Quantitative sonic transit time analysis defines multiple Permian–Cretaceous exhumation events during the breakup of Gondwana

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SUMMARY

The Perth Basin in southwestern Australia has an extended history involving multiple regional unconformity-forming events from the Permian to Cretaceous. The central and southern Perth Basin is the closest basin to the relict triple junction of eastern Gondwana and comprises a complete Permian to Recent stratigraphy, thus recording the full history of the breakup events. We use sonic transit time analysis to quantify the magnitudes of net exhumation and the minimum differences in net exhumation across different time intervals (here called 'interval exhumation') for four stratigraphic periods from 37 wells. We were able to quantify the minimum interval exhumation of the Permian–Triassic, Triassic–Jurassic, Early Cretaceous breakup and post-Early Cretaceous events. The Permian–Triassic and Triassic–Jurassic events recorded spatially varied exhumation, up to 1000 m, across sub-basins. These localized variations are caused primarily by reverse (re-) activation of NW- and N-striking faults in the Permian–Triassic and Triassic–Jurassic events, respectively. The Valanginian breakup unconformity (~133 Ma) records approximately 400 m of basin-wide interval exhumation during the breakup of Gondwana, which implies a change to relatively uniform exhumation on a regional scale. Using published uplift rates for volcanic and non-volcanic passive margins, estimates of the time required for 400 m of exhumation vary from 6 to 20 Ma, respectively. A volcanic margin is far more likely given that post-breakup sedimentation commenced 2–7 Ma after breakup. Lastly, post-breakup interval exhumation ranges from 0 to 800 m. The highest values are in the hangingwall blocks of faults. Up to 200 m may be locally caused by reverse fault re-activation due to the present-day compressional stress state of Australia. The remainder is attributed to regional exhumation caused by dynamic topography in the last 50 Ma.

Key words: Uplift; Erosion; Sonic velocity; Western Australia; Tectonics

INTRODUCTION

The Perth Basin in southwestern Australia has a protracted history involving multiple rifts throughout the Permian and Mesozoic before the eventual drift of greater India, followed by Antarctica. Phases of Permian–Recent subsidence and siliciclastic fill have been interspersed with regional unconformity-forming events. In the central and southern Perth Basin, the most significant unconformities are the Permian–Triassic (~251 Ma), Triassic–Jurassic (~198 Ma), Valanginian (Early Cretaceous; ~133 Ma) and Aptian–Albian (Early Cretaceous; ~113 Ma) (Crostella and Backhouse, 2000). The Permian–Triassic unconformity is associated with the uplift of the Harvey Ridge, a major horst structure that has been postulated to have undergone significantly more exhumation than its adjacent sub-basins (Iasky, 1993). The Triassic–Jurassic unconformity has only been associated with localized exhumation in the southern Perth Basin, which was accommodated by re-activation of the Dunsborough Fault, a major fault that juxtaposes the Perth Basin stratigraphy with the Precambrian Leeuwin Complex (Song and Cawood, 2000). The Valanginian unconformity is associated with the breakup of Gondwana and the drifting of greater India from the Austral–Antarctic portion (Crostella and Backhouse, 2000). The last major recorded unconformity-forming event in the Mesozoic was at the Aptian–Albian boundary, but this is thought to have resulted in relatively little exhumation and structural deformation, and rather represents a hiatus (Crostella and Backhouse, 2000). Rocks that could elucidate on the separation of Australia from Antarctica in the Late Cretaceous (90–87 Ma) are only preserved in a small offshore portion in the Perth Basin. However, exhumation during these times has not been adequately quantified across the Perth Basin, even though its quantification has significant tectonic and petroleum implications. In this study, we use sonic transit time (Δt) analysis as a proxy for exhumation, as has yielded the most precise estimates over other methods of quantification. These data are used to establish the magnitude of net exhumation for each well in the central and southern Perth Basin for stratigraphic formations from four time periods that bracket the key unconformity-forming events. This then allows the elucidation of the basin's exhumation history, insights into the timing and magnitude of structural deformation, and tectonic implications during breakup.

METHOD

Exhumation term definitions

Exhumation is a unique term that describes and measures both the upwards vertical displacement of a rock column (i.e., uplift) and the associated removal of overburden (i.e., erosion), relative to a specified reference frame. To be clear, we use terms defined by Corcoran and Doré (2005) and define a new term 'interval exhumation' (Table 1, Figure 1).

