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Detrital zircon age constraints for the Winton Formation, Queensland: Contextualizing Australia's Late Cretaceous dinosaur faunas

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ABSTRACT

The Winton Formation provides an important snapshot of Australia's late Mesozoic terrestrial biota, boasting a vertebrate fauna that includes dinosaurs, crocodyliforms, aquatic squamates, turtles, lungfish and teleost fishes, and a flora that has previously been considered to include some of the world's earliest known flowering plants. Despite its significance, poor age control has thus far prevented precise regional and global correlations, limiting the depth of paleobiogeographic assessments. The goal of this study was to use U–Pb isotope dating of detrital zircons by laser ablation to refine the depositional age range of selected horizons within the Winton Formation. We applied this technique, with refined instrumental tuning protocols, to systematically investigate detrital zircon grain ages for five samples from different stratigraphic levels and vertebrate-bearing fossil locations throughout the Winton Formation. Seven different metrics for interpreting the maximum depositional age of each of the detrital zircon samples were compared and our results suggest that sedimentation of the Winton Formation commenced no earlier than latest Albian (~103.0–100.5 Ma) and that deposition of the upper vertebrate fossil-rich portion of the section began roughly near or after the Cenomanian–Turonian boundary (93.9 Ma), demonstrating that the formation and its important flora and fauna were deposited primarily during the Late Cretaceous. These results provide a significant advancement in understanding the age of the Winton Formation's flora and fauna, and will help to contextualize Australia's Late Cretaceous terrestrial biota within a broader Gondwanan framework.

1. Introduction

Detrital zircon geochronology has traditionally been used as a provenance tool for reconstructing landscape evolution and tectonics by tracing known age populations of zircons back to their metamorphic or igneous (and in some cases recycled sedimentary) points of origin (e.g., Roback and Walker, 1995; Ireland et al., 1998; Hoskin and Ireland, 2000; Fedo et al., 2003; Adams et al., 2007). Over the past decade sedimentary provenance analysis has evolved significantly due to numerous advances in U–Pb geochronology that have made it possible to rapidly and economically date large populations of detrital minerals, in particular zircon (e.g., Ireland et al., 1998; Kowallis et al., 1998; Hoskin and Ireland, 2000; Fedo et al., 2003; Jackson et al., 2004; Andersen, 2005; Link et al., 2005; Gerdes and Zeh, 2006; Surpless et al., 2006; Gehrels, 2008, 2011; Barbeau et al., 2009; Dickinson and Gehrels, 2009; Frei and Gerdes, 2009; Carrapa, 2010). This has been particularly beneficial in provenance studies focused on tectonic and paleogeographical reconstruction and landscape evolution (Hallsworth et al., 2000; Dickinson and Gehrels, 2003; Kusuhashi et al., 2006; Gonzalez-Leon et al., 2009; Roberts et al., 2012; Babinski et al., 2012; Herve et al., in press).

Although a number of studies have recently focused on the application of detrital zircons and other minerals for maximum depositional age constraint (Dickinson and Gehrels, 2009; Lawton et al., 2010), it is noteworthy that in paleontology, a field for which this approach has great potential, there has been little application of this technique to date (e.g. Jinnah et al., 2009; Chure et al., 2010; Irmis et al., 2011; Varela et al., 2012). Within the field of paleontology, particularly when dealing with continental ecosystems, detrital zircon geochronology has major potential for refining the age of terrestrial floras and faunas, which are often notorious for their poor temporal and stratigraphic controls due to ambiguous biostratigraphy. Detrital zircons are nearly ubiquitous in continental clastic sediments, commonly sourced from syndepositional or closely contemporaneous volcanic rocks (located within or even outside of the basin), which can often

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provide more precise temporal constraints than through biostratigraphy alone. Australia's Winton Formation is a perfect example of a situation where an important floral and faunal assemblage is only grossly constrained biostratigraphically, and ashbeds have yet to be identified. Furthermore, the fact that this important succession likely straddles the middle of the 'Cretaceous quiet zone' makes magnetostratigraphy an unlikely option for improving age constraint. The Winton Formation is an ideal target for this application because of its relative proximity to co-eval volcanic and plutonic source rocks along Australia's east to northeastern coast (New Caledonia and the volcanic rocks of the Whitsunday Volcanic Province) that have the potential to be maximum depositional age constraining provenance sources (dated between 95 and 115 Ma; Bryan et al., 1997, 2012; Cluzel et al., 2011). Both are sparsely preserved, though currently these two sources have been strongly suggested as a potential provenance source for this middle Cretaceous zircon population (Bryan et al., 1997, 2012; Cluzel et al., 2011).

The vertebrate fauna of the Winton Formation includes titanosauriform sauropods (Coombs and Molnar, 1981; Molnar, 2001, 2010, 2011; Molnar and Salisbury, 2005; Salisbury et al., 2006b; Hocknull et al., 2009), megaraptoran theropods (Salisbury, 2003, 2005; Hocknull et al., 2009; Benson et al., 2010; Agnolin et al., 2010; Salisbury et al., 2011; White et al., 2012), thyreophoran and ornithopodan ornithischians (Salisbury, 2005; Hocknull and Cook, 2008), basal eusuchian crocodyliforms (Molnar and Willis, 1996; Salisbury, 2005; Salisbury et al., 2006a), dolicosaurian squamates (Scanlon and Hocknull, 2008), turtles (Molnar, 1991; Salisbury, 2005), dipnoan and teleostean fishes (Dettmann et al., 1992; Kemp, 1997; Faggotter et al., 2007; Berrell et al., 2008, 2011), possible cynodonts and basal mammaliaforms (Salisbury, 2005; Musser et al., 2009), along with likely plesiosaurs (Salisbury, 2005; Salisbury et al., 2006b). Occasional invertebrate fossils have also been recorded (Hocknull, 1997, 2000; Jell, 2004; Cook, 2005). Trace fossils from the Winton Formation include dinosaur tracks at Lark Quarry Conservation Park, indicative of two types of ornithopods and 'possibly' a theropod (Thulborn and Wade, 1984; Romilio and Salisbury, 2011; Romilio et al., 2013).

Upward of 50 plant macrofossil taxa representing 10 different orders are known in the Winton Formation, dominated by conifers and angiosperms, with rarer bennettitaleans, cycadophytes, ferns, ginkgoales (ginkgophytes) and pentoxyloleans (Bose, 1955; Whitehouse, 1955; Peters and Christophel, 1978; Burger and Senior, 1979; Peters, 1985; Burger, 1990; Dettmann et al., 1992; McLoughlin et al., 1995; Pole, 1998; Pole and Douglas, 1999; Dettmann and Clifford, 2000; Pole, 2000a,b; Clifford and Dettmann, 2005; Dettmann et al., 2009; McLoughlin et al., 2010). Cretaceous angiosperm pollen has been well studied in the Eromanga Basin by Bose (1955), Dettmann and Playford (1969), Burger and Senior (1979), Burger (1980, 1986, 1989, and 1990) Dettmann et al. (1992), McLoughlin et al. (1995), Pole and Douglas (1999), Dettmann and Clifford (2000), and Dettmann et al. (2009; and see references therein). The Winton Formation has been placed into Burger's (1990) Suit III biozone, characterized by *Coptospora paradoxa* and *Phimopollenites pannosus*, and on this basis interpreted as being late Albian to early Cenomanian in age. This pollen zone has also been assigned to samples from stratigraphically lower units, including the Toolebuc, Allaru, and Mackunda formations, thereby providing solid, but broad stratigraphic control for this important interval.

In addition, there has not been any attempt to determine the stratigraphic relationship between the numerous fossil-bearing localities. As a consequence, the temporal and paleoenvironmental context of one of Australia's most important Cretaceous terrestrial biota's and its relationship to those from other Gondwanan landmasses is poorly understood.

In lieu of unambiguous ash beds and the volcanoclastic nature of the Winton Formation strata, the goal of our study was to utilize U–Pb detrital zircon geochronology to obtain maximum depositional age estimates for a range of fossil-bearing localities. We present the results from five samples collected from throughout the stratigraphic and geographic ranges of the formation, which significantly refine existing palynologically-based age constraints. This work has significant implications for intrabasinal correlations and understanding the relationship of the Winton vertebrate fauna and flora within a Gondwanan, and indeed, global paleobiogeographic and evolutionary framework.

Institutional abbreviation: *AAC*, Advanced Analytical Center at James Cook University; *GSQ*, Geological Survey Queensland; *JCU*, James Cook University; *UQ*, The University of Queensland.

