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DEPOSITIONAL ENVIRONMENT OF THE LOWER CRETACEOUS (UPPER
ALBIAN) WINTON FORMATION AT ISISFORD, CENTRAL-WEST
QUEENSLAND, AUSTRALIA, INFERRED FROM SANDSTONE CONCRETIONS
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ABSTRACT: Numerous vertebrate and plant fossils have been found in *ex-situ* sandstone concretions near Isisford in central-west Queensland since the mid-1990s. These concretions are found in the Lower Cretaceous portion (upper Albian, 100.5–102.2 Ma) of the Winton Formation. The lower most Winton Formation is thought to have formed in a fluvial channel or flood-basin setting proximal to the Eromanga Sea, but due to the scarcity of good exposures, the local depositional environment at Isisford has not been ascertained. Minimal compression of vertebrate and plant fossils, a lack of grain suturing, predominantly cement-supported fabric, and fractures running through calcite cement, as well as fossil bone and framework grains, indicates that concretions formed during early diagenesis (pre-compactional or syndepositional). Calcite stable-isotope $\delta^{18}\text{O}_{\text{VPDB}}$ values range from –12.25 to –4‰, indicating mixed marine and meteoric pore waters, and $\delta^{13}\text{C}_{\text{VPDB}}$ values range from –5.3 to 4.1‰, indicative of both sulfate reduction and methanogenesis of organic material (including decaying vertebrate soft tissues) in the burial environment. The mixed marine and freshwater signature suggests a marginal marine setting, possibly deltaic or estuarine, connected to the regressive epicontinental Eromanga Seaway at around 102–100 Ma. This is not inconsistent with the lithology from nearby cores, coupled with Isisford fossil-vertebrate ecology (personal observation). Our research demonstrates the utility of investigating *ex-situ* concretions to refine paleoenvironments at localities where little or no outcrop is available and traditional facies analysis is impractical.

INTRODUCTION

Sandstone concretions cemented with calcium carbonate have been reported worldwide, ranging from the centimeter scale (Dix and Mullins 1987; Allison and Pye 1994; Mozley and Davis 2005; Tabor et al. 2007), the decimeter to meter scale (Dix and Mullins 1987; Gregory et al. 1989; Maisey 1991; Pirrie and Marshall 1991; Martill 1993; Hendry et al. 1996; Hendry and Poulson 2006; Wanas 2008; Roberts and Chan 2010; Roberts et al. 2014), to “cannonball” concretions up to 6 m in diameter (Dutton et al. 2000; McBride et al. 2003; McBride and Milliken 2006). The source of calcium

carbonate cement in such concretions is not always clear, potentially coming from organic-matter degradation including biogenic carbonate (Curtis and Coleman 1986; Hendry et al. 1996; Boggs 2009), deeply buried marine rocks (Enos and Kyle 2002), proximal limestone deposits (McBride 1987; Boggs 2009), or pedogenesis (Kraus 1987; Bao et al. 1998; Beckner and Mozley 1998). Some authors suggest that concretions commonly form during early burial at or just below the sediment–water interface, sometimes during single precipitation episodes (Hudson 1978; Carpenter et al. 1988; Mozley and Burns 1993; Duck 1995; Middleton and Nelson 1996; Raiswell and Fisher 2000; Woo and Khim 2006). These shallow-burial concretions can preserve aspects of the original groundwater chemistry and depositional sedimentary fabric (Canfield and Raiswell 1991; Mozley and Burns 1993; El Albani et al. 2001; Roberts and Chan 2010; Dale et al. 2014), which can be useful for interpreting environments of deposition at sites where facies analysis is otherwise difficult because of limited or no exposed host rock. For example, stable-isotope analysis of concretion cement can indicate the influence of marine or meteoric water during cement precipitation (Anderson and Arthur 1983; Hays and Grossman 1991; Faure and Mensing 2005; Zhou et al. 2008), but can be relied upon only if the cement formed during shallow burial, thereby truly reflecting the geochemical signature of the environment of deposition.

Sandstone concretions preserving vertebrate fossils were first recognized in the Lower Cretaceous portion (upper Albian; Tucker et al. 2013) of the Winton Formation at sites near the town of Isisford, central-west Queensland in the mid-1990s (Salisbury et al. 2006a) (this locality is hereafter referred to as “Isisford,” see Figs. 1 and 2). The Isisford concretionary material has previously been described as consisting of medium- to coarse-grained feldspathic to feldspatholithic fluvial sandstone, cemented with either iron-oxide-rich calcite or siderite (Tucker et al. 2013). Most of the Isisford concretions are *ex situ*, occurring within or on top of Cenozoic and Quaternary alluvium, while other concretion-like structures are still partially *in situ* and can be seen eroding out of exposures of Winton Formation. The Isisford fossil fauna is dominated by aquatic and semi-aquatic animals, specifically large-bodied, fast-swimming predatory teleost fishes (ichthyodectiforms including *Cladocycilus geddesi*, and a possible halecomorph (Faggotter et al. 2007; Berrell et al. 2014)), as well as small-bodied (< 1.5 m) basal eusuchian crocodyliforms (*Isisfordia duncani* (Salisbury et al. 2006a)). Although small- to medium-size non-avian dinosaurs have also been discovered (but are yet to be described) (Fletcher et al. 2009), the remains of larger sauropodan dinosaurs commonly found at other fossil sites within the Winton Formation (see Coombs et al. 1981; Molnar 2001; Molnar et al. 2005; Salisbury et al. 2006b; Hocknull et al. 2009; Poropat et al. 2015a, 2015b) are notably absent, despite over a decade of intense collecting. Also conspicuous by their absence are the remains of dipnoan lungfishes and turtles, which are also found at other Winton Formation fossil sites (see Molnar 1991; Dettmann et al. 1992; Kemp 1997).

The depositional setting at these other Winton Formation fossil sites has been interpreted as low-energy fluvial with point-bar deposits, crevasse splays from flood events, and oxbow lakes (Salisbury et al. 2006b; Hocknull et al. 2009; Tucker et al. 2011; Poropat et al. 2015b). Although the Winton Formation has been interpreted on a broad scale to represent fluvial and lacustrine facies (Playford et al. 1975; Senior and Mabbutt

1979; Fielding 1992; Gray et al. 2002; Tucker et al. 2013), Berrell et al. (2014) suggested that the Winton Formation at Isisford might have been deposited in low-energy, potentially tidally influenced distal fluvial channel sets. The ecology of the taxa described so far from Isisford shows a mixture of marine or freshwater open water (open channel or sublittoral), semi-aquatic, and terrestrial fauna, suggesting they were buried in a terrestrial body of water possibly close to the coast of the epicontinental Eromanga Sea. The inferred depositional setting and the extent to which this area was under marine influence is difficult to ascertain based purely on the supposed habitats of extinct vertebrate fauna. Instead, taphonomic analysis of fossil material is often used to quantify the environment of preservation and therefore deposition. Initial taphonomic analysis of the Isisford fossil material suggests that rapid burial allowed for their excellent articulated and complete preservation. However, as taphonomic signatures are not always indicative of specific depositional environments, sedimentological and facies analysis of outcrop are needed.

