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Origin, Evolution and Anatomy of Silt-prone Submarine External Levées

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ABSTRACT

Submarine external levées are constructional features that develop outside slope channel systems, and are a volumetrically significant component of continental margins. However, detailed observations of their process sedimentology and depositional architecture are rare. Extensive exposures of external levées at multiple stratigraphic intervals and well constrained palaeogeographic positions in the Fort Brown Formation, Karoo Basin, South Africa have been calibrated with research boreholes. This integrated dataset permits their origin, evolution and anatomy to be considered, including high-resolution analysis of sedimentary facies distribution, and characterisation of depositional sub-environments. Initiation of external levée construction is commonly marked by deposition of a basal sand-rich facies with sedimentary structures indicating rapid deposition from unconfined flows. These deposits are interpreted as frontal lobes. Propagation of the parent channel, and resultant flow confinement, leads to partial erosion of the frontal lobe and development of constructional relief (levées) by flow overspill and flow stripping. Overall fining- and thinning-upwards profiles reflect increased flow confinement and/or waning flow magnitude through time. Identification of a hierarchy of levée elements is not possible due to the absence of internal bounding surfaces or sharp facies changes. The downslope taper in levée height and increasing channel sinuosity results in increasing numbers of crevasse lobe deposits, and is reflected by the increased occurrences of channel avulsion events downdip. External levées from the Fort Brown Fm. are silt-rich; however their origin, evolution, and distribution of many components (sediment waves, crevasse lobe) share commonalities with mud-rich external levées. An idealised model of the stratigraphic evolution and depositional architecture of external levées is presented, and variations can be attributed to allogenic (e.g. sediment supply) and autogenic (e.g. channel migration) factors. This study provides a reference point to encourage further investigation and testing via numerical and physical experiments, and mapping of high resolution seismic and outcrop datasets.

INTRODUCTION

Submarine levées are often readily identifiable in subsurface seismic and seabed datasets as constructional features that taper away from submarine channel systems and can be kilometres-wide and 10s to 100s of metres thick (e.g. Buffington, 1952; Normark et al., 1980; McHargue and Webb, 1986; Flood and Piper, 1997; Hiscott et al., 1997; Clemenceau et al. 2000; Migeon et al., 2000; 2001; 2004; Babonneau et al. 2002; 2010; Piper and Normark, 2001; Mayall and O'Byrne, 2002; Skene et al., 2002; Deptuck et al., 2003; 2007; Posamentier, 2003; Posamentier and Kolla, 2003; Schwenk et al., 2005; Wynn et al., 2007; Carmichael et al., 2009; Nakajima and Kneller 2013). There is a physiographic difference between external levées (also referred to as *'high-levées'* (Piper et al., 1999) or '*master-bounding levées'* (Posamentier, 2003; Kane et al., 2007)) and internal levées (also referred to as *'inner levées'* (Hübscher et al., 1997; Babonneau et al. 2004; 2010); and *'confined levées'* (Piper et al., 1999; Kane et al., 2007)) *sensu* Kane and Hodgson (2011). External levées that bound channel-belts are built by deposition from the low density upper part of density stratified turbidity currents that overspill erosional or constructional confinement of the related submarine channel system (e.g. Cronin et al., 2000; Hickson and Lowe, 2002; Beaubouef 2004; Kane et al., 2007; Kane and Hodgson, 2011). External levées are generally mud- and silt-rich, although sand-rich external levées (Mayall and O'Byrne, 2002), sand-rich components within external levées (Hiscott et al., 1997), and levées with clay to pebble grain-size ranges (Dykstra et al. 2012) have been documented.

An overall fining- and thinning-upward trend in an external levée succession is commonly reported, which is interpreted to be due to increasing confinement and reducing overspill of turbidity currents through time (e.g. Hiscott et al., 1997; Peakall et al., 2000; Posamentier, 2003; Schwenk et al., 2005). Sand-rich deposits have been found toward the bases of external levées in both modern and ancient examples (Damuth et al., 1988; Clemenceau et al., 2000), which have been interpreted to be deposits from crevasse and avulsion processes and/or earlier frontal lobes that have been overlain by younger levée deposits as the parent channel lengthened (Flood et al., 1995; Flood and Piper, 1997; Kane and Hodgson, 2011). The large-scale architecture and main components of external levées, including sediment waves and crevasse deposits, have been documented from seismic and seabed datasets, however the distribution of sedimentary facies remains poorly constrained. Where the distribution of grain-size and bed thicknesses has been constrained channel proximal to channel distal trends have been identified, i.e. beds are thinner, finer and indicative of lower energy further away from the channel (DeVries and Lindholm, 1994; Piper and Normark, 1997; Beaubouef, 2004; Kane et al., 2007; Kane and Hodgson, 2011). Currently, however, there is no comprehensive assessment of the sub-seismic characteristics and components of external levées. In part, this is because exhumed examples tend to be described from single outcrops, the palaeogeographic context is not always well constrained, and cores and well logs are rarely positioned to intersect these fine-grained features.

Here, however, multiple examples of exhumed silt-rich external levées of the Permian-aged Fort Brown Formation, Laingsburg depocentre, Karoo Basin, South Africa are described in detail. Regional mapping (Di Celma et al. 2011; Brunt et al. 2013a) allows the position of external levée successions on the palaeoslope and their relationship to the parent channel system to be constrained. The multiple outcrop examples are augmented by several fully cored research boreholes that intersect external levées. This unique integrated core and outcrop dataset allows the following objectives to be addressed: i) to describe the depositional architecture and components of multiple external levée successions; ii) to document the distribution of sedimentary facies, and the components of external levées; iii) to discuss the origin and sub-seismic evolution of external levées; and iv) to compare silt-rich external levées with their mud-rich counterparts. The significance of this study is that it syntheses for the first time the origin, sedimentary process evolution, and depositional architecture of multiple silt-rich external levée, which are a major component of continental slope stratigraphic record.

