The tip of the iceberg: U-Pb dating shows that cave systems can be twice as old as their surface expression

Rieneke Weij, Jon Woodhead, Kale Sniderman, John Hellstrom, Liz Reed, Steven Bourne, Russell Drysdale, Tim Pollard

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rieneke.weij@uct.ac.za @rienekeweij www.qte-uct.com

The World Heritage Naracoorte Caves

The World Heritage Naracoorte Caves (southern Australia) are one of world's richest vertebrate fossil sites and preserve the complete record of Pleistocene fauna including the extinct Megafauna such as the Marsupial Lion, Giant Wombat and Giant Kangaroo.

Reed & Bourne, 2009; Reed & Arnold, 2017

Naracoorte Caves

Marsupial Lion
Thylacoleo carnifex

Studying these caves provide us with a unique window into the recent past that experienced 1) major climate change (glacial-interglacial cycles), 2) the arrival of the first humans on the Australian continent and 3) the extinction of Australia's giants.

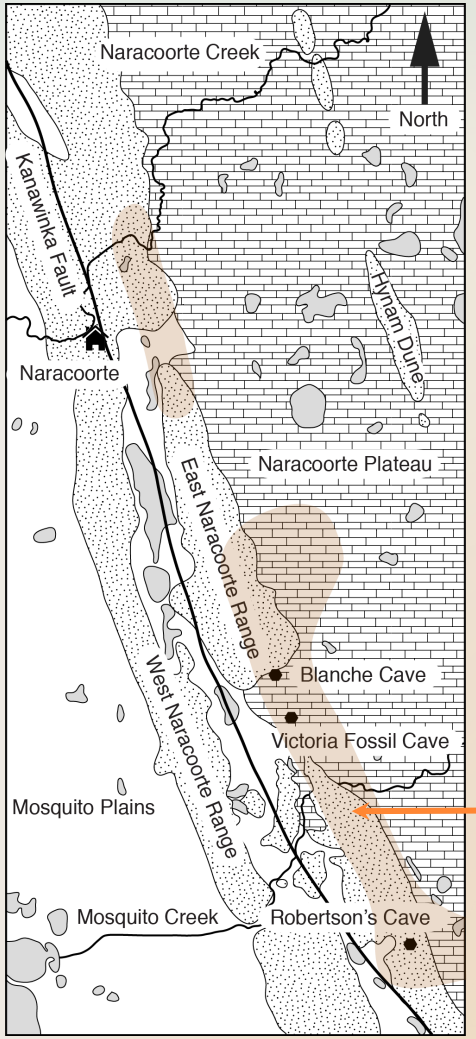
Under the current rapid global warming, studying how environments responded to past climate change becomes increasingly important to better understand what impact climate variability has on the adaptation and survival of regional flora and fauna.

Giant wombat*
Diprotodon

*not in yellow, that's the author ☺

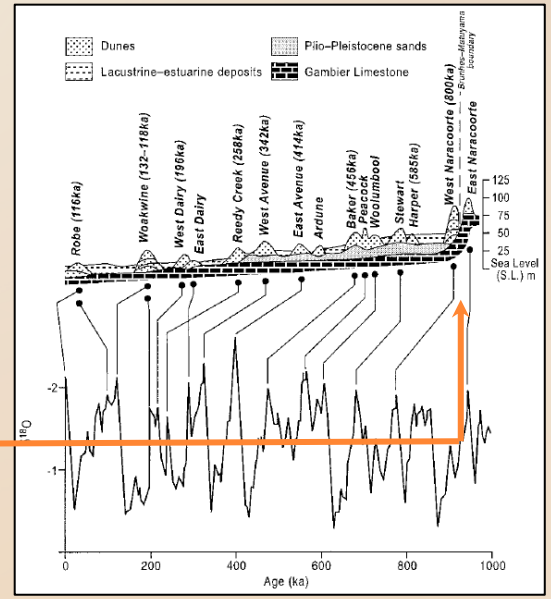
rieneke.weij@uct.ac.za @rienekeweij www.qte-uct.com

Karst and cave development history



Weij et al. 2022 (under review, Nature Comms E&E)

The Naracoorte caves have formed within the Miocene Gambier limestone below the East Naracoorte Range. This range is the first of a set of Late Quaternary fossil beach dunes that record interglacial sea level high stands from Naracoorte westward to the modern coastline.