Although there are abundant concretions at Isisford, there are very few locations where the Winton Formation crops out, which greatly limits the capacity for traditional facies analysis across the site. While concretions preserve part of the original host-rock fabric, their size range (average 30 to 100 cm diameter) and *ex-situ* nature means that they cannot be constrained to specific facies or horizons seen in nearby cores. Nevertheless, the concretions can still be examined for sedimentological structures and geochemical signatures as a broad indicator of the local environment. To this end, the purpose of this investigation is to understand the relative timing of concretion formation at Isisford in order to quantify the pore-water chemistry and reconstruct the depositional environments at Isisford during the late Albian. We therefore chose to analyze the composition of not only the concretion cement, but also the different generations of cement (if apparent). Oxygen stable-isotope analysis of the cement was conducted to confirm the likely environment of formation—terrestrial, marine, or paralic. In addition, we conducted carbon stable-isotope analysis and concretion elemental analyses to determine the burial pore-water chemistry during concretion formation. Together, the results of this study improve our understanding of the environment that allows for exceptional preservation of vertebrate fossils at Isisford during the late Albian.

Geological Setting

The fossil locality of Isisford comprises a 20 km² area situated on private land near the town of Isisford in central-west Queensland within which concretions and bedrock of the Winton Formation are exposed. The Winton Formation forms the uppermost unit in the Rolling Downs Group, in the intracratonic Eromanga Basin (Fig. 2). The formation consists of volcanolithic sandstones interbedded with mudstone and siltstone, with interstitial calcite cement, minor intraformational conglomerate, lignite, and coal, that is chemically altered in part (kaolinized and ferruginized) (Geological Survey of Queensland 1970; Watson 1973; Gray 1975; Campbell and Haig 1999). The volcanolithic component of the Winton Formation sandstones most likely originated from rift-related volcanoes in the Whitsunday Volcanic Province to the east that was carried west as sediment loads by rivers (Bryan et al. 1997, 2000, 2012; Tucker et al. 2013). The Winton Formation conformably overlies the shallow marine Mackunda Formation and unconformably underlies poorly consolidated Quaternary sands, silty sandstones, and

Cenozoic smectitic alluvium consisting of black cracking clays known locally as “blacksoil” (Geological Survey of Queensland 1970; Gray et al. 2002; Jell 2013). Fielding (1992) analyzed core samples from the Winton Formation, selected GSQ Eromanga-1 as a representative section, and divided it into three facies: major channel, flood-basin, and mire. The inferred depositional environment of the Winton Formation overall was that of a freshwater and/or lacustrine alluvial plain, with rivers draining toward the epicontinental Eromanga Sea as it withdrew (Playford et al. 1975; Senior and Mabbutt 1979; Fielding 1992; McLoughlin et al. 1995; Gray et al. 2002).

At Isisford, the exposed surface of the Winton Formation is thought to lie approximately 200 m above the contact with the Mackunda Formation (Tucker et al. 2013). Tucker et al. (2013) found that the Winton Formation at Isisford was deposited during the upper Albian (maximum age of 100.5–102.2 Ma) and suggest that the surface exposures of Winton Formation at Isisford represent an earlier phase of deposition than other vertebrate fossil bearing sites farther north in the Eromanga Basin; the exposed Winton Formation at Isisford is approximately 6–8 million years older than that at Lark Quarry and other vertebrate fossil-bearing sites around Winton.

METHODS

The majority of Winton Formation concretions were collected from Isisford during University of Queensland expeditions between 2001 and 2010, with additional samples collected and field data recorded in April 2013. Positions of sample localities relative to one another are shown in Figure 3. The authors hold all information on sample localities, and permission is required to access the property on which sample localities reside. Concretion morphology was categorized using the classification system devised by Sellés-Martínez (1996). The degree of compaction of vertebrate fossil bone, where visible, was recorded. *Ex-situ* concretions were defined as indurated spherical sandstones not attached to bedrock, essentially “floating” on top of or within the alluvium. In-situ outcrop was identified as exposures of sandstone that were not spherical in shape and/or not indurated and extends through the alluvium at depth. Both fossiliferous and non-fossiliferous concretions were thin sectioned for petrographic analysis. The types and number of grain contacts were counted using randomly placed transects across each thin section, after Taylor (1950) and Boggs (2009). The thin sections were analyzed for mineral and elemental composition using a Hitachi TM3030 Plus scanning electron microscope (SEM) with a Bruker energy dispersive X-ray spectroscope (EDS), and cathodoluminescence (CL) using a Nikon Eclipse E400 POL Luminoscope ELM-3R with *ca* 15 kV beam energy and *ca* 0.3 mA beam current in a 150 Torr vacuum to investigate zonation in carbonate cements. Selected concretions and outcrop samples were also crushed using a tungsten carbide percussion mill and an agate ball mill for whole-rock X-ray diffraction analysis (XRD) to confirm the mineralogy and proportion of the sample cement, using a D8 Advance instrument with 2-theta angle. XRD diffractograms were interpreted using the program DIFFRAC.EVA (Bruker-AXS). Calcite percentages from XRD were also compared to those approximated via thin-section image analysis using the software Fiji (similar to ImageJ, created by Schindelin et al. 2012). In Fiji, we assigned the calcite cement to one color (setting the threshold using a histogram), and from that calculated the percentage of the image represented by that color. Whole-rock samples were analyzed for stable carbon ($^{12}\text{C}/^{13}\text{C}$) and oxygen ($^{16}\text{O}/^{18}\text{O}$) isotopes using

an Isoprime dual-inlet mass spectrometer with Multiprep (DI-IRMS) in the Stable Isotope Geochemistry Laboratory, University of Queensland, using phosphoric acid at 90°C then converted to parts per thousand (per mil, ‰) relative to the Vienna Pee Dee Belemnite (VPDB). Analytical uncertainties were better than $\pm 0.1\text{‰}$ (2σ) based upon on replicate analyses of NBS-18 oxygen and carbon isotope measurements. We also examined historical well logs and ~ 200 m of core from both GSQ Blackall 1 and GSQ Blackall 2 (Almond 1986; Coote 1987), drilled near the towns of Blackall and Isisford in the mid-1980s (shown as GSQB1 and GSQB2 respectively in Figs. 1 and 2) and accessioned at the Department of Natural Resources and Mines Exploration Data Center in Brisbane, Queensland. GSQ Blackall 1 is approximately 85 km east of Isisford, and GSQ Blackall 2 is approximately 40 km north west of Isisford. We obtained a historical well log for a third core, Isis Downs-1, drilled approximately 20 km east of Isisford in 1981 (shown as ID1 in Figs. 1 and 2) (ESSO Australia Pty Ltd. 1981). As the physical core for Isis Downs-1 was not accessioned into any collection, we were not able to examine it for this study.

