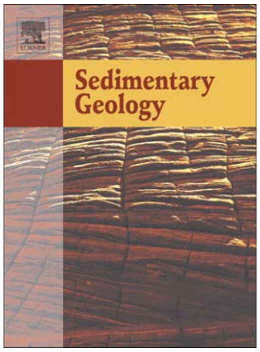

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Investigating the stratigraphy and palaeoenvironments for a suite of newly discovered mid-Cretaceous vertebrate fossil-localities in the Winton Formation, Queensland, Australia

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ABSTRACT

The Winton Formation of central Queensland is recognized as a quintessential source of mid-Cretaceous terrestrial faunas and floras in Australia. However, sedimentological investigations linking fossil assemblages and palaeoenvironments across this unit remain limited. The intent of this study was to interpret depositional environments and improve stratigraphic correlations between multiple fossil localities within the preserved Winton Formation in the Eromanga Basin, including Isisford, Lark Quarry, and Bladensburg National Park. Twenty-three facies and six repeated facies associations were documented, indicating a mosaic of marginal marine to inland alluvial depositional environments. These developed synchronously with the final regression of the Eromanga Seaway from central Australia during the late Albian-early Turonian. Investigations of regional- and local-scale structural features and outcrop, core and well analysis were combined with detrital zircon provenance signatures to help correlate stratigraphy and vertebrate faunas across the basin. Significant palaeoenvironmental differences exist between the lower and upper portions of the preserved Winton Formation, warranting informal subdivisions; a lower tidally influenced fluvial-deltaic member and an upper inland alluvial member. This work further demonstrates that the Isisford fauna is part of the lower member of the preserved Winton Formation; whereas, fossil localities around Winton, including Lark Quarry and Bladensburg National Park, are part of the upper member of the Winton Formation. These results permit a more meaningful framework for both regional and global comparisons of the Winton flora and fauna.

Key Words: Winton Formation; Eromanga Basin; Palaeoenvironments; Gondwana; Cretaceous Australia

1. Introduction

Throughout the Cretaceous, plate reorganization associated with the ongoing fragmentation of Gondwana (rift-drift phase) had profound effects on landscape development and terrestrial ecosystems of South America, India, Madagascar, Africa, Antarctica and Australia (Skelton, 2003). This tectonic event is widely hypothesized to have played a major role in the palaeobiogeographic dispersal and evolutionary patterns that ultimately led to the emergence of modern-day floras and faunas (Stampfli and Borel, 2002; Skelton, 2003; van Hisbergen et al., 2011; Mannion et al., 2012, 2013, 2014). The key to better understand these evolutionary patterns in Earth's history and their effects will be aided by providing high-resolution stratigraphic context coupled with radiometric age dating across the rifting Gondwana. With these results, more reliable linkages between known and yet to be discovered fossil assemblages can be inferred.

A wealth of recent work now suggests that the fragmentation of Gondwanan landmasses commencing in the mid-Cretaceous corresponds with the emergence of geographically distinct archosaurian lineages (Bonaparte 1986; Salgado et al., 1997; Sereno, 1997, Sereno et al., 2004; Benson et al., 2010; Agnolin et al., 2010; Benton et al., 2014). However, many eastern Gondwanan archosaurian assemblages remain poorly understood (Agnolin et al., 2010; Kear and Hamilton-Bruce, 2011). This is especially true for Cretaceous fossil assemblages and ecosystems from Australia. Currently, one of the best records of continental vertebrates and terrestrial ecosystems from the Cretaceous of Australia comes from the expansive deposits of the Winton Formation, in central Queensland. Recent fossil discoveries in the Winton Formation include a diverse range of dinosaurs, including sauropods (*Diamantinasaurus matildae* and *Wintonotitan wattsi*), theropods (*Australovenator wintonensis*), thyreophoran and ornithopod remains, along with crocodilians (*Isisfordia duncani),* ichthyodectiform teleosts and dipnoan lungfishes, aquatic lizards, turtles, invertebrates and a high diversity of plant macrofossils, including some of the world's earliest flowering plants (Molnar, 1980; Dettmann et al., 1992; Kemp, 1997; Molnar, 2001; Salisbury et al., 2003, 2005; Molnar and Salisbury, 2005; Salisbury et al., 2006a,b; Hocknull and Cook, 2008; Hocknull et al., 2009; Agnolin et al., 2010; Molnar, 2010; Fletcher and Salisbury, 2010; Poropat et al., 2013; White et al. 2012, 2013; Leahey and Salisbury, 2013; Berrell 2014; Poropat 2014a,b, 2015a,b; White et al., 2015; Poropat et al., 2016). Yet, site-specific palaeoenvironmental, taphonomic, and geochronologic remain elusive (Tucker et al., 2013, 2016). Therefore, these new assemblages lacked critical stratigraphic context to temporally co-occurring fossil assemblages described by Hocknull et al. (2009) and Poropat et al. (2015a,b), among others.

Historically, the Winton Formation has been interpreted as the uppermost depositional phase of the Eromanga Basin, represented by a westward-thickening continental wedge deposited during the final regression of the Cretaceous Eromanga Shallow Seaway in Queensland (Fig. 1) (Veevers, 2000a,b; MacDonald et al., 2013; Tucker et al., 2016). Recent detrital zircon investigations of the Winton Formation have significantly improved the temporal constraints on deposition of the formation and identified major provenance sources and continental drainage patterns (Tucker et al., 2013, 2016). This work has also permitted a refined understanding of the temporal relationships of its constituent floras and faunas (Mannion et al., 2013; Fletcher et al., 2014a,b; Bell et al., 2015); hence, allowing it to be placed into a more precise global context.

This paper presents the results of a detailed outcrop and core-based sedimentological and stratigraphic investigation of the Winton Formation. The primary goal of this study is to improve understanding of the palaeoenvironments and depositional environments across the expansive and long-lived Winton Formation. In addition, this study is focused on improving the stratigraphic relationships within the formation, and improving the correlation of newly discovered fossil assemblages with three key vertebrate fossil localities across the basin through refined lithostratigraphy, detrital zircon petrofacies and analysis of structural features in the basin.

2. Geological Background

2.1 Basin History

Forming the central sub-basin of the Great Artesian Basin, the Eromanga Basin is interpreted to have formed during the Triassic (Fielding, 1996; Draper, 2002; Gray et al., 2002 Cook et al., 2013). The tectonic morphology of the Eromanga Basin has been debated for many decades, with some researchers concluding that it represents an intracratonic basin (Angevine et al., 1990; Draper, 2002). In contrast, other workers have postulated that the Eromanga Basin formed in a foreland basin setting (e.g., Gallagher, 1990). Yet many important factors have yet to be resolved, including: 1) irregularities in observed basin geometry; 2) whether the tectonic setting was extensional, collisional or primarily rotational; and, 3) how both mantle heat flux and detached slab subduction affected basin morphology (Kuang, 1985; Gallagher and Lambeck, 1989; Krieg and Rogers, 1995; Gurnis et al., 1998; Draper, 2002; Mavromatidis and Hillis, 2005; Heine et al., 2008; Matthews et al., 2011).

Classically, intracratonic basins are interpreted to be associated with failed rift systems and linked to regional subsidence and slow, steady generation of accommodation space, resulting in a broad convex morphology (Kingston et al., 1983; Mitchell and Reading, 1986; Draper, 2002). Instead, the Eromanga Basin displays a concave shape, more typical of a foreland Basin (Gallagher, 1990; Draper, 2002). Moreover, foreland basins are typified by pulsed subsidence and generation of accommodation space (e.g., rapid then slow) that coincides with patterns observed in the Eromanga Basin (Gallagher and Lambeck, 1989). This is reflected in the western portions of the basin, which experienced higher rates of subsidence, due to asymmetric loading as would be expected with thrust loading on the western side of the basin (Gallagher, 1990; Draper, 2002). Furthermore, association of a remnant volcanic arc (Whitsunday Volcanic Province) and late Mesozoic subduction margin along the east coast of Australia lends strong support to a retro-arc foreland basin model (Gallagher and Lambeck, 1989; Gallagher et al., 1994; Russell and Gurnis; 1994; Veevers, 2000a,b; Tucker et al., 2016). This continental margin has been challenged by Bryan et al. (2012, and references therein) as a possible S-LIP, and furthermore by Tucker et al. (2016) as a progressive subduction margin. Unfortunately, the lack of such key features as clearly defined fold and thrust belt to the east of the basin, make it difficult to confirm either of these models.

2.2 Basin Stratigraphy

During the late Mesozoic, the Eromanga Basin was influenced by five long-lived marine transgression of the epeiric Eromanga Seaway into central Australia (Exon and Burger, 1981; Burger, 1986; Draper, 2002; Gray et al., 2002). However, correlation of sea-level cycles recorded in the basin to eustatic sea level curves has proven difficult (Draper, 2002). Sedimentation within the Eromanga Basin is interpreted to have initiated in the Late Triassic (Carnian to Rhaetian), with the Cuddapan Formation and the unconformable, overlying Poolowanna Formation (Fig. 2) (Moore, 1986; Draper, 2002). Early stages of deposition occurred within alluvial to lacustrine depocentres, with initial sea level rise recorded in the uppermost Poolowanna Formation, and is correlated to global sea-level rise during the Toarcian (Moore, 1986). Middle Jurassic (Aalenian-Callovian) deposition is recorded in the Hutton Sandstone and the Birkhead Formation (Exon, 1966; Gray et al., 2002). Sedimentation during these early phases is interpreted to have been dominantly fluvial to aeolian, whereas later phases of sedimentation were dominantly fluvio-lacustrine, associated with a variable influx of volcaniclastics (Almond, 1983). The Upper Jurassic (Oxfordian-Tithonian) sedimentary record is preserved in the Adori Sandstone and Westbourne Formation (Fig. 2) (Gray et al., 2002). Early phases of Late Jurassic sedimentation were dominantly within alluvial depositional settings (dominantly fluvial), followed by a transition to lacustrine and near-shore marine settings in the uppermost Westbourne Formation (Almond, 1983, 1986; Gray et al., 2002). The Late Jurassic to Early Cretaceous (Tithonian to very early Valanginian) basin development is recorded by the Hooray Sandstone and is typified by fluvial depositional environments.

The last phase of deposition occurred during the Early Cretaceous (Valanginian–Albian). The onset of transgression is recorded by deposition of the marginal deltaic Cadna-Owie Formation and is characterised by shallow marine strata at its top. Shallow marine conditions continued until initial regression in the late Albian to early Cenomanian. This fully marine phase is recorded by the deposition of the Wallumbilla and Toolebuc formations, and the Allaru Mudstone (Senior et al., 1975;

Gray et al., 2002). Overlying these units is the Mackunda Formation, which preserves shallow-marine strata that show a distinctive up-section coarsening (shallowing) trend, and indicate early stages of final seaway regression from central Queensland (Exon and Senior, 1976; Price et al., 1985; Moore et al., 1986; Helby et al., 1987; Draper, 2002; Gray et al., 2002). The uppermost preserved unit in the Eromanga Basin is the Winton Formation, which conformably overlies the Mackunda Formation (Whitehouse, 1955).

2.3 The Winton Formation

The preserved Winton Formation is exposed over large portions of central-western Queensland along with portions of northern New South Wales, northwestern South Australia and the southwestern corner of the Northern Territory (Fig. 1). Stratigraphically, in most recent revisions, it is considered the upper-most portion of the Manuka Subgroup (grouped with the Mackunda Formation), and forms the uppermost portion of the Rolling Downs Group (Fig. 2). The Winton Formation (‘Winton Series’) originally described by Dunstan (1916) as a series of sandstones, shales, and minor coal seams, conformably overlying the predominantly marine sediments of the Mackunda Formation.

The preserved Winton Formation ranges in thickness from 400 to 1000 m, with the thickest portions usually in the western part of the basin (Gray et al., 2002); however, original thickness prior to deep basinal weathering was suggested by Mavromatidis and Hillis (2005), and noted by Draper (2002). This study holds to the proposed erosional thickness indicated by Draper (2002; with references therein). The Winton formation is composed of interbedded sandstones, sandy siltstones, siltstones, and mudstones with minor coal seams and intraformational conglomerates (Vine et al., 1967; Casey, 1970; Senior and Mabbutt, 1979; Coote, 1987; Draper, 2002). The

Winton Formation is well known for its flora and fauna, which includes plants, palynomorphs, invertebrates and vertebrates. The plant diversity of the Winton Formation is particularly significant, with a range of taxa including bennettitales, conifers, cycadophytes, ferns, ginkgoes, pentoxyloleans, and most significantly early angiosperms (Burger and Senior, 1979; Burger, 1990; McLoughlin et al., 1995; Pole and Douglas, 1999; Mcloughlin et al., 2010). Angiosperm palynomorphs in the formation have been well-documented (see Dettmann and Playford.1969; Burger 1980, 1986, 1989, 1990, 1993). The Winton formation until recently has been broadly dated between the Albian and Cenomanian based on the occurrence or absence of *Appendicisporites distocarinatus* and *Phimopollenites pannosus* (Helby et al., 1987). More recently, work by Greentree (2011; pg 61), Bryan et al. (2012), and Tucker et al. (2013, 2016) have utilized detrital zircon geochronology to demonstrate a considerably younger age for the upper part of the preserved Winton Formation, consistant with a latest Cenomanian-Turonian age for this part of the stratigraphy. Tucker et al. (2016) used the same approach to constrain the upper Mackunda Formation to latest Albian (~104-102 Ma); which therefore indicates that the base of the Winton Formation must be no older than this.