Adapted from Murray-Wallace et al. (2001)

Dating these dune ridges can tell us when the karst system rose above the vadose zone and when cave formation started.

However, several attempts to date the East Naracoorte Range resulted in TL ages of ~720±70 ka and an AAR* age of 935±178 ka, meaning **it remains uncertain when the Naracoorte caves started to form.**

(Huntley et al. 1993; Murray-Wallace et al. 2001)

*amino acid racemization

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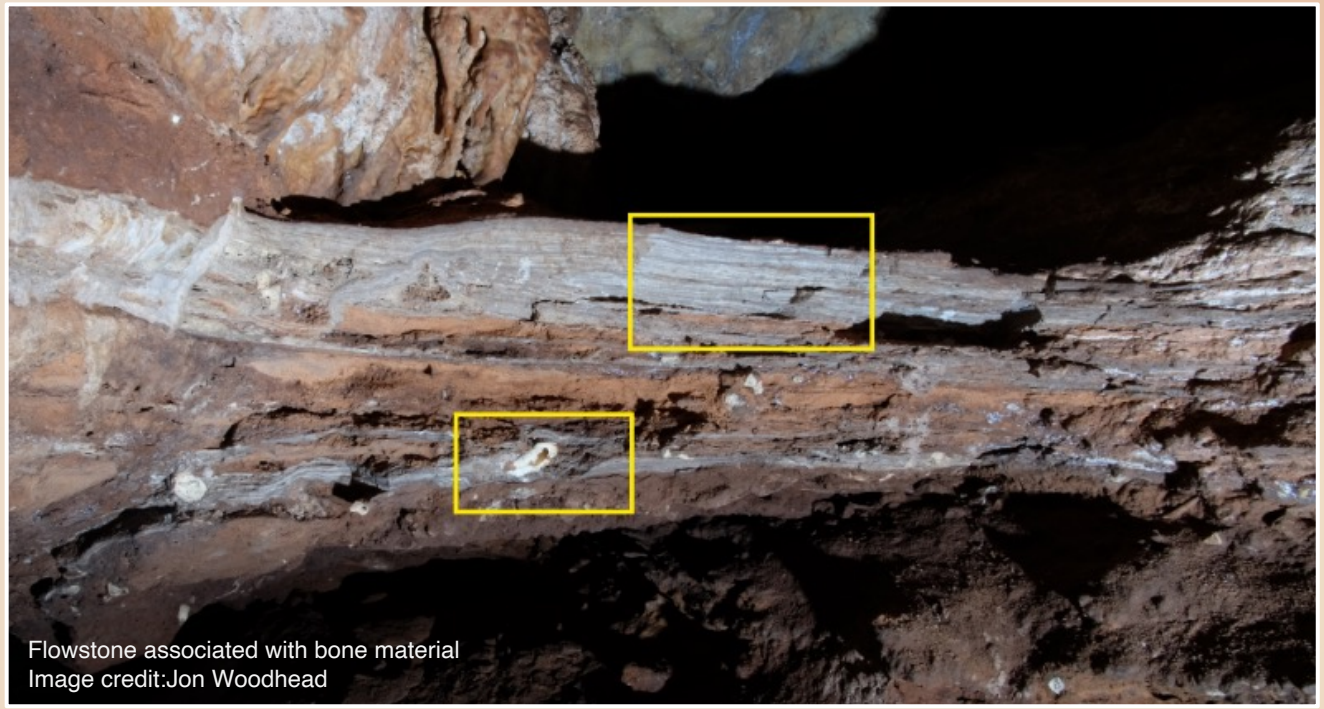
Pleistocene vertebrate fossil deposits

Solution-pipe cave entrance

Window-roof cave entrance

Bone material from Pleistocene fauna was transported into the caves through small dolines or solution pipes by small run-off events, and is excellently preserved in clastic sediment layers or sometimes imbedded within flowstones.



Flowstone associated with bone material
Image credit:Jon Woodhead

Dubious fact: Cave entrances acted as pitfall traps for the Megafauna which fell into the caves and succumbed there. The tragic death for so many of them in the past resulted in a fossil bone treasury for us scientists today!