RESULTS

Description of Concretions

The morphology of the Isisford carbonate concretions range from spherical to oblate spherical or prolate spherical (after Sellés-Martínez 1996), with the appearance of iron staining. Deep fissures run through the majority of the concretions, often resulting in fossil bone being exposed. There is no evidence of bedding-plane refraction; however, the original fabric orientation and concretion axis is not discernible (see Fig. 4A–C, F). Where visible, the parallel bedding planes remain unaltered with no warping at the concretion boundaries. Vertebrate fossils found in some concretions include a range of articulated to partially articulated crocodyliforms (*Isisfordia duncani*), osteichthyans (*Cladocyclus geddesi*, halecomorph indet.), and non-avian dinosaur body fossils, with all excluding one specimen showing no signs of diagenetic deformation (Salisbury 2005; Salisbury et al. 2006a; Fletcher et al. 2009; Berrell et al. 2014). One specimen, a juvenile *I. duncani* cranium (UQL-ISIS-III-5a/b), does exhibit minor dorsoventral compression as evidenced by a lateral shift of the left mandibular ramus.

At UQL-ISIS-II, the only site where the Winton Formation is exposed *in situ*, multiple concretions-like structures are observed partially weathered out of the outcrop in a sinuous bedding-surface oriented line (see Fig. 4D). This *in-situ* outcrop and concretion-like structures are not indurated unlike the “true” *ex-situ* concretions. Fossil wood is found in dense concentrations in parallel beds at some localities (UQL-ISIS-IV and UQL-ISIS-VII), with fragments ranging from 0.2 cm to 5 cm in length. At other localities (UQL-ISIS-I and UQL-ISIS-III) fossil wood fragments ranging from 5 to 15 cm in length are found in sandstone concretions. The density of fossil wood per concretion is variable, with concretions that contain larger pieces of wood being less densely packed (Fig. 4E) than those that contain smaller wood fragments.

The sand grains in the concretions are fine- to medium-grained, poorly to moderately sorted, and subangular to subrounded, and are matrix supported. The only clasts larger than fine- to medium-grained sand are mud rip-up clasts, fossil wood fragments, and vertebrate fossils (Fig. 4E). The UQL-ISIS-X and UQL-ISIS-VII sites have mudstone clasts ranging in size from 0.1 cm to 9 cm, whereas at UQL-ISIS-I, UQL-

ISIS-II, UQL-ISIS-III, and UQL-ISIS-X, micro-scale mud rip-up clasts have been identified in thin section. At UQL-ISIS-IX, no mud rip-up clasts are identified at the macro- or micro-scale. There is no evidence of bed scours adjacent to either fossil wood or vertebrate fossils. Cross sections through the Isisford concretions show no evidence of concentric growth rings. It also appears that the concretions did not always form around a nucleus—fossil wood and vertebrate fossils are not consistently situated in the center of the concretions, although this could be a result of uneven concretion surface weathering. See Table 1 for details on each concretion and outcrop sample.

Petrographic Analysis

The Isisford concretions and sandstone outcrops are classified as feldspathic litharenites (*sensu* Folk 1974) comprising framework grains (70–80%) and carbonate cement (20–30%). Framework grains consist of subangular to subrounded quartz (30–60%), feldspar (30–40%), and well-rounded volcanic lithics (20–30%), with some subangular to subrounded opaque heavy minerals and mud rip-up clasts (5%). Analysis of grain contacts following the approach of Taylor (1950) and Boggs (2009) performed via thin-section traverses indicates that, on average, approximately 21% of grain contacts are tangential (point) and 14% are long contacts. The majority of grains have no contacts (floating, 65%). The degree of compaction of framework grains is consistent throughout each concretion from the center to the outermost edge.

Calcite cement is abundant throughout the Isisford concretions and outcrop comprising, on average, 34.1% of the total rock composition; cement volumes calculated using Fiji image analysis indicate a range from 20.8 to 63.9% (mean = 34.1%, $1\sigma = 10.1$, $n = 15$). Of this, approximately 70% of calcite cement is micritic or microcrystalline in form (Fig. 5). The next most common cement morphology is blocky calcite spar with sweeping extinction in XPL (Fig. 6). Granoblastic calcite crystals are less common and precipitated only in the large intragranular pore spaces in bone (Fig. 7), wood, and occasional larger intergranular pore spaces between clasts. Radial fibrous calcite cement is most common in samples from UQL-ISIS-I, UQL-ISIS-II, and UQL-ISIS-VII, but is less common at UQL-ISIS-III and UQL-ISIS-X. Fascicular-optic fibrous calcite was also observed in some thin sections, identifiable by extinction sweeping in the direction opposite to stage rotation (Fig. 6C, D). Fibers are approximately 200–300 μm long and 20–50 μm wide, and are attached to framework grains indiscriminately.

Mineralogical and Geochemical Analysis

XRD analyses indicate that the Isisford concretion and host-rock samples are dominated by quartz, with relatively less feldspar, and that calcite is typically in the form of magnesium calcite. No siderite or iron oxide responses of note (more than 5%) are observed. Semiquantitative calcite cement volumes in outcrop and concretionary samples calculated from XRD were $\sim 30\%$ (ranging from 12% to 76%; mean = 28.6%, $1\sigma = 0.1$, $n = 19$; the average is skewed by one extreme value). The mean calcite cement volume for concretions alone is 28.0%, and for outcrop, 31.3%. This aligns with the degree of compaction and estimated percentages of calcite seen in thin section (see “Petrographic Analysis” section).

Examination of thin sections under cathodoluminescence (CL) reveals that the electromagnetic spectrum of the calcite cement is orange ($\sim 585\text{--}650\text{ nm}$ wavelength; *sensu* Boggs and Krinsley 2006), with no obvious concentric or sectoral zonation (Fig.

