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Contemporary flowstone development links early hominin bearing cave deposits in South Africa

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ABSTRACT

The Cradle of Humankind cave sites in South Africa preserve fossil evidence of four early hominin taxa: *Australopithecus africanus*, *Australopithecus sediba*, *Paranthropus robustus* and early *Homo*. In order to integrate this record into a pan-African scenario of human evolutionary history it is critical to have reliable dates and temporal ranges for the southern African hominins. In the past a lack of precise and accurate chronological data has prevented the evaluation of the temporal relationships between the various sites. Here we report new uranium–lead (U–Pb) radiometric ages obtained from sheets of calcium carbonate flowstone interbedded between clastic cave sediments at the site of Swartkrans, providing bracketing ages for the fossiliferous deposits. The fossil bearing units of Swartkrans, specifically the Hanging Remnant and Lower Bank of Member 1, are underlain by flowstone layers dated to 2.25 ± 0.05 Ma and 2.25 ± 0.08 Ma and capped by layers of 1.8 ± 0.01 Ma and 1.7 ± 0.07 Ma. The age bracket of the Member 1 deposits is therefore between 2.31 and 1.64 Ma. However, by combining the U–Pb with biostratigraphic data we suggest that this can be narrowed down to between 1.9 and 1.8 Ma. These data can be compared with other recently dated sites and a radiometrically dated U–Pb age sequence formed: Sterkfontein Member 4, Swartkrans Member 1, Malapa, and Cooper's D. From this new U–Pb dataset, a pattern of contemporary flowstone development emerges, with different caves recording the same flowstone-forming event. Specifically overlapping flowstone formation takes place at Swartkrans and Sterkfontein at ~2.29 Ma and ~1.77 Ma, and at Sterkfontein and Malapa at ~2.02 Ma. This suggests a regional control over the nature and timing of speleothem development in cave deposits and these flowstone layers could assist in future correlation, both internal to specific deposits and regionally between sites.

1. Introduction

The single richest source of early hominin fossils and associated fauna within southern Africa is a series of dolomitic karstic caves, known collectively as the 'Cradle of Humankind' World Heritage Site, located 40 km northwest of Johannesburg (Fig. 1). These caves preserve the fossil remains of at least four early hominin taxa: *Australopithecus africanus*, *Australopithecus sediba*, *Paranthropus robustus* and early *Homo* (Berger et al., 2010; Broom, 1938; Clarke et al., 1970; Dart, 1925). One of the most significant outstanding issues in South African paleoanthropology is a precise method for dating the fossil remains of our earliest hominin ancestors, as most age assignments were previously based on biostratigraphic correlations with the better dated East African sites. An accurate understanding of the tempo and mode of hominin evolution is critical for determining the place of these taxa in our evolutionary history.

The South African cave sites contain two main sediment types: fossil bearing clastic sediments (often referred to as breccia) and speleothems. The speleothems consist of chemically precipitated calcium carbonates, typically occurring as stalagmites or flowstones, which are horizontal layers of calcite and rare aragonite, often interbedded with the clastic sediment. The U–Pb chronology of secondary cave carbonates or speleothems is a highly promising new radiometric dating method (Rasbury and Cole, 2009). Following the pioneering work of Smith and Farquhar (1989) and Richards et al. (1998), there are now a growing number of successful studies using U–Pb dating of speleothems (Cliff et al., 2010; Cole et al., 2005; de Ruiter et al., 2009; Lundberg et al., 2000; Pickering et al., 2010; Polyak et al., 2008; Walker et al., 2006; Woodhead et al., 2006, 2010). The flowstones that interdigitate between the cave sediments of the South African sites appear to be closed to U mobility after formation (Pickering et al., 2010) and can be directly dated to provide maximum

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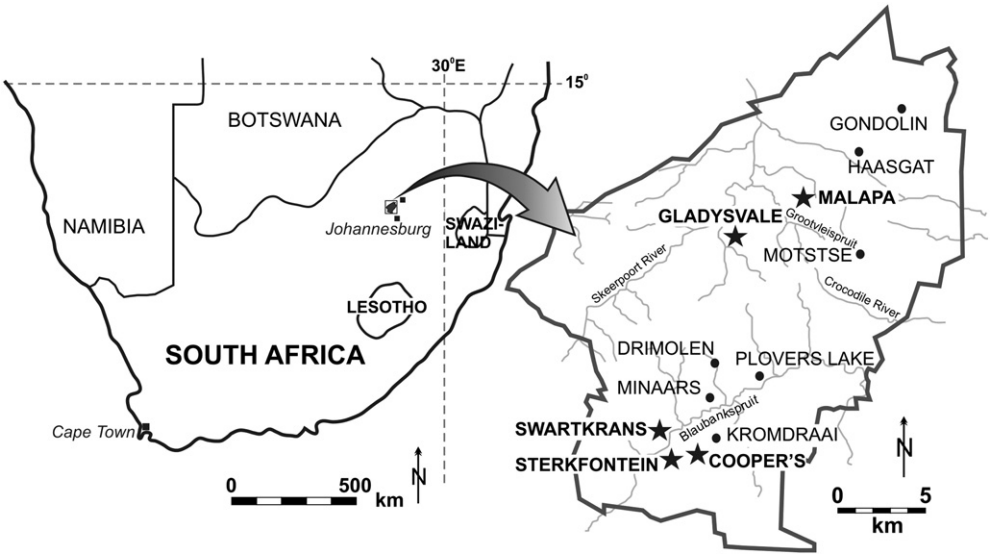

Fig. 1. An overview map showing the position of the "Cradle of Humankind" UNESCO world heritage site within southern Africa (left) and the relative positions of the sites discussed in the text (right).

and minimum ages for the fossil faunas preserved in the clastic sedimentary deposits trapped between them.

