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Wood growth indices as climate indicators from the Upper Cretaceous (Cenomanian–Turonian) portion of the Winton Formation, Australia

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ABSTRACT

Although the mid- to Late Cretaceous is regarded as a global warm period, increasingly a more complex picture of warming and cooling is emerging. New techniques allow more precise dating of terrestrial localities, opening opportunities for using climate proxy approaches on terrestrial fauna and flora to better capture the complexity of Cretaceous climate. Here an attempt is made to understand the seasonality and inter-annual variability of two newly dated localities from the upper preserved portion (Cenomanian–Turonian) of the Winton Formation, Australia. Primarily quantitative approaches to palaeodendrology are used. The results suggest both seasonality and high variability in climate conditions that affect growth between years, including evidence for floods. The longest series (QM F44338) suggests oscillatory patterns of good and poor growth in a 15 year alternating cycle similar to the contemporary Pacific Decadal Oscillation, although other potential explanations should be considered and tested.

1. Introduction

The mid-Cretaceous is often regarded as the warmest period in Earth's history, reaching the Cretaceous Thermal Maximum in the Turonian (89.8–93.9 million years ago; Wilson et al., 2002), although increasingly evidence suggests a much more complex picture with cool events throughout the mid to Late Cretaceous (Veizer et al., 2000; Weissert and Erba, 2004: Haworth et al., 2005). The climatic changes at this time are also associated with the Cenomanian-Turonian Boundary Event or Bonarelli Event (91.5 ± 8.6 million years ago; Selby et al., 2009), which caused significant marine extinctions (Cetean et al., 2008). Although some quantitative studies of the palaeoclimate from terrestrial localities of this period have been conducted (Parrish et al., 1998; Tarduno et al., 1998; Falcon-Lang and Cantrill, 2001; Haworth et al., 2005; Miller et al., 2006), and other qualitative observations of mid to Late Cretaceous greenhouse conditions have been made (Cantrill, 1995), terrestrial localities that fall in this Cretaceous 'quiet zone' are often poorly dated as magnetostratigraphy cannot be used (Tucker et al., 2013), and thus unsuitable for uncovering the finer temporal scale needed to understand the climate of the mid to Late Cretaceous.

The Winton Formation is a terrestrial deposit, which has recently been the subject of improved dating techniques using U–Pb isotope dating of detrital zircons by laser ablation (Tucker et al., 2013). This study has been able to constrain the ages of the fossiliferous sediments of the upper-most exposed portions of the Winton Formation to close to the Cenomanian-Turonian boundary. Foliar physiognomic methods and bioclimatic analysis on both museum collections and new collections from within the Lark Quarry Conservation Area (approximately −23′ 01S, 142′40E, 95 km south-west of Winton, central-western Queensland, Australia), suggest mean annual temperatures (MAT) of ~15 °C from climate leaf-analysis multivariate programme (CLAMP), and ~16 °C from bioclimatic analysis and leaf margin analysis, whilst annual rainfall was likely between 1300 and 1600 mm as estimated from CLAMP, bioclimatic analysis and leaf area analysis (Fletcher et al., 2013, 2014b).

The described fauna of the Winton Formation are consistent with the climate estimates derived from the flora. The basal eusuchian crocodyliform, *Isisfordia duncani* (Salisbury et al., 2006), suggests a MAT over 16 °C if eusuchians are accepted as palaeothermometers (as proposed by Markwick, 1994, 1998). In addition, even cold-adapted modern freshwater turtles require warmest mean monthly temperatures over 17.5 °C (Tarduno et al., 1998), thus the presence of fresh water turtles in the Winton Formation (Molnar, 1991; Salisbury et al., 2006) supports the flora-derived climate estimates above, in that they confirm that the palaeoenvironment of the upper portion of the Winton Formation was warm. Finally, the presence of traces from probable oribatid mites (Fletcher and Salisbury, 2014) may suggest a moist environment (Kellogg and Taylor, 2004) consistent with the rainfall estimates above, although only moist microhabitats are required and the absence of more 'dry-loving' species so far recorded is not evidence of their absence in the fauna. However, the geology of the upper portion of

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the Winton Formation has been interpreted as a freshwater, broad fluvial–lacustrine environment (Exon and Senior, 1976; Tucker et al., 2013) and thus a xeric environment is highly unlikely, even if precipitation was not considered to be local. Although these proxies are able to estimate the averages and minima of the temperature and likely precipitation, they do not indicate how much variability there was in climate between years.

Fossilized wood is commonly preserved from the Devonian onwards, and under the right preservational conditions, allows for detailed examination on the cellular scale (Creber and Chaloner, 1984). In addition, growth rings provide information on intra-annular seasonality and inter-annular variability, and lend themselves to quantitative analysis and comparison to modern flora (Creber and Chaloner, 1984; Francis, 1984; Chaloner and Creber, 1988; Falcon-Lang, 2000a,b).

Silicified wood is rarely found in situ across the Eromanga Basin, but does occur on the surface where the Winton Formation is exposed or partly overlain unconformably by Cenozoic alluvia. Because the wood is indurated compared with the surrounding sediment, even where that sediment has been lithified (pers. obs), and because the Winton Formation is the youngest Cretaceous strata of the Eromanga Basin (Gray et al., 2002), much of this wood is considered to be derived from portions of the Winton Formation that have previously eroded.