2. Geological background

The Eromanga Basin forms a major portion of the Great Artesian Basin (GAB; Fig. 1), the tectonic history of which is still a matter of debate. Studies such as those by Gallagher (1990) have proposed that the GAB occupied a foreland basin setting during the Cretaceous, whereas others, such as Gray et al. (2002), suggest a more complex intracratonic basin setting. Either way, there is consensus that either a major arc- or rift-related volcanic system was located on the eastern margin of the basin, providing a synorogenic source for the abundant feldspathic and volcanolithic petrofacies that characterize the Winton Formation (Bryan et al., 1997). Draper (2002) and others also demonstrated that a large portion of the basin was inundated by an epeiric seaway during the Cretaceous as a result of globally elevated sea levels. There is evidence for two major transgressive–regressive cycles in the basin, though direct correlation to global events is problematic (Gallagher and Lambeck, 1989). Gallagher and Lambeck (1989) suggest that the voluminous input of volcanic detritus into the basin is directly related to the transgression and regression events rather than global effects, although this is debated (Draper, 2002). The richly fossiliferous, alluvial to coastal plain strata of the Winton Formation were deposited following the final regression of the interior sea from central Australia (Draper, 2002).

The Winton Formation is exposed over large portions of Queensland and portions of northern New South Wales, north-western South Australia and the south-western corner of the Northern Territory (Fig. 1). Originally designated the "Winton Series", the unit was initially described by Dunstan (1916), as a succession of terrestrial (alluvial) sandstones, shales and minor coal seams. The Winton Formation overling the dominantly marine Rolling Downs Group, originally defined by Jack (1886) and Dunstan (1916) and unconformably overlain by modern fluvial deposits in the form of 'black soil'. However, the first mention of the Winton Formation and regional synthesis of the Cretaceous nomenclature was not until Whitehouse (1954, 1955), Exon (1966), Casey (1970) and also Senior and Mabbutt (1979), all of whom defined the formation as the upper portion of the Rolling Downs Group and designated it as an Upper Cretaceous continental unit conformably overlying the marine Mackunda Formation and provided the first detailed sedimentologic characterization of the horizons comprising it. More recently, Gray et al. (2002) grouped the Winton together with the Mackunda Formation to form the Manuka Subgroup (Fig. 2).

2.1. Stratigraphy and sedimentology of the Winton Formation

This study focuses on vertebrate fossil-bearing localities within the Winton Formation near Winton (Bladensburg National Park and Lark Quarry Conservation Park) and Isisford (Fig. 2). Additional investigations of GSQ cores (GSQ Eromanga 1 and GSQ Longreach 1) were conducted to place these sites into a regional framework. Exposures of the Winton Formation between Lark Quarry and Bladensburg National Park are continuous and dominated by fine-grained sandstones, siltstones and mudstones. Much of the exposure at both localities is heavily weathered, characterized by kaolinized feldspars and volcanic detritus. Sandstones are typically feldspathic to feldspatholithic, fine to medium grained, well sorted, and exhibit sub-angular to subrounded grains. Sedimentary structures commonly noted in outcrop

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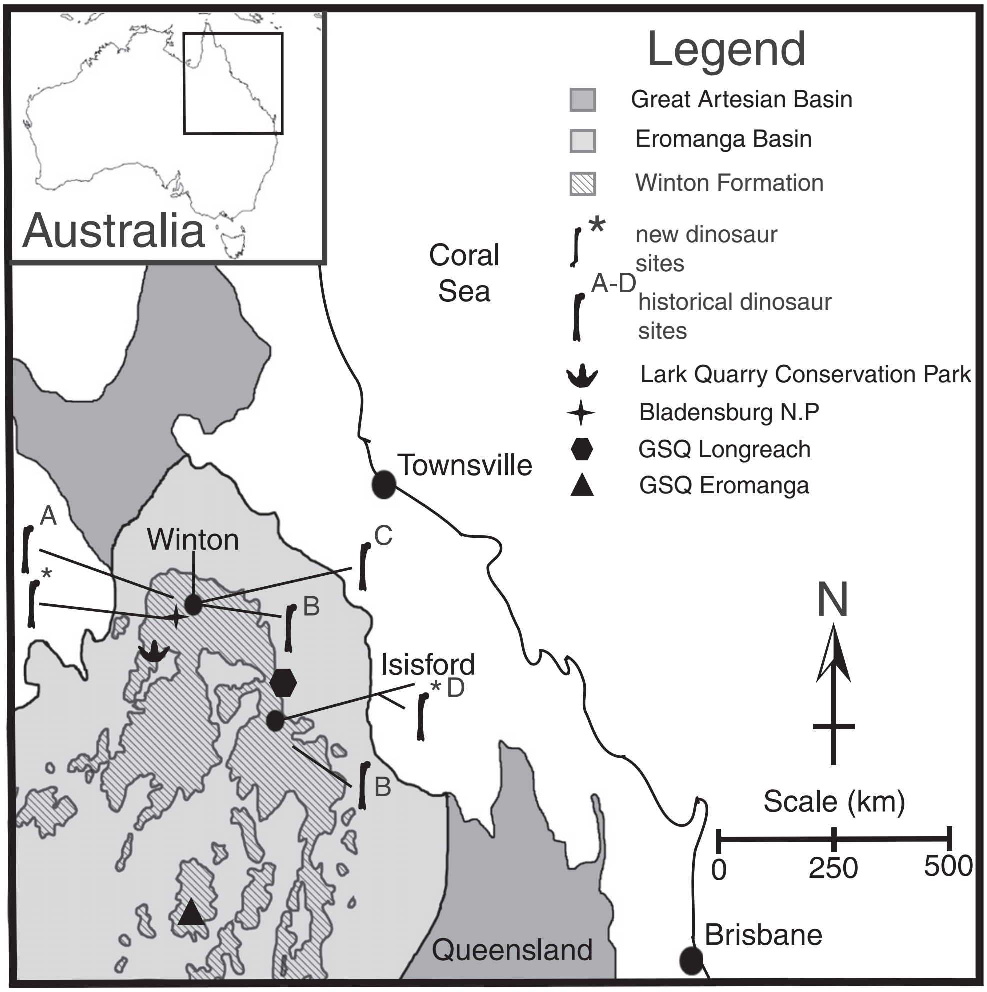

Fig. 1. Map of Queensland, northeastern Australia; displaying the Winton Formation within the Eromanga Basin. Symbols indicate detrital zircon sample locations derived from at or near recently discovered (Bladensburgh National Park and Isisford, Queensland) and historical fossil localities (Lark Quarry Conservation Park) along with samples derived from Geological Survey of Queensland stratigraphic core logs (GSQ Eromanga 1 and GSQ Longreach 1). Also displayed are a number of historical archosaurian fossil assemblage localities throughout the Winton Formation (A–D) based on described findings from but not limited to: Thulborn and Wade (1979), Coombs and Molnar (1981), Thulborn and Wade (1984, 1979, 1989), Dettmann et al. (1992), Molnar (2001), Molnar and Salisbury (2005), Salisbury et al. (2006a,b), Agnolin et al. (2010), Hocknull et al. (2009), and Molnar (2010).

at both localities include, but are not limited to: asymmetrical and symmetrical current ripple cross-lamination, trough and tabular cross-stratification, scour and fill structures, and lenticular channel macroform elements. Mudstones are commonly gray, purple or olive green, and in some areas exposures reveal 'shrink and swell' smectitic characteristics, including haystack mounds and popcorn texturing. Fossil material is commonly exposed at or near the base of (locally know as 'jump-ups'). Well-preserved associated to poorly articulated body fossils, along with mollusk shells, are often only found 1–3 m below the surface. Commonly surface material is typically limited to weathered fossil bone shards.

In contrast, the sedimentology at Isisford presents a dramatic departure from the suite of facies seen at the Bladensburg National Park and Lark Quarry Conservation Park sites, with much of the fossil material preserved in medium-to-coarse grained Fe-oxide and calcite cemented sandstone nodules, some of which are still in situ. The Winton Formation in this area is poorly exposed and mostly covered by 'black soil', a recent alluvial deposit that blankets much of the Eromanga Basin (Twidale, 1966). The large fossil-bearing nodules (many exceeding 3–4 m in diameter) are located at or near the weathering surface, but their precise stratigraphic position within the Winton Formation is difficult to constrain precisely. Only some of the nodules are in situ, including the dinosaur bearing nodule used in this study. Those which are not may represent surface lag, concentrated as erosion of softer, poorly cemented led to stratigraphic condensation of the nodules. Based on correlation with nearby well and core logs (ESSO Australia Isis Downs-1, GSQ Longreach 1, and GSQ Maneroo 1) the stratigraphic position of the Winton Formation surface exposures (and nodule) in the Isisford area is towards the top of the unit in this part of the Eromanga Basin.

The overall character of strata at Bladensburg National Park and Lark Quarry Conservation Park suggests a fluvial origin, with evidence of channels, floodplain mudrocks, crevasse splays, abandoned channels, and oxbow lakes, representative of a broad and expansive fluvial floodplain system. Although some previous studies suggest a dominantly lacustrine setting for parts of the Winton Formation, such as at the famous dinosaur 'stampede' tracksite at Lark Quarry (Thulborn and Wade, 1979, 1984, 1989), we regard this as a relatively less abundant facies within the broader Winton depositional system. Much of the Winton Formation lacks significant surface exposure due to overlying alluvium and deep weathering; however, trenches excavated near fossil localities indicate that the subsurface facies are similar to those at Lark Quarry and Bladensburg National Park.