2.4 Structural Geology

Several major faults have been identified within the Eromanga Basin, including the Canaway Fault, the Weatherby and Cork fault systems, along with numerous shallow synclines and anticlines across the basin (Fig. 3) (Casey, 1967a,b, 1970; Mathur, 1983; Moss and Wake-Dyster, 1983; Moore and Pitt, 1984; Wopfner, 1985; Finlayson et al., 1988; Murray et al., 1989; Green et al., 1991; Cartwright and Lonergan, 1997). These residual features are interpreted to be associated with tectonic subsidence related to plate motions and underlying mantle conditions, such as thermal relaxation (Gallagher and Lambeck, 1989; Gurnis et al., 1998; Watterson et al., 2000; Veevers, 2006; Heine et al., 2008). However, it has generally assumed that the flat-lying nature of most stratigraphic units in the Eromanga Basin underwent minimal tectonic deformation during or following deposition and that most of the units are relatively conformable. However, more recent studies focused on various economic aspects of the basin have resulted in the discovery of pervasive faulting throughout the basin (Esso 1981, Carne and Alexander, 1997; Hower, 2011; Sentry Petroleum, 2011a,b). This work reveals that many individual coal seams are vertically offset by meters to tens of meter in places and are laterally discontinuous over tens of kilometres (Casey, 1967a,b; Hower, 2011; Sentry Petroleum, 2011a,b). This has the potential to dramatically affect how we understand the temporal and stratigraphic relationships of the Winton Formation and has major implications for the age and correlation of fossil assemblages basin-wide (Tucker et al., 2013; Poropat et al., 2015a,b; Tucker et al., 2016). These complications are investigated in greater detail below and used to refine stratigraphic assessments and correlations.

3. Study Area

3.1 Field Locations

Three primary field localities were investigated during this project, including: expansive exposures at (1) Bladensburg National Park (BNP) and (2) Lark Quarry Conservation Park (LQCP), both are near the town of Winton, Queensland, and (3) the richly fossiliferous, but poorly exposed, fossil localities near Isisford (Fig. 4). Nine stratigraphic sections were measured at LQCP and six sections were measured at BNP.

Due to a lack of exposure, no sections were measured at Isisford. Instead, the stratigraphy at this particular locality was investigated and correlated via regional well logs and cores (but see also Syme, 2016). All specific locality information is summarized in Tucker et al. (2013, 2016); Syme et al., (2016); Romillio et al. (2013); and Salisbury (2006a,b).

3.2 Core Logging

Additional analysis of stratigraphic wells from across the basin was conducted in this study, with a focus on wells that transect both the Winton and Mackunda formations. All of these cores and records were investigated at the Geological Survey of Queensland core storage facility in Zillmere, Queensland, where they are stored. In total, 23 wells were studied and described, including eight physical cores, seven digitized core records (i.e., Hylogger records), and the historical core records for eight additional cores (Fig. 4).

4. Methods

4.1 Stratigraphy and Sedimentation

Sedimentologic analysis of the Winton Formation was conducted between 2010 and 2014. Detailed facies and architectural element analysis was performed following the conceptual framework established by Miall (1977, 1985, 2014) and modified by Eberth and Miall (1991), Fielding (2006), Roberts (2007), Jinnah et al. (2009) and (Fielding, 2006 and references therein). For consistency, a uniform set of facies codes was used to describe both the outcrop sections and the cores. In outcrop, detailed measured sections were constructed at the decimetre scale in each of the three study areas using a Jacob’s Staff, Brunton Compass, and GPS. Particular emphasis was placed on understanding and correlating important vertebrate fossil localities in each study area. Many horizons were walked out in order to define the horizontal and lateral continuity of beds and facies.

The following types of field data were collected for each area and section: 1) lithology; 2) the nature of the upper and lower bounding surfaces; 3) external unit geometry and lateral extent (i.e., architectural elements *sensu* Miall, 2014); 4) scale and thickness of units; and 5) sedimentary and biogenic structures. A series of distinct marker horizons, with consistent and distinct lithology and bedding patterns were identified and used to trace outcrops along strike and lateral facies changes. In order to correlate the subsurface geology, core logs and drill records were used to construct a detailed GIS basin model (see below; Fig. 4). Weathered and unweathered colour was recorded using Munsell Colour Chart (2009) and the GSA Rock Colour Chart (Goddard et al., 1980). The study employs the Bann et al. (2008) hierarchy of bioturbation index (BI) for classifying the intensity of bioturbation in a given sedimentary horizon (BI 0 (none) - BI 6 (intense)). These are herein described according to their occurrence within each FA.

4.2 Arc GIS Reconstruction Models and Fence Diagram

A 3D visualization of the subsurface within the study area of Eromanga Basin was created combining a suite of digital resources. Principally, this study utilized ArcGIS 10.1 for digital reconstructions of the basin-wide stratigraphic sections and correlations. This study also utilized 3D GIS within Arc GIS 10.1 to better visualize subsurface geology. All digital work was carried out in accordance with the "*Working with 3D GIS, Using ArcGIS*" (V10.1, 2010). GDA94 is the official geodetic datum adopted nationally across Australia on 1 January 2000. This was the datum used to gain consistency across all raster and vector data displayed. Zone 55 was identified as the most relevant for this portion of the Eromanga Basin. Regional geological maps of the northern and central Eromanga Basin (Rock Unit & Structures) were imported and floated on the digitized topographical surface for the region. The rock units of interest were displayed. Only the fault structures were selected for display. The faults were extruded to provide a pseudo 3D visualization. Both magnetic and gravitational survey raster data were acquired. Three magnetic survey images were considered. This included a 1st vertical derivative regional survey (magmap04) that covered the entire region, a TMI and a higher resolution 1st vertical derivative (GSQP795tmivd1 image) providing a partial coverage. The gravitational material covered a similar expanse as the TMI. Seismic survey data was selected using the 2007 21 December 2D seismic collector sheet. These results were not displayed within the visualization.

Logged drill information from 15 sites (including cores logged as part of this study and additional original GSQ drill logs from surrounding wells) was used to enable stratigraphic surfaces to be interpolated for the Mackunda and Winton formations. To ensure consistent surface interpolations, it was necessary to include both overlying and underlying stratigraphic units. The core length applied relative to RL supplied the vertical component (z), with the positions (x,y) input using the latitude and longitude converted to decimal degrees. Top surfaces of each unit were generated using the Ordinary kriging function. The semivariogram properties used a spherical model to create the surface. The base surface of the Toolebuc Formation was also generated. The function used 12 outer drill core details to create the interpolated surface. The interpolated surface was then used to create a Triangulated Network (TiN).

A traditional block diagram, encompassing all fifteen drill locations was generated using the extrude function. Extrude joins the nominated TiN surfaces and a polygon shape that defines the area of interest. The polygon shape files used to provide the outline for the extrude function were drawn to allow adjustment for faulting. These polygon shapes had to be restricted to slightly inside the outer edge of the TiN to ensure the extruded block created a “closed” shape. The blocks affected by dip-strike faults were adjusted vertically to ensure the fence diagrams would display the faulting appropriately. To create a fence diagram it was necessary to intersect a multipatch (3D) shape with the block diagram. The intersecting multipatch was first drawn as a 2D surface then extruded and converted to a multipatch. The intersect tool was used to generate multipatch files of the intersection between the block unit and fence multipatch.

5. Results

5.1 Sedimentology

Outcrop and core based facies analysis of the Winton Formation and the uppermost sections of the underlying Mackunda Formation resulted in the identification of twenty-three lithofacies (Table 1; in text, all facies codes are listed in descending order of abundance). The repeated occurrence of lithofacies in distinct combinations, together with the presence of diagnostic architectural elements, was used to identify and interpret six (6) facies associations (FA) (Supplementary Fig. 1a [outcrop] and 1b [GSQ core]; Tables 2 and 3). A detailed description of all nine facies associations is presented below, and these are interpreted in terms of their depositional environment. Following the approach and codes of Miall (1985, 1996), architectural elements, or lithosomes, were identified within different facies associations based on their geometry, associated facies, and scale (Table 3).

Bounding surfaces are primarily 0th to 3rd order, but a few rare 4th order surfaces were identified (Supplementary Fig. 2a [outcrop] and 2b [GSQ core]).

Many of the FA's preserved a diverse range of trace fossil morphotypes and are interpreted to have formed within stable long-lived and well-developed horizons. The primary ichnotaxa identified throughout the Winton Formation are *Skolithos*, *Scoyenia*, *Planolities*, insect burrows and galleries, and roots. The association of these particular trace fossils together is characteristic of the *Scoyenia* ichnofacies (Buatois and Mangano, 1995). The *Scoyenia* ichnofacies has been interpreted to represent a continental environment with low-energy flow and periodic subaerial conditions (MacEachern et al., 2010). This is consistent with sedimentological interpretations presented above for the Winton Formation, which indicate fluvial systems with well-defined channel banks and point bars (FA1 and 2), along with incipient paleosol development in many units (FA3-6).

5.1.1 Major Sandstone and Siltstone bodies (FA1)

Description

Major sandstones are a common FA in both outcrop and core (Table 4). FA1 comprises the following lithofacies: Sp, Sh, St, Se, Si, Sd, Sm, Fl, Gmm, Gmx, and Sr (rare) (Table 1). Major siltstone bodies are also commonly exhibited: Sh, Sm, Sd, Se and Gmx (rare). Rarer finely-grained units also occur: Sfv, Ss, Ssc, Fr, Flf, Fsc, C, P, and Pb (Table 2). FA1 units are characterised by subordinate muddy sandstone to sandy siltstone units that exhibit normal grading. Individual sand-silt bodies range from massive (Sm) with only weak evidence of primary bedding (mostly due to weathering) to units that are well-bedded or well-laminated with excellent preservation of internal structures (St, Sp , Si, and Sr in particular). Individual cross-bedding sets (St, Sp) are commonly 0.3–1.3m thick (angle of repose commonly ranges between 10° to 24°), although larger scale cross-sets do exist. FA1 represents thick sandstone bodies not exceeding ~2.0 m thick that typically extend laterally for significant distances, in some cases km's. FA1 is typified by basal 1st to 3rd order erosional bounding surfaces. Where basal 3rd order surfaces are erosional, intraclast conglomerates (Gmx) are commonly observed in the lowermost 0.01–0.10 m of the FA. Upper bounding surfaces in sandstone bodies commonly range from 0th to 3rd order surfaces, whereas 3rd order surfaces are not observed in siltstone bodies (n<2nd order surface(s). In siltstone bodies, individual cross sets (St, Sp, Sr) are more-commonly preserved, and are 0.04–2.0 m thick. Bioturbation structures are also commonly preserved (P, Pb). Other units preserve soft-sediment deformation and dewatering structures, though preservation is poor.

Within FA1, five different architectural elements are recognized (*sensu* Miall, 2010, 2014), including channel elements (CH), lateral accretion elements (LA), sandy bed forms (SB), scour hollows (HO), laminated sands (LS), levee (LV), and floodplain fines (FF) (Table 3). CH ranges in thickness from 0.8–2.0 m and extend laterally for 10.0–40.0 m (sheets can laterally extend for several kilometres). LA's are relatively common and their morphology is typically that of wedges or sheets, though rare lobes and trough-sets are present. LA toe to crest height ranges from 0.3–2.5 m and their widths generally range from 0.1–0.5 m; however, lack of continuous exposures and poor preservation prohibits precise measurements in most cases. SBs are also very common in outcrop, and range in thickness from ~0.5-1.5 m, and typically extends 10's of meters laterally. Other sandstone body architectural elements, such as HO and LS, are present locally, but not common. LV and FF are prevalent in siltstone bodies and are identified in upper and lower sections of the exposed Winton Formation. Both LV and FF commonly range in thickness between 2.0–

4.0 m and between 200- 300 m (variable to outcrop quality). FF commonly presents in planar, thinly-laminated to very thinly-bedded units with associated bioturbation and root traces. FA1 units typically show a BI of 0–1, though 1 is very rare and restricted to finely-grained units.

