



Tracing regional unconformities in intracratonic basins with high-precision zircon CA-TIMS geochronology

Claudio Andrade^{a,b,*}, Paulo M. Vasconcelos^a, Joan Esterle^a, Tracey Crossingham^b, Kasia Sobczak^{b,c}, Heinz-Gerd Holl^b, Suzanne Hurter^{b,d}, Corey Wall^e, James L. Crowley^f

^a School of the Environment, The University of Queensland, Brisbane, Queensland 4067, Australia

^b UQ Gas & Energy Transition Research Centre, The University of Queensland, Brisbane, Queensland 4067, Australia

^c Arrow Energy, 4000 Brisbane, QLD, Australia

^d The Netherlands Organization for Applied Scientific Research (TNO), Utrecht, the Netherlands

^e Pacific Centre for Isotopic and Geochemical Research, Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, British Columbia, Canada

^f Department of Geosciences, Boise State University, Boise, ID 83725, USA

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ABSTRACT

New high-resolution ID-TIMS geochronology of zircon from tuff horizons reveals a regionally traceable temporal hiatus of ~ 3–10 Ma in sedimentation along the contact between the Middle-Upper Jurassic Walloon Coal Measures (WCM) and the Upper Jurassic Springbok Sandstone (SS), Surat Basin, Australia. Undecompressed sedimentation rates of 15–65 m.Ma^{-1} in the WCM drop to apparent sedimentation rates of 0 to 7 m.Ma^{-1} near the WCM-SS transition, rising again to 15–51 m.Ma^{-1} during SS deposition. U-Pb geochronology identifies a hiatus – either a cessation in sedimentation or an erosional event defining a regional unconformity – not discernable from sedimentary features, highlighting the need for high-resolution geochronology in defining key bounding surfaces in sequence stratigraphy of intracratonic basins. Determining the exact position of lithological contacts and characterizing petrophysical properties of units below and above the WCM-SS transition are particularly important in quantifying connectivity between the gas-bearing units below with regional aquifers above the unconformity. As exploration for coal-seam and shale gas in intracratonic sedimentary basins expands globally, identification of major stratigraphic transitions through high-resolution geochronology will help assessing the economic potential and environmental vulnerabilities of such systems.

1. Introduction

Stratigraphic unconformities are notable temporal discontinuities in the geological record, resulting from non-deposition or erosion driven by tectonic activity, base level shifts, or climate change (Blackwelder, 1909; Miall, 2016). While unconformities constitute regional marker horizons in sedimentary basins, identifying and tracing unconformities in intracratonic basins can be challenging due to complex depositional environments and the inherent spatial and temporal discontinuity of fluvial sequences. The ~ 2500 m-thick Surat Basin, one of the most prolific coal-methane provinces in the world (Fig. 1; Towler et al., 2016), records terrestrial successions with minor marine incursions. Coal and methane are primarily hosted in the Middle-Upper Jurassic Walloon Coal Measures (WCM) (Fig. 1; Towler et al., 2016), which is

directly overlain by the Upper Jurassic and regional aquifer Springbok Sandstone (SS) (Office of Groundwater Impact Assessment, 2021). The SS contains sporadic coal seams also hosting gas resources, indicating significant stratigraphic similarities between the WCM and the SS (Rodger et al., 2019; Gaede et al., 2020). Importantly, the nature of the WCM-SS transition poses environmental challenges since the degree of reservoir interconnectedness between the units is difficult to resolve. Protecting regional groundwater resources requires isolating the SS when drilling coal-seam gas wells. Determining if the contact between the two units is regionally correlated and whether it is marked by petrophysical changes help to define the required depths of well isolation. Previous investigations of the nature of the contact between the two units using sequence stratigraphy (Hoffmann et al., 2009), biostratigraphy (Price, 1997; Mckellar, 1998), lithostratigraphy (Exon, 1976;

* Corresponding author.

E-mail address: claudio.luiz@uq.edu.au (C. Andrade).

