

**New $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He constraints on the age of the Upland Complex, central
Mississippi River Valley**

William Odom ^a, Florian Hofmann ^b, Roy Van Arsdale ^c, Darryl Granger ^a

^a Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette,
IN 47907, USA

^b Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E
California Blvd, Pasadena, CA 93225, USA; now at: Department of Earth and Environmental
Sciences, University of Munich, Luisenstr. 37, 80333 Munich, Germany

^c Department of Earth Sciences, University of Memphis, Memphis, TN 38152, USA

Corresponding author: William Odom (odomw@purdue.edu)

Abstract

The Upland Complex is a widespread terrace of the ancestral Mississippi River. It has played a central role in studies of the Pliocene Mississippi River drainage, as well as uplift and seismicity in the central Mississippi River Valley. Previous efforts to date the Upland Complex have yielded a range of age estimates spanning the Miocene through Pleistocene. We dated gravels and Fe-oxide cements from quarries of the Upland Complex in Arkansas, Kentucky, Mississippi, and Tennessee using $^{26}\text{Al}/^{10}\text{Be}$ burial dating and (U-Th)/He geochronology. Our $^{26}\text{Al}/^{10}\text{Be}$ burial dates revealed possible Pliocene-to-Pleistocene depositional ages, while (U-Th)/He dating showed that the onset of weathering dates to at least the Pliocene. Taken together, the $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He age constraints demonstrate that the Upland Complex is at least Pliocene in age, and likely formed during a prolonged period of base level stability that preceded Pleistocene glaciations.

Keywords: Upland Complex, cosmogenic, burial dating, (U-Th)/He, geochronology, Pliocene

Highlights

- $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He dates provide a Pliocene minimum age for the Upland Complex
- The Upland Complex is likely mid-Pliocene and is no older than Late Miocene
- Formation of the Upland Complex may be related to widespread Pliocene aggradation

1. Introduction

The Upland Complex of the central Mississippi River Valley is a high-level terrace of the ancestral Mississippi River (Autin et al., 1991; Van Arsdale et al., 2007; Lumsden et al., 2016). This dominantly sand and gravel terrace deposit has been mapped from Illinois to Louisiana and has been assigned different names in different states. In Illinois and Missouri it is the Mounds gravel (Willman and Frye, 1970; Harrison, et al., 1999), in Kentucky the Lafayette gravel (Potter, 1955a; 1955b) and subsequently the Continental deposits (Olive, 1980), in Arkansas and Tennessee the Upland Complex (Autin et al., 1991; Saucier, 1994), and in Mississippi the pre-loess sand and gravel (Dockery, 1996). The Upland Complex is particularly important for several reasons beyond its significant economic value as the primary source of gravel over its extent (Van Arsdale et al., 2012; Behrman et al., 2019). It has been interpreted to be the southern remnant of a much larger Pliocene Mississippi River floodplain and drainage basin that extended well into Canada (Cox et al., 2014; Cupples and Van Arsdale, 2014; Lumsden et al., 2016). Van Arsdale and Cupples (2013) used the base of the Upland Complex as a structural datum to identify Quaternary fault displacement within the central Mississippi River Valley. Additionally, the base of the Upland Complex's elevation 70 m above the Holocene Mississippi River near Memphis, Tennessee, has been attributed to Quaternary isostatic uplift initiated by Pleistocene sea level decline and commensurate ancestral Ohio and Mississippi river incision. This regional erosion and isostatic uplift may be contributing to Quaternary faulting and ongoing seismicity in the New Madrid seismic zone (Calais et al., 2010; Van Arsdale et al., 2019). Furthermore, Pleistocene erosion of the Upland Complex would have contributed a significant volume of sediment ($>11,460 \text{ km}^3$) to the Pleistocene Mississippi River delta (Van Arsdale et al., 2019).

The Upland Complex is interpreted to be the remnant of a floodplain that once formed a continuous ~150 m thick blanket (Van Arsdale et al., 2019), extending at least 100 km east-west from western Tennessee to Crowley's Ridge in eastern Arkansas, and 700 km north-south along the Mississippi River (Saucier and Snead, 1989; Autin et al., 1991; Van Arsdale et al., 2007; Cox et al., 2014; Cupples and Van Arsdale, 2014; Lumsden et al., 2016). It consists of fluvial gravel and fine-to-coarse-grained quartz sand with minor silt and clay (Autin et al., 1991). Grain diameters are generally less than 2 cm, but individual clasts up to 60 cm in diameter are present (Russell, 1987). Typically, >80% of the gravel consists of well-rounded chert coated with Fe oxides, with the remainder consisting of well-rounded quartz and quartzite (Potter, 1955a; Guccione et al., 1990). The polished red-brown patina on the chert shows no percussion marks, indicating that it is post-depositional (Lumsden et al., 2016). The Upland Complex is capped by a ~2 m thick, Fe-rich paleosol disconformably buried beneath Pleistocene loess that dates up to 250 ka (Markewich et al., 1992). At the base of the Upland Complex is a south-sloping, relatively flat disconformity that overlies Paleogene formations (Saucier, 1994; Van Arsdale et al., 2007).

