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Comment on "Uranium series dating of Great Artesian Basin travertine deposits: Implications for palaeohydrogeology and palaeoclimate" by Priestley et al. (2018)

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ABSTRACT

Widespread travertine deposits occur in the southwestern Great Artesian Basin (GAB) in central Australia. Priestley et al. (2018) reported uranium-series ages of travertine deposits and concluded that elevated travertine deposition rates are synchronous with wet periods and that times of travertine deposition represent times of high regional rainfall. We propose an alternative explanation that CO_2 degassing from the mantle associated with active faulting played a major role in travertine precipitation in the southwestern GAB.

Priestley et al. (2018) reported uranium-series ages of travertine deposits from the southwest section of the Great Artesian Basin (GAB) (Fig. 1). They concluded that elevated travertine deposition rates are synchronous with wet periods and that times of travertine deposition represent times of high regional rainfall. Priestley et al. (2018) argued that their study shows that the travertine deposits of central Australia provide a datable archive of past climate and hydrogeology.

We welcome the comprehensive uranium-series dating study by Priestley et al. (2018) to better understand the connection between travertine deposition and climate. There are not many studies in the scientific literature using travertines as climate archives. However, as we (Ring et al., 2016) also worked on travertine deposits in the southwestern GAB, we take the opportunity to further discuss some issues of travertine precipitation as Ring et al. (2016) proposed that CO_2 degassing from the mantle associated with active faulting played a major role in travertine precipitation in the southwestern GAB.

1. Field and geochemical evidence

We do not disclaim that hydrological conditions in connection with climate can play a role in travertine precipitation. However, carbonate precipitation will only occur if the carbonate saturation state (a function of both the cation concentration and $[CO_3^{2-}]$) is achieved in water. Therefore, a critical condition is the availability of CO_2. According to the treatise on travertine by Pentecost (2005), travertine "precipitation results primarily through the transfer (evasion or invasion) of CO_2 from or to a groundwater source leading to calcium carbonate supersaturation". Thus, travertine precipitation occurs in areas of considerable CO_2 production, the latter of which can happen mainly through dissolution of limestones by percolating water, degradation of organic matter, or mantle degassing.

There is field evidence that travertine formation in the southwestern GAB is controlled by faulting (Fig. 2 in Ring et al., 2016). The travertine occurs as vein deposits, which are intensively fractured; travertine also precipitated on striated fault planes (Fig. 4 in Ring et al., 2016). Such structurally controlled travertine deposits are similar to vein carbonates that have been reported from seismically active geothermal systems (Hancock et al., 1999; Chiodini et al., 2004; Newell et al., 2005; Uysal et al., 2007, 2009). The southwestern GAB is seismically active (South Australian Resources Information Geoserver, SARIG, https://sarig.pir.sa.gov.au/MapViewerJS/).

Geochemical data of free and dissolved gas samples and of travertines in various GAB locations show a significant amount of deep-

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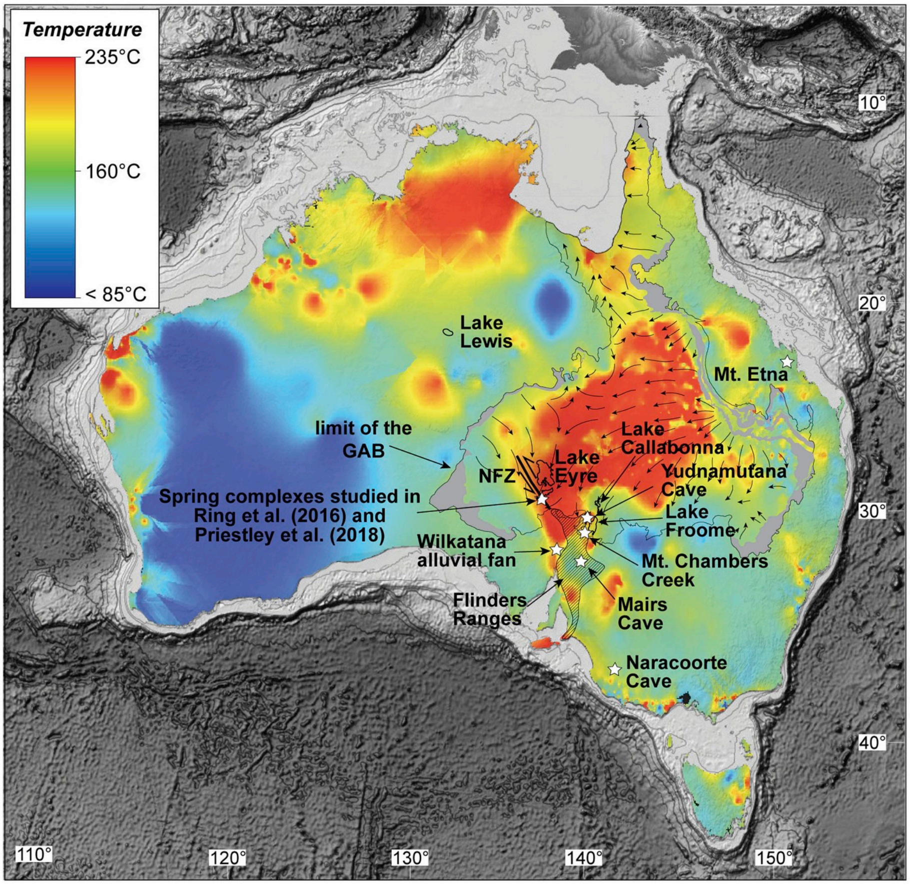

