U–Pb zircon age of the Walloon Coal Measures in the Surat Basin, southeast Queensland: implications for paleogeography and basin subsidence

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The Jurassic Walloon Coal Measures of the Surat Basin were previously estimated to be of Middle Jurassic age, ranging from Aalenian to Callovian, based on an uncalibrated eastern Australian biostratigraphic framework. New U–Pb dates of 162.55 ± 0.05 Ma and 158.86 ± 0.04 Ma obtained from zircons in ash-fall volcanic tuffs now place the Walloon Coal Measures of the Surat Basin in the Upper Jurassic Oxfordian. The new dates have several implications for the interpretation of the Jurassic strata in the Surat Basin. First-order subsidence rates of 61 m/Myr for the Walloon Coal Measures are more akin to those of foreland basins than the previously assumed intracratonic setting. The dates also imply deposition of the Walloon coals in substantially higher latitudes than previously assumed and that they accumulated as peats in mires that experienced more than three months’ continual darkness each winter. Zircon dating of tuffs and associated geochemistry should assist with the correlation of the laterally impersistent coals, fluvial sandstone and mudstone of the Walloon Coal Measures, which are currently difficult to correlate over distances of more than a few kilometres. Dating of the palynostratigraphic zones APJ4.2 to APJ5 (Aequitriradites norrisii Association Zone to Murospora florida Association Zone) will also need to be recalibrated.

KEY WORDS: U–Pb zircon dating, Surat Basin, Walloon Coal Measures, Walloon Subgroup, basin subsidence, Oxfordian, biostratigraphy, paleogeography.

INTRODUCTION

The Walloon Coal Measures (also formally known as the Walloon Subgroup) of the Surat Basin in southeast Queensland and northeast New South Wales contain the majority of Australia’s coal seam gas (CSG) resources, accounting for 64% of the continent’s proven and probable (2P) estimates (Hamilton et al. 2014a). Several studies have provided insight into the geological evolution and characteristics of the Surat Basin in light of recent CSG exploration including studies of the stratigraphy and sedimentology (Ryan et al. 2012; Martin et al. 2013; Hamilton et al. 2014b), coal petrology (Scott et al. 2007), palynology (McKellar 1998), and regional stress regimes (Baker & Skerman 2006). Despite these studies, there remains considerable uncertainty on the basic stratigraphic framework for the Surat Basin owing to the geological heterogeneity of the strata and the thin, discontinuous nature of the coal seams and sandstones. This is evident from several attempts to define and redefine the lithostratigraphic units of the Walloon Coal Measures (Cameron 1970; Scott et al. 2004; Scott 2008; Hamilton et al. 2014b). Consequently, there are numerous inconsistencies in the understanding of the formation and the basin in the literature (Martin et al. 2013; Hamilton et al. 2014b).

The primary method of age determination for the Walloon Coal Measures has been using biostratigraphy within an Australian framework constructed on spore–pollen zones that have not been previously calibrated against the international geological time-scale by isotopic dating of associated tuffs (Price 1997; McKellar 1998; Jell 2013). The age ascribed to the Walloon Coal Measures, both in the Surat and in the neighbouring Clarence-Moreton Basin to the east, varies from Aalenian to Callovian (Gleadow 1990; Burger 1994; Jell 2013), with the consensus being late Bathonian to Callovian (Exon & Burger 1981; Wells & O’Brien 1994; Price 1997; McKellar 1998; Jell 2013). This is a wide range in absolute time from 174.1 Ma to 163.5 Ma (Cohen et al. 2013, updated). The use of biostratigraphy has been limited because of the wide age range of spore–pollen taxa, with zonal index species being rare or even absent (Martin et al. 2013). This paper presents new age dates acquired by U–Pb chemical abrasion isotope dilution thermal ionisation mass spectrometry (CA-TIMS) of zircons obtained from tuff layers within coals of the Walloon Coal Measures. These ash fall tuffs have

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been chosen for dating, as, once deposited on a mire, such tufts remain in situ through to diageneosis (Triplehorn & Bohor 1986). The dating of the numerous, widely distributed tuff beds, offers promise of a new understanding of the stratigraphy and event history of the basin.