Interpretation

FA1 is interpreted to represent meandering fluvial channel deposits. Large-scale macroform elements identified within outcrop, particularly CH and LA, but also SB, and LS, are all consistent with this interpretation (Fig. 5a,-d, 6) (Allen 1963; Nadon, 1994; Miall, 1996, Fielding, 2006; Gibling, 2006; Nichols and Fisher, 2007; Miall, 2014). Finer sediments commonly exhibit well-preserved plant remains, palaeosol and bioturbation structures, indicating channel migration and shortly thereafter bank- levee development (Allen 1963; Miall, 1996). Lateral correlation of these beds suggests that some of these events were extensive features across broad sweeping fluvial flood plains. LA elements are interpreted as ancient point bars and scroll bars, whereas the association of SB and CH in certain areas provide some evidence of high-sinuosity fluvial channels with well-consolidated banks. The complexity and abundance internal bounding surfaces throughout individual FA1 sand bodies suggest that flow waxed and waned over the course of deposition, as would be expected in fluvial channel system. FA1 units commonly fine upwards, suggesting that much of the bed consists of migrating point bars, channel lag and thalweg sediments (Fielding et al., 1999; Miall, 2014).

5.1.2 Minor sandstone and siltstone bodies (FA2)

Description

Minor sandstones are a moderately common FA in both outcrop and core (Table 4). FA2 is composed of the following lithofacies: Sh, Sfv, Sr, Sd, Sm, Si, St, Si, Fl, Gmm, and Gmx. Minor siltstone bodies also commonly exhibit Sr, Sh, St, and Sd; however, finely-grains units also exhibit Fm, Fr, Tlcf, P, and Pb. Generally, individual sand bodies are thinly-bedded with moderately-well preserved sedimentary structures, though few beds can be described as massive, commonly void of internal structure (St, Sr, Sm, and Si). FA2 units are characterised by moderately mature grains, which are commonly fine sands to coarse silts. Unites are composed of subordinate to mature silt grains accompanying with low degrees of clays or sands.

FA2 represents thinly-bedded sandstone bodies that are less than 0.5 m thick (most typically ~0.02- 0.3 m). The lateral extent of these units is variable, but units can extend for 100's of meters to only several meters. All FA2 units generally fine-upward and are typified by basal 2nd-3rd order surfaces that commonly form sharp to erosive contacts. If 3rd order surfaces are preserved, a minor basal intra clay-clast conglomerate normally occurs (Gmx). In sandier units upper bounding surfaces commonly exhibit up to 2nd order surfaces, whereas in silty units 1st to 2nd order upper bounding surfaces commonly co-occur with normal gradation. Internally, individual to multistorey trough and planar-cross stratification is generally small scale (<0.20 m sets), whereas ripple cross-lamination (Sr) is particularly common. Thicker units contain higher percentages of fines (silts/muds), and more often contain moderately to well-preserved silty beds with bioturbation structures (Sm, P, and Pb), including bifurcating vertical burrows/traces.

Within FA2, Levee (LV), Crevasse splay (CS), and Floodplain fines (FF) commonly occur, with moderate preservation of channel elements (CH). LV and FF are prevalent in siltstone bodies and are identified in upper and lower sections of the exposed

Winton Formation. Both LV and FF are commonly multi-storey succession of thinly-bedded to thinly-laminated units. FF commonly presents in planar, muddy, thinly-laminated to very thinly-bedded units with associated bioturbation and bifurcating burrows/traces. FA2 units typically record BI values of 0-2, several horizons have been identified with a BI at 3.

Interpretation

FA2 is interpreted to be associated with a variety of different depositional environments, including low-energy fluvial channel infills, crevasse splays, and levees (Allen 1963; Miall, 1996; Fielding, 2006, Nichols and Fisher, 2007). In certain cases, lateral correlation of FA2 sand bodies indicates these units were hosted within the floodplain and directly associated or adjacent to major channels. In several cases, preserved sedimentary features provide strong evidence for crevasse splay deposits. On the other hand, the presence of upward fining and waning flow features, in combination with CH elements in a handful of FA2 units is interpreted to represent a waning flow stage and channel fill. They may potentially be records of inactive, in filled channels within larger scale fluvial channel belts (Fig. 5b, c, d; 6) (Nichols and Fisher, 2007; Miall, 2014).

5.1.5. Major and Minor Mudstones (FA3)

Description

Major and minor mudstones are a moderately common FA in both outcrop and core (Table 4). FA3 is commonly composed of the following lithofacies: Fm, Fl, Ssc, Flf, Fr, Fsc, VFc, C, PB and P (PB and P preserve more often in thinly bedded unites). Individual mudstone units range from massive (Fm) and void of any internal structure to thinly laminated or ripple cross-laminated (Fl, Fr), to even highly kaolinized-lateritized exhibiting variable preservation of pedogenic structures and ichnotypes (especially Ssc, Fl, Fsc, VFc).

A main preservation bias in upper sections is due to deep chemical weathering and alteration across the basin. These mudstones are characterised by sub-equal ratios of silt and clay, and the sand content is subordinate to both.

FA3 ranges from thinly bedded (0.05-0.3m) to thickly bedded (0.8-2.0 m), but with some units exceeding 3.0 m thick. Bedding styles in FA3 are variable in thickness, morphology, lateral extent and outcrop quality. Lateral continuity for thick- to medium-bedded units can extend for several hundred meters to kilometres; whereas, thinly bedded units laterally pinch out after only several meters to ten's of meters. FA3 is typified by basal 0th to 2nd order surfaces that exhibit gradational to sharp contacts. Upper bounding surfaces commonly preserve 0th to 1st order surfaces. FA3 occurs in three distinctive lithotypes: 1) moderate to highly kaolinized-lateritized units that commonly erode into small cubic ped structures (Fig.5c); 2) bentonitic, very clay rich units that exhibit haystack to popcorn weathering; and 3) highly bioturbated units with evidence of colour mottling and development of weak colour horizons. The third lithotype with weak colour banding is further characterised by blocky pedogenic (mud cracks present but weakly preserved) structures and slickensides with associated trace fossils (vertical tubes), and are in-filled with coarser secondary silt and iron cement. FA3 exhibit the broad range of BI, from 0 to 4, pending both preservation and outcrop quality.

Architectural elements identified within FA3 include, in descending order of abundance, include: FF, LV, and CH (FF). The presence of CH elements packaged within FF elements is distinctive. CH elements are typically observed in thick to massive bedded units, and range 0.7-4.0 m, and laterally extended for 100's m. The presence of CH (FF) suggests abandoned channels characterised by a silty to sandy bases (3rd order surfaces) with erosional contacts, and normally grading. Most significant about this particular CH

(FF) is the large quantities of co-occurring well-preserved plant macrofossils (typically leaves). LV is commonly observed in medium to thick beds, which taper and pinch out. Thickness of LV can range from 0.8-3.2 m, and laterally extend for 200-500 m.

Interpretation

FA3 is interpreted to reflect deposition within low-energy proximal to distal floodplain settings lateral to a major fluvial channel (Allen 1963; Miall, 1996; Ghosh et al., 2006). The range of depositional microenvironments associated with FA3 is interpreted to include: weakly-developed paleosols, levee deposits and channel infill within oxbow lakes, small ephemeral to perennial billabongs (ponds). In the case of CH (FF) macroform elements strongly indicate abandoned channelized structures that were in-filled with both abiotic and biotic material. On the other hand, many FA3 units represent pedogenically modified floodplain deposits (co-occurring weakly preserved mud cracks). The presence of such soil forming features as slickensides, colour mottling and banding, minor Fe-oxide staining, small $CaCO_3$ concretions, and the common presence of bioturbation and root traces all diagnose these deposits as weakly developed paleosols, fitting the classification of 'protosols' (Brown and Kraus, 1987; Retallack, 1997). FA3 units with distinct haystack and popcorn weathering features are interpreted as swelling bentonitic mudstones that imply the presence of devitrified volcanic ashes (Roberts and Hendrix, 2000). However, several of these units were collected and separated to obtain volcanic phenocrysts for radioisotopic dating. However, this approach failed to yield suitable volcanic zircon populations, rather, the zircons were quite mixed, including a range of young and old grains suggesting that these are not primary ashes, but more likely developed as a result of weathering of volcanic-lithic rich sandstones and siltstones. No evidence of primary volcanic ash beds could be identified, although considerable effort was made to determine if such beds exist.

5.1.6. Interlaminated sandy siltstones to silty mudstones (FA4)

Description

Interlaminated sandy siltstones to silty mudstones are moderately common throughout the outcrop and core (Table 4). FA4 is commonly composed of the following lithofacies: Ssc, Sr, Fm, Fr, Fl, Pb, C, and P. FA4 tends to preserve fine to medium scale, horizontal lamina (Sm, Fl, Fr, Fm, Ssc). Individual siltstone and claystone couplets are tightly packed with continuous upper and lower bounding surfaces. In several instances however, planar and ripple cross laminations (Sr) are observed, along with small-scale dewatering features or bioturbation.

FA4 units commonly range in outcrop from 0.1- 3.0 m in thickness and are laterally continuous for up to a kilometre; however, most only extend for a few hundred meters. Internal bounding surfaces are 1st to 2nd order and range from gradational to sharp boundaries. However, in core, three distinct morphologies are identified: 1) tightly packed rythmitic beds (lenticular bedding with 0.01-0.05 m sets) between 0.10-5.0 m-thick; 2) wavy to lenticular-bedding; and 3) thicker, flaser-beds. FA4 is not present in the upper Winton Formation. FA4 commonly preserves bioturbation ichnites with a BI of ~2.

Interpretation

In lower portions of the Winton Formation, FA4 and associated structures indicate deposition within tidal flats and or tidally influenced, distal fluvial channels that are most likely associated with upper to middle delta plain settings (*sensu* Dalrymple and James, 2010; Davis, 2012). In the Mackunda Formation, this FA commonly occurs as tightly packaged units of cyclical tidal rhythmites and non-cyclical couplets of flaser, wavy, and lenticular bedding. It is interpreted that these sedimentary features represent a prograding delta progression from marginal marine, coastal, deltaic, to very distal tidally-influenced fluvial channels in the lower Winton Formation (Pontén and Björklund, 2007). In the upper Winton Formation, FA4 is rare and most likely to have been generated by a secondary or tertiary fluvial channel with waxing and waning flow velocities. Association of ripples, vertebrate tracks, and invertebrate bioturbation markers indicate periods of repeated ponding in inactive fluvial channels, closely followed by minor stream flow (Thulborn and Wade, 1984; Buatois and Mangano, 1995, 2011; Romilio et al., 2013).

5.1.7. Plant-rich Carbonaceous Mudstone to Coal (FA5).

Description

Carbonaceous siltstones, mudstones, and thin coals comprise this FA in both outcrop and core (Table 4). FA5 is commonly composed of the following lithofacies: Ssc, Fl, Fsc, C, Pb and P. FA5 includes a range of thinly- to thick-bedded mudstone units that have moderate to very high amounts of carbonized or whole plant material and coalified plant fragments (Fl, Ssc, Fsc, Fcf).

Individual horizons in outcrop range from 0.05 to 4.0 m thick, but are most typically 0.10 to 2.0 m thick. Units are commonly fine-grained, consisting of silts and muds. The lateral extent of FA5 units is variable, extending up to 150 m. FA5 is typified by upper and lower 0th to 2nd order bounding surfaces, and commonly exhibit sharp contacts. Internal, weakly developed 0th to 1st order laminae are common, defined by plant hash and well-developed coalified fragments concentrated along these boundaries. In outcrop, FA5 is only exposed in the lowermost portion of the upper Winton Formation. Thick repeated occurrences of FA5 can co-occur with Ch (FF). In core, FA5 is identified in both the middle and lower Winton Formation. This facies is absent in all but the very uppermost Mackunda Formation in core. FA5 rarely preserves bioturbation in either outcrop or core, with a BI of 0 to 1.

Interpretation

FA5 is interpreted to represent very low energy anoxic to dysoxic accumulations of plant material mixed with fine-grained sediments that settled out within abandoned channels, oxbow's, billabongs and low-lying ponds and swamps (Allen 1963; Fielding, 1985, 1987; Davies-Vollum and Wing, 1998). FA5 is most common in the uppermost Mackunda and lower Winton formations, and is interpreted to reflect deposition within coastal mires, oxbow lakes and back swamp environments, in upper delta plain settings. Thicker sections of peat to sub-grade coal are interpreted to have been generated in swamp accumulations adjacent to back swamps to very distal fluvial environments (Kraus and Aslan, 1993, Wing 1998). Many FA5 units occur with CH (FF) macroform elements that are interpreted to represent oxbow swamps that formed in abandoned channels (Fig. 5a). However, isolated non-lenticular horizons are likely to have been ponds, minor swamps, or even plant and mud rich flood debris.