Fig. 1. Heat flow map of Australia showing modelled crustal temperature at 5 km depth (www.ga.gov.au) with locations discussed in text and extent of Great Artesian Basin. Surface trace of NFZ is also indicated. Note that NFZ largely coincides with transition from low to high heat flow in south-central Australia (see Ring et al. (2016) for more detail). Recharge areas (grey) with groundwater flow directions are also shown (from Cox and Barron, 1998).

seated gas components (Italiano et al., 2014; Ring et al., 2016). The geochemical features of He and CO_2 dissolved in GAB waters are consistent with the presence of mantle-derived CO_2 (Boreham et al., 2001; Italiano et al., 2014). This indicates that fault zones (e.g. the Norwest Fault Zone (NFZ) discussed in Ring et al., 2016) along which travertine deposition occurs (Fig. 1) is tapping the mantle.

The geochemical and field data indicate that travertines in the southwestern GAB are thermogene deposits (cf., Pentecost, 2005). Thermogene deposits have a more restricted spread in CO_2 than meteogene deposits (which also contain soil and atmospheric CO_2) and regularly occur in regions of recent volcanic or tectonic activity associated with high geothermal gradients (Pentecost, 2005). There is a linear relationship between CO_2 and CH_4 of gas samples extracted from GAB waters, suggesting that the two gas species are closely linked to each other (Italiano et al., 2014). CH_4 is abundant in water-dominated geothermal reservoirs where the mantle-derived CO_2 together with the other carbon components (CO and CH_4) equilibrate as a function of local P-T conditions. This equilibration process, and also the isotopic composition of CH_4 in bubbling gases from the hottest GAB water samples ($\delta^{13}C_{CH4} = -45‰$ and $\delta D_{CH4} = -175‰$), confirms the thermogenic origin of the CO_2 in the GAB and hence the existence of high-temperature geothermal reservoirs (Italiano et al., 2014). The release of mantle-derived volatiles implies a considerable amount of CO_2, as well as the supply of significant amounts of thermal energy to crustal fluids, including ground waters. High heat-flow anomalies in central Australia (Chopra and Holgate, 2005) coincide with seismic velocity anomalies recorded by Saygin and Kennett (2010). This part of central Australia, including the sampling locations of the travertines, has the thinnest crust (~30 km) of the Australian craton (Kennett et al., 2011). Our previous studies indicate that fluid transport was channelized as there is evidence that mantle-derived fluids are focused along the NFZ (Ring et al., 2016).

In summary, structural geology and isotope geochemistry show a connection between travertine deposition and tectonically-controlled CO_2 degassing.

2. U–Th ages and climate

Priestley et al. (2018) showed that spring travertine deposition occurred episodically at 465 ± 50 ka, 370 ± 20 ka, 335 ± 15 ka, 285–240 ka, 185 ± 10 ka, 160–150 ka, 110–100 ka and during the past 30 ka. Some of their ages correlate with wet periods (Fig. 2). However, other travertine deposition times are not related to wet periods and we specifically discuss the 285–240 ka, the 160–150 ka, and the < 30 ka intervals.