The wood sampled for this study is largely comprised of this surface material and has been identified as *Protophyllocladoxylon owensii* Fletcher et al., with likely affinities to modern Podocarpaceae (Fletcher et al., 2014a). In addition to the reasoning above, the material for this study is considered to be autochthonous or para-autochthonous, because the sediments they are associated with are fine clays, dolostones and siltstones (Dettmann et al., 2009) suggesting a low energy depositional environment which is unlikely to have uprooted and transported root and stump material. The low diversity of wood species matches the low diversity of pollen species at site QM L311, whereas other plant macrofossil sites in the upper portion of the Winton Formation are more diverse (e.g. Mcloughlin et al., 1995, 2010) and the pollen type and wood type found at QM L311 are both considered associated with the Podocarpaceae (Dettmann et al., 2009; Fletcher et al., 2014a). The pollen and three dimensionally-preserved macrofossils at this site are very complete, thus it is suggested that they were not transported any great distance. Finally, because the wood is silicified similarly to the preservation of the other macrofossil materials found at QM L311, it is likely that the material was at least buried at approximately the same time as the other plant material, which Dettmann et al. (2009) suggest was replaced with silica early in preservation, during or soon after burial.

To determine the intra-annular seasonality, and inter-annular variability of the climate of the Winton Formation, this paper focuses on quantitative methods analysing aspects of the growth rings of *P. owensii*.

1.1. Geological setting

The Winton Formation is the sediment infilling of the Eromanga Basin and contains rich fossil assemblages in the upper, Cenomanian–Turonian portion. At the time the upper portion of the Winton Formation was deposited, central-western Queensland would have been at approximately 50°S (Li and Powell, 2001). The formation consists of complex and repetitive sediments, including fine- to medium-grained feldspatholithic or lithofeldspathic arenites, siltstones, mudstones and claystones (Fielding, 1992; Romilio and Salisbury, 2011; Romilio et al., 2013; Tucker et al., 2013), with very minor coal seams (Senior et al., 1978), which has been interpreted as a freshwater, broad fluvial–lacustrine environment deposited on an extensive coastal plain as the epicontinental Eromanga Sea withdrew (Exon and Senior, 1976; Tucker et al., 2013).

The Winton Formation crops out over an area from north-western New South Wales, to north-eastern South Australia and throughout central-western Queensland (Fig. 1; Gray et al., 2002). Outcrops of this formation are scattered due to deep weathering and overlaying alluvium. Trenches excavated at the fossiliferous sites from this study, namely Queensland Museum (QM) Locality QM L311 and University of Queensland localities within Bladensburg National Park, suggest that the facies below the surface are a good match (Tucker et al., 2013).

2. Materials and methods

2.1. Preparation

Preparation of the specimens was by conventional rock thin section, ground to varying thicknesses to account for the unique preservational characteristics of each specimen, averaging ~70 μm. The sections were oriented in transverse, radial longitudinal and tangential longitudinal planes. These sections were examined under a Nikon eclipse 50ipol and captured using a Nikon DS-Fi1. Overlapping images of the transverse sections were then stitched together manually using Adobe Photoshop, and measured using ImageJ (Rasband, 1997–2008, version 1.48i). The material described here is accessioned to the Queensland Museum collections (QM), Queensland, Australia.

2.2. Analysis

It is usually considered that only wood from some parts of the tree (trunk and stump but not branch and root) is useful for palaeoclimatic analysis due to the properties of the wood in different parts of the tree (Chapman, 1994; Falcon-Lang, 2005; Schweingruber, 2007), and as it is the stem or trunk that is generally sampled and studied in dendrology (Fritts, 1976; Vincent et al., 2007; Fowler, 2008; Heinrich et al., 2009; Mundo et al., 2012), identification of the likely origin of the wood from within the tree was completed using the characteristics described in Chapman (1994), however, in part because identification of the origin of the wood from Chapman's (1994) characteristics is not certain, we conducted the analysis on all materials and took the likely position of the wood into consideration when interpreting the results, rather than discarding the other materials.

None of the samples were able to meet the ideal prerequisites suggested by Poole and van Bergen (2006) for pre-Quaternary material, such as having a complete cross-section of the organ or having a taxonomically diverse assemblage. However we were able to identify the taxon of all materials used and can thus estimate leaf longevity/retention times from the nearest living relatives, as per Falcon-Lang (1999). We also consider that none of the trunk or stump material is likely to be from juvenile trees primarily due to the shape of the rings in the portions preserved, which lack the curvature that would indicate its position near the core of the tree, but also because there is not a particularly high proportion of early wood and because of the narrow average widths (Creber and Chaloner, 1984).

The quantitative methods and observations of characters used here have all been used previously in palaeodendrology. The presence or absence of rings was recorded as a broad indicator of seasonality (Creber, 1977; Brison et al., 2001). The number of rings indicates the sample size of usable rings for our study, and the relative magnitude or number of tracheids per ring may indicate generally favourable or unfavourable conditions. Average ring width is also regarded as a general indicator of favorability (Fritts, 1976), but is dependent on position in the tree and age (Chapman, 1994), as well as tree architecture (Briffa et al., 1996), and thus must be interpreted with these characteristics in mind. We recorded the absence (scored as 0), presence (1), or high frequency (2) of crush zones in early wood. These sections showed no evidence of fungal hyphae or other evidence of attack, but the few cells within these sections preserved such that they could be measured were unusually large. As such we have interpreted the crush zones as sections of very large, thin-walled early wood cells indicative of very fast growth, without which may skew interpretation towards rings from poorer growth years (Fig. 2). Frost rings, which are usually found