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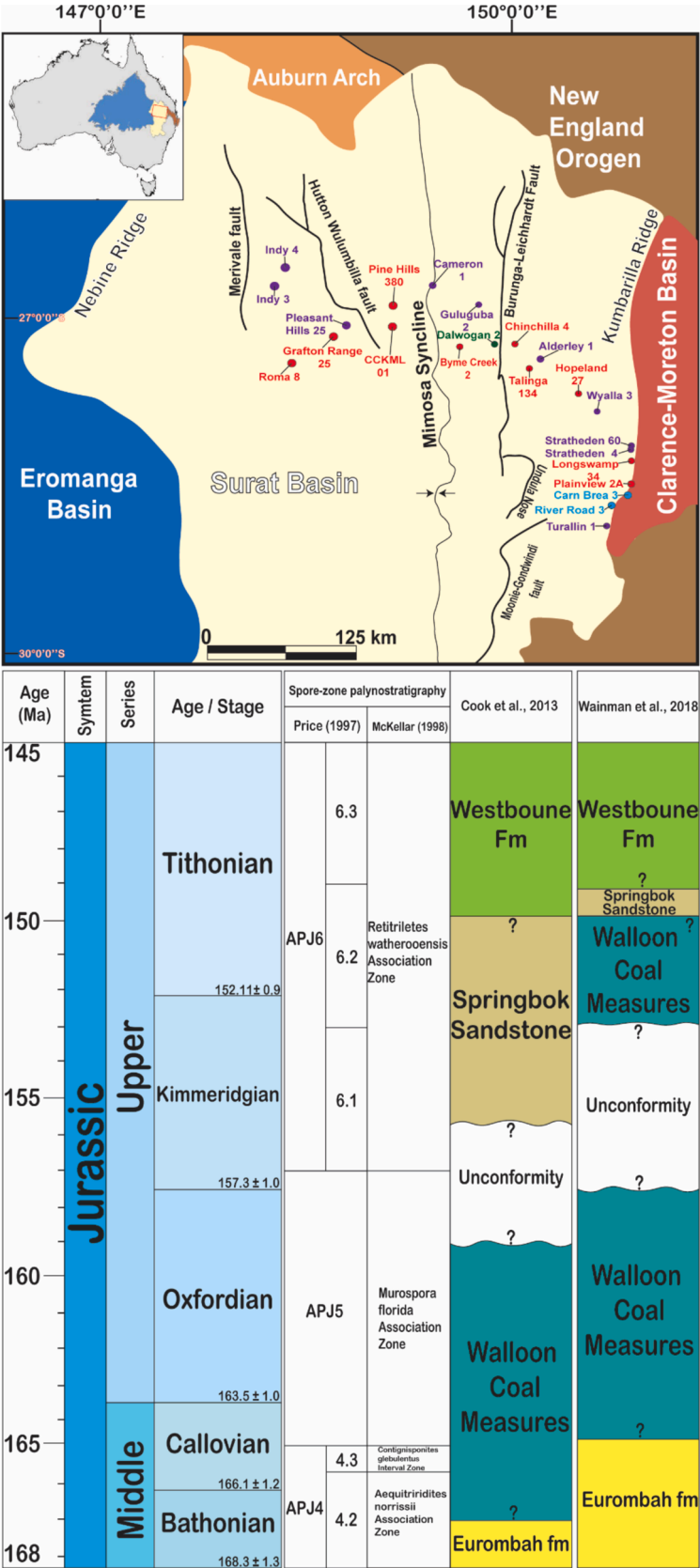


Fig. 1. (A) Map of Surat Basin showing the major structures and well locations of this study. Red dots represent wells selected for the CA-TIMS geochronology, purple dots and blue dots are wells from previous CA-TIMS geochronology studies (Wainman et al., 2018b; Sobczak et al., 2024). (B) Evolution of the Middle to Upper Jurassic stratigraphic framework of the Surat Basin along with spore-pollen palynostratigraphy. Previous studies suggest a 5 Ma unconformity between the WCM and Springbok Sandstone (Fielding, 1996). In contrast, recently published high-resolution geochronology using zircons from air-fall tuff beds suggests continuous deposition between the two units, with a 4.5 Ma hiatus occurring only within the WCM (Wainman et al., 2018b).

Green et al., 1997; Hamilton et al., 2014), detrital zircon LA-ICP-MS geochronology (Hentschel, 2018; Andrade et al., 2023; Asmussen et al., 2023), and local high-resolution ID-TIMS zircon U-Pb geochronology (Wainman et al., 2018a; Wainman et al., 2018b) have significantly advanced our understanding of the transition; however, some issues remain unresolved. Similar lithological characteristics between the WCM and the SS, longevity of bio-zones, lack of precision in detrital zircon geochronology by laser-ablation ICP-MS analysis (Horstwood et al., 2016), and paucity of high-resolution ID-TIMS U-Pb zircon geochronology (Wainman et al., 2018b) make defining the WCM-SS boundary at a regional scale a challenge. Here, new ID-TIMS U-Pb zircon geochronology permits correlating tuff ages across the basin and identifies a regional unconformity within the fluvial-dominated sequences, providing a more precise chronostratigraphic framework for the Jurassic strata in the Surat Basin. Our approach and results also outline the steps required to properly calibrate and correlate chronostratigraphic successions in cratonic basins elsewhere.