3. Detrital zircon geochronology

3.1. Location

Three samples for detrital zircon geochronology were acquired at, or near, key vertebrate fossil localities within the Winton Formation, while two other samples come from Geological Survey Queensland

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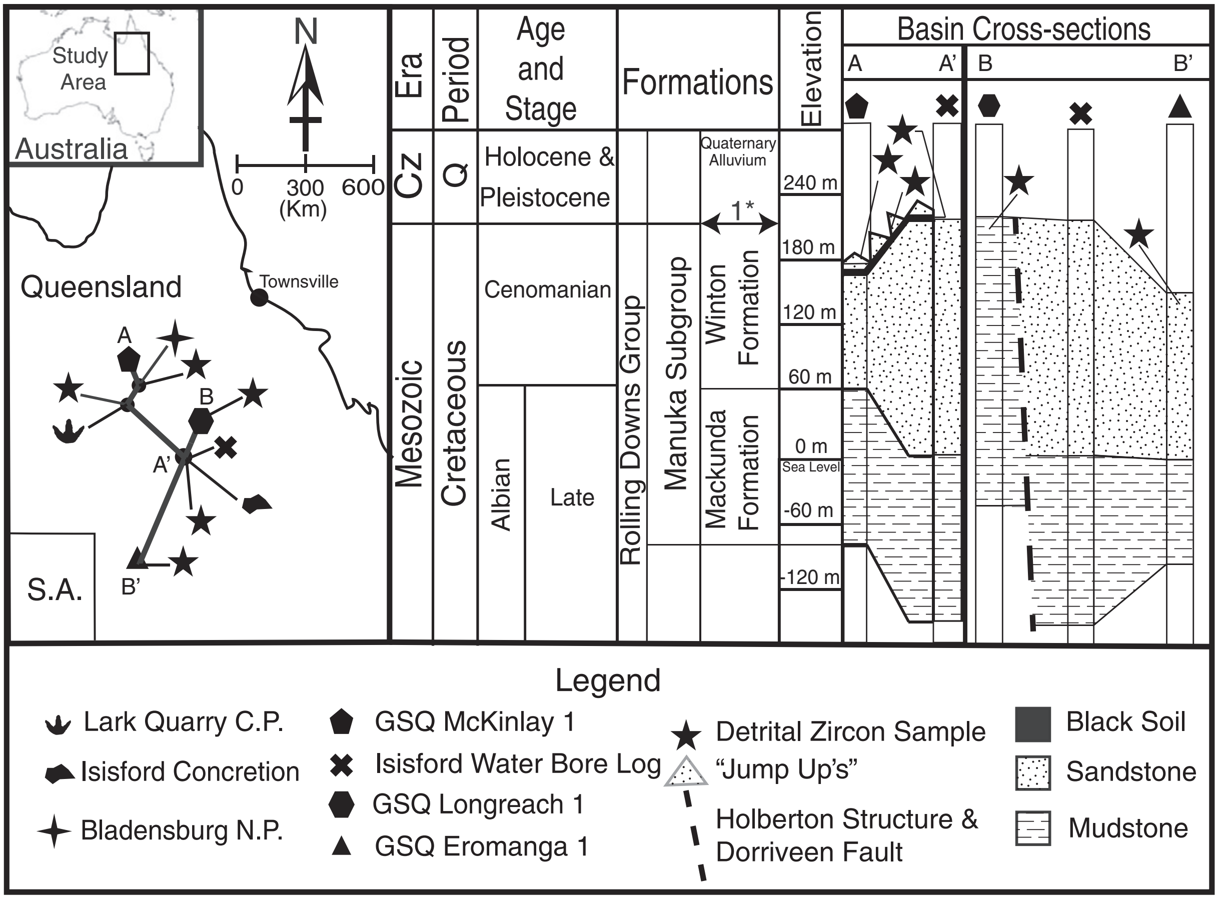

Fig. 2. Cross section of the Central Eromanga Basin, Queensland, with stratigraphic positions of analyzed zircon samples, modified from Draper (2002). Stratigraphic cross-sections A–A′ was based on GSQ McKinlay 1 south to Isisford Water Bore Log, and includes stratigraphic position of detrital zircon samples derived from Lark Quarry Conservation Park, Bladensburg National Park and Isisford, Queensland. Stratigraphic cross-sections B–B′ is a cross-section form GSQ Longreach 1, Isisford Water Bore Log and GSQ Eromanga 1, and includes stratigraphic position of detrital zircon samples derived from GSQ Longreach 1 and GSQ Eromanga 1. (1*) denotes that above the in places (Lark Quarry and Bladensburgh National Park) that the Winton Formation is exposed in 'jump up's' which is capped by laterite and Quaternary alluvium, whereas in other locations (Isisford, Queensland) the upper Winton Formation is very poorly exposed and blanketed by 'black soil'.

(GSQ) cores (Fig. 2). Sampling was conducted to provide spatial coverage across the Winton Formation field areas and range stratigraphically from just below the base of the Winton Formation (i.e., at the top of the Mackunda Formation; GSQ Longreach 1) to the upper-most exposed Winton Formation outcrop in western Queensland (Lark Quarry Conservation Park) (Fig. 2). In total five samples for detrital zircon analysis were collected. Bulk samples (~5–10 kg each) were extracted from freshly exposed, unweathered fine- to medium-grained sandstones, interpreted as low-energy fluvial channel deposits except for Bladensburg National Park, which we interpret as a proximal floodplain deposit.

The first sample was collected from Lark Quarry Conservation Park (Lat: 23°00′58.62″S; Long: 142°24′42.73″E) and was taken from ~1.0 m above the horizon that preserves the famous Lark Quarry dinosaur tracksite (Thulborn and Wade, 1979, 1984, 1989). This was the stratigraphically highest sample collected from the Winton Formation, near the top of the section. The second highest Winton Formation sample comes from Bladensburg National Park (Lat: 22°30′53.35″S; Long: 143°02′19.89″E), ~2–3 m above the main fossil-bearing horizon in the park, slightly lower than the Lark Quarry trackway horizon. The third sample was collected from a locality at Isisford (Lat: 24°15′ 33.51″S; Long: 144°26′29.35″E). It was taken directly from a sandstone nodule that preserves the remains of a presently undescribed dinosaur that is in close proximity to other key fossil-bearing localities in the area (see Salisbury et al., 2006a). The nodule was discovered in-situ in the uppermost portion of the bedrock, but most of it was initially buried by the 'black soil', which directly overlies most of the upper-most unexposed Winton Formation within the Isisford region. The final two samples came from cores drilled in central-western Queensland by Geosciences Queensland (GSQ), including one sample from the GSQ Eromanga 1 core (ERO1-11-001). GSQ Eromanga 1 core was drilled east of Eromanga, Queensland (Lat: 26°36′52.93″S; Long: 143°52′ 48.41″E) and this sample (ERO1-11-001) was collected from the core interval between 16.5 and 26.7 m (boxes 2–5) below surface (roughly 146.0 m above base of the Winton Formation). This sample is taken from the upper-most subsurface section of the recovered core. A second sample was taken from the GSQ Longreach 1 (LO1-11-001) core, which was drilled northeast of Longreach, Queensland (Lat: 23°06′42.93″S; Long: 144°35′58.41″E) and (LO1-11-001) was collected from the core interval between 20.8 and 35.8 m (boxes 1–6) below surface of retrieved core. This sample is collected from the upper most portions of the Makunda Formation (Fig. 2).

3.2. Zircon separation

All samples were crushed and milled in a tungsten carbide disc mill and then sieved using both 250 and 500 μm meshes to enhance the possibility of sampling potential distal volcanic ash derived zircons. The material was washed and decanted numerous times to remove the clay-sized fraction. Heavy minerals were separated using lithium polytungstate adjusted to a specific gravity of 2.85–2.87. Mineral separates were then washed, dried, and a hand magnet was used to remove strongly magnetic minerals, followed by a Frantz magnetic separator at progressively higher magnetic currents of 0.5, 0.8, 1.3, and 1.5, set at a constant 10° side slope. The non-magnetic heavy mineral separates were then selected via hybrid selection protocols that involved handpicking zircons as randomly as possible from the greater population within a defined field of view. Following this, the remainder of each sample was handpicked a second time with the intention of selecting the clearest, most euhedral grains remaining in each sample; with the goal of increasing the likelihood of analyzing maximum age constraining young zircons. For each sample, ~100–150 grains were mounted in a 25 mm epoxy resin puck, polished to expose their mid-sections and imaged using a Jeol JSM5410LV scanning electron microscope with attached cathodoluminescence detector in order to document microstructures, cracks, inclusions and other complexities.

3.3. LA-ICP-MS U–Pb dating of zircon

3.3.1. Experimental approach

All work was done at the Advanced Analytical Centre of James Cook University, using a Coherent GeolasPro 193 nm ArF Excimer laser ablation system connected to a Bruker 820-MS(formerly Varian 820-MS). The ablation cell was connected to the Bruker 820-MS via Tygon tubing and a 3-way mixing bulb (volume ~5 cm^3). The standard cylindrical sample cell was used througout the study, but with a custom-designed polycarbonate insert to reduce the effective volume to 4 cm^3 (see Supplemental materials). This insert combined with the mixing bulb provides both a a very stable time-resolved signal and rapid signal washout.