Given the widespread nature of this deposit, its apparent deposition near the Pliocene-Pleistocene climatic transition, and its proposed triggering relationship with the New Madrid seismic zone (Van Arsdale et al., 2019), constraining the age of the Upland Complex has significant implications for the geomorphic and geodynamic history of central North America. Proposed depositional ages range from Miocene (May, 1981) to Pliocene (Potter, 1955b; Anthony and Granger, 2006; Van Arsdale et al., 2007; 2019), early Pleistocene (Fisk, 1944; Doering, 1958), and Pliocene-Pleistocene (Autin et al., 1991; Rovey and Spoering, 2020). In this paper we present new age determinations for several quarries in Arkansas, Kentucky,

Mississippi, and Tennessee. We use $^{26}\text{Al}/^{10}\text{Be}$ burial dating to constrain minimum and maximum depositional times (supplementing previous work of Van Arsdale et al., 2014) and (U-Th)/He geochronology to provide a minimum age for the terrace from the crystallization of pedogenic goethite cement.

2. Methods

2.1.1. Cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ burial dating

We directly dated terrace deposits of the Upland Complex using the cosmogenic nuclides ^{26}Al and ^{10}Be . Cosmogenic nuclides are rare isotopes that are produced by the interaction of high-energy cosmic particles with Earth's atmosphere and rocks. Most surficial production of in-situ cosmogenic ^{26}Al and ^{10}Be is driven by spallation caused by cosmic-ray produced neutrons. In quartz, spallation of silicon forms ^{26}Al ($t_{1/2} = 0.705$ My), while spallation of oxygen forms ^{10}Be ($t_{1/2} = 1.389$ My) (Nishiizumi, 2004; Chmeleff et al., 2010; Korschinek et al., 2010). Below ~ 3 m of rock, production of cosmogenic nuclides via neutron spallation falls below approximately 1% its surficial value and most production occurs via muon interactions. Muons are secondary cosmic rays produced in the upper atmosphere, and cosmogenic nuclides may be produced from high energy muon reactions or capture of low energy muons. Because muons can penetrate significantly deeper than neutrons – on the order of hundreds of meters – they are an important consideration for post-burial production of cosmogenic nuclides in buried deposits.

2.1.2. Minimum burial age dating

The simplest form of burial dating works under the assumption that buried sediments originated from a steadily eroding landscape. In this scenario, the concentrations of ^{26}Al and

^{10}Be are functions of the cosmogenic nuclide production rates and rock erosion rates. The preburial concentration of a given nuclide is modeled by the equation:

$$N_{i,\text{inh}} = \frac{P_i}{\frac{1}{\tau_i} + \frac{\rho E}{\Lambda}} \quad (1)$$

where $N_{i,\text{inh}}$ is the inherited (pre-burial) concentration of the nuclide (at/g), P_i is the production rate of the nuclide (at/g/yr), τ_i is the radioactive mean-life of the nuclide, ρ is rock density ($\sim 2.6 \text{ g/cm}^3$), E is the pre-burial erosion rate (cm/yr), and Λ is the nucleon attenuation length (160 g/cm^2). As the pre-burial erosion rate increases, the pre-burial concentration of the nuclide will decrease. Eq. (1) shows production by only nucleons for simplicity but can be extended to include muon reactions as well (e.g., Granger and Smith, 2000; Balco, 2017). Following burial, the nuclide's concentration will decrease with time:

$$N_i = N_{i,\text{inh}} e^{-t/\tau_i} \quad (2)$$

where N_i is the measured concentration of the nuclide. Combining Eqs. (1) and (2) yields a model of nuclide concentration N_i that is a function of pre-burial erosion rate and burial age:

$$N_i = \frac{P_i}{\frac{1}{\tau_i} + \frac{\rho E}{\Lambda}} e^{-t/\tau_i} \quad (3)$$

Simultaneously solving Eq. (3) for measured concentrations of ^{26}Al and ^{10}Be yields both the burial age and pre-burial erosion rate, with the assumption that no post-burial production of ^{26}Al or ^{10}Be has occurred. It is appropriate for dating sediments that have been rapidly buried to depths where production via muons is negligible such as in caves (e.g., Granger et al., 1997), but this assumption is often violated in the case of terrace deposits, which can undergo significant post-burial production of cosmogenic nuclides caused by deeply penetrating muons. Post-burial production raises the measured $^{26}\text{Al}/^{10}\text{Be}$ ratio; as such, burial ages calculated using this approach are minimum deposit ages.

