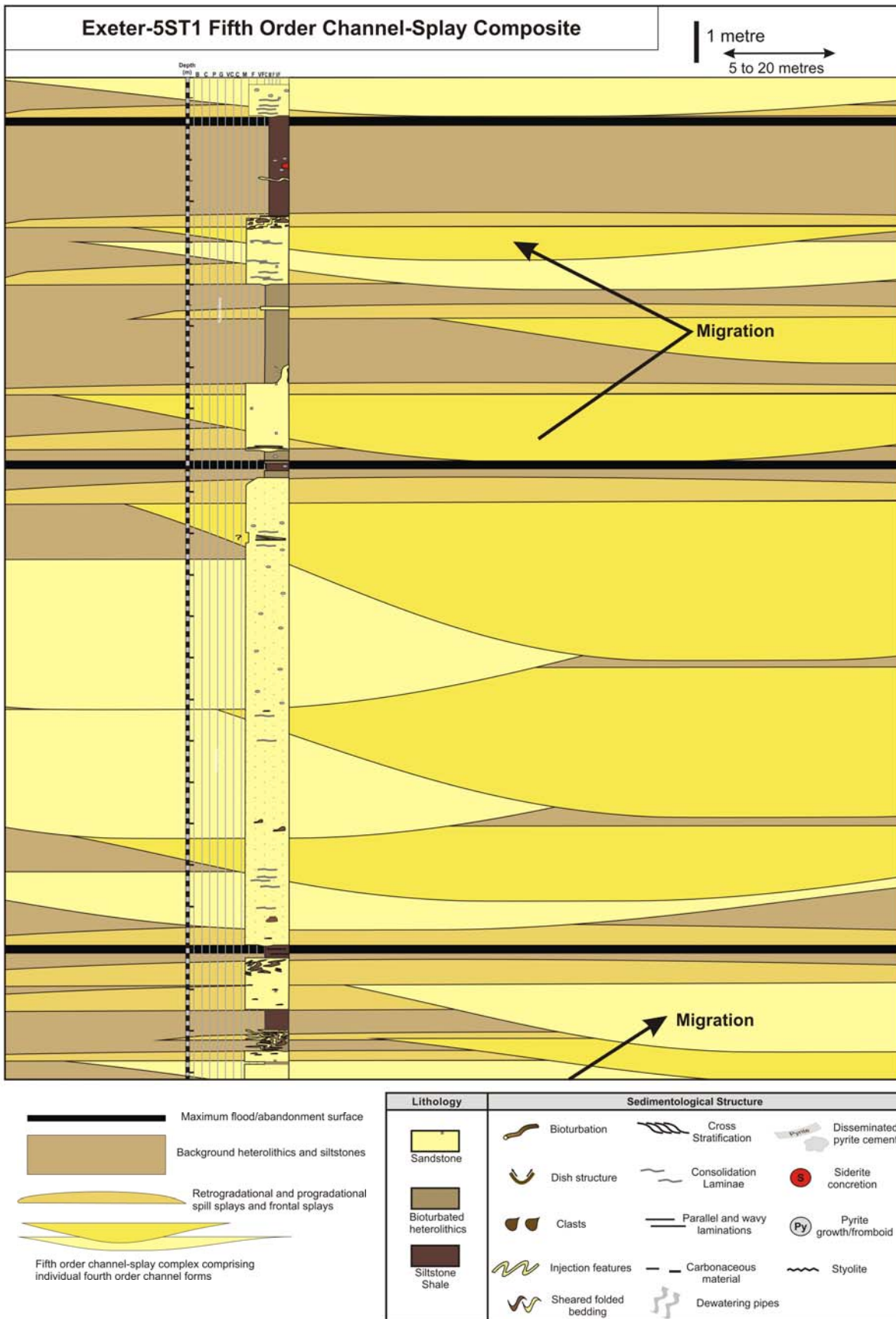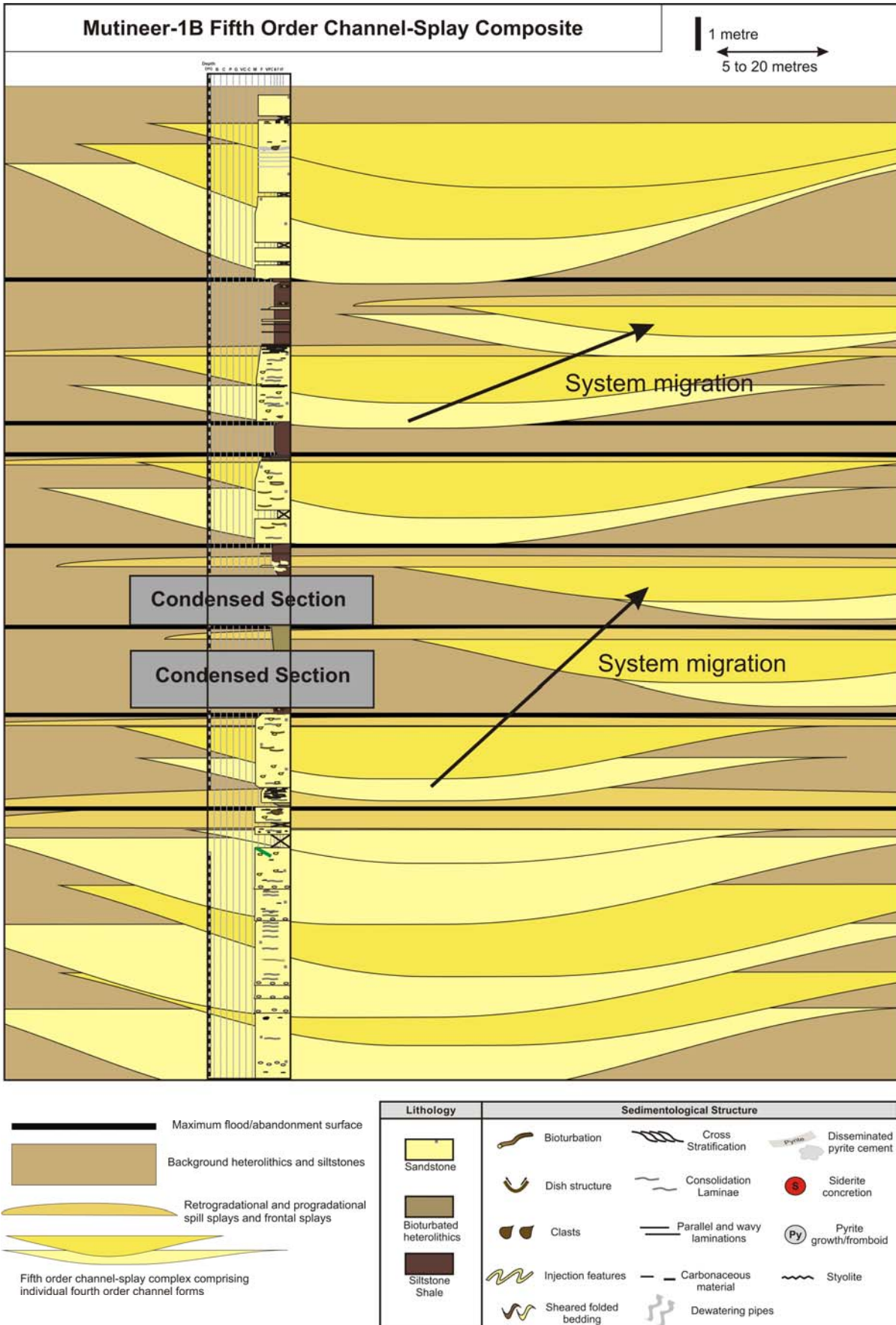
Figure 7-19: Fifth order channel-splay composite log highlighting interpreted stacking of channel forms and splays throughout the Mutineer-1B. This example demonstrates the distal migration of the channel system away from the borehole, preserving only distal splays.
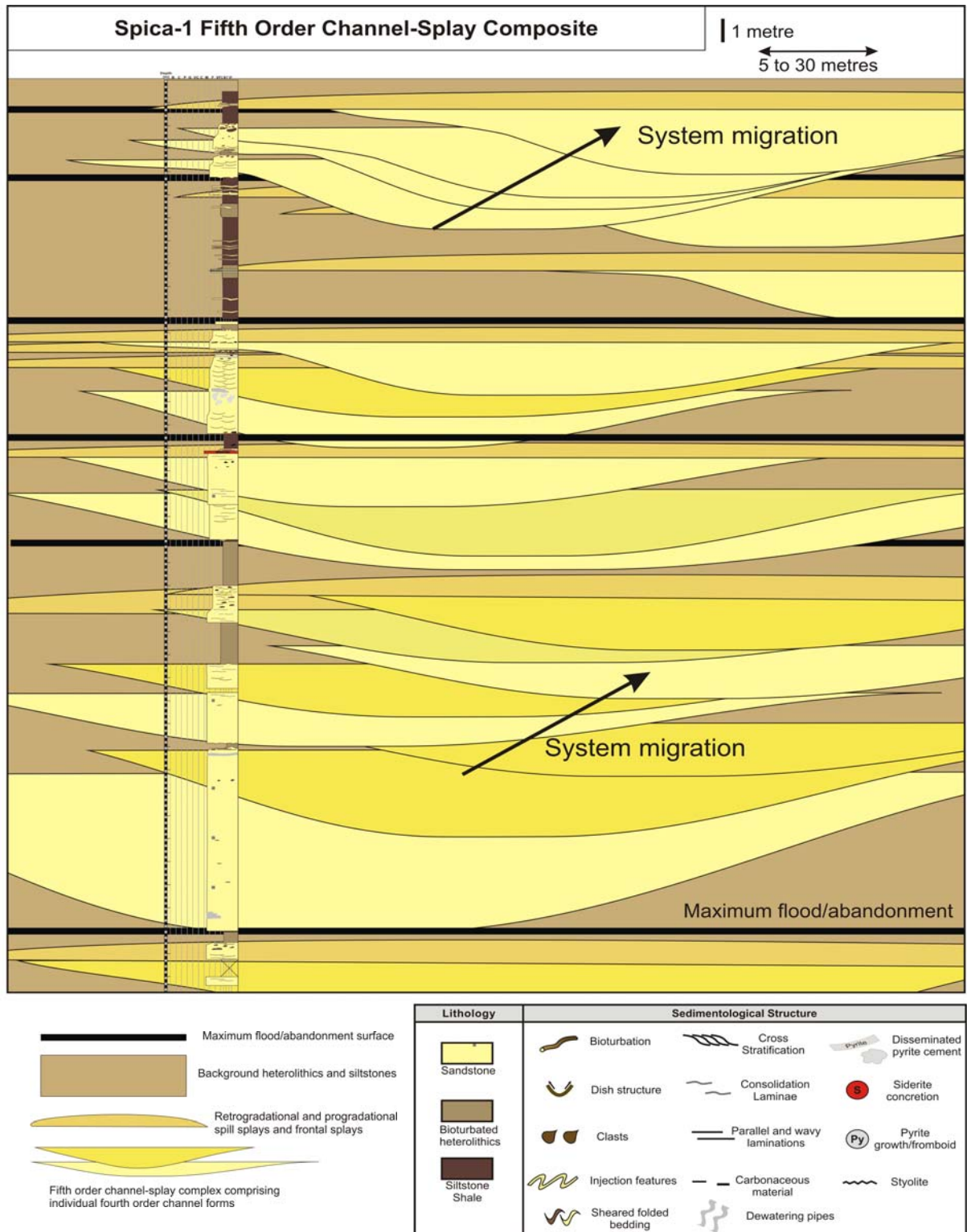
Figure 7-20: Fifth order channel-splay composite log highlighting interpreted stacking of channel forms and splays in Spica-1. This example demonstrates the distal migration of the channel system away from the borehole, preserving only distal splays. It also highlights increasing migration and decreasing channel size over time (up section) in relation to overall retrogradation of the Tithonian Angel system.
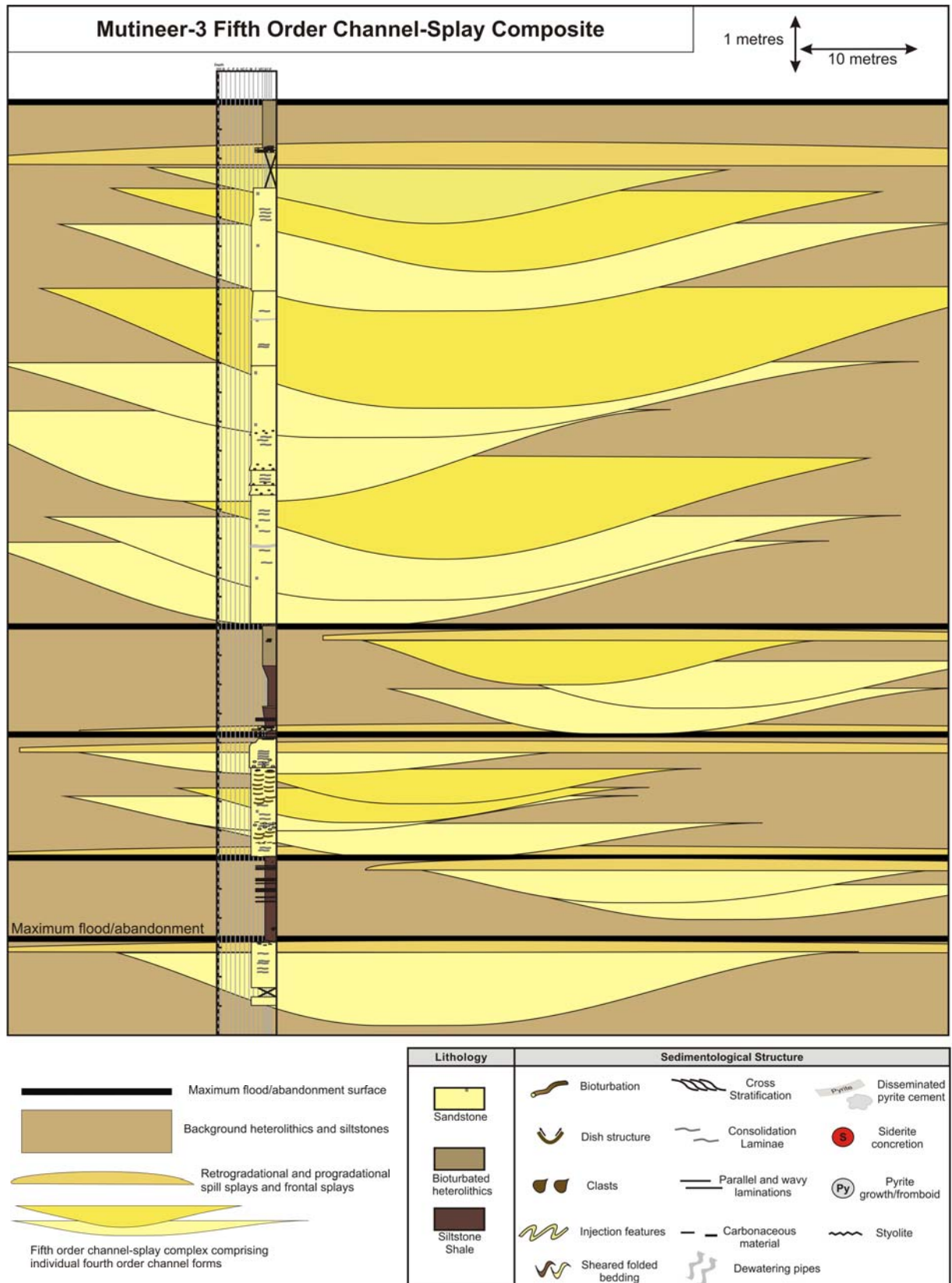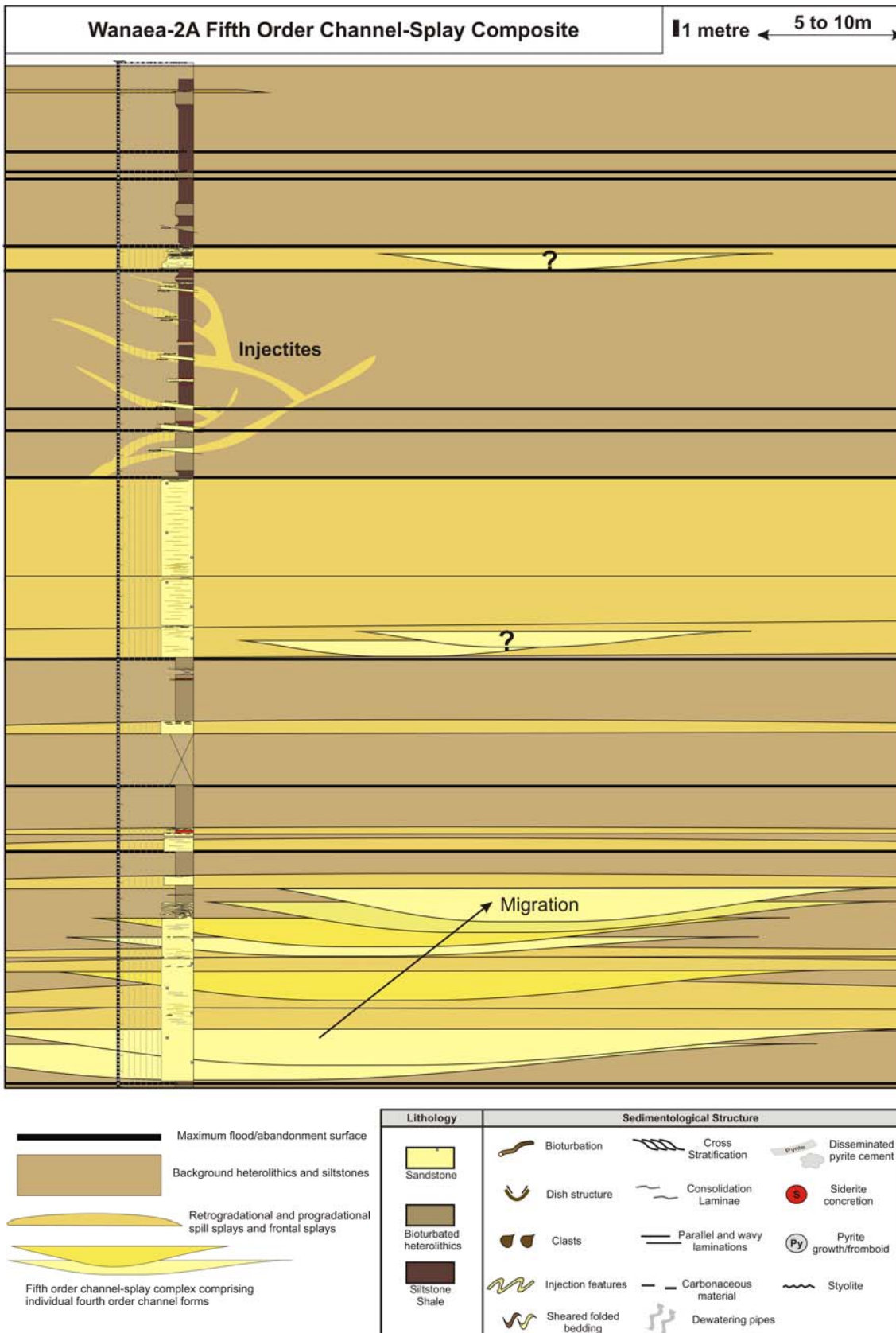
Figure 7-21: Fifth order channel-splay composite log highlighting interpreted stacking of channel forms and splays in Wanaea-2A. The well contains migrational small distributary channel and sheet complexes. A migrational system comprising distributary-sized composite channel-splay complexes is interpreted at the base of the cored succession (2916m to 2930m) which migrates away from the borehole. The individual channel forms are interpreted to be approximately 2 metres thick and 200 metres wide. The migrational belt may be up to 600 metres wide.
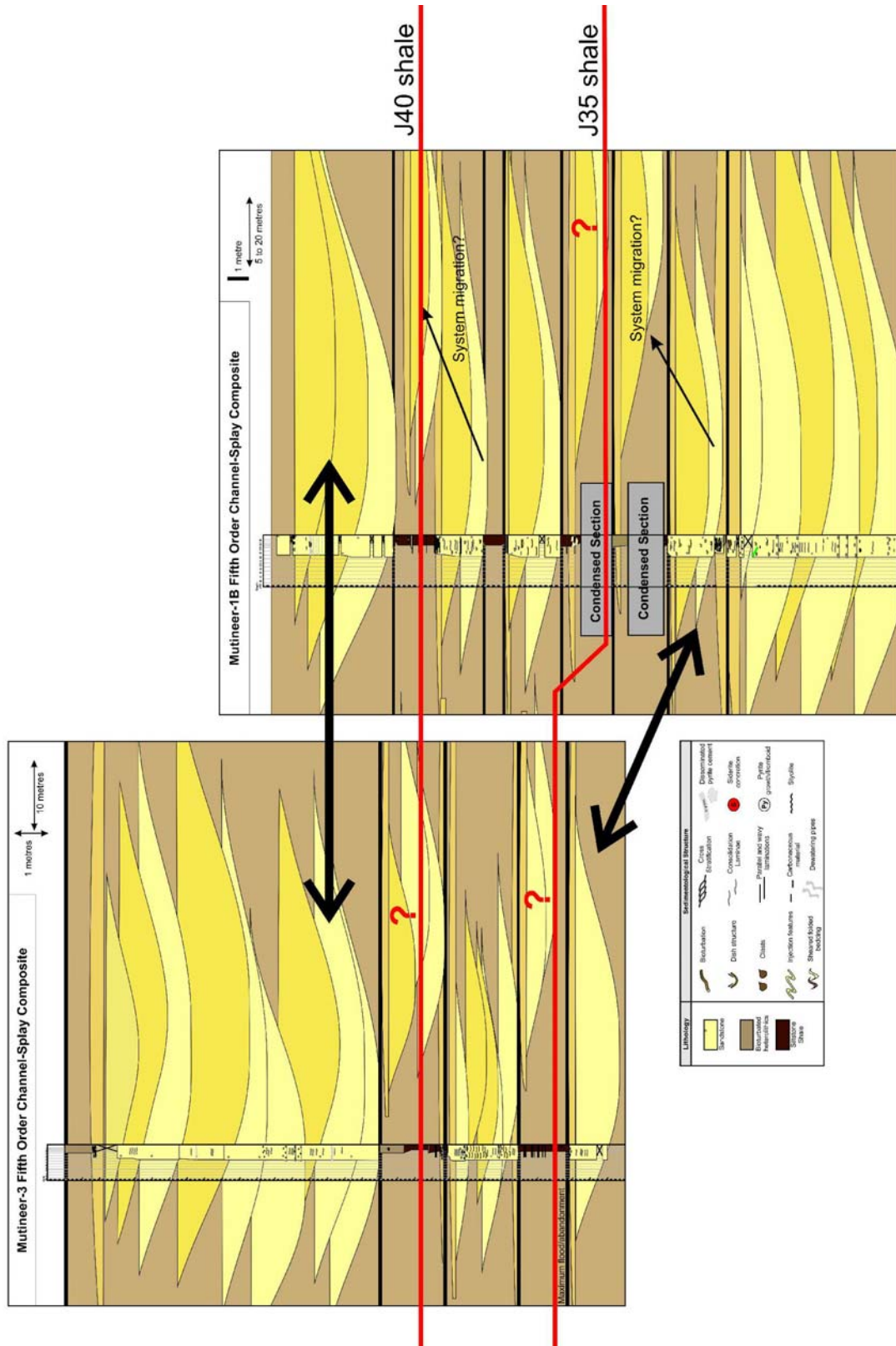
Figure 7-22: Section between Mutineer-1B and Mutineer-3 comparing interpreted fifth order channel-splay systems. The J40 and J35C claystones could be interpreted to represent either abandonment surfaces with channel-splay systems migrating to another location or they could be interpreted to represent regional flooding events. Above the J40 claystone and below the J35C claystone, channelised systems could be interpreted to be laterally amalgamated across both wells.

7.5 Summary

The application of a fourth and fifth order architectural element scheme across the Dampier Sub-basin has led to the analysis of fifth order composite channel-splay and sheet complexes in all cored wells. A fourth order architectural element is interpreted to represent a fourth order channel form which can stack to form a fifth-order composite channel-splay complex. This complex represents a fan lobe unit. There are five differing varieties of fifth order channel-splay and sheet complexes, which are dependant on a combined basinal and lateral change.

Analysis of fourth and fifth order architectural complexes has determined that the largest and most proximal successions of fifth order systems exist in Angel-4, Cossack-1, Montague-1 and Exeter-5ST1. The thinnest and most distal fifth order elements are interpreted from Lambert-2, Wanaea-2A and -3. Lateral migration of fourth and fifth order systems is interpreted to occur in all wells and is represented in the composite plots.

Chapter 8 takes the fourth and fifth order architectural scheme and related interpretations and upscales them into sixth and seventh order systems that represent the evolution of the depositional fan systems of the Tithonian interval.

8 Sixth Order Architectural Analysis and Tithonian Fan Evolution

8.1 Introduction

This chapter combines the fourth and fifth order sequences that represent the development of composite channel-splay and sheet complexes (as discussed in the previous chapter) into:

- sixth order migrational or confined channel complexes (seventh order proximal fan), and;

- sixth order migrational distributary channel and sheet complexes (seventh order distal fan).

It is accomplished through a combination of core, wireline log and seismic reflection data. It is first essential to upscale the determined architectural hierarchy determined in Chapters 6 and 7 into an electrofacies scheme that can be populated across wells that contain no core.

8.2 Electrofacies Associations

Modelling and propagating core descriptions and lithofacies across uncored regions is of prime importance regarding the reservoir understanding of a field or basin. Upscaling of the core lithofacies to log electrofacies will allow the sedimentological and depositional interpretation to be extrapolated across all wells in the north-western region of the Dampier Sub-basin. It will assist both stratigraphic and palaeogeographical interpretation. Electrofacies describe the core-derived lithofacies associations that are identifiable within wireline log successions, although the resolution of this technique is lower than core. Correlation of core with wireline logs was concentrated primarily on log motifs from the gamma ray (GR) curves (Appendix B). Wireline logs are used for characterising different lithologies from uncored wells as well as acquiring lithological information from gaps which result from missing core.

The standard electrofacies classification of Serra *et al.,* (1985) (Figure 8-1 next page) highlights the variation in curve shape and grain-size.

NOTE:
This figure is included on page 178 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 8-1: Electrofacies classification representing the variation in gamma ray curve shape (Serra *et al.,* 1985).

Electrofacies classifications interpreted across the Dampier region were grouped into two categories which are commonly identified within channelised and unchannelised settings (Table 8-1 next page):

i. Amalgamated electrofacies. Two electrofacies classifications which signify channelisation are:

- Amalgamated homogeneous sandstone successions, and;

- Amalgamated fining upward successions.

ii. Layered electrofacies. They signify small distributary channel systems interbedded with unconfined frontal splays. Five electrofacies classifications include:

- Layered smooth and slightly serrated sandstone successions;

- Layered coarsening upward successions;

- Layered fining upward successions;

- Layered egg shaped successions, and;

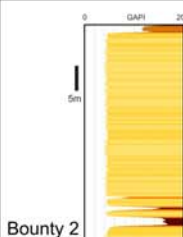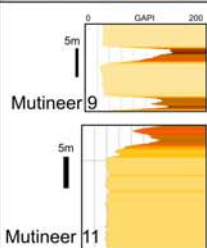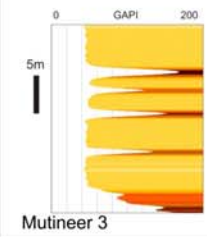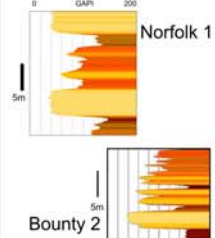- Heterolithics, siltstones and mudstones.
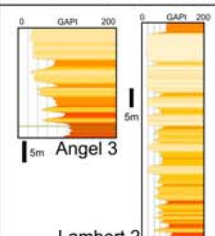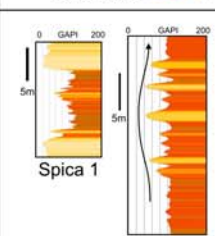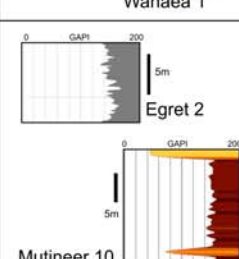
Amalgamated Electrofacies	**Electrofacies 1** **Amalgamated smooth and slightly serrated "cylindrical" log motif**	Cylindrical log motif displays either smooth or slightly serrated character. Associated with core lithofacies A and B. GAPI values typically range from 40 to 60 GAPI. Amalgamated successions range from 3 to over 30 metres thick.	This motif is interpreted to represent amalgamated channel axis and marginal units interbedded with sand-dominated splay associations.	Bounty 2
	Electrofacies 2 **Amalgamated smooth fining upward "bell shaped" log motif**	Represented by successions that display a relatively smooth fining upward transition from sandstone to siltstone and claystone. These units are associated with a vertical change from facies A and B through facies D to facies E and F. The successions can range from 0.5 metre to approximately 3 to 5 metres thick.	This motif can represent lateral migration of a channel system, rapid retrogradation/fan lobe shut down or channel abandonment. This motif can be affected by the invasion of post depositional injectites.	Mutineer 9 Mutineer 11
Layered Electrofacies Classifications	**Electrofacies 3** **Layered smooth and slightly serrated "cylindrical" log motif**	Represented by layered successions of homogenous and parallel laminated sandstones separated by thin heterolithic or shale intervals. This facies is associated with core lithofacies A and B grading rapidly to facies E and F. GAPI values of the sandstones typically range from 40 to 60 GAPI. Stacked layered successions can range up to 15 to 20 metres in thickness.	This motif represents a singular or stacked thin fan lobe units that are either unchannelised or slightly channelised by very small and laterally migrational distributary channel systems.	Mutineer 3
	Electrofacies 4 **Layered and serrated fining upward "bell shaped" log motif**	Represented by layered and stacked successions of thin beds that display an overall fining upward transition from sandstone to siltstone and claystone. These units are associated with a vertical change from facies A and B through facies D to facies E and F. The successions can range from 0.5 metre to approximately 10 metres thick.	This motif is interpreted to primarily represent retrogradation of a fan lobe unit and decreasing net to gross. It can also represent lateral migration away from a channel system with crevasse splay development.	Norfolk 1 Bounty 2
	Electrofacies 5 **Layered and serrated coarsening upward "funnel shape" log motif**	Represented by layered and stacked successions of thin beds that display an overall coarsening upward transition and increasing net to gross from dominantly siltstone to sandstone. These units are associated with a vertical change from facies E and F to Facies D to Facies A and B. The successions can range from 0.5 metre to approximately 10 metres thick.	This motif is interpreted to primarily represent progradation of a fan lobe unit and deposition of frontal splays.	Angel 3 Lambert 2
	Electrofacies 6 **Layered and serrated "egg shape" log motif**	Represented by a rapid increase and decrease in log motif of thin bedded units. They range from 1 to 5 metres in thickness.	This log motif is interpreted to represent the progradation and retrogradation of a dominantly unchannelised frontal splay.	Spica 1 Wanaea 1
	Electrofacies 7 **Serrated high GAPI log character**	Represented by high gamma-ray log values that range from 80 to 200 GAPI.	The log motif of these units is habitually serrated due to the bioturbated heterolithic nature of the sediments. These units represent the E and F core lithofacies.	Egret 2 Mutineer 10

Table 8-1: Table of electrofacies schemes classified for this study from gamma ray logs.

8.3 Sixth Order Architectural Models

Individual fifth order composite channel-splay and sheet complexes, as discussed in Chapter 7, can compensationally stack to form sixth order architectural units. These sixth order units can exist either within a confined channel fairway system on a slope to proximal fan setting, or within a migrational channel and splay complex that compensationally stacks on the mid- to distal fan settings (Figure 8-2). They stack to form an entire seventh order fan system that is interpreted to represent the entire Angel Formation.

NOTE:
This figure is included on page 180 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8-2: Channel and splay hierarchies for the differing architectural orders (after Gardner *et al.,* 2003). A 4th order system is represented by a single storey channel fill which commonly preserves a migrational sedimentary pattern interpreted from core. A 5th order system is represented by a composite channel-splay complex. A 6th order system is represented either by a confined channel complex on a slope or proximal fan setting or by a compensational channel and splay complex in medial to distal fan settings. Channel hierarchies are adapted from those interpreted from the Brushy Canyon outcrops, West Texas (Gardner *et al.,* 2003).

8.3.1 Fifth Order Autocyclic Avulsion and Compensational Stacking

Fifth order composite channel-splay complexes are controlled by autocyclic processes and compensationally stack through avulsion. This same autocyclic process is identified in oil bearing reservoirs of the Paleocene Jotun oil field located in the North Sea (Figure 8-3).

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NOTE:
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the thesis held in the University of Adelaide Library.
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Figure 8-3: Autocyclic compensational stacking of fifth order channel-splay complexes in the Jotun field, North Sea (from Bergslien, 2002). The depositional model interpreted in this field is comparable to that interpreted for the Tithonian interval of the Angel Formation.

As discussed in Section 7.3, fourth order elementary channel-splay bodies stack to form a composite channel-splay system. They stack to a particular thickness that has a certain threshold gradient. Above this threshold, the topographic high of these fifth order composite channel complexes is above the equilibrium profile of the slope. This encourages younger channel complexes to avulse laterally or prograde into a topographic low beside or in front of the channelised system (Figure 8-4). Models describing this behaviour have been created for the Amazon fan (Lopez, 2001) and the Brushy Canyon Formation (Gardener *et al.,* 2003). The degree of avulsion and compensational stacking is highly dependant on the amount of channel sinuosity, the degree of channel axis or thalweg aggradation and the level of confinement. It is interpreted that compensational stacking would increase basinward from proximal to distal settings.

Fifth order sand-dominated sheet and fan lobe systems tend to display lobate profiles that can also drive compensational stacking. It is interpreted that a new lobe deposit will occupy and be confined within a topographic depression against a previous lobe deposit. This depositional control is well expressed in the proximal part of the lobe deposits from the Golo turbidite system where sharp lateral changes are observed from onlap terminations to hemipelagic sedimentation (Gervais *et al.,* 2004).
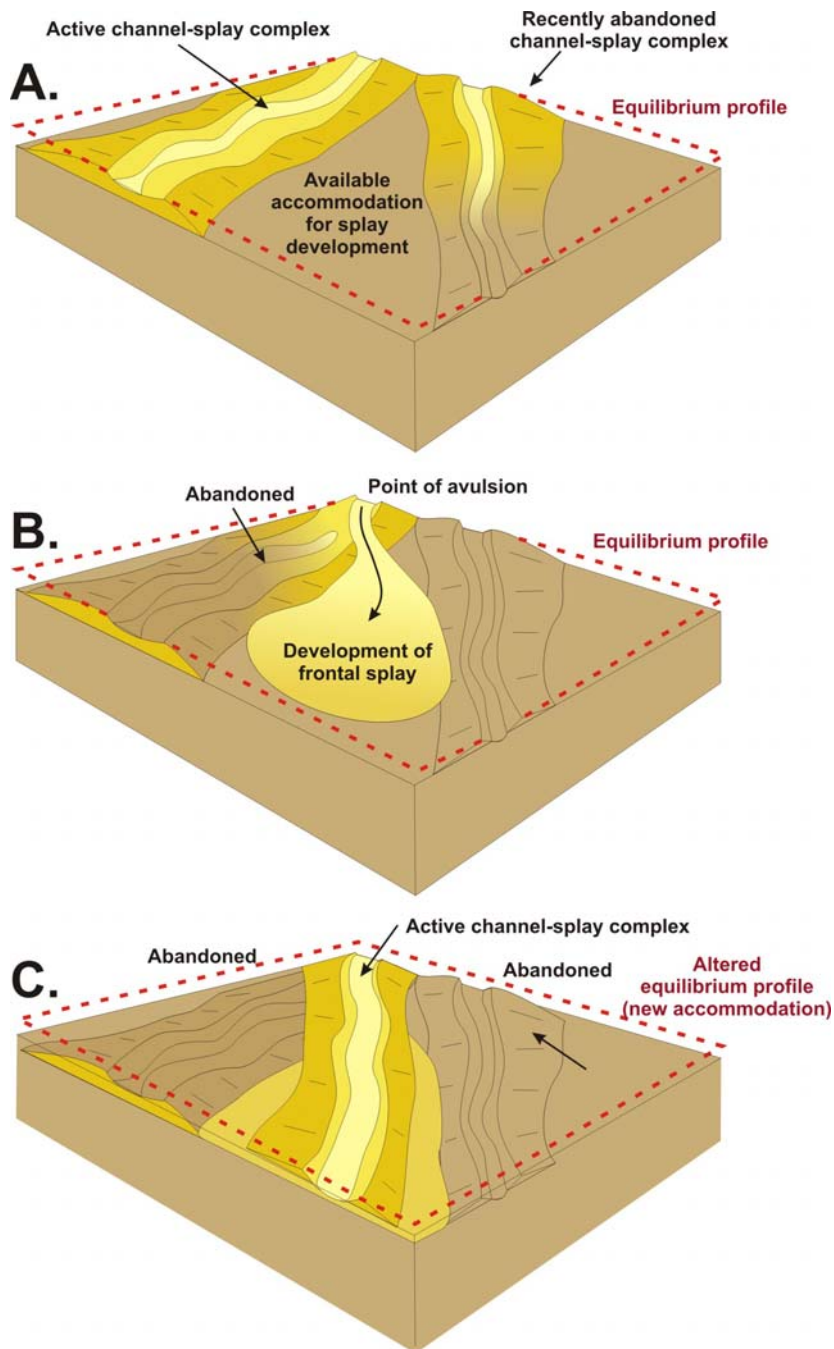
Figure 8-4: Model highlighting the avulsion of fifth order composite channel-splay systems as they prograde downslope. When channel-splay systems reach the equilibrium profile, they are likely to bifurcate. Avulsion is interpreted to occur frequently in distributary channel systems within retrogradational successions (Section 6.2). Model adapted from the Amazon fan system (Lopez, 2001).