The Bruker 820-MS employs an ion mirror design, which reflects the ion beam exiting the skimmer cone by 90° and focusses this into the mass analyzer. Non-ionized large particles and neutrals, as well as partially ionized particles, are not reflected and extracted by a pump located behind the mirror. In this way, the electrostatic mirror acts as a particle size filter to admit only fully atomized and ionized particles into the quardupole mass filter and detector. The advantage of this unique configuration is that it facilitates tuning of the ICP-MS to minimise instrumental mass fractionation focusing on the key ratio of Pb/U, as described below. The instrumental parameters and operating conditions are provided in the Supplemental materials.

All instrument tuning was performed using a 5 Hz repetition rate, 44 μm beam aperture and 6 J/cm^2 energy density, as determined by energy meter at the ablation site. Under these conditions, the ablation rate for NIST 610 and zircon was about 0.1 μm per laser pulse and 0.06 μm per laser pulse respectively. Tuning was achieved by iteratively adjusting the He carrier gas, Ar sampling gas, sheath gas flow rate, RF Power, 1st, 2nd, 3rd Extraction lens and corner lens voltage to achieve $^{238}U/^{232}Th$ ratio ~1, ThO/Th<1% typically 0.5% and $^{206}Pb/^{238}U$ ~0.22 in NIST610. Tuning the instrument towards the 'true' 206Pb/238U ratio thus minimises the magnitude of the total Pb/U fractionation correction applied zircon analyses, thus reducing the inherent uncertainties in this correction procedure where there are large age differences between standard and sample zircons. Using this technique improved the accuracy and reproducibility of zircon U–Pb isotope analysis in our laboratory (See Supplementary Table 1A–E). For sample analysis, the total measurement time was set at 65 s. The first 30 s was for gas blank measurement (laser firing but with the shutter closed), with the shutter opened to allow sample ablation for the final 35 s, standard bracketing was used throughout the study to correct for remaining elemental fractionation and mass bias.

3.3.2. U–Pb dating of the Winton Formation

Approximately 100 detrital zircons for each of the five samples were analyzed using the optimized LA-ICP-MS tuning method outlined above. A 32 μm beam diameter was used for the following samples: Lark Quarry Conservation Park, GSQ Eromanga 1, and GSQ Longreach 1. However, due to the small grain size of samples from Bladensburg National Park and Isisford, a 24 μm beam diameter (spot size) was used for these samples. As different aspect ratio (e.g. laser pit diameter/depth ratio) will have different elemental fractionation characteristics, therefore when one beam size is used (either 24 μm or 32 μm beam), this beam size is uniformly applied to all zircon to be dated including calibration zircon standard. Over the duration of ablation, groups of 10–12 zircon grains were analyzed, followed by at least two analyses each of a primary (GJ-1, 609 Ma, Jackson et al., 2004) and secondary in-house zircon standard (Temora-2 [TEM-2] 416.8 Ma, Black et al., 2003). If grains exhibited a grater discordance of 30%, those grains were omitted from the populations and the study as a whole. All standard analyses were within 2% of the expected ages, and most were within 1% of the expected age. NIST 610 or 612 was analyzed at the beginning and end of each session, and at least once in between, for the purpose of calibrating Th and U concentrations.

3.4. Discussion of detrital zircon geochronology

3.4.1. Youngest detrital zircon age determination

When trying to constrain the maximum depositional age of strata or fossil localities, it is a common practice to identify the youngest detrital zircon grains in a sample in order to determine the youngest possible age of deposition (Rainbird et al., 2001). Recent studies, including a robust investigation by Dickinson and Gehrels (2009), have reappraised the various methodologies for ascertaining the maximum depositional age and highlighted the importance of utilizing several different approaches to obtain the most accurate representation of the maximum depositional age of a sample. This study compares seven of the most common metrics used to determine the maximum depositional age of a detrital zircon datasets (e.g., see Dickinson and Gehrels, 2009; Johnston et al., 2009; Lawton and Bradford, 2011; Robinson et al., 2012), including:1) youngest single grain age (YSG); 2) youngest graphical detrital zircon age (YPP); 3) youngest detrital zircon age (YDZ); 4) the weighted mean average age (YC1σ) (+3); 5) Weighted Average; 6) weighted mean average age (YC2σ) (+3); and 7) TuffZirc (Zircon Age Extractor) (+6).

YSG involves singling out the single youngest detrital zircon grain within the population, however this approach is highly questionable and the least rigorous method because it represents only a single data point (Dickinson and Gehrels, 2009). As such, this study employs six other methods to provide a more reliable youngest maximum depositional age approximation. YPP is the youngest graphical detrital zircon age peak recorded on the histogram; and is obtained by identifying the first maximum age peak (several grains or grain cluster (DZ≥3)) along an age-probability plot or age distribution curve, calculated within ISOPLOT (Ludwig, 2009; Dickinson and Gehrels, 2009; Lawton and Bradford, 2011). YDZ is calculated using an algorithm within ISOPLOT, which extracts the youngest subset of DZ ages within the whole DZ population using a Monte Carlo analysis (Dickinson and Gehrels, 2009; Ludwig, 2009). YC1σ (+3) and YC2σ (+3) or the weighted mean averages at 1 and 2 σ, respectively, incorporate both internal analytical error and external error of the youngest population within the tested group of grains (Dickinson and Gehrels, 2009; Jones et al., 2009). Dickinson and Gehrels (2009) and others apply a minimum of two grains (n≥2) to achieve a maximum depositional age result, however in this study, we used a minimum three grain cluster limit. YC1σ (+3) and YC2σ (+3) are derived from the AGE PICK program, generated by the University of Arizona LaserChron Center. Weighted Average is also an algorithm within Isoplot that utilizes age values and errors to generate an inverse variance-weighted average that helps to deal with excessive scatter within a batch of grains (Ludwig, 2009). The last metric applied in this study is the TuffZirc age extractor (+6), an Isoplot algorithm (originally based on the TuffZirc algorithm by Ludwig and Mundil (2002)) that implements a mathematically based approach on the loss and inheritance of Pb and its error (Ludwig, 2009). It is suggested by Ludwig (2009) to include

10 or more grains within the process, however as this study seeks the youngest maximum depositional age, the youngest six grains were utilized from each population as it is the minimum number of grains required for the program to run. Together, seven methodologies are utilized and evaluated for each sample in order to the most reliable maximum depositional age for the Winton Formation.

3.4.2. Potential sources of bias in detrital zircon studies

A number of recent studies have highlighted the potential for error and bias in detrital zircon studies. Most of these studies focus on but are not limited to hydrological sorting, transport variability and affects to deposition by climate (Hietpas et al., 2011; Lawrence et al., 2011). These biases mostly affect studies dealing with provenance-based detrital zircons studies, and have little bearing on studies focused on maximum depositional age reconstruction. The obvious exception is that techniques, such as multiple sampling of grains and high-resolution CL imaging to identify grain irregularities or cores, are in fact pertinent to maximum depositional age-based studies like this one, and were applied to this study.

4. Results

4.1. Lark Quarry sample

Zircon grain morphology ranges from euhedral to abraded and well rounded. Overall zircon grains derived from these rocks are smaller (75 μm ≥ n ≤ 100 μm) than those in other samples. Ninety grains were analyzed (76 reported), yielding multiple age populations, mostly composed of various Mesozoic populations (70%), with the remaining grains dominantly from Paleozoic sources (24%), and a few Pre-Cambrian grains (6%). Of the Mesozoic grains, the dominate population is within the Cretaceous (68%) of which 33% are Late Cretaceous and 67% are Early Cretaceous. The remaining populations are divided between the Jurassic (13%) and Triassic (19%). Analytically this sample yields the youngest maximum detrital zircon grain ages of all five samples. Results of the seven methodologies are as follows: YSG is 92.5 (±1.2) Ma (Supplementary Table 1a), YPP is 93.0 Ma (Fig. 3, Table 1), YDZ is 94.5 (+2.1/−2.3) Ma (Table 1), YC1σ (+3) is 94.5 (±1.8) Ma (Table 1), Weighted Average is 94.5 (±5.3) Ma (Table 1), YC2σ (+3) is 94.5 (±3.1) Ma (Table 1), and TuffZirc is 97.5 (+0.3/−3.0) Ma (Table 1).