GEOLOGICAL SETTING

The Surat Basin is widely regarded as an intracratonic basin with marine and non-marine strata (Green et al. 1997a; Martin et al. 2013) covering over 300 000 km² of southeast Queensland and northeast NSW (Goscombe & Coxhead 1995). It overlies the Permo-Triassic Bowen and Gunnedah basins and forms part of the Great Australian Superbasin (Goscombe & Coxhead 1995; Jell 2013). The Walloon Coal Measures crop out in an arcuate belt between the towns of Morven and Dalby in the north of the basin and are widespread in the subsurface, gently dipping to the southwest (Hamilton et al. 2014b). Structures in the Surat Basin include the Mimos Syncline, the Burunga Fault and the St George-Bollon Slope, which are expressions of structures in the underlying Bowen Basin (Scott 2008; Ryan et al. 2012). The Kogan Nose and the Undulla Nose likely were structurally active during the deposition of the Walloon Coal Measures and further tightened owing to reactivation of basement structures in the Late Cretaceous to Cenozoic (Hamilton et al. 2014b). Tectonic activity during the deposition of the Surat Basin, however, remains poorly understood (Hamilton et al. 2014b). The Central West Fold Belt and the New England Fold Belt bound the basin to the south. The Clarence-Moreton Basin and New England Orogen lie to the east with the Kumbarilla Ridge (or Gatton Arch) marking the boundary between the Clarence-Moreton and Surat Basins (Goscombe & Coxhead 1995; Holcombe et al. 1997; Pinder 2004). The basin passes into the Eromanga Basin to the west across the Nebe Ridge and Cunnamulla Shelf (Goscombe & Coxhead 1995; Jell 2013).

The Surat Basin originated in the Rhaetian (latest Triassic) after a period of folding, uplift and penepalana-tion across eastern Australia (Jell 2013). Accommodation space in the Surat Basin is interpreted to have been created by two episodes of thermal relaxation and a period of lithospheric flexure through the Jurassic and into the Cretaceous, allowing 1800 m of strata to be deposited (Exon 1976; Goscombe & Coxhead 1995; Green et al. 1997a; Korsch & Totterdell 2009). Controls on the rate of subsidence in the Surat Basin remain enigmatic with multiple interpretations ranging from rifting, to thermal sag after the cessation of volcanic-arc activity, to viscous corner flow in the mantle wedge above a subducting plate (Korsch et al. 1989; McKellar 2004; Hoffmann et al. 2009; Korsch & Totterdell 2009). Six sedimentary cycles, consisting of a series of fining-upward cycles, have been recognised in the Surat Basin (Exon & Burger 1981). Each cycle consists of an upward succession of strata deposited by (a) braided streams, (b) meandering streams and (c) swamps, lakes, deltas and shallow seas (Exon 1976; Exon & Burger 1981; Jell 2013). These cycles were interpreted by Exon & Burger (1981) to be created by changes in base level driven by eustatic sea-level change. The Walloon Coal Measures form the upper part of the second sedimentary cycle of Exon & Burger (1981), with deposition in swamp, lacustrine and fluvial environments (Ryan et al. 2012; Martin et al. 2013; Hamilton et al. 2014b). Volcanism was pervasive during the deposition of the Walloon Coal Measures and overlying formations; whether this was intrabasinal or extrabasinal remains a topic of debate (Yago 1996a; Boult et al. 1998; Turner et al. 2009). Sedimentation continued in a similar fashion until the Early Cretaceous when eustatic sea-level fluctuations allowed for marine incursions into the basin with the deposition of marine and paralic formations (Jell 2013). Basin inversion in the middle to late Cretaceous led to the erosion of ~2 km of strata resulting from rebound of the lithosphere after the cessation of subduction off the east coast of Australia (Hoffmann et al. 2009; Waschbusch et al. 2009). Subsequently the Surat Basin has been relatively quiescent, except for some minor post-Mesozoic adjustment of faults (Scott 2008).

