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CLIMATE AS A STRATIGRAPHIC TOOL FOR BASIN MARGIN DEPOSITION IN INTRACONTINENTAL BASINS

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ABSTRACT

In intracontinental basins stratigraphic packages are not as predictable as those deposited in marine settings, namely due to a lack over an overriding control on deposition. Deposition in intracontinental basins is controlled by tectonics, climatic variations, and sediment supply. Complexity is added as deposition is affected by both autocyclic localised variations (e.g., lobe switching) and larger scale allocyclic variations such as climate forcing, leading to rapid changes in depositional environment. This research considers a basin margin depositional system predominately controlled by climatic variations and presents a model to highlight how the individual depositional environments respond to wetting and drying events. Alluvial fan related environments (e.g., talus cone, debris flows, sheetfloods) prograde into the basin during increased humidity, whereas increased aridity leads to retrogradation. Fluvial environments (e.g., fluvial, palaeosol) react in the same manner, prograding during humid climates and retrograding during increasing aridity. Lacustrine environments expand in the basin centre during increased humidity, and desiccate and shrink during arid climates. Finally, aeolian environments decrease in magnitude and migration is reduced during increased humidity but grow in extent during increased aridity. A case study from the end-Carboniferous to Permian Cutler Group (undifferentiated) in the western U.S.A. is used to build the model as it comprises an exceptionally well-preserved basin margin system.

KEY WORDS: Basin margins, intracontinental, arid sedimentology, cyclostratigraphy, alluvial fans

INTRODUCTION

Sequence stratigraphical principles have limited applicability in intracontinental endorheic basins where deposition is disconnected from marine settings (Shanley & McCabe, 1994; Huaidan, 1991). This effect is accentuated along basin margins where the predominant controls are from quasi-periodic changes in tectonics or climate (Perlmutter & Matthews, 1992; Weissmann & Fogg, 1999). As these controls are relatively unpredictable, and readily switch between allo- and autocyclic variations, it is difficult to identify marker horizons that correlate across the basin (Howell & Mountney, 1997; Terrizzano *et al.*, 2017). This research considers how the sedimentary systems respond to climatic variations, and how this leads to noticeable variations in sedimentary deposits both spatially across the basin and over time. A case study from the Paradox Basin, western U.S.A. (Fig. 1) highlights how both allocyclic and autocyclic climatic variations can be used predict sedimentation in a relatively tectonically quiescent basin setting.

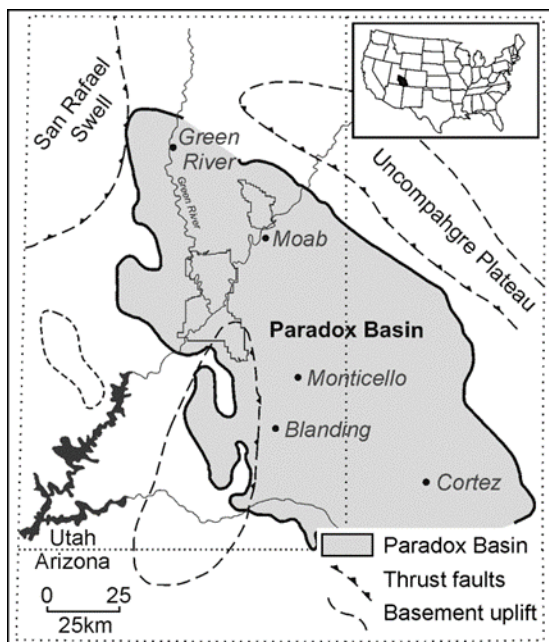


Figure 1. The model of climatic cyclicity discussed in this paper is based on the Permian-aged fan systems of the Cutler Group, Paradox Basin, western U.S.A. The Paradox Basin is an intracontinental foreland basin which formed in front of the Uncompahgre Uplift, an outlier of the Ancestral Rocky Mountains. (Adapted from Nuccio & Condon, 1996).

This study considers the deposits of the Cutler Group (undifferentiated) a large-scale basin margin depositional system deposited into the Paradox Basin throughout the late Carboniferous

to Permian (Mack & Rasmussen, 1984; Dubiel *et al.*, 2009; Sweet, 2017). The Paradox Basin sits over the adjoining Four Corner States (Fig. 1) and is an intracratonic foreland basin bounded to the northeast by the Uncompahgre Uplift (Baars & Stevenson, 1981; Kluth & DuChene, 2009). For the majority of the late Carboniferous and Permian the Paradox Basin was disconnected from any marine influence (Dubiel *et al.*, 1996). This persisted until the Guadalupian Epoch, where a shallow marine incursion occurred from the northwest (Fig. 2). Therefore, it can be suggested that the main control on deposition during the early pre-Guadalupian Paradox Basin fill was climatic. This especially relates to the basin margin depositional system as this was fully disconnected from the distal seaway. The effect of the marine incursions on the distal Cutler Group deposits are well studied (Mountney & Jagger, 2004; Jordan & Mountney, 2010), but the controls on the undifferentiated deposits are poorly understood.

The Cutler Group (undifferentiated) deposited as a series of alluvial fans, fluvial systems, and subordinate fan-surface lacustrine systems which graded to the southwest into basin centre aeolian, lacustrine, and axial fluvial systems (Mack & Rasmussen, 1984; Shultz, 1984; Sweet, 2017). The identified variations occur because of both localised autocyclic variations (i.e. lobe switching, vegetation), halokinetic controls (e.g., Venus *et al.*, 2015) and by regional allocyclic control including climate (e.g., Waters *et al.*, 2010; Ventra *et al.*, 2017), tectonics (e.g., Harvey *et al.*, 2005; Goswami, 2018), and sediment supply.

This paper presents a qualitative assessment of how climate can lead to vertical facies changes. These observations are based on the interpretation of logs and panel diagrams taken from an 80 km long broadly west-east trending lobe of the Cutler Group, undifferentiated, in the area surrounding Moab, eastern Utah, to assess how these deposits evolved through time. As there are a lack of correlatable horizons in terrestrial sediments (i.e. limited palynology, no foraminifera and, in the case of the Cutler Group, no volcanoclastic horizons) this study will

allow for similar climatically controlled depositional systems to be better understood in subsurface systems. This has implications for understanding the complex homogeneity of these systems.

GEOLOGICAL BACKGROUND

2.1 Cyclicity in arid continental basins

Despite the limitations of sequence stratigraphy in endorheic continental basins, the response of different types of cyclicity (i.e. tectonic vs. climatic) can be identified in the deposits. However, it can be challenging to differentiate between regionally forced and more local cyclicity (Shanley & McCabe, 1994) as the response of sedimentation can produce similar sedimentary structures at outcrop scale (Howell & Mountney, 1997). Without means to accurately date the deposits it is difficult to isolate periods of missing time, either through localised erosion or non-deposition. As such, correlation between the strata proves challenging even in well-exposed basins (Perlmutter & Matthews, 1992). Despite this, if both the palaeolatitude and type of the basin is known, then the response of the depositional environments to any climatic variations can be used to predict how facies distributions would have evolved both spatially and temporally (Miall, 1980; McDonald *et al.*, 2003; D'arcy *et al.*, 2017). It is important to note that alluvial fans are also controlled by changes in sediment supply, base level, and tectonics (Alexander & Leeder, 1987; Blair, 1987; Harvey *et al.*, 2005; Ventra *et al.*, 2017; Mirabella *et al.*, 2018).