There is a long-term trend of strengthening continent-wide aridity in Australia and aridification intensified between 700 and 400 ka (Fujioka and Chappell, 2010). This aridification extended to the east coast by ca. 300 ka (Hocknull et al., 2007), so all of eastern and central Australia was arid by 300 ka. Travertine deposition within the 285–240 ka period (see Fig. 7 in Priestley et al., 2018) is interpreted by Priestley et al. (2018) as indicating an increase in fluvial activity in central Australia (Nanson et al., 2008) but if travertine deposition really is related to moister climates, older travertines should be more widely preserved. In addition, Ayliffe et al. (1998) concluded that during the 280–200 ka period there is virtually no speleothem activity recorded in Australia, which is inconsistent with a pluvial episode at this time. Nevertheless, pluvial intervals cannot be eliminated as a source of travertine in the last 300 ka, despite the overall aridification trend.

Priestley et al. (2018) argued that high fluvial activity prevailed between 150 and 140 ka throughout central and southern Australia coinciding with one of their travertine U-series ages of 149 ka. Magee et al. (2004) showed that the most pronounced aridity in the past 150 ka, as recorded in the Lake Eyre Basin, occurred in the latter half of MIS 6 (i.e. 150-130 Ma, Fig. 2). Two of our samples from Strangways Spring