8). The orange luminescence color confirms the presence of minimal Mn^{2+} activator ions and indicates that the cement is predominantly magnesian calcite with minimal manganese and ferroan calcite or siderite minimal to absent (see Boggs and Krinsley 2006; Hiatt and Pufahl 2014). However, minor areas of yellow luminescence ($\sim 575\text{--}585$ nm wavelength) can be seen around the margins of some grains, indicating calcite with a higher relative levels of Mn^{2+} activator ions than Fe^{2+} or Fe^{3+} (see Hiatt and Pufahl 2014).

SEM and EDS indicate a strong calcium response from areas containing cement, which confirms the initial analysis of the cement as calcite. These analyses also indicate the presence of silica- and aluminum-rich grains, which are consistent with the presence of quartz, plagioclase, and volcanolithic framework grains, respectively (Fig. 8D). Similarly, opaque minerals bordering osteons and fossil bone surfaces contain manganese and oxygen in some crystals, and iron in others. This suggests that a combination of reduction of Mn^{2+} and precipitation of a manganese oxide and precipitation of an iron-rich mineral (hematite) occurred prior to formation of magnesian calcite cement.

Stable-Isotope Analysis

The $\delta^{18}\text{O}_{\text{VPDB}}$ value of the calcite cement across all sites ranges from -12.25 to -4‰ (mean = -8.3‰ , $1\sigma = 2.66$, $n = 18$) and $\delta^{13}\text{C}_{\text{VPDB}}$ ranges from -5.3 to 4.1‰ (mean = -0.1‰ , $1\sigma = 2.67$, $n = 18$). A moderate positive linear correlation exists between $\delta^{18}\text{O}_{\text{VPDB}}$ and $\delta^{13}\text{C}_{\text{VPDB}}$ across all Isisford localities ($R^2 = 0.56$). There appears to be no correlation between the stable-isotope ratios against either the sample type (vertebrate-fossil-bearing concretions versus outcrop) or spatial distribution of the samples (see Fig. 9). For example, the range of $\delta^{18}\text{O}_{\text{VPDB}}$ for vertebrate-fossil-bearing concretions (-10.27‰ to -4.7‰) overlaps the $\delta^{18}\text{O}_{\text{VPDB}}$ range for both concretions with plant-fossil material (-11.4‰ to -5.48‰) and concretions with no visible fossil material (-12.25‰ to -7.08‰). Similarly, while UQL-ISIS-I, -III, and -IX are all located within several hundred meters of each other, the calcite stable-isotope signature ($\delta^{18}\text{O}_{\text{VPDB}}$ of -11.9‰ to -5.3‰ , and $\delta^{13}\text{C}_{\text{VPDB}}$ of -5.3‰ to 3.4‰) is not distinct from that of UQL-ISIS-II, -IV, -VII, and -X, located between 5 to 10 km away ($\delta^{18}\text{O}_{\text{VPDB}}$ of -12.3‰ to -4.7‰ , and $\delta^{13}\text{C}_{\text{VPDB}}$ of -4.9‰ to 4.1‰) (see Figs. 3, 9). The moderate negative correlation seen when grouping all data also remains when data are grouped separately by either sample type or sample locality; $\delta^{18}\text{O}_{\text{VPDB}}$ per sample type show moderate negative linear correlations with R^2 values of 0.60 for vertebrate-fossil-bearing concretions, 0.73 for plant-fossil-bearing concretions, and 0.75 for concretions with no visible fossils. See Table 1 for more details.

Core Facies Analysis

Organic-rich, fine-scale interlaminated and interbedded siltstones, silty sandstones, and fine-to very fine-grained sandstones are present in the GSQ Blackall 1 and GSQ Blackall 2 cores (see Fig. 10). Thin (1–2 cm thick) coal beds are interspersed throughout. Minor planar cross bedding was also observed. Although the Isisford outcrop and concretionary material at UQL-ISIS-II cannot be tied to a specific horizon in the GSQ Blackall 1 or GSQ Blackall 2 cores, they are most similar to what we identified as Facies 2 and 7. Facies 2 and 7 consist of very fine- to fine-grained sandstone, well sorted, subrounded, with minor siltstone laminations, mudstone clasts, and plant material (most often in the form of coal), and differ only in color (orange-yellow in Facies 2 versus

brown-gray in Facies 7) and structure (planar cross-bedding is seen in Facies 2 whereas planar lamination is more common in Facies 7). We identified the boundary between the Mackunda and Winton formations in these cores by a decrease in shell fragments and bioturbation up-hole, combined with the appearance of plant-fossil material in the form of thin (1–2 cm) coal beds. In GSQ Blackall 1 (~ 85 km east of Isisford) the contact between the Winton Formation and Mackunda Formation is at 28 m below ground level. However, in GSQ Blackall 2 (~ 40 km northwest of Isisford) this contact is at 130 m below ground level, and historical records for Isis Downs-1 (~ 20 km east of Isisford) show the contact at 205 m below ground level (ESSO Australia Pty Ltd. 1981). Normal faults running mostly north–south are commonly identified in the Cretaceous units of the Eromanga Basin (see Exon et al. 1976), so it is possible that the shallow contact between the Winton Formation and Mackunda Formation at GSQ Blackall 1 is related to regional faulting. It is not clear how close the Winton Formation outcrop at Isisford is to the contact with the underlying Mackunda Formation, although Tucker et al. (2013) suggest that it is likely that the contact is approximately 200 m below ground level.

DISCUSSION

Concretion Morphology and Calcite Cement Formation

The cement-supported nature of the spherical to oblate spherical Isisford concretions, and lack of grain contacts or suturing, indicate that calcite cement at Isisford precipitated syndepositionally. As early cement formation can limit compaction and preserve initial porosity (Pittman and Larese 1991; Mozley and Burns 1993; Raiswell and Fisher 2000), this shallow-burial calcite cement limited post-burial fossil deformation. We did not observe cone-in-cone structures or dewatering structures, which, if present, would have suggested deeper burial prior to cement precipitation. Concretions with early-forming cements may initially be poorly lithified and “plastic” but still rigid enough to withstand compaction, which can result in pervasive growth rather than concentric growth of the concretion (Pittman and Larese 1991; Mozley 1996; Raiswell and Fisher 2000). This plasticity may have led to the minor deformation of the juvenile *I. duncani* skull (UQL-ISIS-III-5a/b), while leaving the surrounding framework grains largely uncompacted. If the calcite cement had grown pervasively rather than concentrically, the Isisford concretions would potentially remain permeable and porous and therefore susceptible to changes in pore-water chemistry and resulting fluctuations in isotope signature. Concentric growth, however, would have been seen as calcite cement zonation under CL, which is not the case for the Isisford concretions.