5.1.8. Intraformational Conglomerate (FA6)

Description

Intraformational conglomerate is a rare FA in outcrop and was not observed in core (Table 4). FA6 is characterised by dominantly matrix supported intraformational-paraconglomerate composed of the following lithofacies: Gmm, Gmx, Sh, and Ss. FA6 deposits are typically unstratified, dominated by matrix supported pebble to cobble sized, intraformational, mudstone and siltstone rip-up clasts. Matrix varies from very coarse sand to very fine silt. FA6 units lack internal structure. In outcrop FA6 units are roughly 1.0 m in thickness, and some units can be traced laterally for quite some distance in LQCP and BNP. Beds are moderately continuous, but thickness varies laterally to form discontinuous lens-like to sheet-like geometries. Basal bounding surfaces are incised, indicated by 4th order surfaces, and are very irregular in nature. Upper surfaces commonly grade weakly into overlying FA and can exhibit sharp upper surfaces. FA6 does not preserve any bioturbation (BI of 0), and not fossil material has been described or identified from this unit.

Interpretation

The matrix-supported nature of these intraformational conglomerates indicates that they may be small, localized debris flows or dilute debris flows that maintained matrix support over fairly long run-out distances prior to frictionally freezing. In particular, several distinct horizons observed at both LQCP and BNP are interpreted as localized debris flows. The upper bounding surfaces of this FA are typically gradational, indicating a return to normal stream flow conditions following these events. These localized events are interpreted to represent possible channel bar erosion or rip-up clasts originating from channel evulsion; clasts are fairly rounded indicating a minor to moderate distance of travel. For lager debris flows, it is perhaps possible that these units are associated with periods of intense volcanic eruptions to the east in the Whitsundays Volcanic Province, and hence, they may represent the distal expression of in channel lahars. This possibility has not been explored in detail.

5.2 Stratigraphy

Vertical and horizontal stratigraphic relationships are unclear between LQCP and BNP. Based solely on average strike and dip (n<1º NE; in agreement with Senior et al., 1978), LQCP should be slightly higher stratigraphically than BNP and hence, slightly younger. However, traditional inferences of ‘layer cake’ stratigraphy, a poor understanding of the stratigraphic relationships throughout the Winton outcrop area exists, and hence the relationship between LQCP and BNP is not certain, although the two areas are both interpreted be part of the upper-most preserved Winton Formation.

5.2.1 Outcrop Stratigraphy

Lowermost exposures at LQCP and BNP are very similar with minor differences, most notably is higher levels of sand at BNP, whereas LQCP contained more silt. Overall, lower units contain fair amounts of muds, clays and supporting matrix. Commonly, units are composed of repetitive packages of FA2 and FA3 (interbedded), with minor occurrences of interlaminated-interbedded FA1, FA3, FA5 (Fig. 6). FA2 occurs in eight distinctive successive step-like beds, commonly 0.4-1.3 m in thickness. In between each FA2 are groupings of interbedded and repeated FA1-FA4 units with very infrequent beds of FA5 (FA3 contains high percentages of silt progressing up-section). Several major, but isolated lenticular bodies preserve FA5; at its thickest part ranges between 0.8-1.0 m and commonly pinch-out laterally. FA5 is interpreted to be in-filled abandoned channels with preserved plant remains and trace fossils preserved therein. FA2, FA2 and FA3 average between 0.02-0.4 m in thickness. The common association of FA1, and FA2 is interpreted to be in-channel to directly adjacent to actively migrating channels. Stacked successions of FA3 (sometimes interbedded with FA2) exhibit both paleosol and bioturbation characteristics. This likely represents minor bank and levee development to well-developed and long-lived bank (Fig. 6a,b). Both cross bedding (FA2) and very small-scale ripple lamination reflects in-channel activity is common in FA1-FA2, and is interpreted to represent channel fill. The ratio between channel/overbank percentages is estimated between 80/20%; however, this may be erroneous considering poor local preservation quality. Palaeocurrent data based on in-channel features indicates meandering-channel orientations of a westerly orientation to northwesterly (335º-334º), with other studies indication that overall palaeocurrent orientation to be to the southwest (MacDonald et al., 2013; Tucker et al., 2016).

Continuing up section, exposed units are moderately altered (Fig. 6a). Minor to moderate spheroidal weathering structures are observed within these units. There is a distinct lack of muddy facies FA3 in the middle sections of exposed units, where a distinct thickening of FA1-FA2 is observed. FA3 is rare, but if present likely represent waning channel floods or short-term levee development. Overall, better quality of outcrop is at LQCP; however, large-scale architectural notes are better preserved in BNP. This includes many channelized elements (point bars and scroll bars) in FA1-FA2. Interlaminated finely grains sandstones and siltstone (FA3) are interpreted to represents saturated sediment deposited during waxing and waning flow periods (Fig. 6a).

Lowermost portion of the uppermost Winton Formation are commonly composed of thicker units of FA1, common forming weathered cliffs. Along with fine-grained FA1 and FA2 commonly preserve numerous paleosol indicators, bioturbation, and root traces (Fig. 7). These units are interpreted to represent migratory channels, which developed into a moderately to poorly drained floodplain. Also common is the co-occurrence of FA1, FA2, and FA4 is commonly capped by FA6. FA1 is a great deal coarser and occasionally grain supported or granular in nature. The increase of overall grain size strongly indicates a rise in fluvial energy from lower channelized structures identified in the basal exposures. FA4 is best preserved in these sections, and interpreted to be a repetitive waxing and waning of flow within these channels. Just below the uppermost, highly altered outcrop, isolated units are a thick-bedded paraconglomerate (FA7) are interpreted to represent in-channel to fairly expansive flooding event(s). The uppermost sections of the Winton Formation range from highly lateritic to extremely kaolinized, and correlation of these units is particularly challenging.

5.2.2 Core Stratigraphy

As noted above, this study also surveyed Geological Survey of Queensland's (GSQ) cores GSQ Eromanga 1, GSQ Blackall 2, GSQ McKinley 1, GSQ Maneroo 1, and GSQ Longreach 1-1B in order to produce a more reliable broad-scale palaeoenvironmental reconstruction for the Eromanga Basin. Other then GSQ Longreach 1-1B, all cores contain the Winton Formation (exposed in the uppermost sections of the core), and all cores preserve the underlying Mackunda Formation. Herein is a summary of results.

It has been interpreted that the upper Mackunda Formation was deposited during dominantly shallow marine to fluvial dominated deltaic systems (lower-upper delta plain) (Bhattacharya and Walker, 1992; Helland-Hansen and Gjellberg, 1994; Bhattacharya, 2010), and is in agreement with this study. Within the lower Mackunda Formation, units distinctly lack any sand-size particles. Bedded units are characterised by mud-rich, well preserved tidal to proximal shallow marine rhythmite sequences. This section of core also records the lowermost occurrence of calcite and other evaporates mineral(s) within the strata. These minerals can occur in discrete lamina (during deposition) or as crack and fissure infill (post-deposition). In core, no obvious marine trace fossils were identified, however there were many horizons that displayed deformation as a result of dewatering.

Yet, throughout the middle and upper sections of the Mackunda Formation, units exhibit a coarsening-up characteristic. Unit's progress from interlaminated clay-rich muds to silt-rich muds with interlaminated to interbedded very fine-grained siltstones (generally exhibited as wavy to lenticular bedding). It is likely that many of these deposits in the middle Mackunda Formation indicates a transition from the shallow marine depositional conditions to delta front and pro deltaic conditions (Bhattacharya, 2010). The upper Mackunda is much the same; however, strata become more heterolithic, shifting between flaser, wavy and lenticular bedding styles, signifies mixed energies as these areas transitioned from delta-front to upper delta plain to the lower delta plain in the very lowermost Winton Formation.

The contact between the lowermost Winton Formation and uppermost Mackunda Formation is diagnosed by the lowermost major coal seam (Fig. 8), which follows the criteria established by Draper (2002). The contact between the Mackunda and Winton formations is currently challenged by Greentree (2011); yet, this study finds multiple lines of evidence to corroborate the original interpretation. In many cores, these lower-most coal seams were often accompanied by the last occurrence of marine bivalve shells and shell hash layer, and the first occurrences of distinct sand-sized particles. High degrees of coalified plant debris likely indicate the local to regional development of coastal mires, swamps, wetlands or coastal woodlands (Fig. 8c). Furthermore, youngest maximum depositional grain populations for the upper-most Mackunda Formation (GSQ Longreach 1-1A) indicates a depositional episode at or younger then 103-101 Ma, with the lowermost Winton Formation (Isisford) deposited shortly thereafter (Tucker et al., 2013, 2016).

Transitioning into the lower Winton Formation, units shift from muddy-silty tidally influenced distal channelized units. Both facies and textural notes indicate a higher degree of subaerial development of poorly drained muds and primitive soils, along with the development of co-occurring back swamps and coastal environments. Many units within the lower Winton Formation denote moderate to minor tidal influence including flaser bedding and ripple lamination with mud drapes. Yet, a distinct and sharp contrast is observed in the uppermost Winton Formation, and is interpreted as an array of fully terrestrial alluvial depositional environment. The uppermost beds of the Winton Formation in core are commonly very coarse- to finely-grained sandstones and interbedded coarse siltstones. Both macro and micro-scale sedimentary features that were identified in core correspond to those identified in fluvial-alluvial depositional environments described from outcrop.

6. Discussion

6.1 Depositional environments

This study is focused on providing more localized environmental context and stratigraphic control to accompany recent fossil discoveries in the Winton Formation. Our basin-wide reconstruction for the mid-Cretaceous indicates much of the Winton formation was deposited during the terminal phase of the Eromanga Sea (Fig. 9). Therefore, the major mechanism of environmental change at a regional scale was the regression from marine to continental ecosystems. This is in agreement with many previously published studies (Veevers, 2006, 2012; and references therein). However, the tempo of this transition and how it affected the local flora and fauna remains vague in the current literature (Fletcher et al., 2014a,b, 2015). Our initial results indicate that within the eastern portions of the basin, the early stages of regression occurred in the upper Mackunda Formation, at an age no earlier than 104 Ma. By 102 Ma, strata of the conformably overlying Winton Formation indicate deltaic to coastal environmental conditions. Therefore, the regression of the Eromanga Seaway began at 104 Ma in the far eastern portions of the basin, and continued to throughout the Cenomanian and into the Turonian, with fully alluvial conditions existing throughout the basin by at least 94-92 Ma. To better understand the evolution of these ecosystems during this period, we synthesize our recent sedimentological data with available stratigraphic and tectonic information.

6.1.1 Middle to upper Mackunda Formation

Much of the Mackunda Formation and underlying strata have been interpreted to represent shallow marine conditions (Fig. 9) (Draper, 2002; Veevers, 2000a,b,c). However, the patterns of sediment emplacement changes in the lowermost portions of the upper Mackunda Formation, indicating a progressive shift in deposition from shallow marine (shelf) to a shallowing-up deltaic environment. This is identified in all stratigraphic logs west of Isisford, Queensland, indicating that the regression of this shallow seaway was gradual in nature. Co-occurring fossil vertebrate and invertebrate records include terrestrial archosaurs Muttaburrasaurus longmani and fragmentary ctenochasmtoid pterosaur material (Bartholomai and Molnar, 1981; Fletcher and Salisbury, 2010), marine reptiles (polycotylid or polycotylid-like plesiosaurians), chondrichthyan(s) (Kemp, 1991; Kemp and Ward, 1995), ichthyodectiform and teleosts fish (Cook, 2012; Berrell et al., 2014) ammonites (*Myloceras* and *Labeceras*), the belemnite *Dimitobelus diptychus*, along with various forms of bivalves (*Laevidentalium cretaustralium*) and gastropods (Stillwell, 1999; Henderson and Kennedy, 2002; Kear, 2003; Williamson et al., 2012).

6.1.2 Lower Winton Formation

The first appearance of coal marks the Mackunda-Winton formation contact and suggests a transition from marine to tidally influenced alluvial deposition as a result of steady drop in sea level and the progradation of a large delta system westward by 101 Ma (Fig. 9). In the eastern portion of the Eromanga, the lower Winton Formation reflects fluvial to tidally influenced lower delta plain to upper delta plain sequences. Many associated environments likely represent very broad lower delta plain wetlands, swamps, and marshes rich in floral accumulation within anoxic environments (Fig. 9). Furthermore, the upper to lower delta plain environments preserve a mixed assemblage of marine and terrestrial taxa (Salisbury et al., 2006a; Berrell et al., 2014). In the central portions of the Eromanga, sediments reflect the transition from marine to prodelta or near shore. However, in the west, facies still reflect marine influences on sedimentary successions. Skeletal remains are uncommonly well-preserved, with skeletal elements not only associated but commonly articulated. The high degree of preservation is largely the result of skeletal material being preserved in calcite cemented-volcanilithic-rich sandstone nodules (Syme et al., 2016). These nodules are commonly preserved within FA1, FA3, FA4. Fossil remains include *Isisfordia duncani*, a eusuchian crocodyliform, large-bodied predatory fishes and a newly-discovered, but yet to be described dinosaurian taxa (Salisbury et al., 2006a,b; Faggotter et al. 2007; Berrell et al. 2014). The co-occurrence of transitional sedimentological facies and sedimentary structures (distal-fluvial-deltaic to tidal rhythmites) along with a transitional faunal assemblage (possible marine and freshwater taxa) indicates that this assemblage was representing a marginal marine to very distal continental (transitional) system.