2. Geological context

The Upper Triassic-Lower Cretaceous Surat Basin spans ~ 300,000 km² extending 450 km east–west and 800 km north–south across southern Queensland and northern New South Wales, Australia (Exon, 1976; Cook et al., 2013). It hosts up to 2,500 m of sediments with complex depositional histories that reflect an interplay between eustatic sea level changes and climate, partially controlled by reactivation of basement structures that border a downwarping basin (Cook et al., 2013). Underlying geological structures reactivated throughout the Jurassic impacted sedimentation, subsidence, and geometry of the Surat Basin (Hamilton et al., 2014; He et al., 2021; Andrade et al., 2023). There are numerous unresolved hypotheses for the origin of the Surat: back-arc extension (Korsch et al., 1989), retro-foreland (Raza et al., 2009; Babaahmadi et al., 2019), intracratonic sag (Fielding et al., 1996), or dynamic platform tilting (Waschbusch et al., 2009; Foley et al., 2021). The WCM and SS consist of similar lithologies, including lithic-quartzose sandstones, siltstones, shales, carbonaceous mudstones, coals, and thin ash-fall tuff layers, all deposited in a fluvial-lacustrine setting (Exon, 1966; Green et al., 1997; Hamilton et al., 2014). Despite the similarities, the WCM contains a higher concentration of siltstones, shales, carbonaceous mudstones, tuffs, and, importantly, coal beds when compared to the sandstone-dominated SS (Green et al., 1997). In *Well Completion Reports* (WCR), the WCM-SS contact is demarked by petrophysical approaches (gamma-ray, resistivity, sonic or density logs) or the abundance of stacked sandstones at the base of the SS (Green et al., 1997; Geological Survey of Queensland – GSQ Open Data (*Well Completion Reports*)). Thus, the position of this contact is not consistent across the basin or among coal-seam gas operators. Despite evidence of widespread volcanism during sedimentation, recorded by the presence of numerous tuff beds, the location and nature of the volcanic source, whether intra- or extra-basinal, remains contentious (Fielding et al., 1996; Wainman et al., 2018b; Foley et al., 2021).

2.1. The WCM-SS transition

Some investigators suggest that the WCM-SS boundary marks a major regional unconformity dated at ~ 163–157 Ma based on spore-pollen assemblages (Price, 1997; McKellar, 1998). While Middle-Late Jurassic biostratigraphy provides useful chronostratigraphic controls on the transition from the WCM to the SS, uncalibrated biozones results in large uncertainties that challenge placing a defined age on the transition between the two units. For that reason, other authors propose continuous deposition across the two units (Exon, 1976; Green et al., 1997; Wainman et al., 2018b). For some of these authors, the thicker and more abundant coal beds in the WCM and the more prominent sandstone-dominated horizons in the SS indicate two distinct depositional cycles, named Second and Third Sedimentary Cycles (Exon, 1976;

Exon and Burger, 1981). Other investigators interpret erosional unconformable surfaces at the base of the SS to represent local rather than regional features because lithologies and siliciclastic facies are similar across both units (Green et al., 1997; Wainman et al., 2018b). Interestingly, Green et al. (1997) observed decreased gamma-ray readings with increased resistivity at the contact, interpreting this as a potential regional erosional surface, although they only noted local depositional discontinuities. These apparent discontinuities vary throughout the northern segment of the basin, and the lithological similarities both above and below them makes it difficult to confidently define the WCM-SS boundary (Wainman et al., 2018b; Asmussen et al., 2023). High-precision zircon CA-TIMS geochronology of ash-fall tuffs has refined the stratigraphic age of the Walloon Coal Measures (WCM), indicating that this unit is Upper Jurassic rather than the previously suggested Middle Jurassic (Wainman et al., 2018a). This approach appears ideally suited for addressing the chronostratigraphic questions regarding the WCM-SS transition.