SEDIMENTOLOGY AND KEY ARCHITECTURAL COMPONENTS OF EXTERNAL LEVÉES

Process sedimentology of a levée

External levées are built by sediment-laden flows that undergo two main processes of overbanking; i) flow stripping and ii) overspill (Peakall et al., 2000; Kane et al. 2010). Flow stripping was originally described as a process whereby large-to-medium magnitude stratified flows split into two main components as the flow navigates a channel bend; the coarser fraction of the flow remains confined by the channel, whereas the upper finer grained fraction escapes confinement, depositing beyond the levée crest (Piper and Normark, 1983; Bowen et al., 1984; Leeder, 1999; Peakall et al., 2000). Overspill is the process that occurs when a turbidity current is thicker than the depth of channel confinement, allowing part of the flow to escape beyond the crest of the external levée (Hay et al., 1982; Clark and Pickering, 1996; Hübscher et al., 1997).

When individual flows escape from channel confinement they undergo expansion, resulting in rapid deposition. The bulk of the sediment within the flow is deposited in channel-proximal areas with individual beds thinning and fining away from the channel. Levées taper in thickness away from the channel because of this channel-proximal to channel-distal relationship, which controls the distribution of sedimentary facies and sand within a levée.

Components of an external levée

The characteristics of external levées vary depending on grain-size range, stratal relationship to the channel, conduit history etc., which are discussed in more detail below; however there are some general features that are common to most systems and have been described in the literature. Figure 1 illustrates the broad scale geometry and common characteristics of an external levée as described from reflection seismic and sidescan sonar datasets (e.g. Clemenceau et al., 2000; Migeon et al., 2000; 2001; 2004; Skene et al., 2002; Deptuck et al., 2003; 2007; Babonneau et al., 2010) and outcrop observations (Hickson and Lowe, 2002; Browne and Slatt, 2002; Beaubouef, 2004; Kane et al., 2007; Figueiredo et al., 2010; Campion et al., 2011; Kane and Hodgson, 2011; Khan and Arnott, 2011). Kane and Hodgson (2011) provided a scheme to sub-divide external levées about the external levée crest, which is the highest point of the external levée and is aligned sub-parallel to the channel belt. Levée crests might be constructional where there is stratigraphic continuity with the conduit-fill and separate strata that dip towards the channel from strata that dip away from the channel, or form cut crests where erosion and/or remobilisation results in lateral stratigraphic discontinuity (Kane and Hodgson, 2011). The inner external levée refers to the area channel-proximal to the levée crest (Kane et al., 2007; Kane and Hodgson, 2011). The deposits are more sand prone due to their proximal location and are also prone to instability and mass movement toward the channel conduit.

The outer external levée refers to the area outboard of the levée crest (Kane et al., 2007; Kane and Hodgson, 2011), where overall the deposits are thinner and finer grained compared to inner external levée areas with rare soft-sediment deformation (Kane et al., 2007; 2010).

Here, this broad scale subdivision of an external levée relative to the levée crest is modified to account for proximity to the channel through time and space.

GEOLOGICAL SETTING AND STRATIGRAPHY

The study area lies within the Laingsburg depocentre, SW Karoo Basin, South Africa (Figs. 2 and 3), which is interpreted to be part of the fill of a retroarc basin (e.g. Cole, 1992; Visser, 1993; Veevers et al., 1994) where subsidence was initially load-driven through dynamic subduction and later dominated by flexural loading of a retro-arc thrust belt during the Triassic (Tankard et al., 2009). The progradational basin-floor to upper-slope succession shown in Figure 3 (A and B), is over 1.4 km thick (Flint et al., 2011) and crops out along a series of east-west trending, eastward plunging, post depositional anticlines and synclines, near the town of Laingsburg, Western Cape, South Africa. Deep-water deposition began with the distal basin-floor Collingham and Vischkuil Formations (Van der Merwe et al., 2009; 2010). These deposits are overlain by basin-floor and base-of-slope fan systems of the Laingsburg Formation (Units A and B; e.g., Sixsmith et al., 2004; Brunt et al., 2013a; Fig. 3A). The overlying muddy slope succession of the Fort Brown Formation, the focus of this study, is punctuated by sandstone rich Units C-G, which comprise slope channel-levée systems (Grecula et al. 2003; Figueiredo et al. 2010; Hodgson et al. 2011; Di Celma et al. 2011; Fig. 3A), which crop out as a series of prominent ridges separated by recessive mudstone units. The deep-water succession is late Permian in age (Fildani et al. 2009).

A long-lived sediment entry point is interpreted SW of the closure of the Baviaans syncline that was active during the deposition of Units B, C and D (Di Celma et al. 2011; Hodgson et al. 2011; Brunt et al. 2013a). During the deposition of Unit E the main input point was along strike to the north with incisional channels identified in the Zoutkloof and Heuningberg areas (Figueiredo et al. 2010; 2013).

Unit C is the lowermost sandstone-prone unit of the Fort Brown Formation, and it includes two regional mudstones that separate the succession into sand-prone Sub-units C1, C2, and C3 (Di Celma et al., 2011). Each sub-unit is interpreted as a lowstand systems tract, with Unit C forming a lowstand sequence set that, combined with the overlying 25 m thick regional mudstone (separating Units C and D), forms a composite sequence (Flint et al., 2011). Di Celma et al. (2011) mapped and described a basinward progradational trend from Sub-unit C1 to C2, with a landward stepping/retrogradational component during the deposition of Sub-unit C3, suggesting a waxing then waning of overall flow energy and volume throughout Unit C time. In proximal areas of the Baviaans syncline Sub-unit C2 comprises an external levée-confined channelised system that incises through C1 and removes 30 m of the underlying mudstone between Unit B and Sub-unit C1 (Hodgson et al., 2011; Di Celma et al., 2011).

In proximal areas of the Baviaans syncline, Unit D, which is interpreted as a second lowstand sequence set (Flint et al., 2011), crops out as a 2 km apparent width, >100 m thick, entrenched slope valley fill. The fill of the slope valley is bounded by a composite erosion surface and external levées; a 70 m (maximum) thick western levée and a 30 m (maximum) thick eastern levée (Hodgson et al., 2011). Down-dip, Unit D becomes less entrenched, and confined by external levées (Brunt et al., 2013b) before transitioning to unconfined terminal lobe deposits over a distance of >80 km.

Unit E and Unit F with their overlying regional mudstones (E-F mudstone and F-G mudstone) each comprise a lowstand sequence set of a composite sequence, with each lowstand sequence set comprising three sequences (Sub-units E1, E2 and E3, and Sub-units F1, F2, F3; Flint et al., 2011; Figueiredo et al., 2010).

By area and volume, the thin-bedded sandstone- and siltstone-prone heterolithics interpreted as external levée deposits form the major constituent of lithostratigraphic units in the Fort Brown Fm. (Figueiredo et al. 2010).