2.2 Climatic controls

Climate (Fig. 2) can be considered as the controlling factor in the development of sedimentology, architectural element distribution, and depositional environment growth and progradation in basin margin settings (Harvey & Wells, 1994; Harvey, 2004; Ventra *et al.*, 2009; Ventra *et al.*, 2017). Climatic variations occur at a shorter wavelength than those driven by tectonics causing climatic variations to overprint tectonics (Allen & Densmore, 2000; Allen

et al., 2013). Continental climatic cyclicity is most evident in lacustrine settings due to recognisable water level fluctuations (Sáez & Cabrera, 2002; Kemp *et al.*, 2017), but the climate signature can also be identified in basin margin alluvial fan and fluvial systems.

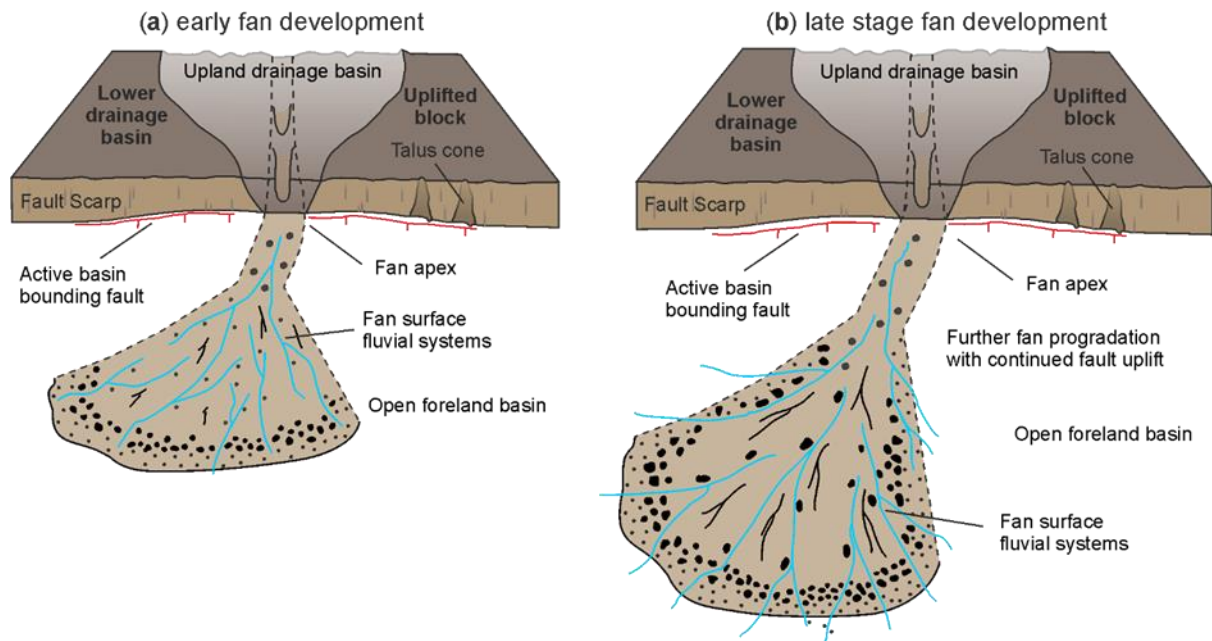


Figure 2. It is commonly accepted that the location of a basin margin depositional system (e.g., alluvial fans) is controlled by tectonic activity. Alluvial fan environments require an emergent landmass to provide a source of detrital material, thus causing early stage fan development (A). Cyclic tectonic movement can cause a rejuvenation of available source sediment. As uplift continues, it leads to an increased amount of fan entrenchment and the progradation of the fan system in a continually elongate manner, this is considered to be later-stage fan development (B). (Adapted from Lecce, 1990).

During periods of increased aridity typical transport mechanisms to basin margin settings through debris flows and fluvial systems shut down leading to lobe abandonment and reworking through wind-driven deflation (Blissenbach, 1954; Terrizzano *et al.*, 2017) leading to aggradation or retrogradation of these depositional environments. Alluvial fan deflation is minimised in cases of fan surface vegetation or case hardening due to extended subaerial exposure (Blair, 1987). These horizons can act as decent climatic marker beds within the

alluvial fan deposits (Blum, 1993). Where there is deposition, the main processes are from bedrock failure (Blissenbach, 1954).

Periods of prolonged increased humidity, for example through more meteoric water input or seasonal water table fluctuations, promote deposition through debris flows and fluvial mechanisms causing alluvial fan growth and progradation (Howell & Mountney, 1997; Harries *et al.*, 2017; Mather *et al.*, 2017). The influx of meteoric water heightens the probability of slope failure promoting deposition through mass-wasting events, such as debris flows and point-sourced sheetfloods (Chou *et al.*, 2017; Schulte *et al.*, 2016; Pope *et al.*, 2016). Episodic storm events, such as the Permian megamonsoons of the Paradox Basin lead to increased flashy run-off from upland fluvial systems (Soreghan *et al.*, 2002) and progradation of basin margin systems (Dubiel *et al.*, 1996). Relatively more humid climates can promote the growth of vegetation which stabilises the surface of basin margin depositional environments. Allocyclically, there tends to be an increase in humidity during interglacial periods (Harvey *et al.*, 2005).

Research into climatic controls on deposition (i.e., Blair & McPherson, 1994) suggests that debris flow- and fluvially-fed basin margins develop across a wide range of climatic conditions and only the temporal persistence of individual transport processes is associated with wetting and drying (Stoffel *et al.*, 2014; Savi *et al.*, 2016).

2.2.1 Tectonic cyclicality

It is widely accepted that tectonic controls (Fig. 3) determine where fans occur along the basin margin (Jones *et al.*, 2014). As they are sourced from unstable emergent ground, they occur in the majority of tectonic regimes (Leeder & Mack, 2001; Waters *et al.*, 2010; Sözbilir *et al.*, 2011; Terrizzano *et al.*, 2017) as tectonics generate accommodation space, elevated

topography, and a basin edge increase in gradient (Blair & McPherson, 1994) which facilitates growth and progradation of these basin margin depositional systems.