8.3.2 Sixth Order Allocyclic Models

Sixth order architectural elements are interpreted to be primarily driven by allocyclic controls. They are bound by surfaces that are interpreted to represent maximum flooding events. They can prograde during lowstand conditions and aggrade/retrograde throughout late lowstand to transgressive times in relation to a fluctuating relative sea level. Development of a sixth order system is directly related to the slope equilibrium profile, which affects the amount of accommodation space available at any one time (Figure 8-5). This profile can be disrupted by tectonic deformation (Pirmez *et al.,* 2000) or changes in flow parameters which include sediment flux, grainsize and efficiency that change from lowstand to highstand conditions (Kneller, 2003).
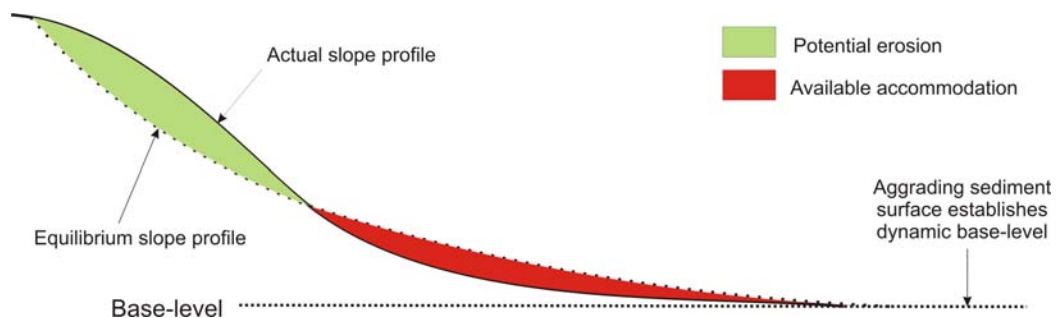
Figure 8-5: Standard relationship between an equilibrium profile and a true slope profile. Regions of erosion and accommodation space are created in relation to the equilibrium profile and the location of the prevailing base-level (modified from Kneller, 2003 and Samuel *et al.,* 2003).

Two models describe the development of sixth order fan complexes. They are the:

- sixth order progradational model, and;

- sixth order aggradational and retrogradational model.

8.3.2.1 Sixth Order Allocyclic Progradational Model

A sixth order progradational model is related to an interpreted sequence boundary and lowstand event, which tends to supply the receiving basin with gravity flows that are large, dense and highly erosional. They have the ability to decrease the slope gradient and compress the equilibrium profile (Figure 8-6). This results in a shift in the equilibrium profile, leading to erosive downcutting of older fan lobe deposits and the commencement of migrational and confined sixth order channel complex (Figure 8-2). For channel fill to be preserved within a channel feature, the profile would require positive accommodation (Section 8.3.2.2).
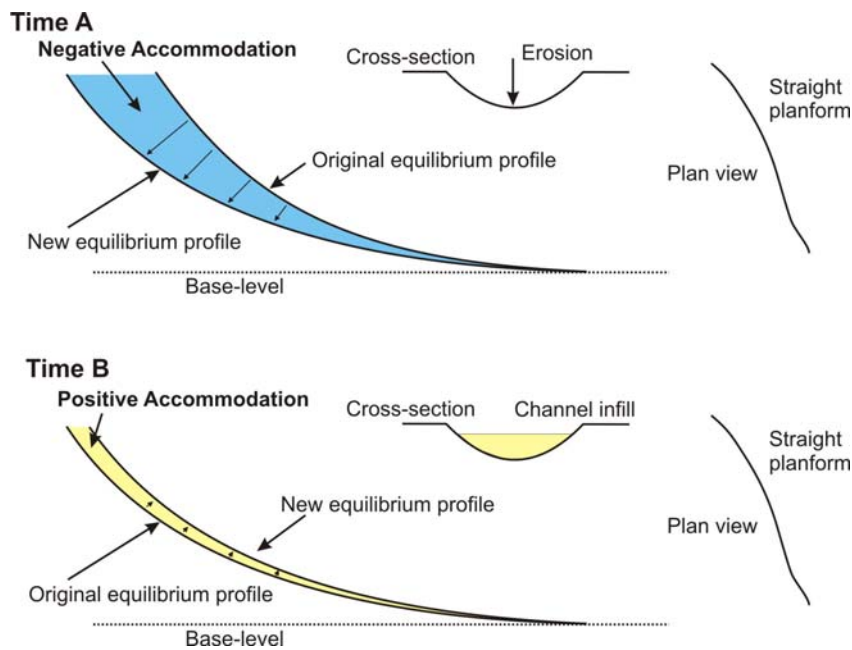
Figure 8-6: Model highlighting the change in equilibrium profile with early to late lowstand. The initial fall in sea level forces a change in flow parameters such as an increase in flow size or density. This results in the formation of negative slope accommodation through erosion. Positive slope accommodation and channel infill commences during late lowstand when flow parameters such as flow size and density decrease (adapted from Kneller, 2003).

Fifth order channel-splay and sheet complexes deposited within a sixth order progradational setting in the Angel Formation display many characteristics.

i. High net-to-gross sandstone in association with the lowstand conditions. This is evident in core and on wireline logs.

ii. Low channel sinuosity with occasional to rare avulsion. Channel systems are dominantly straight with sandy margins and levees of low relief. They are typically erosive systems in regards to the slope equilibrium profile (Kneller, 2003 and Gervais *et al.,* 2004). This leads to fan shape that is more elongated downslope than laterally extensive (Figure 8-8). If avulsion occurs within this setting, abandonment of older fifth order channel-splay systems can result.

iii. Progradation of individual fan lobe and sheet systems results in significant bypass through mixed erosional-depositional channel systems with the majority of deposition occurring at the mouths of distributary channel systems.

iv. Degree of confinement within entrenched channel systems created during the cut phase is high. As the system continues to prograde and bypass remains active within channel systems, the erosional relief will increase. With backfilling, this will result in the preservation of thick channel fill successions within a sixth order confining channel complex (Figure 8-8).

v. Amalgamation of fifth order architectural units will increase at a particular position on the slope to basin profile as progradation continues. Active downcutting of channel systems into older fifth order successions through erosional slope equilibrium processes will result in the removal of sediment (Figure 8-8).

8.3.2.2 Sixth Order Allocyclic Aggradational and Retrogradational Model

The sixth order aggradational and retrogradation model is related to late lowstand and transgressive periods of time. Flow parameters transform with the commencement of late lowstand and early transgression as the gravity flows start becoming smaller and less dense. This results in a steepening of the equilibrium profile and the generation of accommodation space (Figure 8-7). Over time, it results in the retrogradational "backstepping" of fan lobes towards the shelf.
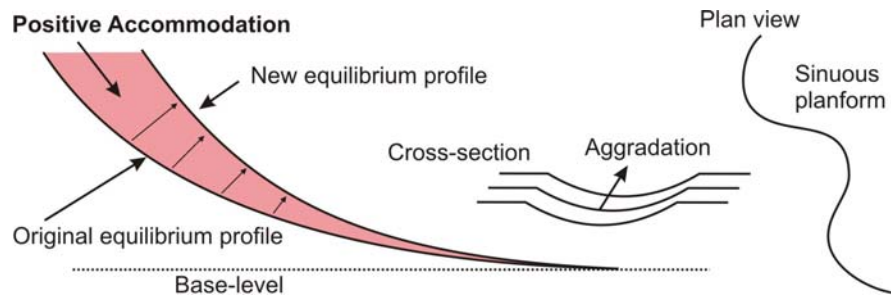
Figure 8-7: Model highlighting the change in equilibrium profile with transgression and fan retrogradation. This change in profile is brought about by a change in flow parameters such as a decrease in flow size or density. It leads to aggradation of channel systems and increased sinuousity (adapted from Kneller, 2003).

Fifth order channel and splay complexes deposited within these settings in the Angel Formation are interpreted to display many characteristics.

i. Sandstones become increasingly clay-rich. This is evident in core and on wireline logs.

ii. Aggradation and retrogradation of individual fan lobe units is related to fan backstepping with the majority of deposition occurring either as overspill at channel margins as they infill or at the mouths of distributary channel systems.

iii. Channel sinuosity increases with relation to increasing clay content and decreased flow size. Channel avulsion is common with increasing channel height and infill (Section 6.2).

iv. Amalgamation of individual channel systems decreases as fourth order elementary channel systems decrease in size and become interbedded with sheet complexes (Figure 8-8).

v. Slump successions/hybrid flows exist within these systems and are interpreted to overlie channel systems in Spica-1 and Lambert-2 that exist within a retrogradational succession. Similar units have been noted within the sediments of the Hecho Group, Pyrenees (Cronin *et al.,* 1998).

vi. Geometries of the individual fourth order and composite fifth order channel-splay complexes decrease in size (Figure 8-8).

vii. The overall sixth order retrogradational succession is more laterally spread out and greater in size than the progradational succession (Figure 8-8).

Sixth Order Aggradation and Retrogradation

- Channel forms decreasing in size and are less amalgamated
- Increased sinuosity and avulsion of channels resulting in laterally wide and thinner fan systems
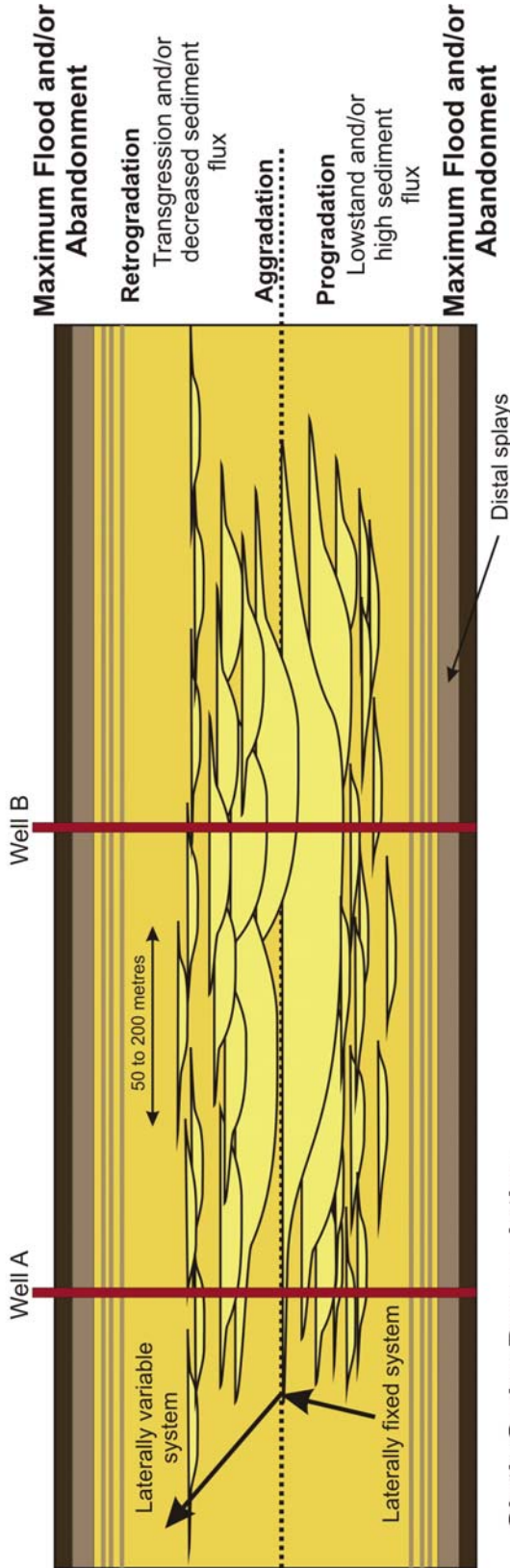
Sixth Order Progradation

- Channel forms increasing in size and amalgamation.
- Low sinuosity and avulsion - channel forms are straight and remain dominantly fixed resulting in laterally small fans

Maximum Flood and/or Abandonment

Retrogradation
Transgression and/or decreased sediment flux

Aggradation

Progradation
Lowstand and/or high sediment flux

Maximum Flood and/or Abandonment

Well A

Well B

50 to 200 metres

Laterally variable system

Laterally fixed system

Distal splays

Figure 8-8: Sixth order allocyclic progradational and aggradational/retrogradational models. During progradation, channel forms increase in size and erosive capability (becoming increasingly amalgamated) and are not highly sinuous. During aggradation and retrogradation, channels decrease in size, become more depositional, less amalgamated and are sinuous. They are more laterally spread out than progradational channel networks.

8.4 Field-Scale Analysis of Sixth Order Architectural Elements and Tithonian Fan Evolution

Five field-scale regions were selected for analysis in terms of their variation in distance to the shelf in order to capture the basinward variability in sixth order architecture. It is interpreted that sixth order allocyclic complexes stack to form a seventh order fan system, which represents the Tithonian component of the Angel Formation. The biostratigraphic data and cross sections used in this analysis can be found in Chapter 4.5 and Appendix D.

Individual field regions were grouped into two categories dependant on the dominant location of the sediment source (Figure 8-9).

i.   The Parker Terrace Systems (sediment primarily sourced from the Rankin Platform). It includes the:

- Mutineer region (seventh order lower slope to proximal fan setting);

- Egret and Montague field region (seventh order proximal to medial fan setting), and;

- Lambert field region (seventh order medial fan setting).

ii. The Central Dampier Systems (sediment primarily sourced from southeastern Beagle Sub-basin and Legendre Trend). It includes the:

- Angel field region (seventh order lower slope to proximal fan setting), and;

- Wanaea and Cossack fields region (seventh order medial to distal fan setting).
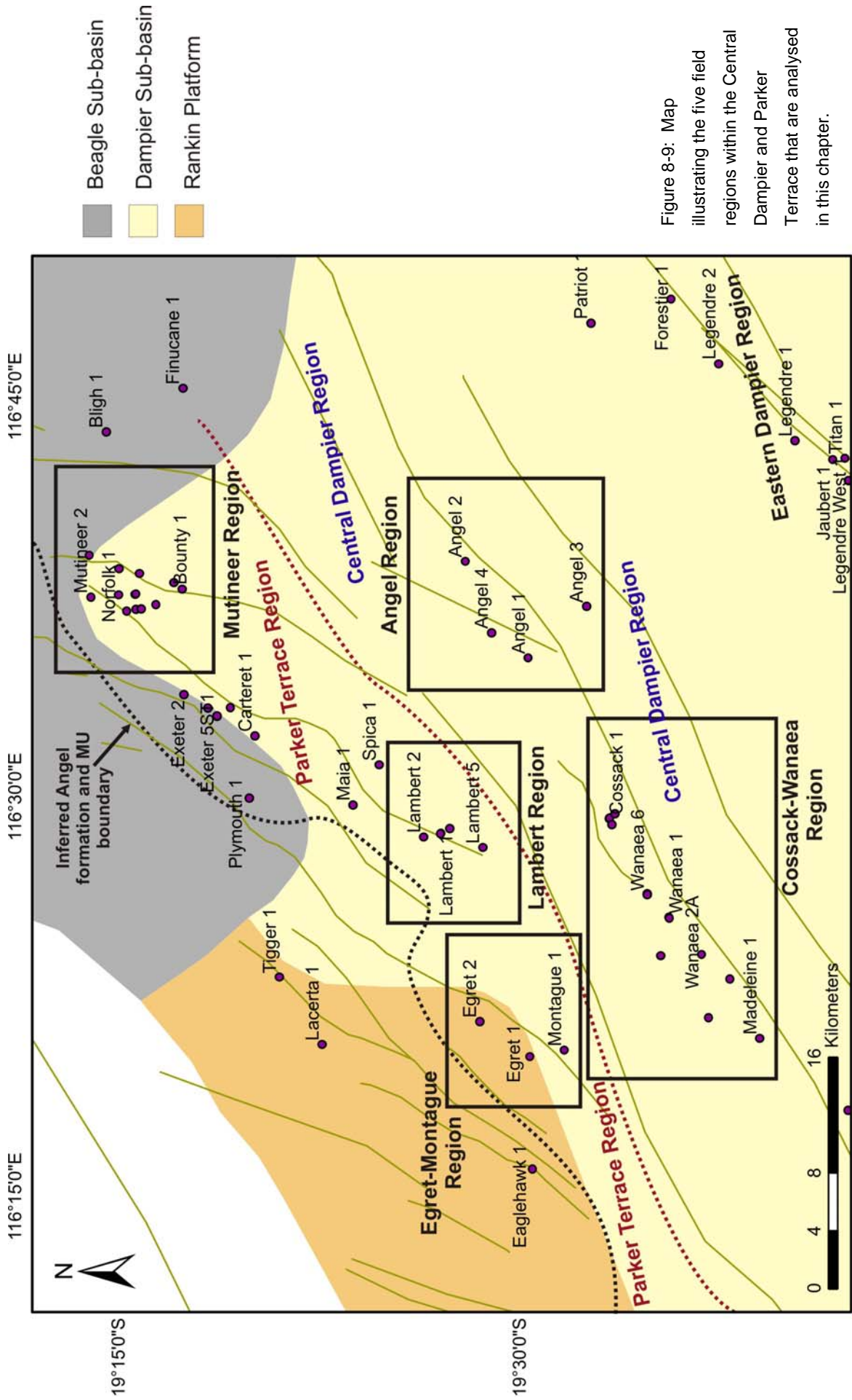
Figure 8-9: Map illustrating the five field regions within the Central Dampier and Parker Terrace that are analysed in this chapter.

8.4.1 The Parker Terrace Region

The Parker Terrace depositional systems are those that are interpreted to have been primarily sourced from the Rankin Platform. Three systems were examined (Figure 8-10).

    i.   The Mutineer region (seventh order lower slope to proximal fan setting).

    ii. The Egret-Montague field region (seventh order proximal to medial fan setting).

    iii. The Lambert field region (seventh order medial to distal fan setting).

NOTE:
This figure is included on page 189 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8-10: Block model of the seventh order mixed sand- and mud-dominated ramp model against the Rankin Platform highlighting the different regions and their interpreted positions on the ramp (adapted from Reading and Richards, 1994). The model represents maximum Tithonian progradation.

8.4.1.1 The Mutineer Region

The Mutineer field is located in the northwestern region of the Dampier Sub-basin that borders the Beagle Sub-basin and Rankin Trend. It contains 14 wells interpreted to rest within a seventh order lower slope to proximal fan setting. Faulted anticlinal closes that contain the Tithonian oil reservoirs were formed through drape of the Angel sandstone over a succession of rifted blocks which were inverted during the Tertiary (Auld and Redfern, 2003). Fault systems interpreted from three dimensional seismic reflection data across the Dampier region highlighted within the Mutineer region a series of north-striking obliquely-trended regional faults with associated synthetic northeast-striking normal faults.   They form a network of half graben and relay systems that are interpreted to partially influence the depositional pattern of fifth order composite channel-splay systems and their resultant sixth order depositional fans through Tithonian time (Figure 8-11).
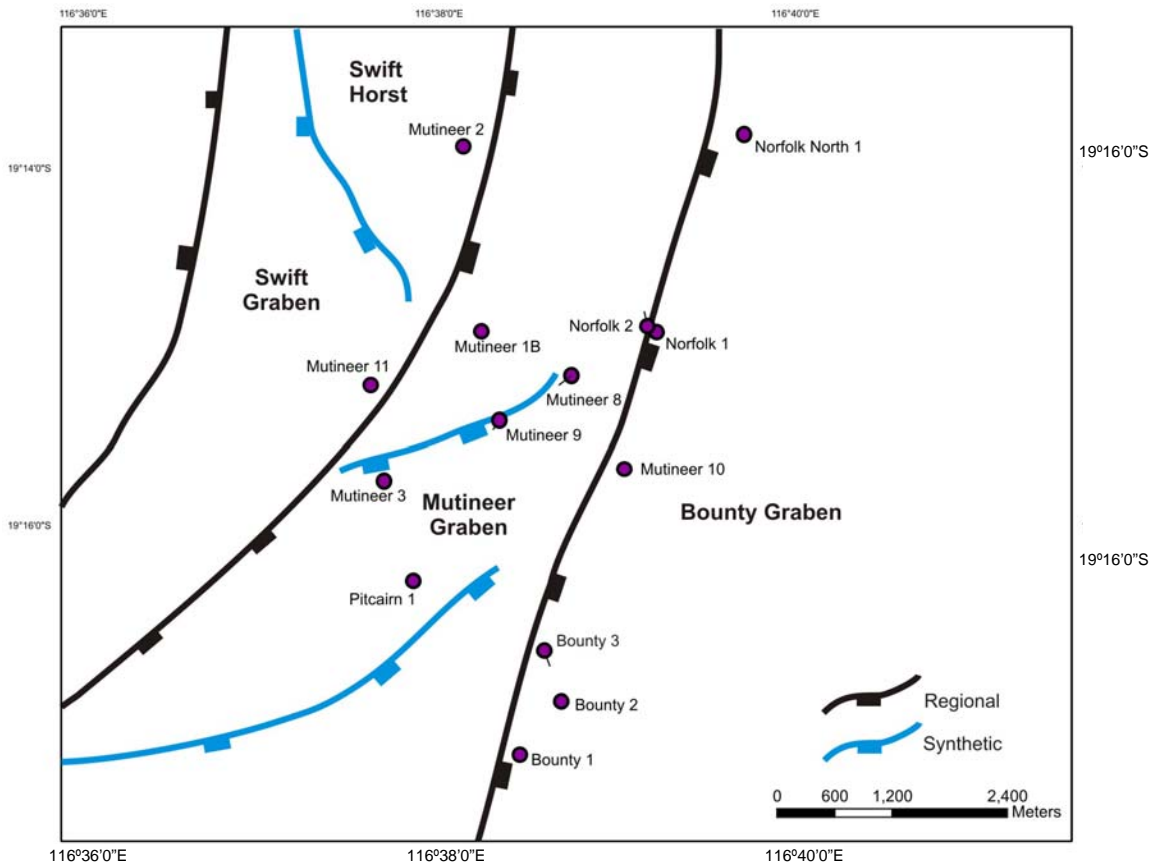
Figure 8-11: Well location map of the Mutineer field region with interpreted horst and half graben networks.

From earlier architectural analysis (Chapters 5, 6 and 7), it was determined that:

- the depositional system contained amalgamated unstructured and parallel structured sandstones interbedded with heterolithics and dewatered sandstones (based on core interpretation of Mutineer-1B and 3 (Appendix B));

- dominant lithofacies associations are homogenous channel fills (both axial and marginal) with preserved progradational and retrogradational splays;

- there is clear recognition of amalgamated 4th order migrational channel architectural elements, and;

- Model A and B overlain by Model E are the most common fifth order architectural packages (Table 7-1). These channel-splay complexes are migrational and compensationally stack (Figures 8-3 and 8-4).

Biostratigraphic interpretation through the Mutineer field (Figure 8-12 and 8-13) illustrates the amalgamated nature of the fifth and sixth order packages and the variation in bed thicknesses over the short field distance. A succession of palaeogeographical maps and seismic transects through the field are discussed and represented individually in Figures 8-15 to 8-27. Progradational and retrogradational trends are interpreted from log stacking patterns. The maps are represented together in Figure 8-28 (A3 foldout).
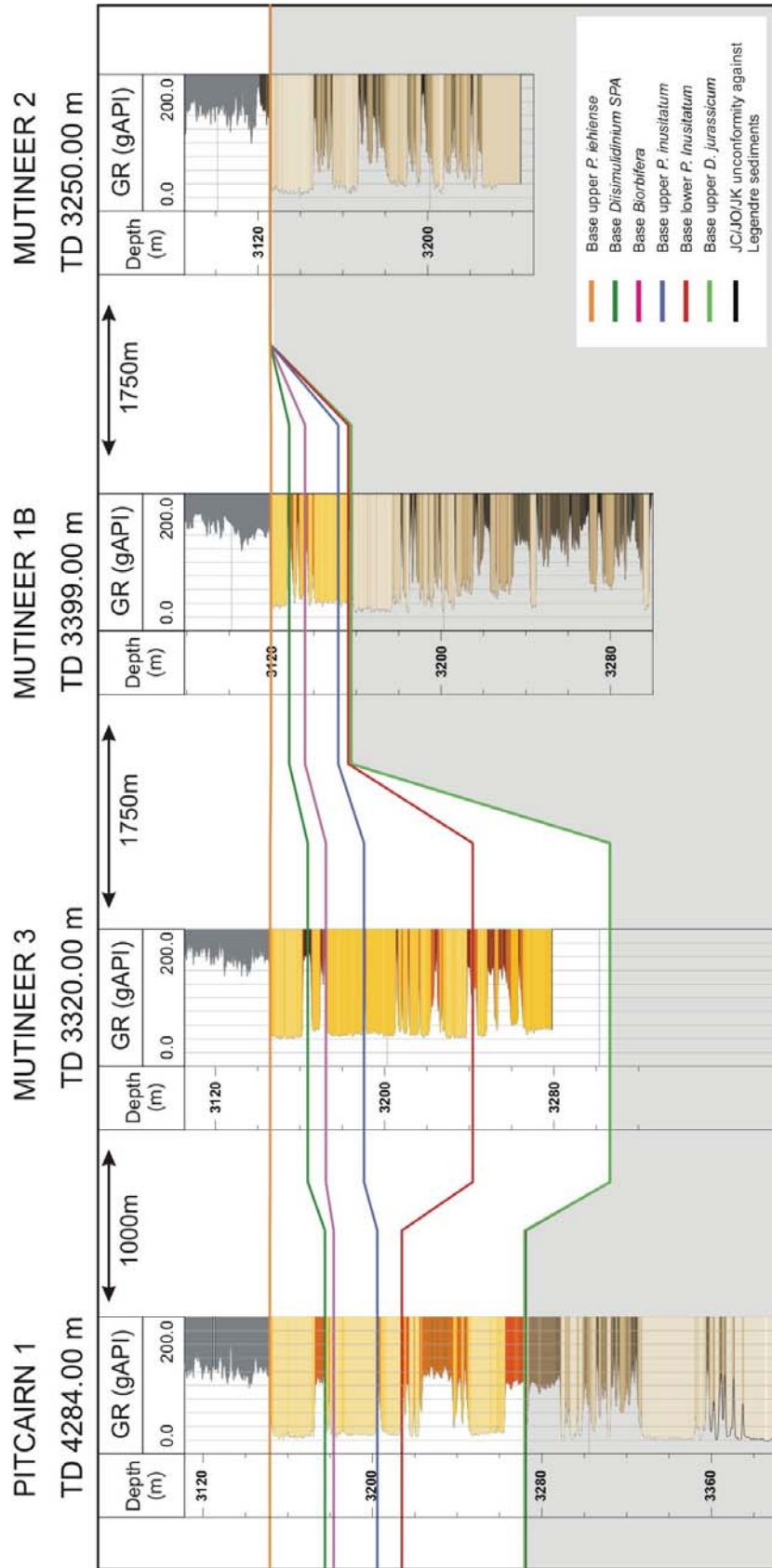
Figure 8-12: Biostratigraphic transect from north to south through the western Mutineer field. It illustrates the unconformable nature of Tithonian sediments against the Early to Middle Jurassic Legendre sediments. The Angel Formation was not intersected in Mutineer-2.
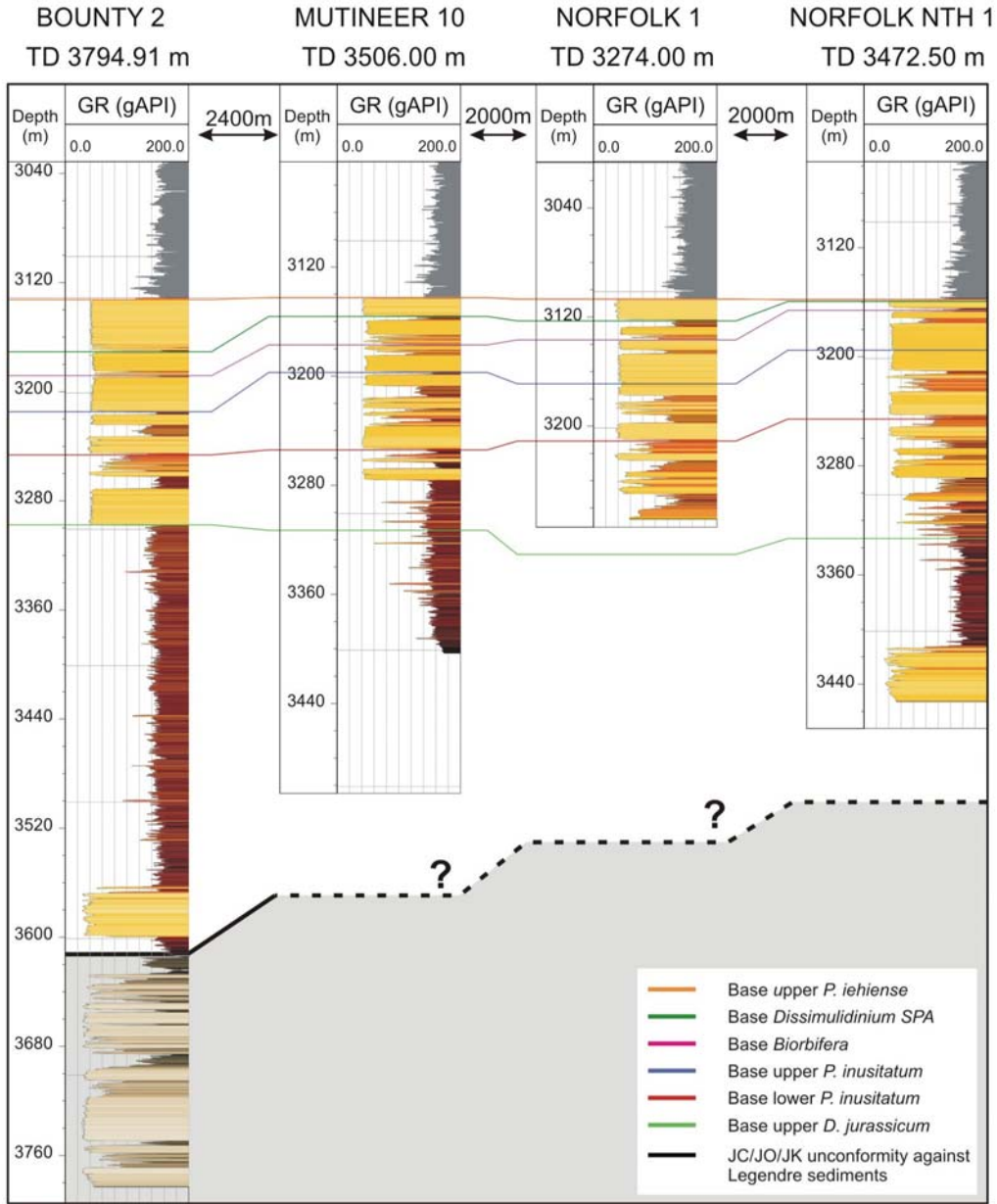
Figure 8-13: Biostratigraphic transect from north to south through the eastern Mutineer field (Bounty and Norfolk region). It demonstrates the presence of ample accommodation space during early Tithonian time, resulting in the deposition of *O. montgomeryi* and *D. jurassicum* sediments.

8.4.1.1.1   Lower *D. jurassicum*, *O. montgomeryi* and *C. perforans* system

The lower *D. jurassicum*, *O. montgomeryi* and *C. perforans* system is represented by a period of basin starvation. Maximum flooding across the region in combination with syn-rift fault-controlled subsidence led to deposition of fine-grained sediments within the Bounty Graben. Within this graben, lower *D. jurassicum*, *O. montgomeryi* and *C. perforans* sediments overlie Oxfordian sandstones in Norfolk North-1 and Bathonian-aged Legendre sediments in Bounty-2 and 3 (Figure 8-15). A lowstand event is interpreted to exist at the base of the *D. jurassicum* succession.

Norfolk North-1, Bounty-2, Bounty-3 and Mutineer-10 all intersected lower *D. jurassicum* and *O. montgomeryi* siltstones and heterolithic sediments. An early fan system interpreted to be prograding from the north was intersected in Norfolk North-1, Mutineer-10 and Bounty-2. The presence of these sediments suggests that there was depositional confinement within the Bounty Graben (Figure 8-15).

Mutineer-11, Mutineer-1B, Pitcairn-1 and Norfolk-2 all failed to intersect lower *D. jurassicum*, *O. montgomeryi* and *C. perforans* sediments due to a preserved JC/JO/JK multiple unconformity surface between *P. iehiense* sediments and the Legendre Formation. These wells are situated on uplifted footwalls and may have experienced sediment removal during lowstand events (Figure 8-15). Sandstones of lower *D. jurassicum, O. montgomeryi* and *C. perforans*-age may have been sourced from the west and be confined to half graben systems throughout the Mutineer Graben region. All wells within the graben that rest within half graben lows of the synthetic fault systems did not intersect lower *D. jurassicum* sediments as the wells reached total depth in *P. iehiense*-aged sediments.

Figure 8-15: Palaeogeographical map highlighting the depositional nature of the Angel Formation during lower *D. jurassicum, O. montgomeryi* and *C. perforans* time. Deposition occurred primarily within the Bounty Graben with unconformities existing on fault highs in the Mutineer Graben. Depocentres were not intersected in the Mutineer Graben as wells reached total depth in *P. iehiense* sediments. They may contain sandstones sourced from the west. The black bars next to logs represent ten vertical metres.

8.4.1.1.2 Upper *D. jurassicum* System

The upper *D. jurassicum* system comprises two sixth order systems, which represent a directional change in sediment source and progradation. A relative lowstand event is interpreted at the base of this system (Figures 8-12 and 8-13)

Upper *D. jurassicum* Unit One

This unit is interpreted to comprise fifth order composite channel-splay complexes that were dominantly sourced from the Swift Graben (Figure 8-16). These channel complexes may have propagated along the scarp of the southerly-dipping normal fault that separates the Swift Graben from the Swift horst block (Figure 8-16). These systems feed the sixth order fan system prograding across the Mutineer and Bounty Grabens. Amalgamated cylindrical log and fining upward motifs of Electrofacies 1 and 2 dominate log successions of Pitcairn-1, Mutineer-3, Bounty-2 and -3 implying the existence of fifth order composite channel-splay complexes up to 30 metres thick. These complexes are overlain by retrogradational splays in Pitcairn-1 and Mutineer-3.

No preserved sedimentation was intersected by Mutineer 11, Mutineer-1B and Mutineer-2. These regions represent faulted highs that were eroded during a later lowstand event. A second progradational sixth order system from the north is interpreted to have been intersected by Norfolk-1 and Norfolk North-1. The layered coarsening and fining upward log motifs of Electrofacies 4 and 5 dominate this package suggesting an early stage of progradation. It is not correlated to the sixth order fan system around Pitcairn-1 and Bounty-2 as there is no strong occurrence of time-equivalent sandstone preserved within Mutineer-10 (Figure 8-16).

Upper *D. jurassicum* Unit Two

This system illustrates a change in source direction from the Swift Graben to the northwestern and northern regions of the Bounty Graben (Figure 8-17). Inconsequential sediment input is interpreted from the Swift Graben.