METHODOLOGY AND DATASET

Field-based sedimentological and stratigraphic observations include 37 measured sections (1.6 km cumulative thickness logged at 1:50), 23 sections on the southern limb of the Heuningberg anticline and 14 sections on the southern limb of the Baviaans syncline (Fig. 3). External levée deposits have been described and interpreted in detail (logged at 1:10) from three cored research boreholes (Bav 1A, Bav 2 and Bav 6), drilled behind outcrops of the informally named CD Ridge (Hodgson et al., 2011) allowing for subsurface correlation and calibration. The geometry of external levées has been constrained using the regionally mapped mudstones as datums (Figueiredo et al., 2010; Di Celma et al., 2011; Hodgson et al., 2011).

SEDIMENTARY FACIES ASSOCIATIONS

Sedimentary facies identified in the Fort Brown Fm. have been described in detail previously (Figueiredo et al. 2010; Di Celma et al. 2011; Hodgson et al. 2011; Morris et al. in press). Here, we focus on the external levée successions, where seven main sedimentary facies associations have been identified: **Lf1 –** Siltstone-prone thin-bedded heterolithics; **Lf2 –** Sandstone-prone thin-bedded heterolithics; **Lf3 –** Sandstone-prone thick bedded heterolithics; **Lf4 –** Structured sandstone; **Lf5 –** Thick siltstone bedsets; **Lf6 –** Siltstone and mudstone couplets; and **Lf7 –** Deformed deposits. Description and interpretations of these facies associations are illustrated in Table 1.

CD RIDGE –EXTERNAL LEVÉE ARCHITECTURE

On the southern limb of the Baviaans syncline, Sub-unit C2 (Figs. 4 and 5) crops out at the CD Ridge, as a submarine channel system confined by external levées. The full lateral extent of the C2 channel complex set is not preserved as Unit D locally incises through the entire Unit C stratigraphy forming an entrenched slope valley, with an apparent width of ~2 km and >100 m deep. The architecture of the Sub-unit C2 channel complex set and Unit D entrenched slope valley fill was captured through field observations and mapping by Hodgson et al. (2011). Six fully cored research boreholes were later drilled on the CD Ridge. Bav 1A and Bav 2 captured the proximal external levée of Unit D whereas Bav 6 captured C2-aged distal external levée deposits.

Unit D external levée – CD Ridge

The CD Ridge outcrop is a rare example where the conjugate external levées of a slope valley are preserved in cross-section (Fig. 4). The unique dataset of outcrop and behind outcrop research boreholes enables detailed characterisation of the sedimentary facies and grain-size distribution, stratal relationships and relation to the genetically related channel to be defined within a well constrained geometric framework.

Geometry

External levées are characterised by a wedge-shaped geometry, thinning and tapering away from their parent channel (Skene et al., 2002; Kane et al., 2007; 2010; Birman et al., 2009; Nakajima and Kneller, 2013). The wedge-shaped geometry has been documented in outcrop (Kane and Hodgson, 2011) and reflection seismic studies (McHargue and Webb, 1986; Kolla and Coumes, 1987; Clemenceau et al., 2000; Babonneau et al. 2002; Posamentier, 2003; Posamentier and Kolla, 2003).

The correlation panels in Figures 4 and 5 show the cross-sectional geometry of the Unit C and D external levées. This geometry is constrained through regional mapping of underlying sand-prone datums (BC interfan for Unit C and Sub-unit C3 for Unit D). There is no evidence of truncated beds or basal erosion at outcrop, so the wedge geometry is depositional in nature. It has not been possible to calculate accurately the mathematical description of the shapes of the wedge, following Nakijima and Kneller (2013) as the top of the Unit D external levee is poorly constrained.

Palaeocurrents

The palaeocurrent roses show the data collected from measurement of ripple lamination in the external levées of Unit D (Fig. 5). The proximal external levée shows a dispersive pattern (variation over 180°) with palaeocurrents trends towards the NW and the ENE are recorded in the lowermost 10 m of the lower proximal external levée. The more distal levées of both D and C2 show a uniform, narrow distribution of palaeocurrents towards the E.

The more dispersive distribution of palaeocurrents in the lower proximal external levée is likely to be a function of sampling and limitations of the outcrop, as there is a higher frequency occurrences of ripple and climbing ripple lamination in the lower proximal external levée compared to the more siltstone-rich upper proximal external levée. The decreasing sandstone content in the upper levée results in poorer quality outcrop from which to measure palaeoflow indicators. The narrow distribution of palaeocurrents in the distal external levée, which are at a slight angle to the general trend of the channels, is likely be a function of the dataset limitations, as measurements have been taken across one 2D (slightly oblique) cross-section through an individual levée from channel proximal to distal, and no other parts of the levée have been sampled for palaeocurrents. It is also possible that some topographical control at the time of deposition may have affected where and how the flows dispersed.

External levée asymmetry

The mechanisms that lead to external levée asymmetry are best understood using experimental techniques. There have been many studies that document flow behaviour and depositional characteristics within and outside channels (Peakall et al. 2007; Kane et al. 2008; 2009; 2010; Straub et al. 2008a; 2008b; Amos et al., 2010). Experimental investigations using straight and sinuous channels have shown that straight channels produce axi-symmetrical levées whereas asymmetric levées are associated with sinuous channels with higher/thicker outer bend levées and smaller inner bend levées (Straub et al., 2008a; 2008b). Observations of modern day channel systems indicate that the Coriolis Effect will deflect flows, preferentially building higher external levées on the right-hand side in the northern hemisphere and left-hand side in the southern hemisphere (Komar, 1969; Bowen et al., 1984; Kolla and Coumes, 1987; Skene 1998; Posamentier and Kolla, 2003; Cossu et al., 2010; Peakall et al. 2012). The impact of the Coriolis Effect has been documented in flume tank experiments where the tanks are able to rotate in order to account for the Coriolis Effect (e.g. Cossu et al. 2010, Wells and Cossu 2013). Asymmetry in grain-size profiles is also recorded in external levées with the outer bend levée being coarser grained than the inner bend levée attributed to super-elevation of overspilling flows as they navigate channel bends (Peakall et al., 2007; Straub et al., 2008b; Kane et al., 2010; Amos et al., 2010).