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Ages of the fossil and dune deposits reported in literature

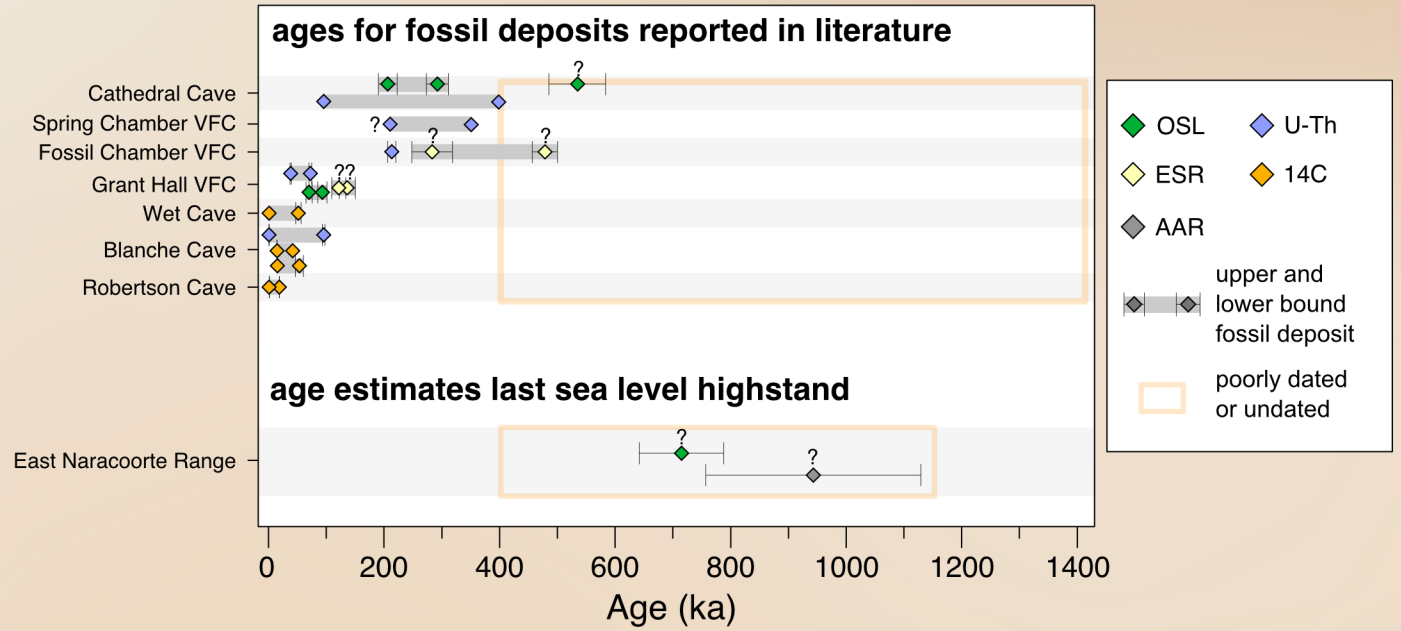
The fossil deposits have been dated (or estimated) using:

- U-Th TIMS dating from flowstones ‘bracketing’ clastic fossil-bearing layers (Moriarty et al. 2000)
- Electron Spin Resonance (Grün et al. 2001)
- Optically Stimulated Luminescence (Roberts et al. 2001; Prideaux et al. 2007; Arnold et al. 2022)

Bulk of the sediments date between 300-200 ka →

Currently, the oldest deposit dated is 528±41 ka →

Ages estimates of last sea level highstand 970-700 ka →



Weij et al. 2022 (in review, Nature Comms E&E)

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State of the field

The Naracoorte Caves most likely developed between 1.1 and 0.9 Ma (White & Webb, 2015). However, this estimate is based on TL and AAR ages with large uncertainties (see slide #5)

Speleothems grew periodically between 0 and 500 ka based on U-Th dating (Ayliffe et al., 1998), but what happened before that?

The bulk of the fossil deposits date between 300 and 200 ka, yet this is just the tip of the iceberg (Reed & Arnold, 2017; ABC news article, 2020).