Under CL, the calcite cement fluoresces bright yellow around grain boundaries, and is quenched to orange throughout the rest of the calcite crystals, with no pattern of zonation. Brightly fluorescing calcite cement is indicative of Mn^{2+} ions, with more Fe^{2+} and/or Fe^{3+} quenching fluorescence. Dissolved manganese (in the form of Mn^{2+}) is found in higher concentrations in fresh waters than in marine waters (Pfretzschner 2004), and in dysoxic to anoxic pore waters (Hiatt and Pufahl 2014). The presence of manganese calcite rather than ferroan calcite cement is also evidence for a shallow burial depth at the time of cement precipitation (Irwin et al. 1977; Curtis and Coleman 1986; Curtis et al. 1986; Middleton and Nelson 1996; Chan et al. 2000). The lack of cement zonation indicates that continuous precipitation of calcite cement at Isisford occurred in a subsurface regime. As such, we propose that the Mn^{2+} -rich calcite and Mn^{2+} -poor calcite

are authigenic and the concretions formed initially from an evolving fluid under manganese and iron reducing conditions, followed by a switch to oxidizing conditions. Depositional Environment Inferred from Oxygen and Carbon Stable Isotopes

As we propose that the calcite cement formed during early burial, we compared stable-isotope data to the shallow-burial end members shown in Figure 11 to determine the likely environment of formation of calcite cement. Shallow-burial end members used in comparison with our data were sourced from the following papers dealing with the isotopic composition of calcite cements in Cretaceous aged sandstones and concretions forming in freshwater, deltaic, estuarine, and shallow marine deposits (given the unknown stratigraphic position of the Winton Formation at Isisford in relation to the conformably underlying marine Mackunda Formation): Sass and Kolodny (1972), Longstaffe and Ayalon (1987), Carpenter et al. (1988), Gregory et al. (1989), Pirrie and Marshall (1991), Hendry et al. (1996), El Albani et al. (2001), McBride et al. (2003), McBride and Milliken (2006), Montaggioni (2009), and Nyman et al. (2014) (see Fig. 11).

The $\delta^{18}\text{O}_{\text{VPDB}}$ values for the Isisford calcite indicates a mixture of fresh and marine water in pore fluids, and closely aligns with the deltaic end member shown in Figure 11. We attribute the wide range of $\delta^{13}\text{C}_{\text{VPDB}}$ in the Isisford calcite cement (-5.3 to 4.1 ‰) to fluctuations between methanogenesis and sulfate reduction under anaerobic oxidizing conditions, and varying input of organic matter between aerobic and anaerobic zones. These fluctuations may also result from differing ratios of fresh and marine water in pore fluids. The moderate negative linear relationship between $\delta^{13}\text{C}_{\text{VPDB}}$ and $\delta^{18}\text{O}_{\text{VPDB}}$ seen in Figure 9 ($R^2 = 0.56$) may be indicative of this relationship: freshwater (more negative $\delta^{18}\text{O}_{\text{VPDB}}$) correlating with more positive $\delta^{13}\text{C}_{\text{VPDB}}$, indicative of methanogenesis, and marine water (more positive $\delta^{18}\text{O}_{\text{VPDB}}$) correlating with more negative $\delta^{13}\text{C}_{\text{VPDB}}$, indicative of sulfate reduction. This strongly suggests that the Isisford calcite-cemented concretions were formed in pore waters containing a mixture of marine and fresh water.

An approximate $\delta^{18}\text{O}_{\text{VSMOW}}$ value for Winton Formation pore waters at Isisford can be calculated from the calcite $\delta^{18}\text{O}_{\text{VPDB}}$ values, if either the water temperature or $\delta^{18}\text{O}_{\text{VSMOW}}$ of late Albian deltaic surface water can be quantified. The $\delta^{18}\text{O}_{\text{VSMOW}}$ of Gondwanan Cretaceous meteoric waters have been estimated at $\delta^{18}\text{O}_{\text{VSMOW}} -20$ ‰ (Gregory et al. 1989), and marine waters have been estimated as $\delta^{18}\text{O}_{\text{VSMOW}} -1$ ‰ (the estimate for Cretaceous marine water worldwide) with Eromanga Sea bottom waters relatively depleted in ^{18}O , ranging from $\delta^{18}\text{O}_{\text{VSMOW}}$ of 2.6 ‰ to -3.4 ‰ (Shackleton and Kennett 1975; De Lurio and Frakes 1999; Ferguson et al. 1999). Cool water temperatures have previously been estimated for the Eromanga Sea during the Early Cretaceous, with seasonal freezing conditions in the southern portion of the sea between latitudes 70° and 50° S proposed (Haig 1979; Gregory et al. 1989; Dettmann et al. 1992; Frakes et al. 1995; Frakes 1997). Although the presence of these seasonal freezing conditions are debated (Douglas and Williams 1982; Jell and Duncan 1986), there still appears to be a consensus on relatively cool water and air temperatures across eastern Australia during the Early Cretaceous between approximately 10 and 18°C for 54° south, the approximate location of Isisford during the late Albian (based on van Hinsbergen et al. 2015) (Stevens and Clayton 1971; Frakes 1997; Williamson 2006; Hay 2011; Price et al. 2012; Fletcher

et al. 2014). Given an approximate range of water temperatures between 10 and 18°C, the possible $\delta^{18}\text{O}_{\text{VSMOW}}$ values were calculated using (after O’Neil et al. 1969; Kim et al. 1997; and Leng et al. 2004):

$$T = 13.8 - 4.58 (\delta_c - \delta_w) + 0.08 (\delta_c - \delta_w)^2 \quad (1)$$

where T is temperature in degrees Celsius, δ_c is the calcite cement $\delta^{18}\text{O}_{\text{VPDB}}$ in ‰, and δ_w is the surface water $\delta^{18}\text{O}_{\text{VSMOW}}$ in ‰. From this, we determined that given a temperature range of 10–18°C, the $\delta^{18}\text{O}_{\text{VSMOW}}$ range for Isisford deltaic or estuarine surface waters had an approximate minimum of –9.13‰ and an approximate maximum of –7.39‰.