STRATIGRAPHY

The Walloon Coal Measures, the formal lithostrati-graphic name currently for the stratigraphic unit recognised by Geoscience Australia (2014) and the Geological Survey of Queensland (Jell 2013), was first referenced by Bryan (1944) with the official type section described by Cameron (1970). A basic outline of Jurassic lithostratigraphic units of the Surat Basin is shown in Figure 1. The Walloon Coal Measures are regionally extensive, thin to the west and 350–450 m thick (Goscombe & Coxhead 1995; Jell 2013). The formation forms the lower part of the coal-bearing Injune Creek Group, underlain conformably by the Hutton Sandstone or Eurombah Formation and overlain unconformably by the Springbok Sandstone, also part of the Injune Creek Group (Exon 1966). The Springbok Sandstone unconformably overlies the Walloon Coal Measures, with incision being greater in the eastern part of the basin (Hamilton et al. 2014b). However, the length of time represented by this hiatus in sedimentation is not known. The Walloon Coal Measures incorporates four members: Taroom Coal Measures, Tangalooma Sandstone, the Maclean Sandstone Member (found only in NSW) and Taroom Coal Measures (Geoscience Australia 2014). Although the Walloon Coal Measures are formally ranked as a formation (Geoscience Australia 2014), a number of workers informally assign the Walloons subgroup status including the transitional Durabilla/Eurombah Formation between the underlying Hutton Sandstone and the overlying Taroom Coal Measures (Jones & Patrick 1981; Scott et al. 2004; Hamilton et al. 2014b). The definition of the Walloon Coal Measures has been revised several times since the unit was first recognised as the Walloon beds by Cameron (1907), in his effort to describe the Mesozoic succession in the Walloon-Rosewood Coalfield, to the west of Ipswich (Queensland). It was further described by Jensen (1921) as the Calcareous (or Lower) Walloon and as part of the Injune Creek Beds by Reeves (1947) before being designated as the Walloon Coal Measures by Whitehouse (1954) during hydrological investigation in
the Great Artesian Basin. After petroleum discoveries in the Surat Basin, numerous attempts have been made to divide and amalgamate coal-bearing units of the Injune Creek Group and the Walloon Coal Measures (Scott et al. 2004; Scott 2008). Debate continues on the stratigraphic status of the Walloon Coal Measures (vs the Walloon Subgroup terminology; Jell 2013) owing to the localised occurrence of the members in the Surat Basin and the recognition and geological separation of the Eurombah and Durabilla formations (lability, coal-content and porosity contrasts) from both the Walloon Coal Measures and the Hutton Sandstone (Swarbrick et al. 1973; Green et al. 1997a; Scott et al. 2004; Scott 2008). More recent work by Hamilton et al. (2014b) has broken down the Walloon Coal Measures (Subgroup) further in an informal fashion by incorporating less extensive, erosionally truncated units including the lower Juandah Coal Measures and the Hutton Sandstone (Swarbrick et al. 1973; Green et al. 1997a; Scott et al. 2004; Scott 2008). More recent work by Hamilton et al. (2014b) has broken down the Walloon Coal Measures (Subgroup) further in an informal fashion by incorporating less extensive, erosionally truncated units including the lower Juandah Coal Measures and the Hutton Sandstone or Wambo sandstone, and the upper Juandah Coal Measures. The Durabilla Formation is amalgamated with the Eurombah Formation owing to difficulties differentiating between the two using wireline responses (Hamilton et al. 2014b). Importantly, the lateral stratigraphic relationships of subunits of the Walloon Coal Measures in the Surat Basin with the incomplete section of the formation in the Clarence-Moretton Basin by Cameron (1970) (where the type section of the formation has been formally defined) remains unknown. Comprehension of these relationships is integral to resolution of the present nomenclatural debacle.

No attempt has been made to collate the diverse coal-bed nomenclature associated with the Walloon Coal Measures, with coal-bed names varying between exploration companies, mines and geographic districts (Scott 2008). Current lithostratigraphic and coal-bed lithostratigraphic frameworks are discredited, as other correlation methods change the interpretation of depositional-basin architecture (Martin et al. 2013).