6.1.3 Upper Winton Formation

The upper Winton Formation is described from observations based on outcrop and core (Fig. 6,7,8,9). At basin scale, deposition within the upper Winton Formation strongly indicates alluvial-fluvial mechanisms for transport and emplacement of sediments. By correlating local deposition regionally, multiple broad-sweeping meandering channels across a developing floodplain can be identified (Fig. 9). On a local scale, channel deposits indicate active migration and channel development throughout the floodplain. Co-occurring levee, overbank, splay, and abandoned channel deposits are common. Floodplain fines preserve weakly to intensely bioturbated protosol to histosol horizons, and indicate evidence of deep-reaching bifurcating roots. These strata preserve a broad suite of plant remains including leaves, branches, and stumps. A recently completed review of the Winton Formation floral assemblages by Fletcher et al. (2014a,b, 2015) strongly corroborates these facies-based palaeoenvironmental interpretation. Furthermore, invertebrate assemblages (unionids) from both LQCP and BNP also indicate freshwater continental ecosystems (similar to those described by Thompson and Stilwell, 2010) . Vertebrate assemblages range from singular, isolated individuals multitaxic or monotaxic (small) bonebeds, both with variable preservational quality. Currently, bonebeds or concentrations of vertebrate material are interpreted as hydraulically sorted in nature, commonly exhibiting pre- and post-burial weathering. However, fossils do not exhibit abrasion or rounding, suggesting that they were entombed near-to the location of death. Currently described within the recent literature are the partial skeletons a non-avian theropod (*Australovenator wintonensis*), along with fragmentary remains of several titanosauriform sauropods, *Diamantinasaurus matildae*, *Savannasaurus elliottorum* and *Wintonotitan wattsi* (Molnar, 2001; Salisbury et al., 2003, 2005; Molnar and Salisbury, 2005; Salisbury et al., 2006b; Hocknull and Cook, 2008; Hocknull et al., 2009; Agnolin et al., 2010; Molnar, 2010; White et al. 2012, 2013; Leahey and Salisbury, 2013; Poropat 2014a,b; White et al., 2015; Cook et al., 2016; Poropat et al., 2016; White et al. 2016).

The Winton Formation also preserves a broad suite of macrovertebrate traces, with some representing the only known trace-evidence of that organism within Queensland or Australia. Track diversity includes two ichnotaxa that can be attributed to ornithopods: *Wintonopus latomorum*, and a large track type recently reassigned to cf. *Iguanodontipus* (Romilio and Salisbury, 2014). Originally, Thulborn and Wade (1979) interpreted the Lark Quarry trackway to preserve a 'pursuit scenario' set within lacustrine setting, yet, recent revisions by Romilio et al. (2013; 2014) have interpreted Lark Quarry to preserve a time-averaged (day's) track assemblage along a developing riverbank undergoing a waning flow period. Track evidence indicates that trackmakers interacted with both higher flow depths (swimming tracks) and shallower depths (walking and running) within a short period of time (days). Co-occurring sedimentary structures including uni-directional current ripples, bioturbation, and minor to moderate dewatering features offers support that the waning of current flow did not last long enough for the track horizon to develop mud cracks or pedogenic features. Rather, it is noted that the track horizon is directly overlain by a multi-story channel sandstone, indicating a return of waxing flow conditions.

6.2 Revised stratigraphy and regional correlations

Across the Eromanga Basin, the Winton Formation is extremely flat-lying with typical dip angles of less than 2°. This, coupled with very low-relief across much of the basin, has resulted in the assumption that many of the surface exposures, and hence, the flora and fauna from the formation were temporally comparable across the basin.

However, this stratigraphic relationship has been questioned based on the presence of distinctly different maximum depositional age profiles from detrital zircon samples that were collected at different fossil localities across the basin (Tucker et al., 2013; 2016).

In an attempt to further evaluate this question, a synthesis of available core, geophysical, and structural data across the Eromanga Basin was compiled and used to identify key structural complexities in the basin and the hypothesis that different fossil localities across the basin may represent different stratigraphic intervals within the Winton Formation. This is plausible with a near-continuous spectra of detrital zircon grain ages between ~200–92 Ma were observed by Tucker et al., (2013, 2016) from nearly 720 detrital zircon analyses conducted for the Winton and Mackunda formations. This suggests that arc volcanism was relatively continuous throughout the Mesozoic, and that syndepositional, or near syn-depositional volcanic detritus was continuously shed into the basin (Tucker et al., 2013, 2016).

Very similar grain age populations between the top of the Mackunda Formation and lowermost portions of the Winton Formation supports the long-held notion of a conformable, albeit regressive relationship between these two formations (Exon and Senior, 1976; Casey, 1970; Draper, 2002; Tucker et al., 2013, 2016). However, a distinct shift in the maximum depositional age between Winton samples from lower and higher stratigraphic sections indicate a possible stratigraphic discontinuity or a major fault and juxtaposition of lower and upper portions of the preserved Winton Formation in the field area. Specifically, the Isisford maximum depositional age assessment is near to that of the lower Winton and upper Mackunda formation samples, yet the nearby localities of Bladensburg and Lark Quarry, yield significantly younger maximum depositional ages (92–

94 Ma) (Tucker et al., 2013, 2016). In light of these stratigraphic issues, a review of the structural geology of the area reveals numerous small faults along the eastern flank of the Eromanga Basin, which may have a direct impact on the correlation between fossil sites between Isisford and Winton, Qld (Fig. 3). Localities to the east of the fault system, including Lark Quarry Conservation Park and Bladensburg National Park, sit on the hanging wall of this large normal fault system, whereas the Isisford locality is situated on the footwall. Post-deposition normal fault movement is interpreted. This would account for both the unusually tidal to marine nature of the Isisford locality and fauna (e.g., Salisbury et al., 2006a; Syme et al., 2016), as well as the major difference in maximum depositional ages observed from detrital zircons at this locality. Considered together, these two lines of evidence suggest that the Isisford fossil locality is part of the lower, marine influenced lower member of the preserved Winton Formation, whereas the BNP and LQCP sites are assigned to the upper member of the preserved Winton Formation.

Faunal assemblages that are similar to each other have been discovered in the vicinity of LQCP and BNP. As described by Hocknull et al. (2009) and Poropat et al., (2015a,b), site locations are geographically within 10’s km and also situated stratigraphically in the very uppermost exposed Winton Formation. Structurally, the well-documented Cork and Wetherby fault systems lie between several of these, with, LQCP and BNP lying to the east of the fault, and sites (AODL85) described by Poropat et al. (2015a,b, and others) lying to the west (Salisbury et al., 2006a; Hocknull and Cook, 2008; Hocknull et al., 2009; White et al., 2012, Leahey & Salisbury, 2013; White et al.,2013; Poropat 2015a,b; White, 2016). Yet, detrital samples collected from key stratigraphic levels on both sides of the fault systems indicate little vertical offset, as both preserve a youngest maximum depositional age no older than 92–94 Ma. Pervasive faulting and the resulting offsets are also reflected in the basinal models produced in ARC GIS by this study via core logs and historical records. Therefore this study also suggests that fossil assemblages near to Winton and McKinlay, Queensland, are temporally and stratigraphically similar; however, little site-specific sedimentological or taphonomic information has been published, and this determination has yet to be confirmed.

7. Conclusion

Detailed facies and architectural analysis of the Winton Formation, coupled with a review of existing floral and faunal data, detrital zircon data, and compilation of structural and stratigraphic data into a basin model, has resulted in an enhanced understanding of the palaeoenvironments and stratigraphic relationships of these newly discovered fossil assemblage sites. Twenty-three re-occurring facies were identified and utilized to construct six distinct facies associations. Each facies association was coupled with available palaeontological data to document a transition between shallow marine and tidal conditions in the upper Mackunda and lower Winton formations to fully alluvial depositional environments in the upper Winton Formation (based on the erosional thickness). The Eromanga Basins was fully inundated with the last stages of a shallow marine seaway no later than 104 Ma, followed by the development of a westward expanding delta and progradational river system by 101 Ma and thereafter (Tucker et al., 2013, 2016). The upper Winton Formation represents an alluvial floodplain depositional environment that hosted multiple migrating channels within a low-lying flood plain (Fig. 9,10).

Detrital zircon data and basin modelling were critical to documenting cryptic stratigraphic relationships within the basin, showing that distinct lower and upper Winton

Formation outcrop areas exist within the study area. Based on these results, faunal assemblages and strata at LQCP and BNP are near contemporaneous and represent the upper Winton Formation. On the other hand, fossil assemblages and exposures near Isisford, Queensland are unique to those in the central portions of the Eromanga Basin and interpreted to represent the lower Winton Formation.

For the first time, this study has confidently provided a robust geological and palaeontological-based framework for relating various Winton based fossil assemblages. Furthermore, this framework will allow much more accurate comparisons between Winton taxa to similar forms in other locations around Gondwana (i.e., the Rio Limay Subgroup of the Neuquén Basin of Argentina, and the Santo Anastácio and Adamantina Formations of the Bauru Basin, of Brazil).

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Figure 1 Map of eastern Australia displaying surface exposures of the Winton and Mackunda formations in the Eromanga Basin of Queensland, Australia. Symbols identify locations of fossil assemblages and GSQ Core localities, which were utilized for both stratigraphic and temporal correlation. Map is modified from GeoScience Australia 2013.

Figure 2 Geochronology for the Middle Jurassic to Quaternary sedimentary units within the Eromanga Basin including stratigraphic location of several newly discovered archosaurian assemblages in the Winton Formation from Isisford Qld (1*) and Lark Quarry Conservation Park & Bladensburg National Park (2*). Modified from Draper et al., 2002 & Tucker et al., 2013.

Figure 3 Map of exposed faults and structures within the exposed Winton and Mackunda formations within the study area. This figure highlights historical identified (A. Hoffmann et al., 1991), along with recently identified (B. Howler et al., 2011) fault systems near to recently described fossil assemblages (Salisbury 2006a,b). Map modified from GeoScience Australia 2013.

Figure 4 Arc GIS (10.1) Geo-referenced based map of exposed Winton and Mackunda Formation, along with the expansive Quaternary Alluvium and Black Soil across the study area. Map also displays location of all field sights and core localities across the study area. Cross section A-A’ displays the fairly constantly gentle dip across the basin and the general thickening of the Winton Formation in the west. Accompanying table provides borehole location information for physically surveyed core at the Geological Survey of Queensland in Zillmere, Queensland.

Figure 5 Outcrop Facies associations (white), bounding surfaces (black), and fluvial architecture (green) in outcrop at both Lark Quarry Conversation Park and Bladensburg National Park: A) Single in-filled abandoned channel (CH(FF)) bounded by a basal 4th order erosive surface, B) Multistorey FA1 scroll bars, each bounded by erosive 3rd order surface, C) Moderately developed palaeosol, D) Basal sheet FA2 overlain by angular bedded course grained FA1, E) Basal tuffaceous mudstone overlain by multistory FA1.

Figure 6 Observed facies associations in the lower Winton Formation with outlined stratigraphic section of Hades Hill at Lark Quarry Conservation Park: A) Uppermost section of the lower exposed Winton Formation with interbedding of FA2 and multistory FA2; B) middle lower exposures with basal interbedded siltstone; C) middle lower exposed massive bedded FA5 tuffaceous mudstone.

Figure 7 Facies associations observed in outcrop of the upper Winton Formation: Section type 1 dominantly contains poorly to moderately developed palaeosols to protosols (8a,b,c). These stable and developing horizons preserve a broad suite of soil, floral and bioturbation indicators (8a,b), incised banks (9c) that commonly form short cliff-like structures (8d,e). On the other hand, Section type 2 is typified by lower bank and levee deposits that are then incised by a very active group of channel coarse grained cross bedded sandstones (8f,g,h).

Figure 8 Facies associations observed in cored sections of the Winton and Mackunda Formation: A) upper Winton Formation sections dominated by massively bedded FA1 with 2nd to 3rd, B) The lower Winton contains a great deal more heterolithic lamina and bedding dominantly silty in nature, C) The conformable contact between the Winton and Mackunda Formation is identified by the first occurring coal measure, D) The uppermost Mackunda is distinctly silt and mud dominated with very thick beds of tidal rhythmites and deformed lenticular lamina.