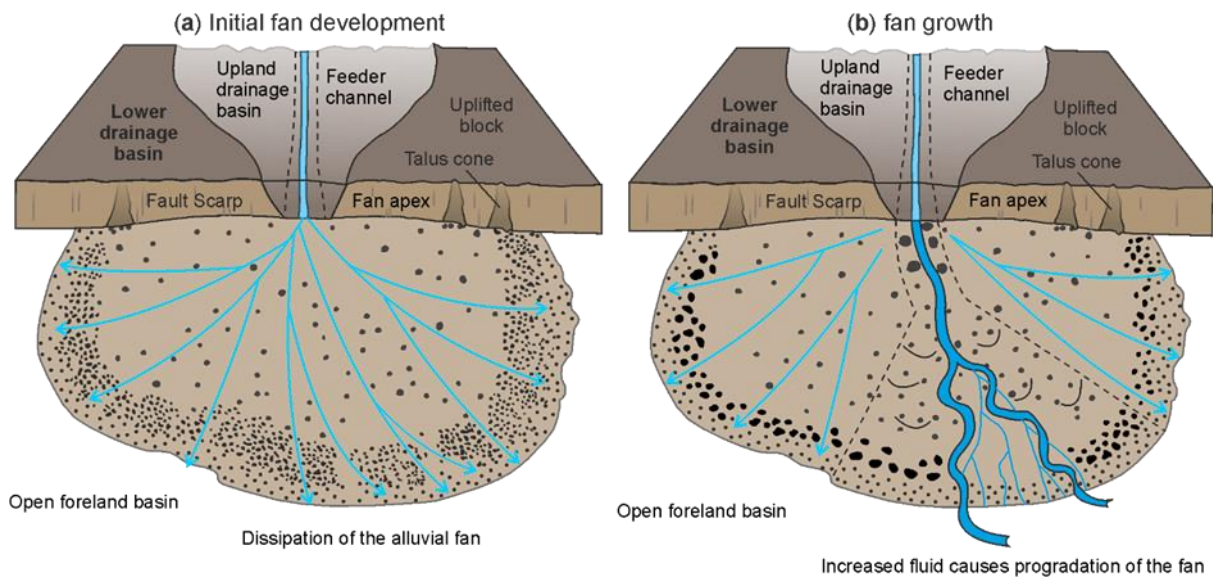


Figure 3. Fans prograde throughout continental basins due to changes in climatic regime. Mass wasting events occur through all climatic regimes (initial fan development; A), but secondary water driven environments are more common during humid cycles, and lead to build-up and progradation of the fan (fan growth; B). During periods of increased aridity, the fan becomes deflated through interaction with wind-blown secondary environments. (Adapted from Lecce, 1990)

2.2.2 Autocyclic controls

Deposition within basin margin settings can also be controlled by localised autocyclic variations, such as lobe switching and abandonment, channel avulsion, and surface vegetation (Blair, 1987). Fan head entrenchment is also cyclic in basin margin settings, especially within alluvial fans. It occurs due to either tectonic uplift exceeding sedimentation rate to the fan or due to downcutting from fluvial environments (French, 1987; Lecce, 1990). Sediment supply is complex due to proximity to unstable sediment sources. The rate of sediment supply into continental basins is difficult to quantify, as it is dependent on many variables, including bedrock denudation, surface stabilisation, bedrock lithology, climate, and tectonic evolution (Jackson & Leeder, 1994; Leeder *et al.*, 1998; Zhang, 2018). Sediment supply also changes

along the basin margin due to non-uniformity or overtime through unsteadiness (Colombo, 1994).

2.3 Background of the Cutler Group

This work considers the late-Carboniferous to early Permian basin margin deposits of the Cutler Group (undifferentiated), Paradox Basin, western U.S.A. (Fig. 1). The Paradox Basin is an intracratonic basin formed in the foreland of the Uncompahgre Uplift, an outlier of the Ancestral Rocky Mountains formed as a result of the Ouachita – Marathon orogenic event (Mallory, 1958; Kluth & Coney, 1981; Lindsey *et al.*, 1986; Yang & Dorobek, 1995; Hoy & Ridgway, 2003; Trudgill, 2011). The Uncompahgre is the source for most of the detrital material shed into the basin throughout the end-Carboniferous and Permian periods. By the end of the Carboniferous, the climate had switched from sub-humid to arid (Rankey & Fan, 1997; Soreghan *et al.*, 2002; Tanner, 2018) and deposition was mainly terrestrial with sporadic flooding from epicontinental seas (Condon & Huffman, 1997). The Cutler Group grades from alluvial and fluvial fan deposits along the basin margin into subdivided contemporaneous environments in the basin centre (e.g., Condon & Huffman, 1997; Barbeau, 2003).

METHODOLOGY

24 sedimentary logs, covering a cf. 80km east-west trending transect of the Cutler Group from the undifferentiated deposits of the basin margin to the subdivided deposits of the basin center in proximity to the town of Moab (Fig. 1), were interpreted to allow for the identification of repetitive wetting and drying cycles within the sediments (Fig. 4). The response of these deposits to drying and wetting is predictable across the basin, these responses have been used to identify the cyclicity in these deposits.

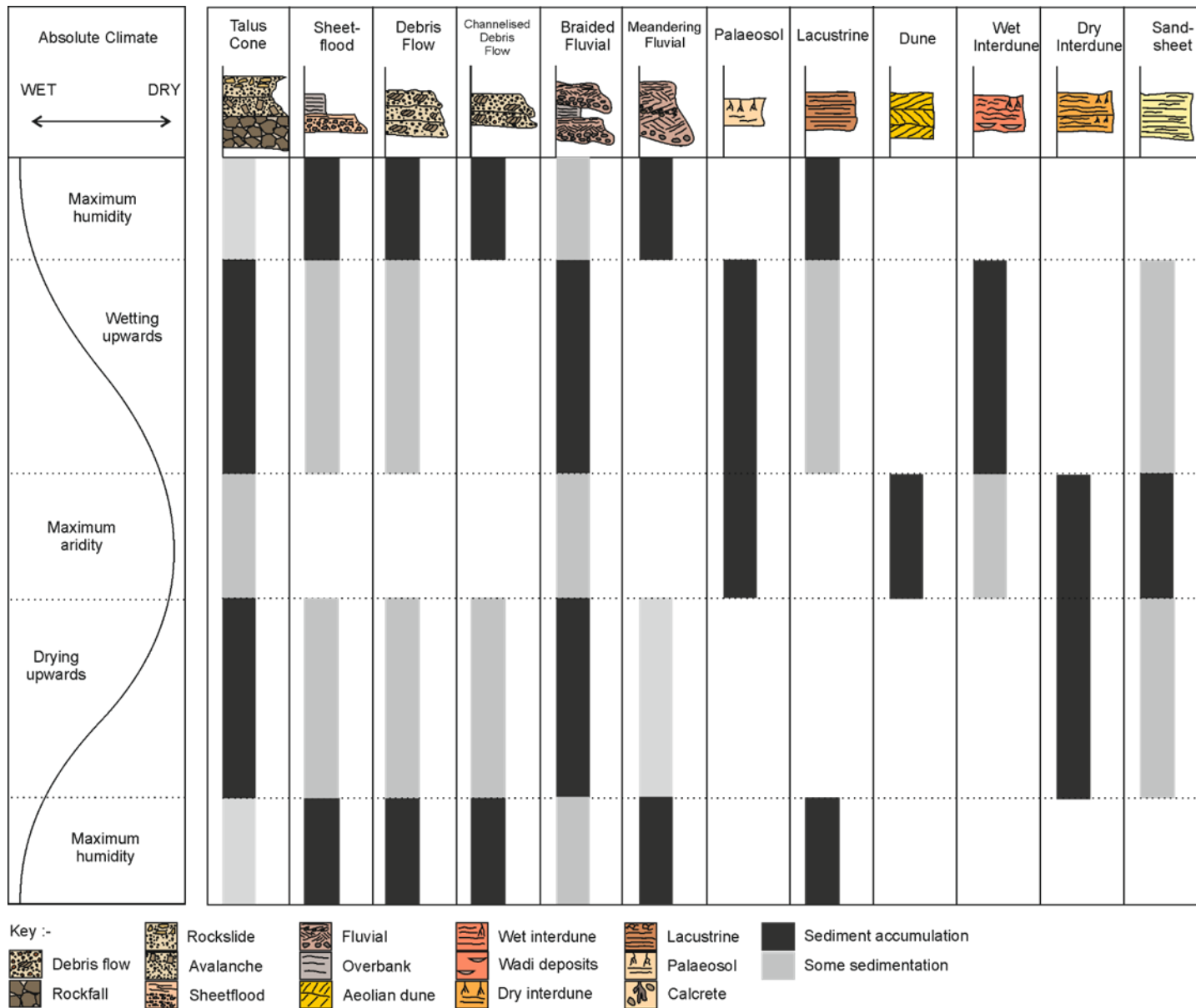


Figure 4. The point of initiation can be observed for each of the fan-related architectural elements in relation to sections of the absolute climate cycle (maximum humidity – maximum aridity – maximum humidity). The sections outlined by black boxes show periods of common sediment accumulation within the element, whereas the grey boxes depict occasional sediment accumulation. The blank sections suggest that architectural element growth is lacking at this stage of the climatic cycle.