The Walloon Coal Measures in the Surat Basin were considered to have been Middle Jurassic and no younger than Callovian, using spore–pollen biostratigraphy (Price 1997; McKellar 1998; Geoscience Australia 2014), with some estimates of the formation, in the Clarence-Moretton Basin, to the east, being as old as Aalenian (Burger 1994). The previously estimated age of the underlying Hutton Sandstone ranges from Aalenian to Bathonian, while the overlying Springbok Sandstone has been considered to be Late Jurassic/Oxfordian from biostratigraphy (Price 1997; McKellar 1998; Geoscience Australia 2014). However, these ages now need to be revised, based on the radiometric dates obtained herein from the Walloon Coal Measures.

**METHODOLOGY**

**Tuff sampling**

Stratheden 4 (Geoscience Australia well code GA ENO 554973, Geological Survey of Queensland well code ARM
Stratheden 4), a CSG well on the eastern edge of the Surat Basin, near the town of Dalby on the eastern flank of the Kumbarilla Ridge (27°11′58″S, 151°01′04″E) (Figure 2) was selected for this study. It was drilled to a total depth of 531.16 m in April 2008, permitting extraction of 380 m of continuous core from the Walloon Coal Measures (Oberhardt 2008). The Walloon Coal Measures intersected between 122 and 489 m; however, the interval was not fully cored (Oberhardt 2008). This core is stored at the Exploration Data Centre, Zillmere by the Geological Survey of Queensland (Department of Natural Resources and Mines). The core was logged at a scale of 1:100 with tuff beds greater than 5 cm interbedded between coals sampled (Figure 3). The bottom of the core is »19 m above the base of the Taroom Coal Measures (determined from wireline logs) and the top is in the upper Juandah Coal Measures, 11 m below the unconformity with the Springbok Sandstone. Alluvium (0–69 m), Springbok Sandstone (69–122 m), Eurombah Formation (489–519 m) and the Hutton Sandstone (>519.48 m) were also intersected in the well.

Two tuffs were selected and dated. Sample GA2180600 (Geoscience Australia sample code) is from the Taroom Coal Measures at depth of 396.41–396.46 m and sample GA2180601 is from the Juandah Coal Measures at depth of 182.84–183.04 m. Zircon separation by standard methods was performed at the Australian National University. Zircons were analysed at Boise State University by U–Pb chemical abrasion isotope dilution thermal ionisation mass spectrometry (CA-TIMS) and laser ablation inductively coupled plasma (LA-ICPMS) methods (see Supplementary Papers for details). Cathodoluminescence (CL) images of zircons, CA-TIMS and LA-ICPMS results are given in the Supplementary Papers. U–Pb dates are plotted in Figure 4 with errors given at 2σ.

**ZIRCON DATES AND IMPLICATIONS**

CL images show the zircon grains from both samples are elongate and prismatic, and have simple oscillatory zoning. Six zircon grains from GA2180601 yielded equivalent 206Pb/238U dates with a weighted mean of 158.86 ± 0.04 Ma (MSWD = 1.5, probability of fit = 0.18; Figure 4). Chemistry of the zircons from LA-ICPMS suggest a mafic magma from (1) relatively high and variable Th/U and (2) variable Eu anomalies, including some that are very small (Figure 5). Seven zircon grains from GA2180600 yielded equivalent 206Pb/238U dates with a weighted mean of 162.55 ± 0.06 Ma (MSWD = 0.6, probability of fit = 0.74; Figure 4). Three other grains from GA2180600 yielded older dates of 162.8 ± 0.1, 169.9 ± 0.2 and 171.2 ± 0.2 Ma imply they contain inherited components. Chemistry of the zircons from LA-ICPMS suggests a granitic magma demonstrated by low Th/U and Eu/Eu∗ ratios (Figure 5).