Figure 9 Simplified palaeogeographic maps modified from Veevers (2000a,b,c; and references therein) with symbols showing the retreat of the Eromanga Seaway: A) No older than 104–102 Ma, the first occurrence of coastal deposits in the far east of the basin, as the central and western cores preserve dominantly shallow marine conditions, B) No older than 100–102Ma, the lower Winton Formation preserve distal deltaic to coastal environments; however far western cores preserve shallow marine sediments, C) No older than 92–94Ma, the middle Winton Formation deposited preserves fully terrestrial environments except the farthest western core which preserved coastal-rhythmites, D) The transition into the upper Winton Formation which is estimated to be deposited no older than 92 Ma, in all cores preserves terrestrial associations of sediments and both trace and body fossil assemblages. Temporal rates, palaeocurrent and sediment source terranes discussed in detail within Tucker et al. (2016).

Figure 10 Artistic reconstruction of the uppermost Winton Formation based on sedimentological, trace and body fossil assemblages at Lark Quarry Conservation Park. Reconstruction done by Owen Li (Petrified Pencils, 2013).

Table 1 Lithofacies codes identified in the Winton and Mackunda formations. Modified from Miall, 2010.

Table 2 Facies associations identified in in the Winton and Mackunda formations. Modified from Miall, 2010.

Table 3 Architectural elements (lithosomes) identified in the Winton Formation outcrops of Lark Quarry Conservation Park and Bladensburg National Park. Modified from Miall, 2010, 2014.

Table 4 Identified facies in the Winton and Mackunda formations (FA1-FA6).

Supplementary Figure 1a Typical outcrop patterns of Facies Associations 1-6 in outcrop at both Lark Quarry Conservation Park and Bladensburg National Park.

Supplementary Figure 1b Typical patterns of Facies Associations 1-6 in core.

Supplementary Figure 2a Observed hierarchy of bounding surfaces in outcrop of the Winton Formation at Lark Quarry Conservation Park and Bladensburg National Park.

Supplementary Figure 2b Observed hierarchy of bounding surfaces in core from both the Winton and Mackunda formation from around the study area. Certain areas provide some evidence of high-sinuosity fluvial channels with well-defined margins. The complexity and abundance internal bounding surfaces throughout individual FA1 sand bodies suggest that flow waxed and waned over the course of deposition, as would be expected in fluvial channel system. FA1 units commonly fine upwards, suggesting that much of the bed is composed of migrating point bars, channel lag and thalweg sediments (Miall, 2014).

Table 1

Facies Code	**Lithofacies**	**Sedimentary Structures**	**Interpretations**
Gmm	massive, matrix supported gravel	grading	debris flow deposits
Gmx	thin-lamina, matrix supported gravel	grading- erosional surface interlaminated conglomerate	debris flow deposits- fine scale
Sm	sand, very coarse, maybe pebbly	massive bedded	gravity flow
Sp	sand, very coarse, maybe pebbly	grouped planar crossbeds	transverse bar (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of all types	lower flow regime ripples
Sh	sand, very fine to very coarse, maybe pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (I and U flow regime)
Si	sand, fine	low angle (<10°) crossbedded	scour fills, crevasse splays, antidunes
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours including	scour fills

		eta cross-stratification	
Se	erosional scours with intraclasts	crude cross bedding	scour fills
St	sand, fine to very coarse, rare pebble inclusions	solitary (theta) or grouped (pi) trough cross beds	dunes (lower flow regime)
Sfv	coarse to fine	inclusions of rare fossil deposits	channel and overbank or waning flood deposits
Sd	sand-silt with minor pebble inclusion	cosets of low angle (10° to 20°) tabular cross bedding	stacked channel fills
Ssc	fine sand, silt, mud	fine lamination	overbank or waning flood deposits
Fl	sand, silt, mud	fine lamination	overbank or waning flood deposits
Flf	sand, silt, mud and fossils	massive bedded	overbank or waning flood deposits
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits

Fr	silt, mud	rootlets	soil
Fsc	silt, mud	laminated to massive	backswamp deposits
Tlcf	silt, mud, clay	thin interbedded to interlaminated sheets	waxing and waning flow, tidal influence
VFc	fine to very fine clay	bedded to massive	shallow lagoon, shore/delta
PB	fine -very fine clay, lignite-coal	roots	preserved root(s), and root systems
P	carbonate	pedogenic features (primitive)	soil (primitive)
C	coal	plants, mud, mud films	decay plant matter, swamp

Facies Assemblages	Facies Codes																							Sediment Size	Arch. Elem.	Bounding Surfaces	Unweathered & Weathered Colour	Depositional Environment
	Gmm	**Gmx**	**Sm**	**Sp**	**Sr**	**Sh**	**Si**	**Ss**	**Se**	**St**	**Sfv**	**Sd**	**Ssc**	**Fl**	**Flf**	**Fm**	**Fr**	**Fsc**	**Tlcf**	**VFc**	**Pb**	**P**	**C**					

Table 2

FA1: Major Sandstones & Siltstones	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	cU-fU (710-180µ)	CH, LA, SB, HO, LS, LV FF	3rd - 1st	UW: N9, 5Y-5/2, 5Y-8/4, 10R-7/4, 5Y-7/2 W: 5R-4/5, 10YR-8/2, 5Y-7/6 10YR-7/4	migrating fluvial channel (waxing and waning flow)
FA2: Minor Sandstones & Siltstones	[redacted]	[redacted]	[redacted]			[redacted]	[redacted]	[redacted]		[redacted]	[redacted]	[redacted]		[redacted]		[redacted]	[redacted]		[redacted]	[redacted]	[redacted]	[redacted]		mU-fL (400-125µ)	CS, LV, CH, FF	3rd - 1st	UW: 5Y-5/2, 5Y-7/2, N7, N9, W: 5R-4/5, 10YR-7/4, 10YR-8/2, 5Y-7/6, 10YR-8/6	very low flow fluvial channel (ephemeral) to flooding sand sheets
FA3: Major & Minor Mudstones													[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	fU-vfU (200-88µ)	FF, LV, Ch(FF)	3rd – 0th	UW: 5Y-5/2, 5Y-7/2, N4-4, 5R-7/4, 5P-6/2 W: 5R-4/5, 5R-2/6, 10YR-8/2,	major over-bank fines, weekly developed soil

																											5Y-7/6	
FA4: Inter- Maminated Silt & mudstone					●								●	●		●	●		●	●	●	●	●	cL-fL (600-140µ)	LV, FF	3rd – 0th	UW: N7, 5Y-5/2, 5Y-7/2, 5R- 6/1 W: 5R-4/5, 5R-2/6, 10YR-7/4, 10YR-8/6, 5Y-7/6, N8, N2, N1	commonly preserved oxbow lakes, minor backswamp or poorly drained marshes
FA5: Plant-Rich Mudstones													●	●				●	●	●	●	●	●	fU-vfU (200-88µ)	Ch(FF), FF	2nd – 0th	UW/W: 5Y-5/2, N2, N1	floodplains, infilled oxbow lakes, minor and poorly drained marshes
FA6: Intra- Formation	●	●				●		●																vcL-fL, (1200	[redacted]	4th	UW/W: 5Y-5/2 & 5R-2/6	flood deposit

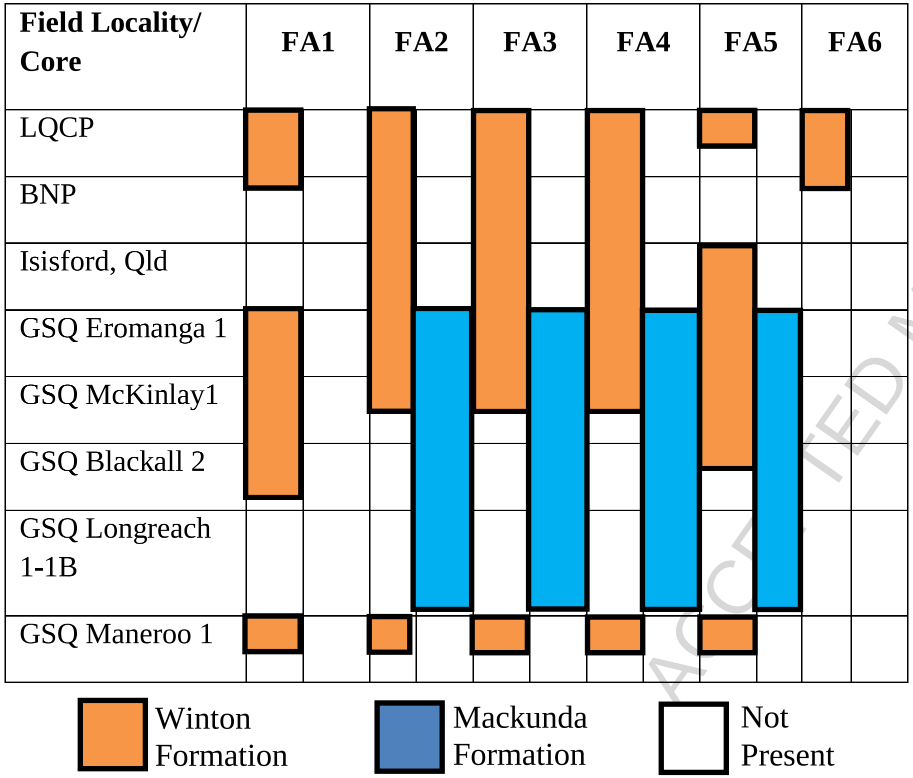
Conglomerate																								-150µ)				

Table 3

Element	Symbol	Facies	Geometry & Relationship
Channels	CH	Any Combination	Sheet, concave-up erosional base, commonly bounded by 3rd to 5th order surfaces
Lateral-Accretion Macroforms	LA	St, Sp, Sh, SI Se, Ss, Sr	Wedge, sheet; characterized by internal lateral accretion, 3rd-5th order surfaces, flat-based erosion surface
Scour Hollows	HO	St, SI, Sr	Scoop-shaped hollow with asymmetric fill
Laminated Sand Sheets	LS	Sh, SI, Sp, Sr	Laterally continuous sheets, blankets
Levee	LV	Fl, P, C, PB, Flf, Fm	Ovebank flooding with pedogenic and soil development
Floodplain Fines	FF	Fl, P, C, PB	Deposits of overbank sheet flows, floodplain ponds and swamps
Abandoned	CH(FF)	Fl, P, C, PB, Flf, Fm	Product of chute or neck cut-off, stream

Channel			migration

Table 4

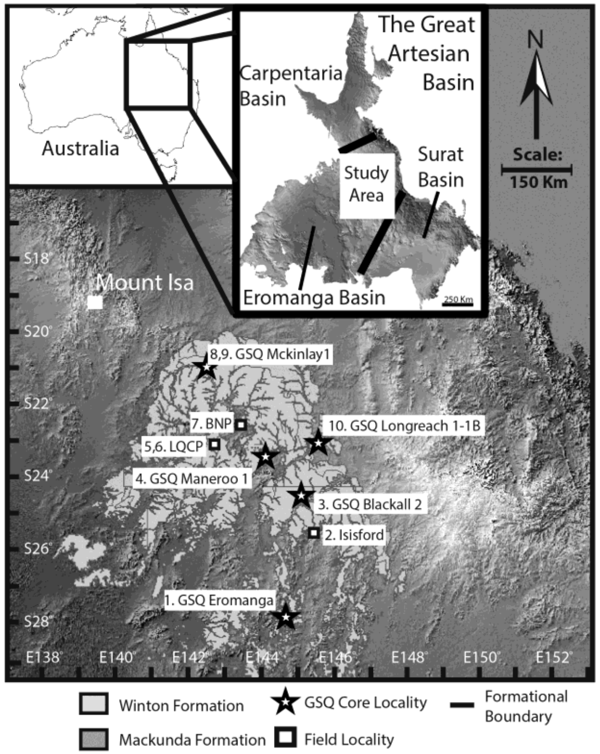


Field Locality/ Core	FA1	FA2	FA3	FA4	FA5	FA6
LQCP	🟧	🟧	🟧	🟧	🟧	🟧
BNP	☐	🟧	🟧	🟧	☐	☐
Isisford, Qld	☐	🟧	🟧	🟧	🟧	☐
GSQ Eromanga 1	🟧	🟧 🟦	🟧 🟦	🟧 🟦	🟧 🟦	☐
GSQ McKinlay1	🟧	🟧 🟦	🟧 🟦	🟧 🟦	🟧 🟦	☐
GSQ Blackall 2	🟧	🟦	🟦	🟦	🟧 🟦	☐
GSQ Longreach 1-1B	☐	🟦	🟦	🟦	🟦	☐
GSQ Maneroo 1	🟧	🟧	🟧	🟧	🟧	☐