Fifth order composite channel-splay systems comprising amalgamated sandstones (Electrofacies 1 and 2) are identifiable in Norfolk North-1, Norfolk-1, Mutineer-8 and -9. They stack to form two sixth order complexes containing southerly-trending channelised fairways and splays that are dominantly retrogradational towards the north. Layered cylindrical and fining upward electrofacies prevail in the southern wells (Figure 8-17). They are interpreted to signify the aggradation and retrogradation of small distributary-sized fifth order channel-splay systems.
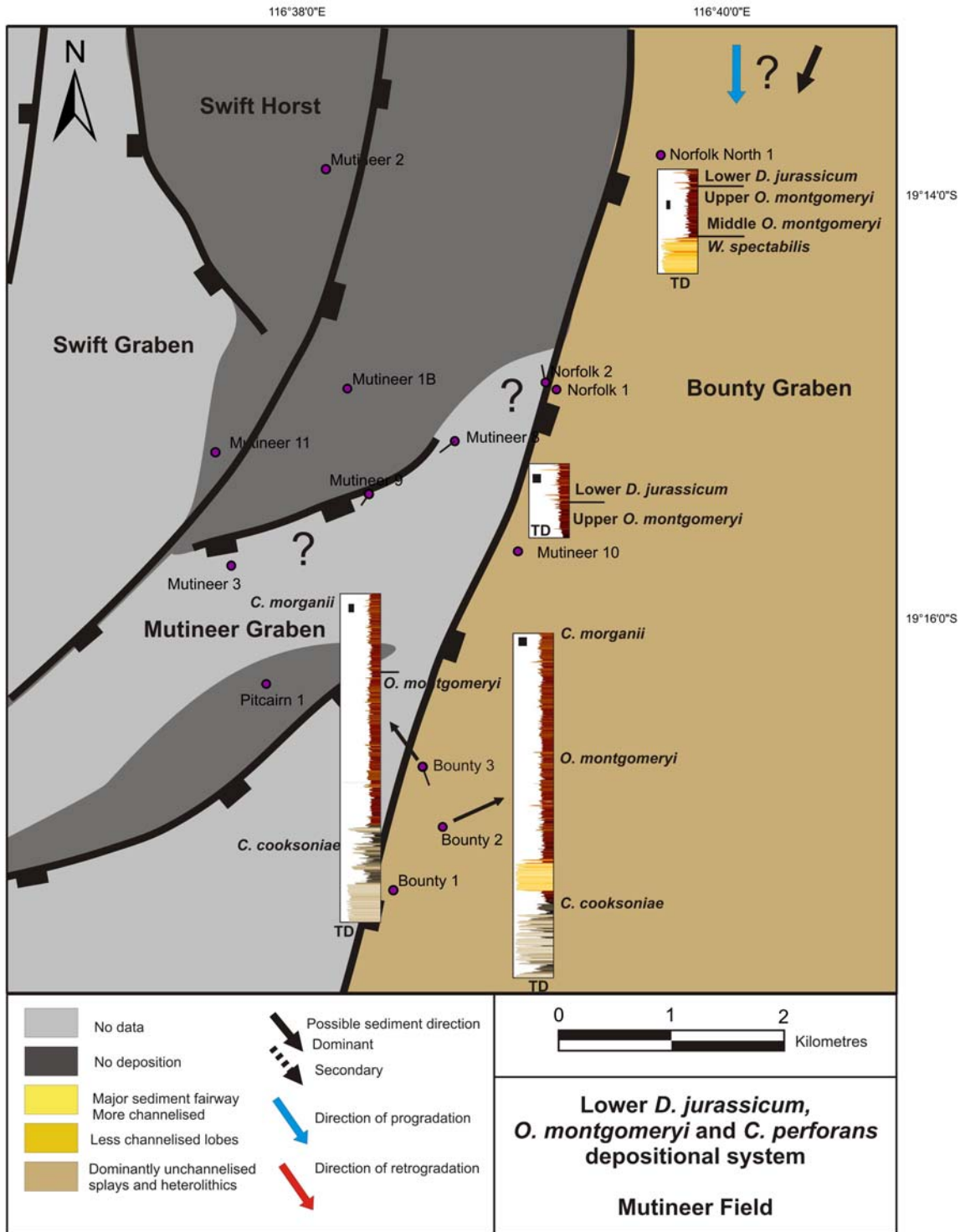
Figure 8-16: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 1 upper *D. jurassicum* time. Propagation of fifth order channel-splay complexes occurs across the Mutineer and Bounty grabens with unconformities existing on faulted highs in the Mutineer Graben. The black bars next to logs represent ten vertical metres.
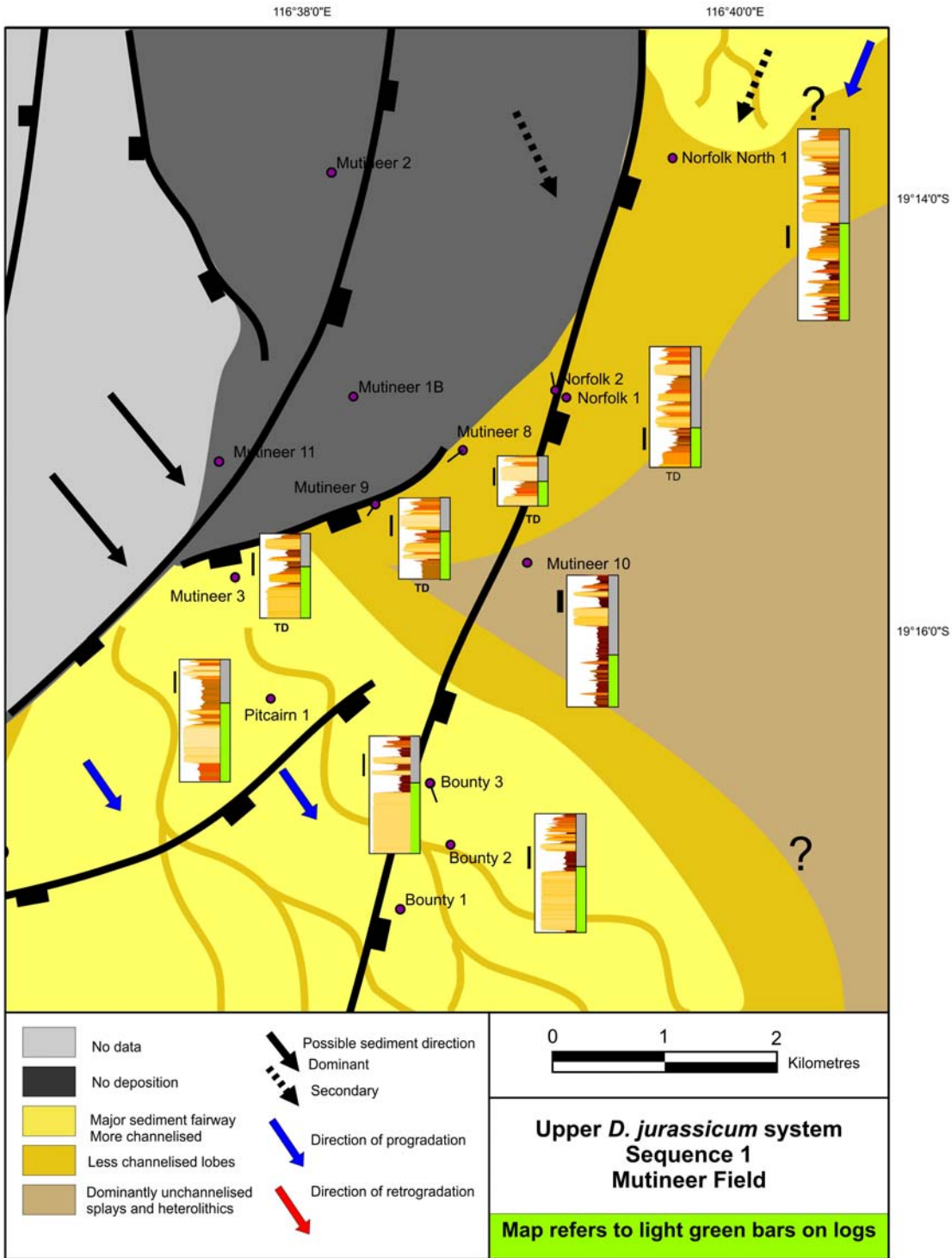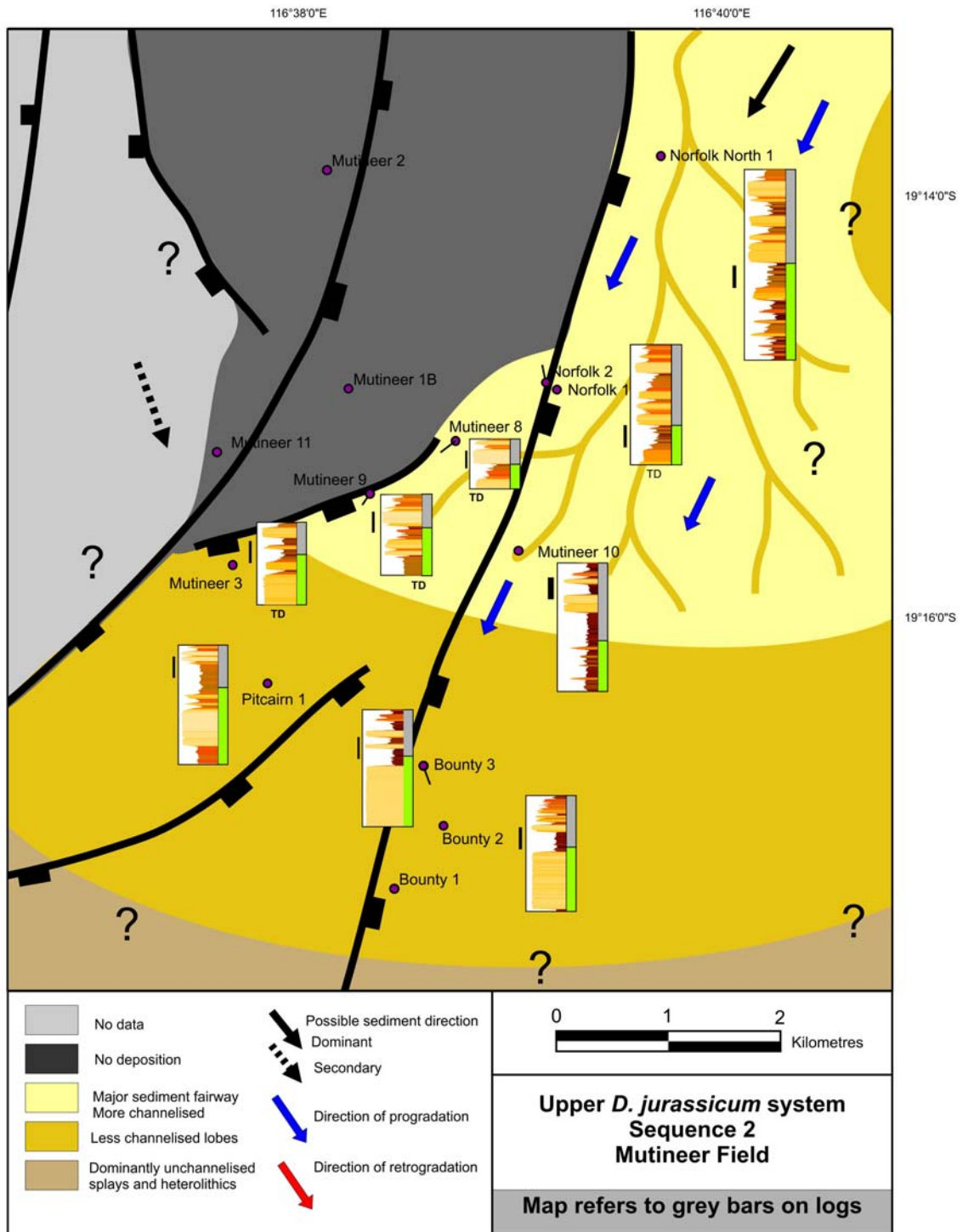
Figure 8-17: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 2 upper *D. jurassicum* time. A change in source direction results in deposition within the Bounty Graben and partially within the Mutineer Graben with unconformities existing on fault highs in the Mutineer Graben. The black bars next to logs represent ten vertical metres.

8.4.1.1.3 Lower *P. inusitatum* System

The lower *P. inusitatum* system contains two sixth order sequences that represent the stacking behaviour of fifth order channel-splay and sheet complexes (Figures 8-18, 8-19 and 8-20). A relative lowstand is interpreted to exist at the base of this unit (Base *Egmontodinium*) (Figures 8-12 and 8-13).

Lower *P. inusitatum* Unit One

This unit is represented by the progradational component of a sixth order complex. Fifth order composite channel-splay complexes sourced from the northwest and north (Figure 8-18). Systems containing various sized fourth order channel bodies are evident in Mutineer-3, -8, -9, -10, -11, Norfolk-1, Norfolk North-1, Bounty-2 and -3. Composite fifth order systems up to 25 metres thick were intersected by Mutineer-11 and Mutineer-10 (Figure 8-18). The location of the channelised fairway through the Mutineer Graben suggests that composite fifth order systems were influenced by syn-tectonic movement. No sedimentation is preserved within Mutineer-1B, Norfolk-2 or Pitcairn-1 during this time, which indicates that they were located off-axis of the channelised fairway through the Mutineer Graben (Figure 8-18). This system is represented by the progradational sixth order model where channel systems are highly amalgamated, sand-rich but laterally confined (Section 8.3.2.1).

Lower *P. inusitatum* Unit Two

This unit represents the retrogradational component of the sixth order complex of Unit 1 which is interpreted to be related to a local decrease in sediment supply (refer Section 9.3.1). It retrogrades towards the north and northwest (Figure 8-19). The fifth order composite channel-splay complexes range from a few metres (Mutineer-10 and Bounty-2) to over 25 metres thick (Mutineer-11). They represent the dominant aggradational development and retrogradational infilling of fourth order channel systems and the backstepping of the fan system towards sediment feeders located in the Swift Graben and north of the Bounty Graben. Thin (less than 3 metres) composite channel-splay systems identified within Mutineer-3 suggest that the well may be located off-axis of the channelised fairway propagating south of Mutineer-8 and -9 (Figure 8-19). Unchannelised splays and heterolithic units dominate the southern region of the Bounty Graben which were intersected by Bounty-2, Bounty-3 and Mutineer-10. Mutineer-1B, Pitcairn-1 and Norfolk-2 all remained on uplifted footwall blocks receiving little sedimentation (Figure 8-19). The thick amalgamated succession within Mutineer-11 is interpreted to represent the strong aggradational infilling of the confined sixth order complex that develops within proximal sediment fairways.

Lower *P. inusitatum* Sequence Three

This unit represents the progradation of a new sixth order complex which continues into upper *P. inusitatum* time. Sediment is transported from across the Mutineer Graben and the northern Bounty Graben into the southern Bounty Graben (Figure 8-20). Fifth order composite channel-splay units in Mutineer-3, -8 and -9 represent continued deposition of channel-splay complex systems throughout the Mutineer Graben. Similar units exist in Norfolk North-1, sourced from the Beagle Sub-basin. Thinner amalgamated units (less than 10 metres) present in Bounty-2, -3 and Mutineer-10 are interpreted to represent the distal downslope transition to layered fifth order distributary channel units and sheet complexes that form a fan lobe unit (Bounty-2 and 3) (Figure 8-20). Sediment input is

interpreted to have been sourced from both the Swift Graben and the northern Bounty Graben. A channel feeder system may have existed against the scarp of the Swift horst, providing a conduit for sediment from the west (Figure 8-21). Sediment may have also been sourced from the northern Mutineer Graben (Figure 8-20).

Figure 8-18: Palaeogeographical map highlighting the progradational nature of the Angel Formation during Unit 1 lower *P. inusitatum* time. It is represented by the presence of amalgamated and layered cylindrical, coarsening and fining upward log motifs of Electrofacies 1, 2, 4 and 5. A channelised fairway is interpreted to have propagated through the Mutineer Graben.

Figure 8-19: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 2 lower *P. inusitatum* time. Sixth order retrogradation dominates. Channel systems decrease in size and become less amalgamated (Mutineer-3). Amalgamated and layered cylindrical, coarsening and fining upward log motifs of all electrofacies types are evident within this unit.

Figure 8-20: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 3 lower *P. inusitatum* time. It is dominated by thick amalgamated units of Electrofacies 1 and 2 in Mutineer-3, 8 and 9 with thinner units in Mutineer 11, Mutineer-1B, Pitcairn-1, Bounty-2 and 3. Layered units of Electrofacies 3, 4 and 5 are more evident in the northern region of the Bounty Graben in Mutineer-10, Norfolk-1 and Norfolk North-1.
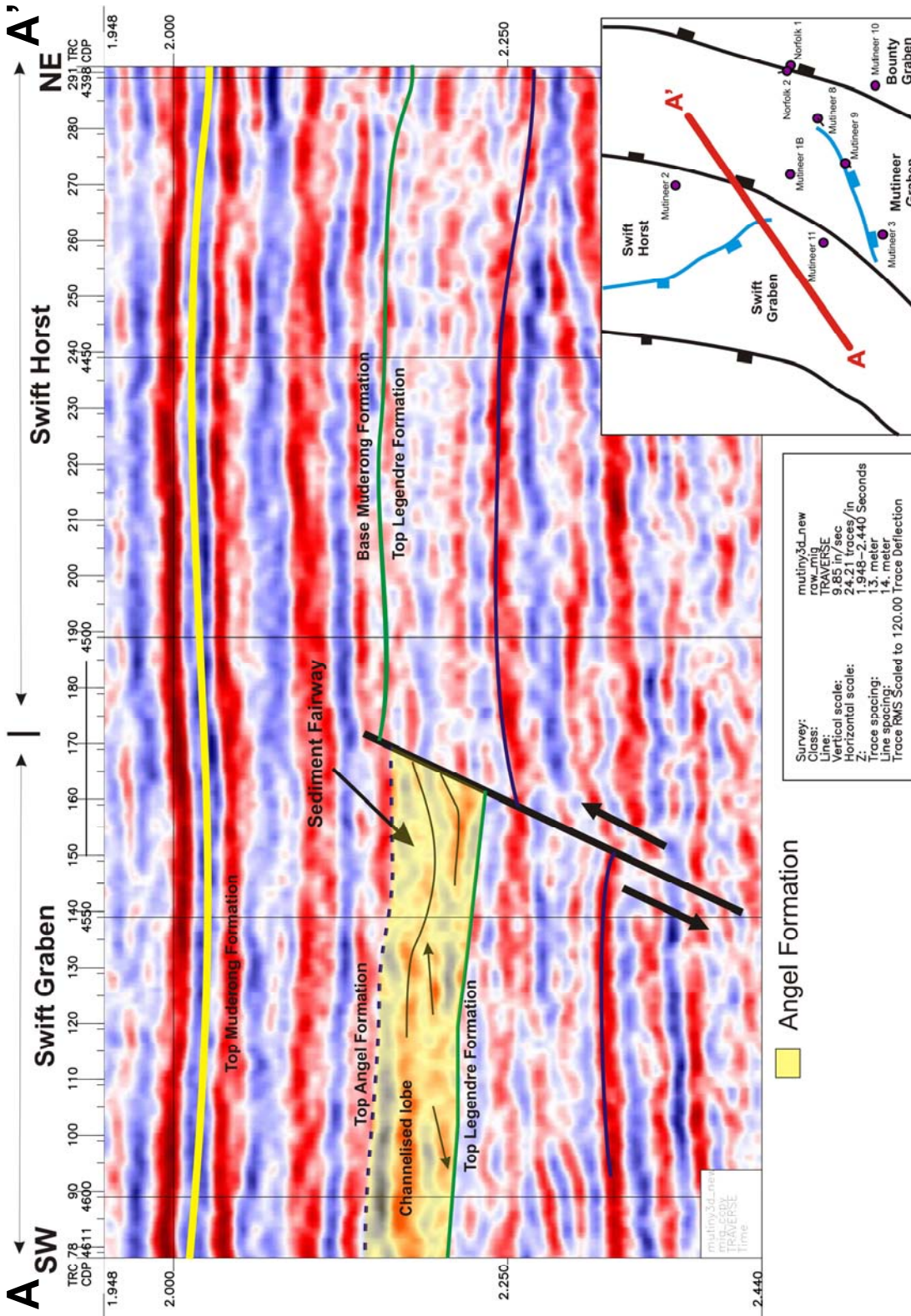
Figure 8-21: Interpreted sediment feeder system against the fault scarp separating the Swift Graben from the Swift horst. The feeder system is approximately 500 metres wide. The channel system would have dominantly been an area of active bypass and erosion.

8.4.1.1.4   Upper *P. inusitatum* System

This unit represents the aggradational and retrogradational component of the sixth order migrational channel complex that commenced during late lower *P. inusitatum* time (Figure 8-20).

Upper *P. inusitatum* Unit One

All wells except Norfolk-2 contain highly amalgamated and high net-to-gross fifth order channel-splay complexes that stack to form a dominantly late progradational to aggradational component of the sixth order system that commenced during lower *P. inusitatum* time (Unit 3) (Figure 8-22). Preserved fifth order composite channel-splay systems are present in the basal sections of the logs from Mutineer-8 and -11. The thickest of all units are present within Bounty-2 and -3 and are interpreted to represent southward progradation. Accommodation space is available basinward as the overall system progrades. Sediment is transported into the system from both source points located within the Swift Graben and north of the Bounty Graben is extreme, resulting in the formation of a highly sand-rich, rapidly prograding fan system towards the south. A sand-rich ramp setting of Reading and Richards (1994) could be more representative of the system at this time instead of a mixed mud-sand ramp system (Figure 2-9). The sand-rich ramp system comprises of straight sand-rich distributary channel systems.

Upper *P. inusitatum* Unit Two

This unit represents dominant retrogradation of the sixth order migrational channel complex (Figure 8-23). Sedimentation is concentrated in wells proximal to main feeder systems in the Swift Graben and the northern region of the Bounty Graben. Thick fifth order complexes were deposited in these regions through aggradation and retrogradation of the unit towards the north and northwest. Sedimentation also occurred in Norfolk-2 over the footwall of the Bounty Graben bordering fault. This represents either the infilling of possible fault-created accommodation space where Norfolk-1 is situated (Figure 8-23) or retrogradation towards a feeder system situated within the northern Mutineer Graben. This unit is not recognised in Mutineer-1B, Mutineer-3, Pitcairn-1 and Bounty-2 and -3 (Figure 8-23), which is expected from a retrogradational system. Any heterolithic or mudstone units deposited within these wells during the abandonment may have been removed by younger channelised systems.
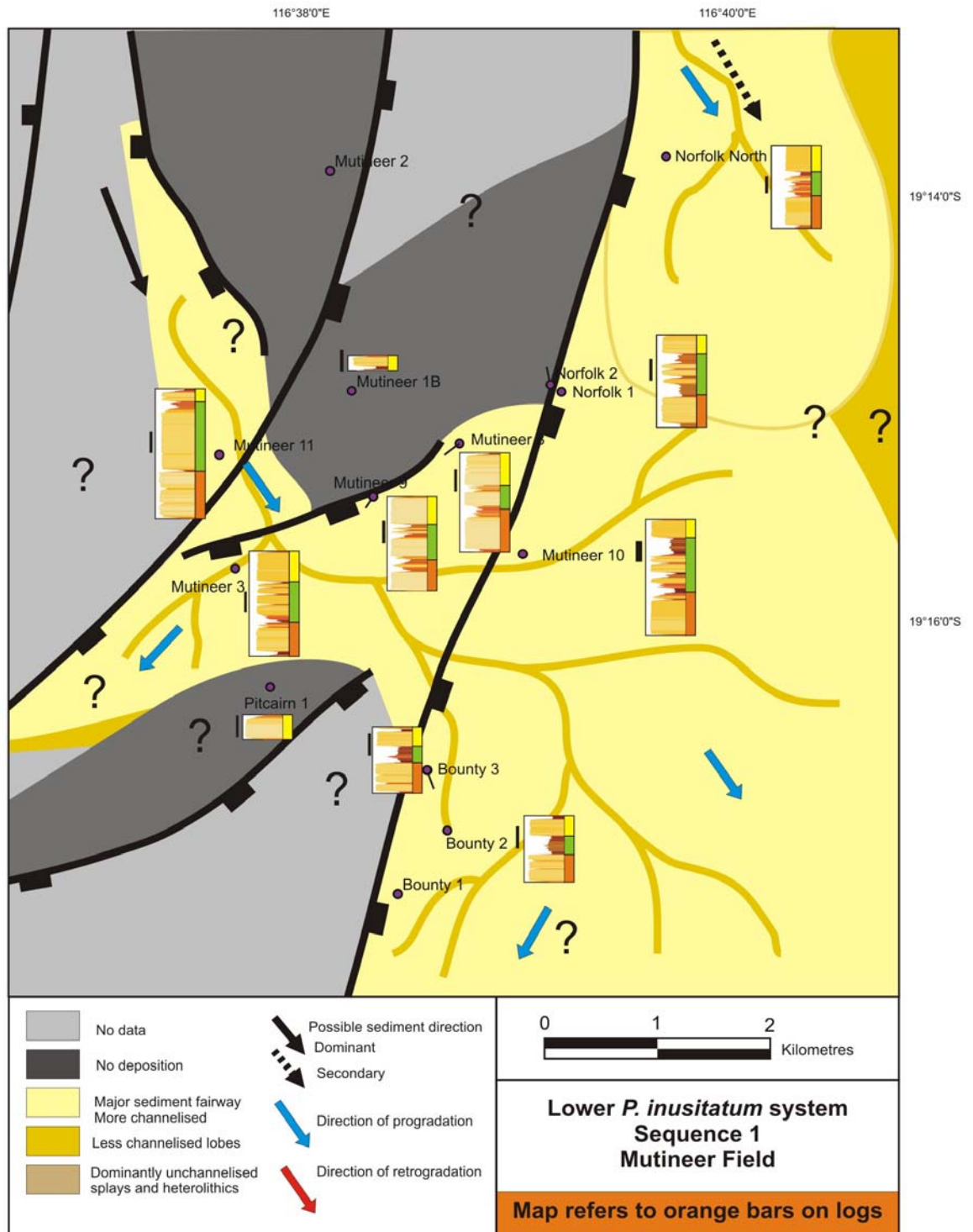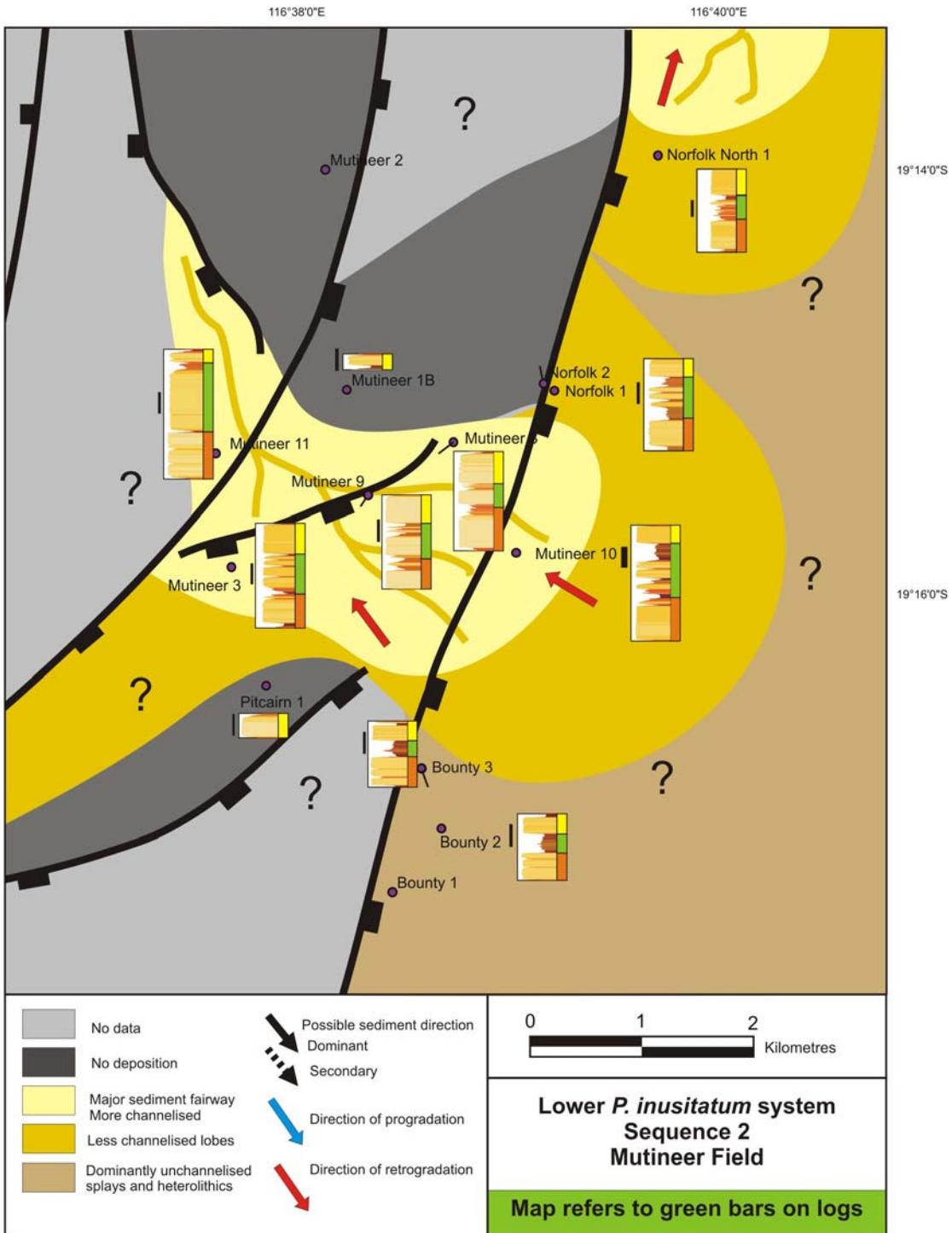
Figure 8-22: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Sequence 1 upper *P. inusitatum* time.   This unit is dominantly characterised by the presence of thick bedded cylindrical log motifs of Electrofacies 1. Some layered electrofacies are identifiable within Mutineer 8 and 11. The black bars next to logs represent ten vertical metres.
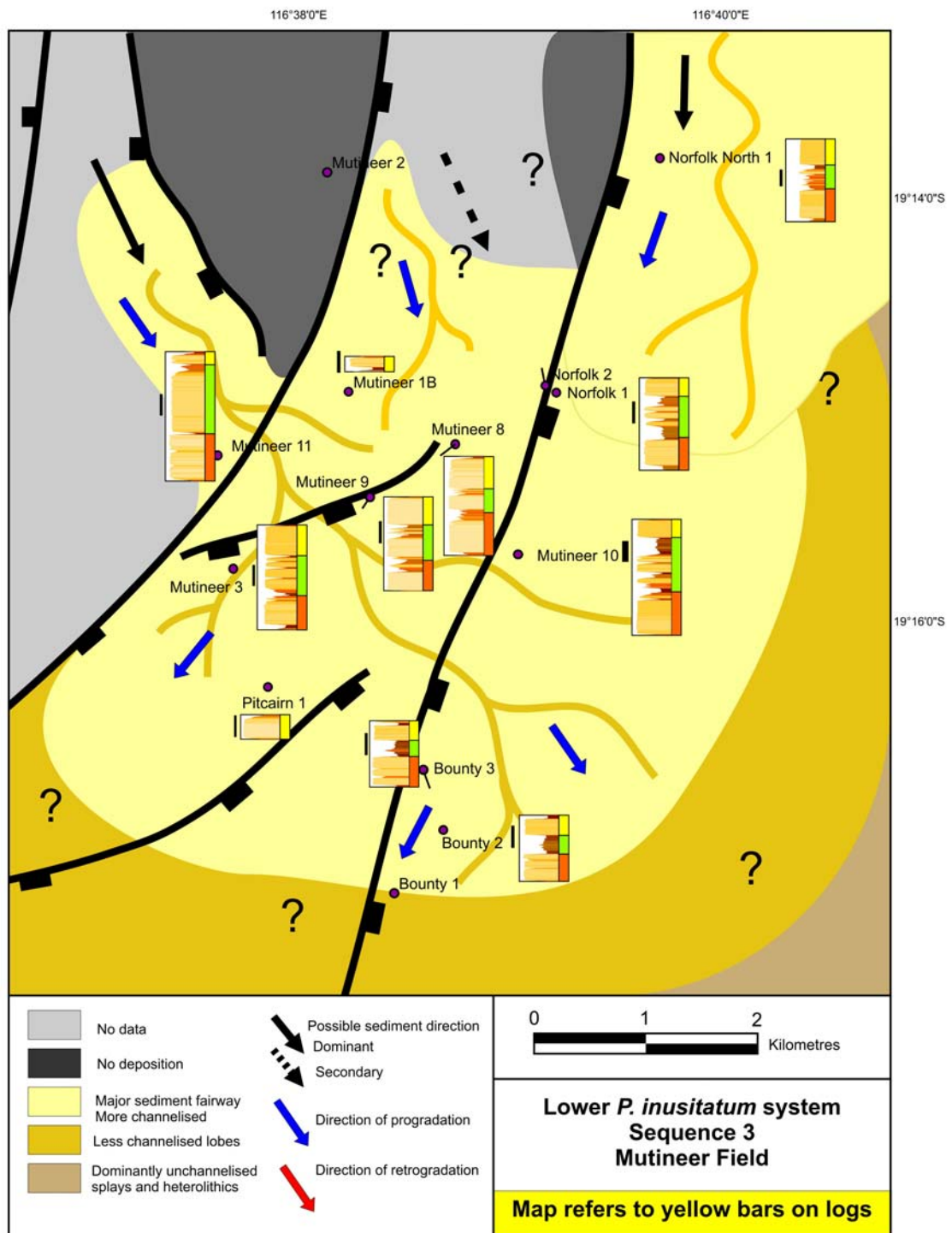
Figure 8-23: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 2 upper *P. inusitatum* time. Retrogradation of the depositional system towards the feeders dominates this unit.   It is characterised by amalgamated cylindrical and fining upward successions of Electrofacies 1 and 2. The black bars next to logs represent ten vertical metres.

8.4.1.1.5 *Biorbifera* System

The *Biorbifera* system is characterised by a sixth order migrational channel complex which contains a small progradational and a large aggradational to retrogradational component (Figure 8-24 and 8-25).

Biorbifera System Unit One

This unit represents the early progradational component of the sixth order system. It is dominated by layered coarsening upward successions of Electrofacies 5, which are confined to the Bounty Graben (Norfolk North-1, Norfolk-1, Mutineer-10 and Bounty-2 and 3). No active deposition occurred in the Swift and Mutineer grabens, which suggests either:

- renewed tectonic movement along the western margin of the Bounty Graben, resulting in the generation of new accommodation space;

- the existence of a relative lowstand event during *I. kondratjevii* to Early *Biorbifera* time, or;

- the re-routing of sediment elsewhere (Figure 8-24).

The units in the Bounty Graben appear stacked (Mutineer-10 and Bounty-3). They are thin units (less than 10 metres) representing distributary-sized channel and sheet systems prograding from the north (Figure 8-24). Active fault movement could be interpreted for this unit as sedimentation is concentrated along the hanging wall depocentre of the graben.