Individual depositional environments are deposited at a specific point within the absolute climatic cycle or 'ACC' (Fig. 4) and evolve from that point in response to wetting or drying events. An idealised climatic cycle grades from a point of maximum humidity, through a stage of drying upwards, until the climate reaches a point of maximum aridity, then through a stage of wetting upwards to again reach the point of maximum humidity.

DEPOSITIONAL ENVIRONMENTS

Basin margin depositional systems are fed through debris-driven (i.e. talus cones, debris flows) or water-driven (i.e. sheet-flood, immature and mature fluvial) mechanisms. Other depositional mechanisms in intracontinental basins include aeolian, lacustrine, and related palaeosols. The depositional environments below are common and accepted in continental basin margin environments and have also been interpreted from logs of the Cutler Group (e.g., Boothroyd, 1972; Blair & McPherson, 1994; Blair & McPherson, 2009; Yu, 2019).

4.1 Initiation

Each depositional environment is initiated at a different point within the ACC. Figure 4 highlights the stage within the ACC that this initiation occurs, based on the interpretation of the sedimentary logs.

4.1.1 Initiation of the talus cone

Deposition in talus cones comprises rockslides, avalanches, and rockfalls (Albjär *et al.*, 1979) initiated by the destabilisation of emergent basin bounding highs (e.g., Thapa *et al.*, 2017). Deposition is mainly driven by tectonically driven uplift and initiation occurs episodically throughout the entire ACC. Increased water encourages bedrock failure, therefore deposition to the talus cone is more prominent within the wetting upwards and drying upwards stages of the ACC. The talus cone element is less prominent at the point of maximum humidity, as debris flows and fluvial systems dominate overprinting the bedrock-failure driven deposits, as well as remobilising existing deposits.

4.1.2 Initiation of sheetfloods

Deposition of sheetfloods occurs when the amount of meteoric water added exceeds the capacity of mountain feeder channels at the apex of the fan leading to flooding and the dispersal of sediment on the basin floor (Hogg, 1982). These flood events are often hyperconcentrated and wane rapidly (Tunbridge, 1981). As such, sheetfloods are mainly deposited at the point of maximum humidity in the ACC, and subordinately during the wetting- and drying stage of the cycle. The high energy of sheetflood events can lead to the remobilisation of accumulated sediment along the basin margin and within fan piedmont zones.

4.1.3 Initiation of debris flows

Debris flows are sourced from loose sediment remobilised through processes such as oversteepening, increased water content, or seismic activity (Griffiths *et al.*, 2004). Debris flows are the main source of sediment to alluvial fan lobes (Blair & McPherson, 1994). Initiation requires an elevated entrainment of water within loose sediment accumulated on basin highs. Therefore, debris flows are usually deposited at the point of maximum humidity in the ACC as well as during the wetting- and drying upwards stages, where water is still present (or being added) to the system. Debris flow deposition usually ceases during periods of maximum aridity, allowing for deflation, or even retrogradation, of the debris flow elements.

4.1.4 Initiation of channelised debris flows

Incised channels are formed due to non-depositing fluvial systems dominating the fan surface (Whipple & Dunne, 1992). These channels are then episodically utilised by debris flows, leading to the preservation of channelised debris flow deposits. It is common for the sediment load of these debris flows to outpace the capacity of the channels leading to deposition of levee structures outside of typical 'channel' forms (Whipple & Dunne, 1992). As initiation is the same as that for debris flows, deposition occurs at the point of maximum humidity alongside the drying upwards stage that directly follows. In contrast to debris flows, this element rarely

occurs during the period of wetting-upwards, as fluvial deposition is lessened during the preceding period of maximum aridity.

4.1.5 Initiation of braided fluvial

The proximal extent of continental basins is often dominated by braided fluvial systems, especially on the surface of alluvial fans (Rust, 1977). Periods of maximum humidity are usually dominated by debris flows along basin margins; therefore, fluvial systems are mostly initiated in the wetting and drying stages of the ACC. Braided fluvial systems can sometimes persist throughout periods of maximum aridity, resulting in abandoned fan surface channels.

4.1.6 Initiation of meandering fluvial

Meandering fluvial environments predominately occur towards the basin centre, either representing a maturation of the overall fluvial environments or as axial systems (Weissmann *et al.*, 2010). They commonly form as a response to a more stabilised humid climate, and initiate at the point of wetting of maximum humidity within the ACC. Due to this stabilisation, and the increased amount of incision of these fluvial bodies over time, they can also occur, albeit less frequently, during the drying upwards stage of the ACC.

4.1.7 Initiation of palaeosols

Pedogenesis often occurs on the surface of stabilised alluvial fan lobes or on the floodplain during periods of reduced fluvial avulsion (Wagner *et al.*, 2012). The formation of palaeosols requires some humidity, therefore they commonly initiate during maximum humidity or the wetting upwards stages of the ACC. Development of calcretes within these palaeosolic horizons supports an eventual return to an arid climatic regime (Wagner *et al.*, 2012).

4.1.8 Initiation of lacustrine

Lacustrine systems are common in continental basins and are initiated either due to ephemeral influx of fluvial waters (Cojan, 1993) or due to a rise in the water table (Uhrin & Sztanó, 2012).

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Sedimentation in lacustrine environments can be clastic, sourced from the fluvial systems, or evaporitic due to the drying and contraction of the water body. Lacustrine deposits mainly occur at the point of maximum humidity in the ACC, but also subordinately within the wetting-upwards stage of the cycle. Occasionally, there will be deposition in the drying-upwards stage as even though the lack of fluvial systems elsewhere means that there is no recharge of clastic sediments, evaporite deposition can occur.

4.1.9 Initiation of Aeolian Systems

Well established aeolian environments predominately occur in the basin centre (Mountney *et al.*, 1998), however, smaller scale wind-blown environments also occur in interlobe settings in the proximal basin (Kocurek, 1981). The most common aeolian deposits are dune forms, which initiate during periods of drying upwards in ACC, becoming progressively more established towards the point of maximum aridity. Dry interdunes are also commonly deposited during periods of drying upwards and the point of maximum aridity, whereas wet interdunes more commonly occur during wetting upwards in the ACC, and either form due to an overall rise in the water table or due to an increase in meteoric water.