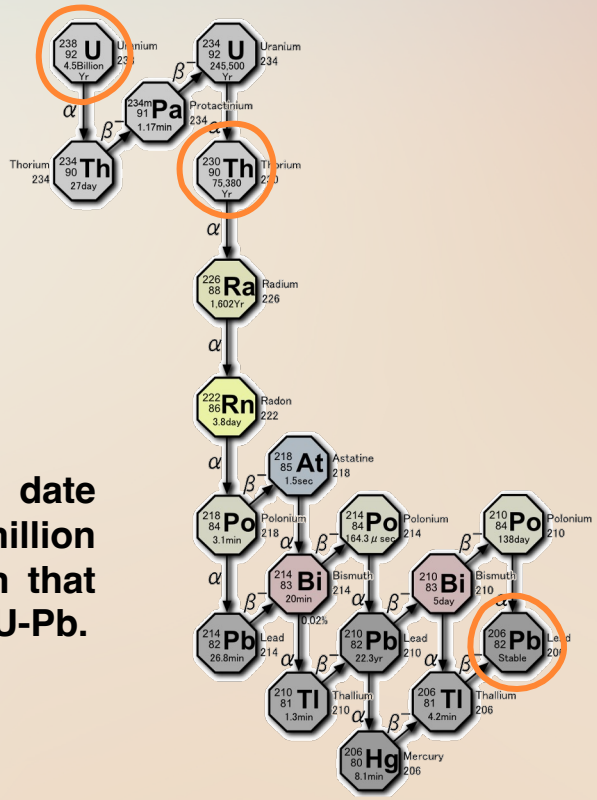
The antiquity of the World Heritage Naracoorte Caves remains uncertain. Robust chronology is required to understand changes in climate and biodiversity during the recent past (0 to ~1 Ma). This study aims to provide such chronology by U-Th-Pb dating speleothems from these caves.

Robust chronology from speleothems using U-Th-Pb

In (very very) short, the U-Th-Pb chronometer is based on the natural radioactive decay of ^{238}U into one of the daughter isotopes ^{230}Th, known as the U-Th chronometer) and ultimately into stable isotope ^{206}Pb.

The U-Th chronometer can date speleothems up to ~ half a million years and anything older than that can (potentially) be dated with U-Pb.

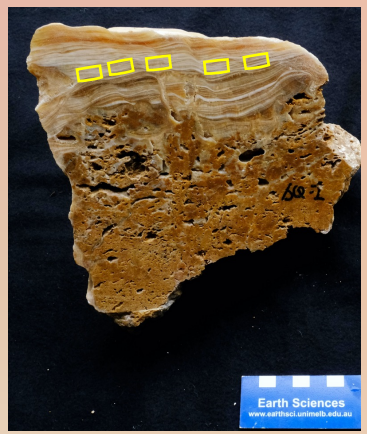
(see: Richards et al., 1998; Woodhead, 2006; Woodhead & Pickering, 2012; Woodhead et al., 2012)

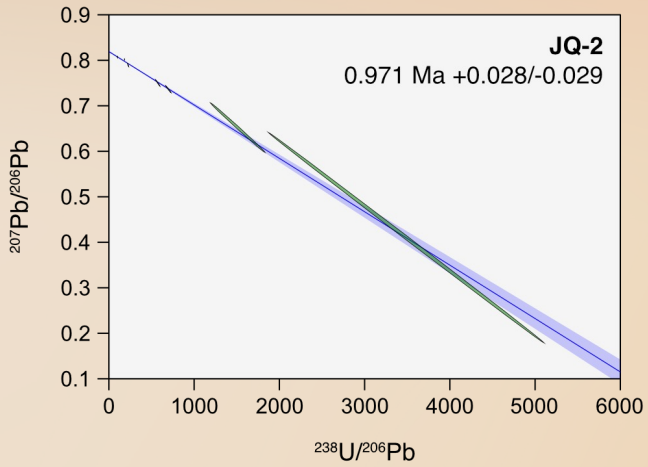


One of the U-series decay chains

To produce a U-Pb age, we:

- drill out multiple aliquots from a single growth layer →
- separate the U and Pb isotopes using chromatography
- measure the isotopes with MC-ICPMS
- produce a TW-isochron to obtain a U-Pb age →





⇨ Check out this much **quicker** (hooray!) chemistry protocol: Engel et al., 2020

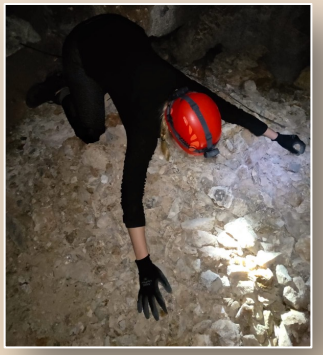
rieneke.weij@uct.ac.za @rienekeweij www.qte-uct.com

Beyond 500 ka: new, robust chronology from speleothems

Reconnaissance U-Th dating of ~300 pieces of speleothem rubble* showed that 10% is at the limit of the U-Th chronometer or exceeds the infinite age isochron.