🟧 Winton Formation

🟦 Mackunda Formation

☐ Not Present


Australia
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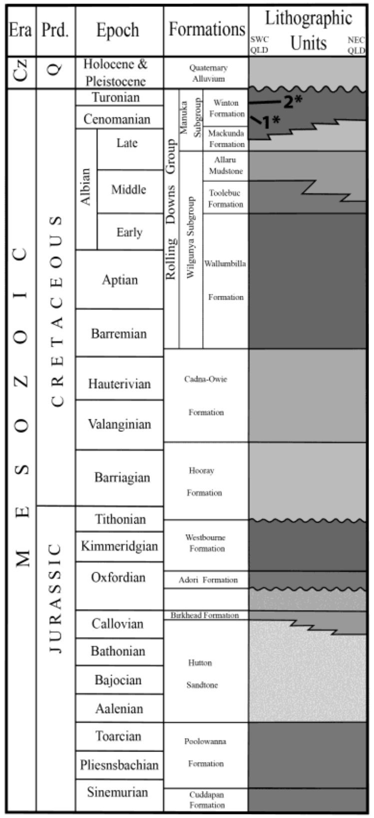
Basin
Carpentaria
Basin
Study
Area
Surat
Basin
Eromanga Basin
250 Km
N
Scale:
150 Km
Mount Isa
S18°
S20°
S22°
S24°
S26°
S28°
8,9. GSQ Mckinlay1
7. BNP
10. GSQ Longreach 1-1B
5,6. LQCP
4. GSQ Maneroo 1
3. GSQ Blackall 2
2. Isisford
1. GSQ Eromanga
E138°
E140°
E142°
E144°
E146°
E148°
E150°
E152°
Winton Formation
Mackunda Formation
GSQ Core Locality
Field Locality
Formational
Boundary

Fig. 1


Era
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Formations
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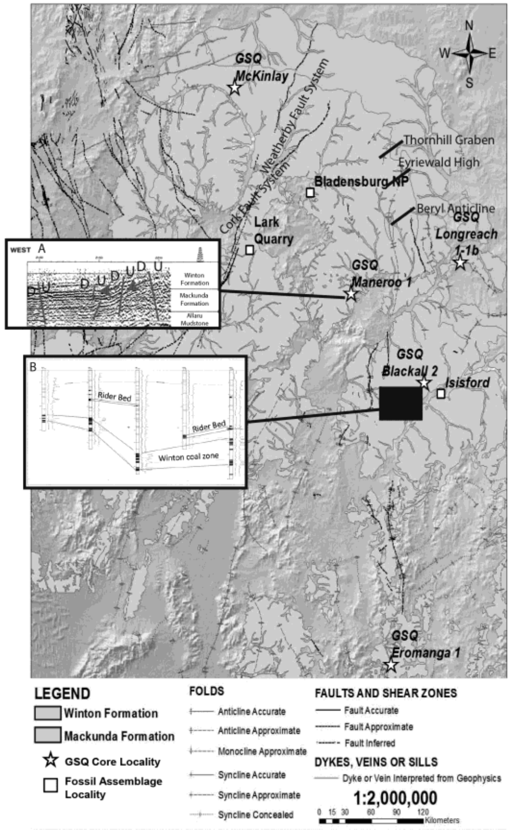
Holocene & Pleistocene
Quaternary Alluvium
MESOZOIC
CRETACEOUS
Turonian
Cenomanian
Albian
Late
Middle
Early
Aptian
Barremian
Hauterivian
Valanginian
Barriagian
Rolling Downs Group
Manuka Subgroup
Wilgunya Subgroup
Winton Formation
Mackunda Formation
Allaru Mudstone
Toolebuc Formation
Wallumbilla Formation
2*
1*
Cadna-Owie Formation
Hooray Formation
JURASSIC
Tithonian
Kimmeridgian
Oxfordian
Callovian
Bathonian
Bajocian
Aalenian
Toarcian
Pliesnsbachian
Sinemurian
Westbourne Formation
Adori Formation
Birkhead Formation
Hutton Sandtone
Poolowanna Formation
Cuddapan Formation

Fig. 2


N
W
E
S
GSQ McKinlay
Weatherby Fault System
Cork Fault System
Thornhill Graben
Eyriewald High
Bladensburg NP
Beryl Anticline
GSQ Longreach 1-1b
Lark Quarry
GSQ Maneroo 1
WEST
A
D
U
Winton Formation
Mackunda Formation
Allaru Mudstone
B
Rider Bed
Winton coal zone
GSQ Blackall 2
Isisford
GSQ Eromanga 1
LEGEND
Winton Formation
Mackunda Formation
GSQ Core Locality
Fossil Assemblage Locality
FOLDS
Anticline Accurate
Anticline Approximate
Monocline Approximate
Syncline Accurate
Syncline Approximate
Syncline Concealed
FAULTS AND SHEAR ZONES
Fault Accurate
Fault Approximate
Fault Inferred
DYKES, VEINS OR SILLS
Dyke or Vein Interpreted from Geophysics
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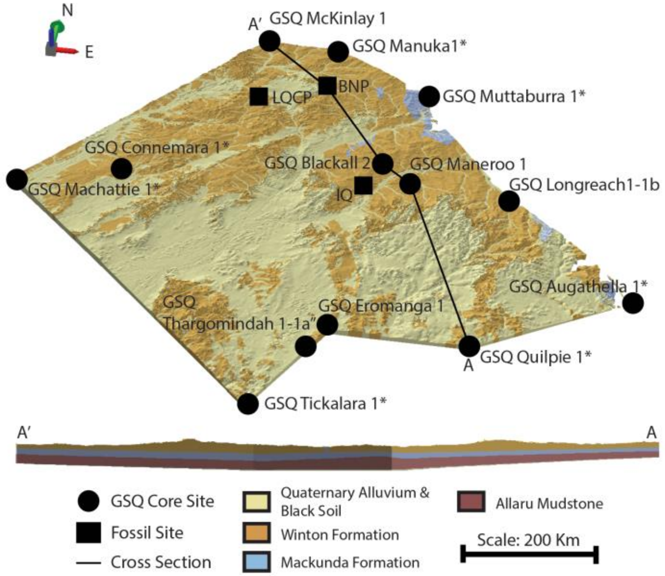
30
60
90
120
Kilometers

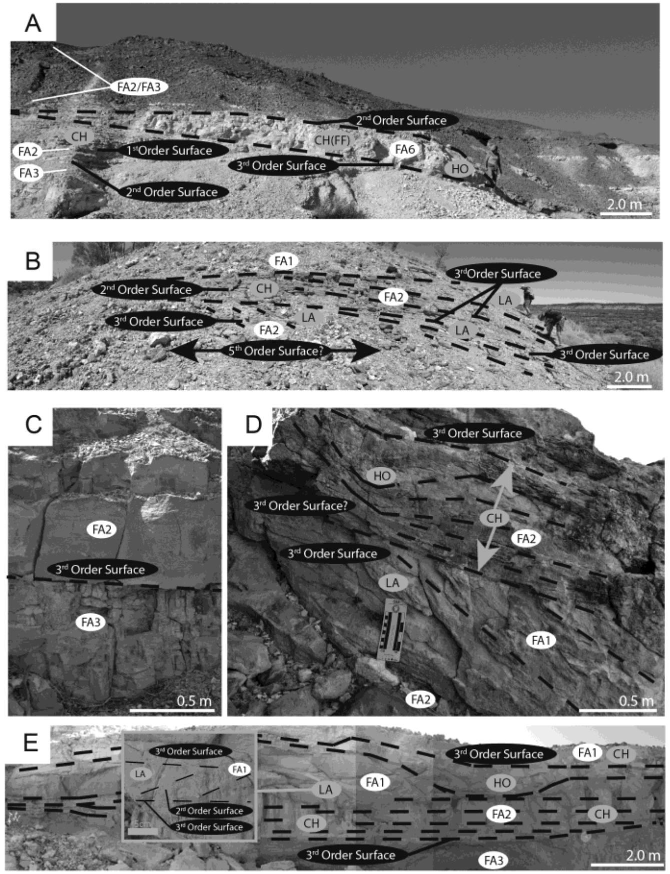
Fig. 3



Bore Hole (physically logged)	Latitude	Longitude	Depth Logged	Formations
GSQ Eromanga 1	S26.6147	E143.8801	250m	Winton & Mackunda formations
GSQ McKinlay 1	S21.5925	E142.2597	240m	Winton & Mackunda formations
GSQ Blackall 2	S24.1626	E144.2236	300m	Winton & Mackunda formations
GSQ Longreach 1-1B	S23.1119	E144.5996	350m	Mackunda Formation only
GSQ Maneroo 1	S23.3859	E144.4679	420m	Winton & Mackunda formations

*Digital or historical records

Fig. 4


A
FA2/FA3
2nd Order Surface
CH
CH(FF)
FA2
1st Order Surface
FA6
FA3
3rd Order Surface
HO
2nd Order Surface
2.0 m
B
FA1
3rd Order Surface
2nd Order Surface
CH
FA2
LA
3rd Order Surface
LA
FA2
LA
5th Order Surface?
3rd Order Surface
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C
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FA3
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D
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FA2
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3rd Order Surface
FA3
2.0 m

Fig. 5

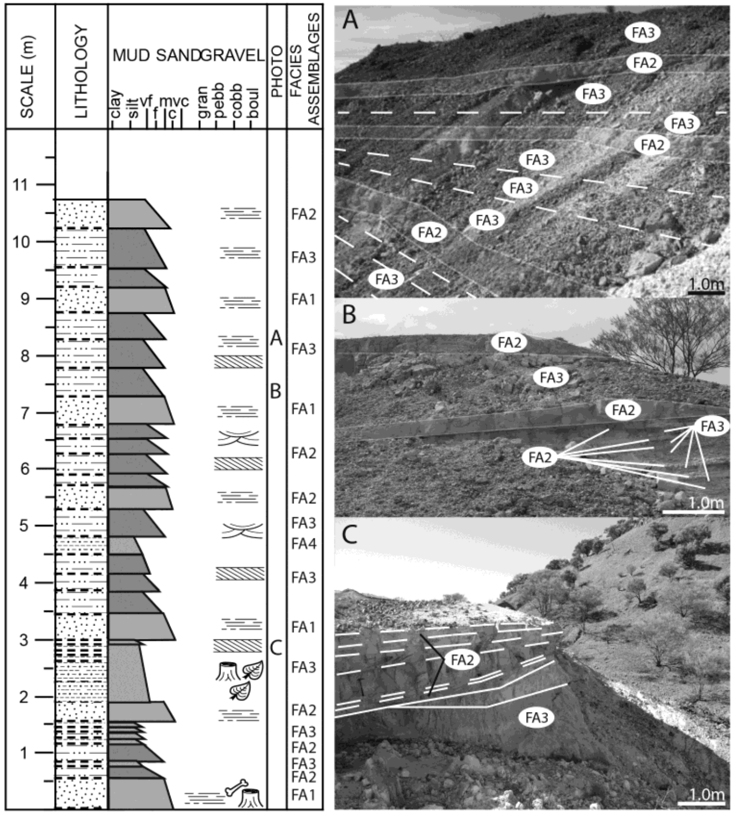
SCALE (m)
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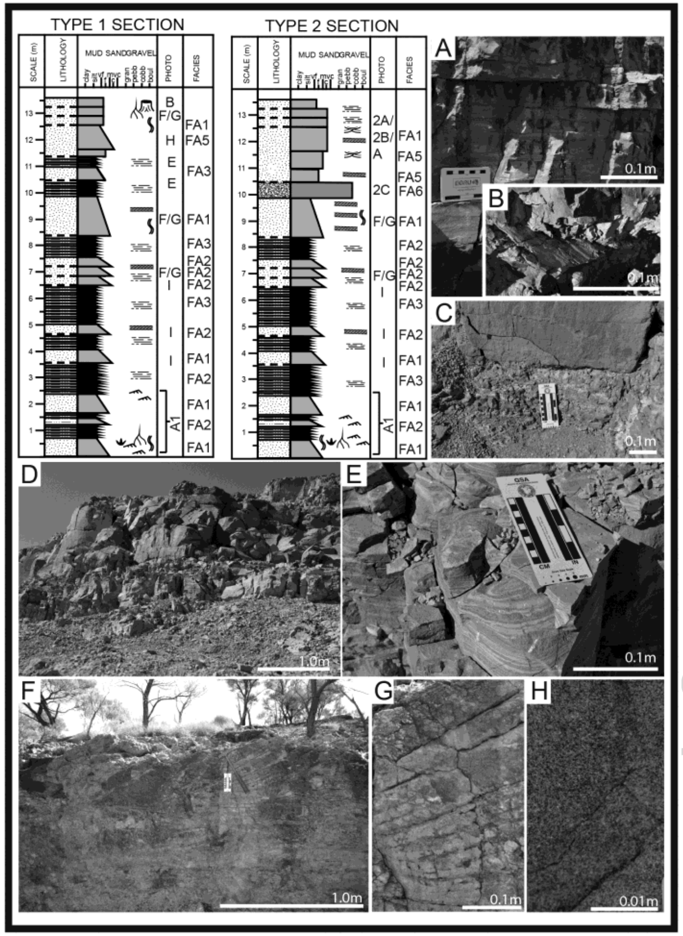
Fig. 6