Towards the edges of the erg, where the available sediment is too sparse to facilitate the formation of dunes, sandsheets are common (Kocurek & Nielson, 1986). Similar to the climate needed to initiate dune growth, sandsheets occur at the point of maximum aridity, however unlike the dunes they occur subordinately during the wetting and drying upwards stages of the ACC. This is an instance where the preserved facies are controlled by sediment supply over climatic variations.

4.2 Response to Climate Variations

After the initiation of each depositional environment, the deposition then responds to further wetting or drying of the climate following the ACC. Eventually, deposition switches to another

environment, a response that is predictable in the depositional record (Fig. 5 and Fig. 6). These temporal changes in depositional environment at a single point in space can indicate an evolving climate signature. The following responses to climatic variation are observed within the depositional record of the Cutler Group (undifferentiated).

4.2.1 Talus cone

Increased humidity leads to more destabilisation of bedrock, as such, more deposition occurs within talus cone environments (Fig. 5A). A wetter climate leads not only to an increase in deposits from bedrock failure but also an increase in the amount of debris flows intercalated with talus cone deposits. With increasing aridity, there is an increased dominance of rock fall deposits as these are derived mainly from tectonic instability instead of climate. However, as rock falls act as background sedimentation along basin margins, and are predominately caused by tectonic instability, periods of depositional quiescence are also common. A drier climate also leads to deflation in the talus cone.

4.2.2 Sheetflood

Increased humidity leads to an increase in run-off and in turn, an increase in sheetflood events (Fig. 5B). When run-off increase is prolonged (e.g., during the Permian Megamonsoons) the sediment supply depletes as sediment is transported at a greater rate than it is generated causing the sheetflood deposits of the sink to fine over time. With increased aridity, sheetfloods are a less common depositional mechanism. Instead, run-off is commonly confined within fluvial channels.

4.2.3 Debris flow

Increased humidity leads to both an increase in the amount of debris flow deposition and the distance that these propagate in the basin meaning the deposits become thicker and more dominant in the depositional record (Fig. 5C). Eventually, wetter climates lead to a gradation into sheetflood deposits. It is also important to consider that water driven debris flows

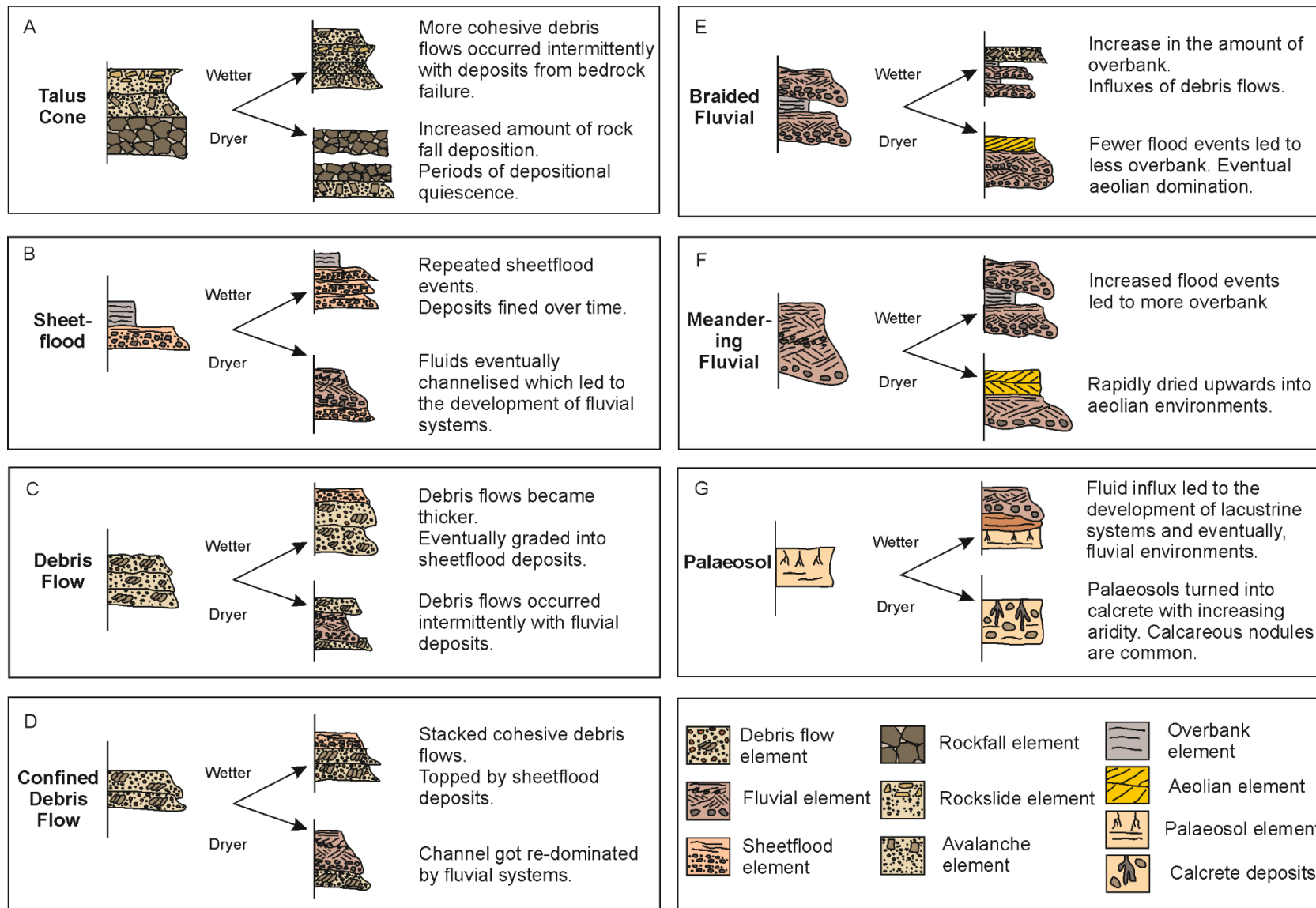


Figure 5. The response of the environments of the Cutler Group (undifferentiated) to climatic variations. A) Talus cone. B) Sheetflood. C) Debris flow. D) Confined debris flow. E) Braided fluvial. F) Meandering fluvial. G) Palaeosol.

(cohesive) travel further within basin margin depositional systems that air driven debris flows (non-cohesive). With increasing aridity, debris flows deposit less frequently deflate and begin to retrograde back towards the basin margin whilst the existing deposits deflate. Often, deposition is replaced with that of fluvial systems.

4.2.4 Channelised Debris Flows

In a similar manner to debris flows, with an increasing humidity there is an increase in the amount of channelised debris flow deposits, however, due to the utilisation of pre-existing channels these propagate even further into the basin (Fig. 5D). Again, wetter climates eventually lead to sheetflood deposits. Increasing aridity leads to fluvial systems becoming re-established within the remnant channel forms.

4.2.5 Braided Fluvial

With increased humidity, braided fluvial environments become more common alongside an increased amount of flooding events, and resultant floodplain deposition (Fig. 5E). Importantly, these braided fluvial systems are eventually overtaken by debris flows as the climate becomes wetter. Increasing aridity leads first to a reduction in the amount of deposition on the floodplain, followed by channel abandonment, and eventual dominance of aeolian processes.