Biorbifera System Unit Two

This unit represents the strongly aggradational to retrogradational component of the sixth order migrational channel complex. It is dominated by a strongly aggradational and retrogradational influx of sediment from the Swift, Mutineer and northern Bounty grabens (Figure 8-25). Tectonism during this time is deemed inactive as onlap is interpreted onto footwall highs and progradation of fifth order channel-splay systems is interpreted from the Swift and Mutineer grabens. Preserved thickness of this package suggests that sediment flux to the region was high during this period and was actively competing against an increasingly dominant transgressive sea. This resulted in the formation of thin progradational and thick aggradational and retrogradational packages (Figure 8-25). As the entire system becomes more retrogradational, the channel systems become more distributary-sized and less amalgamated. The existence of distributary-sized channel systems around Mutineer is supported by the cored succession from this interval, which is interpreted to represent fifth order Model D and is full of dewatered features and small channel lags (Appendix B).
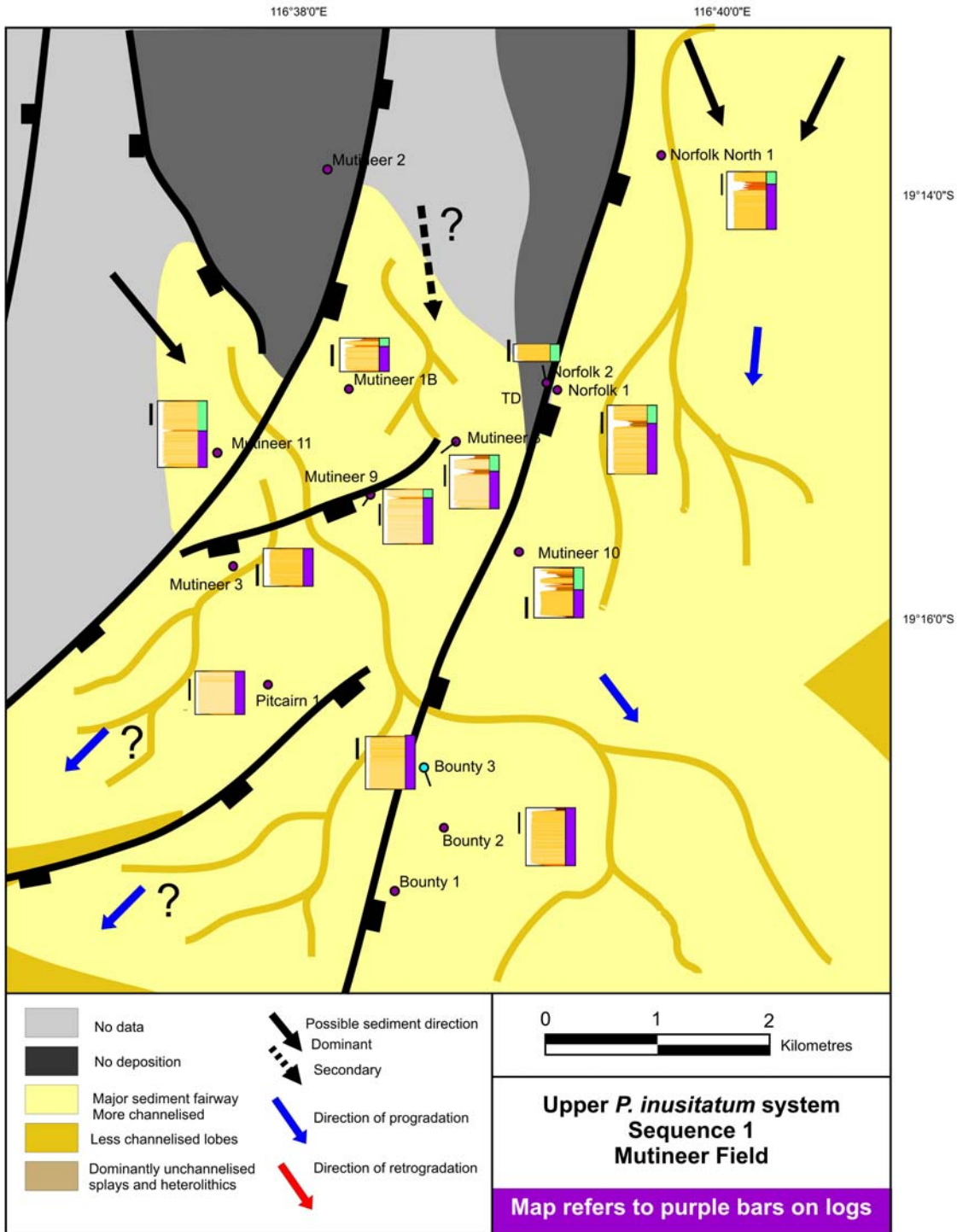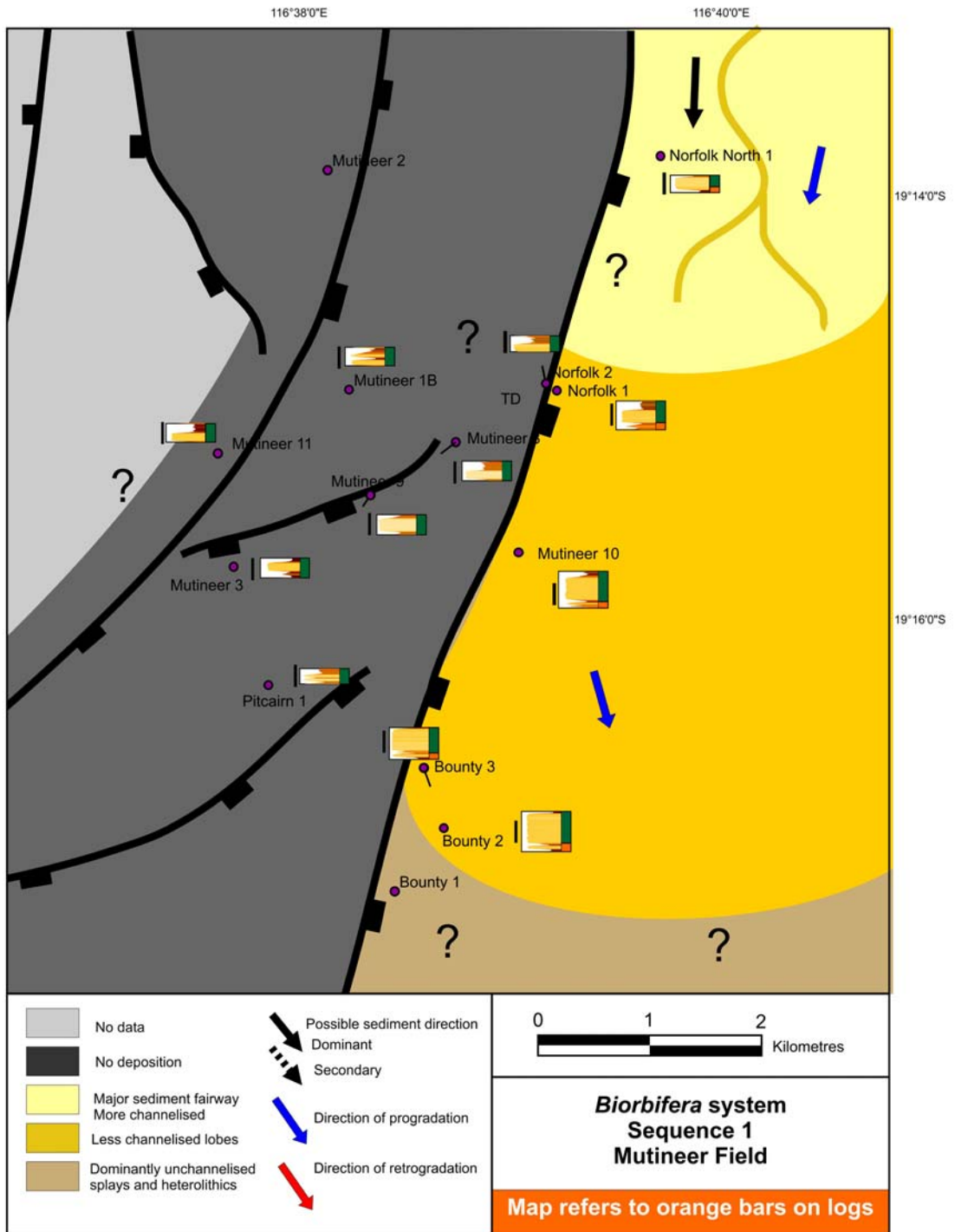
Figure 8-24: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 1 *Biorbifera* time. Deposition is confined to the Bounty Graben. No active deposition occurred in the Swift and Mutineer grabens. This suggests either renewed tectonic movement along the western margin of the Bounty Graben, resulting in the generation of new accommodation space or the existence of a relative lowstand event during *I. kondratjevii* to Early *Biorbifera* time that resulted in the removal of sediment. The black bars next to logs represent ten vertical metres.
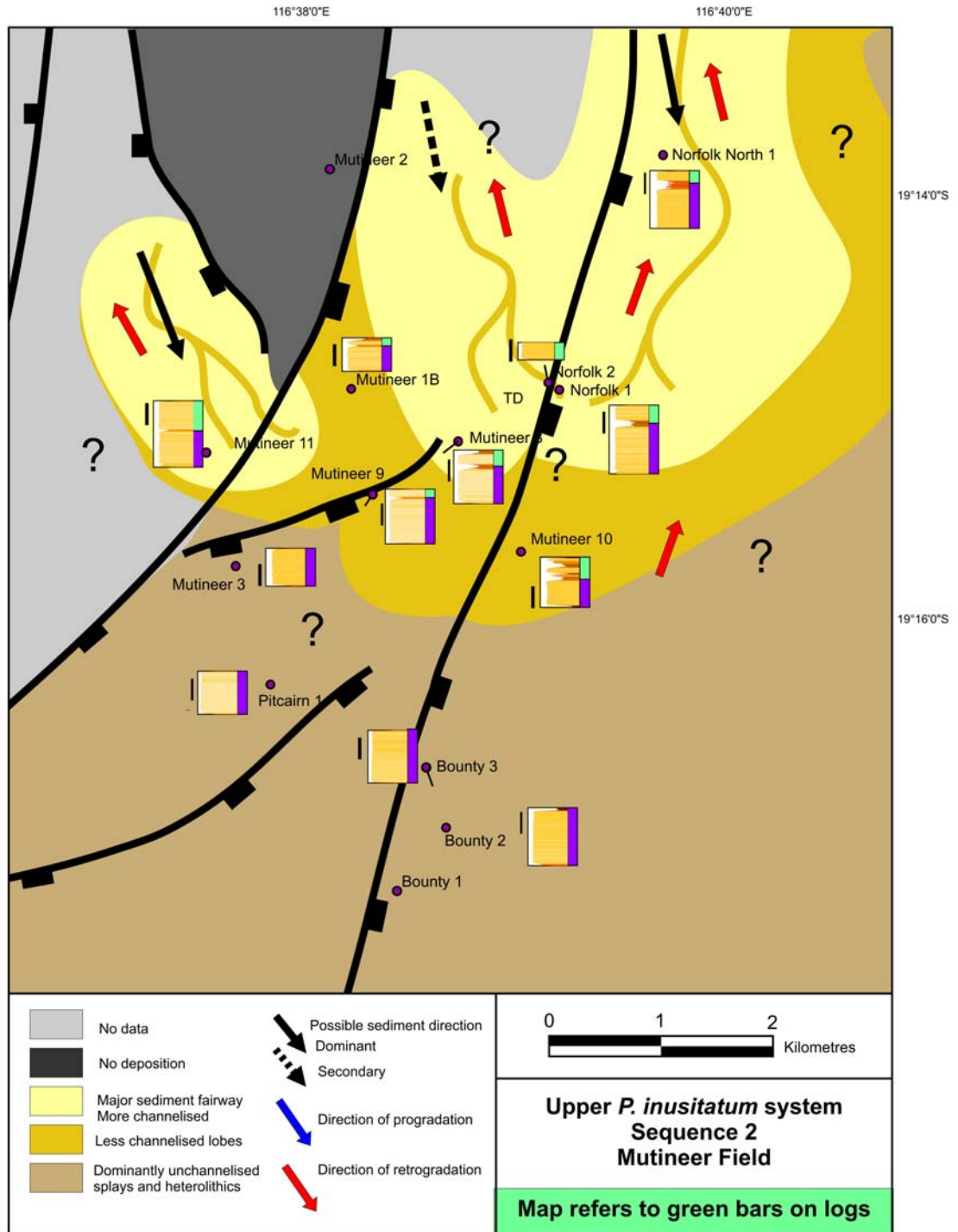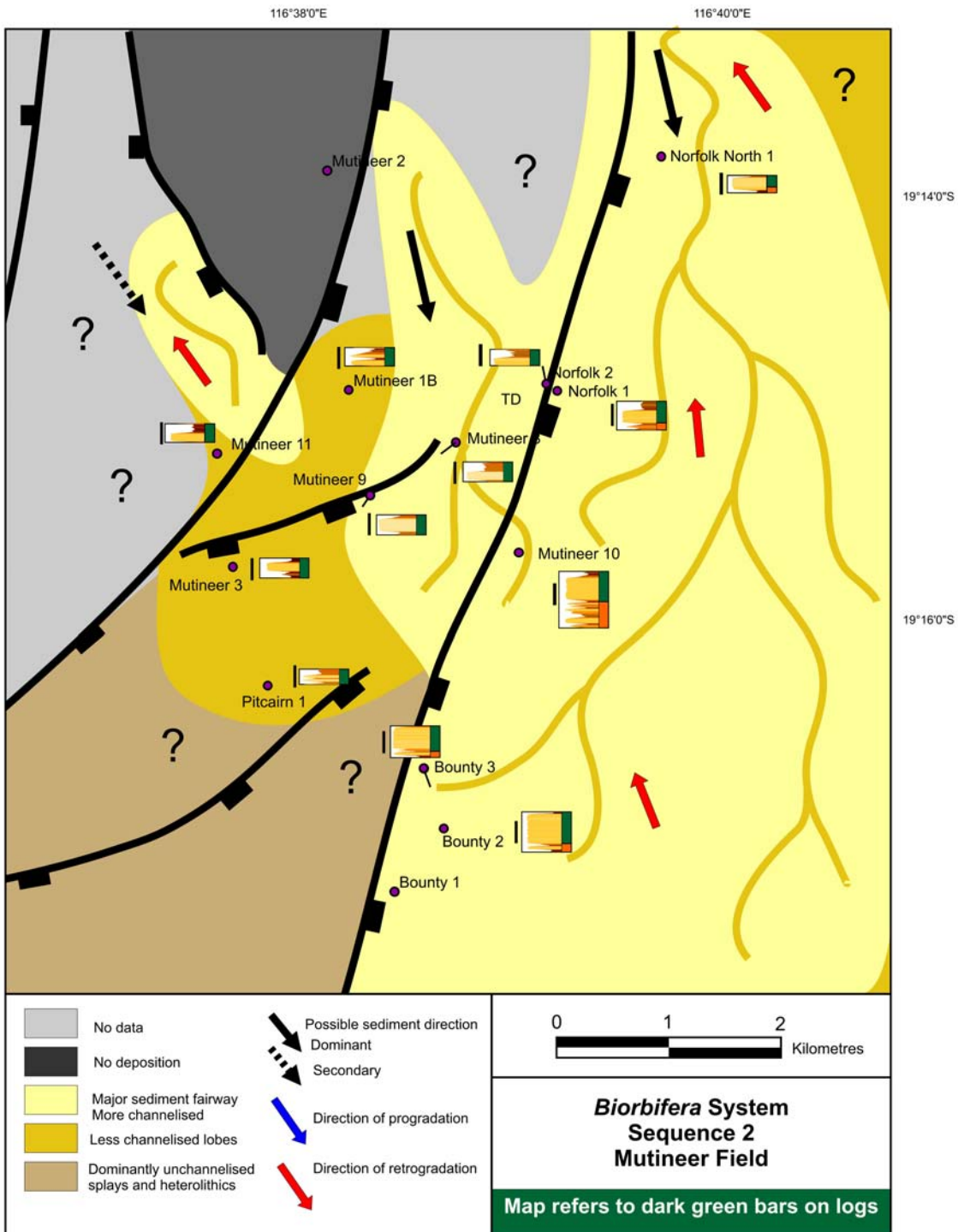
Figure 8-25: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 2 *Biorbifera* time. This unit is dominated by amalgamated cylindrical and fining upward successions of Electrofacies 1 and 2 (Norfolk North 1, Norfolk 1 and 2, Bounty-2 and 3 and Mutineer-3, 8, 9, 10 and 11) along with the layered units of Electrofacies 4 and 5 (Mutineer-1B and Pitcairn-1).

8.4.1.1.6 *Dissimulidinium* System

The *Dissimulidinium* system represents one sixth order complex that is characterised by two sequences that represent a small progradational and a large aggradational to retrogradational unit (Figures 8-26 and 8-27). It is similar to the *Biorbifera* system. A relative lowstand event is interpreted at the base of this unit.

Dissimulidinium System Unit One

This unit is interpreted to represent a southward prograding system which is being ponded within the Swift, Mutineer and southern Bounty half graben systems (Figure 8-26). The units are thin and sediment is expected to have been removed by younger fifth order composite channel-splay systems. It is interpreted that active movement along fault systems occurred during this time. No active sedimentation occurred in Norfolk North-1 or Mutineer-1B, -8 or -9 (Figure 8-26) and it is interpreted that the sediment source from the northern Bounty Graben was shut down by this time in relation to transgression.

Dissimulidinium System Unit Two

This unit is interpreted, like *Biorbifera* unit 2, to represent a strongly aggradation and retrogradational depositional system towards the northwest (Figure 8-27). Annealing of fault-controlled accommodation along with the onlapping of sediments onto faulted highs is clearly defined within Norfolk-2 and Mutineer-1B, -8 and -9 (Figure 8-27).

8.4.1.1.7 Upper *P. iehiense* System

The upper *P. iehiense* system was not intersected in the Mutineer region due to the sediment source shutting down, relocating elsewhere or not prograding far enough south to be preserved in the geological record.
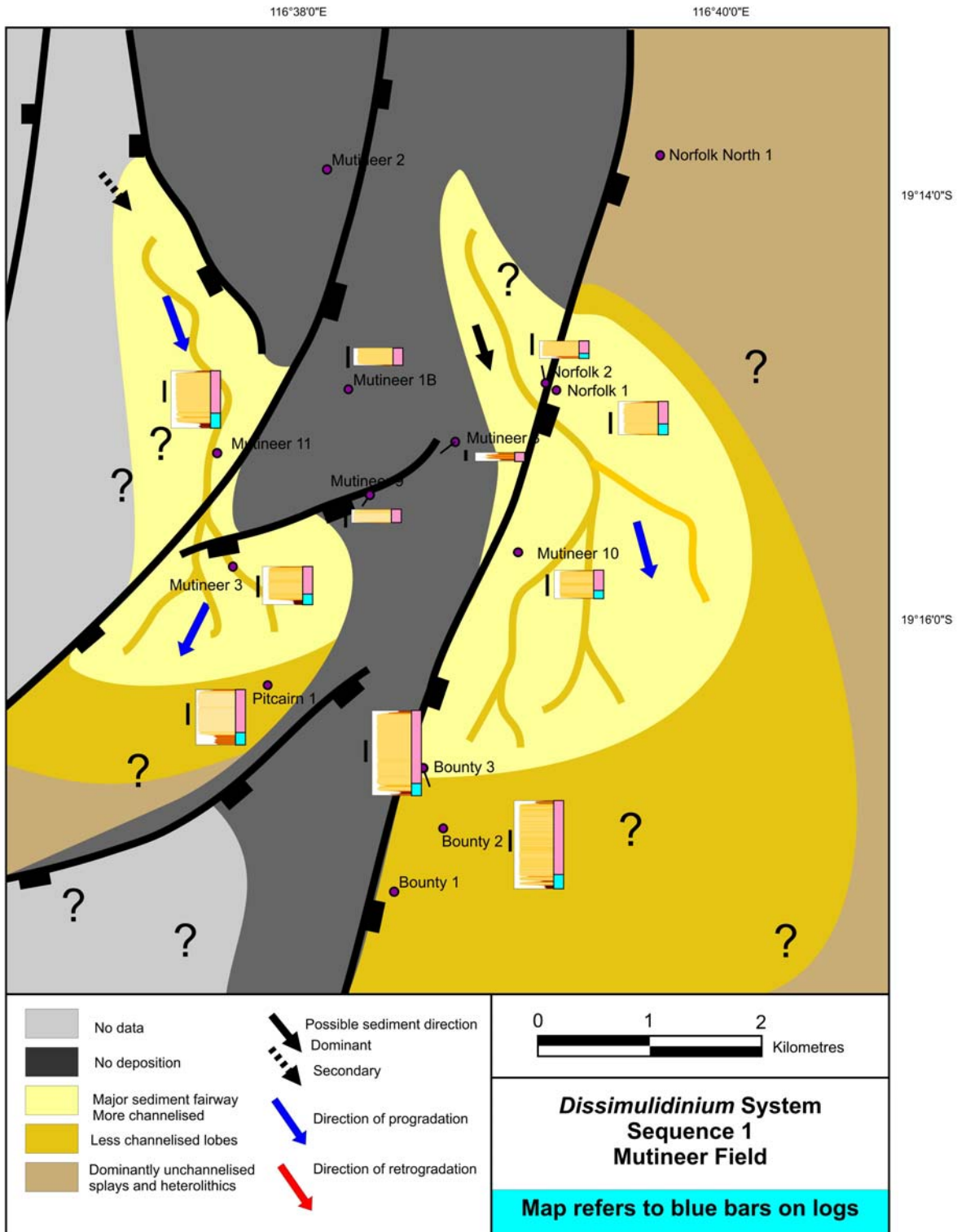
Figure 8-26: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Unit 1 *Dissimulidinium* time. This unit is represented by thin amalgamated and layered cylindrical units of Electrofacies 1 and 3. Active tectonism resulting in flow deflection and ponding within fault-created accommodation is interpreted for the unit. The black bars next to logs represent ten vertical metres.
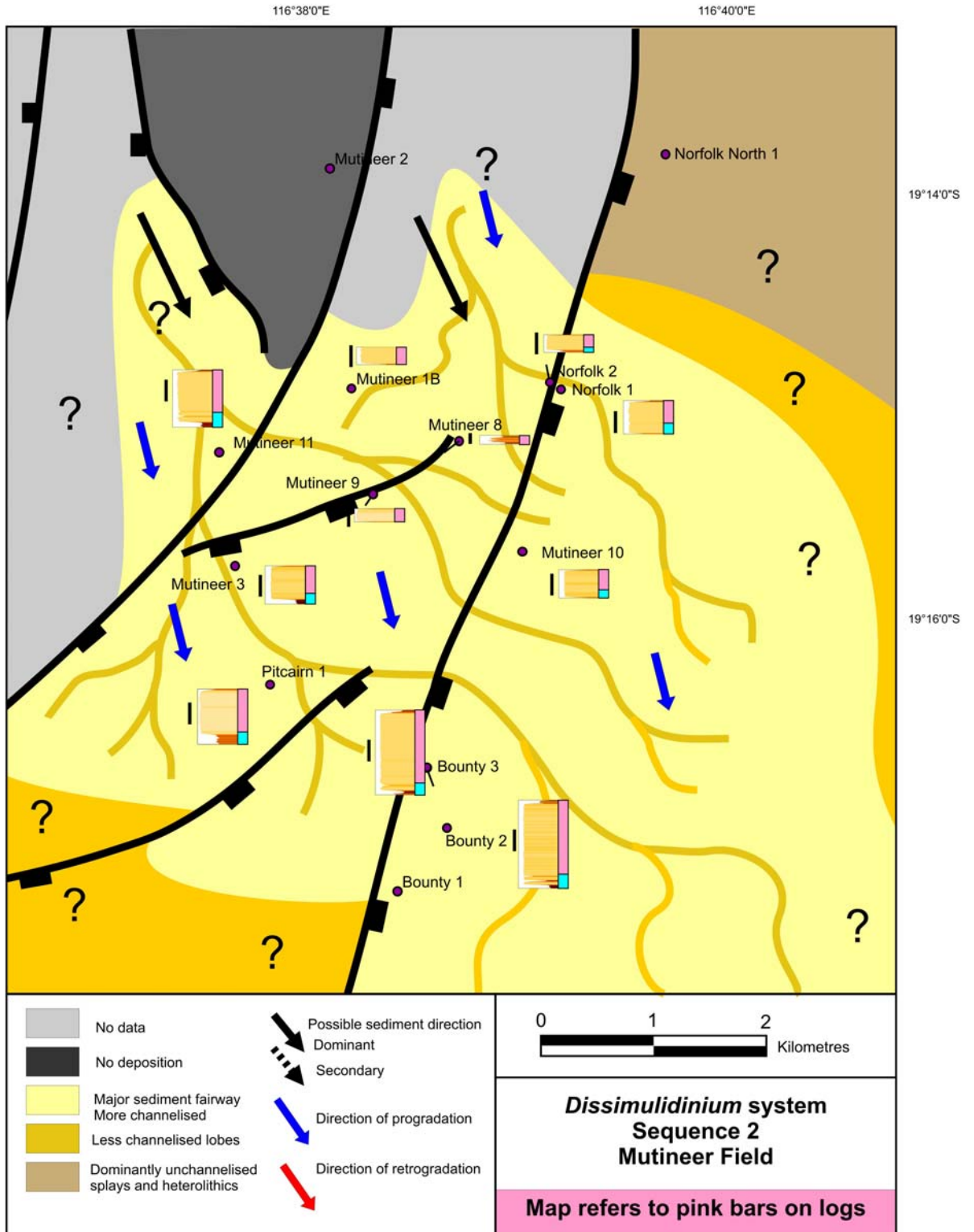
Figure 8-27: Palaeogeographical map highlighting the depositional nature of the Angel Formation during Sequence 2 *Dissimulidinium* time. It is a strongly aggradation and retrogradational depositional system. The measured dips from the Mutineer-1B image log are interpreted to represent lateral bedding with channel migration. This unit is dominantly represented by thick amalgamated cylindrical units of Electrofacies 1 with one example of layered units in Mutineer 8. The black bars next to logs represent ten vertical metres.

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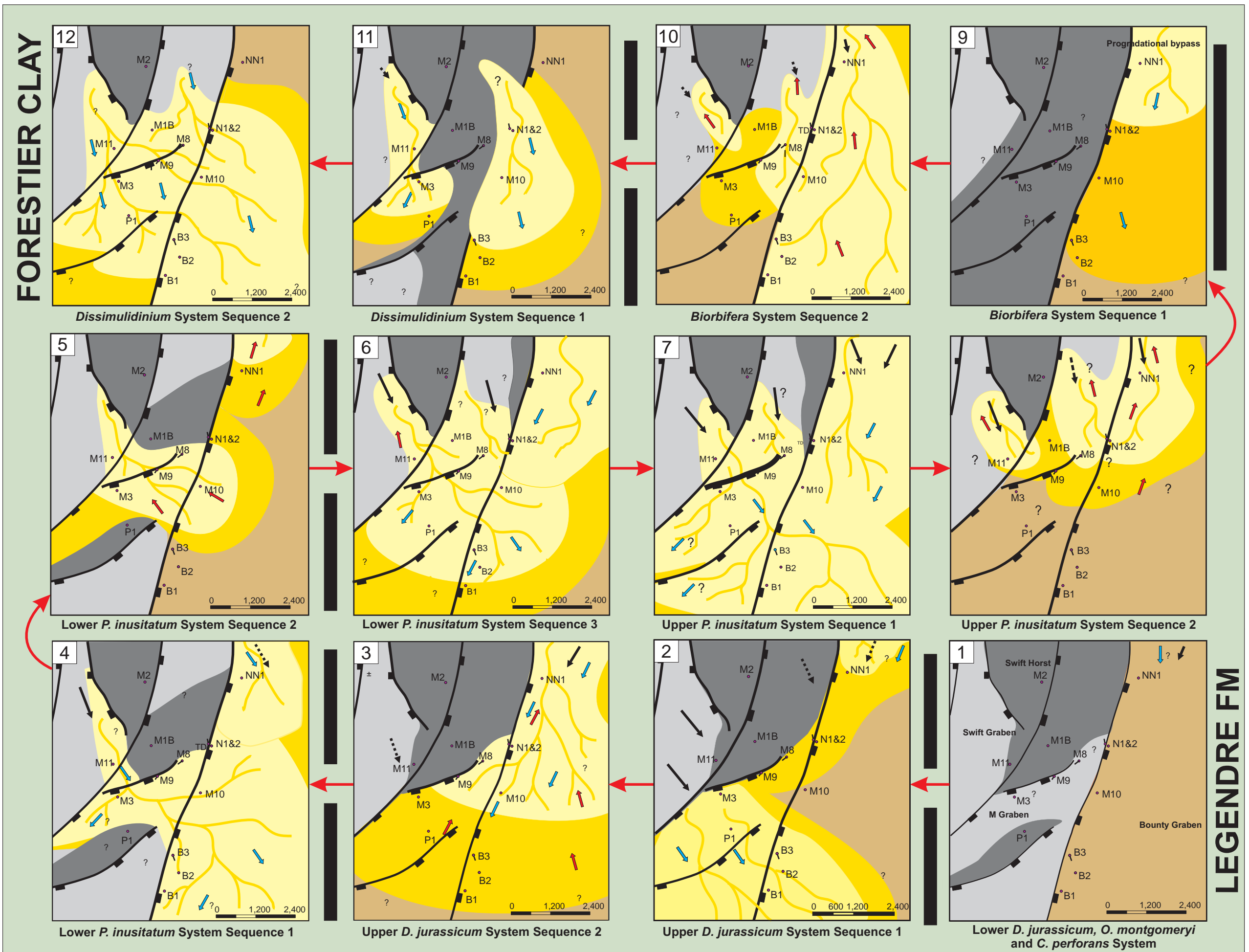
Figure 8-28: Palaeogeographical variation of depositional systems over the Tithonian in the Mutineer region. It demonstrates the variation in source direction and possible structural confinement. Sixth order lowstands are represented by the black boxes. Five in total exist across the region. The retrogradational nature of the Lower *P. inusitatum* sequence 2 package is interpreted to be a variation in sediment supply and not a true regional lowstand event (refer Section 9.3.1).

8.4.1.2 The Egret-Montague Region

The Egret-Montague region rests on the Parker Terrace located along the western edge of the Dampier Sub-basin (Figure 8-29). The depositional system is located within a series of en-echelon and tilted Triassic to Early Jurassic horst blocks against the Rankin Platform and is interpreted to be a seventh order proximal fan setting.
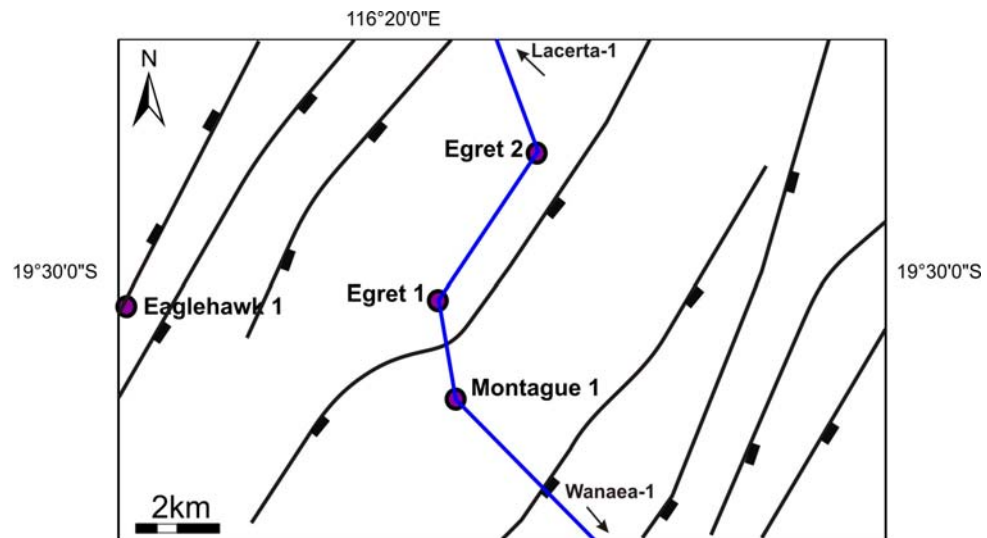
Figure 8-29: Map of the Egret-Montague region. Transect line is illustrated in Figure 8-30.

Depositional systems located within seventh order proximal fan localities are dominated by erosional and mixed erosional-depositional channel systems that promote sediment bypass during lowstand events.   They can become aggradational and depositional with transgression, which results in channel infilling. The degree of initial channel incision with the lowstand event in combination with the repeated ratio of channel erosion to fill is strongly dependant on the location of the system on a slope profile and its gradient.

From earlier architectural analysis (Chapters 5, 6 and 7), it was determined that:

- the depositional system is sand-rich and varies from highly amalgamated and homogeneous (Montague-1 core) to less amalgamated and variable (Egret-2 core);

- the dominant lithofacies associations are homogenous channel fills with preserved progradational and retrogradational splays (e.g. Egret-2 contained thick crevasse splay successions and injected zones);

- there is clear recognition of amalgamated 4th order migrational channel architectural elements in both wells;

- Models A and C are the fifth order packages identified within Montague-1, which represent large composite channel systems within a major channelised fairway (Table 7-1), and;

- Models B, C, D and E are the fifth order packages identified within Egret-2 (Table 7-1). They represent composite channel-splay and sheet systems located off-axis of a major sediment fairway.

An interpreted section through the Egret – Montague region (Figure 8-30) demonstrates the nature of this depositional system that is situated off the Rankin Platform. It is separated into the following systems:

- The *O. montgomeryi* system;

- The lower *D. jurassicum* system;

- The upper *D. jurassicum* system, and;

- The *P. iehiense* system.
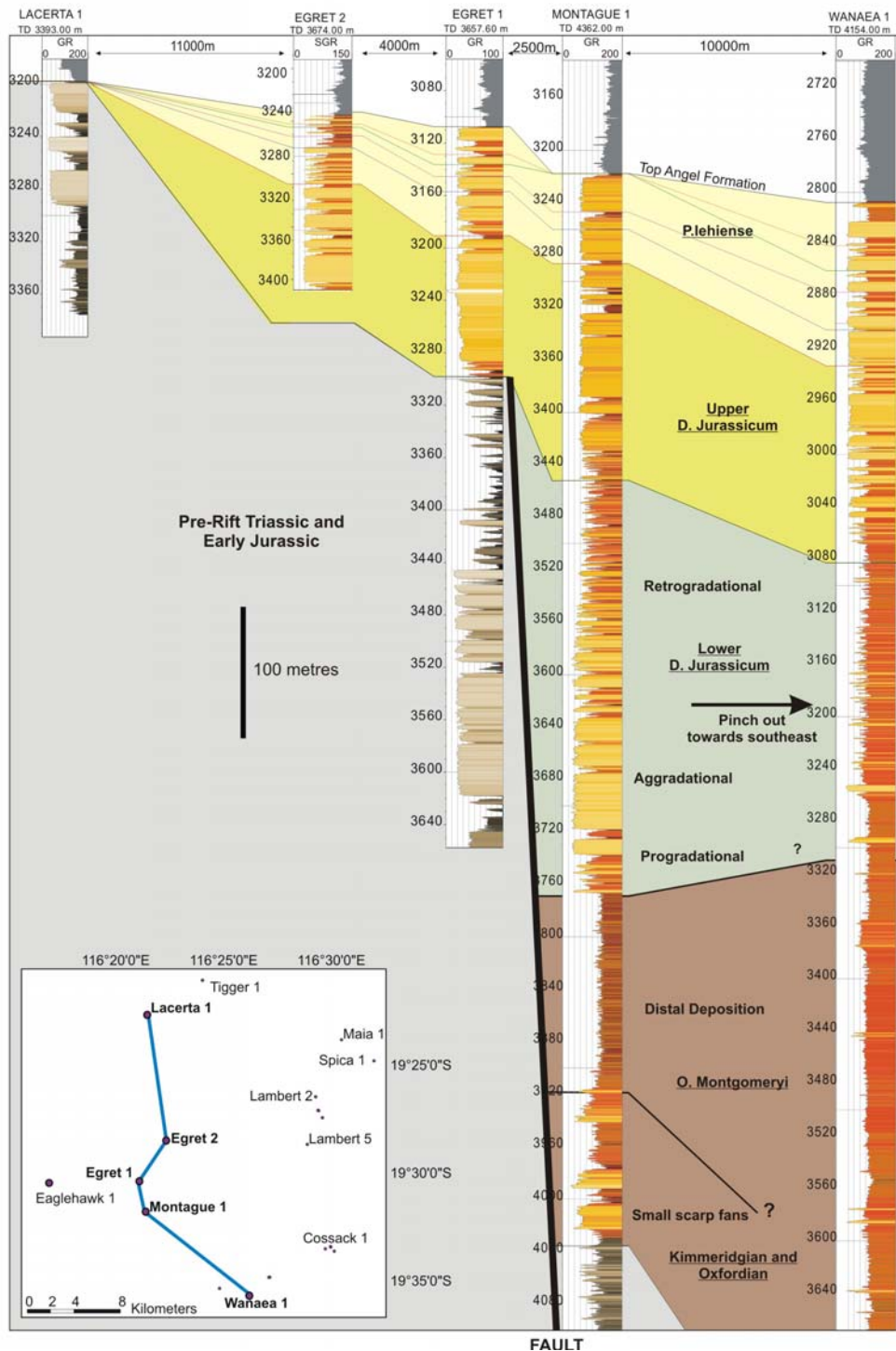
Figure 8-30: Section from Lacerta-1 in the northwest to Wanaea-1 in the southeast through the Egret and Montague region. The line illustrates the faulted margin of the Dampier Sub-basin where Late Jurassic (*P. iehiense*) sediments rest upon Triassic sediments faulted during Early to Middle Jurassic times. Sediment removal is interpreted to have occurred from these Triassic blocks which could have sourced Oxfordian, Kimmeridgian and Tithonian fan systems in the central Dampier Sub-basin. It is difficult to interpret as Late Jurassic and Early Cretaceous sediments are not preserved upslope on the Rankin Trend near Eaglehawk-1 due to their removal during Valanginian time. This unconformity overlies early Jurassic sediments (B.O.C. of Australia, 1973).

8.4.1.2.1 *O. montgomeryi* system

O. montgomeryi sediments in the Egret – Montague region comprise fine-grained sediments deposited during a time of abandonment (Figure 8-30). No sediments are preserved in Egret-1 or -2 due to the existence of a base upper *D. jurassicum* unconformity with Triassic sediments. The lowstand event responsible for the unconformity is interpreted to have removed the *O. montgomeryi* to lower *D. jurassicum* sediment (Figure 8-30).

8.4.1.2.2 Lower *D. jurassicum* system

The lower *D. jurassicum* interval intersected by Montague-1 consists of a large sixth order progradational, aggradational and retrogradational system spanning 330 vertical metres (Figure 8-30). The retrogradation package alone is 200 metres thick. At the base of the unit, a relative lowstand event is interpreted. The fifth order composite channel-splay complexes are interpreted to range up to 20 metres thick. Towards the top of the unit, the fifth order channel-splay complexes are interpreted to be more distributary-like interbedded with retrogradational unconfined splays and fan abandonment successions. There are no lower *D. jurassicum* sediments preserved in Egret-1 or -2 due to a base upper *D. jurassicum* unconformity (Figure 8-30).