Term	Definition

Net exhumation	The difference between present-day burial depth of a reference unit/formation and its maximum burial depth prior to exhumation.
Gross exhumation	The magnitude of erosion that must have occurred at a particular unconformity prior to post-exhumation re-burial.
Interval exhumation	The difference in net exhumation between two chronostratigraphic intervals (i.e., the minimum gross exhumation).

Table 1. Definitions of exhumation terms

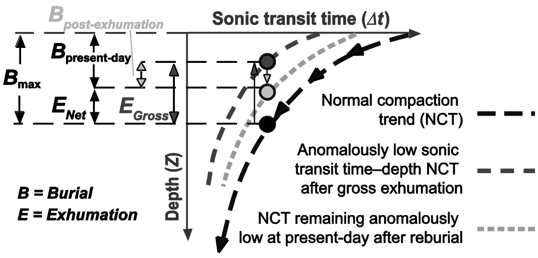

Figure 1. Graphical representation of exhumation and burial in sonic transit time analysis.

Satisfied variables in sonic transit time analysis

Sonic transit time provides the most precise quantification of exhumation, although it is limited to well locations. Its main assumption is that compaction is an irreversible process that is not modified during exhumation. This assumption is valid in most consolidated rocks. However, there are several variables that must be satisfied prior to correct application (Corcoran and Doré, 2005). These require one or more formations that: (a) are acoustically-homogeneous (lithology, grain size and mineralogy/diagenesis), thick and laterally extensive; (b) hydrostatically pore fluid pressured; (c) brine saturated, and, most importantly; (d) have experienced steady porosity reduction during mechanical and thermochemical compaction. Additionally, the integrity/reliability of the normal compaction trend (NCT) is vital (i.e., a formation which has not experienced exhumation). Similarly, the reliability of collected sonic logs depend on borehole/casing quality and any tool issues. The central and southern Perth Basin has four intervals that satisfy the above variables and bracket key unconformities: (a) the Permian Sue Group; (b) the Triassic Lesueur Sandstone; (c) the Jurassic–lowermost Cretaceous stratigraphy, and; (d) the Lower Cretaceous Warnbro Group. Only shale, claystone and mudstone were used as these have more predictable properties than other rock types.

Analytical techniques

Data from all wells in the southern half of the Perth Basin were considered for sonic transit time analysis, but only wells that contained sonic transit time wireline data (Δt), gamma ray wireline logs, formation tops data and lithological data from cuttings or cores were utilized. From a total of 45 petroleum and stratigraphic exploration wells, 37 included digitized versions of these data. Additionally, caliper logs and formation tests helped identify anomalous or erroneous sonic transit times caused by borehole discrepancy or overpressures. Data were first corrected for borehole quality. Sonic transit time data were removed that were >3 μm ft^{-1} from the median sonic value over a 10 m interval or >15% from the supposed borehole width in a calliper log. The remaining data were edited to include only shale, claystone and mudstone using lithology and gamma ray logs. To avoid interactions with surrounding rock types, only intervals >5 m were considered, and an arithmetic mean was calculated at the midpoint depth of each shale unit. This rigorous processing yielded between 1 and 50 points per well.

A normal compaction trend was then constructed from wells that displayed the highest sonic transit time–depth relationship (i.e., at maximum burial depth) (*cf.*, Corcoran and Doré, 2005). For Jurassic–lowermost Cretaceous and Lower Cretaceous stratigraphy, these included four wells in the offshore basin, which yielded correlation coefficients of 0.977 and 0.938, respectively. These wells were not deep enough to penetrate into the Triassic/Permian strata. Therefore, the least exhumed wells in the southernmost sub-basin were used, but these are partially exhumed, so 480 m had to be added to all Triassic/Permian net exhumation magnitudes to avoid having impossible exhumation estimates. Correlation coefficients are only 0.722 and 0.705 for the Permian and Triassic strata, respectively, so caution must be exercised when interpreting these data due to the uncertainty.

Net exhumation was then calculated for each well's chronostratigraphic intervals (Figure 2). In essence, net exhumation is quantified by measuring the depth difference between a data point's shale unit midpoint depth and its respective depth on the NCT. The interval exhumation may then be calculated by subtracting the difference between an older interval and its adjacent younger interval (e.g., between Permian and Triassic intervals). Note that these are minimum estimates post-exhumation reburial is not taken into account. Nevertheless, in any specific interval, exhumation magnitudes relative to other wells are quantifiable.