The correlation panel in Figure 5 shows that the Unit D external levées are asymmetric, with a maximum thickness of 70 m on the western side of the D slope valley and 30 m on the eastern side. Hodgson et al. (2011) reported that the Unit D slope valley also preserves an asymmetric fill with remnants of channel elements and channel complexes preserved within the slope valley recording an initial westward stacking, and a younger aggradational stacking pattern towards the western edge of the valley. This prolonged, westward stacking pattern is interpreted to have resulted in preferential overspill to the west and the construction of a higher western external levée. This effect may have been accentuated by a long lasting bend in the slope valley, and/or the influence of the

Coriolis Effect that led to more overspill and flow stripping onto the western levée. In the late Permian, the western levée would have been the palaeo-north levée in a mid-latitude (60° South) setting (e.g. Faure and Cole, 1999), which is an ideal situation for the influence of the Coriolis Effect and the construction of a larger levée.

Depositional environments of external levées

Using the distribution of sedimentary facies, bed thicknesses and downlap patterns, the external levée is subdivided into lower proximal external levée (Fig. 6), upper proximal external levée (Fig. 7) and distal external levée (Fig 8). Upper and lower proximal external levée in part incorporates inner external levée (Kane and Hodgson 2011) whereas distal external levée only relates to the outer external levée (Kane and Hodgson 2011).

Proximal external levée

Within the western proximal external levée of Unit D on the CD Ridge an abrupt facies change takes place across a thin fining- and thinning-upward unit to a siltstone-prone succession (Fig. 5 and 6) at 25 m above the base. This change allows division of the proximal external levée into two sections based on facies characteristics; lower proximal external levée and upper proximal external levée, although the change is likely to be time transgressive along the length of an external levée.

Lower proximal external levée

Description: In the lower proximal external levée succession in core from borehole Bav 1A, the lowermost 25 m of Unit D comprises thicker bedded (0.1-0.4 m) very fine sandstone and coarse siltstone beds dominated by Lf3 and Lf4 (Fig. 6C and D). Decimetre-scale erosion surfaces are present and the dominant sedimentary features are aggradational sinusoidal bedforms and stoss-side preserved climbing ripple cross-lamination. Individual beds can be walked out for over 450 m laterally as they thin, fine (to Lf1) and downlap onto the underlying mudstone.

Interpretation: The highly aggradational nature and unidirectional palaeocurrents towards the NW indicate rapid deposition from turbidity currents. This is interpreted as a response to rapid flow expansion downstream from channel mouths and/or from overspill adjacent to confinement. The presence of small scale erosion surfaces suggests that flows were occasionally of a high enough viscosity and velocity to rework the top of beds.

Upper proximal external levée

Above the 20-25 m position in both core and at outcrop, the entire levée becomes finer grained (~5-10% very fine-grained sandstone) and thinner bedded, dominated by Lf5 (Fig. 6E and 6F). Sinusoidal and aggradational bedforms are observed, mud drapes and bioturbation are more abundant, and erosion is rare, as the beds thin and fine upwards through the upper proximal external levée.

Interpretation: The fine grained and thin-bedded upper proximal levée succession indicates that only the upper dilute parts of flows could spill onto the levée as the height between the base of the flow and the levée crest increased through erosion and/or construction of the levée. The decreasing occurrence of erosion surfaces combined with the aggradational facies suggests that the turbidity currents were highly depositional and non-erosive as they escaped confinement and rapidly lost capacity.

Distal external levée

Unit D distal external levée (captured through field observations) is dominated by Lf1 and Lf2 (Fig. 7), beds are thin (0.01-0.15 m), however stoss-side preserved ripple cross-lamination and sinusoidal lamination is still present. Beds are laterally continuous but outcrop quality makes it difficult to follow individual thin beds more than 50 m laterally. Within the distal external levée deposits of Unit D, there is gradual thinning and fining upward pattern at outcrop.

The Sub-unit C2 distal external levée captured in Bav 6 (Fig. 8) is a thin-bedded (1-5 cm) succession dominated by current ripple laminae, mudstone drapes and associated low intensity bioturbation with 10-12% sandstone (Fig. 8). The lowermost metre of the levée (Fig 7A and 7C) is characterised by Lf1 before becoming Lf2 dominated. Overall, the 22 m thick unit fines and thins upward as shown by both the core and gamma ray logs in Figure 8.

Interpretation: The lateral facies change from the proximal to distal Unit D external levée succession is a consequence of flow expansion and loss of competence, resulting in deposition of the coarsest fraction of the flow in channel proximal locations.

Sedimentary facies and grain-size distribution

Detailed facies analysis of external levées has been carried out using both outcrop and core datasets to constrain the strike distribution of sedimentary facies. Figure 9 shows a synthesis of the facies distribution through a cross-section of an idealised external levée that has been constructed using data and observations from several external levée successions in sub-units C2, F2 and Unit D (using the facies recorded in Table 1). The eastern external levée of Unit D can be traced for 8 km where it thins and fines from 22 m adjacent to the D-cut to <0.5 m. Over this strike distance the sandstone content decreases from 50% to 7% whereas beds thin from an average of ~15 cm to 5 cm (Fig. 10). A strikingly similar decay rate in sandstone content from the levée crest is recorded from the conjugate western Unit D external levée (Fig. 10). Sandstone content decrease from the levée crest follows an exponential decay rate. An exponential decrease in sandstone percentage has also been recorded in the external levées in the Cretaceous Rosario Fm. (Kane et al. 2007). Although outcrop limitations preclude accurate analysis of bed thickness decay rates these are more gradual than the decrease in sandstone percentage away from the levée crest. This indicates that sand is preferentially deposited close to the levée crest.

Stratal relationship to surrounding stratigraphy (downlap)

In many 2D seismic cross sections through external levées, individual reflectors are observed to downlap onto underlying strata away from genetically related channels (e.g. Lopez, 2001). In external levées of the Fort Brown Formation, this downlap pattern is also observed as individual beds thin and fine laterally and downlap onto the underlying mudstones. This is documented in Unit D (Fig. 5) and Sub-unit F2 (Fig. 11), where sandstone beds have been walked out and correlated for up to 700 m obliquely across strike from their genetically related channel system. Individual beds show lateral facies changes where beds thin and fine away from the channel, with stoss-side preserved bedforms passing into low-angle (<10°) climbing ripple cross lamination and current ripple lamination.