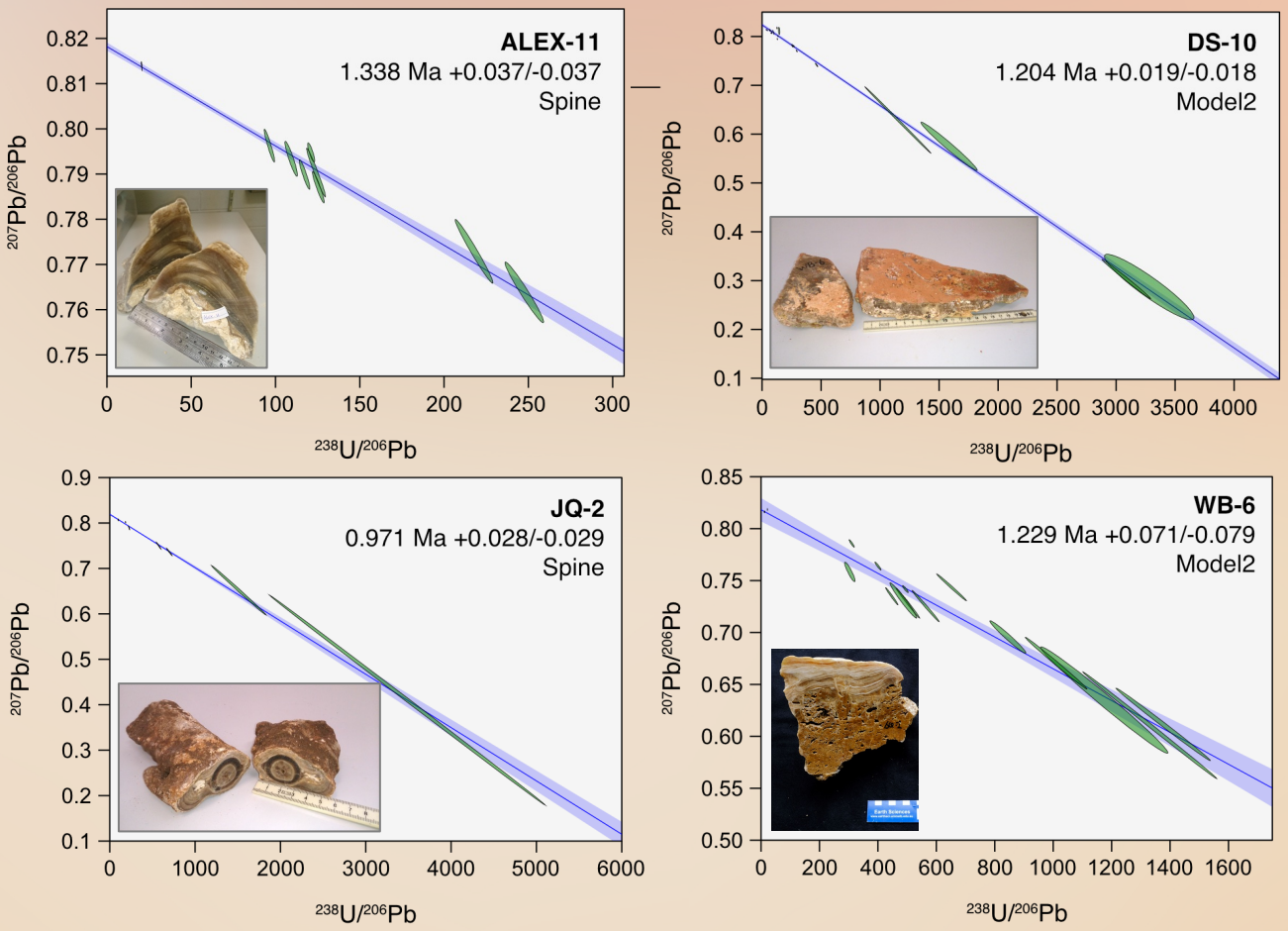
In other words, about 30 samples seemed older than 500 ka and were selected for U-Pb dating.