8.4.1.2.3 Upper *D. jurassicum* system

The upper *D. jurassicum* system contains compensationally stacked and amalgamated fifth order composite channel-splay complexes that produce packages up to 25 metres thick (Figure 8-30). A relative lowstand event is interpreted at the base of this unit. Progradational and retrogradational trends are identifiable in all three wells. Egret-1 is interpreted to rest within a confined channel complex (Figure 8-31). The well intersected amalgamated fifth order composite channel complexes forming a succession over 80 metres thick (Figure 8-30). It represents the repeated incision and infilling of a sediment fairway that may have been confined.   Egret-2 is interpreted to have been located off-axis of the confined channel complex (Figures 8-31 and 8-32). It contains fifth order channel-splay units that rest marginal to the main channel fairway. They are less amalgamated units.

8.4.1.2.4 *P. iehiense* system

The *P. iehiense* system comprises compensationally stacked fifth order channel-splay complexes that range up to 20 metres thick in Montague-1 and 10 metres thick in Egret-1. This variation in thickness suggests that accommodation space was ample in the Montague-1 region (Figures 8-30 and 8-31). Three lowstand events are interpreted within this unit (base *I. kondratjevii*, base *Dissimulidinium* and base *B. simplex*) (Figure 8-30).

Three composite channel-splay complexes were intersected by Montague-1, the largest being over 40 metres thick during *Biorbifera* time (Figure 8-30). Abandonment quickly followed this channel complex, resulting in the deposition of fine-grained sediments during *Dissimulidinium* and upper *P. iehiense* time. This occurred in relation to major retrogradation towards the shelf of the depositional system in response to late Tithonian transgression (Figures 8-30 and 8-31).

Egret-1 and -2 are interpreted to be situated closer to the shelfal source. They contain *Biorbifera*, *Dissimulidinium* and upper *P. iehiense* successions deposited through retrogradational backstepping of the seventh order system towards the shelf (Figure 8-30). Egret-1 contains fifth order composite channel-splay systems up to 15 metres thick with associated retrogradational splays. These systems are interpreted to have been migrational and compensationally stacked. Egret-1 lies within a channelised fairway when compared to Egret-2 (Figure 8-31). Fifth order architectural analysis of core from Egret-2 demonstrated the presence of isolated retrogradational splays and thin distributary-like channel systems that would have existed adjacent to a channel fairway (Table 7-1). The presence of stacked crevasse splay successions and the recognition of sandstone injection features in the core (3248 – 3250.5 metres and 3281.5 – 3283.5 metres respectively) further support this concept (Section 9.5).

Dissimulidinium and upper *P. iehiense* sediments are preserved within Egret-1 and -2 signify that continued retrogradation of the seventh order fan system resulted in the backfilling of the channelised fairway and the development of fan lobe units comprising of distributary-sized fifth order channel-splay systems (Figure 8-30).

A west to east trending seismic transect through Egret-2 illustrates the location of Egret-2 in relation to an interpreted channelised fairway against the Rankin Platform (Figure 8-32). Further downslope in Egret-1 (Figure 8-33), the fairway is no longer visible and lobate features are interpreted. This could indicate that channel systems are becoming increasingly distributary-like from Egret-2 to Egret-1 during Late Tithonian time in relation to retrogradation (Figure 8-31). As there is no preserved Late Jurassic and Early Cretaceous sediments preserved on the Rankin Platform near the Egret field, it is interpreted that the sediments were fed either through fault relay systems from the north or by channel or canyon features sourced directly by the platform to the east (Figure 8-31).
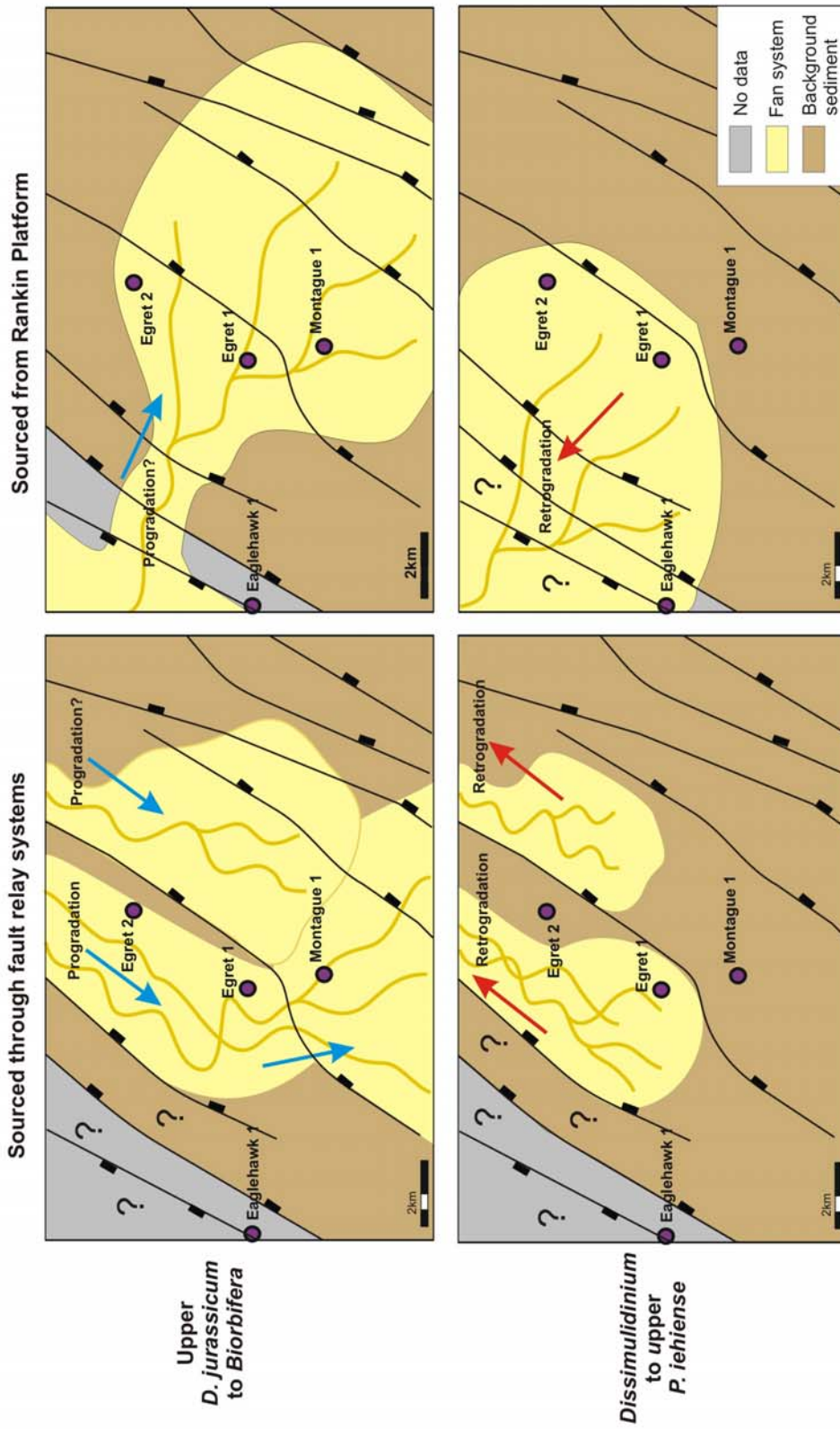
Figure 8-31: Maps of upper *D. jurassicum* to *Biorbifera* and *Dissimulidinium* to upper *P. iehiense* demonstrating the retrogradational nature of the fan systems in the Egret-Montague region. They are interpreted to backstep towards the Rankin Platform either through fault relays or through proximal channel or canyon complexes on the platform. As Late Jurassic and Early Cretaceous sediment was removed during Valanginian time at Eaglehawk-1, multiple interpretations are viable.
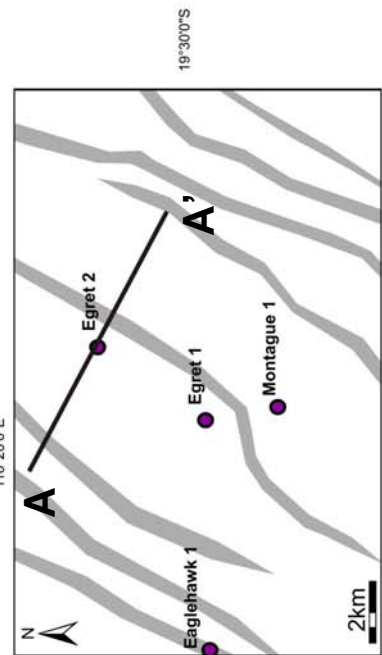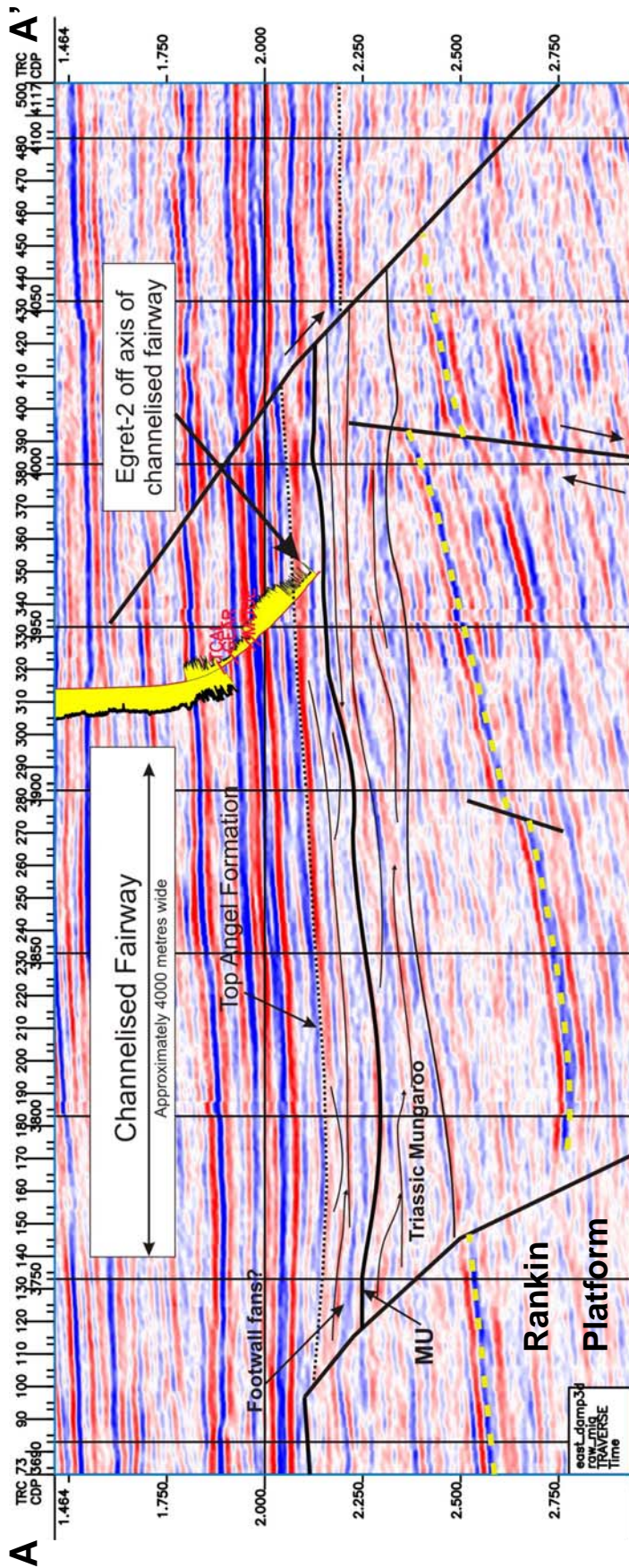
Figure 8-32: Northwest – southeast transect through Egret-2 highlighting the seismic architecture of the Tithonian interval. Channelisation against the Rankin Trend is evident and is controlled by faulting.
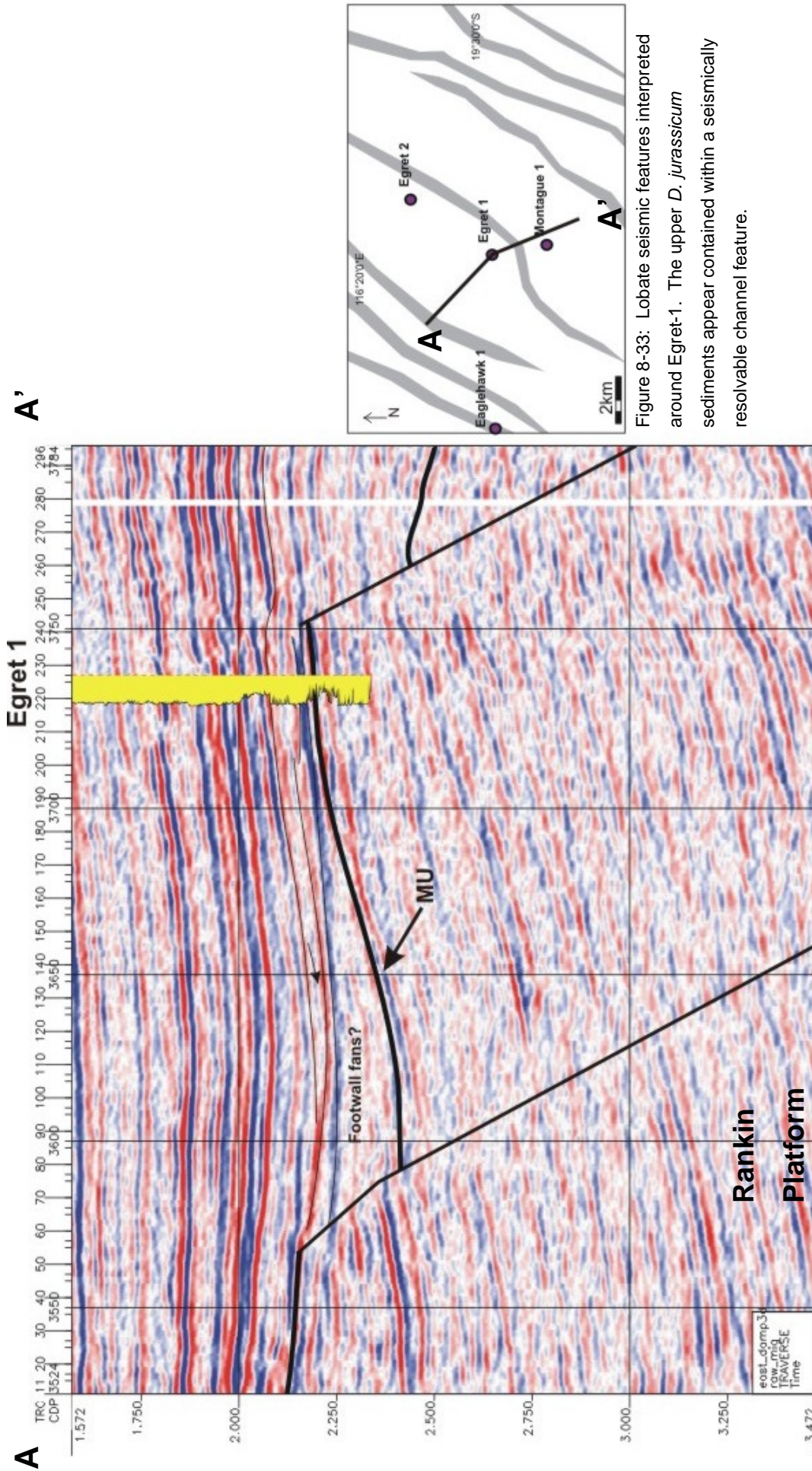
Figure 8-33: Lobate seismic features interpreted around Egret-1. The upper *D. jurassicum* sediments appear contained within a seismically resolvable channel feature.

8.4.1.3 The Lambert Region

The Lambert region is located on the western margin along the Rankin Platform. It is interpreted to have been deposited within a seventh order medial fan setting.   The region contains six wells located along a section spanning five kilometres (Figure 8-34).
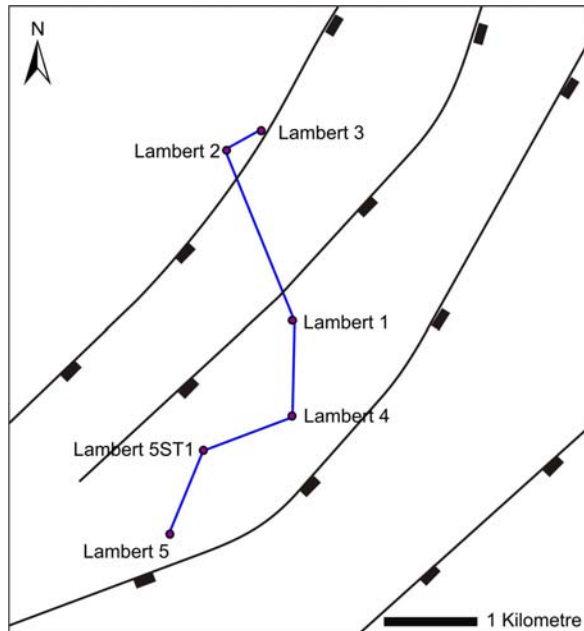
Figure 8-34: Map of the Lambert region highlighting the six wells. The section is represented in Figure 8-35.

From earlier architectural analysis (Chapters 5, 6 and 7), it was determined that:

- the depositional system comprises interbedded amalgamated and layered successions of sandstone with common dewatering structures and injection-related features (based on core interpretation of Lambert-2 (Appendix B));

- the dominant lithofacies associations are channel fills (both axial and marginal) with preserved progradational and retrogradational splays and abandonment successions;

- there is clear recognition of amalgamated 4th order migrational distributary-sized channel elements, and;

- Models B, C, D and E are the fifth order packages identified within Lambert-2. They represent distributary-sized channel systems interbedded with sheet systems and splays.

An interpreted biostratigraphic section across the field (Figure 8-35) illustrates the tabular lateral continuity of sixth order migrational channel complexes across a five kilometre distance. Each unit displays clear bed thickness variation, interpreted downdip pinch-out towards the south and interpreted onlap onto channelised unconformable surfaces towards the north. This suggests that channel systems in the Lambert region are dominantly distributary-sized. The region is separated into five key packages which reflect the stacking of fifth order channel-splay complexes into sixth order migrational channel complexes over the Tithonian interval. They are the:

- *O. montgomeryi* to middle lower *D. jurassicum* system;

- middle lower *D. jurassicum* to upper *D. jurassicum* system;

- lower *P. inusitatum* system;

- upper *P. inusitatum* and *Biorbifera* system, and;

- *Dissimulidinium* and upper *P. iehiense* system.

8.4.1.3.1 *O. montgomeryi* to middle lower *D. jurassicum* system

The *O. montgomeryi* and lower *D. jurassicum* system is represented by a full progradational, aggradational and retrogradational system spanning approximately 150 metres in Lambert-1.

8.4.1.3.2 Middle lower *D. jurassicum* to upper *D. jurassicum* system

This system is represented by a full progradational, aggradational and retrogradational sixth order system which may be controlled by either faulting or a relative lowstand event during lower *D. jurassicum* time (Figure 8-35). Ample accommodation space was available in the half graben systems near Lambert-1, -4, -5 and -5ST1. Less sediment is preserved within Lambert-2 and -3 suggesting either significant sediment bypass through erosive channel systems or syn-depositional faulting reduced the amount of available accommodation on the faulted high (Figure 8-35).

8.4.1.3.3 Lower *P. inusitatum* system

The lower *P. inusitatum* system is interpreted to be a dominantly progradational sixth order complex sourced from the north and northeastern regions (Figure 8-35 and 8-36A). Coarsening upward log profiles signifies strong progradation and the presence of compensationally stacking fifth order composite channel-splay complexes and resultant fan lobes. Some fault control may have been active during the early stages of this system which could have driven sediment through the Lambert-1 and Lambert-4 region (Figure 8-36A). The fifth order channel-splay complexes around Lambert-1 and -4 are interpreted to have been highly migrational.

8.4.1.3.4 Upper *P. inusitatum* and *Biorbifera* system

Two sixth order systems existed during upper *P. inusitatum* and *Biorbifera* time which are separated by the *I. kondratjevii* lowstand event. They are interpreted to represent amalgamated fifth order channel-splay complexes that are continuing to prograde towards the south through Lambert-4 and -5 (Figures 8-35 and 8-36B). Thin units within Lambert-1 towards the north are interpreted to rest off-axis of the channelised fairway. They contain thin distributary units and preserved unconfined retrogradational splays deposited outside the confines of a channel levee complex (Figure 8-36B). Heterolithic intervals intersected in Lambert-2 and -3 suggest the presence of levee and abandonment successions located laterally to the channelised fairway (Figure 8-36B). Thin depositional units within these wells suggest crevasse splay deposition (Figure 8-35).

8.4.1.3.5 *Dissimulidinium* and upper *P. iehiense* system

Two sixth order migrational channel complexes existed during *Dissimulidinium* and upper *P. iehiense* time. They are overlain by the *Dissimulidinium* lowstand and separated by the *B. simplex* lowstand

event.   They contain layered successions of stacked multistorey depositional distributary systems interbedded with fifth order sheet complexes (fifth order models C, D and E) (Figure 8-35 and 8-36C). These units are interpreted to be highly aggradational and retrogradational. The region experienced high sediment flux in relation to relative lowstands (base *Dissimulidinium* and *B. simplex*) that were later challenged by a strong transgressive sea. This resulted in the preservation of a thick aggradational to retrogradational package of sediments concentrated towards the northeastern source (Figure 8-36C).
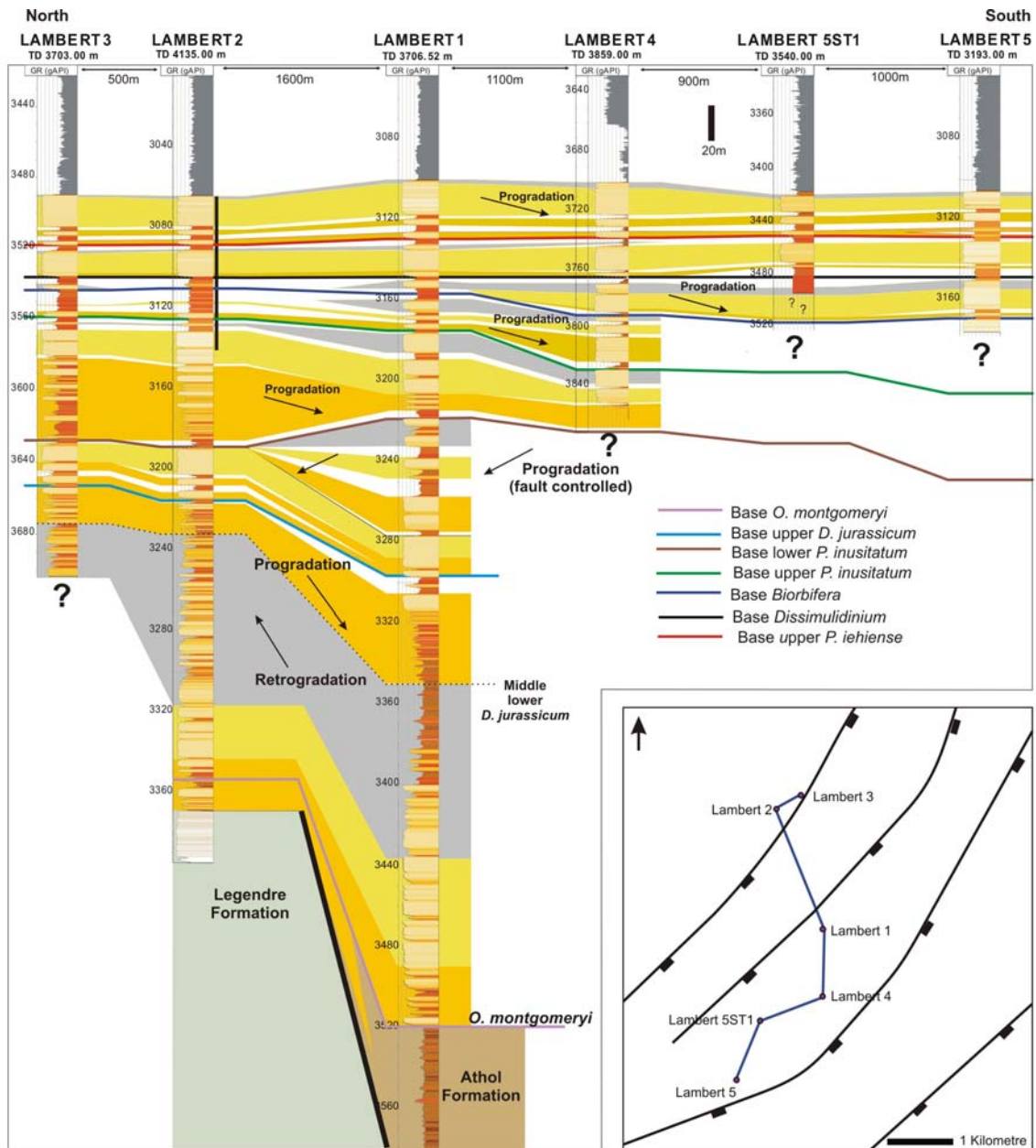
Figure 8-35: Biostratigraphic section through the Lambert field highlighting the development of fifth and sixth order channel and splay complexes. An interpreted section with palynology is available in Appendix D.

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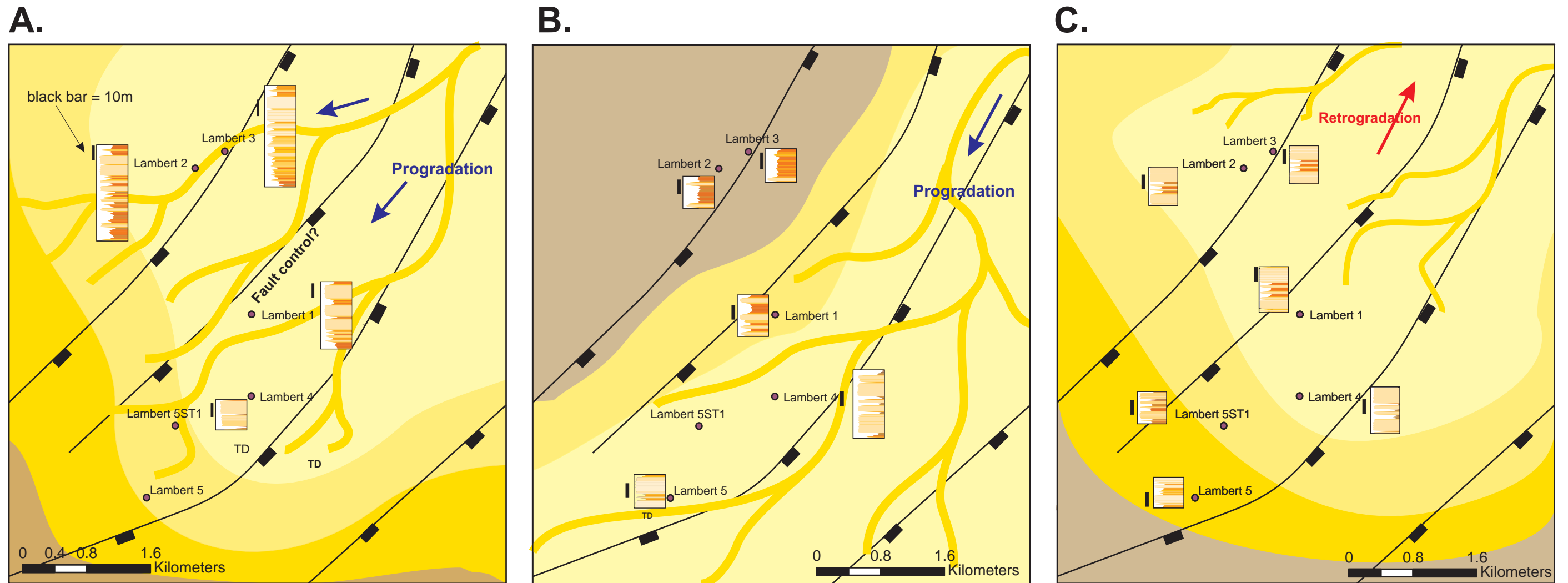
A.

Map of Lower *P. inusitatum* time within the Lambert field highlighting the progradational nature of fifth order composite channel-splay systems from the northeast. The logs are dominantly represented by layered and serrated coarsening upward motif of Electrofacies 5 overlain by the layered and amalgamated cylindrical motifs of Electrofacies 1 and 3. The succession in Lambert-4 is similar to that preserved within Lambert-1 (Lambert-4 reached total depth midway within this system).

B.

The Upper *P. inusitatum* and *Biorbifera* system represents two sixth order migrational channel complexes. The log motifs are represented by the layered and amalgamated cylindrical motifs of Electrofacies 1 and 3. The sixth order complexes are interpreted to be confined by fault systems along Lambert -1 and -4. Sedimentation in Lambert-2 and -3 comprise dominantly of fine-grained sediments.

C.

Map of *Dissimulidinium* and Upper *P. iehiense* sedimentation in the Lambert region. Retrogradation is interpreted to have occurred towards the north-eastern source. These units contain distributary-sized fifth order composite channel-splay systems interbedded with fifth order sheet complexes. The *Dissimulodinium* and Upper *P. iehiense* units are represented by the layered and amalgamated cylindrical motifs of Electrofacies 1 and 3.

Figure 8-36: Palaeogeographical maps highlighting the evolution of fan systems across the Lambert region.

8.4.2 The Central Dampier Region

The central Dampier depositional systems are those that are interpreted to have been primarily sourced from the southeastern Beagle Sub-basin and Legendre Trend to the east. Two systems were analysed (Figure 8-37). They are:

- Angel field region (seventh order lower slope to proximal fan setting), and;

- Wanaea and Cossack fields region (seventh order medial to distal fan setting).

NOTE:
This figure is included on page 229 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8-37: Block model of the seventh order mixed sand-mud ramp model for the central Dampier Sub-basin highlighting the Angel, Cossack and Wanaea regions and their interpreted positions on the ramp (adapted from Reading and Richards, 1994). The model represents maximum Tithonian progradation.

8.4.2.1 The Angel Region

The Angel field is located within the north-central region of the Dampier Sub-basin (Figure 8-38) and is interpreted to rest within a seventh order lower slope to proximal fan location. It comprises four wells straddling the Madeleine fault (Figure 8-38). From earlier architectural analysis (Chapters 5, 6 and 7), it was determined that:

- the depositional system is highly amalgamated, homogenous and sand-rich (based on core interpretation of Angel-4 (Appendix B));

- the dominant lithofacies associations are channel lags and fills (both axial and marginal) with some progradational and retrogradational splays preserved;

- there is clear recognition of amalgamated 4th order migrational channel architectural elements, and;

- Model A and B overlain by Model E are the most common fifth order architectural packages (Table 7-1).
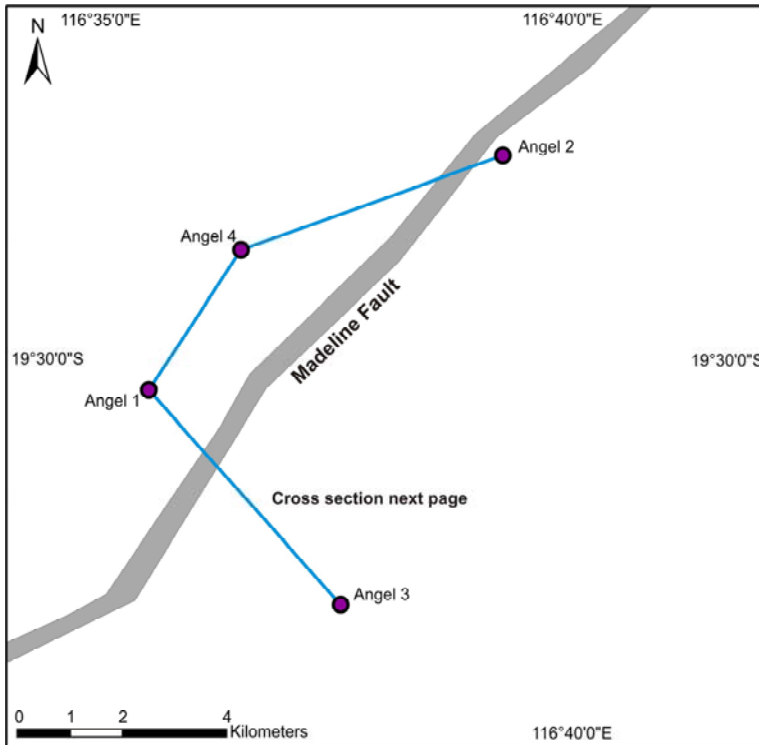
Figure 8-38: Map of the Angel field illustrating the location of the four wells. The blue section correlates to Figure 8-39.

Biostratigraphic interpretation through the Angel field (Figure 8-39) illustrates the amalgamated nature of the fifth order composite channel-splay units into sixth order migrational channel packages. The Tithonian interval in this field is separated into three sixth order systems which include the:

- *O. montgomeryi* and *C. perforans* system;

- Lower *D. jurassicum* system, and;

- Upper *D. jurassicum* and *P. iehiense* system.
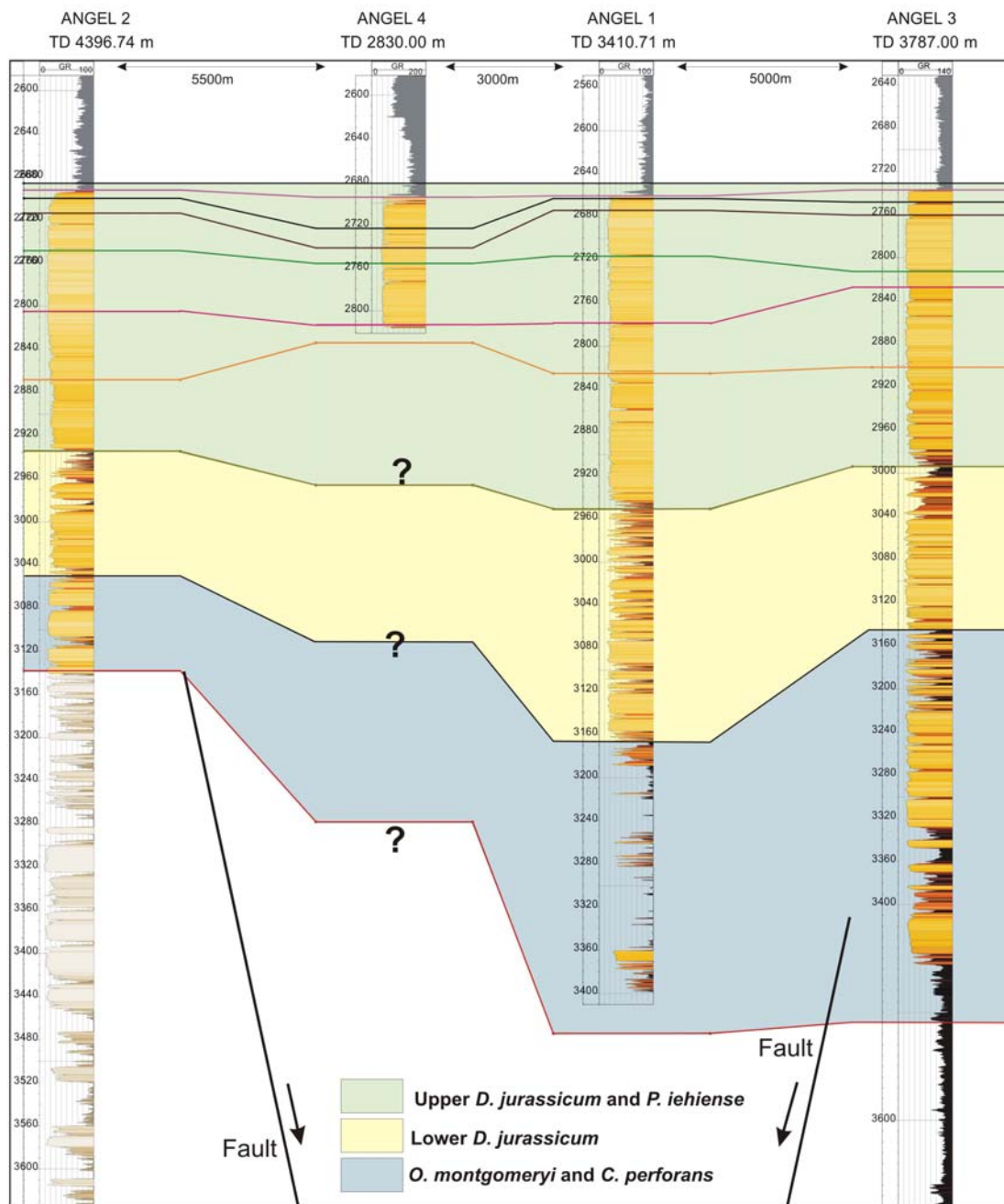
Figure 8-39: Biostratigraphic interpretation through the Angel field highlighting the high level of amalgamation, high sandstone net-to-gross and bed thickness variability across the Madeline fault system. Angel-2 and -3 rest on the upthrown block, Angel-1 and -4 within the downthrown graben.

8.4.2.1.1 *C. perforans* and *O. montgomeryi* system

One sixth order complex is clearly recognised along the eastern upthrown side of the Madeleine Fault (Angel-2 and -3) (Figure 8-39). These wells contain fifth order composite channel-splay units ranging from 10 to 30 metres thick that are interpreted to comprise of compensationally stacked and migrational fifth order composite channel complexes with associated splays.