Recent U-Pb detrital zircon geochronology on lithic sandstones indicates a lateral and vertical provenance change along the WCM-SS contact. An increased contribution of Triassic material (235–225 Ma) occurs towards the east (Andrade et al., 2023), and a short-lived regional basement input is observed at the contact (Asmussen et al., 2023). Although these recent studies have advanced the understanding of the stratigraphy of the Surat Basin, additional high-precision geochronological data are required within the WCM-SS transition to better define the nature of the stratigraphic boundary. As accurately determining the boundary between the WCM and SS and understanding their interconnectivity is crucial for calibrating groundwater flow models and assessing the impact of coal seam gas extraction on surrounding aquifers (Kieft et al., 2015; Office of Groundwater Impact Assessment, 2016, 2019, 2021), we have placed additional effort in sampling and dating regionally representative samples: 124 zircons from 25 additional tuff beds from 10 regionally distributed wells.

3. Samples and methods

Detailed stratigraphic description of 10 drill-cores permitted identifying and sampling 25 possible volcanic ash horizons from the northern basin segment. After zircon separation and cathodoluminescence analysis, samples containing detrital zircons of plutonic origin were screened out and 25 samples from 10 drill cores were deemed to represent true ash falls containing volcanic zircons (*Supplementary Material 1*). High-resolution geochronology by chemical-abrasion-isotope-dilution thermal ionization mass spectrometry (CA-ID-TIMS) on 124 volcanic zircon grains from the 25 samples, following established procedures outlined in *Supplementary Material 1*, provides a comprehensive chronostratigraphic record for the northeastern part of the basin. These new high-resolution results, combined with 34 published U-Pb CA-ID-TIMS tuff ages for the WCM and SS intervals (Wainman et al., 2018a; Wainman et al., 2018b), permit correlating tuff ages on the northern segment of the basin. Apparent sedimentation rates for time-calibrated intervals or units were estimated from basic age-depth relationships ($\text{depth} \div (\text{age} 2 - \text{age} 1)$), without correcting for compaction (Fig. 2).

4. Results

The 124 high resolution U-Pb zircon dates obtained for 25 samples from 10 wells sampled the WCM-SS transition (see *Supplemental Material 2*) at various depths. The combined dataset clusters into two age groups, with apparent hiatuses within the ~ 160–150 Ma interval (Fig. 2; *Supplemental Material 2*). In the western segment of the basin, a depositional hiatus of ~ 3.5 Ma is defined by two tuff units separated by 2.5 m of sediments in the Grafton Range 25 well (Fig. 3). In the more centrally placed CCKML well, two tuff units separated by 7 cm of sediments record zircon U-Pb ages of 157.41 ± 0.04 and 151.13 ± 0.04 Ma for two ash layers, representing a gap in sedimentation or an erosive

