Listening to the rocks: Caves, chronologies and environments associated with human evolution in the Cradle of Humankind

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Provocation 1: Caves and hominid fossil-bearing deposits of the Cradle of Humankind

The Cradle of Humankind (Cradle) UNESCO World Heritage Site in South Africa is among the world's richest landscapes for understanding early human ancestry and the geological worlds that early humans once inhabited. The fossil sites in the Cradle are hosted within the Malmani Subgroup of the Transvaal Supergroup, a carbonate platform sequence formed more than 2,500 million years ago. These dolomitic formations, subdivided into the Monte Christo, Lyttelton, Eccles, Frisco, and Oaktree formations, have experienced several episodes of erosion and tectonism which gave birth to the cave systems. Later, the caves opened to the surface and accepted sediments and fossils, leading to the preservation of bones that represent several species of humans and animals that lived in the past 4 million years. The discovery of fossils in the caves is linked

to the late-nineteenth-century gold rush in Johannesburg, when the demand for lime needed for gold processing and cement production led to quarrying of the dolomites. Searching for lime deposits, miners and geologists uncovered the fossil bones by accident.

Among the 16 hominin-bearing fossil localities of the Cradle, some of the notable sites are Sterkfontein, Swartkrans, Malapa, Drimolen, Kromdraai, and Rising Star. Sterkfontein has yielded many *Australopithecus africanus* fossils, amongst which are the famous individuals dubbed "Mrs Ples" and "Little Foot". Swartkrans is well-known for *Paranthropus robustus* and evidence of the earliest controlled use of fire. Malapa is the home of *Australopithecus sediba*, which bridges ape-like and human-like traits. The focus of the first talk was the Rising Star Cave, a cave system extending more than four kilometres and descending over 30 metres beneath the surface. Within its Dinaledi and Lesedi chambers, over 2,500 fossil elements belonging exclusively to *Homo naledi* were discovered (Dirks et al., 2015, 2017). These remains lie more than 120 metres from the cave entrance, sealed within fine muddy sediments devoid of other large fauna and coarse sediments (Berger et al., 2025). Their isolation and context present a profound enigma: how did the bodies arrive there, and what story does the geology tell about their final resting place?

Sedimentological analysis revealed that the Dinaledi Subsystem was filled by low-energy muddy deposits rather than catastrophic flood or debris flows. Unlike sites such as Sterkfontein and Drimolen, there is no evidence of coarse sediments consistent with high-energy transport capable of moving articulated skeletons (Berger et al., 2025). This lack suggests deliberate placement or natural entrapment under extremely calm conditions. Geological studies for testing the burial hypothesis utilized stratigraphic disturbance and geochemical analyses of sediments. Trace-element analyses revealed distinctive patterns in calcium, zinc, and other metals that differentiate bone diagenesis from host-sediment chemistry (Berger et al., 2025). These micro-signatures helped reconstruct post-mortem processes, clarifying that the fossils were chemically isolated over time.

Provocation 2: Geochronology of complex stratigraphy in the Cradle of Humankind

The second talk focused on determining the radiometric dates of cave deposits for indirect dating of the fossils they contain. Two methods commonly used in the Cradle were discussed. These are cosmogenic nuclide burial dating of quartz in the sediments and uranium-decay chain dating of speleothems. Speleothems are rocks formed inside a cave by precipitation from water dripping and flowing over walls and floors of the cave. In the Cradle they commonly have a calcium carbonate composition dominantly represented by the mineral calcite. Stalagmites, stalactites and flowstones are the most common forms of speleothems, and in the caves flowstones have become the favourite form to use for determining the ages of fossil-bearing rocks. That is because flowstones can underlie and overlie the rocks that contain fossils and thus can provide bracketing dates for the deposits.

Cosmogenic nuclide burial dating is based on a paradox: it measures what happens when rocks are no longer exposed to the sky. At Earth's surface, high-energy cosmic rays strike mineral lattices, producing rare isotopes at known rates. When the rock becomes buried, that cosmic bombardment ceases, and the isotopes decay at predictable speeds. Measuring the remaining ratio between beryllium-10 (^{10}Be) and aluminium-26 (^{26}Al) tells us how long the rock has been shielded from the surface, that is, how long it has been part of the deposits underground.