This sixth order system is interpreted to be a small-scale migrational channel complex (Figure 8-40A). It displays a progradational, aggradational and retrogradational pattern towards maximum flood conditions at the J28 (Top *O. montgomeryi*) boundary (Figure 8-39). A proportion of the progradational phase is interpreted to be absent in Angel-2, indicating that the area experienced sediment bypass and erosive channelisation into the Legendre Formation. It is interpreted that sedimentation during this time was sourced primarily from the eastern regions (Figure 8-40A).

A condensed section exists within the downthrown fault depocentre intersected by Angel-1 (Figure 8-39 and 8-40A). A seismic transect from Angel-3 to Angel-1 demonstrates the onlapping nature of fan sediments against the main unconformity (JC, JO, JK) and the tilted upthrown side of the Madeline Fault (Figure 8-41). This suggests syn-depositional movement of the Madeleine Fault resulting in tilting of the horst block towards the east, leading to the confinement of sediment on the eastern side of the fault (Figure 8-40A).

8.4.2.1.2 Lower *D. jurassicum* system

One sixth order migrational channel complex comprising amalgamated and layered fifth order composite channel-splay complexes is evident in all three wells. A higher degree of composite channel complex amalgamation is more evident in Angel-2 and -3 suggesting sediment is still sourced from the east (Figure 8-40B). A relative lowstand event is interpreted to have existed at the base of this unit (Figure 8-39). Preserved thickness of lower *D. jurassicum* sediments is greater in Angel-1, suggesting that sediments bypassed the Madeline Fault and were deposited within the half graben. This resulted in the development of a layered sheet-like system with depositional distributary channels (Figure 8-40B). The autocyclic nature of fifth order channel-splay complexes and their resultant fan lobes is evident within Angel-1.

8.4.2.1.3 Upper *D. jurassicum* and *P. iehiense* system

This package of sediments is interpreted to contain up to five highly amalgamated sixth order migrational channel complexes. There is little to no preservation of intra-successional retrogradational fine-grained sediments (Figure 8-40C). High sediment flux to the Angel region resulted in rapid and forceful progradation of the sixth order systems with clear coarsening upward progradational log motifs preserved in Angel-2 and -3 (Figures 8-39 and 8-40C). Maximum sediment flux is interpreted to have occurred during *P. inusitatum* (lower *P. iehiense*) time around Angel-1. Thinner packages of upper *D. jurassicum* and lower *P. iehiense* sediments are preserved in Angel-4 (Figure 8-39). They may have been either cut down through younger channelisation or *P. inusitatum*-aged sediments in Angel-1 may have been partially sourced from the west (Figure 8-40C). Relative lowstand events are interpreted to

have existed at the base of the *Egmontodinium*, *I. kondratjevii*, *Dissimulidinium* and *B. simplex* time. They are not strongly preserved with deposits indicative of abandonment due to the sandy nature, high sediment flux and proximity of the system to the palaeoshelf.

An interpreted seismic transect from Angel-3 to Angel-4 (Figure 8-42) illustrates the presence of amalgamated sixth order migrational channel complexes (Figure 8-2) which span up to three kilometres in width. Angel-4 is interpreted to be located on the margin of the systems (Figure 8-42). A crevasse splay deposit approximately one metre thick (2740m) and the presence of stacked retrogradational splay deposits (spill phases of composite channel complexes) up to three metres thick (2699m – 2702m and 2772m – 2774m) in Angel-4 core supports this interpretation.

The location of the amalgamated sixth order migrational channel complexes is interpreted to have been controlled by Madeline Fault. The complexes are located dominantly within the half graben against the fault scarp (Figures 8-40C and 8-42), which suggests syn-depositional movement of the fault during upper *D. jurassicum* and *P. iehiense* time. This movement provided a line of accommodation against the fault scarp which the migrational channel complexes used to propagate south.

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C. perforans and O. montgomeryi

Progradation

Madeline Fault

Onlap

Sediment starvation

Progradation

Retrogradation

Onlap

Retrogradation

Progradation

A.

Map of *C. perforans* and *O. montgomeryi* sedimentation in the Angel region. Sediment is interpreted to be sourced from the east and onlapped against the tilted upthrown side of the Madeline fault. A full sixth order progradational, aggradational and retrogradational succession of sediments is recognised in Angel-3. The lack of a progradational succession in Angel-2 suggests the removal of sediment through channel erosion and sediment bypass during late progradational time whilst the downthrown side of the fault experienced sediment starvation around Angel-1.

Lower D. jurassicum

Madeline Fault

Depocentre

Retrogradation

Bypass

Progradation

Retrogradation

Bypass
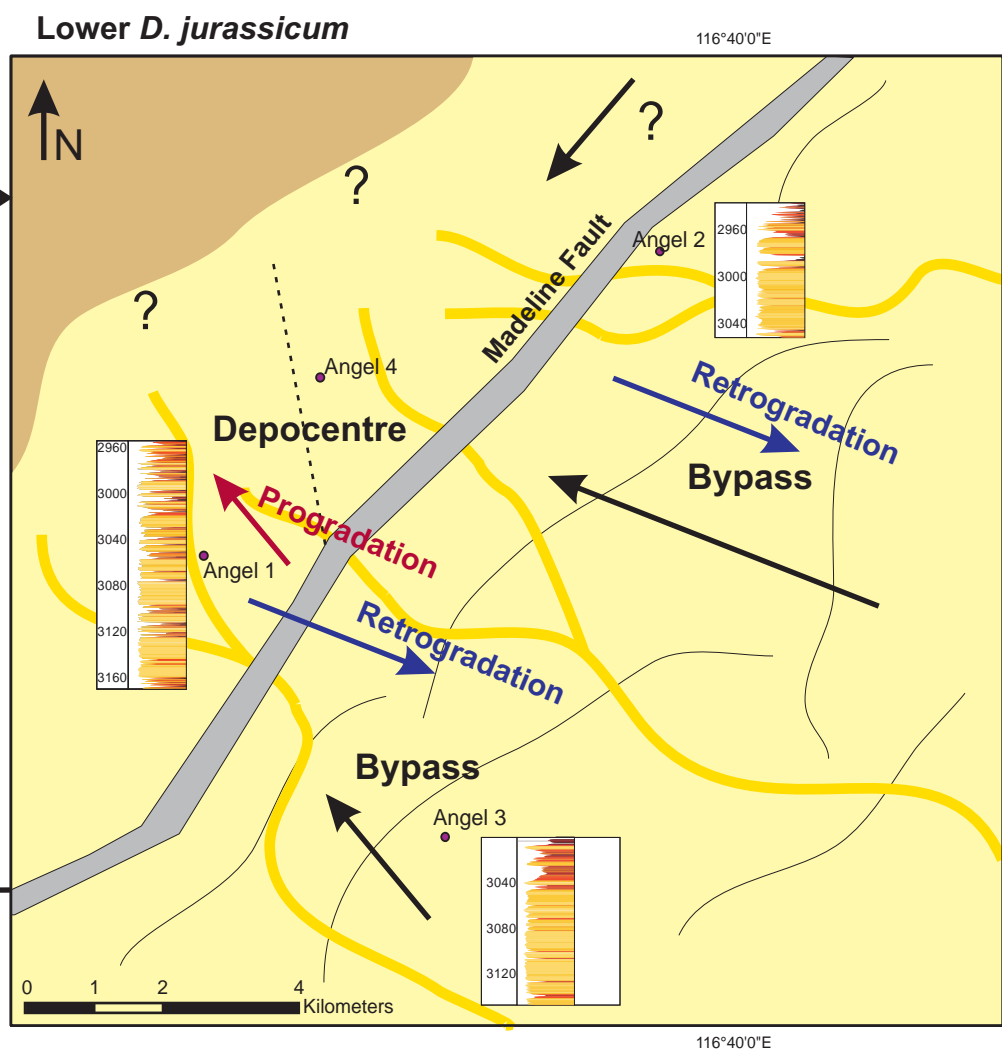
B.

Map of Lower *D. jurassicum* sedimentation in the Angel region. Sedimentation is interpreted to be sourced from the east. Most deposition occurred within the western half graben of the Madeline Fault. A full sixth order progradational, aggradational and retrogradational succession is preserved within Angel-1. The fifth order units range up to 20 metres thick within the well, suggesting development of distributary-sized composite channel-splay complexes.

Upper D. jurassicum and P. iehiense

Retrogradation towards N/NW (Thick *B. simplex/C. calabaza*)

Strong progradation

Strong progradation

Strong progradation?

Madeline Fault

Sixth order migrational channel belt

Thin *B. simplex/C. calabaza*

Strong progradation

P. inusitatum depocentre

Strong progradation
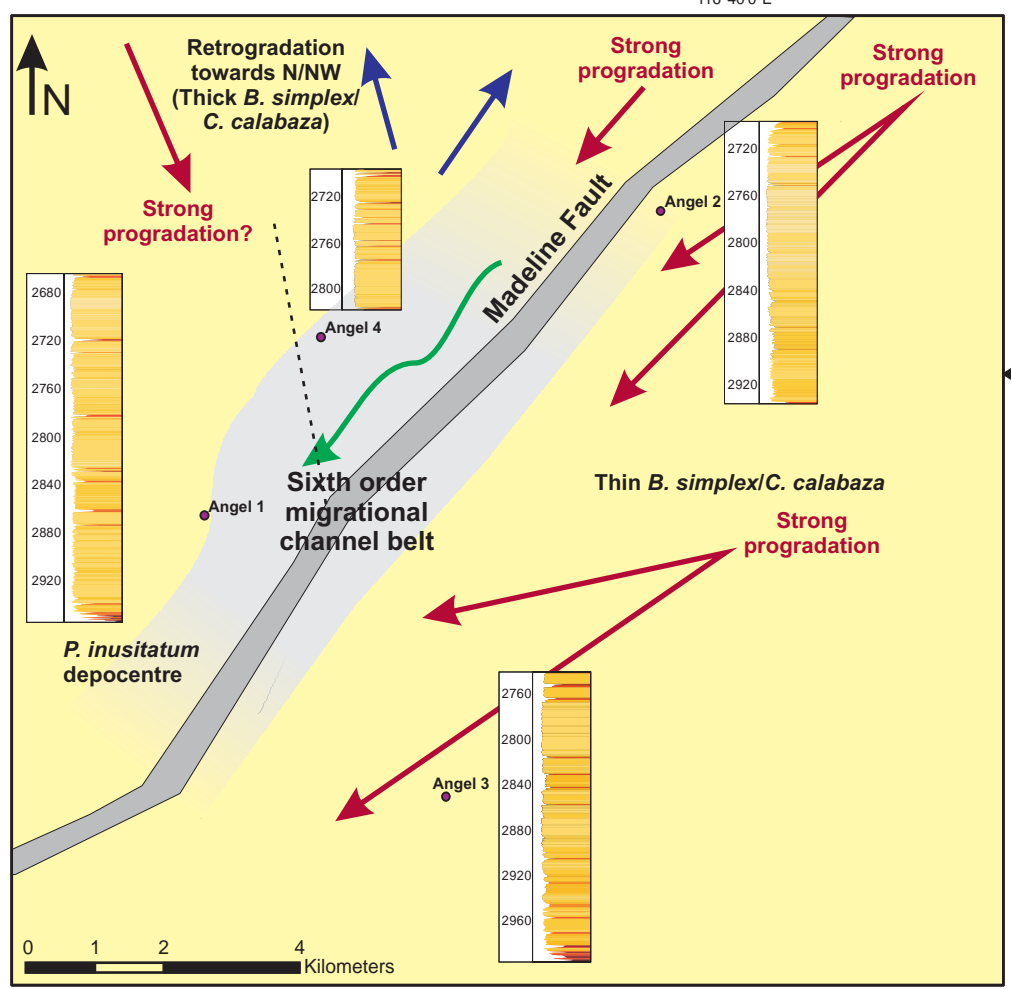
C.

Map of Upper *D. jurassicum* and *P. iehiense* sedimentation across the Angel region. Extremely high sedimentation rates result in the progradation of the system from the north, northeast and possibly northwest across the region. The presence of thinner beds within Angel-4 suggests it is located off-centre of the major sediment fairway located against the Madeline Fault.

Figure 8-40

Palaeogeographical maps highlighting the depositional evolution of fan systems across the Angel field.
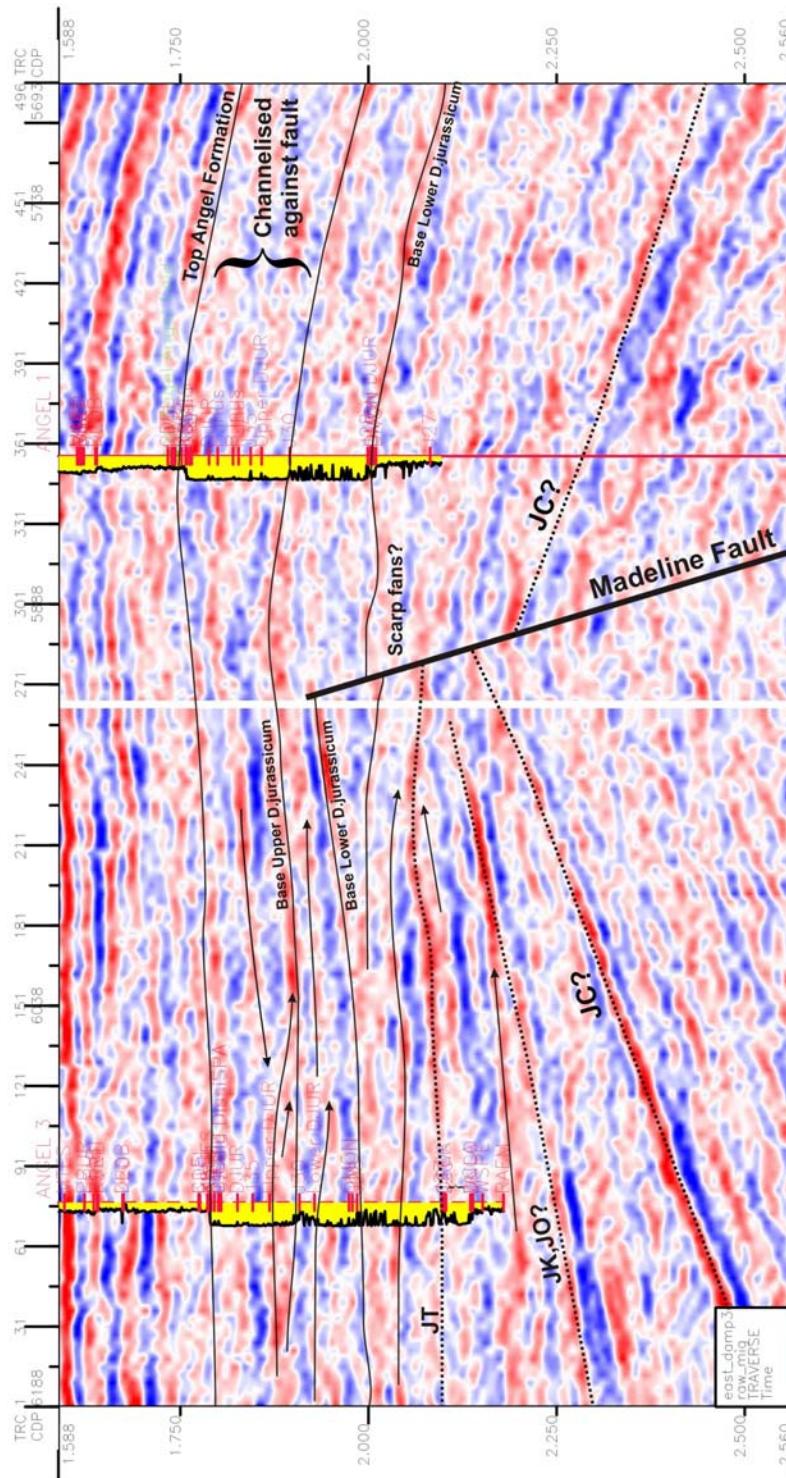
Figure 8-41: Seismic transect through Angel-3 and Angel-1 highlighting the onlapping nature of lower *D. jurassicum*, *O. montgomeryi* and *C. perforans* sediments from the east. It demonstrates that syn-depositional fault movement along the Madeline fault system occurred during the early Tithonian which resulted in further confinement of fan systems east of the fault. The regional Callovian (JC), Oxfordian-Kimmeridgian (JO-JK) and Tithonian (JT) unconformities are identifiable within the section.
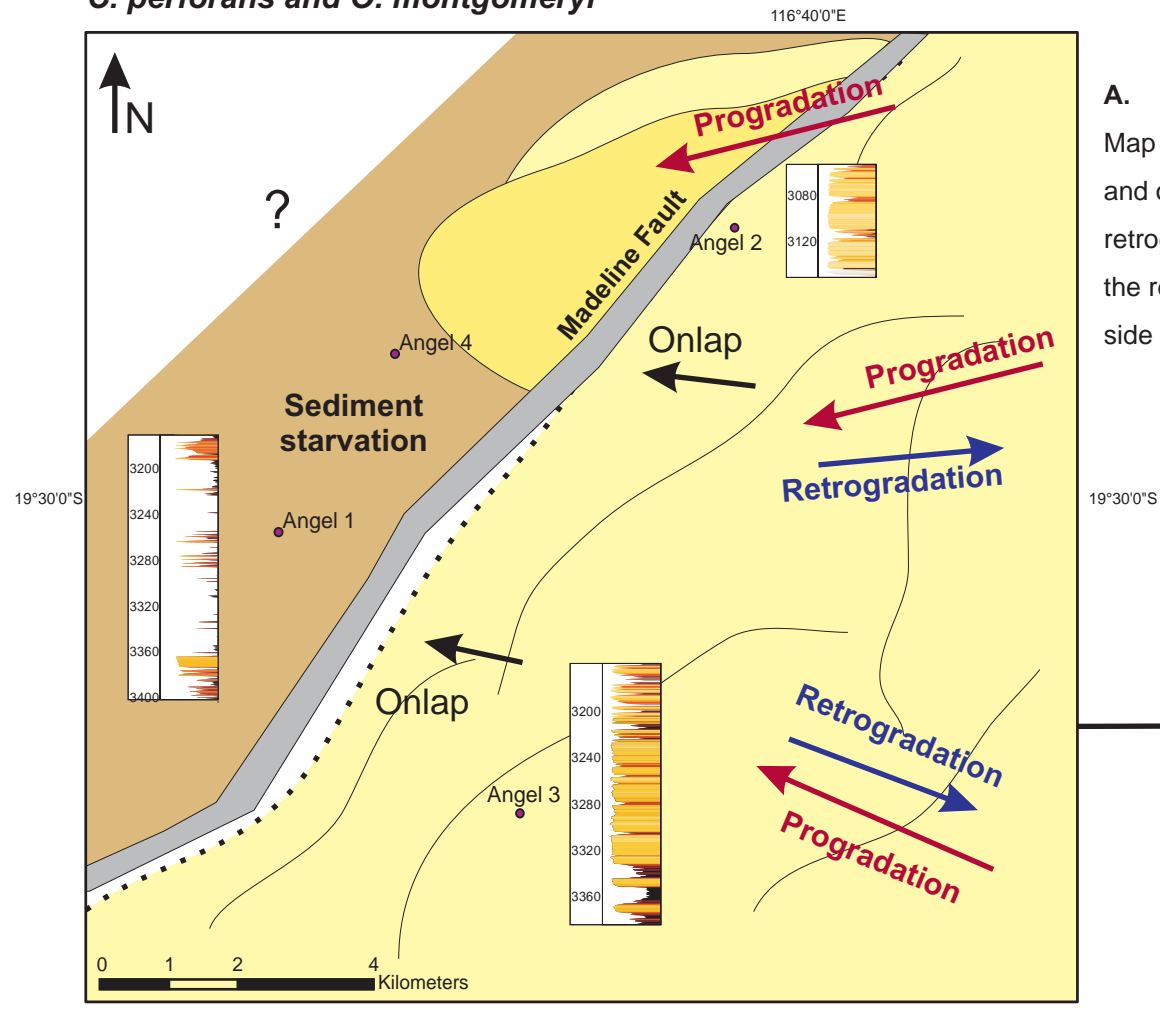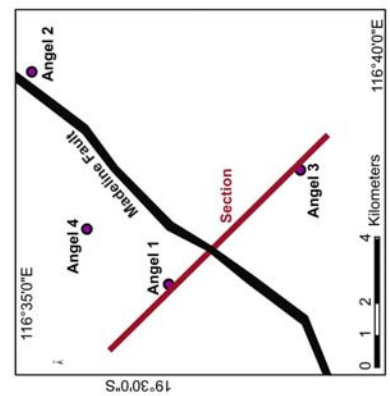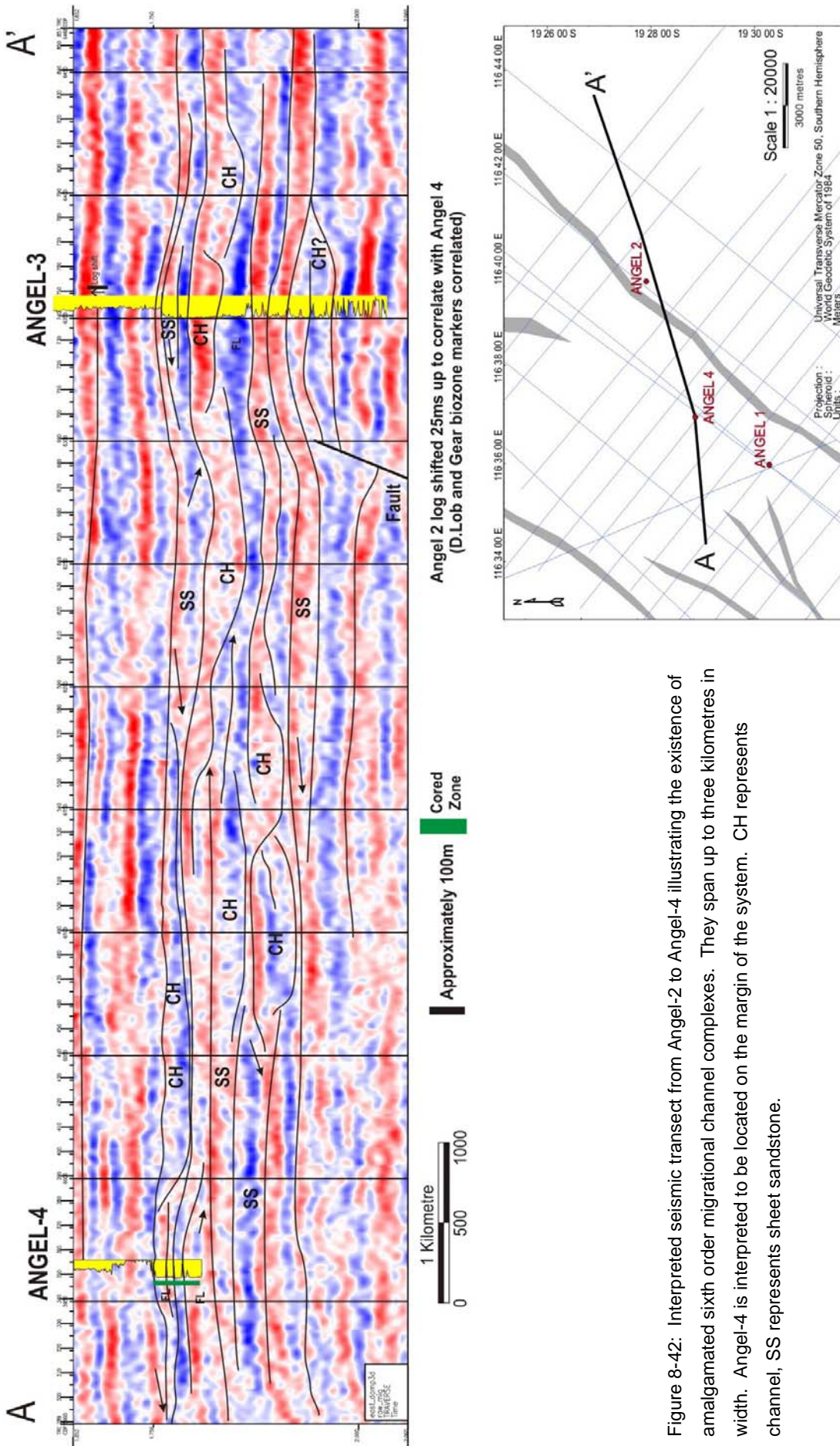
Figure 8-42: Interpreted seismic transect from Angel-2 to Angel-4 illustrating the existence of amalgamated sixth order migrational channel complexes. They span up to three kilometres in width. Angel-4 is interpreted to be located on the margin of the system. CH represents channel, SS represents sheet sandstone.

8.4.2.2 The Cossack and Wanaea Region

The Cossack and Wanaea fields are located downdip of the Angel field in the Dampier Sub-basin rift depocentre. They are situated within a seventh order medial to distal ramp setting. They contain 14 wells located along a section spanning 17 kilometres (Figure 8-43).
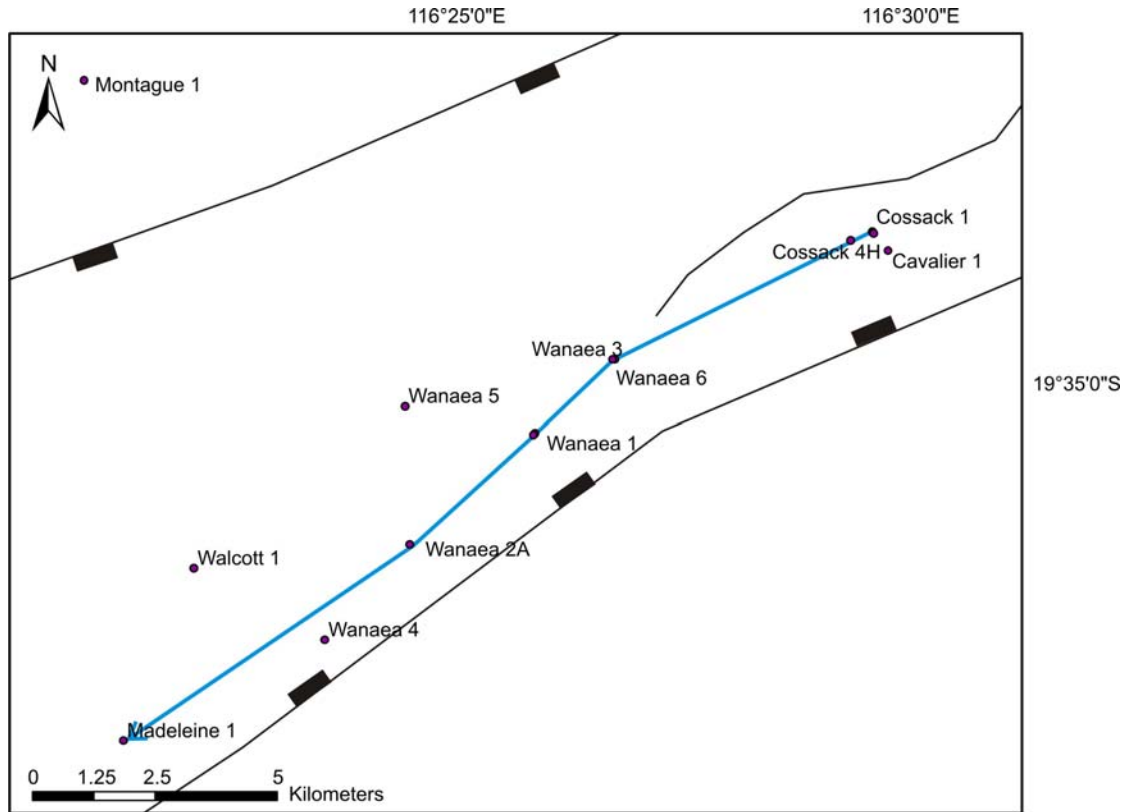
Figure 8-43: Map of the Cossack and Wanaea region. The fields are located along the inverted Madeline fault system.

From earlier architectural analysis (Chapters 5, 6 and 7), it was determined that:

- the depositional system is layered with common sand- and silt-dominated splays (based on core interpretation of Wanaea-2A and -3 (Appendix B));

- the dominant lithofacies associations are frontal splays with occasional channel fills (both axial and marginal);

- there are infrequent fourth order migrational distributary-sized channel elements, and;

- Models C, D and E overlain are the most common fifth order architectural packages. Models A and B were present in Wanaea-3 suggesting it is placed more proximal than Wanaea-2A. Due to the distal nature of the wells, differentiating between fifth and sixth order systems in core is difficult.

An interpreted biostratigraphic section through the two fields (Figure 8-44) highlights the distal nature of this system within the central Dampier Sub-basin. It shows the thinning of interbedded fifth order composite channel-splay and sheet systems bound by maximum flooding surfaces towards the

southwest. Relative lowstand events are interpreted to exist at the base of the lower *D. jurassicum*, upper *D. jurassicum*, *I. kondratjevii*, *Dissimulidinium* and *B. simplex* units (Figure 8-44). Cossack-1 is interpreted to be the most proximal well as it contains a high amount of channel amalgamation (Figure 8-44). Individual fifth order complexes ranging up to 20 metres thick suggest a strong presence of amalgamated distal to mid-fan distributary channel systems.

Progradation is interpreted to have occurred across this region primarily from the northeast during *O. montgomeryi* and *D. jurassicum* time. This led to the deposition of aggradational fifth order composite channel-splay and sheet complexes in Cossack-1, Wanaea-3 and Wanaea-1 (Figure 8-44). These units are interpreted to represent the point of maximum progradation of the seventh order fan system into the Wanaea region, which occurred during lower *P. inusitatum* time. Aggradation and retrogradational dominated the region after this point. Thin sheet complexes comprising stacked unchannelised sand-dominated splays exist across the region and where fifth order units exceed 10 metres in thickness, small (metre depth scale) distributary channel systems may have existed (Figure 8-44). The entire Tithonian system thins towards Madeline-1 in the southwest which contains sand-dominated unchannelised splay deposits.

8.5 Summary

Research into the evolution of fan systems across the western and central Dampier Sub-basin was carried out by comparing the architectural motifs created in Chapters 6 and 7 with wireline successions to form an electrofacies scheme. This scheme, in combination with palynology, cross-sections and seismic data, was used in an investigation into the evolution of Tithonian fan systems across the region. Further discussion of Tithonian stratigraphy and fan evolution along with related syn-depositional tectonism is covered in the next chapter (Sections 9.3 and 9.4 respectively).
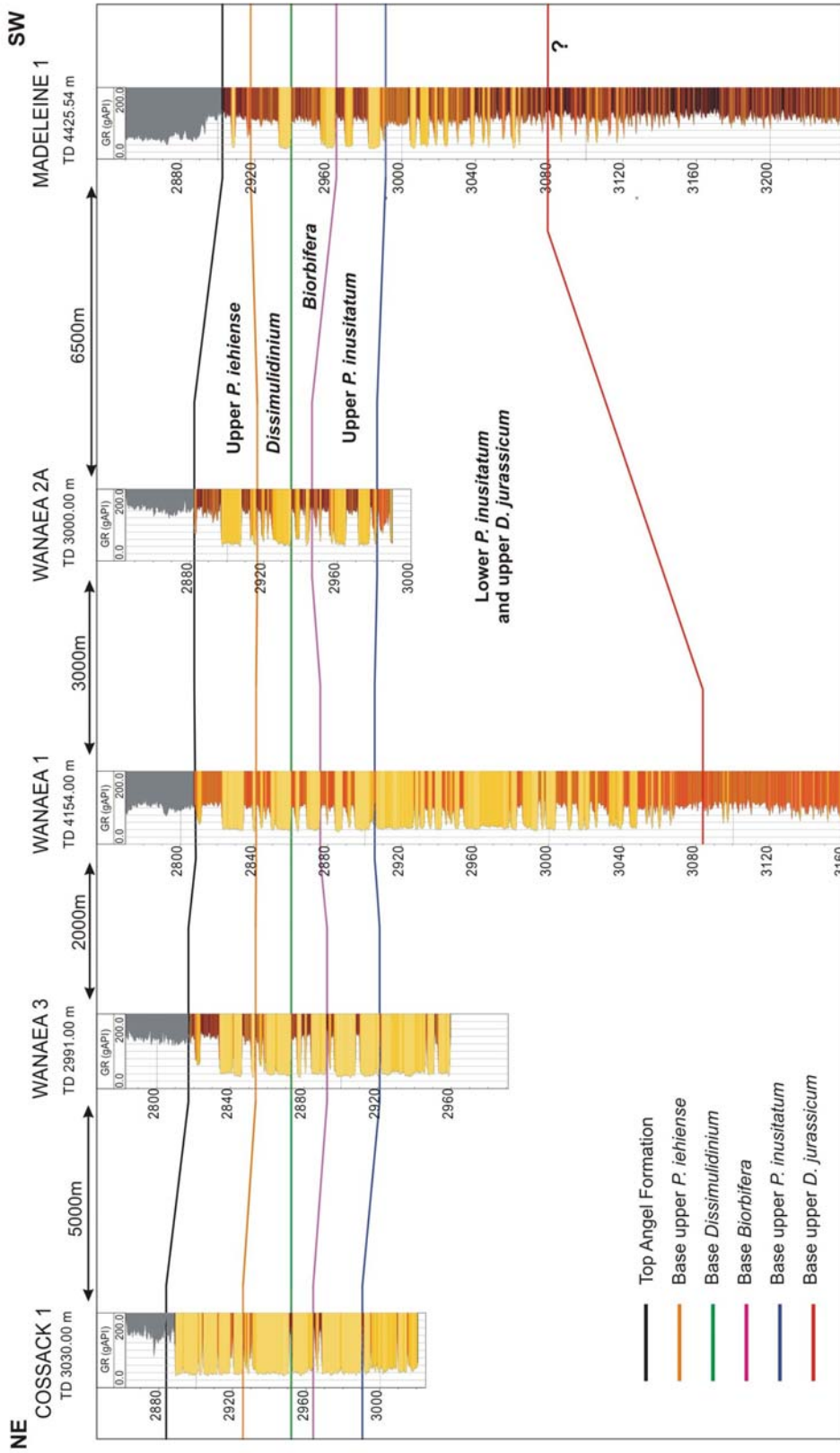
Figure 8-44: Interpreted biostratigraphic section from Cossack-1 to Madeline-1 illustrating the distal and layered nature of the depositional system within the central Dampier Sub-basin. Thinning of fifth order fan lobe systems bound by maximum flooding surfaces occurs towards Madeliene-1 in the southwest.

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9 Discussion

This study represents a fresh perspective into the sedimentological and architectural nature of the Tithonian depositional system that existed within the central and western regions of the Dampier Sub-basin. It has shown that the system can be broken into seven architectural orders ranging from core to basin scale that can used to investigate the fan evolution. This chapter contains a discussion of key outcomes determined through this research. It incorporates previous basin research from literature and addresses the implications it may have on future exploration and development within the sub-basin.

9.1   Sedimentological Process Model for the Angel Sandstone

Core and lithofacies interpretation in Chapter 5 demonstrated that the unstructured and homogenous sandstones of the Angel Formation were most likely deposited through the continuous aggradation of quasi-steady fluidised high density turbidity flows as suggested by Kneller and Branney (1995). These sand-rich gravity flows are fluidised and stratified high density turbidity currents that are strongly comparable with other classifications such as density concentrated flows (Mulder and Alexander, 2001) and densites (Gani, 2004). There are many sedimentological features that support this interpretation.

i. The existence of parallel consolidation laminae throughout the sandstone. Laminae are not always identifiable in core. Comparative analysis of core with borehole image data from Mutineer-1B (Appendix B) demonstrated that cored intervals of sandstone that appear structureless to the naked eye are, in fact, stratified with bed thicknesses ranging from 10 to 50 centimetres thick (Figure 8-14).

ii. The occasional identification of small intervals of clasts and laminae deposited by waning flows throughout homogenous sandstone units (i.e. Figures 5-9 and 5-10).

iii. The rarity of large-scale slump successions. Small remobilised hybrid flow-like units are common in Egret-2, Lambert-2, Exeter-5ST1 and Spica-1 (Lithofacies K Section 5.5.5). They are less than one metre thick and overlie homogenous and dominantly unstructured sandstone intervals.

Stratification forms within homogenous sandstones that are deposited by aggradational high density turbidity flows through either fluctuations in downward grain flux, flow unsteadiness (pulsing flow), heterogeneities in grain-size (Kneller and Branney, 1995) or by the simple stacking of small-scaled individual flow events.