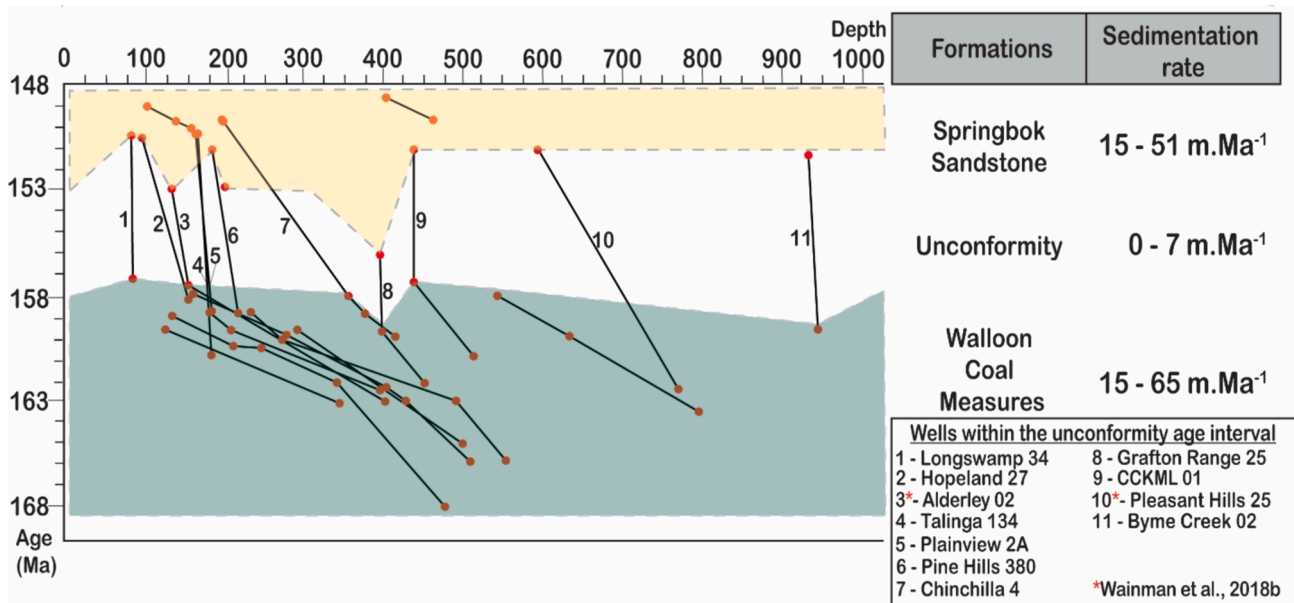


Fig. 2. Depth versus age graph illustrates the sedimentation rate for the WCM and SS. Both units record sedimentation rates in the 15 – 65 m.Ma⁻¹ range before and after the unconformity. However, apparent sedimentation rates drop to ~ 0–7 m.Ma⁻¹ in the interval containing the inferred unconformity.

phase that lasted ~ 8.5 Ma. In the eastern segment of the basin – Longswamp 34 well – two tuff units separated by 1.5 m of sediments represent an age gap of ~ 6 Ma (157.25 ± 0.03 to 150.46 ± 0.03 Ma). Less well-defined sedimentation hiatuses occur in six other wells (Fig. 3). In those wells, thin sedimentary sequences exist in the 160–150 Ma interval, but apparent sedimentation rates drop precipitously (4.17 m.Ma⁻¹ at Pine Hills 380; 1.43 m.Ma⁻¹ at Byrne Creek; 1.61 m.Ma⁻¹ at Talinga; 7.57 m.Ma⁻¹ at Hopeland 27; 2.38 m.Ma⁻¹ at Plainview 2A; Fig. 3) from the estimated uncompacted sedimentation rates of 15–65 m.Ma⁻¹ during the WCM and 15–51 m.Ma⁻¹ during SS deposition (Supplementary Material 2; also Wainman et al., 2018b).

5. Discussion

5.1. CA-ID-TIMS U-Pb tuffs zircon ages and interpretation of the WCM-SS unconformity

The presence of recognizable – based on color, texture, clay mineralogy, zirconium content (measured by hand-held XRF), and sudden appearance within organic-rich horizons – tuff beds, the effective screening of sedimentary zircons not associated with ash falls, and the comprehensive high-resolution geochronology carried out on volcanic zircons in this study clearly identify changes in sedimentation at or near the WCM-SS contact. The nearly complete absence of sediments between two adjacent tuff units of very distinct ages in three wells – Grafton Range 25, CCKML 01, and Longswamp 34 (Fig. 3) – is best explained by an unconformity caused by either non-deposition or erosion. The sedimentation gaps in these three wells define a diachronous unconformity across the basin, and we interpret that unconformity as the stratigraphic contact between the WCM-SS.

In other wells, located in both eastern and western segments of the basin, sedimentation hiatuses also occur but are less well defined because thin sedimentary units occur between the two tuff beds defining the age gaps (Fig. 3). The thin sedimentary units in these intervals could be possibly interpreted as condensed sections, representing periods in the history of the Surat basin when sedimentation slowed significantly, or they could alternatively result from differential compaction (Shields et al., 2017). Differential compaction in this interval alone is unlikely because the lithologies in those units are very similar to units immediately above and below them. A period of significantly slowed

sedimentation, as opposed to non-sedimentation or erosion, is possible; but to determine if erosion or slowed or non-sedimentation occurred along all contacts, we need greater sampling density and additional geochronology along the WCM-SS contact. A likely scenario in the wells that contain thin sedimentary layers between the disparate tuff ages is that in these wells we most likely did not sample the exact tuff units that truly define the unconformity (i.e., the last tuff horizon in the WCM and first tuff within the SS), as suggested by the following observations: 1) large variations in apparent sedimentation rates are present in this group of wells without significant trends across the basin; 2) a verified hiatus is documented in a well (Longswamp 34) adjacent to wells showing apparent sedimentation rates of 7.57 and 2.38 m.Ma⁻¹ (Plainview 2 A and Hopeland 27; Fig. 3); 3) undated tuff beds (Fig. 3) are present within the sedimentary interval where the apparent unconformity should occur. Thus, for those wells we have constrained the approximate interval but not precisely identified the unconformity. Significantly, the abrupt decrease in apparent sedimentation rates, and the definition of true unconformities in at least three wells clearly indicate that an unconformity exists within the intervals illustrated in Fig. 3, and that this unconformity must define the WCM-SS contact. The exact position and ages of the unconformities at each of the other wells remains to be determined through more detailed sampling and geochronology. Also importantly, the geochronological age gaps identified in this study fall within those found in previous research; however, these earlier studies either applied lower-resolution methods (e.g., Andrade et al., 2023; Asmussen et al., 2023) or did not sample the ash beds immediately adjacent to the hiatuses identified here. Importantly, high resolution geochronology by Wainman et al. (2018b) also measured an ~ 4.5 Ma age gap (157.57 ± 0.05 to 152.99 ± 0.06 Ma) in the Alderley 1 well, which the authors interpreted as an unconformity within the WCM. In contrast, we identify the recurrent age hiatuses across the basin as the WCM-SS contact.