Because the Eromanga Sea was an epicontinental sea, we compared the results of this study with that of another Cretaceous epicontinental sea, the Western Interior Seaway (WIS) in North America (Longstaffe and Ayalon 1987; Carpenter et al. 1988; Coniglio et al. 2000; McBride et al. 2003; McBride and Milliken 2006; Nyman et al. 2014). A maximum $\delta^{18}\text{O}_{\text{VSMOW}}$ value of –2‰ for marine water in the WIS has been proposed, as the influx of freshwater into the WIS with $\delta^{18}\text{O}_{\text{VSMOW}}$ values of approximately –15‰ to –14‰ may have relatively depleted the proportion of ^{18}O (Coniglio et al. 2000). According to Carpenter et al. (1988), the mean oxygen isotope composition of calcite precipitating from open water in the eastern WIS during the Maastrichtian was $\delta^{18}\text{O}_{\text{VPDB}}$ –0.85‰ and $\delta^{13}\text{C}_{\text{VPDB}}$ –0.26‰. Even with this potential negative shift in epicontinental-sea $\delta^{18}\text{O}_{\text{VSMOW}}$ for the Eromanga Sea, the $\delta^{18}\text{O}_{\text{VPDB}}$ ratios detected in the Isisford calcite cement (ranging from –12.25 ‰ to –4 ‰) and calculated $\delta^{18}\text{O}_{\text{VSMOW}}$ ranging from –9.13‰ to –7.39‰ (for temperatures between 10 and 18°C), supports our hypothesis that a mixture of both marine and fresh water was present in the surface waters at Isisford such as would be seen in a deltaic or estuarine regime.

Depositional Environment Inferred from Core Lithology

Given the mixed marine and freshwater signatures detected in isotopic analysis, the heterolithic bedding (with repeated sandstone, silty sandstone, and siltstone packages) observed in the cores relatively close to Isisford suggest a paralic depositional environment with alternating energy levels as could be seen in a deltaic or estuarine setting (e.g., Galloway 1975; Willis et al. 1999; Bhattacharya et al. 2003; Weiguo et al. 2011). This lithology is similar to that observed in the underlying Mackunda Formation. It has long been recognized that the transition from the shallow marine Mackunda Formation to the terrestrial Winton Formation is difficult to distinguish using lithology and wire logging; decreasing marine invertebrate fossils and bioturbation coupled with increasing fossil terrestrial plant material, specifically the presence of the first clear coal bed, seems to provide a clearer indication of this contact (Exon and Senior 1976; Senior et al. 1978; Fielding 1992; Draper 2002). As the Mackunda Formation is recognized as a paralic or marginal marine unit deposited as the Eromanga Sea regressed, we propose that the Winton Formation at Isisford represents the continuation of the Eromanga Sea regression as this marginal marine setting became more terrestrially influenced. According to sedimentological analysis by Fielding (1992), “bedload/suspended load” and “flood-basin deposits” for the Winton Formation consist of very fine-grained lithic sandstones with ripple cross-lamination or flat lamination, and plant debris in the form of fossil wood fragments. A similar lithology is seen in outcrop and in the concretions at

Isisford, but with less common ripple cross lamination and more small- to medium-scale planar and parallel cross bedding, and some large-scale concave tabular cross-bedding.

Mud clasts, resembling rip-up clasts, are seen both in concretionary material and the GSQ Blackall 1 and GSQ Blackall 2 cores. Rip-up clasts typically result from coarser sediment flowing over muds or silts in higher-energy settings, “picking up” mud clasts and redepositing them in lower-energy floodplain settings. Fielding (1992) used the presence of siltstone clasts in the definition of a major channel facies in the Winton Formation. It is likely that the presence of mud rip-up clasts in the mixed marine–freshwater fine-grained sandstone at Isisford indicates an estuarine or deltaic-plain distributary-channel facies (*sensu* Fielding (1985)), where bedloads of fine-sand-size grains in suspension periodically washed over mud or silt deposits, picking up mud rip-up clasts, leading to fine sands deposited with mud clasts interspersed with lower-energy periods of silt deposition. Although this lithology is not specific to deltaic or estuarine environments, it does align with the interpretation of a deltaic or estuarine depositional setting garnered from the isotopic analysis.

Inferred Faunal Environmental Ranges

The presence of a mixed marine–freshwater environment at Isisford during the late Albian supports the hypothesized mid-Cretaceous northward regression of the epicontinental Eromanga Sea, with maximum flooding occurring during the early Albian and a regressive phase spanning from the late early to early late Albian through to the Cenomanian (Exon and Senior 1976; Frakes et al. 1987; Campbell and Haig 1999; Draper 2002). New dates for the lower Winton Formation at Isisford by Tucker et al. (2013) combined with the sedimentological and geochemical analysis in this paper indicate that the Eromanga Sea shoreline was close to the Isisford area during the late Albian (100.5–102.2 Ma). The presence of semi-aquatic eusuchian crocodyliforms (*Isisfordia duncani*) and small-bodied non-avian terrestrial dinosaurs and terrestrial plant material implies a connection to a terrestrial setting. However, fossils of *Cladocycclus geddesi* (an osteichthyan fish) fossils found at Isisford strongly support a connection to marine environments. *Cladocycclus* spp. are known from marginal marine, lacustrine, and lagoonal units from similarly aged Cretaceous deposits in South America (Martill 1993; Brito 2007) and Morocco (Martill et al. 2011). Members of this genus have been interpreted as predatory marine fishes with a tolerance for brackish water (juveniles are interpreted to have shoaled in relatively safer shallower brackish waters) (Brito 2007). The highly articulated and nearly complete preservation of *C. geddesi* (QM F44329) suggests autochthonous deposition and lack of transport (personal observation). This in turn suggests that this individual lived in the same environment as it was preserved (see Syme and Salisbury 2014). Given the depositional environment at Isisford likely represented a brackish-water lower delta plain or estuary, the preferred habitat of *C. geddesi* likely included brackish waters as well as the open marine waters of the Eromanga Sea.

Although typical freshwater vertebrate and invertebrate taxa (including lungfish, turtles, and bivalves) have been described from the exposed portions of the uppermost Winton Formation, they have yet to be recovered from the lower portion of the Winton Formation at Isisford, either in concretions or in outcrop. The absence of these animals from the Isisford assemblage may be further evidence of more brackish to marine water

conditions in a lower delta plain during the late Albian. However, it is also possible that the difference in faunal composition between Isisford and other Winton Formation fossil sites is either temporal (as the Isisford locality sediments were deposited 6 to 8 million years prior to the uppermost Winton Formation sediments) or due to taphonomic preservational bias.