4.2. Bladensburg National Park sample

Zircon grain morphology ranged from euhedral to abraded and well rounded, though were distinctly larger than those collected at Lark Quarry (100 μm ≥ n ≤ 200 μm). Ninety grains were analyzed (82 reported), yielding multiple age populations, mostly composed of various Mesozoic populations (65%), with the remaining grains of Paleozoic (26%) and a few Pre-Cambrian grains (9%). Of the Mesozoic grains, the dominate population is Cretaceous (68%) of which 25% are Late Cretaceous and 75% are Early Cretaceous. The remaining populations are divided between Jurassic (13%) and Triassic (19%). Analytically this sample produced the second youngest detrital signature and the seven methods results were as follows: YSG is 93.3 (±1.2) (Supplementary Table 1b), YPP is 96.0 Ma (Fig. 3, Table 1), YDZ is 93.8 (+1.9/−1.8) Ma (Table 1), and YC1σ (+3) is 94.0 (±1.7) Ma (Table 1), Weighted Average is 94.0 (±1.4) Ma (Table 1), YC2σ (+3) is 94.5 (±2.9) Ma (Table 1), and TuffZirc is 95.6 (+2.2/−2.3) Ma (Table 1).

4.3. Isisford sample

Zircon grains are typically large with well preserved euhedral crystals, although older grains are commonly abraded and well rounded, and average grain size ranged between 100 μm ≥ n ≤ 150 μm.

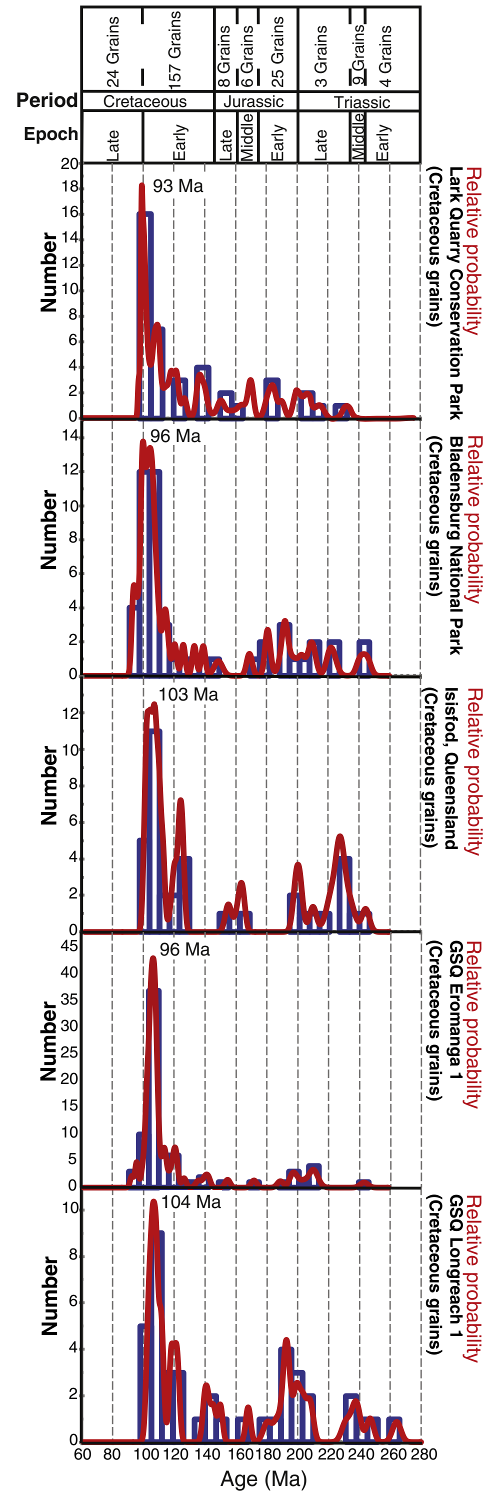

Fig. 3. Youngest graphical (histogram based) detrital zircon age peak (YPP) results for all samples (Lark Quarry Conservation Park at 93 Ma; Bladensburg National Park at 94 Ma; 103 Ma; fossil entombing nodules from Isisfor Queensland at 103 Ma; GSQ Eromanga 1 core at 96 Ma; and GSQ Longreach 1 core at 104 Ma), based on the first maximum age peak (several grains or grain cluster (DZ ≥ 3)) along an age-probability plot or age distribution curve presented and calculated within ISOPLOT (Dickinson and Gehrels, 2009; Ludwig, 2009).

Seventy two grains were analyzed (62 reported), yielding multiple age populations, mostly composed of various Mesozoic populations (65%), and lesser Paleozoic (22%) and a few Pre-Cambrian grains (13%). Of the Mesozoic grains, the dominate population is Cretaceous (63%) of that Cretaceous population 100% are Early Cretaceous. The remaining

Table 1
A compilation of all metric's utilized within the study. YSG of all six populations presented with a ±1σ error. YPP or the graphical age based on a histogram derived from Isoplot (see Fig. 3). YDZ of all six populations is presented with the Age, range (+ or −) and the confidence of that metric. YC1σ (+3) of all six populations is presented with the Final Age, Weighted Mean Average, Systematical error and MSWD at a ±1σ error. Weighted Average of all six populations is presented with the Age, Confidence, the amount of grains rejected, MSWD and the overall probability. YC2σ (+3) of all six populations is presented with the Final Age, Weighted Mean Average, Systematic Error, and MSDW at a ±2σ error. TuffZirc of all six populations is presented with the Final Age, Confidence, and the Group Size (the number excluded against the grains used by the metric).

Analysis		Sample					
		Lark Quarry Conservation Park	Bladensburg National Park	Isisford Queensland	GSQ Eromanga 1	GSQ Longreach 1	Cenomanian and Younger (24 grains)
YSG		Age ±1σ	Age ±1σ	Age ±1σ	Age ±1σ	Age ±1σ	Age ±1σ
		92.5 ±1.2	93.3 ±1.2	100.5 ±1.1	93.0 ±1.1	102.5 ±1.3	92.5 ±1.2
YPP (see Fig. 4)	Age	93.0	96.0	103.0	96.0	104.0	98.0
YDZ	Age	94.3	93.8	101.3	95.6	102.8	91.8
	Range	+2.1/−2.3	+1.9/−1.8	+1.5/−1.8	+1.8/−1.9	+1.7/−2.1	+1.6/−2.3
	Confidence	95%	95%	95%	95%	95%	95%
YC1σ(+3)	Final Age	94.5 ±1.8(1.9%)	94.0 ±1.7(1.8%)	101.6 ±1.8(1.7%)	95.2 ±1.6(1.7%)	103.1 ±2.0(1.9%)	92.9 ±1.7(1.8%)
	Weighted Mean Age	94.5 ±1.5(1.5%)	94.0 ±1.4(1.5%)	101.6 ±1.4(1.3%)	95.2 ±1.2(1.3%)	103.1 ±1.7(1.6%)	92.2 ±1.4(1.5%)
	Systematic Error	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%
	MSWD	2.8	0.9	0.4	2.7	0.4	0.1
Weighted Average (+3)	Age	94.5(±5.3)	94.0(±1.4)	101.6(±1.3)	95.2(±4.4)	103.2(±1.5)	92.9(±1.3)
	Confidence	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%
	Rejection	0	0	0	0	0	0
	MSWD	2.8	0.89	.72	2.7	0.61	0.110
	Probability	0.061	0.41	0.49	0.067	0.55	0.90
YC2σ(+3)	Final Age	94.5 ±3.1(3.3%)	94.0 ±2.9(3.1%)	101.6 ±2.9(2.9%)	95.2 ±2.7(2.8%)	103.1 ±3.5(3.4%)	92.9 ±2.9(3.2%)
	Weighted Mean Age	94.5 ±2.9(3.1%)	94.0 ±2.7(2.9%)	101.6 ±2.7(1.3%)	95.2 ±2.5(2.6%)	103.1 ±1.7(3.2%)	92.9 ±2.8(3.0%)
	Systematic Error	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%
	MSWD	0.7	0.2	0.2	0.7	0.1	0.0
Tuff-Zirc (+6)	Age	97.5 +0.3 −3.0	95.6 +2.2 −2.3	102.2 +1.85 −1.85	101.1 +1.3 −1.4	104.3 +1.6 −1.8	93.5 +2.1 −1.0
	Confidence	93.8%	93.8%	96.9%	75%	96.9%	96.9%
	Group Size	5 of 6	5 of 6	6 of 6	3 of 6	6 of 6	6 of 6

populations are divided between Jurassic (7%) and Triassic (27%). Analytically this sample produced the second oldest maximum depositional ages of all five samples. The seven age metrics are as follows: YSG is100.5 (±1.1) Ma (Supplementary Table 1c), YPP is 103 Ma (Fig. 3, Table 1), YDZ is 101.3 (+1.8/−1.8) Ma (Table 1), YC1σ (+3) Isisford is 101.6 (±1.8) (Table 1), Weighted Average is 101.6 (±1.3) Ma (Table 1), YC2σ (+3) is 101.6 (±2.9) Ma (Table 1), and TuffZirc is 102.2 (+1.9/−1.9) Ma (Table 1).