Our geochronologically-defined unconformity is near but slightly younger than a proposed unconformity – ~163–158 Ma – previously identified based on U-Pb methodology, its more robust calibration, and the increased sampling density presented here permit better defining the age gaps along the WCM-SS contact.

Operationally important, in some places the U-Pb age gap corresponds to the WCM-SS boundary as defined in well completion reports (e.g., Grafton Range 25), but in other places the U-Pb age gap falls above

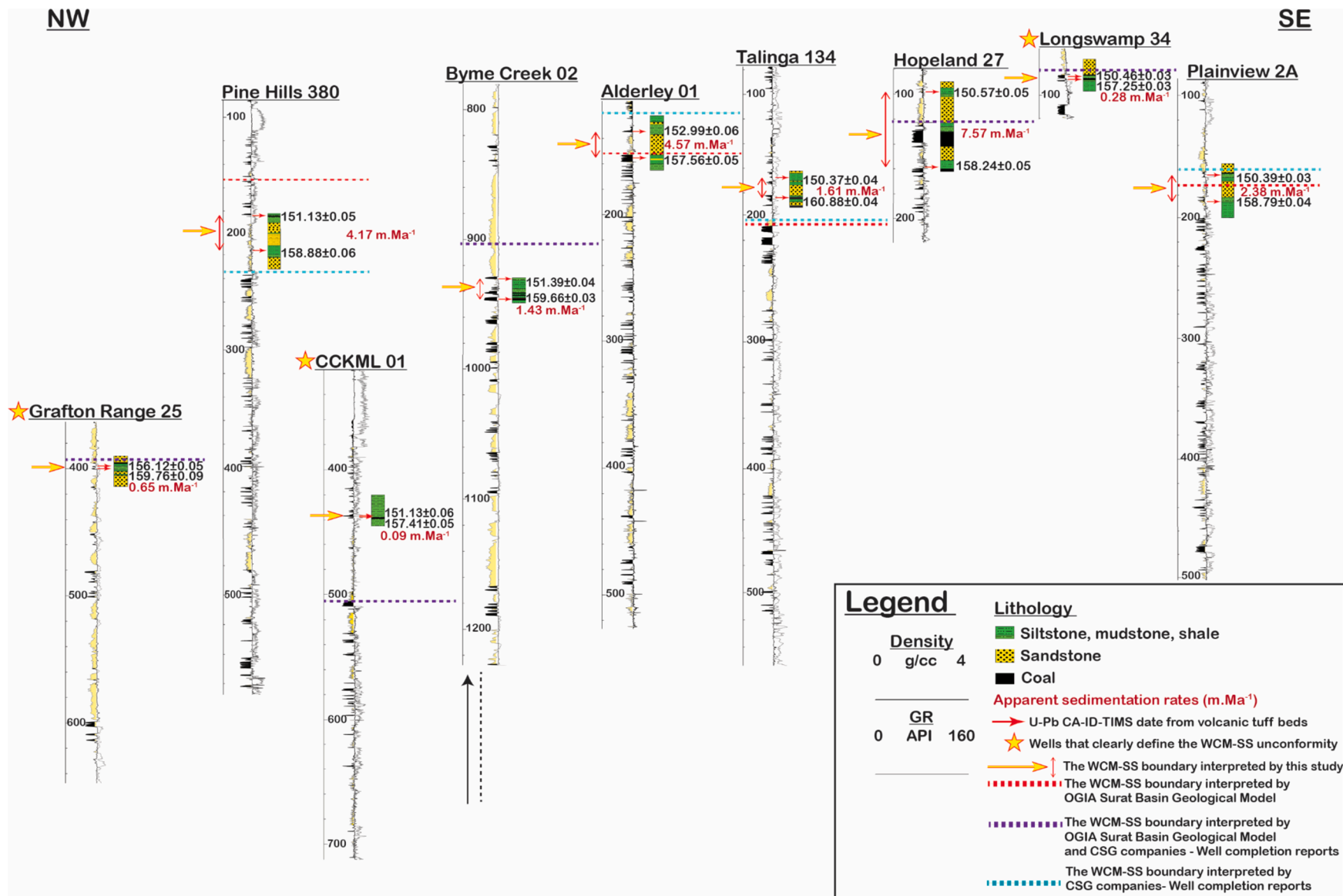


Fig. 3. Cross-section presenting the new high-resolution ID-TIMS tuff ages along with the calculated apparent sedimentation rates. The proposed WCM-SS unconformity is well-defined in the Grafton Range 25, CCKML 01, and Longswamp 34 where a period of non-deposition or erosion occurs. Other wells indicate minimal deposition between the tuff ages, but with significant decrease in the apparent sedimentation rates at the transition. Note that the Byme Creek 02 is not to scale and has been moved upwards for better representation of the ages. The high-resolution ID-TIMS tuff ages for Alderley 01 are from [Wainman et al.\(2018b\)](#).

(e.g., CCKM 01) or below (e.g., Byrne Creek 02) it (Fig. 3). The discrepancy arises from the fact that the WCM-SS contact has been traditionally identified either by petrophysical approaches (gamma-ray, resistivity, sonic or density logs) or by the increased presence of stacked sandstones at the base of the SS (Green, et al., 1997; Well Completion Reports). Defining stratigraphic units based on physical properties has led to conflicting views on the position of the WCM-SS contact (Green et al., 1997; Wainman et al., 2018b). To be consistent with modern approaches in chronostratigraphy (Gradstein and Agterberg, 2022; Miall, 2022), we propose that age gaps as measured in this study are the most robust identifiers of major stratigraphic boundaries in the northern segment of the Surat Basin. Thus, the WCM-SS boundary is a regional and diachronous unconformity defined by an age gap between ~ 160 and ~ 150 Ma. Exact chronostratigraphic positions of the gaps are precisely defined for three wells (Fig. 3); for the