CONCLUSION

Analysis of the Winton Formation concretions and outcrop at Isisford has provided a clearer understanding of the depositional environment in which crocodyliforms, osteichthyan fish, and non-avian dinosaurs were preserved. Petrographic analyses and the presence of undistorted vertebrate fossils indicate that sandstone concretions formed syndepositionally prior to compaction due to early diagenesis (the Diagenetic Stage, after Sellés-Martínez (1996)), close to or at the sediment–water interface, via precipitation of calcite cement. The calcite cement composition reflects the evolution of near-surface pore-water chemistry from relatively Mn^{2+} rich to relatively Mn^{2+} poor during manganese reduction. Minor iron reduction and sulfate reduction occurred prior to methanogenesis during further calcite precipitation as burial depth increased. Oxygen and carbon stable-isotope analysis indicates that calcite precipitated from brackish pore waters, associated with a mixing of marine and freshwater. The combination of brackish-water signatures along with heterolithic bedding and fossil terrestrial flora and fauna suggests that the lower portion of the Lower Cretaceous Winton Formation (upper Albian) was deposited under fluctuating energy levels in a mixed marine–freshwater setting, possibly fluvial channels in a delta or estuary, connected to the Eromanga Sea. Even with limited lithological data available at the site, we have demonstrated how isotopic analysis of concretionary cements has enhanced our interpretation of this Late Cretaceous environment.

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FIGURE CAPTIONS

FIG. 1.—Location of the Eromanga Basin (orange) in Australia, with an inset map showing the exposure of Cretaceous sedimentary units near Isisford in central-west

Queensland. The locations of core logs examined in this study are also shown: GSQ Blackall 1 (GCSQB1), GSQ Blackall 2 (GSQB2), and Isis-Downs 1 (ID1).

FIG. 2.—Stratigraphy of the Winton Formation in the Eromanga Basin, central-west Queensland, after Gray et al. (2002), Tucker et al. (2013), and Berrell et al. (2014). Concretions and fossil material from Isisford come from the lower part of the Winton Formation, and are upper Albian in age. Core logs from GSQ Blackall 1 (GCSQB1), GSQ Blackall 2 (GSQB2), and Isis-Downs 1 (ID1) are also shown.

FIG. 3.—Location of sample sites at Isisford relative to each other. Geographical features have not been included. Lower Cretaceous (upper Albian) outcrop and *ex-situ* concretion locations are shown in light green with pale yellow indicating location of Cenozoic smectitic alluvium (“blacksoil”) and Quaternary alluvium. The site names are abbreviated as “UQL-ISIS.” The sites examined in this study are UQL-ISIS-I, UQL-ISIS-II, UQL-ISIS-III, UQL-ISIS-IV, UQL-ISIS-VII, UQL-ISIS-IX, and UQL-ISIS-X.

FIG. 4.—Concretions from the Isisford locality. **A)** UQL-ISIS-I oblate and prolate spherical concretions both approximately 70 cm in diameter. **B)** UQL-ISIS-IX-2 which contained the paratype skull of *Isisfordia duncani* (QM F44320), approximately 30 cm in diameter. **C)** UQL-ISIS II-4 spherical and heavily weathered concretion with fossil wood. Scale bar is 30 cm. **D)** UQL-ISIS-II-3 showing sinuous morphology. Scale bar is 40 cm. **E)** UQL-ISIS-VII-1 concretion with mud clasts and fossil wood. Scale bar is 10 cm. **F)** Holotype of *Isisfordia duncani* (QM F36211), preserved in and prepared from a fractured oblate spherical concretion from UQL-ISIS-I-3.

FIG. 5.—Photomicrographs in PPL and XPL of Isisford thin sections. **A)** PPL micrograph showing junction between cloudy micritic calcite cement (bottom left arrow) and stained calcite cement (top right arrow), from UQL-ISIS-I-12 (1-9). **B)** XPL micrograph of same area shown in Part A with junction marked by dashed white line. **C)** PPL micrograph of colorless calcite cement (one portion indicated by arrow) also from UQL-ISIS-I-12 (1-9). **D)** XPL micrograph of same area as shown in Part C.

FIG. 6.—Photomicrographs in PPL and XPL of thin sections of UQL-ISIS-III-29B. Note that extinction sweeps in direction opposite to stage rotation. **A)** Fascicular-optic fibrous calcite cement in PPL. Arrow points to a calcite crystal. **B)** Calcite cement in XPL, with box marking calcite crystal with sweeping extinction. **C)** Close-up of box from Part B, in XPL, with arrow pointing toward calcite crystal showing sweeping extinction. **D)** The same area in XPL with stage rotated 25 degrees counterclockwise. Extinction moves in a clockwise direction as marked by the black arrow, indicative of fascicular optic calcite.

FIG. 7.—Photomicrographs in PPL of thin sections (30 μ m). **A)** PPL, non-avian dinosaur bone showing apatite (a) and calcite (c) crystals, and the bone (b) with an opaque mineral rim preliminarily identified as hematite or a manganese oxide (d) within osteons, from UQL-ISIS-III-29A. Note that calcite cement did not completely fill osteons. **B)** XPL, non-avian dinosaur bone from Part A. **C)** Enlarged view of non-avian dinosaur bone with manganese oxide rim (d) and calcite crystals (c) in osteons. Hematite or manganese oxide cement precipitated within the surrounding osteocytes (e) of the interstitial lamellae. From UQL-ISIS-III-29A. **D)** Hematite or manganese oxide crystals (d) in the osteons of non-avian dinosaur bone (b) from UQL-ISIS-X-G5-25-1.

FIG. 8.—Images of UQL-ISIS-I-145. **A)** PPL. **B)** XPL. **C)** Cathodoluminescence, with orange fluorescence ($\sim$ 585–650 nm) indicating calcite cement with no zonation. Note the

relatively small yellow fluorescence ($\sim 575\text{--}585\text{ nm}$) indicating the presence of a higher proportion of Mn^{2+} activator ions, indicating evolution of fluid composition during early burial and cementation. **D**) EDX image confirms the presence of calcium (blue) in cement, with grains containing silica (yellow) and aluminum (purple). The same area of Mn^{2+} activator ions fluorescing yellow under CL appears blue under EDX, confirming that it is calcite cement with more Mn^{2+} ions.

FIG. 9.—Scatterplot of $\delta^{13}\text{C}_{\text{VPDB}}$ versus $\delta^{18}\text{O}_{\text{VPDB}}$ for all Isisford samples grouped by sample type. There is a moderate negative linear correlation between $\delta^{13}\text{C}_{\text{VPDB}}$ and $\delta^{18}\text{O}_{\text{VPDB}}$ ($y = -0.7514x - 6.369$, $R^2 = 0.56$).