4.2.6 Meandering Fluvial

Like the braided fluvial environment, the meandering fluvial environment becomes more prominent with increasing humidity (Fig. 5F). There is also an increase in overbank deposition. As meandering fluvial systems preferentially occur towards the basin centre, deposition does not grade into debris flows. With increasing aridity, meandering fluvial channels are rapidly abandoned and deflated until aeolian environments overtake deposition.

4.2.7 Palaeosols

With increasing humidity palaeosols are affected by an overall rise in the water table (Fig. 5G). Lacustrine bodies eventually form in areas of depression, followed by fluvial environments prograding into the basin. With increasing aridity, calcareous nodules begin to form throughout the palaeosols, eventually leading to calcrete formation indicating periods of maximum aridity.

4.2.8 Lacustrine

With increasing humidity lacustrine environments grow in extent within the basin centre and the resultant deposits become more substantial (Fig. 6A). This response is highly predictable. Increasing aridity leads to shrinkage of these lacustrine environments, leading to desiccation at the margins and eventual the eventual pedogenesis of these margins.

4.2.9 Aeolian

Aeolian dunes (Fig. 6B), wet (Fig. 6C), and dry (Fig. 6D) interdunes are part of a cohesive system when considering the response to climatic variations. Increasing humidity leads to a reduction in magnitude of aeolian dunes, as well as restricting bedform migration across the basin floor. There is also a coeval increase in amount of wet interdunes fed either from encroaching fluvial systems from the basin margin, leading to deposition of wadis, or from an overall rise in the water table. With increasing aridity, the wet interdunes dry-out leading to desiccation and occasional evaporite formation. As the wet interdunes dry they pass through a 'damp' stage, typified by the presence of adhesion ripples. Eventually, interdunes become dry, migration increases, and the dune forms grow. Increasing aridity also leads to a greater lateral extent of the aeolian erg.

Sandsheets occur at the margins of the erg where sediment supply is too low to facilitate dune growth (Fig. 6E). With increasing humidity fluvial systems prograde over the sandsheet, commonly sourced from the basin margin. With increasing aridity, the erg migrates over the sandsheet environments as it grows in size.

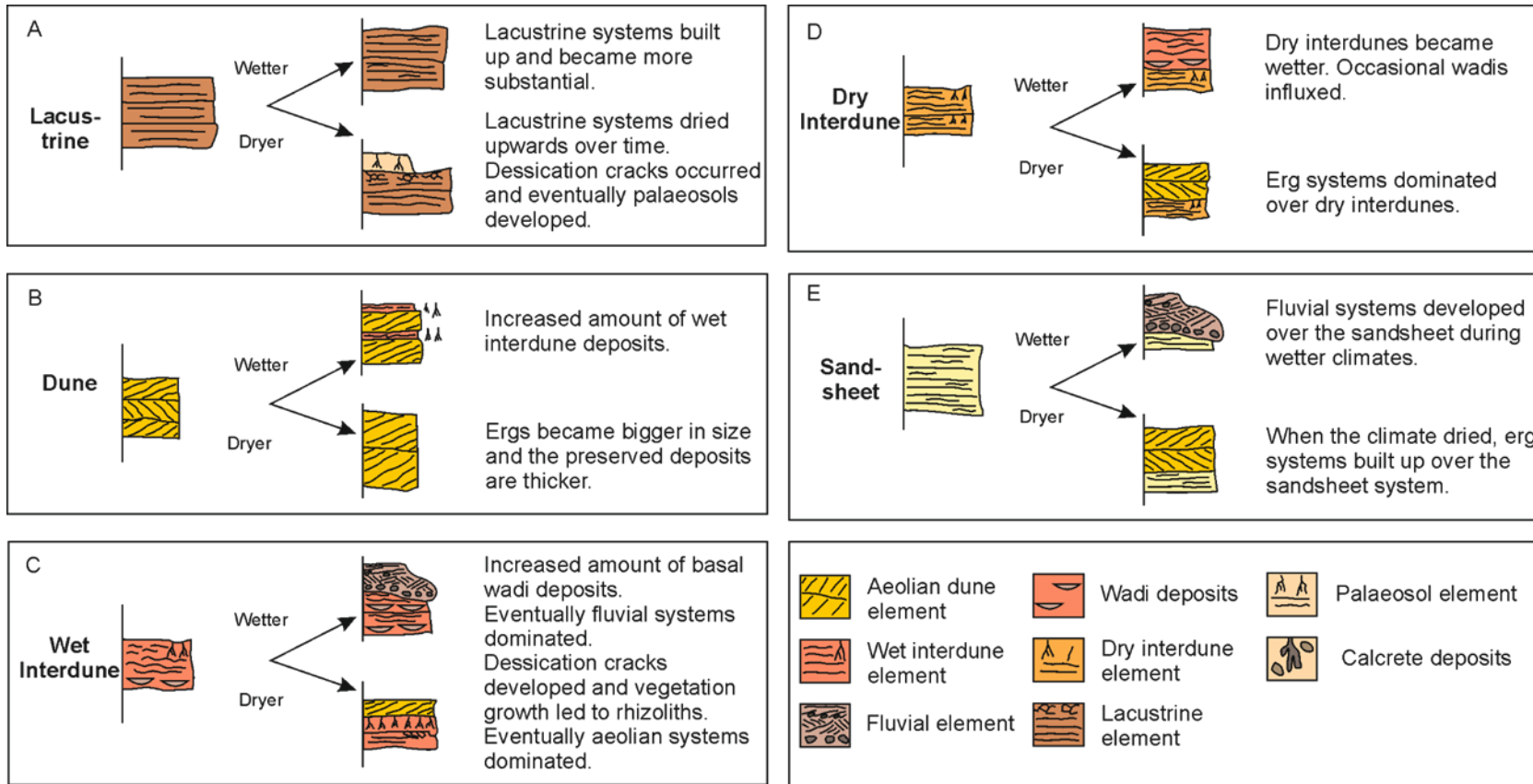


Figure 6. The response of the environments of the more distal Cutler Group (undifferentiated) to climatic variations. A) Lacustrine. B) Dune. C) Wet interdune. D) Dry interdune. E) Sandsheet.

DISCUSSION

Both lithostratigraphy and sequence stratigraphy have limitations when applied to deposits within continental settings as there is influence from both autogenic and localised depositional controls, and well as larger scale allocyclic variations, which all lead to spatial and temporal variations in subsequent deposits (Catuneanu, 2002). Establishing the response of arid continental basin margin deposits to this cyclic variation aids in the time-stratigraphical interpretation of the deposits. As intracontinental basins are isolated from the effects of sea-level sequence stratigraphy is not a plausible technique to understand the basin-scale correlation of the systems. It is also common that the deposits of continental margins experience extended periods of depositional quiescence or erosion (Shanley & McCabe, 1994) resulting in to missing time in the sedimentary record.