The existence of stratification within the cores suggests that sandstones of the Tithonian Angel Formation were not deposited by sand-dominated debris flows. This statement, however, does not signify that these flows may not have existed within the entire region. Resultant deposits from these flows may exist against fault scarps of the Rankin Platform. Several of the aggradational high density turbidity events that deposited the Angel Formation sandstone may have transformed from slope

failures and sand-dominated debris flows (or hyperconcentrated density flows as suggested by Mulder and Alexander (2001)) (Figure 9-1). Sand-dominated debris flows could have occurred during *Dissimulidinium* and upper *P. iehiense* time. High sediment flux and accommodation in relation to a transgressive sea may have occurred within upslope fault systems, especially if was connected to a fluvio-deltaic system. Oversteepening of sediment in combination with a possible tectonic event could result in a sand-dominated slump or debris flow event (Figure 9-1).
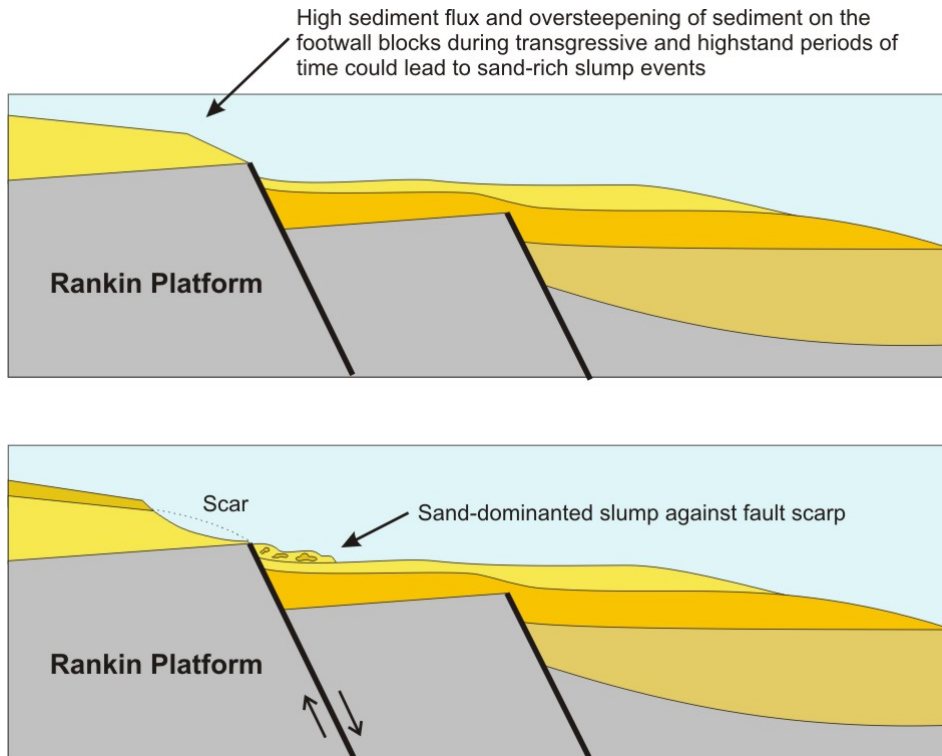
Figure 9-1: Initiation of a sand-dominated slump or debris flow off the Rankin Platform. These slump events may have occurred during Late Tithonian time as oversteepening of sediment occurs within oblique fault systems and relays in relation to a rising eustatic or relative sea-level.

9.2 Depositional Systems of Mutti (1985) - Reclassification of the Tithonian System

This study has revealed that the degree of channelisation within the Tithonian interval of the Angel Formation has been previously underestimated in previous literature. Barber (1994a; 1994b) interpreted that the channelised lobes that existed in the Dampier sub-basin during early Oxfordian time were replaced by more widespread, massive, detached, non-channelised lobes interpreted to compare with a Type 1 system (Mutti, 1985) during Tithonian time (Figure 9-2). This study has recognised that the Tithonian interval of the Angel Formation along the central and western regions of the basin is more accurately represented by a Type 2 system (Mutti, 1985) that comprises channel forms that pass into attached lobes. Clear evidence for this conclusion includes:

- occasional erosive bases in core indicative of channelisation;

- thick lag deposits in Angel-4 and Lambert-1, and;

- visible channel-like seismic features in the Angel field. Many other channel forms would be below seismic resolution and therefore not imaged.

This interpretation is also supported by the aggradational post-rift and transgressive nature of the Dampier sub-basin during Tithonian time. Some flow events may have been fuelled by upslope failure events triggered by tectonic activity or high sediment flux (as discussed in Section 9.1), however it is interpreted that some flow events may have also been sourced from a fluvio-deltaic system situated on either the Rankin Platform or within the eastern Beagle Sub-basin. A dominant third-order eustatic transgressive system controlled much of the Tithonian depositional system resulting in the overall deposition of Type 2 systems in the sub-basin. The retrogradational nature of the fan systems towards shelfal regions in connection with the third-order eustatic sea-level rise is interpreted within the Mutineer/Exeter, Wanaea/Cossack, Egret and Lambert regions after *P. inusitatum* time.

Barber (1994a; 1994b) based his conclusion of a Type 1 system primarily on a seismic reflection dataset. This would have introduced bias as the interpretation is based on the recognition of seismically resolvable features. As channel forms and mounded seismic facies were not often recognised in the Angel Formation, a Type 1 classification was applied. This study has demonstrated, through core interpretation that most channel forms and their fill are not seismically resolvable features. They would have to exceed 30 to 50 metres in thickness to be identified in seismic. In addition to this, these sand-filled channel forms often eroded into sand-dominated progradational splay systems, resulting in poor seismic impedance contrast between channel and splay features. Without significant seismic impedance contrast, differentiating between these features and interpreting them would be impossible.

The adoption of the Type 2 model of Mutti (1985) as opposed to the Type 1 model would incorporate a greater extent of sand-on-sand amalgamation through channelisation into reservoir models. This would result in an improved estimation of connectivity between reservoir units.
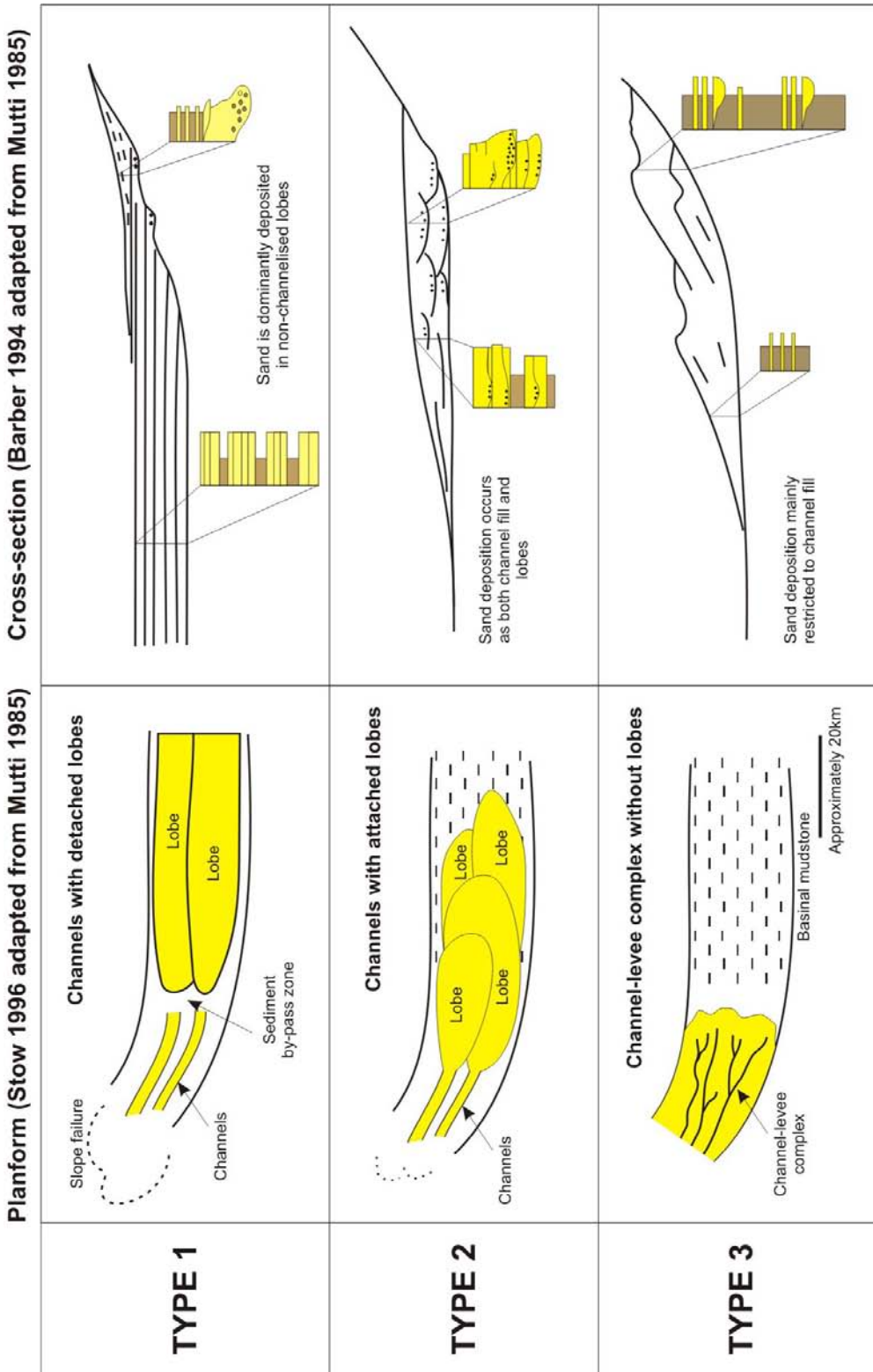
Figure 9-2: Plan and cross-sectional views of the three main types of depositional systems of Mutti (1985). Previous research conducted by Barber (1994a; 1994b) on the Dampier Sub-basin classified the Tithonian system as Type 1. This research has shown that the system is better represented by Type 2 has it comprises both channel fills and lobes.

9.3   Tithonian Stratigraphy and Fan Evolution

The sixth and seventh order stratigraphic style of the Tithonian interval of the Dampier Sub-basin within five individual field regions was discussed in Chapter 9.   This section discusses fan evolution and stratigraphy within a greater regional context.

9.3.1 Parker Terrace

Analysis of fifth and sixth order architectures in three differing regions across the Parker Terrace demonstrated that multiple fan systems evolved along the Rankin Platform during Tithonian time. These fan systems are interpreted to be small, ranging from 10 to 15km in size, which may coalesce against one another. They form a seventh order system that is best described as a curved system comprising of north and northwestern sourced coalescing fans as classified by Mattern (2005) (Figure 9-3).
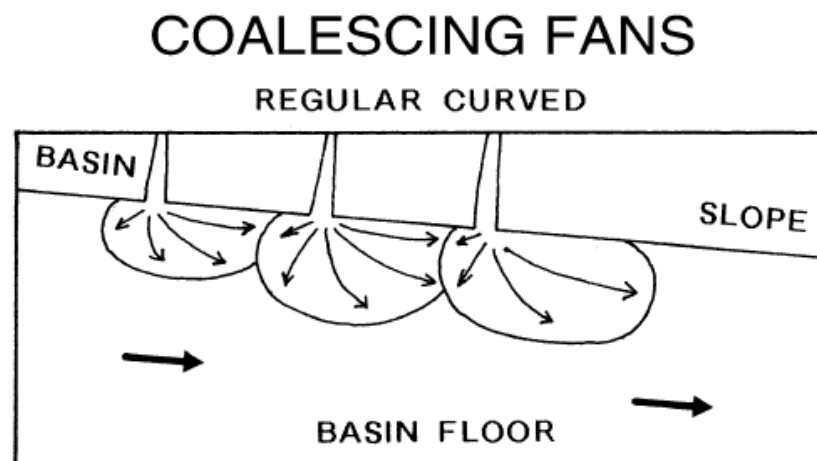
Figure 9-3: Differing sand-dominated submarine fan systems in plan view (modified from Mattern, 2005). The fan systems evolving off the Rankin Platform are interpreted to form a curved system trending towards the southeast. This trend was recognised in the Lambert region. This model indicates the existence of a seventh order basinal gradient towards the southwest.

The Parker Terrace experienced high sediment flux from lower *D. jurassicum* to upper *P. inusitatum* time. This resulted in strong progradation of sixth order systems towards the southeast, which are separated by interpreted lowstand events primarily related to a fourth or fifth order magnitude fall (Section 2.5.3) (Table 9-1 next page):

Table 9-1: Lowstand events identified along the Parker Terrace. It shows that many of the lowstand events were regional across the Parker Terrace. Non-regional events could be localised abandonment related to variation in sediment supply or autocyclic switching of the fan system.

Relative Lowstand Event	Field region/s where the event was recognised
Base *O. montgomeryi*	Lambert (regional?)
Base lower *D. jurassicum*	Egret-Montague and Lambert?
Base upper *D. jurassicum*	All three regions (regional lowstand)
Base *Egmontodinium*	All three regions (regional lowstand)
Intra P. inusitatum	Mutineer (local variation)
Base *I. kondratjevii*	All three regions (regional lowstand)
Base *Dissimulidinium*	All three regions (regional lowstand)
Base *B. simplex*	Egret-Montague and Lambert only. Fan systems around Mutineer were abandoned by this time.

Transgression in relation to basin subsidence and a rising relative sea-level (third order sea-level cycle magnitude (Table 2-3)) resulted in a change from progradational fifth and sixth order systems along the Parker Terrace during *P. inusitatum* time to large aggradational and retrogradational fifth and sixth order systems during *Biorbifera* to upper *P. iehiense* time. This change was also documented by Miller (1996). Fan systems around the Mutineer region were the first to be abandoned with transgression as no upper *P. iehiense* sedimentation was preserved and *Dissimulidinium* sedimentation was sourced purely from the west (Figure 8-27). Both the Egret and Lambert regions received sedimentation during upper *P. iehiense* time, however, retrogradation of the fan systems during this time is clearly demonstrated (i.e. no preserved upper *P. iehiense* sedimentation in Montague-1 (Figure 8-30)).

9.3.2 Central Dampier Sub-basin

Analysis of fifth and sixth order architectures in the Angel, Cossack and Wanaea regions across the central Dampier Sub-basin has demonstrated that basinward thinning occurred towards the southeast from the northern regions during Tithonian time (Figure 8-44). This gradient is supported by the Parker Terrace fan systems that curve and prograde towards the southeast (Figure 9-3).

Sedimentation within the Angel region was dominantly sourced from the Legendre Trend in the east during *C. perforans* and *O. montgomeryi* time (Figure 8-40A). This area, along with the Cossack and Wanaea region, went on to experience high sediment flux and strong progradation towards the south and southeast during *P. inusitatum* time. This was interpreted to be due to a lowstand event that occurred during *Egmontodinium* time. Miller (1996) also supported this progradational direction from the north and interpreted it to have commenced during lower *D. jurassicum* time. This unit

(*P. inusitatum*) is interpreted to represent the point of maximum progradation of the seventh order fan system (Figure 9-4) and is correlatable to the interpreted lowstand events, high sediment influx and strong progradation of the upper *D. jurassicum* and *P. inusitatum* systems along the Parker Terrace (Section 8.4.1). Visible retrogradation of sixth order complexes in the Wanaea and Cossack fields in relation to Late Jurassic transgression commenced during *Biorbifera* time (Figure 8-44). This resulted in the formation of thick aggradational and retrogradational packages in the Angel region as large sixth order migrational channel complexes started to infill and aggrade.

NOTE:
This figure is included on page 249 of the print copy of the thesis held in the University of Adelaide Library.

Figure 9-4: Model highlighting the progradational, aggradational and retrogradational systems of the Central Dampier. The dominant change from progradational to retrogradational sedimentation occurred during *P. inusitatum* time. This change is also recognised in Tithonian systems along the Parker Terrace (adapted from Hodgson *et al.,* 2006).

The central Dampier Sub-basin fan system is interpreted to be a large seventh order fan system up to 50 kilometres in length spanning the Oxfordian and Tithonian. It received very high sediment influx from a northeastern source. The identification of large sixth order migrational channel complexes up to three kilometres wide and 300 metres deep in the Angel region (Figure 8-42) represent a major conduit for sediment input into the Angel, Cossack and Wanaea regions. They are interpreted to have existed from upper *D. jurassicum* to upper *P. iehiense* time, allowing gravity flows to bypass the Angel region and deposit downslope in the Cossack and Wanaea regions during times of relative lowstand. These lowstand events are interpreted to be primarily caused by a fourth or fifth order relative sea level magnitude fall (Section 2.5.3) include (Table 9-2 next page):

Table 9-2: Interpreted lowstand events within the Central Dampier Sub-basin with comparison to those identified along the Parker Terrace. Many of the lowstand events are regional across the western Dampier Sub-basin. Non-regional events could be localised abandonment related to variation in sediment supply or autocyclic switching of the fan system.

Relative Lowstand Event	Central Dampier region/s where lowstand event was recognised	Parker Terrace region/s where lowstand event was recognised
Base *O. montgomeryi*	Angel only (Wanaea wells reached TD before intersecting the event).	Lambert
Base lower *D. jurassicum*	Angel and Wanaea	Egret-Montague, Lambert?
Base upper *D. jurassicum*	Angel (distal deposition only in Wanaea)	All three regions (regional lowstand)
Base *Egmontodinium*	Angel and Wanaea	All three regions (regional lowstand)
Base *I. kondratjevii*	Wanaea and Angel (?)	All three regions (regional lowstand)
Base *Dissimulidinium*	Angel and Wanaea	All three regions (regional lowstand)
Base *B. simplex*	Angel and Wanaea	Egret-Montague and Lambert only. Fan systems around Mutineer were abandoned by this time.

Regional lowstand events across the central and western Dampier Sub-basin are interpreted to have occurred at the base of the upper *D. jurassicum*, *Egmontodinium*, *I. kondratjevii*, *Dissimulidinium* and *B. simplex* times. It demonstrates that the Mutineer fan system was the only one to shut down early during *B. simplex* time, suggesting that sediment may have been rerouted elsewhere.

It is interpreted that some sediment was delivered to the Wanaea-Cossack region from the Parker Terrace, which was found to contain primarily distributary and mid-fan sized channel systems up to 500 to 700 metres wide, forming fan systems up to 10km in size. Sedimentation in the Wanaea region, which is located approximately 10 kilometres from Montague-1 and 8 kilometres from Lambert-5, may have been partially sourced from the coalescing fans in the Egret-Montague and Lambert regions during maximum fan progradation at *P. inusitatum* time.

9.4 Influence of Syn-Depositional Tectonism

9.4.1 Lithofacies Distribution

Syn-depositional tectonic activity within the Angel field occurred primarily during *C. perforans*, *O. montgomeryi* and *D. jurassicum* time, resulting in the ponding of sediments on the eastern side of the Madeleine Fault (Figure 8-41). This outcome correlates to that of Miller (1996) who stated that tectonism had a greater influence on stratigraphic development than eustacy within the immediate post-rift system (*W. spectabilis* (base Kimmeridgian) to middle *O. montgomeryi*).

Pryer *et al.,* (2002) interpreted the occurrence of block rotational event during Tithonian time along the Rankin Platform, suggesting rotation and inversion of northwest trending Permian transfer faults. Northward tilting of the blocks resulted in reactivation of Jurassic transfer faults, producing either footwall inversion or normal fault movement. This further resulted in the generation of depocentres within downthrown grabens. As many of the fields in the northwestern Dampier rest within complicated structural zones that underwent transpressional movement during the Middle Jurassic, it is interpreted that fault movement may have occurred during Tithonian time in relation to the block rotational event of Pryer *et al.,* (2002). This movement may have been concentrated along the western margin of the Dampier Sub-basin, resulting in *Biorbifera* and *Dissimulidinium*-aged tectonism in the Lambert and Mutineer regions.

Biostratigraphic data suggests that episodes of sediment starvation on rotated footwalls highs may have occurred between *C. perforans* and lower *D. jurassicum* time (Mutineer and Lambert regions) and during *Biorbifera* (Mutineer and Lambert regions) and *Dissimulidinium* time (Mutineer region). Fault control is interpreted to have led to the concentration of channel complexes against footwall scarps which could further lead to fault-related flow stripping on the uplifted footwall (Figure 9-5).

NOTE:
This figure is included on page 251 of the print copy of
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Figure 9-5: Schematic block diagram illustrating the interpreted impact of syndepositional faulting on gravity flow deposition in the Mutineer region. The model is adapted on that of Hodgson and Haughton (2004) which is modelled on the El Cautivo fault zone, SE Spain. It demonstrates the influence of normal fault movement on channel locations and localised accommodation space.

9.4.2 Location of Feeder Systems into the Sub-basin

Slope and basin floor feeder localities can be controlled by tectonism. There are two recognised varieties of fault-controlled feeder pathways in the Dampier Sub-basin. They are:

- hanging wall feeder systems, and;

- fault relay feeder systems.

Hanging wall feeder systems were interpreted to exist in the Angel region. The location of the Madeleine Fault controlled the downslope propagation of the sixth order migrational channel complex where slight movement along the fault during *D. jurassicum* time is interpreted to have initiated the pathway. Continued infilling and reincision of the channel complex over time resulted in the migration of individual fifth order composite channel systems across and against the scarp (Figure 8-42). This fault control on pathway propagation suggests that any future exploration of inverted structural highs along this fault have a good chance of intersecting reservoir units comprising channelised features if the fault was slightly active during Tithonian time. Exploration along the Madeline fault system towards the Beagle Sub-basin could identify larger-scaled channel and canyon features.

Fault relay systems along the Rankin Platform, as suggested by Stein (1994), are interpreted to control sediment pathways into the basin from the western margin. Channelised systems in the Egret field region were interpreted to be concentrated within the downthrown segment of the relay against the scarp of the footwall (Figures 8-31 and 8.32). Sand-dominated slumps as described in Section 9.1 may also be present. Due to the presence of the Valanginian disconformity that separates Aptian sediment from Triassic sediment in Eaglehawk-1, it is impossible to state if a fluvio-deltaic or a shallow marine system existed on the Rankin Platform during this time (Figure 8-31). Comparable fault relay-related feeder systems have been interpreted along the Helmsdale fault within Kimmeridgian successions of the North Sea (Pickering, 1984, Wignall and Pickering, 1993, Underhill, 1994) (Figure 9-6 next page).

A.

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the thesis held in the University of Adelaide Library.
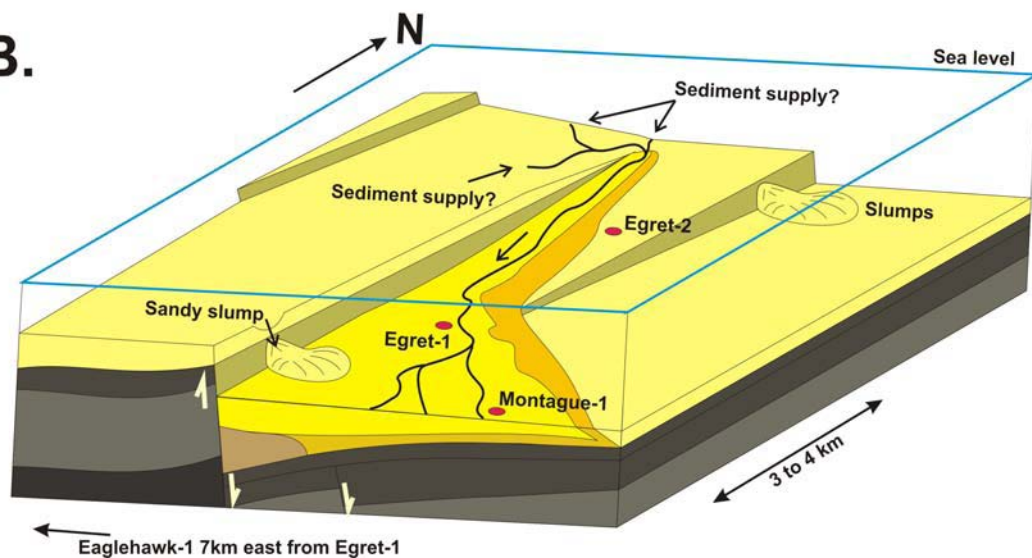
Figure 9-6: Comparative fault relay feeder models from the Helmsdale fault region of the North Sea (Underhill, 1994) (A) and the Egret region of the Dampier Sub-basin (B). The Dampier Sub-basin model differs from the North Sea model as it is completely submerged and is interpreted to exist during a post-rift setting where significant basin infilling has already occurred. This setting leads to the deposition of thick sandstones on relay zones during retrogradation. If sediment becomes unstable through high sediment flux or tectonics, sand-rich slumps can occur down the scarp (Section 9.1).

9.5 Post-depositional Injectites: Varieties, Models and Implications

Worldwide research has demonstrated that sandstone fluidisation and injectite features through low permeable units can influence overall reservoir distribution, volumetrics, pore-scale reservoir properties, hydrocarbon recovery and enhance connectivity between isolated reservoir units (Figure 9-7) (Jenssen *et al.,* 1993; Timbrell, 1993; Lonergan and Cartwright, 1999; Duranti *et al.,* 2002; Hurst and Cartwright, 2007 and Jackson, 2007)

The effect of small scale injectites on reservoir performance are becoming increasingly evident from field studies on the Balder, Jotun and Alba fields (Bergslien, 2002; Duranti *et al.,* 2002; Guargena *et al.,* 2007). Analysis on the style of injectites in the western Dampier region is critical in order to predict their influence on reservoir performance.

Two varieties of injectites are recognised within the western Dampier region. They include:

- Lateral injectites that are present in overbank and levee successions adjacent to slope and proximal fan channels, and;

- Polygonal fault injectites that invade sealing lithologies overlying reservoir zones.

NOTE:
This figure is included on page 254 of the print copy of the thesis held in the University of Adelaide Library.

Figure 9-7: Influence of sediment overpressure, remobilisation and injection on reservoir geology (Lonergan *et al.,* 2000).

9.5.1 Lateral Levee Injectites

The lateral placement of sandstone injection features adjacent to a sandy feeder complex has been recognised in outcrop from Californian Miocene sediments in the United States (Hurst *et al.,* 2003), the Late Jurassic Hareelv Formation in Greenland (Surlyk, 1987) and the Vocontian blue marls formation in France (Parize *et al.,* 2007) (Figure 9-8). Lateral injectites are identified within Angel Formation on the margins of channel complexes in the Egret, Lambert and Wanaea field regions.

NOTE:
This figure is included on page 255 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 9-8: Lateral injectites into overbank units adjacent to a channel form from the Vocontian blue marls formation in France (Parize *et al.,* 2007). Injectites can propagate over hundreds of metres from the channel feature.

Understanding the effect of injectites located in channel-levee system on the resultant architecture and reservoir volume is essential for field development. Jackson (2007) recommended the following architectural aspects should be taken into consideration when analysing the distribution of injectites adjacent to a slope feeder system.

    i. The largest clastic dikes form at the margins of the depositional system from which they are sourced.

    ii. Elongated alignment of channel-margin clastic dikes occurs along the slope channels.

    iii. Injectites have a preferred alignment parallel to the margins of the slope channel where they are developed above the channel axes.

9.5.1.1 Egret Field Lateral Injectites

Egret-1 and -2 represent a central channel axis and margin system respectively that existed during *P. iehiense* time (Section 8.4.1.2). Preserved injectites within Egret-2 are interpreted to have been laterally sourced from the Egret-1 central channel system where overpressure existed in relation to increasing burial (Figure 9-9). The injectites present in Egret -2 are ptygmatic in nature, suggesting that overpressure occurred during early burial.
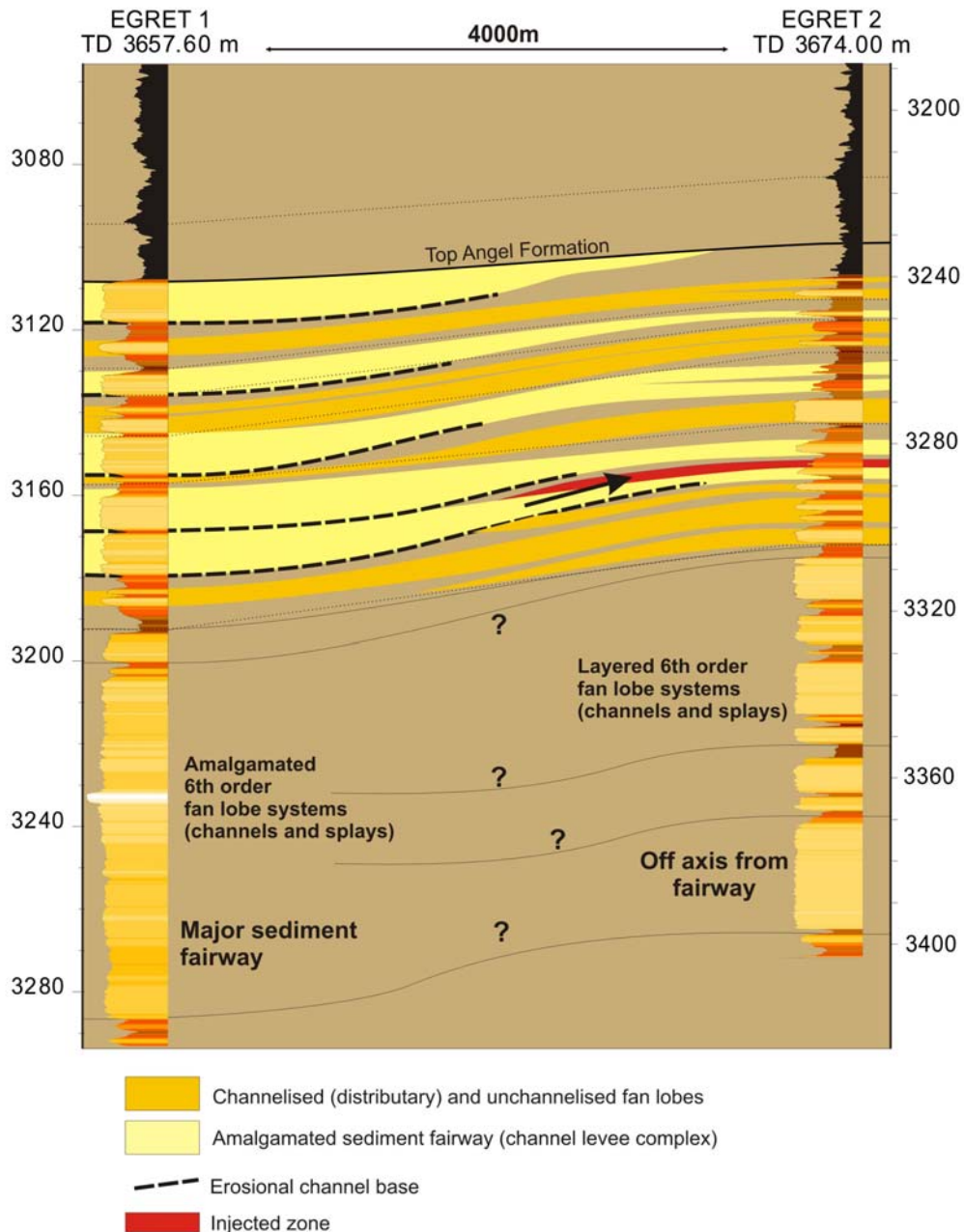
Figure 9-9: Section through Egret-1 and 2 demonstrating the change from a dominantly channelised system (Egret -1) to an off-axis channel margin and splay system (Egret-2) that existed during *P. iehiense* time. An injected zone over 1 metre thick present within Egret-2 is interpreted to have been laterally sourced from overpressured sandstones within the Egret-1 channel systems.

9.5.1.2 Lambert Field Lateral Injectites

Injectites are interpreted to occur in the Lambert field within abandoned and overbank heterolithics that are located adjacent to a channelised fairway of upper *P. inusitatum* and *Biorbifera* age (Section 8.4.1.3) (Figure 9-10). Lambert-2 and -3 were located off-axis of a channelised fairway which continued to deposit sediment downslope in Lambert-1, -4, -5 and -5ST1 (Figure 8-36). Core from Lambert-2 revealed injectites, which are larger and more sharp-sided in comparison to the ptygmatic injectites identified within Egret-2. This suggests a later stage of injection at deep burial that may have been influenced by the existence of polygonal faulting within the unit (Figure 9-11).

Duranti *et al.* (2002) suggested that the existence of remobilised sandstones could be analysed using sonic and density logs as tested on the Nauchlan Member of the Alba Field, North Sea. He found that remobilised sediments can demonstrate a combined higher average bulk density (RHOB) and faster acoustic velocity (DT) than their depositional counterparts (Figure 9-12). This method was applied to the lateral injectites within Lambert-2 with success when correlated with core (Figure 9-13). When it was not correlated with core, the method was found to be inconsistent. It was recognised that not only do the sonic and density logs identify sediments affected by post-depositional fluidisation, but they can also identify sediments that were affected by the immediate dewatering of flows as they were deposited (i.e. dish and pipe structures) (Figure 9-13). These features are very common in progradational and retrogradational splay and sheet systems (i.e. Lambert-2, Wanaea-2A and -3). Sediments within progradational and retrogradational splays also typically comprise a finer grain-size (tighter grain packing) and contain organic fines (which can become pyritised with increasing burial). Both these features can affect the sonic and density logs. It was found in the Lambert field that dish and pipe-structured sandstones can produce log signatures at the base and top of sandstone units that can be misinterpreted as post-depositional fluidisation as described by Duranti *et al.,* 2002 (Figure 9-13).

This method clearly demonstrates that the sandstone unit in Lambert-3, which is correlatable to the injected zone in Lambert-2, is depositional and not injected. This signifies that the injection processes that occurred within Lambert-2 are local (Figure 9-14). Based on the predictive suggestions of Jackson (2007), it could be interpreted that Lambert-2 was more proximal to the channelised fairway than Lambert-3 (Figure 9-14).
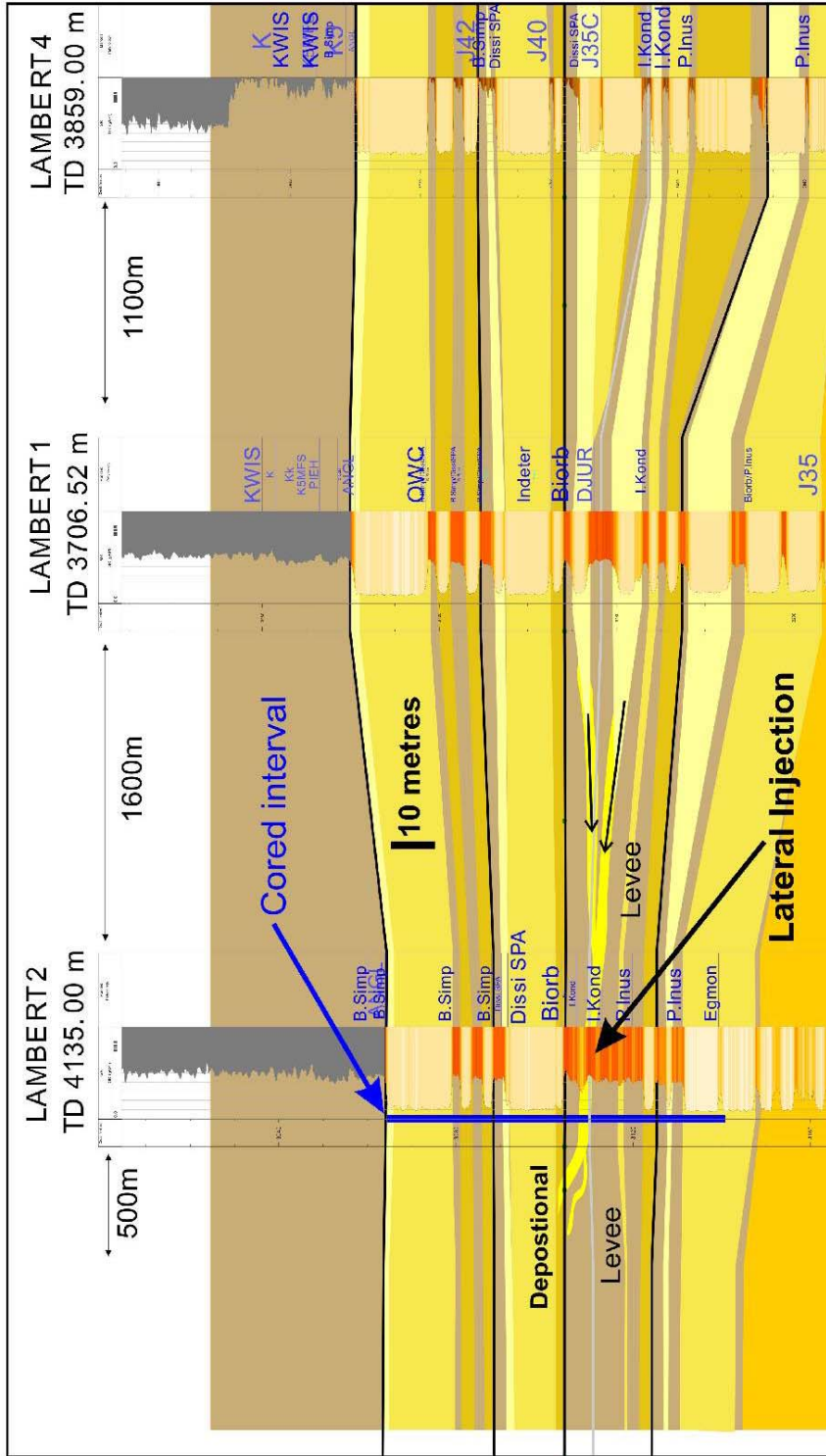
Figure 9-10: Biostratigraphic section through the Lambert field highlighting the injected zones and their location within the overall stratigraphic framework (injected zones in red). It is interpreted that the injectites are local to Lambert-2 only.