However, the story is not so straightforward in a cave. Muons are subatomic particles that can penetrate deep underground and produce cosmogenic isotopes, continuing to create nuclides even after burial. Understanding their contribution requires detailed modelling of depth, density, and geometry.

Uranium-based dating is conducted primarily through two radiometric methods, uranium-thorium (U-Th) and uranium-lead (U-Pb) dating, both of which rely on the natural radioactive decay of uranium isotopes but differ in their applicable materials, time ranges, and precision. In the (U-Th) method, the age of a sample

is determined by measuring the ratio between the parent isotope (^{238}U) and its intermediate daughter isotope (^{230}Th). Because uranium is soluble in water while thorium is not, freshly precipitated speleothems initially contain uranium but virtually no thorium. Over time, ^{230}Th accumulates through radioactive decay, allowing the time since mineral formation to be calculated. This technique is particularly effective for dating speleothems ranging from a few thousand years to about half-a-million years old.

The U-Pb method, in contrast, tracks the complete decay chain from ^{238}U to stable ^{206}Pb. Thus, the U-Pb system extends the datable range from hundreds of thousands to billions of years.

The (U-Th) dating technique was used to determine the ages of speleothems associated with the *Homo naledi*-bearing sediments, and yielded formation ages ranging between approximately 350,000 and 240,000 years ago, constraining the period during which the *Homo naledi* fossils were deposited in the Dinaledi Chamber (Robbins et al., 2021; Makhubela and Kramers, 2022). These results imply that *Homo naledi* persisted much later than previously thought, surviving into the Middle Pleistocene, a time when early *Homo sapiens* and other advanced hominins were already evolving elsewhere.

In a new cave called UW105, located within the Rising Star property, the combination of cosmogenic nuclide burial dating and U-Pb results points to a complex, multi-phase history of sediment infilling, collapse, and calcite sealing. This cave, though extensively damaged by lime mining activities, preserves a remarkable assemblage of fossils, including hominin remains, within the remnants of its breccia deposits. Despite the severe loss of stratigraphic context caused by mining activity, the site retains significant scientific potential.

Through the combined application of cosmogenic nuclide burial dating and U-Pb dating, the depositional history, geological context, and chronological framework are being reconstructed.

Provocation 3: Past landscape, environment, and climate reconstruction of the Cradle of Humankind

The third talk focused on reconstructing the past landscapes, environments, and climates of the Cradle to contextualize the fossil record and the evolution of the caves discussed in the previous talks. This work integrates (U-Th) dating, cosmogenic nuclide analyses, and stable isotope geochemistry to establish a detailed environmental framework for understanding how climate and surface processes influenced cave formation, fossil preservation, and hominin occupation. The talk highlighted the Lefika la Noka (LLN) tufa site (Onyeogu et al., 2025), a carbonate deposit formed by precipitation of calcium carbonate from spring and stream waters at the surface. Tufa deposits, unlike the speleothems that form inside caves, accumulate in open-air environments and record changes in hydrology, vegetation, and climate over time. The LLN tufas provide an invaluable surface analogue to the underground records of the Cradle, preserving evidence of freshwater flow, vegetation dynamics, and sedimentation that shaped the landscape above the fossil-bearing caves.

(U-Th) dating of the LLN tufas established the timing of carbonate precipitation episodes, providing chronological anchors for interpreting the environmental record. The (U-Th) ages, combined with microstratigraphic and geochemical observations, reveal alternating phases of tufa formation and erosion, which correspond to shifts between wetter and drier climatic periods in the Cradle during the late Quaternary.

To refine the paleoenvironmental reconstruction, stable carbon isotope ($\delta^{13}C$) analyses of the tufa were used to infer vegetation cover and atmospheric carbon dynamics. Carbon isotopes discriminate between plants that use different photosynthetic pathways: C_3 plants typical of trees and shrubs, and C_4 plants typical of tropical grasses. The isotopic results from LLN show oscillations between

C_3- and C_4-dominated vegetation, indicating alternations between wetter, wooded environments and more arid, grassy conditions. These vegetation shifts correspond closely with regional climatic fluctuations and demonstrate the responsiveness of the Cradle's landscape to changing moisture regimes.

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