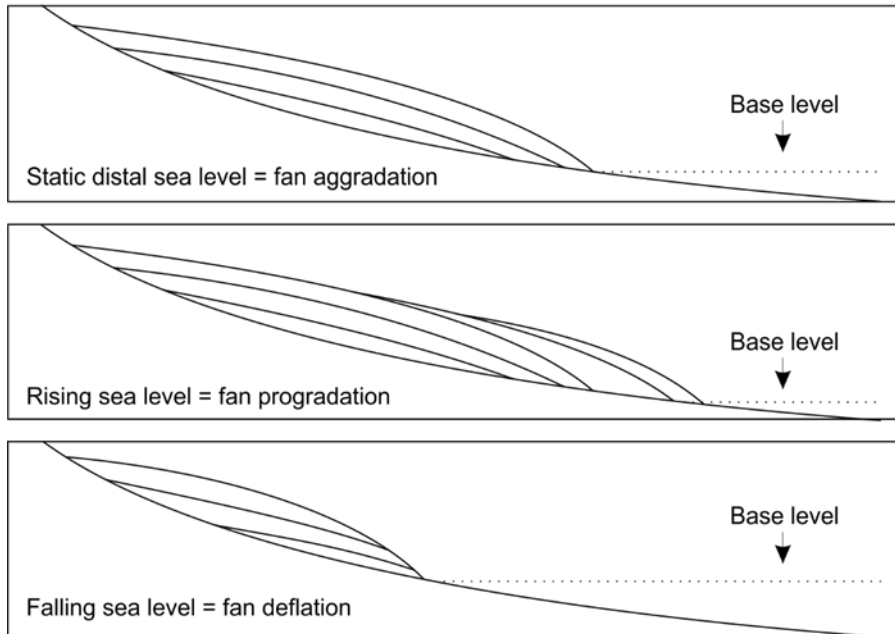
5.1 Spatial Controls

Climatic alterations alter the spatial distribution of arid continental deposits as they cause expansion and contractions of common depositional environments. For example, during increased humidity alluvial fans prograde into the basin. In contrast to this, a drier climate causes fan retrogradation. It should be noted that fans naturally prograde over time, regardless of climate (Harvey *et al.*, 1999). Spatial controls have been described by Howell and Mountney (1997) in the continental deposits of the Rotliegend Group, North Sea.

5.2 Preservation potential

The preservation of sedimentary deposits is directly related to base level, the definition of which for continental deposits is commonly divided into 'dynamic' and 'stratigraphic' base level. 'Dynamic' base level (Fig. 7a) is considered as the point of sea level (Bates & Jackson, 1987), but as the depositional environments of the Paradox Basin were isolated from marine environments in the late Carboniferous to Permian, the use of this is problematic in the case of the Cutler Group (undifferentiated). As such, this work uses the concept of 'stratigraphic' base level (Fig. 7b), which is considered to be point of equilibrium where neither deposition or

(a) Dynamic base level



(b) Stratigraphic base level

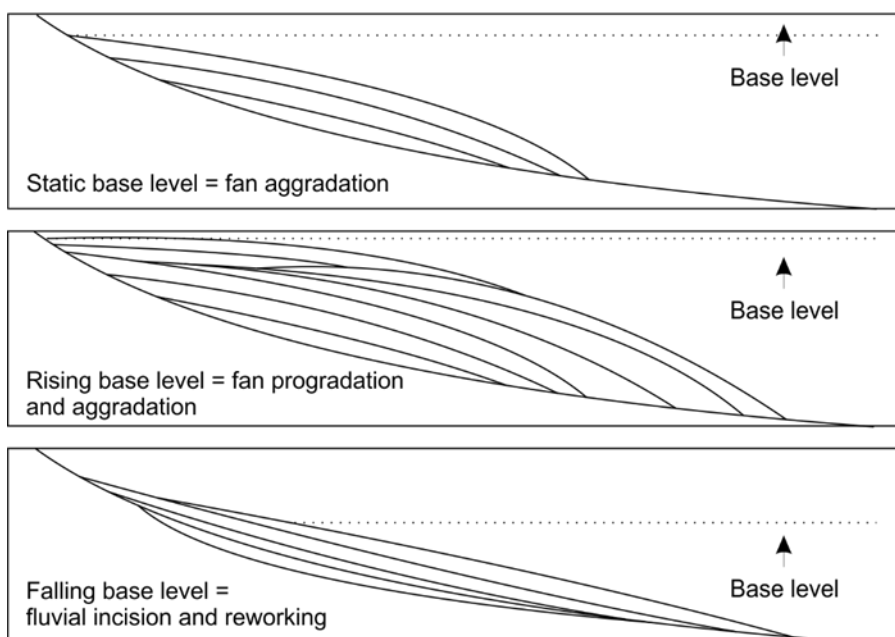


Figure 7. Base level in alluvial fans is either described as 'dynamic' or 'stratigraphic'. 'Dynamic' base level is the point of sea level in the distal basin. Sea-level rise leads to fan progradation, whereas sea-level fall leads to fan deflation. 'Stratigraphic' base level is the line of equilibrium where no deposition or erosion occurs. A rise in the 'stratigraphic' base level leads to fan aggradation and progradation whereas falling base level leads to fluvial reworking. This work focuses mainly on the idea of 'stratigraphic' base level. After Bates & Jackson, 1984; Harvey, 2002; Sloss, 1962; Wheeler, 1964.

erosion occurs (Wheeler, 1964; Sloss, 1962). The main effect of changing stratigraphic base level on basin margin deposits is to the profile of the fan surface fluvial systems (Blissenbach, 1954). If the base level stays static, fluvial influence tends to weaken, which leads to an increase in debris flow deposits (Harvey, 2002). As the rate of sediment accumulation and subsequent preservation can change the sediments deposits within a basin margin system, care is needed when trying to use cyclicity to correlate across a basin. On top of base level, the amount of preservation is controlled both by depositional environment and climate at the time of deposition. The preservation potential of the deposits described from the Cutler Group (undifferentiated) is detailed in Figure 8.

As the talus cone overlaps onto the steep hinterland, the deposits are unstable and often rework in due to destabilisation and remobilisation. Sheetfloods are sourced when the meteoric water in the feeder channels of the talus cone outpaces capacity. As sheetfloods lead to laterally extensive deposits, the top surface is often channelised by subsequent fluvial systems. The base of the sheetflood is often preserved, especially if it becomes vegetated and subsequently stabilised. The loose sediment of the talus cone is the main source for debris flows which are mobilised due to either over-steeping of the talus cone or due to the entrainment of fluid in the deposits. As debris flows deposit in the piedmont zone and are coarse-grained, the preservation potential is relatively high, despite depositing above base level. The preservation of channelised debris flows is elevated still as the deposits are constrained within a channel form.

The fluvial systems of the Cutler Group (undifferentiated) are disconnected from marine influence and commonly die out in the basin centre. Close to the source fluvial systems deposit above stratigraphic base level but incise below this by the basin centre. The majority of the Cutler Group (undifferentiated) fluvial systems were ephemeral. The seasonal re-introduction of water led to a degree of reworking of the fluvial (and fan surface) sediments. It is noted that episodic hyperconcentration of sediment in ephemeral systems can lead to both rapid