other wells, only approximate positions are defined by the U-Pb zircon ages, as shown in Fig. 3. Our geochronologically-defined stratigraphic contacts provide the opportunity for better calibrating petrophysical discontinuities across the basin and possibly using the cheaper and more readily available petrophysical data to better define the WCM-SS regionally (e.g., Andrade, 2024).

The regional unconformity is diachronous along the northern segment of the Surat Basin, and it probably reflects differential basin uplift and/or subsidence – as suggested by changes in provenance – during the transition between the WCM and the SS (Babaahmadi et al., 2019; Andrade et al., 2023; Asmussen et al., 2023). An important consequence of this study is that we now have a chronostratigraphically calibrated reference horizon – the unconformity between the WCM and the SS – to evaluate the post Kimmeridgian tectonic and structural evolution of the Surat Basin.

Another important implication is that the diachronous nature of the unconformity indicates that Surat Basin sedimentation resumed in the west before sediments started to accumulate again in the east. A possible explanation for this feature is that the eastern section of the basin remained more elevated longer than its western counterpart, focusing sediment supply into the western segment of the basin from 156.12 ± 0.05 to 152.99 ± 0.06 Ma, when sedimentation on the eastern segment of the basin resumed. Further support for this interpretation is the brief influx of hinterland material at the WCM-SS transition, which is more prominently observed along the western margin of the basin (Asmussen et al., 2023). Alternatively, more complex sedimentation patterns may have resulted in resumption of sedimentation irregularly across the northern segment of the basin. Only more detailed high-resolution geochronology – provided tuff units can be identified and sampled – can resolve this issue. Importantly, sediment sources also appear to have shifted after the unconformity, as suggested by the increase in 235–225 Ma detrital zircons in the western segment of the basin immediately after the unconformity (Andrade et al., 2023; Asmussen et al., 2023).