BEDFORMS AND OTHER ARCHITECTURAL ELEMENTS

Sediment waves

Distribution and significance

Sediment waves are large-scale bedforms commonly found on the outer bend external levées where flow stripping processes are dominant, as well as areas of the continental rise and slope (Normark et al., 1980; Nakajima et al., 1998; Migeon et al., 2000; 2001; 2004; Lewis and Pantin, 2002; Wynn and Stow, 2002; Droz et al., 2003; Posamentier and Kolla, 2003; Deptuck et al., 2007; Campion et al., 2011). Wave crests are generally oriented perpendicular to the down-levée slope flow direction, generally parallel to the channel and they nearly always migrate upslope, opposite to the flow direction of the turbidity currents that build them (Wynn et al., 2002; Posamentier and Kolla, 2003). Sediment waves are typically composed of turbidite silts with occasional mm to cm thick beds of sand (Normark et al., 2002; Wynn and Stow, 2002); wavelengths range between 0.2-7 km and heights between 10-60 m but they can reach up to 100 m (Normark et al., 1980; Migeon et al., 2000;

2001; 2004). Sediment waves associated with channel-levées are considered to be sand-rich relative to sediment waves occurring on abyssal plains, upper submarine slopes and unchannelised slopes (Migeon et al., 2000), although few examples have been described from outcrop due to their scale and fine-grained nature (see Campion et al., 2011 for a notable exception).

Sub-unit E2: sediment waves at outcrop?

Sub-unit E2 comprises a series of very fine sandstone beds in a succession dominated by thin-bedded (1-5 cm) siltstones. The sandstone beds thicken and step towards the west to form a shingled stacking pattern (Fig. 12). Individual beds can be walked out for 100 m and become thicker (from 10-to-80 cm) and more amalgamated towards the west. The sandstone beds, where they are not amalgamated, are interbedded with coarse-to-very coarse grained siltstone. The sandstone beds contain climbing ripple cross-lamination, sinusoidal bedforms, stoss-side preserved climbing ripple cross-lamination and parallel lamination. The palaeocurrent distribution measured from ripples within the sandstone rich beds indicates a dominant SE direction within a very narrow range (Fig. 12D). This is opposite to the shingle and thickening direction (towards the NW).

Interpretation

The thick-bedded heteroliths (Lf3) and structured sandstone facies (Lf4) are characterised by dm-scale sinusoidal stoss-side preserved bedforms and low-to-high angle (10-25°) climbing ripple lamination, locally with stoss-side preservation. These sedimentary structures are indicative of deposition by continued unidirectional, non-uniform flows (Allen 1973; Kneller 1995) with high rates of sediment fallout, attributed to rapid flow expansion and deposition from moderate-to-low concentration turbidity currents as flows moved from confined to unconfined settings. The presence of the shingled and thickening bedsets at this locality (Fig. 12), which are stacked in the opposite direction to the palaeocurrents (Fig. 12D), suggest that this deposit is likely part of the upstream facing and migrating sand prone area of a sediment wave (Fig. 13). This interpretation is supported by an E2 channel to the southwest (Figueiredo et al., 2010), however, the silt-prone nature of the large bedform precludes confident interpretation. Posamentier and Kolla (2003) suggested that the presence of sediment wave fields on an external levée may result in an uneven sand distribution through thicker sand deposits becoming trapped on the steeper upstream facing sides of the wave (Fig. 13).

Crevasse lobes and channels

Crevasse lobes are deposits that form where sand-prone turbidity currents breach an existing external levée, and are commonly found beyond the outer bend of a sinuous channel (Damuth et al., 1988; Posamentier and Kolla, 2003; Fildani and Normark, 2004; Armitage et al., 2012; Brunt et al., 2013b; Maier et al., 2013). As the flows escape from confinement they undergo expansion, reducing carrying capacity and resulting in rapid deposition. Commonly, the flows form sheets as they spread laterally over large areas. Posamentier and Kolla, (2003) documented an example from the Gulf of Mexico covering 50 km^2. Continued breaching of the levée may lead to avulsion (Damuth et al., 1988; Armitage et al., 2012) and development of a crevasse channel as documented in Unit D by Brunt et al. (2013b).

Crevasse lobes:

Description: Anomalously thick (1-10 m) tabular packages of sandstone (outcrop width ranging from 100-2000 m) occur locally within an overall thinly bedded siltstone prone external levée successions. An example is presented within Unit D at Slagtersfontein (Fig. 2) where a 55 m-thick external levée succession overlies a 40 m-thick terminal lobe succession (Fig. 14). The external levée is punctuated by several sandstone packages (0.5 to 4 m in thickness), that comprise 30% of the succession (Fig. 14). The sandstone packages are up to one kilometre in width, but are mostly 100 - 200 m wide.

A tripartite structure is identified in individual beds of sandstone packages (Fig. 15): (1) The basal contact is sharp, with minor erosion, overlain by contorted or disaggregated thinly bedded sandstone / siltstone; (2) the middle section normally comprises structureless sandstone beds, although cross bedding and ripple cross lamination is also common, and (3) a sharp to gradational boundary separates the middle from upper section, which is typically finer grained and darker due to a more argillaceous composition and the inclusion of mudstone clasts and/or organic fragments (Fig. 15).

Crevasse lobes:

Interpretation: The tabular sandstone packages found within thin-bedded external levée deposits are interpreted as crevasse lobes. When several packages are found together, such as at Slagtersfontein, they form a crevasse lobe complex, which suggests a long lived spill point (Fig. 14). Thin crevasse lobes or individual beds may represent a single levée breach event (Fig. 15). The basal surface and contorted bedding represent part of the external levée that becomes remobilised during failure. The overlying sand is deposited from the heads of within-channel turbulent currents that spill through the levée breach. Rapid flow expansion leads to a drop in the sediment carrying capacity and consequently rapid sedimentation (Hiscott, 1994; Kneller, 1995). Structureless sandstones are the likely result of this capacity driven sedimentation (Kneller, 1995); however the common occurrence of climbing ripples and cross bedding within crevasse lobes suggests maintenance of flow capacity, perhaps through flow acceleration due to the gradient of the external levée. The upper division is interpreted to form through becoming charged with finer-grained sediment during the levée breach forming a cohesive tail to the flow, and a deposit that shares affinities with a linked debrite (Haughton et al. 2009). Terlaky and Arnott (Accepted Article) have described matrix-rich sandstone beds that they interpreted as deposits of upflow avulsion. associate with interpreted avulsion splays, and erosion of levees.