The weighted mean CA-TIMS U–Pb dates are the interpreted ages of ash deposition based on the high probability of fit (0.18–0.74), large numbers of grains dated, and morphology and zoning that are consistent with volcanic zircon. The source of the volcanism remains uncertain. Possible volcanic sources are: (1) rift related bi-modal volcanism on the Marion Plateau (162.0–154.3 Ma) (Jell 2013); (2) intraplate volcanism of the Wellington–Muswellbrook–Narrabbri region of northeastern NSW (217–148 Ma) (Dulhunty 1967); and (3) volcanic centres to the northeast of the Clarence-Moreton Basin (Yago 1996b).

The dates reported here, which are the first radiometric dates recorded from the Walloon Coal Measures, have significant implications on our understanding of the Surat Basin and its formation. The most important is reassignment of the Walloon Coal Measures, from the Middle Jurassic, to the Upper Jurassic Oxfordian Stage. Taking into account the 2σ confidence of ±1 Ma for the lower and upper limits of the Oxfordian (163.5–157.3 Ma), determined by the International Commission on Stratigraphy (Gradstein et al. 2012; Cohen et al. 2013, updated), the Walloon Coal Measures lie entirely within the Oxfordian (Figure 6).

Current time-stratigraphic interpretations associated with the palynostratigraphic units defined by authors

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**Figure 2** Location of Stratheden 4 in the Surat Basin and the geological context of the basin.
Figure 3 Graphic log for Stratheden 4, and the intervals from where tuffs were sampled (396.46–41 and 183.04–182.84m) for CA-TIMS dating and analysed by LA-ICPMS.
including Helby et al. (1987) and Price (1997) will need to be revised, to take into account not only the age assigned here to the Walloon Coal Measures (in the Surat Basin), but also the more constrained time interval for deposition of the unit. Either (1) the oldest section is unlikely to fall into the Aequitriradites norrisii Association Zone of APJ4.2 and Contignisporites glebulentus/cooksoniae Interval Zone of APJ4.3 that covers the Bathonian–Callovian transition, or (2) the first appearance datums need to be recalibrated in the Surat Basin (Price 1997; McKellar 1998). Biostratigraphic work needs to focus on finding the base of the Murospora florida Association Zone of APJ5 in the Surat Basin. This may be challenging in light of the near absence of Murospora florida in the Walloon Coal Measures as a consequence of the ecological niche of its parent plant, apteridophyte tree fern and the diachronous nature of the basal Walloon Coal Measures from the Surat into the Clarence-Moreton Basin (McKellar 1998; Martin et al. 2013).

The extent of erosion before deposition of the overlying Springbok Sandstone can now be more accurately defined. The hiatus was likely much shorter than previously assumed (McKellar 1998; Hamilton et al. 2014b) and occurred in the late Oxfordian as opposed to across the

Figure 4 Plots of CA-TIMS U–Pb dates from zircon, using Isoplot 3.0 (Ludwig 2003). For the concordia plot, the grey ellipse in the sample of GA2180600 is not included in weighted mean calculation, and two older analyses from this tuff are not shown. The grey rectangle behind concordia line represents the 2σ uncertainty on concordia. For the 206Pb/238U plot, error bars are at 2σ. Weighted mean dates are shown and represented by the grey boxes behind the error bars. Three older dates, of which two (169.9 ± 0.2 and 171.2 ± 0.2 Ma) are omitted for being detrital in origin and being substantially older than other dated zircons.

Figure 5 Plots of Th/U vs Eu/Eu* and Nb/Th vs Eu/Eu* concentrations for GA2180600 and GA2180601, illustrating the different source magmas of the zircons of the two tuffs.
Figure 6  Previous lithostratigraphic framework for the Middle to Upper Jurassic of the Surat Basin based on biostratigraphic correlation, and a suggested lithostratigraphic based on isotopic dating of two tuff samples in accordance with geological time-scales defined by Gradstein et al. (2012) and Ogg et al. (2012).
late Callovian/early Oxfordian boundary. Until a tuff horizon is dated in the Springbok Sandstone or the base of the Westbourne Formation, the duration of the hiatus will remain uncertain.

