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Comparison of U–Th, paleomagnetism, and cosmogenic burial methods for dating caves: Implications for landscape evolution studies

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Abstract

Caves are useful in landscape evolution studies because they often mark the level of previous water tables and, when dated, yield incision rates. Dating caves is problematic, however, because their ages are only constrained by the oldest deposits contained within, which may be far younger than the cave itself. We dated cave deposits in the Sierra Nevada using U–Th dating of speleothems, paleomagnetic dating of fine sediment, and cosmogenic ^{26}Al/^{10}Be burial dating of coarse sediment. The sampled caves formed sequentially as the water table lowered, providing an important stratigraphic test for the dating methods. Large discrepancies between deposit ages from similar cave levels demonstrate that, even when accurately determined, deposit ages can seriously underestimate the timing of cave development. Drip-type speleothems are most prone to this minimum age bias because they can accumulate long after caves form, and because the U–Th method is limited to ~400 ka. Paleomagnetic dating requires correlation with the global reversal chronology, and is hindered by a lack of continuous stratigraphy. The fine sediment analyzed for paleomagnetism is also highly susceptible to remobilization and deposition in cave passages well above base level. Cosmogenic ^{26}Al/^{10}Be dates bedload material deposited when caves were at or very near river level, and can date material as old as ~5 Ma. In the Sierra Nevada, speleothem U–Th ages and sediment burial ages from the same cave levels differ by as much as an order of magnitude. These results suggest speleothem ages alone may significantly underestimate cave ages

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and thereby overestimate rates of landscape evolution. Cosmogenic burial dating of coarse clastic sediment appears to be the most reliable method for dating cave development in mountainous regions.

Keywords: geochronology; Uranium-series; paleomagnetism; cosmogenic nuclides; caves; landscape evolution; Sierra Nevada

1. Introduction

Landscape evolution studies require dated geomorphic markers to document long-term erosion rates and reconstruct past landforms. Examples of such markers include fluvial or strath terraces, volcanic deposits, and erosional surfaces (e.g., [1–5]). However, geomorphic markers are commonly absent from rapidly eroding landscapes such as mountain belts, either because conditions were not conducive to their development, or because they were destroyed by erosion after they formed. Where markers are present, determining their age frequently poses a serious challenge.

Caves may be useful geomorphic markers because their development is often tied to river position, and because they are frequently located in landscapes lacking terraces or other markers. Although caves are limited to landscapes underlain by carbonate rock, such landscapes represent ~12% of the Earth's ice-free land surface [6], and are relatively common in mountainous regions. Certain caves can record landscape changes because they form at the water table and are subsequently left perched in valley walls as local base level is lowered by bedrock incision. When dated, these caves provide rates of incision, the primary erosional process governing the pace at which landscapes evolve (e.g., [7–15]).

Archeological, paleontological, and paleoclimatological studies seek to date specific deposits within caves (e.g., [16–18]). Landscape evolution studies differ somewhat because they seek the age of the cave itself. This poses a unique challenge for geochronology, as caves are voids that cannot be directly dated [19]. Although in certain rare cases Ar–Ar dating of clays produced during hydrothermal-related sulfuric acid dissolution can directly date cave development [20], this dissolution mechanism is limited to only a few sites globally. Far more common are caves formed by carbonic acid dissolution [6,21], whose ages must be younger than their host bedrock and older than materials deposited within them. As most caves are much younger than their host bedrock, cave ages are usually constrained by dating either clastic sediment carried into the cave by fluvial processes, or calcite speleothems formed in situ by meteoric drip water. Speleothems may be dated by U-series (typically ^{234}U–^{230}Th), and sediment by paleomagnetism and cosmogenic ^{26}Al/^{10}Be burial dating.

Any cave deposit necessarily postdates cave development, so deposit ages provide only minimum ages for cave development [7,19]. Correspondingly, rates of incision based on cave ages must be considered maximum rates [7,8]. The degree to which sediment and speleothem deposition accurately captures the timing of cave development has not previously been explored in detail. Here we compare ages for cave deposits in the Sierra Nevada, California, determined by U–Th, paleomagnetic, and cosmogenic burial dating. While each dating method has limitations, our results suggest that both speleothem U–Th dating and fine sediment paleomagnetism are particularly susceptible to potentially large systematic biases in cave age.

2. Cave development and landscape evolution

Cave passages form by dissolution of carbonate rock along paths of greatest groundwater discharge. Vadose passages form above the water table and typically consist of narrow, sinuous, and often steeply dipping canyon passages, while phreatic passages form at or below the water table and typically consist of tubes with rounded cross sections [21]. Although deep phreatic passages can form well below the water table, their U-shaped longitudinal profiles are distinct from the low-gradient profiles of shallow phreatic tubes formed along water table surfaces [6,21,22]; these latter passages are most useful in cave-based landscape evolution studies. The simplest caves form when portions of rivers are briefly diverted into canyon walls, dissolving phreatic passages parallel to canyon walls (Fig. 1, left). Alternatively, sinking tributary streams dissolve cave passages along water table surfaces graded to river level (Fig. 1,