4.4. GSQ Eromanga 1 core sample

Zircon grain morphology ranges from euhedral to abraded, well rounded grains with average grain size between 90 μm≥n≤200 μm. Also, these zircons had the greatest color variations among the zircon than other samples. Ninety-nine grains were analyzed (99 reported), yielding multiple age populations, mostly composed of various Mesozoic populations (80%) and much fewer Paleozoic grains (15%) and Pre-Cambrian grains (5%). Cretaceous grains (84%) dominated the Mesozoic population, of which 6% are Late Cretaceous and 94% are Early Cretaceous. The Jurassic (6%) and Triassic (10%) grains represent the other Mesozoic populations. Maximum depositional ages are as follows: YSG is 93.0 (±1.1) Ma (Supplementary Table 1d), YPP is 96.0 Ma (Fig. 3, Table 1), YDZ is 95.6 (+1.8/−1.9) Ma (Table 1), YC1σ (+3) is 95.2 (±1.6) Ma (Table 1), Weighted Average is 101.6 (±1.3) Ma (Table 1), YC2σ (+3) is 95.2 (±2.7) Ma (Table 1), and TuffZirc is 101.1 (+1.3/−1.4) Ma (Table 1).

4.5. GSQ Longreach 1 core sample

Zircon grain morphology is characterized by notably fewer euhedral crystals. Many of the grains within the sample are abraded and well rounded with average grain size between 90 μm≥n≤150 μm. Seventy-three grains were analyzed (69 reported), yielding multiple age populations, represented by Mesozoic (57%), Paleozoic (29%) and a few Pre-Cambrian (14%) grains. Early Cretaceous grains (57%) dominate the Mesozoic populations with fewer Jurassic (25%) and Triassic (18%) grains. Analytically this sample contains the oldest maximum depositional ages; YSG is 102.5 (±1.3) Ma (Supplementary Table 1e), YPP is 104 Ma (Fig. 3, Table 1), YDZ is 102.8 (+1.7/−2.1) Ma (Table 1), YC1σ (+3) is 103.1 (±2.0) Ma (Table 1), Weighted Average is 103.2 (±1.5) Ma (Table 1), YC2σ (+3) is 103.1 (±3.5) Ma (Table 1), and TuffZirc is 104.3 (+1.6/−1.8) Ma (Table 1).

4.6. Youngest grains

Of the five detrital zircon analyses, three samples (Lark Quarry, Bladensburg National Park, and GSQ Eromanga 1) had three or more grains at or younger than the Albian-Cenomanian boundary (n≤100.5 Ma). To test the robustness of the youngest maximum depositional ages, the twenty-four youngest grains in this study (effectively all Late Cretaceous grains) were grouped and analyzed as a separate sample. Using this approach, the maximum depositional age metrics for the entire study (n=388 grains) produces the following ages: YSG is 92.5 (±1.2) Ma (Table 1, Supplementary Table 1a,b,d), YPP is 98 Ma (Table 1), YDZ is 91.8 (+1.6/−2.3) Ma (Table 1), YC1σ (+3) is 92.9 (±1.7) Ma (Table 1),Weighted Average is 92.9 (±1.3) Ma (Table 1), YC2σ (+3) is 92.9 (±2.9) Ma (Table 1), and TuffZirc is 93.5 (+2.1/−1.0) Ma (Table 1) (see Supplementary Fig. 1 for Concordia Plots). Using this approach, one can make a much stronger argument for a younger (post-Cenomanian/Turonian boundary) depositional age for Winton Formation, at least the upper fossiliferous portion of the unit.

5. Discussion

5.1. Maximum depositional ages

The aim of this study was to determine the youngest maximum deposition age of the Winton Formation and to temporally constrain its globally significant fauna and flora (Fig. 4). The youngest single grain ages (YSG) for all five samples range from 92.5 Ma at Lark Quarry, at the top of the section, to 102.5 Ma in the GSQ Longreach 1 core,

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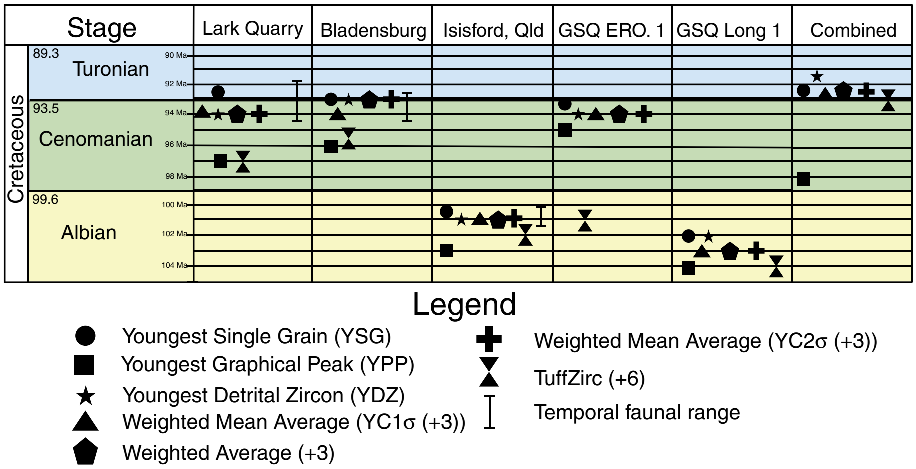

Fig. 4. Temporal relationship of the seven metrics (YSG, YPP, YDZ, YC1σ (+3), Weighted Average, YC2σ (+3), and TuffZirc (+6)) utilized with in this study, of the six populations (Lark Quarry Conservation Park, Bladensburg National Park, Isisford, GSQ Eromanga 1, GSQ Longreach 1 and the youngest combined population). Temporal constraint is suggested for the faunal assemblages at each of the three fossil localities (Lark Quarry Conservation Park, Bladensburg National Park, and Isisford, Queensland).

from the uppermost sections the Mackunda Formation. If the single grain age is taken as a proxy for the youngest maximum age of the lower to middle portions of the Winton Formation, it strongly supports continued deposition of the formation into the Turonian or earlier (Grandstein and Ogg, 2004; Walker and Geissman, 2009; Ogg and Hinnov, 2012) (Fig. 4). However, these ages are based on single grains and may be erroneous; hence they should be used with caution. However, the value of identifying YSG ages is that they may actually indicate a small, but true population of younger grain ages that can be verified through additional zircon analyses. On the other hand, the application of the TuffZirc and YPP metrics demonstrably produces the oldest ages, and is considered much less sensitive for the interpretation of the maximum youngest depositional age. Given this insensitivity, we recommend against using these two metrics for this application. Thus, excluding the insensitive TuffZirc and YPP ages, along with the potentially inaccurate YSG ages, we find that each of the other metrics yields relatively similar and robust maximum depositional age constraints for the upper fossiliferous portion of the Winton Formation (i.e., Lark Quarry, Bladensburg National Park, GSQ Eromanga-1), between 92.5 Ma and 95.6 Ma. However, when all samples are complied (n = 388 grains), there is a solid population, and the application of the four preferred maximum depositional age metrics strongly implies a post-Cenomanian age (≤93.6 Ma) for the depositional age of the upper fossil-bearing portion of the Winton Formation. Based on this study, the base of the Winton Formation appears to be at or near the Albian/Cenomanian boundary, whereas the upper Winton Formation very likely continued into or past the early Turonian. It should also be highlighted that in the review by Dickinson and Gehrels (2009) the following variances within the methodologies are as follows; YSG and YC1σ (+3) on average are within 5 Ma of deposition, YDZ is within 2 Ma, YPP only 5% of the time younger than that of depositional age and YC1σ (+3) is older by 10 Ma and is not a more reserved measure. Also it should be noted that these derived zircon ages only represent an age for the youngest sediment sources and are not a true depositional age of the formation. Additionally, given that the uppermost 10–20 m of the Winton Formation was not sampled, it may well be these horizons they preserve detrital zircons that are younger still. Minimally the results of this study suggest that the uppermost portions of the Winton strata in the northern part of the basin were deposited near to or after the Cenomanian/Turonian boundary. Our findings significantly improve upon continental biostratigraphic age control for the Winton Formation and support assertions by Helby et al. (1987) that the deposition of the Winton Formation may extend into the early Turonian.

5.2. Age of Winton Formation vertebrate fossil localities

The stratigraphic position of the various samples that we have considered and their respective ages indicate that the age of the basal-most Winton Formation and its overlying thickness vary throughout the basin. Fielding (1992) has shown that in marginal regions of the Eromanga Basin, the Winton Formation is less than 100 m thick, but that the unit thickens to more than 1200 m in central areas about the Queensland-South Australian border. The Isisford sample, which sits approximately 200 m above the inferred contact with the Mackunda Formation, is here dated as late Albian. This age is closer to that of the geographically proximate GSQ Longreach 1 sample than any of the other samples that we considered.