RESULTS & DISCUSSION

Exhumation history of the central and southern Perth during and after Gondwana breakup

The quantification of net exhumation of different time periods permits interpretations regarding the spatial and temporal evolution of exhumation on Gondwana (Figure 2, Figure 3). The results that were obtained from this study were compared to independent qualitative and quantitative exhumation results to assist quality control and interpretation. The most import of these is thermal history data obtained from vitrinite reflectance (*cf.*, Iasky, 1993). Available Permian vitrinite reflectance indicates 2 km of exhumation on the NW-striking Harvey Ridge (Iasky, 1993), more than double of our interval exhumation magnitude (890 m; Figure 3). However, this is the only Permian exhumed block that has previously been identified, whereas sonic transit time analysis indicates 700 m of interval exhumation for the well Rutile 1, which is in the hangingwall blocks of imbricate fault system including the NW-striking Sabina and N-striking Busselton Faults (Figure 2). The Sabina Fault is more likely to have been (re-)activated because other wells along the Busselton Fault show no interval exhumation and NW-striking faults were most likely to have been re-activated (Song and Cawood, 2000). Exhumation at the Triassic–Jurassic boundary has only ever been interpreted as a localized uplift event resulting in re-activation of the N-striking Dunsborough Fault and uplift of the adjacent Leeuwin Complex and, possibly, the Vasse Shelf (Iasky, 1993; Song and Cawood, 2000). Unfortunately, the Vasse Shelf sonic transit time analysis is limited to Permian and post-breakup stratigraphy, so it is uncertain where ~1000 m of interval exhumation occurred (Figure 3). Vitrinite reflectance does not show higher values than other sub-basins in samples from Triassic to Cretaceous stratigraphy. Yet, sonic transit time analysis shows 200–400 m of interval exhumation in the hangingwall block of the Busselton Fault. As the Busselton and Dunsborough Faults strike and dip in similar directions, it can be expected they re-activated at the same time. A significant proportion of the 1000 m interval exhumation between the Permian and post-breakup Early Cretaceous may be accounted for during the Triassic–Jurassic unconformity, although this interpretation is tentative.

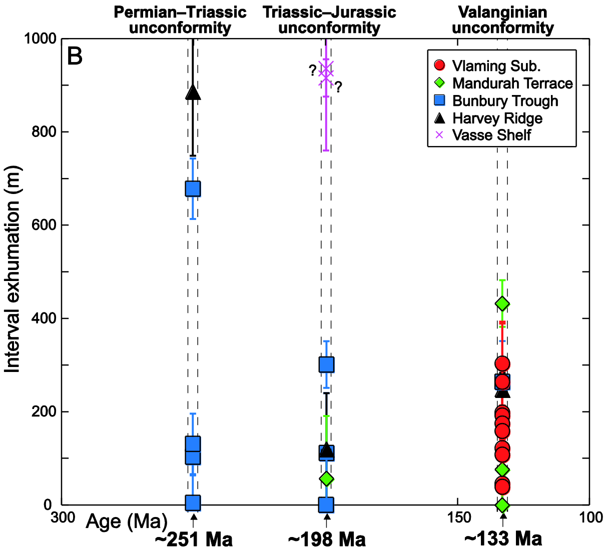

Figure 3. Minimum interval exhumation at each unconformity-forming event, by sub-basin.

The Valanginian breakup of Gondwana recorded 0–300 m interval exhumation during this time, with the exception of Cockburn 1 (420 m; Figure 3). Jurassic–Cretaceous thermal data is unable to identify exhumation magnitudes that fall within this range of uncertainty. All interval exhumation magnitudes are the same within associated sonic transit time uncertainty, and so probably represent a regional exhumation over the entire central and southern Perth Basin. This is significantly different from the localized variations in interval exhumation observed at the Permian–Triassic and Triassic–Jurassic unconformities. There appears to be a switch in paradigm from localized exhumation of sub-basins/blocks during the Permian–Jurassic to regional exhumation at the Valanginian.

The absence of Late Cretaceous to Tertiary sedimentary rocks in the onshore Perth Basin makes an assessment of the interval exhumation at and after the Aptian–Albian boundary difficult to assess. The remainder of the net exhumation (0–800 m; Figure 2) could have occurred at this boundary or afterwards.