DISCUSSION

Stratigraphic evolution of an idealised external levée succession

The synthesis of observations and interpretations from multiple external levée successions in the Fort Brown Fm. permits an idealised stratigraphic evolution to be developed. Figures 16 and 17 illustrate the main architectural elements and their common stratigraphic and geographic distribution in external levées. Commonly, levée initiation is marked by a basal sand-rich facies with sedimentary structures that indicate rapid deposition from unconfined sand-rich flows. These successions are interpreted to be partially preserved frontal lobes (or frontal splays) and refers to deposits from unconfined flows that form sand-rich units with high amplitude continuous reflection seismic character basinward of levéed channels (Flood and Piper, 1997; Posamentier and Kolla, 2003). A frontal lobe may not be present due to a lack of accommodation, and they are more commonly identified farther down the slope. Commonly in the Fort Brown Fm., frontal lobes have been partly removed by basinward propagation of genetically-related channels systems, as interpreted in Unit B (Brunt et al. 2013b), Unit C (Kane and Hodgson 2011; Hodgson et al. 2011), Unit D (Brunt et al. 2013a) and Units E and F (Figueiredo et al. 2010; Brunt et al., 2013a, b). Similar evolutionary trends where basal frontal lobes are partially eroded by a genetically-related channel and overlain by external levées have been described in the subsurface (Flood and Piper, 1997; Lopez, 2001; Babonneau et al., 2002; Fonnesu, 2003; Ferry et al., 2005; Bastia and Radhakrishna, 2010; and Maier et al., 2013) and outcrop (Gardner et al., 2003; Beaubouef, 2004). The feeder channel can cut through the frontal lobe anywhere from the axis, resulting in a forward stepping frontal lobe stacking pattern, to the fringe, producing a laterally offset stacking pattern (see Morris et al. in press).

Flow stripping and overspill processes build levées that increase flow confinement resulting in channel propagation. The consequence is preferential filtering of the finer and more dilute parts of stratified flows and the initiation of external levées. Further progradation of the channel will increase flow confinement through a combination of both levée construction and erosion, and therefore, increasingly dilute parts of stratified flows overspill, and individual beds recorded in the levée become thinner and finer grained. This study of exhumed external levées supports lower resolution observations on their depositional architecture from seismic datasets and confirms that the wedge shaped geometry is controlled by downlap of beds that fine and thin away from the channel (Fig. 5, 11, 16). Asymmetry of levée geometry and architecture is controlled by in-channel processes such as channel sinuosity and stacking patterns, which also influences the distribution of sediment waves and crevasse lobes (Fig. 16, 17).

Average sedimentation rate on the external levée will decrease as confinement increases; it will be lowest around the time of highest confinement, and will increase again during aggradation of the channel system as confinement decreases. During the abandonment of the channel-levée system, either through aggradation of the entire system or up-dip avulsion, there is a reduction in the rate of sediment supplied to the external levée. Unit D at the CD Ridge is an example of an underfilled slope valley, recorded as a 25 m thick mudstone directly overlying the preserved remnants of the active fill, interpreted to have been deposited during the abandonment of the whole system.

External levées as a record of channel migration

External levée successions typically thin and fine upward due to increased flow confinement through time as the height between levée crest and channel base increases (Hiscott et al., 1997; Lopez, 2001; see D in Fig.6 and C2 in Fig. 8). However the amount of overspill from a flow is influenced by many parameters such as flow magnitude, channel curvature and the straight-line distance between the parent channel and the levée crest. Nonetheless, as external levées record sedimentation from multiple channel elements and channel complexes they could provide a more complete record of the evolution of the system, such as channel migration patterns, and number of channel complexes than the complicated stratigraphy preserved within the channel systems. For example, during a period of lateral stepping one external levée will become increasingly proximal to the active channel as the other external levée becomes more distal. Thicker and coarser beds will be deposited on the levée that the active channel is stepping toward, and a coarsening and thickening upward package may be recorded. In the case of the Unit D slope valley on the CD Ridge, the prolonged westward migration of individual channel elements and channel complexes resulted in asymmetric levée heights, with the larger, more sand rich external levée constructed on the western edge of the valley (Fig. 4, 5). This may have been accentuated by the influence of the Coriolis Effect. Coarsening and thickening upward packages are not identified, although preservation potential would be low as westward migration of the channels led to erosion of the proximal external levée. Even if a coarsening-and-thickening upward pattern was identified this could be interpreted as the result of waxing sediment supply through time rather than a record of channel migration in the main conduit.

The stratal relationship of the external levées to the adjacent channelized fill is also important to consider if external levée successions are be used as records of channel evolution. This approach has more potential where (part of) the external levée succession can be demonstrated to aggrade at a similar rate to the channel building a constructional crest and, therefore, making the channel-fill and the levée time-equivalent. Clearly, the approach will not work where external levées that have been cut by a younger channel system meaning that the bulk of the levée is not genetically related to the adjacent channel-fill.

External levée hierarchy

Hierarchies of component architectural elements in a range of siliciclastic settings have been developed that use bounding surfaces, stacking patterns and depositional geometries to aid comparison of scales and processes across different systems (e.g. Mutti and Normark, 1987; Miall, 1988; Clark and Pickering, 1996; Sprague et al., 2002; Prélat et al. 2009). External levées are constructed by numerous flows that partially escape from slope channel systems, which comprise channel elements, channel complexes and channel complex sets (e.g. Sprague et al., 2002; Di Celma et al., 2011). At the CD Ridge, both Unit C2 and Unit D have composite basal erosion surfaces with multiple remnant channel complexes preserved within a composite erosion surface (Hodgson et al., 2011); as a result the external levée successions of Unit C and D preserve a cryptic depositional record of the evolution of component channel elements, channel complexes, and channel complex sets. Logically, therefore, a hierarchy of architectural elements in external levées that include levée elements, levée complexes and levée complex sets should be present. However, there are several factors that make the identification of a hierarchy in external levée successions challenging compared to other systems. For example, there are a lack of abrupt stratigraphic facies changes and mappable bounding surfaces that are used in channel hierarchy schemes, and the aggradational stacking of elements with similar geometries in contrast to compensational stacking and avulsion surfaces used in lobe hierarchy schemes. In addition, the thickness and geometry of a single deposit on an external levée is dependent on the distance from the parent channel, the slope of the levée, the curvature of a channel bend, the height of levée crest to channel base, and the flow magnitude (thickness and grain-size range). These parameters will be slightly different after every flow event meaning that discrete package of similar sedimentary facies, or clear bed thickness trends at different scales, are unlikely to develop unless the system is close to an equilibrium state.