Our results indicate that vertebrate fossil-bearing localities in the Winton area (Lark Quarry and Bladensburg National Park) are of a similar age (statistically close to overlapping), deposited near to or after the early Turonian–late Cenomanian, respectively. This result is consistent with the very shallow dip (~8°) in the broader Winton area, and the apparent continuity of strata between the two localities. Other fossil sites in the Winton area, such as those on Alni Station, 50 km NW of Winton (Lat: 22°11′00″S; Long: 142°28′00″E; Coombs and Molnar, 1981; Molnar, 2001, 2010, 2011; Molnar and Salisbury, 2005), Belmont Station, 60 km NE Winton (22°5′S, 143°30′E; Clifford and Dettmann, 2005; Salisbury, 2003, 2005; Salisbury et al., 2006a,b, 2007; Scanlon and Hocknull, 2008; Hocknull and Cook, 2008) and Lovelle Downs Station/Elderslie Station, 48 km WNW of Winton (Lat: 22°11′59″S; Long: 142°31′43″E; Dettmann et al., 2009; Hocknull et al., 2009; White et al., 2012) are therefore likely to be of similar depositional history, and would be no older than the Cenomanian/Turonian boundary. The latter sites traverse a low ridge between Lovelle Downs Station and Elderslie Station, and are all within a few kilometers of each other (Dettmann et al., 2009; Hocknull et al., 2009; White et al., 2012). This area is 30 km northwest of Bladensburg National Park and 100 km northwest of Lark Quarry Conservation Park. Previously, Dettmann et al. (2009; whose age assessment was followed by Hocknull et al., 2009) proposed that the floral assemblage from the Lovelle Downs/Elderslie locality was from the late Albian. This assessment was based primarily on the presence of *Cicatricosisporites* and *Crybelosporites* pollen in association with *Clavatipollenites* and *Phimopollenites*, indicating that the sediments were within the *C. paradoxa* or *P. pannosus* spore–pollen zones (of Helby et al., 1987) and therefore could not be older than middle Albian. A late Albian age was proposed by Dettmann et al. (2009) because the sediments that the fossils were found in were

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within ~265 m of the contact with the underlying Mackunda Formation (Watson, 1973). However, based on the relatively close proximity of the Lovelle Downs/Elderslie locality to Bladensburg National Park (~30 km), and the likely stratigraphic continuity between these two areas and Lark Quarry, we suspect that an early Turonian–middle Cenomanian age is more likely.

There are notable differences between the vertebrate assemblages of Isisford and those from the Winton area (Bladensburg, Lark Quarry, Elderslie, Lovelle Downs, Alni, Belmont). The remains of titanosauriform sauropods are the most abundant vertebrate fossils encountered at sites around Winton (Coombs and Molnar, 1981; Molnar, 2001, 2010, 2011; Molnar and Salisbury, 2005; Salisbury et al., 2006b; Hocknull et al., 2009). Those that have been described to date are usually preserved as either isolated elements or as partial, disarticulated and associated skeletons, often in multi-individual bone beds and associated with isolated and frequently reworked micro-vertebrate remains (Salisbury, 2005; Salisbury et al., 2006b; Hocknull et al., 2009; Molnar, 2010). Disarticulated or semi-articulated and associated skeletons, such as the holotype of *Diamantinasaurus matildae* (Hocknull et al., 2009), have proven to be much less common. The latter specimen was found in association with a partial, disarticulated theropod skeleton, *Australovenator wintonensis* (Hocknull et al., 2009; White et al., 2012). Thus far, other smaller-bodied taxa from Winton sites have only been described on the basis of isolated elements (Dettmann et al., 1992; Kemp, 1997; Salisbury, 2003, 2005; Hocknull and Cook, 2008; Scanlon and Hocknull, 2008; Musser et al., 2009; Salisbury et al., 2011). The Isisford assemblage, on the other hand, is thus far devoid of sauropods. The most commonly encountered vertebrates are teleost fishes (Berrell et al., 2008, 2011) and small-bodied crocodyliforms (Salisbury et al., 2006a). Dinosaurs are rare, but those that have been discovered and prepared to date are all small (cow-sized or smaller; Fletcher et al., 2009). In nearly all instances, the vertebrate fossils from the Isisford localities are either near-complete or partial skeletons, with elements preserved in full articulation, semi-articulation or close association. With the exception of the crocodyliform remains, none of the other micro-vertebrates recovered from the Winton sites has turned up at Isisford (including lungfishes and turtles).

While many of the differences between the faunal and floral assemblages of the Winton sites and Isisford may relate to taphonomy and depositional setting, it is also likely that the overall biotic composition of each area was distinct in its own right. This study indicates that vertebrate fossil-bearing sites in the two areas have distinctly different maximum depositional age profiles, with the Winton sites being middle at least mid Cenomanian, but likely post-Cenomanian, and the Isisford sites yielding a very early Cenomanian (100.5–102.2 Ma) maximum depositional age. Interestingly, the stratigraphic position of the fossil-bearing horizon at Isisford (as represented by the nodule sampled herein) appears to be well above the Winton-Makunda boundary in this part of the Eromanga Basin. Combined with an older age, this strongly suggests local variation in deposition across the basin, such that the age and depth of boundary between the Winton and Munkunda Formation may vary geographically. With more precise temporal and stratigraphic constraints, it should also be possible to more closely examine the variations in depositional history of the Winton Formation.

5.3. Recalibrating palynomorph zones

As far back as the 1950s, problems were recognized with the utilization of pollen as a temporal constraint, due to spores being highly susceptible to reworking in the same potential manner as the entombing host-rock. In ideal conditions, all constituents of a rock may be structurally preserved through reworking, but in reality pollen grains are commonly altered, damaged, or annihilated from the record (Muir, 1966). It is also now acknowledged that a greater stratigraphic disturbance of pollen is due to marine transgressive and regressive cycles. With three of the four formations within the Rolling Downs Group represented by *P. pannosus* (Toolebuc, Allaru Mudstone, Mackunda Formation and the Winton Formation), the first three of which span marine phases, many problems could arise. However when the detrital zircon results are coupled with palynological data, a more reliable interpretation can be formulated.

Historically, palynology and plant macrofossils have been utilized for bracketing a temporal constraint for mid-Jurassic to mid-Cretaceous sediments within the Eromanga Basin strata (Hutton Sandstone to the Winton Formation) since the mid-sixties (Vine and Day, 1965; Evans, 1966). In previous literature (Burger, 1990 and references therein, Sec. 2.2; and McLoughlin et al., 1995) the relative age of the Winton Formation relative to other units was been based on the occurrence of *P. pannosus* and *Appendicisporites distocarinatus*, (Dettmann and Playford, 1969; Burger, 1973; Dettmann, 1973, 1994; Morgan, 1980; Burger, 1993). However, Helby et al. (1987) placed the Winton Formation between the Albian and the Cenomanian, noting the possibility that deposition could have extended into the early Turonian. Recently, McLoughlin et al. (2010; pg. 4) noted that plant remains and palynological data have yet to obtain a definitive age determination of the upper Winton Formation. Detrital zircons obtained just below the contact between the upper-most Mackunda Formation date around 102 Ma to 103 Ma (latest Albian; see sec 3.5.5), thus supporting McLoughlin et al. (2010) age position of samples recovered from the base of the Winton Formation. However Dettmann et al. (2009) described *Lovellea wintonensis* from surface deposits as late-Albian in age based on reports and site descriptions from Peters and Christophel (1978; pg. 3119–3120) for Lovelle Downs, 48 km WNW of Winton Queensland. An earlier site description of Lovelle Downs by the Peters and Christophel (1978) study originally described the floral assemblage being entombed within an exposed lenticular body containing silicified plant remains "just above" the supposed Winton Formation but failed to described the body in detail (Peters and Christophel (1978; pg. 3119)). It is worth noting here that a plethora of plant remains occur within in a distinct horizon that occurs both upon exposed surfaces and also within lenticular bodies at the base of 'jump ups' (buttes). These common localities occur in the upper exposed and preserved Winton Formation throughout the Winton area, including multiple sites just to the south of Lovelle Downs at Bladensburg National Park and Lark Quarry Conservation Park. The stratigraphic position of surface and entombed remains is interpreted as portions of the lower–upper to upper sections of the preserved and exposed Winton Formation, which is in agreement with the observations noted by Peters and Christophel (1978, pg. 3120), McLoughlin et al. (1995; pg. 274) and Pole and Douglas (1999, p. 542). These lenticular beds occur 1–3 m vertically below Lark Quarry's DZ samples described in this study, which are estimated at 92 ($\pm$1.2) Ma to 94.5 ($\pm$1.3) Ma in the early to mid-Turonian to very Late Cenomanian, and just 2–4 m vertically above the dinosaur bone bed quarries at Bladensburg National Park, which are estimated to be between 93.3 ($\pm$1.2) and 95.6 ($\pm$1.4) Ma in the early Turonian to Late Cenomanian (if error is taken into account, then statistically both sites temporally overlap) (Figs. 5 and 6). Thus, adjustment of the spore–pollen zones originally described by Helby et al. (1987), Partridge (2006) and other authors is needed (Figs. 5 and 6). This 'new' temporal placement of the upper sections of the Winton Formation partly supports the original observations of Helby et al. (1987) (Fig. 6).