Geodynamic implications of a local to regional exhumation regime switch during breakup

There are apparent changes of observed exhumation paradigms before, during and after the rifting of Gondwana. Quantified exhumation magnitudes permit investigation of crust–mantle interactions that drove these exhumation events, particularly for the breakup unconformity and post-rifting. The largest interval exhumation variations (0–1000 m; up to 2000 m calculated from thermal history from Iasky, 1993) over short distances (<100 km) in the Permian–Jurassic Perth Basin have previously been attributed to rapid mantle upwelling (Iasky, 1993). This has particularly been suggested for the Permian–Triassic unconformity to account for rapid coalification and anomalously high vitrinite reflectance on the Vasse Shelf and Harvey Ridge, respectively (Iasky, 1993). However, interval exhumation variations over such short distances of both the Harvey Ridge and Vasse Shelf relative to the other sub-basins are unlikely to form solely as a result of mantle upwelling. A component of compressional stress is required to induce localized reverse fault (re-) activation. No studies have yet been undertaken to discern between these two processes, and so neither the rate nor duration of uplift can be reliably quantified during the Permian and Mesozoic unconformity-forming events in southwestern Australia.

During the Valanginian unconformity-forming event, which is associated with the rifting of greater India from Australia, the minimum interval exhumation was relatively minor (0–400 m). Interval exhumation here, particularly for the 300–400 m range for onshore wells, are reburied here by an average 100 m, and so probably represent the maximum exhumation at the Valanginian unconformity (i.e., ~400 m). This breakup event has been attributed to either volcanic or non-volcanic passive eastern Gondwana margin, depending on whether now-offshore large volcanic plateaus (Wallaby, Zenith and Naturaliste Plateaus) erupted during breakup, but these are not yet precisely dated (Coffin and Eldholm, 1992). Independently constrained numerical modelling by Leroy et al., (2008) yielded exhumation rates of 20 and 70 m Ma^{-1} for non-volcanic and volcanic margins. Given that the interval exhumation during the Valanginian unconformity event was approximately 400 m, then between 6 and 20 Ma was required to produce this exhumation using the volcanic and non-volcanic margin settings. However, the post-breakup hiatus was a maximum of 7 Ma before deposition of the Warnbro Group began (Crostella and Backhouse, 2000). Therefore, if the published exhumation rate models, palynomorphs interpretations of the Warnbro Group and our quantification of exhumation magnitudes are correct, the breakup of Gondwana must have been in a volcanic-margin setting.

After breakup, the Perth stratigraphy has still experienced 0 to 800 m of net exhumation. For onshore wells with a maximum of 50 m of post-exhumation reburial, net exhumation effectively equals gross exhumation. Dynamic topography and epeirogenic studies have indicated that up to 200 m of regional exhumation can be attributed to the east–west compressive stress field that Australia currently experiences when flexure is considered, implying that a significant proportion of this last stage of exhumation is caused by epeirogenic processes (Czarnota et al., 2014). The most likely cause for observed post-breakup exhumation is a resultant long-wavelength inversion of the Perth Basin caused by interaction between the rapidly migrating Australian Plate over a mantle hotspot. From the analysis of longitudinal river profile studies across Western Australia, several studies have suggested that the entire southwest was uplifted during the last 50 Ma between 200–500 m (Czarnota et al., 2014). Therefore, wells with the highest exhumation magnitudes (580–790 m) in this study probably experienced interplay between localized reverse fault re-activation and regional uplift, whereas those with lower exhumation magnitudes (180–490 m) were caused by regional uplift alone. The present-day Australian surface is being uplifted at a rate of 10–50 m Ma^{-1}, where the southwest is probably restricted to the slower values to allow erosional processes to keep track with formed surface relief (Czarnota et al., 2014). Dynamic topography studies indicate that this exhumation of the Australian southwest occurred during the last 50 Ma. Using our reliable post-breakup exhumation magnitudes of 350–500 m, post-breakup epeirogeny could have occurred for 10 to 50 Ma, but was probably nearer to 50 Ma to allow erosional processes to keep track with uplift.