Of those, we successfully (= accurately and precisely) dated 15 speleothem samples with U-Pb techniques for the first time **extending the Naracoorte record way beyond 500 ka with ages ranging from 600 ka to 1.3 million years!**



*already broken material →

Some examples of isochrons and corresponding ages:



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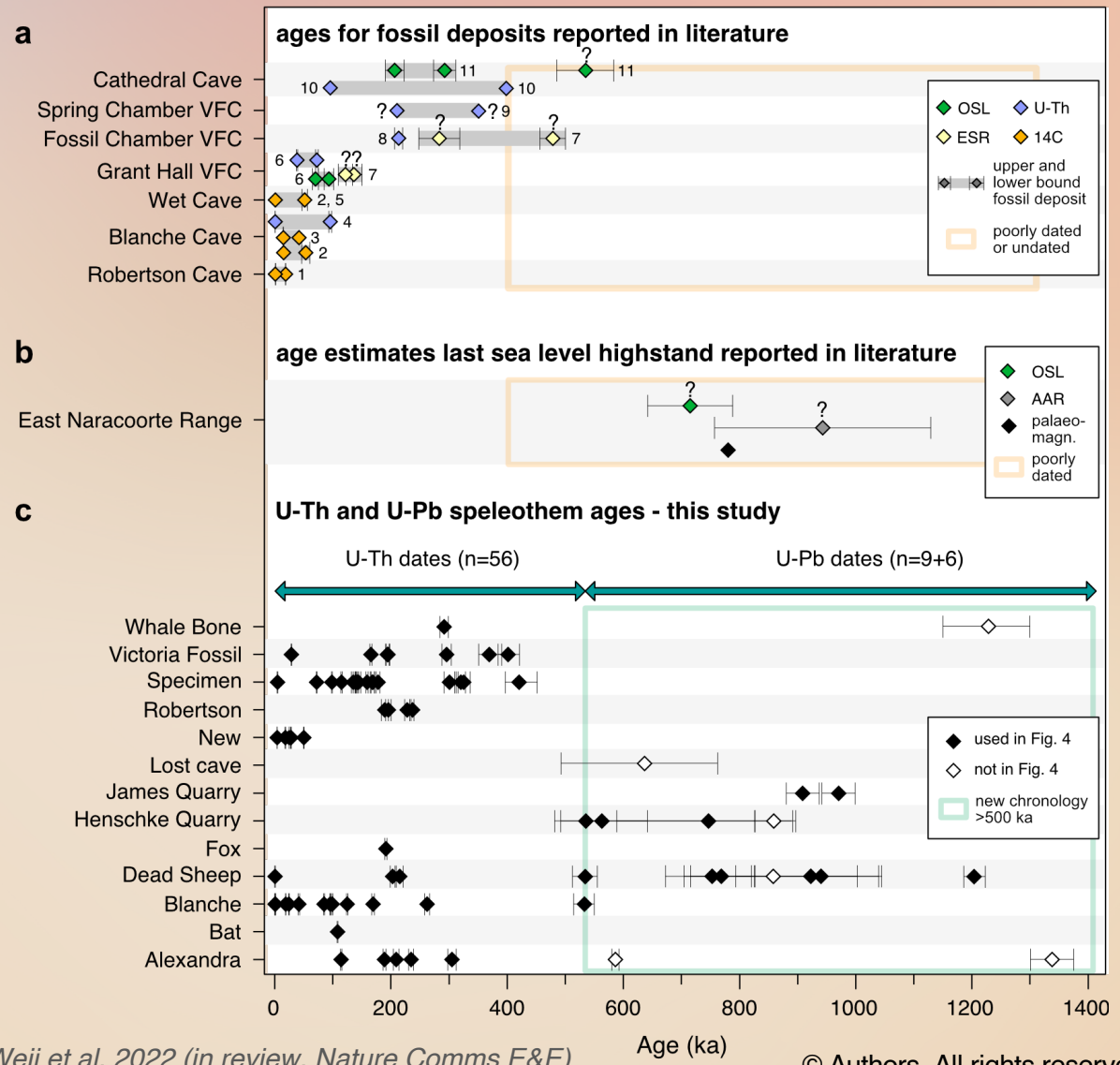
Beyond 500 ka: new, robust chronology from speleothems

Our new chronology extends the current understanding of **initial speleothem formation** by **~70%** and the **antiquity of initial cave development** at this site by at least **~20%.**



Weij et al. 2022 (in review, Nature Comms E&E)