5.4. Implications for paleobiogeography

The rapid separation of Gondwana, principally during the Cretaceous, represented one of the most important paleobiogeographic dispersal and subsequent vicariance events in Earth history. Archosaurian evolutionary lineages, post-separation of Gondwana, have been widely described as evolutionarily unique to their Laurasia counterparts (Bonaparte, 1986; Agnolin et al., 2010). However, the

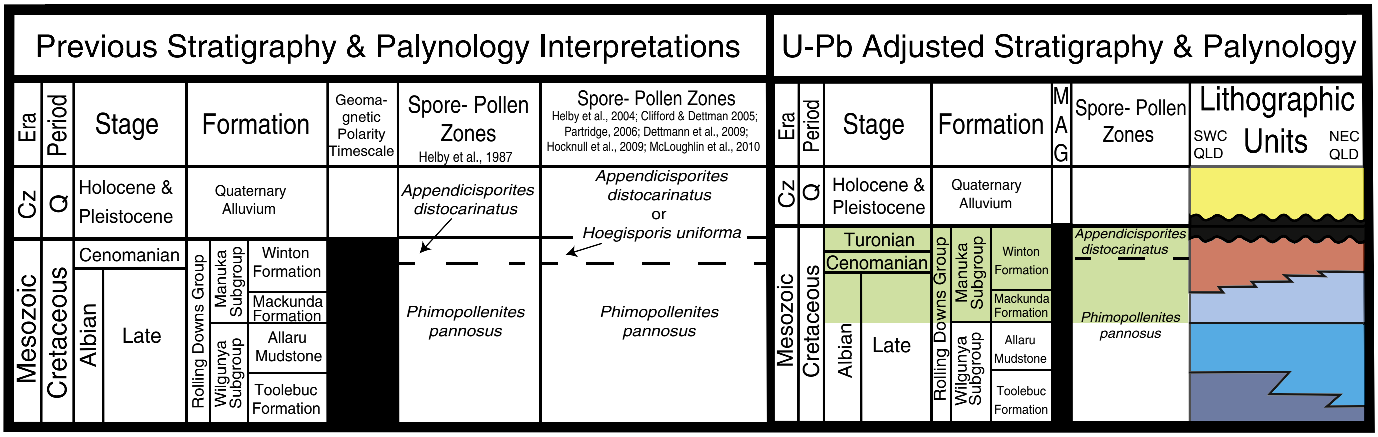

Fig. 5. (right) Original and revised chronostratigraphy; Original chronostratigraphy based on *Appendicisporites distocarinatus* and *Phimopollenites pannosus* spore–pollen zones originally described by Helby et al. (1987), and (left) revised to be based on *A. distocarinatus* (*Hoegisporis uniforma*) and *P. pannosus* by Clifford and Dettmann (2005), Partridge (2006), Dettmann et al. (2009), Hocknull et al. (2009) and McLoughlin et al. (2010). Revised spore–pollen zonation was based on detrital zircon geochronological information interpreted within this study.

relationship of fossils from the eastern-most portion of Gondwana, in particular Australia, is still poorly understood due to a sparse and poorly dated fossil record. The many recent discoveries of new archosaurian taxa in the Winton Formation are beginning to shed light on the radiation and dispersal of dinosaurian clades between South America and Australia via Antarctica. However, to understand this relationship fully, prior to this study had been undertaken that we could reliably place these taxa into a rigorous temporal framework. The second temporal constraint used by many studies including Molnar (1980), Coombs and Molnar (1981), Dettmann et al. (1992), Molnar and Willis (1996), Molnar (2001), Molnar and Salisbury (2005), Salisbury et al. (2006a,b), Hocknull et al. (2009), Fletcher and Salisbury (2010), and Molnar (2010) has been an association with the *P. pannosus* palynomorph zone (Suite III; Burger, 1990 and therein). However, problems arise with the utilization of this method when it is not used in association with other temporal constraining methods. *P. pannosus* spans four stratigraphic units (the Toolebuc Formation, the Allaru Mudstone, the Mackunda Formation, and the Winton Formation), over a time span of about 15 My.

With each new discovery, along with the re-description of previously-identified taxa, it is becoming increasingly apparent that Australian taxa have strong evolutionary ties to similarly aged forms from South America. Agnolin et al. (2010) revised much of the non-avian dinosaur taxa from the Winton Formation, and found that the majority had affinities to other Gondwanan taxa, particularly from South America, rather than Laurasia. With the implementation of the chronostratigraphic framework generated by this study, for the first time paleontologists can better place Australia's early Late Cretaceous biota (including recently discovered undescribed taxa) into a meaningful global context (Sereno, 1997, page 474; Sereno et al., 2004). By continuing to place each fossil horizon into a temporal framework based on geochronology we can better compare Australian taxa with coeval forms from other parts of the world (Upchurch et al., 2007; Upchurch, 2008).

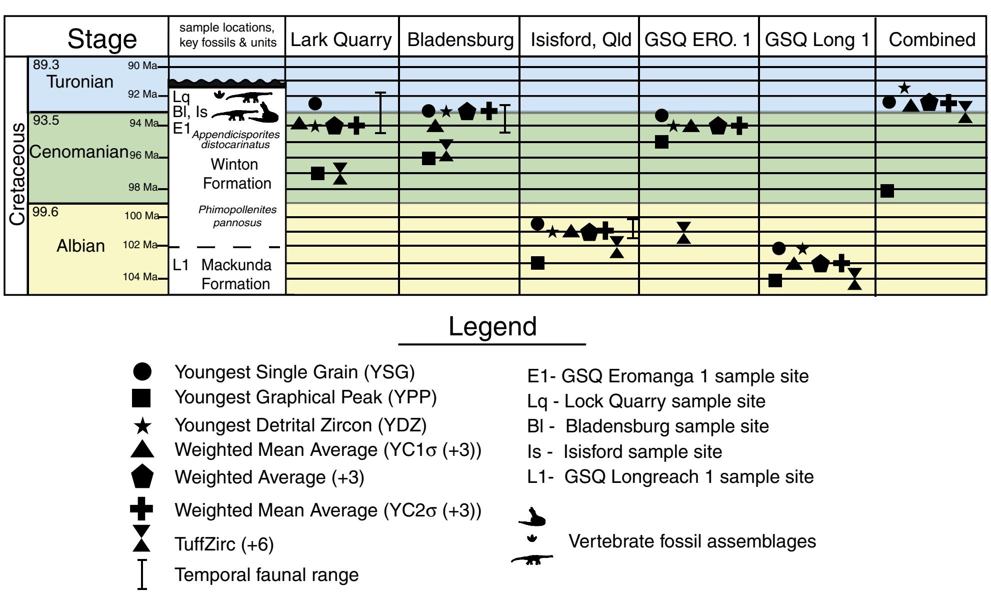

Fig. 6. Interpreted temporal relationships (based on the temporal relationship of the seven metrics (YSG, YPP, YDZ, YC1σ (+3), Weighted Average, YC2σ (+3), and TuffZirc (+6)) utilized with in this study, seen on the right) for detrital zircon samples derived from the three faunal assemblage localities in the upper Winton Formation (Lark Quarry Conservation Park, Bladensburg National Park, and Isisford, Queensland), along with the temporal placement of detrital samples derived from GSQ core logs (GSQ Eromanga 1, GSQ Longreach 1) and the interpreted position of the conformable contact between the underlying Mackunda Formation and the Winton Formation.

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6. Conclusions

To accurately contextualize the Winton Formation's terrestrial Cretaceous vertebrate biota improved temporal and stratigraphic resolution is paramount. We attempted to address this problem by testing the potential of utilizing U–Pb LA-ICP-MS detrital zircon geochronology to refine the age of the formation by systematically investigating the youngest maximum depositional age of zircons at different stratigraphic levels and locations throughout the unit. We analyzed five samples (six populations; see sec 4.6) and compared different approaches (seven) to interpret the youngest maximum depositional age in order to both refine the age of the formation and to improve regional stratigraphic relationships between widely separated fossil assemblages. Of the seven approaches (YSG, YPP, YDZ, YC1σ (+3), Weighted Average, YC2σ (+3), and TuffZirc (+6)), five metric's are recommended for deriving the youngest maximum depositional age (YSG (when coupled with other metrics), YDZ, YC1σ (+3), Weighted Average, YC2σ (+3)). Our results demonstrate that the formation was largely deposited during or shortly after a long period of intense volcanic activity along the eastern margin of Australia, with erosion of the resulting topography the main source of sediment. We identified multiple temporally arrayed Cretaceous volcanic sources that fed the formation, and that the youngest of theses populations was likely deposited syndepositionally, providing greatly improved age constraints on deposition. Using various metrics for interpreting maximum depositional age, we find that the youngest samples from Lark Quarry Conservation Park Bladensburg National Park and drill-core GSQ Eromanga 1 ranged between 92.5 (±1.2) and 93.3 (±1.2) Ma, and indicate that deposition of the Winton Formation and associated fossil material occurred within the early-Turonian to Turonian–Cenomanian boundary (Fig. 6). As a result, the previously interpreted earliest known flowering plants occurred at or younger than the early-Turonian to Turonian–Cenomanian boundary rather than previously indicated. Fossil material collected from the uppermost underlying Mackunda Formation is interpreted to be around 102.5 to 104 Ma.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2012.12.009.

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