Under favourable conditions (high U and low initial Pb contents), the U–Pb method is also potentially much more precise than other existing dating techniques, such as U–Pb on fossil teeth (Balter et al., 2008), ESR on teeth (Curnoe et al., 2001) and burial dating of the sediments (Partridge et al., 2003), with errors that typically approach, and are sometimes below the 1% level. Here we present a new U–Pb chronology for the fossiliferous cave fills of Swartkrans and compare this to the published chronologies for the nearby sites of Sterkfontein (Pickering and Kramers, 2010; Pickering et al., 2010), Cooper's Cave (de Ruiter et al., 2009), and Malapa (Dirks et al., 2010) (Fig. 1). This is the first seriation of the South African hominin cave deposits based upon direct radiometric dating, allowing us to correlate between the sites using flowstones as markers and to assign ages to fossil bearing layers sandwiched between the dated flowstones. A similar approach to seriation of the South African cave sites uses the palaeomagnetic signals preserved in the flowstone and sediment layers to produce a relative chronology, complemented by the faunal records of the sites (Adams et al., 2007, 2010; Herries, 2003; Herries et al., 2006a,b, 2009, 2010). The direct dating, seriation and possible correlation of the sites and their associated hominin and other faunal fossils are fundamental to unravelling many important biogeographic issues. For instance, questions which revolve around the ancestry of *P. robustus* and whether it is derived from *A. africanus* or *Paranthropus aethiopicus* (Clarke, 2008; Johanson and White, 1979; Kimbel et al., 1988), or perhaps even the origin of the genus *Homo* (Berger et al., 2010), require an accurate understanding of the relative ages of the fossils assigned to these taxa.

2. Regional geology and karst relationships

The Bloubank River valley is host to several hominin bearing cave sites, including the Swartkrans, Sterkfontein, Cooper's, Malapa, and Gladysdale Caves (Fig. 1). These caves have formed traps for surface sediments over a period of several million years and, as a result of the abundance of early hominin and other fossils preserved in the sediments, their stratigraphic relationships have been the subject of much investigation (Brain, 1958, 1993; Clarke, 2007; Cooke, 1938; de Ruiter et al., 2009; Dirks et al., 2010; Partridge, 1978; Pickering and Kramers, 2010; Wilkinson, 1983). The fossil bearing sediments have been classified into different members (Brain, 1993; Partridge, 1978), units (de Ruiter et al., 2009), or facies (Dirks et al., 2010) depending on the sites. Here we provide a brief overview of Swartkrans, Sterkfontein, Cooper's Cave and Malapa (see Fig. 2), and propose a general model for the accumulation of the deposits preserved in these caves.

Swartkrans is situated on the north side of the Bloubank Valley, and occurs on the intersection of two fault traces that trend roughly East–West and North–South (Brain, 1993). Most of the original roof of the cave has been removed by erosion, exposing the fossil bearing sediments to the surface. The stratigraphy is complex, with evidence for several cycles of deposition and erosion (Brain, 1993, 1995). Five remaining members incorporating six discrete fossiliferous deposits are recognised, these being from oldest to youngest: Member 1 (consisting of the Hanging Remnant (HR) and Lower Bank (LB) deposits), Member 2, Member 3, Member 4 and Member 5. The world's largest sample of *P. robustus*, consisting of approximately 400 fossils from as many as 150 individuals, is derived from Swartkrans, as well as some 29 fossils assigned to perhaps 10 individuals of early *Homo* (Brain, 1981; Clarke, 1977; de Ruiter, 2001; Grine et al., 1996), making this the first South African site recording the co-occurrence of multiple hominin species (Broom and Robinson, 1950).

The Sterkfontein Caves occur on the south side of the Bloubank Valley and constitute one of the richest hominin-bearing sites in the world, with fossil remains of *A. africanus* and an as yet unnamed australopithecine in Member 4 and the Silberberg Grotto (Clarke, 1977, 2008; Dart, 1925; Wood and Richmond, 2000), alongside chronologically younger traces of early *Homo* in Member 5 (Kuman and Clarke, 2000; Pickering and Kramers, 2010). The cave system was developed by a simple solution excavation of the dolomite host rock along fracture systems, and today fossil-bearing sediments are exposed at surface, as well as underground. The most enduring interpretive description of the sediments is the member system proposed by Partridge (Partridge, 1978, 2000; Partridge and Watt, 1991), where the deposits are classified into six members, 1 to 6, oldest to youngest, respectively. This system was recently reviewed in detail by Pickering and Kramers (2010) who argue that, while the main fossil bearing sediments fall into Members 2, 4 and 5, the Member 3 terminology should be abandoned.

The site of Cooper's Cave is situated about 1 km east of Sterkfontein on the south flank of the Bloubank Valley and consists of a collection of three spatially distinct infills (Cooper's A, B, and D), all of which preserve fossil-bearing sediments. The Cooper's D deposits have been thoroughly excavated, yielding an abundant