The new dates have interesting implications for paleo-geography and paleoecology because, according to current plate tectonic reconstructions, they indicate that the coals of the Surat Basin accumulated as peats in paleolatitudes higher than 75°S (Klooijwijk 1996; Blakey 2011; Boucot et al. 2013) compared with the 55°S–65°S previously assumed based on a Middle Jurassic age (Veevers et al. 1991; Balme et al. 1995). A position that was well within the polar zone (66°S and higher) would have experienced extreme seasonality, with winter darkness lasting at least three months and continuous daylight for three months during the summer. The climate, despite being in high latitudes, is interpreted as temperate (up to 10°C), humid and with high rainfall (~1000 mm/yr) based on palynofloral assemblages and global climate models, suitable for peat accumulation (Balme et al. 1985; McKellar 1998; Martin et al. 2013). It is well documented that similar climatic conditions existed in the Late Cretaceous and from the late Paleocene–Early Eocene allowing for warm, mid-latitude flora to migrate poleward as climatic belts expanded globally. Irrespective of limitations of existing at high latitudes (Spicer & Chapman 1990; Wing et al. 2005). The winter darkness would have restricted primary productivity to the spring to autumn months, even if conditions for coal accumulation and its subsequent preservation were otherwise suitable. Models of peat growth rates in the high latitudes range from approximately 0.01 to 0.05 mm/yr and can be exceeded by basin subsidence, causing mires to be inundated by clastics or drowned by flooding with the creation of lakes (McCabe 1991; Bohacs & Suter 1997; Loisel et al. 2012). This may explain the thin nature of the Walloon coal beds. Other high-latitude coals, such as those from the Cretaceous of Antarctica and Alaska, also have thin, discontinuous seams (Spicer & Parrish 1986; Macdonald & Francis 1992).

A first-order estimate of subsidence rates can be defined using the equations and methodologies of Allen & Allen (2013). Using the new U–Pb dates and stratal thicknesses from core, a basin subsidence rate of ~61 m/Myr is calculated. This is similar; although slightly higher; to subsidence rates calculated for the late Mesozoic foreland basins of the western United States that on average, range from ~51 to ~35 m/Myr over the lifetime of a basin (Cross 1986). By comparison, the calculated rate of subsidence of ~25 to 5 m/Myr for the cratonic Williston Basin in the northern United States (DeRito et al. 1983) is considerably lower. Despite the complex prehistory of the Surat Basin (riifting and foreland loading) influencing depositional architecture (McKellar 1998), theories of continental, intracratonic sag for the Surat Basin, including subduction-related dynamic platform tilting and intracratonic sag (Green et al. 1997b; Waschbusch et al. 2009; Jell 2013), are now questionable.

SUMMARY

U–Pb zircon dating of ca 159 Ma and 162 Ma tuffs place the Walloon Coal Measures in the Oxfordian, which is substantially younger than previous estimates based on eastern Australian biostratigraphic frameworks. These dates also place the Surat Basin at higher latitudes (~75°S) during the deposition of the Walloon Coal Measures than previously assumed. The coals accumulated as peats in mires that experienced at least three months of continual darkness per year. The new dates allow for precision in measuring basin subsidence rates, which may help determine the tectonic setting of the basin: subsidence rates were more similar to those of foreland rather than intracratonic basins. The dates will also provide the basis for a new, more precise biostratigraphic framework for the Jurassic of Australia. Lithostratigraphic correlation of strata of the Walloon Coal Measures within the Surat Basin has long been difficult owing to the heterolithic, laterally impersistent coals and sandstones. Dating of zircons (and associated geochemistry) from additional volcanic tuffs offers the possibility of more precise correlations across the Surat Basin and further afield that may allow for the development of better non-marine sequence-stratigraphic models.

SUPPLEMENTAL PAPERS

Analytical Methods

Figure 1 Cathodoluminescence (CL) images of selected zircons extracted from the two tuff samples from Stratheden 4. Grains dated by CA-TIMS and spot analysed by LA-ICPMS are shown.

Table 1 CA-TIMS data from GA2180600 and GA2180601 in Stratheden 4.

Table 2 U–Pb geochronological analyses and trace element concentrations.

Supplemental data is available alongside the online version of the article, at http://dx.doi.org/10.1080/08120099.2015.1106975

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