Despite these difficulties, identification of a hierarchy in external levées would provide a direct correlation between levées and their associated channel elements, channel complexes and channel complex sets. As there is a more complete depositional record of channel-levée system evolution, this would permit an assessment of the degree of sediment bypass into the deeper basin during different stratigraphic intervals. Given the number of beds in an external levée succession, a statistical approach to bed thickness patterns in channel-levée systems where the number of channel complexes is known may help to identify a hierarchy of levée elements.

Crevasse lobes – where and when?

The geographical distribution of crevasse lobes in Unit D of the Fort Brown Fm. indicates that breaches in an external levée are more commonly recorded in basinward localities. In Unit D, crevasse lobes have not been observed in up-dip areas such as the CD Ridge. This is interpreted to be because a deep confining surface of the D slope valley coupled with the high external levées limited the potential for sand-prone flows to breaches in the external levée. The crevasse lobe complex described in Unit D at Slagtersfontein occurs 50 km down dip of the CD Ridge (Figs. 2 and 14). Therefore, the longitudinal increase in crevasse lobes and channels is likely related to the basinward reduction in relief between the external levée crest and channel base (Fig. 17). Decreasing downdip confinement may not be wholly responsible for the presence of crevasse deposits. The combined effects of increased channel sinuosity and channel aggradation increase the likelihood for breaches in an external levée and the deposition of crevasse lobes. Peakall et al. (2000) stated that bends in submarine channels develop at slower rates compared to their fluvial counterparts, suggesting that sinuosity increases with time and maturity (e.g. Maier et al., 2013). Therefore crevasse lobes are more likely to occur and be preserved when a mature and sinuous channel-levée system has been established.

A breach in the external levée and formation of a crevasse lobe may lead to the development of a crevasse channel, such as documented within Unit D at Geelbek by Brunt et al. (2013a), and be the precursor to a channel avulsion events (e.g. Fildani and Normark, 2004; Armitage et al., 2012). If crevasse processes precede avulsion events they are more likely to occur in basinward areas, and in the upper stratigraphy of an external levée succession, when levée crest to channel depth height is low and when a degree of stable sinuosity has been established.

Comparison to other systems

A spectrum of external levée dimensions and geometries have been described in the literature (e.g. Skene et al.2002; Nakajima and Kneller, 2013), and range from mud-rich (e.g. Flood and Piper, 1997) to sand-rich (e.g. Mayall and O'Byrne, 2002). The external levées from the Fort Brown Fm. described herein are silt-rich and contain only minor amounts of clay in the form of drapes in distal external levée successions. This is likely to result in significant differences in the architecture and stratigraphic relationship to the genetically-related channel systems, compared to mud-rich systems. A critical difference is that mud-rich external levées are likely to have more cohesive strength and are therefore more difficult for flows to erode. Characteristically, mud-rich external levées, such as in the Amazon and Indus systems, can construct significant morphological features that reach >100 m in height (Kolla and Coumes, 1983; 1987; McHargue and Webb, 1986; Carmichael et al., 2009), and commonly confine highly aggradation channel systems that can be active 10s of metres above the regional slope (Normark et al., 1997; Lopez, 2001). Silt-rich levées are more easily eroded meaning that wider channel belts can form by lateral stepping of component channels. Also, silt-rich levées are unlikely to build such significant relief above the regional slope meaning that their bathymetric influence on younger systems is less pronounced. Nonetheless, many of the key component features and the origin and evolution are common to both mud-rich and silt-rich external levées.

CONCLUSIONS

This study utilises a unique dataset that integrates research boreholes with extensive outcrops where sustained field mapping allows the palaeogeographic context of different stratigraphic units to be well constrained. This has permitted a comprehensive description of multiple exhumed silt-rich submarine external levées in which the internal facies relationships have been constrained and all the major components have been identified, including sediment waves and crevasse lobes. As the palaeogeographic position and the orientation of the external levée to the parent channel systems are well constrained the distribution of sand, sedimentary facies and sand distributions are related to position on the palaeoslope, the distance from the parent channel system, confinement of the channel and the magnitude of turbidity currents. Sedimentary facies of the external levées are dominated by tractional structures including aggradational dm-scale sinusoidal stoss-side preserved bedforms, low-to-high angle climbing ripple lamination and stoss-side preserved current ripple laminae. These facies indicate high rates of sediment fallout, attributed to rapid flow expansion and deposition from turbidity currents escaping from confinement, where the highest volumes of sand are deposited closer to the confinement with an exponential decrease in sand percentage recorded perpendicular from the levées crest. The documented downlap of beds that fine and thin away from the channels onto underlying muds reflects commonly identified seismic architecture observed in the subsurface. This geometry suggests progradation, which typically results in coarsening- and thickening upwards. However, in the construction of an external levée there is a key morphometric feedback where the widely documented fining and thinning upwards trend is attributed to increasing confinement of individual flows and/or the waning of the system as it begins to backstep. Perturbations to this trend can develop depending on the evolution of the parent channel system (e.g. Kane et al. 2007).

Locally preserved basal sand-rich deposits are interpreted to record the preservation of a frontal lobe deposited prior to the lengthening of the channel. This suggests that where there is useable accommodation external levées initiate through formation of a frontal lobe, followed by propagation of the channel and increased flow confinement and the development of an external levée by flow overspill. A down-slope increase in the number of crevasse lobe deposits is related to the lower relief between channel base and levée crest, and increased sinuosity. This distribution reflects the propensity of channel avulsion in downdip areas.

The distinctive aggradational sedimentary facies of the external levées, dominated by climbing ripple laminae and sinusoidal bedforms identified at outcrop could aid the identification of external levée successions in less well constrained outcrop, and in core and seismic datasets. This is significant as external levée deposits, although perceived to be composed of mud and silts can preserve sandstone-prone units with good laterally connectivity, and therefore have the potential to form, or contribute to, hydrocarbon reservoirs.