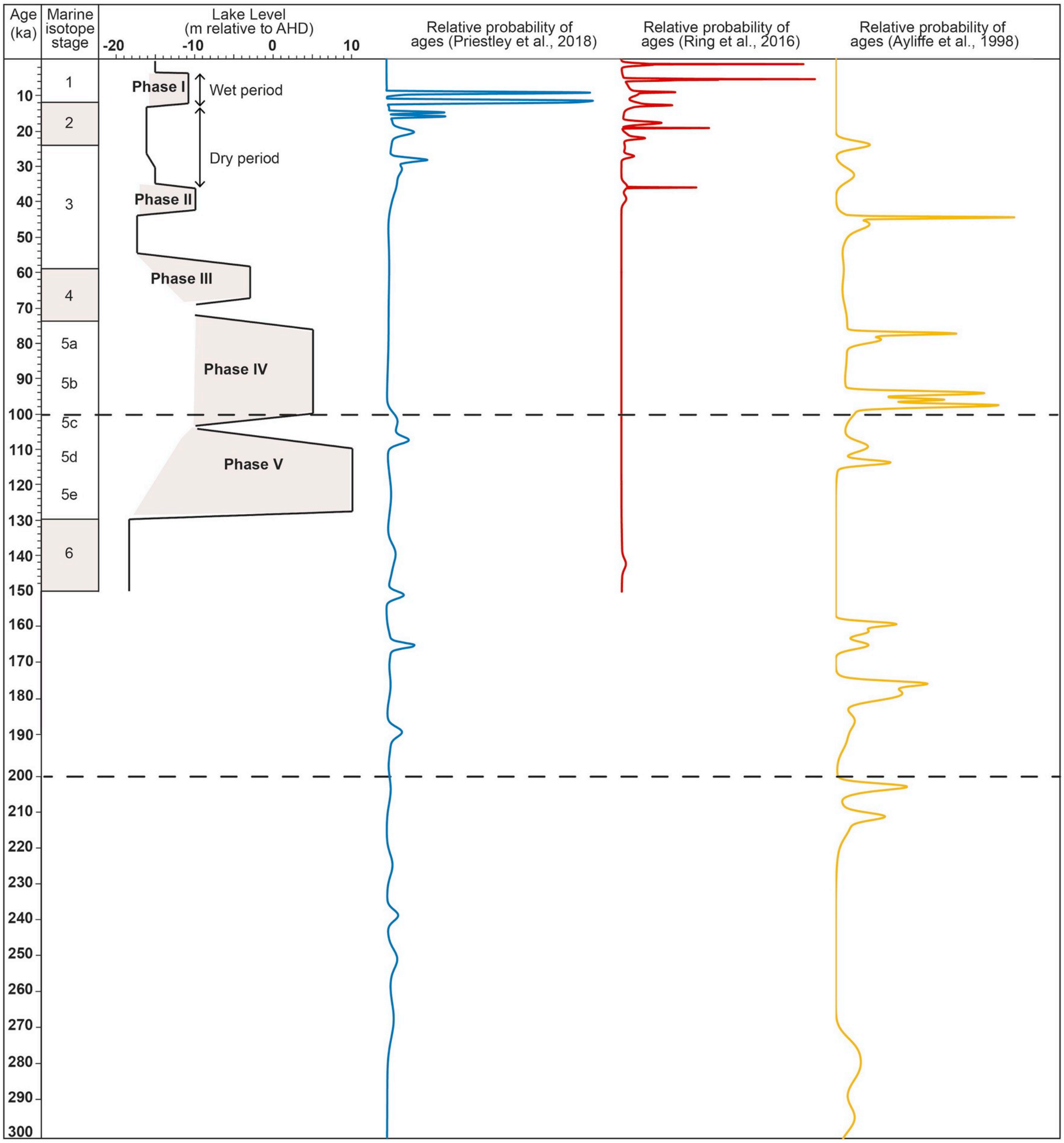

Fig. 2. Correlation of U-series ages of Priestley et al. (2018) and Ring et al. (2016) with late Quaternary climate proxies such as lake-level curve for Lake Eyre for the past 150 ka (Magee et al., 2004) and speleothem age probability density distribution (Ayliffe et al., 1998) for past 300 ka. Wet periods inferred from lake levels in Lake Eyre highlighted in grey for phase I to V. AHD = Australian height datum (mean sea level).

in the southwestern GAB yielded ages (141 ± 14 ka and 142 ± 2.9 ka; Ring et al., 2016) falling within this MIS 6 arid phase (Fig. 2).

Priestley et al. (2018) further claimed that in the last 30,000 years, age peaks at 26–20 ka, 15 ka, and 12 ka (Fig. 2) from Strangways and nearby Sulphiric springs are related to wet periods. They base their inference on a number of proxies throughout Australia, especially on records from Lake Frome, Lake Callabonna, Lake Lewis and from Mt. Chambers Creek (see references in Priestley et al., 2018) (Fig. 1). As we will show below, there are some regional variations in the climate proxies. Lake Eyre is located in close proximity to the travertine samples reported in Priestley et al. (2018) (Fig. 1), and the Lake Eyre records show a dry period between 34–12 ka (Magee et al., 2004). Combined, Priestley et al. (2018) and Ring et al. (2016) reported 24 U–Th ages of travertine falling within this dry (34–12 ka) period (Fig. 2). However, there is evidence for a relatively wet early part of the extended Last Glacial Maximum (LGM) with temperate and sub-tropical catchments in eastern Australia showing enhanced precipitation between ca. 35 and 28 ka (e.g. Hesse et al., 2018). This is followed by a drier (but still not very arid) phase between 26 and 19 ka. Further, alluvial fans formed in parts of the Flinders Ranges at ca. 30 ka (Quigley et al., 2007) indicating enhanced river flow. In short, it is not conclusive if the 26–20 ka period represents dry or wet conditions, but conditions were likely wetter before 26 ka, but no travertines are recorded.

In Mairs Cave in the Flinders Ranges of South Australia (Fig. 1) speleothem growth between 19 and 16 ka reflects a short and wet interval, which ended abruptly with a shift to drier conditions at 15.8 ka as indicated by a sudden significant increase in $\delta^{18}O$ and $\delta^{13}C$ values (Treble et al., 2017). Nine travertine U–Th ages of Priestley et al. (2018) are between 15.8 and 12 ka and fall into this dry climate interval (Fig. 2). However, since Mairs Cave is located more than 200 km south of the travertine deposits, more climate records closer to the Lake Eyre are required to conclusively assess the commencement of an arid period at 15.8 ka. Indeed, U–Th speleothem age data were interpreted as indicating humid climate conditions at ~12–11 ka for the Yudnamutana cave, a site much closer to the GAB springs (Quigley et al., 2010).

The mid-to late Holocene saw a shift to more arid conditions in central/southern Australia (May et al., 2015). The Holocene speleothem records from the Flinders Ranges (including parts of the Lake Eyre catchment) show that calcite deposition in the speleothems ended at about 5 ka, which has been interpreted by Quigley et al. (2010) to reflect the onset of modern more arid conditions. This is consistent with enhanced dust signatures from ca. 5 ka to the present (Gingele et al., 2007), and reduced inflow into Lake Eyre, which established its modern playa regime at this time (Magee et al., 2004). Travertines of less than 5 ka are present in the GAB (Fig. 2). However, according to Magee et al. (2004), reduced inflow after 4 ka established the modern ephemerally flooded playa regime. Significant flood events were recorded for the Wilkatana alluvial fans in the west-central Flinders ranges (Fig. 1), which occurred at 4.2 ± 0.6 ka, 3.1 ± 0.2 to 1.8 ± 0.1 ka, and between c. 1.8 ka and the present (Quigley et al., 2010). Although these were transient flood events, it cannot be ruled out that they might have influenced ground water tables sufficiently to generate spring deposits. Nevertheless, travertine deposition occurred since the creation of the GAB groundwater system over the last ~2 Ma (cf., Radke et al., 2000) regardless of whether regional rainfall was high or low.