CONCLUSIONS

This study successfully uses sonic transit time analysis to quantify the magnitudes of net exhumation and the differences in net exhumation across different time intervals (here called 'interval exhumation') for four stratigraphic periods from 37 wells in the central and southern Perth Basin. Interval exhumation prior to the breakup of Gondwana was defined by 1000 m of Permian–Triassic re-activation of NW-striking faults and exhumation of the Harvey Ridge; and up to 1000 m of Triassic–Jurassic re-activation of N-striking faults and exhumation of the Vasse Shelf. The Valanginian unconformity recorded 400 m of basin-wide exhumation, which required 6 to 20 Ma for volcanic and non-volcanic margins, respectively. Given rapid onset of post-breakup deposition, a volcanic eastern Gondwana margin is far more likely. Post-breakup interval exhumation ranges from 0 to 800 m, with the highest values in the hangingwall blocks of faults. A maximum of 200 m may be locally attributed to reverse fault re-activation due to the present-day compressional stress state of Australia. The remainder is attributed to regional exhumation caused by dynamic topography in the last 50 Ma.

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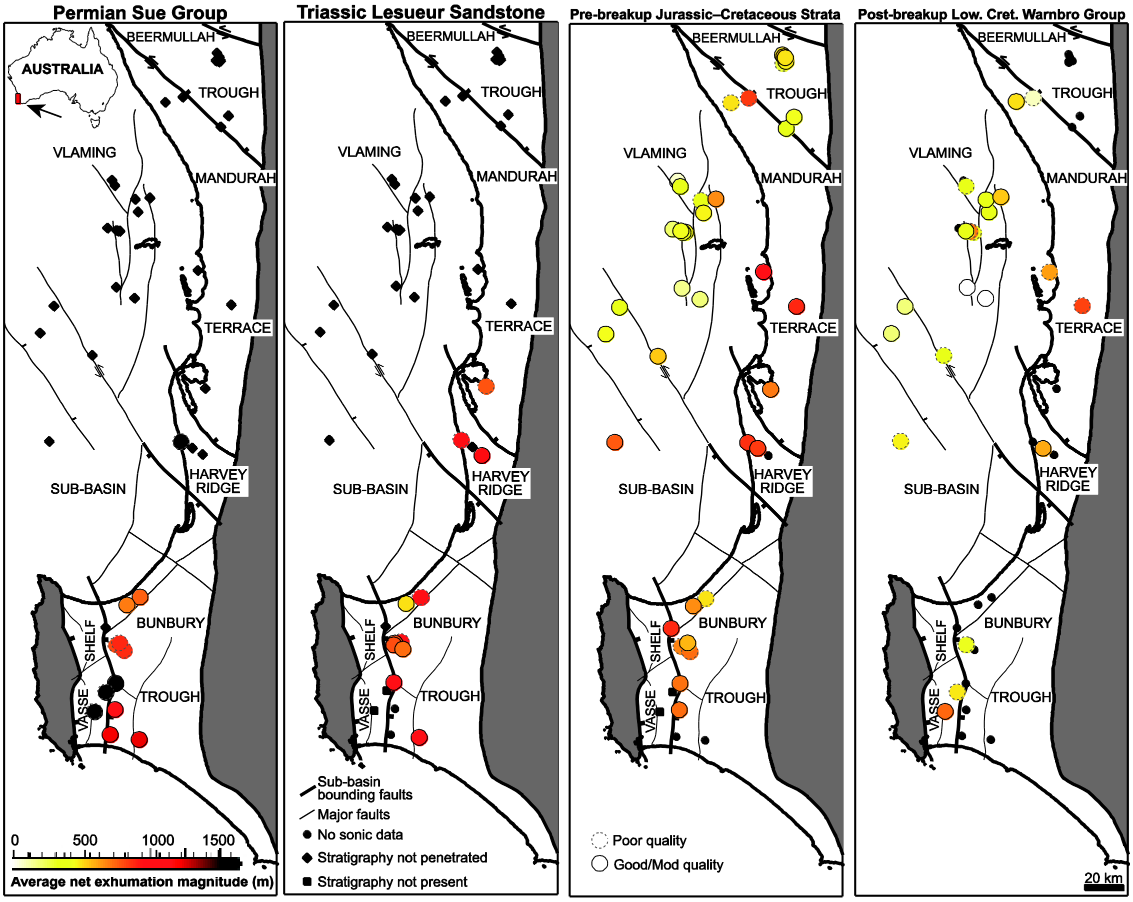

Figure 2. Spatial and temporal variation in net exhumation magnitudes for wells of each chronostratigraphic interval.