FIG. 10.—Lithological logs and facies analysis of GSQ Blackall 1 and GSQ Blackall 2 core. Core localities are shown in Figure 1, and simplified logs are shown in Figure 2. Facies 1: very fine grained orange-yellow sandstone (SS) interbedded with siltstone (SL), 1–3 mm laminations, SS is well rounded, well sorted, grain supported, friable, with mudstone (MS) clasts. Facies 2: fine grained orange-grey-yellow SS with SL laminations and SL/MS clasts, some planar cross bedding. Facies 3: dark grey MS, minor plant fossils. Facies 4: very fine to fine grained grey-brown SS with some SL laminations, subrounded, well sorted, grain supported, friable, with carbonaceous material (coal), plant fossils, and MS/SL clasts, similar to Facies 2. Facies 5: fine grained grey-brown SS with red MS laminations. Facies 6: very fine to fine grained grey SS with SL laminations, well sorted, subrounded-rounded, grain supported, with some planar cross bedding, MS/SL clasts, carbonaceous material (coal), minor bioturbation, and plant fossils, similar to Facies 1. Facies 7: very fine to fine grained grey-brown SS with some SL laminations, subrounded, well sorted, grain supported, friable, with some carbonaceous material (coal), and some MS/SL clasts. Similar to Facies 4. Facies 8: yellow-white MS, with rootlets. Similar to Facies 3. Facies 9: fine grained grey sandy SL, subrounded, moderately sorted, grain supported, with plant fossils and bioturbation. Facies 10: grey SL, minor bioturbation. Facies 11: dark grey-grey MS, some SS laminations.

FIG. 11.—Plot of $\delta^{13}\text{C}_{\text{VPDB}}$ versus $\delta^{18}\text{O}_{\text{VPDB}}$ in calcite cements from both sandstone concretions and nonconcretionary sandstones (in purple), plotted against typical isotopic values recorded for various environments by El Albani et al. (2001)¹, Gregory et al. (1989)², Hendry et al. (1996)³, Longstaffe and Ayalon (1987)⁴, McBride and Milliken (2006)⁵, Pirrie and Marshall (1991)⁶, and Sass and Kolodny (1972)⁷, and modified from figures in Carpenter et al. (1988)⁸, Coniglio et al. (2000)⁹, McBride et al. (2003)¹⁰, Montaggioni (2009)¹¹, and Nyman et al. (2014)¹². All values come from calcite cement interpreted as precipitated during shallow burial. The Isisford cement values overlap the “Fluvial,” “Deltaic,” “Tidal deltaic,” “Fluvial–deltaic–near-shore marine,” and “Near-shore, shallow marine” end members.

- Kw Winton Formation
- Klm Mackunda Formation
- Kla Allaru Mudstone
- Klo Toolebuc Formation
- Klu Wallumbilla Formation

UQL-ISIS-IV ●

UQL-ISIS-VII ●

● UQL-ISIS-X

● UQL-ISIS-III

● UQL-ISIS-I

● UQL-ISIS-II

UQL-ISIS-IX

5 km

Table 1.—Lithological and geochemical properties of all concretionary and host-rock sandstone samples collected from Isisford between the mid-1990s and 2012. Samples are arranged by sample site name (ISIS-I, ISIS-II, ISIS-III, ISIS-IV, ISIS-VII, ISIS-IX, and ISIS X), with characteristics including sample type, morphology of concretion (where applicable), calcite-cement stable isotopes of $\delta^{13}\text{C}_{\text{VPDB}}$ and $\delta^{18}\text{O}_{\text{VPDB}}$, and proportions of calcite cement measured using Fiji image analysis, and XRD. As the concretions are not *in situ*, the orientation of major and minor axis could not be determined, and therefore spheroid concretions are denoted as potentially oblate or prolate.

Sample name	Sample type and morphology	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰)	$\delta^{18}\text{O}_{\text{VPDB}}$ (‰)	Cement % (Fiji)*	Cement % (XRD)
UQL-ISIS-I 12 (1-19)	Oblate or prolate spheroid concretion, fossil wood	1.0	−10.13	35.6	31.1
UQL-ISIS-I 45 (2-2)	Oblate or prolate spheroid concretion, no visible fossil	−0.6	−8.02	42.9	20.7
UQL-ISIS-I 54 (13)	Indeterminate (fragment) concretion, fossil wood	0.1	−7.39	63.9	76.2
UQL-ISIS-I 101	Indeterminate (fragment) concretion, no visible fossil	3.4	−11.91	30.0	27.8
QM F44192	Oblate or prolate spheroid concretion, vertebrate fossil	−0.7	−6.55	28.8	26.8
UQL-ISIS-I averages		0.6	−8.8	40.2	36.5
UQL-ISIS-II 103-1 (A)	Non-concretion outcrop	0.2	−11.04	35.6	41.3
UQL-ISIS-II 103-1 (B)	Non-concretion outcrop	0.4	−12.08	-	39.5
UQL-ISIS-II 104	Oblate or prolate spheroid concretion, fossil wood	−3.6	−5.82	33.7	34
UQL-ISIS-II averages		−1.0	−9.6	34.7	38.3
UQL-ISIS-III 10	Spherical concretion, fossil wood	−0.4	−5.48	-	27.8
UQL-ISIS-III 23	Oblate or prolate spheroid concretion, vertebrate fossil	−1.5	−5.30	34.2	29.2
UQL-ISIS-III 29 (A)	Spherical concretion, vertebrate fossil	−0.2	−8.00	37.1	12.2**
UQL-ISIS-III 29 (F)	Spherical concretion, vertebrate fossil	−0.2	−6.50	24.9	21.2
UQL-ISIS-III averages		−0.6	−6.3	32.1	22.6
UQL-ISIS-IV 3	Spherical concretion, no visible fossil	3.5	−12.25	20.8	16.7
UQL-ISIS-IV averages		3.5	−12.3	20.8	16.7
UQL-ISIS-VII 2 (1)	Oblate or prolate spheroid concretion, fossil wood	4.1	−11.40	32.9	18.8
UQL-ISIS-VII 5	Spherical concretion, no visible fossil	−4.9	−7.08	-	26.2
UQL-ISIS-VII averages		−0.4	−9.2	32.9	22.5
UQL-ISIS-IX 2	Spherical concretion, vertebrate fossil	−5.3	−5.4	31.2	28.4
UQL-ISIS-IX averages		−5.3	−5.4	31.2	28.4
UQL-ISIS-X 15	Oblate or prolate spheroid concretion, vertebrate fossil	3.2	−10.27	23.2	16.4
UQL-ISIS-X F4-51	Oblate or prolate spheroid concretion, vertebrate fossil	−1.0	−4.70	36.7	23.3
UQL-ISIS-X averages		1.1	−7.5	30.0	19.9

* “-” denotes that slide was not available for Fiji image analysis.

** ISIS III 29A sample analyzed for XRD contained fossilized bone, hence the calculated calcite percentage is lower than seen in the Fiji image analysis.