There has been continuous water recharge from the uplifted margin in eastern Australia to the central GAB from about 2 Ma to modern times (Habermehl, 1996). Stable isotope ($\delta^{18}O$ and δD) signatures of the GAB waters have been geographically stable and relatively uniform in the last 1 Ma, with no evidence of paleoclimatic variations (Radke et al., 2000). Hydraulic gradients and conductivities of aquifers are very low. Therefore, groundwater velocity is very slow (1–5 m yr^{-1}) (Habermehl, 1980). Moreover, almost the entire groundwater circulation in the GAB is under confined conditions (Cox and Barron, 1998; Radke et al., 2000; Habermehl and Pestov, 2002), which cannot easily be periodically/systematically affected by paleoclimatic conditions.

In summary, as suggested by Priestley et al. (2018), some travertines in the southwestern GAB represent times of increased regional rainfall. Nonetheless, a number of travertines were deposited during arid conditions. Thus, there seems to be no unique climate control on travertine deposition in the GAB.

3. Linking CO_2 degassing in seismically active zones to water discharge

Although we disagree that climate was the main controlling factor for vein travertine precipitation in central Australia, we acknowledge that travertine deposition in different geological and geographical settings can be affected by both hydrological conditions and seismicity (e.g., Minissale et al., 2002; Faccenna et al., 2008; Vigranoli et al., 2016; Uysal et al., 2009, 2011; 2019; De Filippis et al., 2012). De Filippis et al. (2013) showed that plateau or bedded travertines grows through lateral progradation when the water table is high during warm and/or humid periods, whereas vein travertines grows vertically during dry periods. The comparative model of De Filippis et al. (2013) proposes that the volume of water discharge is the main factor controlling the differences in the morphostratigraphic architecture of travertine.

All samples investigated by Ring et al. (2016) and samples reported by Priestley et al. (2018, e.g., their Fig. 2D) are vein travertines. Similar travertine deposits in seismically active regions in Turkey occur as fissure and injection veins (up to several decimetres thick). These travertine deposits are interpreted to be the product of rapid (lasting less than a few hundred years) precipitation from upward moving spring waters during seismic cycles (Uysal et al., 2007, 2009). Similarly, Priestley et al. (2018) reported that banded calcite veins show transient spring activity at 20.3 ± 1.6, 15.8 ± 0.2, 12.3 ± 0.1 to 11.6 ± 0.1, and 10.1 ± 0.1 to 9.3 ± 0.1 ka, with each episode lasting only a few hundred years. These ages are largely consistent with episodic veining events reported by Ring et al. (2016), with age clusters occurring every ~3–5 ka (see Fig. 6 in Ring et al., 2016).

Travertine deposition is still active in the GAB due to continuous availability and high CO_2 content in the GAB waters. The newly formed fracture systems are filled by travertine following seismic events, while recent precipitation takes place through mound spring vents forming circular ponds (Fig. 4c in Ring et al., 2016). Water outflow through artificial bores results in travertine deposition as soon as the water reaches the surface (Fig. 4d in Ring et al., 2016). This shows that wherever artesian water finds pathways to the surface it instantaneously precipitates carbonate due to pressure release (cf., Uysal et al., 2019). Therefore, immediately after the formation of fracture systems travertine precipitation commences, independent of regional climate. The current travertine deposition in central Australia occurs in an arid climate. We therefore propose that at least some of the U–Th ages reported by Priestley et al. (2018) and Ring et al. (2016) provide minimum ages of movement at the NFZ, and are not primarily controlled by regional climate.

4. Conclusions

Priestley et al. (2018) conducted a comprehensive uranium-series dating study of travertine deposits in central Australia, which helps to better understand the connection between travertine deposition and climate. Priestley et al. (2018) interpret the times of travertine deposition as representing times of high rainfall regionally. In contrast, we suggest that travertine precipitation in central Australia largely results from significant CO_2 production due to mantle degassing related to active tectonics.

Declaration of competing interest

We know of no conflicts of interest associated with this publication, and there has been no financial support for this work that could have influenced its outcome.

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