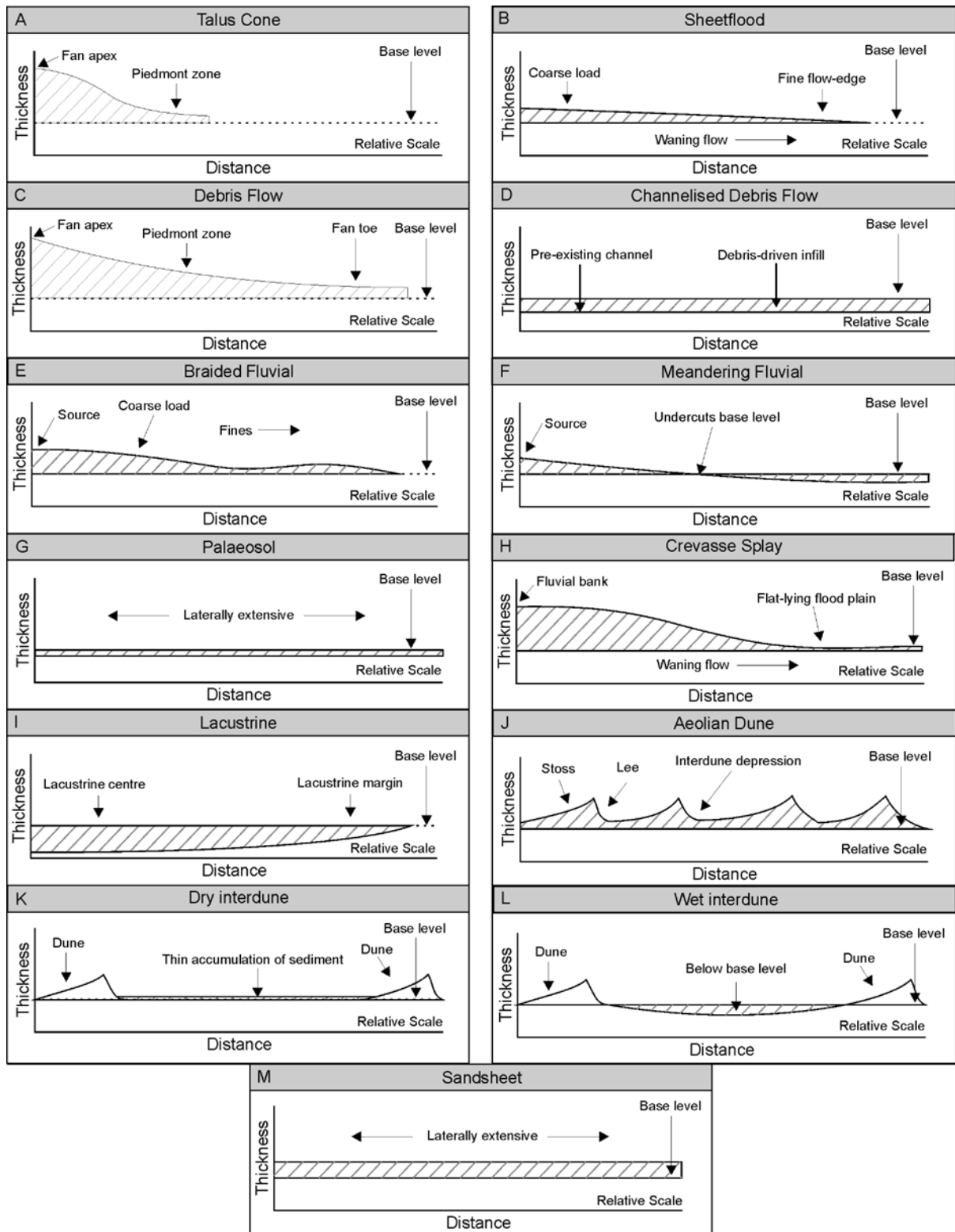


Figure 8. Each of the architectural elements extend for varying distances in both thickness and in lateral distance within the basin. Both the thickness and distance can alter depending upon the dominant climatic regime, and the amount of sediment supply during deposition, therefore the scales are relative to these inputs, but the size of these environments relate to fan-scale deposition. After deposition, the nature of the systems directly relate to the preservation potential; A) talus cone, B) sheetflood, C) debris flow, D) channelised debris flow, E) braided fluvial, F) meandering fluvial, G) palaeosol, H) crevasse splay, I) lacustrine, J) aeolian dune, K) dry interdune, L) wet interdune, and M) sandsheet.

deposition and an increased preservation potential (Pierson, 2005). Avulsion in braided fluvial systems can lead to vegetation and stabilisation of the floodplain, as evidenced by the palaeosols of the Cutler Group (undifferentiated). As palaeosols are naturally stabilised by vegetation, the preservation potential is high. These floodplain settings also saw episodic deposition from crevasse splays. These have relatively high preservation potential, unless a secondary flood occurs at the same breach point, reworking the initial deposits.

As lacustrine deposits occur below stratigraphic base level, the preservation of the deposits depends on the water depth. For example, thicker lacustrine deposits are preserved in the centre of the lake body, thinning towards the margins. As it is difficult to rework sediments deposited below base level these lacustrine systems have a high preservation potential.

Aeolian sediment is easy to remobilise unless there is some early-stage diagenetic cementation or a coeval rise in the water table increasing cohesion of the deposits. Wet interdunes have a high preservation potential due to increased sediment cohesion due to being wet. Dry interdunes have lower preservation potential, often preserved as thin and parallel bedded sandstone bodies. Finally, as sediment moves across sandsheets in a state of bypass, the migratory bedforms have a low preservation potential, apart from thin sandstone beds.

5.3 Cyclicity in the Paradox Basin

The Paradox Basin has localised alterations in base level which led to the creation of small-scale accommodation space, progradation or retrogradation of the system, as well as the occurrence of secondary time-equivalent depositional environments. An example of localised variations in base level is where underlying evaporates led to the generation of salt-controlled mini-basins (Banham & Mountney, 2013). The salt walls developed parallel with the basin margin and acted as a restriction to depositional systems throughout this complex area. As a result of this, it is difficult to assume a constant rate of base-level change when analysing both the depositional features and the cyclicity. These alterations in base level can also affect the cyclicity in the deposits, which can override the climatic cyclicity.

Contemporaneous environments often interact within basin margin systems leading to the juxtaposition of varying ages of deposits along the same lithological horizons. Use of climatic cyclicity can mitigate the effects of this to a certain extent. For example, aeolian deposition occurs in more arid climates and will therefore correlate to contemporaneous basin centre deposits that display similar aridity. The diachronous nature of the deposits can also result from the lateral arrested development of the basin margin environments. In addition to this, the effects of alluvial fan lobe switching can have an effect on the depositional systems observed at outcrop scale, depending on lobe exposure. Analysis based on climatic variations gives a framework by which to understand the correlation of these deposits, but the controlling factor of climate is not as predictable as sea-level in the marine environments. Additional studies could add to the nature of these correlation surfaces, for example key stratigraphic surfaces can be identified using detrital grain analysis to assess changes in lithological composition (Amorosi & Zuffa, 2011).

CONCLUSIONS

Depositional environments in arid continental basin margin settings respond differently to wetting and drying cycles observed in the given absolute climatic cycle. For example, when the climate undergoes a period of wetting, the coarse-grained proximal deposits transmute upwards into debris-driven depositional environments, whereas if the climate dries, the system becomes overtaken by fluvial processes. The talus cone element is the exception as it becomes dominated by bedrock failure-driven depositional mechanisms. Water driven processes grade into debris-flows with increased meteoric water in the system, whereas drying causes aeolian depositional environments to dominate deposition in the basin. These observed responses to climatic cyclicity are applied to logs taken from exposures across the Paradox Basin in order to determine the climate at the time of deposition. This can be used to evaluate how the basin sediments cyclostratographically correlate as a whole. It is also important to evaluate the effect of preservation potential. Environments that deposit below 'stratigraphic' base level are easier to preserve in the sedimentary record.

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