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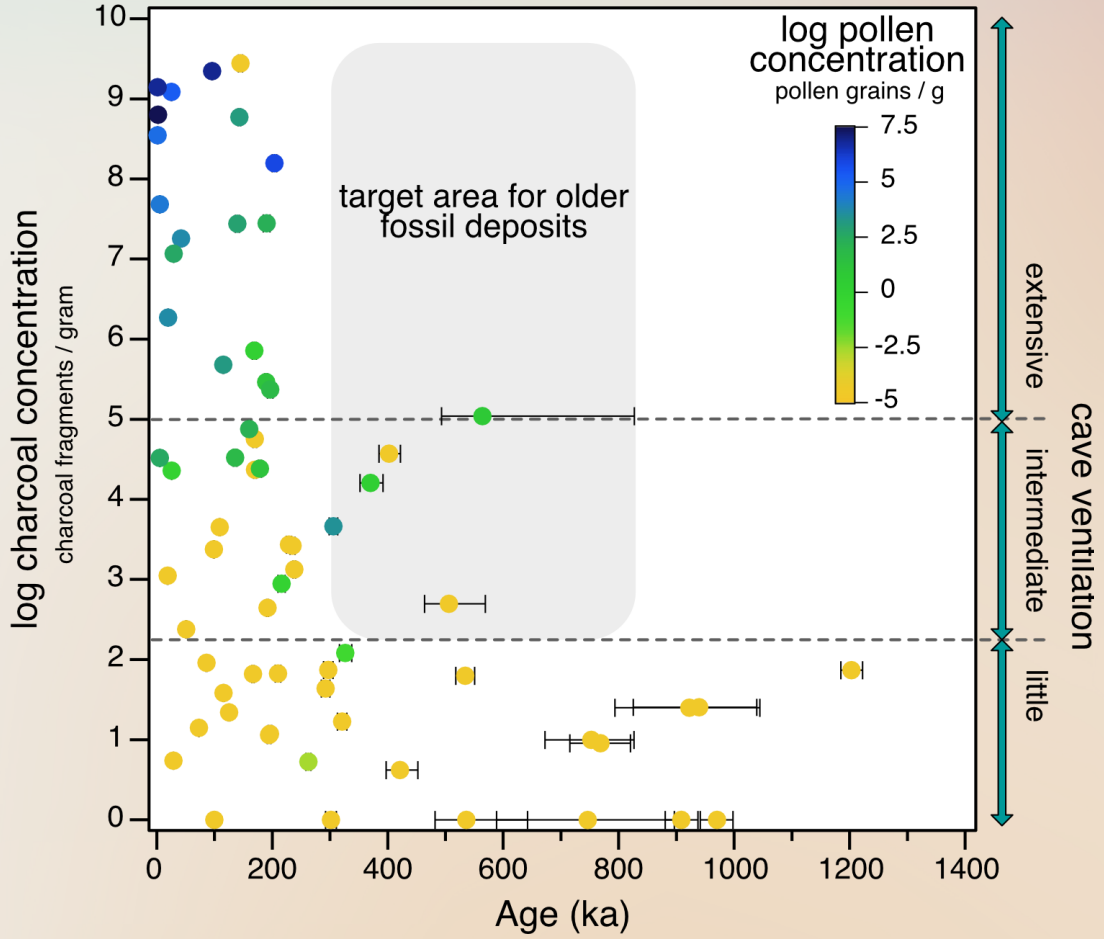
Cave opening and potential for fossil deposit beyond 500 ka



Weij et al. 2022 (in review, Nature Comms E&E)

Charcoal (and pollen) concentrations in our speleothem samples:

- independent proxies of cave openness
- 1.3 Ma – 600 ka: caves closed to the surfaces
- 600 – 250 ka: caves started to open
- From 250 ka: well-ventilated caves with larger/more extensive opening

This study shows that the Naracoorte Caves are much older than previously thought (> 1 Ma) and provides an upper limit (600 ka) for the antiquity of the fossil deposits.

rieneke.weij@uct.ac.za @rienekeweij www.qte-uct.com

Summary

Initial cave development started twice as early as initial cave entrance development and demonstrates that these processes can be widely separated in time.

The advantages of our approach are:

1) use of the U-Th-Pb system → firmer basis for establishing the minimum age of cave openings than other techniques

2) charcoal and pollen → independent proxies → demonstrate temporal and spatial trends in cave ventilation.

For further reading: stay tuned, our study is currently in review at Nature Communications Earth and Environments and will hopefully be published soon! ☺

These techniques can place robust constraints on the temporal extent of the fossil record in caves worldwide.

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Find me on Twitter: @rienekeweij
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