Curiously, the unconformity identified by geochronology does not appear to result in any obvious change in sediment type, composition, or texture. In the wells we investigated (Fig. 3), the unconformity sits within variably coarse to very fine-grained lithic sandstones, siltstones, carbonaceous mudstones, coal-bearing units, $\pm$ tuff beds, without drastic changes in sediment type, depositional feature, or cementation below or above the unconformity, as documented in Andrade (2024). Therefore, defining the WCM-Springbok chronological contact solely based on the occurrence of the last thick-coal bed or first amalgamated sandstones is only feasible at a few locations, if at all.

5.2. Possible Causes of the WCM-SS unconformity

The Upper Jurassic is a period of major global tectonic reorganization (Seton et al., 2012), such as the “Argoland breakup” event along northwestern Australia (Gallagher et al., 1994; Turner et al., 2009), increased magmatic activity in eastern Gondwana (Mortimer et al., 2015; Wainman et al., 2019), and changes in subduction dynamics along

eastern Australia (Korsch et al., 2009; Waschbusch et al., 2009). Intra-plate faulting in eastern Australia – e.g., the 162–152 Ma Demon fault – probably drove deformation within intracratonic basins and resulted in differential uplift of faulted blocks within these basins (Babaahmadi et al., 2019). The Upper Jurassic WCM-SS unconformity defined here – ~160 to ~ 150 Ma – is coeval with those events.

The diachronous unconformity and differential basin infilling defined in this study may have resulted from this heightened Upper Jurassic tectonism.

5.3. Implications for the chronostratigraphy of intracratonic sedimentary basins

High-resolution zircon U-Pb geochronology has become a necessary tool in the calibration of global biostratigraphy (Vail et al., 1984) and climatic excursions (Gröcke, 2002), but to our knowledge it is not often used in chronostratigraphic calibration in hydrocarbon-rich intracratonic basins. Such intracratonic basins, such as the Solimões and Parnaíba Basins, Brazil, the Michigan and Williston Basins, USA, and the Murzuk Basin, Libya, are examples of systems where stratigraphic complexities and differential compaction hinder proper regional correlation of hydrocarbon-bearing strata (Kingston and Matzko, 1995; Davidson et al., 2000; Burgess, 2019). For example, the lateral variability of the fluvial-dominated depositional system of the Early Devonian Murzuk Basin, combined with multiple regional tectonic events that drove uplift and produced unconformities, complicates regional correlation of hydrocarbon rich strata basinwide (Najem et al., 2015). On the other hand, the Solimões and Parnaíba Basins exhibit intense magmatic activity that complicates thermal histories and hamper regional correlations of hydrocarbon-bearing strata (Filho et al., 2008). Thus, the absence of reliable regional age controls poses significant challenges in accurately assessing the hydrocarbon potential and environmental sensitivities in these basins. Refining their chronostratigraphic framework with ID-TIMS U-Pb geochronology of volcanic zircons from tuff horizons, as illustrated here, is the most robust approach for resolving the chronostratigraphic evolution of intracratonic basins that in places may lack precise biostratigraphic zones to permit the high-resolution chronostratigraphy commonly carried out in open marine basins.

6. Conclusions

High-resolution ID-TIMS geochronology of zircons from interbedded tuffs reveal a regional unconformity of variable duration – ~3 to 10 Ma – at the Jurassic Walloon Coal Measures- Springbok Sandstone transition in the Surat Basin, Australia. Apparent sedimentation rates drop abruptly from ~ 15–65 m/Ma⁻¹ below the unconformity to 0–7 m/Ma⁻¹ near the unconformity, rising again to 15–51 m/Ma⁻¹ above it. The exact position of the unconformity is identified in three wells, one in the west, one in the center, and one in the east segment of the basin, confirming that the unconformity is regional. The position of the unconformity is approximated in several other wells. The WCM-SS unconformity is diachronous across the northern segment of the basin, possibly reflecting differential deformation patterns or complex sedimentary supply systems. Major shifts in global plate reorganization and increased tectonic activity in eastern Gondwana are contemporaneous with the Middle-Upper Jurassic unconformity identified in the Surat Basin.

CRedit authorship contribution statement

Claudio Andrade: Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Paulo M. Vasconcelos:** Writing – review & editing, Supervision, Investigation. **Joan Esterle:** Writing – review & editing, Conceptualization. **Tracey Crossingham:** Methodology. **Kasia Sobczak:** Methodology. **Heinz-Gerd Holl:** Project

administration, Methodology. **Suzanne Hurter:** Supervision, Resources, Project administration, Funding acquisition. **Corey Wall:** Validation, Methodology. **James L. Crowley:** Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gr.2024.11.009>.

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