Lambert 2 core (3105.5m)

Figure 9-11: Hydrocarbon saturated lateral injection features from Lambert-2 (fluorescence photo from Woodside, 1996). These features may increase vertical and lateral connectivity and act as thief zones. The fluorescent core photo was taken on the opposite slab to the plain light photograph.

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This figure is included on page 259 of the print copy of the thesis held in the University of Adelaide Library.

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This figure is included on page 260 of the print copy of
the thesis held in the University of Adelaide Library.

Figure 9-12: Cartoon demonstrating the variation in sonic and formation density data between deformed and undeformed sediments (from well 16/26-15 Alba Field taken from Duranti *et al.,* 2002). The concept of the increased log signatures is sound when correlated with core but should be used with caution. Due to the presence of pyrite and sporadic dolomite cement in the Dampier Sub-basin, the method can not be used confidently. Based on the established architectural models, a similar log signature to the one above exists within the progradational and retrogradational successions of fan development. It could be mistaken for fluidisation as it also represents the cementation of finer grained clastic material (tighter packing) and the presence of fines.
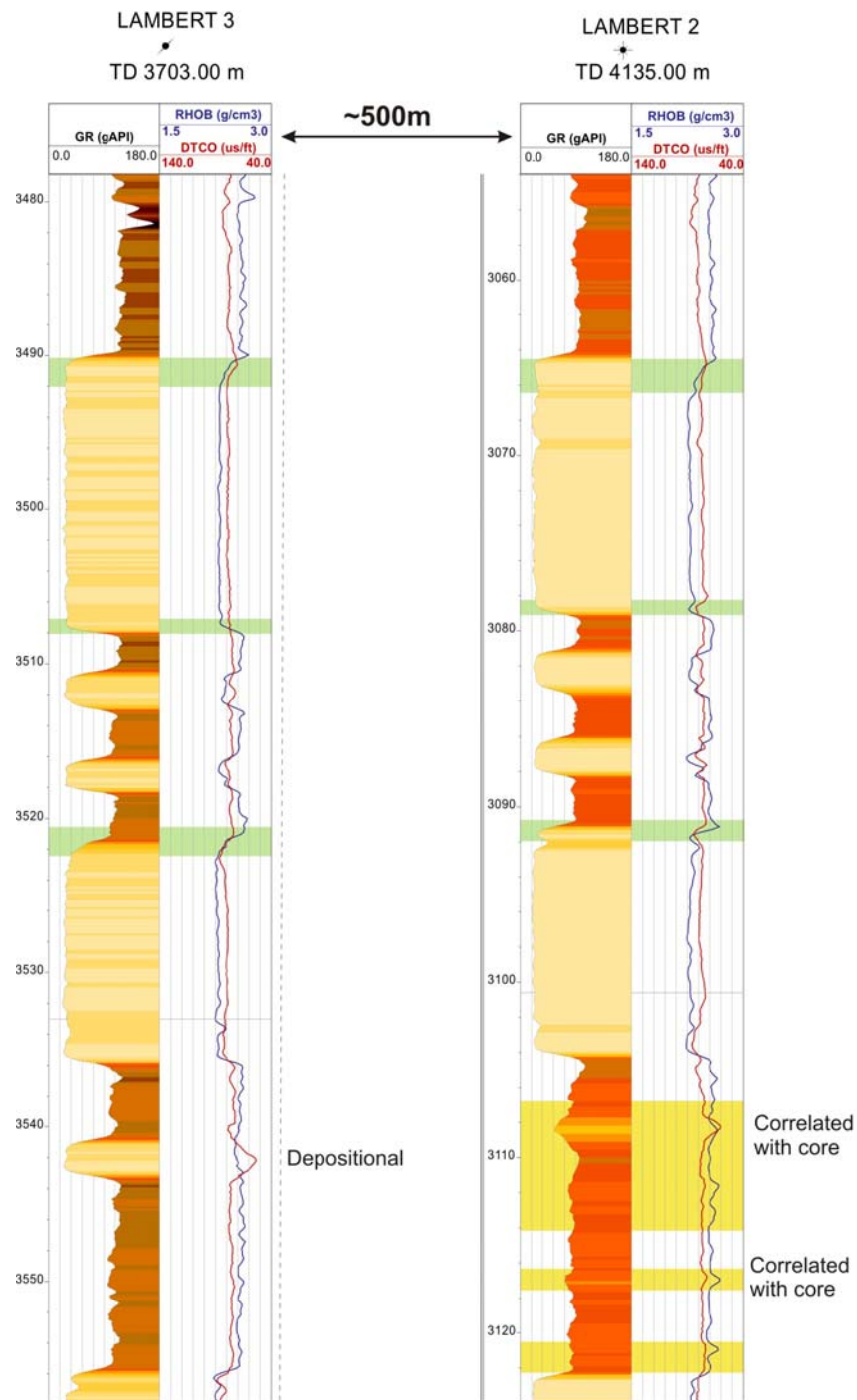
Figure 9-13: Sonic and formation density logs over the fluidised and injected zone in Lambert-2 correlated to Lambert-3. The injected zones (shaded in yellow) are compared with core. They show a clear sharp increase in both formation density and sonic that represents injected zones. The correlatable sandstone in Lambert-3 is depositional, shown by the opposite directional parting of sonic and density logs. This suggests that the injection activity in Lambert-2 was localised only to that well. Other areas in the logs which could be mistaken for post-depositional fluidisation are shaded in green. The density and sonic log response in these zones are interpreted to be the signatures from dish and pipe structures that formed through the immediate fluidisation and dewatering of depositional flows. They were correlated against core. These zones should not be considered in determining deformational style of the reservoir.
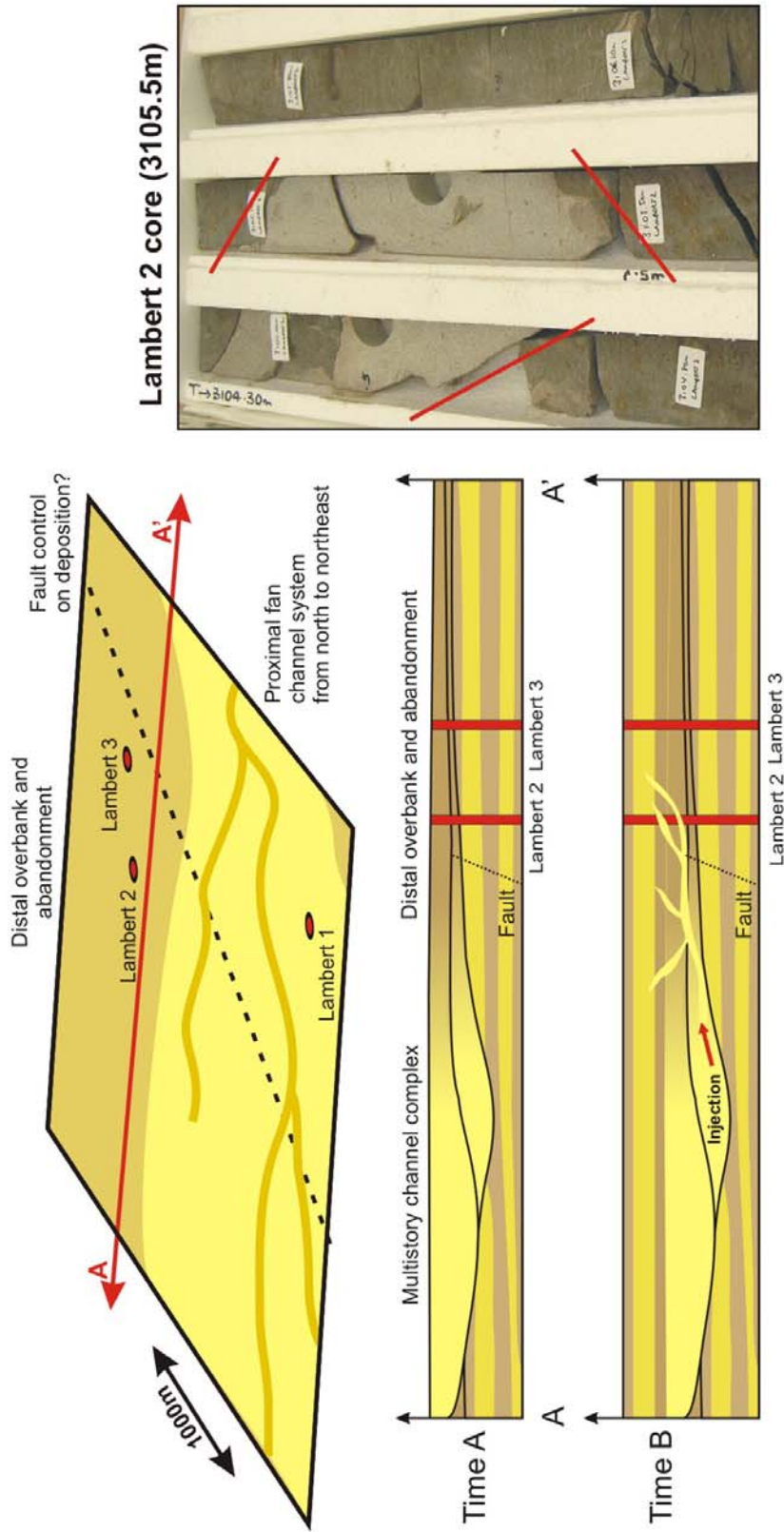
Figure 9-14: Palaeogeographical representation of the upper *P. inusitatum* and *Biorbifera* aged sediments in the Lambert field. Lambert-2 and -3 rest on an abandoned overbank setting with an interpreted sixth order migrational channel complex towards the south. With increasing burial, the sandstones infilling the channel complex became overpressured and injected laterally into the overbank sediments preserved in Lambert-2 and -3.

9.5.2 Sub-Vertical Polygonal Fault Injectites

Top seal breaching and sediment remobilisation can occur due to propagating polygonal faults intersecting an overpressured sandstone body (Jackson, 2007). Polygonal faults are early compaction-related normal faults that form between layer-bound stratigraphic units (Lonergan *et al.,* 2000). Seismic analysis of the Alba field located in the central North Sea has demonstrated that polygonal faulting can provide a pathway of weakness for injection from overpressured sandstones (Lonergan and Cartwright, 1999; Hillier and Cosgrove, 2002; Jackson, 2007). Polygonal fault-related injectites can vertically connect reservoir units and act as hydrocarbon thief zones if extensively developed.

Core interpretation of Wanaea-2A shows the presence of injection features in polygonal fault systems that exist within the overlying seal (Section 5.5.4 and Figure 5.52). Hydrocarbon fluorescence was detected in injection features along the fault systems at 2869 metres (Woodside, 1991) which indicates that fluidisation and injection occurred prior to the charging of the reservoir (Figure 9-15). Like Lambert-2, these injection features could potentially represent conduits that can greatly influence the vertical and lateral connectivity of the Wanaea field. It is more likely that the sands within these features are too tight.

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This figure is included on page 263 of the print copy of the thesis held in the University of Adelaide Library.

Figure 9-15: Development of injectite-influenced reservoir similar to that interpreted for the Wanaea field. Injection takes place at a shallow burial depth (up to a few hundred metres). It can be followed by the development of localised cement. After burial, hydrocarbon migration and reservoir charging occurs. Patches of earlier developed cement can prevent the migration of petroleum into some injectite systems. Later developed cement can lock hydrocarbon in place (after Jonk *et al.,* 2005).

9.6 Implications for Future Exploration and Development in the Dampier Sub-basin

The Dampier Sub-basin has been extensively explored since 1968 when Legendre-1 proved the existence of hydrocarbons within Late Jurassic sediment. Since that time, the majority of structural traps within the basin have been explored. Geoscience Australia (2005) predicts that up to 167 million barrels of oil, 0.4 trillion cubic feet of gas and 26 million barrels of condensate can be discovered in the Dampier Sub-basin and adjoining Rankin Platform over the next ten to fifteen years (value is calculated for the Angel, Legendre and Mungaroo Formations). Clearly stratigraphic and combination structural and stratigraphic plays within the Angel Formation hold a large percentage of the remaining prospectivity.

Stratigraphic traps have become increasingly predominant in mature basins around the world (Allen *et al.,* 2006) and the Dampier Sub-basin is no exception. This study proposes a high resolution architectural template that can be applied to a greater extent within the basin and can be tied with seismic interpretation. This further analysis into reservoir distribution could potentially lead to the identification of the following stratigraphic plays.

i. Fan and feeder pinchout plays against the Valanginian disconformity along the Rankin Platform and southern Beagle sub-basin. Seismic interpretation along with palaeocurrent information is required to establish prospective locations (basinal feeder systems).

ii. Sand-dominated slump or debris flow plays along the western margin of the sub-basin during Late Tithonian time. These features, if large enough, could be mounded in shape and surrounded by sealing heterolithics or mudstones.

Stratigraphic trap exploration is currently a high risk venture. Low reservoir acoustic impedance contrast due to low gross reservoir thickness or homogenous sediment can complicate the identification of stratigraphic plays. Exploratory risks associated with stratigraphic plays include up-dip and injection-related seal failure. Enhanced prediction of lateral architectural variability away from the borehole and on seismic reflection datasets is required to appropriately understand and constrain these risks. This study represents one such step towards the successful identification and exploitation of stratigraphic hydrocarbon accumulations.

10 Summary, Conclusions and Recommendations

The aim of this research was to examine the sedimentological processes, internal architecture and depositional evolution of the Tithonian succession of the Angel sandstone in the northwestern Dampier Sub-basin. It was completed in order to improve the current understanding of a deep marine system whose architecture is below that which can be resolved with conventional seismic data. The objectives of this research (as listed in Section 1.3) were to:

- devise an appropriate core lithofacies scheme based on ten wells and interpret depositional processes that are responsible for them (Section 10.1);

- devise applicable lithofacies associations (Section 10.2);

- examine differing scales of architectural elements and their stratigraphic relationships;

- devise applicable lateral and downslope models addressing autocyclic and allocyclic patterns (Section 10.3);

- analyse larger-scaled architecture and fan evolution in five field regions that rest within proximal, medial and distal settings (Section 10.4);

- investigate and discuss non-stratigraphic variables that could have governed the evolution of the depositional system such as post-depositional deformation and syn-depositional tectonism (Section 10.5), and;

- discuss research implications and their relationship to future exploration and development programs planned for the Dampier Sub-basin (Section 10.6).

This thesis was structured so that it upscaled the sedimentological and architectural analysis from the smallest core-scaled element to the largest wireline- and seismic-scaled element. The developed architectural scheme was further used to examine the Tithonian evolution of the fan systems in the sub-basin.

10.1 Core Lithofacies and Depositional Processes

Eleven cores totalling 547 metres were analysed from the northwestern Dampier Sub-basin in order to determine the range of sedimentological processes that were responsible for the Angel sandstone and resultant lithofacies. Eleven lithofacies classifications were created that cover both primary depositional and secondary remobilised lithofacies types. These core-scaled lithofacies represent first and second order architectural elements (Figure 2-15 and Table 2-5).

The eleven classifications include:

- homogenous unstructured and parallel stratified sandstones (Lithofacies A);

- dish and pipe structured sandstones (Lithofacies B);

- clast-dominated sandstones (Lithofacies C);

- laminated sandstones (Lithofacies D);

- bioturbated heterolithics (Lithofacies E), and;

- structureless to laminated siltstones and mudstones (Lithofacies F).

- ptygmatic injectites (Lithofacies G);

- deformed and sheared mudstone breccia (Lithofacies H);

- discordant sandstone bodies in sandstones and heterolithics (Lithofacies I);

- discordant sandstone bodies in mudstones (Lithofacies J), and;

- contorted sandstone (Lithofacies K).

Primary depositional lithofacies (such as Lithofacies A – E) were found to be deposited primarily through continuous aggradation of quasi-steady high density turbidity flows as suggested by Kneller and Branney (1995). The change in lithofacies from homogenous unstructured sandstones to dewatered sandstones to laminated sandstones represents either a downslope or lateral "overspill" waning of flow events. They were interpreted to not be deposited through sandy debris flows as suggested by Shanmugam and Moiola (1995) as they contain parallel stratification. Large-scaled sand-dominated slump features indicative of sandy debris flows were not recognised, however they may have formed through sediment oversteepening and failure during Late Tithonian time along the Rankin Platform (Figure 9-1).   Linked debrites and transitional hybrid flows were also identified.

Secondary "deformed" lithofacies classification contained all lithofacies that were created through post-depositional remobilisation of sediment following a significant period of deposition and/or burial. They include Lithofacies G (ptygmatic injectites), H (injectite breccia (could also be interpreted as linked debrites)), I (sandstone pillars) and J (sandstone dykes). These units are the products of post-depositional overpressuring that led to the injection of sandstones into overlying and lateral finer-grained units. These secondary lithofacies varieties were identified in all wells.

10.2 Lithofacies Associations

Seven lithofacies associations were created which represent third order architectural elements (Figure 2-15 and Table 2-5). They were separated into two categories dependant on their association with channelisation. Channelised lithofacies associations included:

- crevasse splays (Lithofacies Association 1);

- channel axis and thalweg units (Lithofacies Association 2);

- channel margin and levee units (Lithofacies Association 3), and;

- channel abandonment units (Lithofacies Association 4).

Crevasse splay deposits contain finer-grained sandstones which can be stacked to form multi-storey splays and be overlain by either channel fill sandstones or heterolithics. They are the product of flow-stripping where stratified flows become hydraulically separated at channel bends (Figure 6-5 and 6-6).

Two varieties of crevasse splay are recognised.

   i. Progradational crevasse splays develop during progradational times and can lead to channel
       avulsion.

   ii. Retrogradational "overspill" crevasse splays are produced when a channel system has
       become or is close to being infilled through aggradation. This results in increased overspill
       outside the channel system.

Channel axis (or thalweg) fill deposits typically appear ungraded, have a sharp basal contact with
underlying sediments and can be unstructured or contain parallel stratification (Figure 6-8 and 6-9).
They represent the high density turbiditic sandstone fill of the central axis (or thalweg) of a channel
system and are recognisable in all wells. Individual channel fill units can amalgamate, representing
repetitive incisional and infilling events from channel migration. Very coarse-grained channel base
lags, which represent bypass, are often preserved (Figure 6-10).

Channel margin and levee deposits tend to overlie channel fill deposits. They can be overlain by
younger channel fills, interbedded with heterolithic overbank successions and display occasional dish
and pipe structures. They are deposited through overspill of turbulent flows from the main channel
axis. Two varieties of margin were recognised.

   i. Channel margin deposits (Figure 6-11) are at the verge of the channel system and are
       represented by parallel stratified and dewatered sandstones. They are common in Egret-2,
       Montague-1, Lambert-2 (Figure 6-12 and 6-13), Mutineer-1B (Figure 6-13), Mutineer-3, Spica-
       1, Wanaea-2A and Wanaea-3.

   ii. Levee overbank deposits (Figure 6-11) are outside the channel system and are represented
       by silt-dominated laminated sandstones and siltstones. They could be interpreted to have
       been deformed into injection-related breccia as injection features invade the levee interpreted
       to be adjacent to overpressured channel complexes. They are recognised in Lambert-2,
       Spica-1, Exeter-5ST1, Wanaea-2A and Wanaea-3 (Figure 6-16).

Channel abandonment deposits are represented by a sharp transition from unstructured or parallel
structured sandstones to heterolithics, siltstones and mudstones (Figure 6-21). The upper bed contact
is often affected by post-depositional fluidisation and invasion of sandstones into the overlying fine-
grained sediments, resulting in the formation of rip-down clasts. Channel abandonment occurs
through up-slope channel avulsion or a change in sediment flux in relation to a fluctuating relative sea-
level. These units can be interpreted differently as being the product of post-depositional fluidisation
at the upper bed contact which can destroy primary sedimentary structure (Figure 6-23).

Unchannelised lithofacies associations include proximal sand-dominated frontal splays, distal silt-
dominated frontal splays and splay abandonment units.

Proximal sand-dominated frontal splays comprise interbedded successions of parallel stratified,
dewatered and laminated sandstones with hybrid flows, linked debrites and ptygmatic injectites
(Figure 6-24). They often grade into laminated and bioturbated heterolithics. They can be erosively

cut by younger channel systems. They represent the sandier fraction of waning, laterally spreading and unconfined low density turbulent flow events from the mouths of distributary channel systems (Figure 6-25). These units can amalgamate to form sheet complexes identified in Lambert-2, Wanaea-2A and -3.

Distal silt-dominated frontal splays comprise interbedded laminated sandstones and bioturbated heterolithics which are often interbedded with proximal frontal splays. They represent the distal and siltier fraction of waning, unconfined low density turbulent flow events from distributary channel systems (Figure 6-28).

Splay abandonment units are represented by siltstones and mudstones signify quiescent depositional conditions in association with fan abandonment. In some cases, they could represent maximum flood events.

10.3 Upscaled Architectural Elements and Stratigraphic Relationships

The lithofacies associations were upscaled into fourth, fifth and sixth order architectural elements that represent the development of a composite channel-splay or sheet complex.

10.3.1 Fourth Order Single Storey Channel Form

A fourth order architectural element was interpreted to be a migrational or aggradational single storey elementary channel feature, which can comprise channel lags and fills that are overlain by channel margin deposits (Figure 7-2). A comparison with modern, subsurface and ancient outcrop data suggested that distributary channel systems in the Angel Formation should be no thinner than approximately one metre. This value is not definitive as the thickness of a unit identified in core would often represent the marginal component and not just the remnant part of the central axis of the channel feature. Aspect ratios for the Angel Formation channels range probably from 4:1 to 100:1 as determined from comparable analogues by Clark and Pickering (1996) (Figures 7.3 and 7.4).

10.3.2   Fifth Order Autocyclic Multistorey Composite Channel-Splay and Sheet Complexes

Fifth order architectural elements comprise either a sheet complex (unchannelised) or a composite channel-splay complex (channelised).

A composite sheet complex comprises progradational splays overlain by retrogradational splays that stack to form a sheet complex. No channelisation is preserved. This complex exists within outer fan regions.

A composite channel-splay complex contains multiple fourth order channel forms formed through repetitive cycles of incision and infilling that are overlain by a retrogradational splay unit (Figure 7-5). They are created through a combination of channel erosion and bypass, channel infill, channel

overspill and retrogradational splay development which rest upon the progradational splay component of a sheet complex. They contain multiple channel forms that can migrate and compensationally stack (Figure 7-7).

Preserved fifth order composite channel-splay and sheet complexes can vary according to either their position on the slope to basin profile or their position within a laterally migrational system. Five transitional models were interpreted with Model E representing a sheet complex. Each successive model represented either the downslope change from a proximal to distal fan setting (Figure 7-14); or the lateral change from a central position to a marginal and overbank position of a channel complex where there is an increase in the amount of amalgamation surfaces, parallel stratification, dewatered structures and splays (Figure 7-15).

The interpretation of fifth order architectural complexes within cored intervals determined that Angel-4, Cossack-1, Montague-1 and Exeter-5ST1 contained a combination of the more proximal varieties of fifth order models (Models A, B, C) signifying that they existed within a proximal channelised fairway. Lambert-2, Wanaea-2A and -3 were found to contain the more distal varieties of fifth order models (Models D and E) signifying that they existed within a distal setting containing interbedded composite channel-splay complexes of a distributary nature with sheet complexes. Composite channel-splay plots from Cossack-1 (Figure 7-16), Exeter-5ST1 (Figure 7-17), Mutineer-3 (Figure 7-18), Mutineer-1B (Figure 7-19), Spica-1 (Figure 7-20), and Wanaea-2A (Figure 7-21) demonstrated the migrational and compensational behaviour of the multi-storey channel complexes from proximal to distal settings. These results led to a reclassification of the Angel formation depositional system in terms of depositional systems as described by Mutti (1985). Barber (1994a; 1994b) stated that the Tithonian Angel Formation was a Type 1 depositional system which comprised of detached unchannelised lobes (Figure 9.2). This study found that a Type 2 classification of channel fills with attached lobes better represents the Tithonian interval of the Dampier Sub-basin.

10.3.3 Sixth Order Allocyclic Migrational and Confined Channel Complexes

Sixth order architectural elements comprise multiple migrational and compensationally stacked fifth order complexes that are dominantly bound by sequence boundaries and flood events. They are governed by variations in slope equilibrium profiles which can result in negative (lowstand) or positive accommodation (transgression).

Two sixth order allocyclic models were created. The sixth order progradational model is related to early and late lowstand time as high sediment flux is received in the basin (Figure 8-6). This results initially in a decrease in accommodation as the slope equilibrium profile shifts, leading to erosive downcutting of previous channel fills and progradation of fan lobes. A shift in the equilibrium profile during late lowstand results in a change in accommodation from negative to positive, resulting in renewed slope and basin accommodation and early aggradation of sediment in previously erosive channel systems. Fifth order composite channel-splay and sheet systems deposited during sixth order progradational time display high net to gross sandstones, low channel sinuousity and avulsion, high channel confinement of early aggradational deposits and increased amalgamation of channel

forms at a particular point on the slope to basin profile as downcutting increases with continued progradation (Figure 8-8).

The sixth order aggradational and retrogradational model is related to transgression (Figure 8-7). Gravity flow events become smaller and less dense over time, which results in a steepening of the equilibrium profile and the creation of positive slope and basin floor accommodation. It results in retrogradational backstepping of fan systems. Fifth order channel-splay systems deposited within a sixth order aggradational to retrogradational system become increasingly clay-rich, are more sinuous, have more avulsive events as channels aggrade above the equilibrium profile, and become less amalgamated as elementary fourth order channel forms decrease in size and become interbedded with sheet complexes (Figure 8-8).

10.4 Architectural Analysis and Evolution of Fan Systems from Five Field Regions

The sixth order architecture and fan evolution of five regions across the northwestern Dampier Sub-basin were examined. Biostratigraphic data from open file well completion reports and donated by Santos Ltd was used to assist correlations. They were separated into two main localities. The Parker Terrace was found to comprise a seventh order system that contains small, curved coalescing fan systems up to 10 to 15km in size separated by seven regional and local lowstand events (Table 9-1). These include the fan systems from the Mutineer, Lambert and Egret-Montague regions.

Analysis of the Mutineer region determined the following.

i.   Fine-grained sedimentation was restricted to the Bounty graben during lower *D. jurassicum*, *O. montgomeryi* and *C. perforans* time (Figure 8-15).

ii. Two sixth order packages prograded across the region during upper *D. jurassicum* time. The first system was sourced from the Swift Graben and north of the Bounty Graben (Figure 8-16). The second system prograded from the northern region of the Bounty Graben as early abandonment was felt in the Swift Graben (Figure 8-17).

iii. Two sixth order packages prograded across the region during lower *P. inusitatum* time. The first sixth order system was sourced from the Swift and northern Bounty grabens (Figures 8-18 and 8-19). No sedimentation was preserved at Mutineer-1B, Norfolk-2 or Pitcairn-1, suggesting they were located on footwall highs. The second sixth order system (which continues into upper *P. inusitatum* time, was sourced from the Swift, Mutineer and northern Bounty grabens (Figure 8-20). Sedimentation was preserved during this time on the previously starved footwall highs of Mutineer-1B, Norfolk-2 and Pitcairn-1.

iv. Continuation of the sixth order package from lower *P. inusitatum* time prograded across the region during upper *P. inusitatum* time. High sediment flux to the region resulted in the development of large fifth order channel-splay complexes. Sediment was sourced from the Swift, northern Bounty and possibly the northern Mutineer Graben (Figure 8-22). This system

represents maximum progradation of the entire Tithonian succession. Retrogradation occurred towards all three interpreted source points (Figure 8-23).

v.   A sixth order package comprising a small progradational unit (Figure 8-24) and a thick aggradational to retrogradational unit (Figure 8-25) existed during *Biorbifera* time. The majority of this package was confined to the Bounty Graben, suggesting possible tectonic activity.

vi. A sixth order package similar to the *Biorbifera* package existed during *Dissimulidinium* time. Sediment was sourced from the Swift and Mutineer grabens during progradational time which was ponded within the Bounty Graben and west of the Mutineer Graben suggesting tectonic activity (Figure 8-26). Retrogradation resulted in the backstepping of the system towards the sources. No sediment input occurred from the northern Bounty Graben (Figure 8-27).

vii. No upper *P. iehiense* sedimentation was preserved within this region as the entire system was abandoned and possibly rerouted elsewhere closer to the palaeoshelf.

Analysis of the Egret-Montague region determined the following.

i.   The *O. montgomeryi* package comprised fine-grained sediments deposited during a time of abandonment. No *O. montgomeryi* sediments are preserved in Egret-1 or -2 (Figure 8-30).

ii. A large sixth order package existed during lower *D. jurassicum* time which deposited over 330 metres of sediment in Montague-1. No *D. jurassicum* sediments are preserved in Egret-1 or -2 (Figure 8-30).

iii. Two sixth order packages comprising compensationally stacked fifth order complexes existed during upper *D. jurassicum* time. The basal sixth order unit in Egret-1 is amalgamated, suggesting the presence of a sixth order confined channel complex. Egret-2 is located off-axis of this fairway (Figure 8-31).

iv. The *P. iehiense* system contains three sixth order packages (Figure 8-30). Egret-1 remained located within a channelised fairway setting whereas Egret-2 remained off-axis (Figure 8-31). Complete abandonment in the Montague-1 region occurred during *Biorbifera* time in relation to the third order magnitude relative sea level transgression that occurred during Tithonian time (Figure 8-30).

Analysis of the Lambert region determined the following.

i.   A sixth order package existed during *O. montgomeryi* to middle lower *D. jurassicum* time which is interpreted to have been sourced from the Rankin Platform. This contradicts observations made by Jablonski (1997) who stated that the Rankin Platform was flooded at the time (Figure 8-35).

ii. A sixth order package existed from middle lower *D. jurassicum* to upper *D. jurassicum* time (Figure 8-35). Possible fault-controlled accommodation may have occurred during upper *D. jurassicum* time in Lambert-1 with bypass occurring in Lambert-2 and -3.

iii. A sixth order dominantly progradational package existed during lower *P. inusitatum* time (Figures 8-35 and 8-36A).

iv. Two sixth order packages separated by a lowstand event during *I. kondratjevii* time existed during upper *P. inusitatum* and *Biorbifera* time. Starvation occurred around Lambert-2 and -3 as a migrational channel complex bypassed them to the east and was possibly controlled by syn-depositional movement of the Lambert fault systems (Figures 8-35 and 8-36B).

v. Two sixth order packages separated by the *B. simplex* lowstand event existed during *Dissimulidinium* and upper *P. iehiense* time (Figure 8-35). They contain fifth order channel-splay systems that are interpreted to be distributary-sized and highly migrational. They are interbedded with sheet complexes (Figure 8-36C). These packages represent the retrogradational backstepping of the Lambert fan system towards the palaeoshelf in relation to Tithonian transgression.

The Central Dampier region contains the Angel and Cossack-Wanaea regions. It was determined that the region contains a large seventh order fan system (Figure 8-37) that is separated by seven regional and local lowstand events (Table 9-2). It is interpreted to extend up to 50km through the central axis of the sub-basin. Examination of the Angel region determined the following.

i. A sixth order package of sediments existed during *O. montgomeryi* and *C. perforans* time (visible in Angel-3) (Figures 8-39 and 8-40A). These sediments were sourced from the east and ponded against the tilted footwall block of the Madeline fault which is interpreted to be active during this time. Sedimentation may have occurred over the fault north of Angel-4. Fine-grained sediments dominate this unit in Angel-1.

ii. A sixth order package existed during lower *D. jurassicum* time (Figures 8-39 and 8-40B). Sediments sourced from the eastern regions breached the fault and deposited fifth order channel-splay and sheet complexes on the western downthrown side of the fault. Bypass of sediments occurred at Angel-3 and Angel-2 and was identified through the amalgamation of fifth order channel-splay complexes.

iii. The upper *D. jurassicum* and *P. iehiense* units comprise five highly amalgamated sixth order units (Figure 8-39). They are separated by the *I. kondratjevii*, *Dissimulidinium* and *B. simplex* sequence boundaries. These units are highly sand-rich. Amalgamated sixth order migrational channel complexes spanning three kilometres were identified on seismic near Angel-2. The location of these complexes is controlled by the Madeline fault system which suggests active syn-depositional tectonism during this time (Figure 8-40C).

Analysis of the Cossack-Wanaea region demonstrated that sixth order units thin dramatically towards the southeast (Figure 8-44). Cossack-1 is the most proximal well as it contains strong amalgamation of fifth order composite channel-splay complexes. Individual fifth order complexes range up to 20 metres thick, suggesting that distributary channel systems existed in the region. The progradation of sixth order complexes occurred during *O. montgomeryi* to *D. jurassicum* time leading up to the point of

maximum progradation that occurred during early *P. inusitatum* time. Commencing *P. iehiense* time, there was a continuing decrease in sedimentation up to complete abandonment by *B. simplex* time.

10.5 Non-Stratigraphic Controls on Preserved Architecture

Two varieties of non-stratigraphic controls on architecture were identified within the Dampier Sub-basin. They include:

- syn-depositional tectonism, and;
- post-depositional sandstone injection.

10.5.1 Syn-Depositional Tectonism

Active tectonism in the Tithonian is interpreted to have partially controlled lithofacies distribution and the location of feeder complexes into the sub-basin. This was evident mainly in the Angel region during *O. montgomeryi* and *C. perforans* time (Figure 8-41) and along the Rankin Platform in the Egret field region (Figure 9-6).

10.5.2 Post-Depositional Deformation of Reservoirs

Overpressuring, fluidisation and injection of reservoir sandstones occurred in the western Dampier Sub-basin. Two varieties of post-depositional injection features were recognised.

i. Lateral injectites occur when overpressured channel sandstones inject laterally into levee and overbank successions. They can occur during early burial which produces ptygmatic injectites (Lithofacies G), or during late burial which produces sharp-sided injectites (Lithofacies J). Early burial lateral injectites were recognised in Egret-2, which were sourced from the channelised fairway that existed during *P. iehiense* time adjacent to the well (Figure 9-9). Later burial lateral injectites were recognised in Lambert-2, which were sourced from the channelised fairway that existed during upper *P. inusitatum* to *Biorbifera* time (Figure 9-10). Injectites from both wells contained hydrocarbon, signifying that these systems could affect the lateral and vertical connectivity but are most likely too tight.

ii. Sub-vertical polygonal fault injectites were identified in Wanaea-2A in the overlying seal of the reservoir (Figure 5-52). They were found to contain hydrocarbon. These injectites were created when propagating polygonal faults intersected overpressured sandstone. Like lateral injectite features, they can act as hydrocarbon thief zones (Figure 9-15).

Both varieties of injection features should be incorporated into field-scale modelling as they can significantly influence reservoir distribution, volumetrics and recovery.

10.6 Future Exploration and Development in the Dampier Sub-basin

Stratigraphic trap exploration within the Dampier Sub-basin is considered to be a high risk venture. Low reservoir acoustic impedance contrasts due to low gross reservoir thickness and homogeneity of sedimentary packages in the Dampier Sub-basin can complicate the identification of stratigraphic plays. The high resolution architectural system suggested by this study could be used in combination with seismic interpretation to constrain the exploratory risk. It could help to improve prediction of lateral architectural variability away from the borehole and on seismic reflection datasets.

10.7 Future Research Recommendations

Based on the results of this study, future research could include the following.

i. The combination of the architectural scheme developed in this study with a full seismic interpretation study across the Dampier region utilising recent seismic reflection surveys (Demeter and 2006 CVSN06 Mutineer Exeter surveys). This would combine the architectural scheme with a full stratigraphic framework for the basin, which in turn can lead to the identification of future exploratory targets including fault scarp derived, sand-dominated mass transport complexes and new laterally confined fan systems sourced off the Rankin Platform.

ii. The creation of different depositional models and 3D reservoir models for field regions in order to analyse the extent of vertical/lateral connectivity and degree of composite channel compartmentalisation. It could be completed by varying the architectural geometries and stacking behaviours of channel-splay complexes. These models could be constructed with the assistance of production data from fields situated within the study region.

iii. The increased use of image logs for reservoir characterisation. The comparison of core to image log facies was confidently completed in Mutineer-IB and can be found in the appendices. Future wells drilled in the basin could have a detailed lithofacies analysis completed on the intersected reservoir through image log interpretation. Tying the logs with sidewall core data would provide information on lithology, porosity and permeability. The increased use of image logs for future wells in the basin would provide architectural and sedimentological information from wells that aren't cored through time and cost constraints.

iv. An investigation into the potential usefulness of chemostratigraphy. If effective, it could offer an additional correlative dataset that could be used in conjunction with palynology. This has been successfully used for stratigraphic analysis in other deep marine reservoirs located along the western margin of Australia (pers comm. D. Whittam, 2005), and within other turbiditic successions worldwide (e.g. Madeira Abyssal Plain (Pearce and Jarvis, 1995)).

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