TYPE 1 SECTION
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1.0m
0.01m

Fig. 7

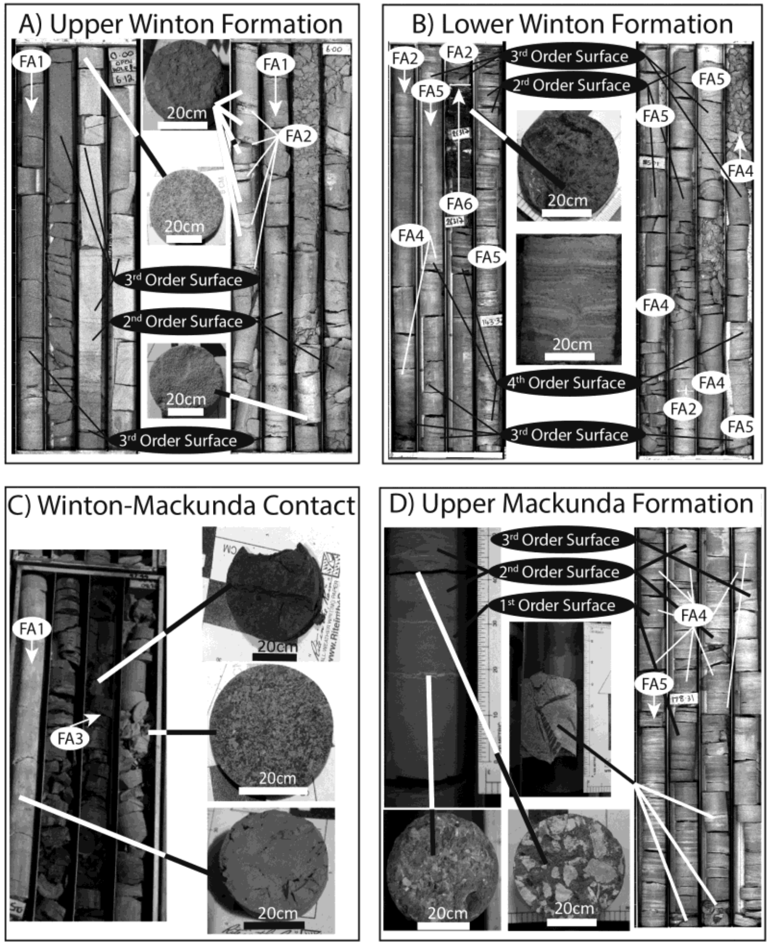

A) Upper Winton Formation
FA1
FA1
FA2
20cm
20cm
3rd Order Surface
2nd Order Surface
20cm
3rd Order Surface
B) Lower Winton Formation
FA2
FA2
3rd Order Surface
2nd Order Surface
FA5
FA5
FA5
20cm
FA4
FA6
FA4
FA5
FA4
20cm
4th Order Surface
FA4
FA2
FA5
3rd Order Surface
C) Winton-Mackunda Contact
FA1
20cm
FA3
20cm
20cm
D) Upper Mackunda Formation
3rd Order Surface
2nd Order Surface
1st Order Surface
FA4
FA5
20cm
20cm

Fig. 8

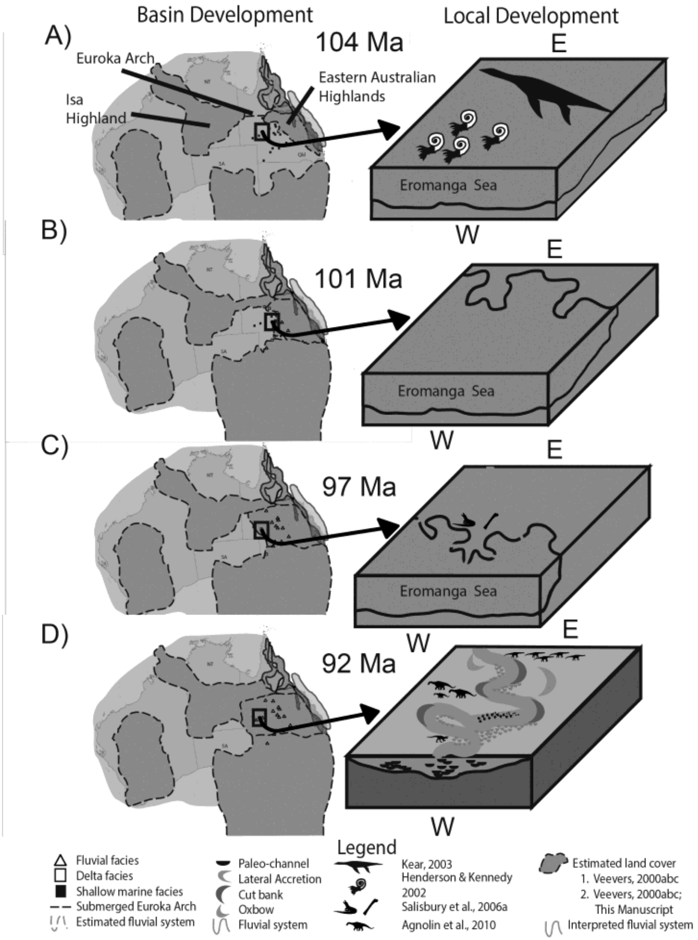

Basin Development
Local Development
A)
104 Ma
Euroka Arch
Isa
Highland
Eastern Australian
Highlands
E
Eromanga Sea
W
B)
101 Ma
E
Eromanga Sea
W
C)
97 Ma
E
Eromanga Sea
W
D)
92 Ma
E
W
Legend
Fluvial facies
Delta facies
Shallow marine facies
Submerged Euroka Arch
Estimated fluvial system
Paleo-channel
Lateral Accretion
Cut bank
Oxbow
Fluvial system
Kear, 2003
Henderson & Kennedy 2002
Salisbury et al., 2006a
Agnolin et al., 2010
Estimated land cover
1. Veevers, 2000abc
2. Veevers, 2000abc; This Manuscript
Interpreted fluvial system

Fig. 9

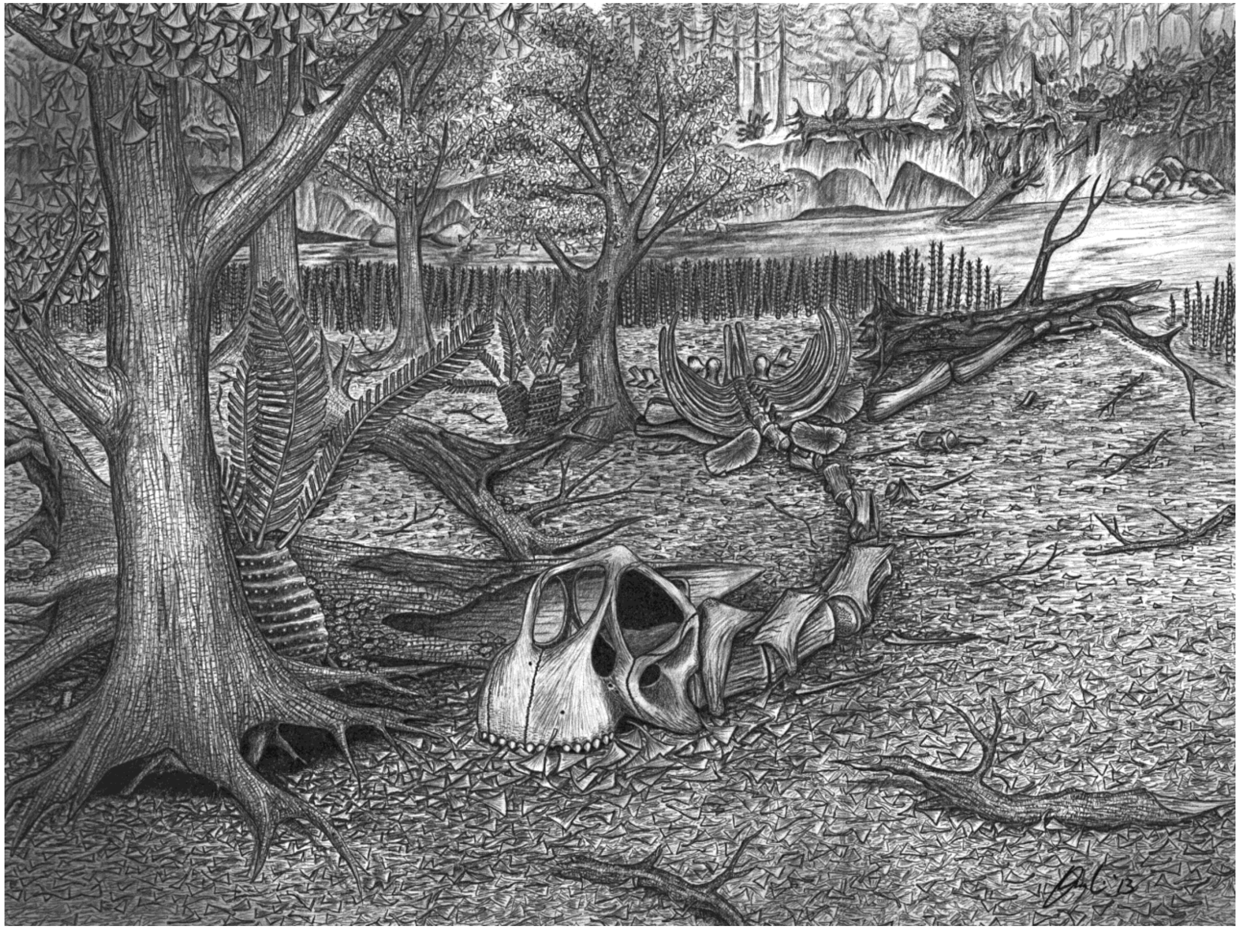
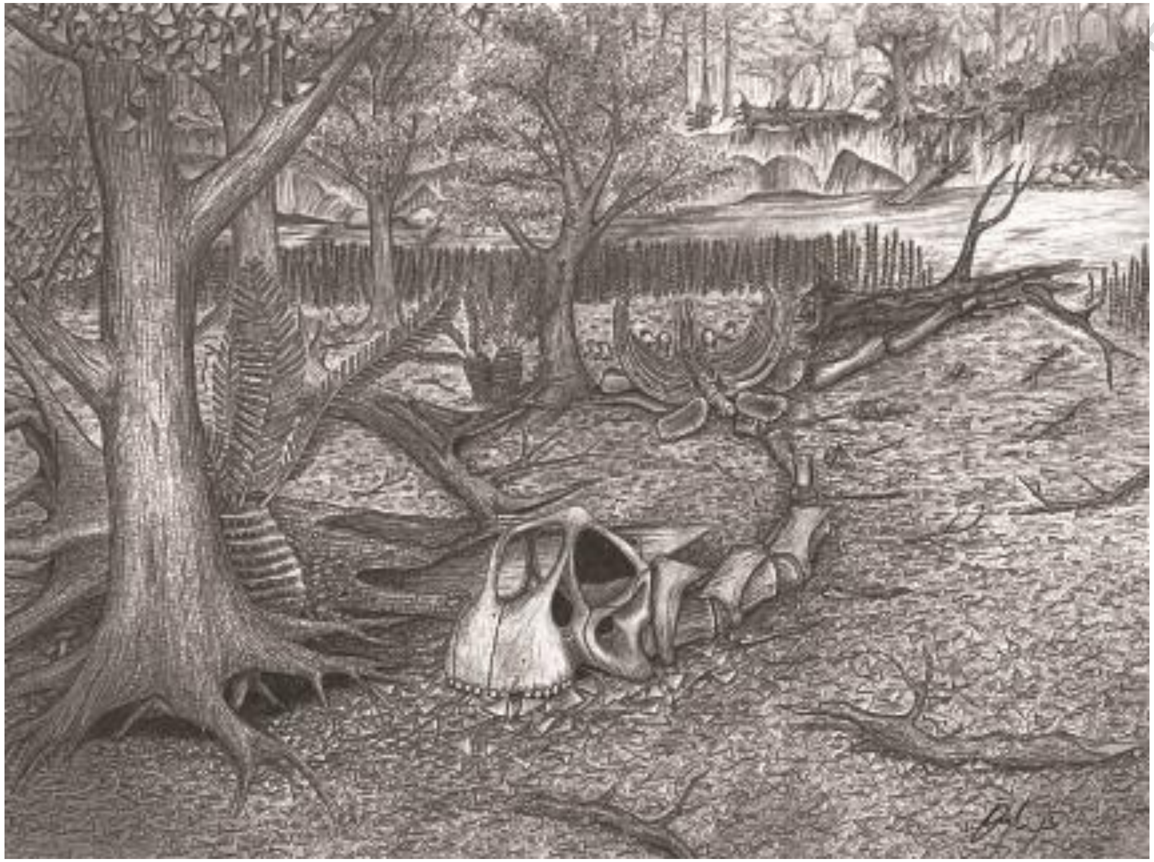


Fig. 10



Graphical abstract