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Figure captions

Fig. 1. Cartoon of an external levée and slope valley-fill that highlights the nomenclature used and the key components identified and characterised in this study. These features are not discrete areas on the levée, however, this subdivision allows individual components of the levée to be examined. Heavier stipple indicates relatively higher amount of sand.

Fig. 2. Location map that highlights the study area near the town of Laingsburg, Western Cape, South Africa (inset maps). The pale grey area marks the outcrops of the Laingsburg Formation and the darker grey shows the outcrop pattern of the Fort Brown Formation. The boxed areas show the geographic position of figures referenced throughout the paper.

Fig. 3. (A) Stratigraphic column showing the generalised stratigraphy of the Ecca Group. (B) Expanded stratigraphic column showing the units described in this study (Units C-F of the Fort Brown Formation) are highlighted. Vertical scale is in kilometres. (C) Expanded location map showing the geographical distribution of the data. The white and black dots represent sedimentary log positions; the red and black dots highlight the positions of the Bav 1a, Bav 2 and Bav 6 research boreholes. The green, blue, red and orange lines highlight the positions of the correlation panels constructed in this study. The green, blue and orange boxes correspond to the stratigraphic intervals highlighted on the stratigraphic column of (B).

Fig. 4. Inset map (top right) showing the location of the CD Ridge outcrop, south limb of the Baviaans syncline. Annotated aerial photograph (top left) that illustrates the location of the Unit D incision through Unit C stratigraphy. The CD Ridge correlation panel (bottom) of Hodgson et al. (2011) captures the Unit D entrenched slope valley. The locations of the cored research boreholes drilled as part of this study are shown on both the aerial photograph and the correlation panel.

Fig. 5. A) CD Ridge panel constructed using outcrop logs (this study), the box highlights the expanded panels of B. Rose diagrams showing palaeocurrent measurements collected from each of the panels; i) palaeocurrents from the Unit D western external levée, ii) palaeocurrents from the Unit D eastern external levée, and iii) palaeocurrents from the Sub-unit C2 eastern external levée. B) Expanded correlation panel showing the western Unit D external levée where several beds that have been walked out and downlap onto the underlying mudstone.

Fig. 6. (A) Gamma ray log and (B) Sedimentary log of the Unit D proximal external levée from research borehole Bav 1a. (C) Representative outcrop facies photographs of the lowermost 25 m of the Unit D external levée, on the CD Ridge, part of the lower proximal external levée. (Di-Diii) Core facies photographs from the lower proximal external levée of Unit D. (E) Annotated core photographs from the lower proximal external levée with sedimentary structures highlighted. (F) Representative outcrop facies photographs of the upper proximal external levée of Unit D on the CD Ridge (Gi-Giii) Core facies photographs from the upper proximal external levée of Unit D. (H) Annotated core facies photographs from the upper proximal external levée with the sedimentary structures highlighted. (Rucksack, notebook, pencil and grain size card for scale).

Fig. 7. (A) Sedimentary log through the eastern Unit D distal external levée at the Paardekraal river section (UTM: 476839, 6323945). (B-L) Outcrop facies photos showing the thin bedded deposits, typical of Lf1 and Lf2, found within distal areas of the external levée deposit (notebook (20.5 cm), pencil (15 cm) and measuring tape (27 cm shown) for scale).

Fig. 8. (A) Gamma ray log and B) Sedimentary log through Sub-unit C2 collected from the Bav 6 core. (C-F) Core facies photographs, locations indicated by the boxes on the sedimentary log within the 22 m thick C2 external levée succession. (G and H) Outcrop facies photographs from the C2 external levée at the Paardekraal river section (UTM: 476827, 6323820).

Fig. 9. Cartoon through an external levée showing the distribution of the dominant facies associations observed within the Unit D external levée from channel proximal to channel distal locations. The gradational boundaries illustrate that boundaries between dominant facies are transitional.

Fig. 10. Cartoon illustrating the distribution of sandstone within the Unit D external levée from channel proximal to channel distal locations. Inset graph showing the % sandstone for conjugate external levée against distance from the levée crest with an exponential best fit line. From this dataset, there is a non-linear relationship between distance from the channel and percentage sandstone content of the levée. Downlap arrows are inferred timelines.

Fig. 11. Correlation panel through part of the Sub-unit F2 proximal external levée on the southern limb of the Heuningberg anticline (see Fig. 3). This panel shows individual beds that have been correlated and walked out, which downlap onto the underlying mudstone, away from the parent channel to the south.

Fig. 12. (A) Photo panel showing the shingled sandstone beds that form part of interpreted sediment waves on the proximal external levée of Sub-unit E2 cropping out on the south limb of the Heuningberg anticline (see Fig. 3). (B) Trace of the upstream accreting beds (to NW) shown on the photopanel of A). C) Correlation panel of correlated sedimentary logs (D) Palaeocurrent rose showing a dominant palaeocurrent direction towards the southeast.

Fig. 13. (A) Cartoon of sediment waves outboard of the levée crest, showing the broad scale geometries, aggrading upslope in the opposite direction to the flow direction (adapted from Migeon et al., 2000). (B) Inset schematic of sediment waves, showing where sand becomes trapped on the upstream facing limb of the wave, allowing for shingling and migration upslope, in the opposite direction to turbidity current flow.

Fig. 14. Correlation panel constructed from logged sections measured at the eastern margin of the Slagtersfontein channel complex. Terminal lobes at the base of Unit D are overlain by external levée deposits, which incorporate a number of crevasse lobes, which are variable in geometry and thickness. The succession is incised by a late-stage channel that cuts down from high within Unit D.

Fig. 15. Photograph of a single crevasse lobe bed demonstrating the tripartite divisions. The lower part consists of a thin band of disorganised fragments of levée; the middle part is clean sandstone and ranges in character from structureless to well-developed tractional bedforms. The upper part is argillaceous and often contains mud clasts or dispersed organic matter such as plant fragments.

Fig. 16. Block diagram showing the spatial relationship of the main features and nomenclature used to describe channel-levée systems.

Fig. 17. Cartoon section parallel to a levée crest that shows the down-dip of evolution of levées and their stratal relationships to lobes; from small levées associated with entrenched channels, to levée-confined channels, to the down-dip association of decreasing levée height and increasing occurrences of crevasse lobes and channels, to the levée-lobe transition zone where lobe deposition dominates.

Table 1: Table showing the seven main sedimentary facies associations identified in the external levée successions of the Fort Brown Formation.