2.1.3. Maximum burial age dating

Post-burial production by muons causes Eq. (3) to underestimate the true age. We can place a maximum bound on the burial age by considering the maximum post-burial production by muons. If we assume that the sampled deposit was previously thicker and has been eroding over time, then the present depth of the sample is its minimum depth since the time of deposition. The production rate by muons at the present depth is therefore the maximum that the sample has experienced, and we can use its current depth to constrain the maximum depositional age. The maximum age may be modeled by adding a post-burial component to Eq. (3):

$$N_i = \frac{P_{i,z}}{\frac{1}{\tau_i} + \frac{\rho E}{\Lambda}} e^{-t/\tau_i} + P_{i,z} \tau_i (1 - e^{-t/\tau_i}) \quad (4)$$

where $P_{i,z}$ is the production rate of a given nuclide at the modern burial depth (at/g/yr). The value of $P_{i,z}$ for a given location may be estimated using exponential approximations (e.g., Granger and Smith, 2000; Schaller et al., 2001; Braucher et al., 2013) or computerized models based on geological calibration sites (e.g., Marrero et al., 2016; Balco, 2017). We calculated muogenic production rates using the parameters: $\alpha = 1$, $\sigma_{0,10} = 0.251 \mu\text{b}$, $\sigma_{0,26} = 4.21 \mu\text{b}$ (Marrero et al., 2016). As with the minimum burial age approach, Eq. (4) may also be solved simultaneously for measured concentrations of ^{26}Al and ^{10}Be . One complication brought on by high post-burial production, however, is that the maximum ages may be unconstrained, placing no upper bound on the true age. We have modified the traditional minimum-maximum burial dating approach to generate relative likelihood functions for the ages of dated deposits, as detailed in Section 4.2.

2.1.4. $^{26}\text{Al}/^{10}\text{Be}$ sample preparation

For this study, quartz sand, quartzite clasts, and chert clasts were collected from terrace deposits at depths ranging from 9-15 m below the contact between the Upland Complex and overlying loess. We sampled four locations for cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ burial dating: the Drum, Kuhn, Mid-South, and Tri-County quarries (Fig. 1). Individual clasts that were large enough for measurement (≥ 4 g) were manually crushed. Smaller gravels were mixed and crushed in the cases of VA-MID (m) and VA-TRI (m). Gravels and sands were sieved to 250-500 μm and rinsed with deionized water to remove fine materials, then run through a magnetic separator and heavy liquids (lithium heteropolytungstate) to remove contaminant minerals. All samples were subjected to selective dissolution in heated 1% HF/HNO₃. Sample aliquots were subsequently analyzed via inductively coupled plasma optical emission spectrometry (ICP-OES) to determine aluminum content as a test of purity.

Sufficiently pure quartz samples received ~ 260 μg of ^9Be carrier and were dissolved in concentrated HF/HNO₃. Aliquots were taken from each dissolved solution to measure final Al content. The samples were then evaporated, and excess Fe/Ti oxides removed via precipitation at pH ~ 14 in sodium hydroxide. Al and Be hydroxides were precipitated, rinsed, and redissolved prior to separation by cation and anion exchange column chromatography. The isolated Al and Be were converted to aluminum chloride and beryllium nitrate, dried, and decomposed to oxides by calcination with a propane torch. Al and Be oxide powders were then mixed with niobium and loaded into stainless steel cathodes. $^{27}\text{Al}/^{26}\text{Al}$ and $^{10}\text{Be}/^9\text{Be}$ ratios were measured at PRIME Lab via accelerator mass spectrometry (AMS) against the standards of Nishiizumi (2004) and Nishiizumi et al. (2007). Total Al, Be carrier, and AMS measurements are available in the supplementary data section.

2.2.1. (U-Th)/He dating

(U-Th)/He dating of goethite was used to determine the formation age of Fe-oxide cement of the Upland Complex. The goethite cement in the interstitial space of this quartz-dominated sand displays a mostly botryoidal growth texture (see supplementary figures), which is developed on length scales of tens of micrometers. Poly-crystalline goethite aggregates typically retain >90% of radiogenic He at earth-surface conditions and on timescales of millions of years, as shown by previous diffusion experiments and $^4\text{He}/^3\text{He}$ studies (e.g., Shuster et al., 2005; Vasconcelos et al., 2013; Hofmann et al., 2017). SEM images reveal homogenous goethitic material without obvious grain boundaries or inclusions of tens to hundreds of micrometers in diameter. Therefore, the goethite cement of the Upland Complex is a valid target phase for (U-Th)/He dating. Previous studies on Fe-oxides formed in weathering environments, most of all duricrusts (e.g. Vasconcelos et al., 2013; Riffel et al., 2016; Allard et al., 2018; Monteiro et al., 2018), have yielded geologically meaningful ages using similar material. Analytical procedures, including laser heating, helium measurement, sample dissolution, and elemental analysis, followed the ones outlined in Hofmann et al. (2020).

These ages provide information on the timescales of post-depositional weathering and soil formation. Fe-rich surficial systems frequently display dissolution of previous generations of Fe-oxide and re-precipitation to form new material (e.g., Hofmann et al., 2017; Monteiro et al., 2018). This cycling of Fe-oxides through dissolution-precipitation reactions leads to an age distribution skewed towards more recent ages. We therefore dated >100 aliquots to explore the temporal range of weathering and the earliest phase of post-depositional weathering, which can yield constraints on the depositional age of the Upland Complex.

2.2.2. Sample preparation

We sampled the Upland Complex for goethite (U-Th)/He dating in four different quarries: De Soto quarry, Drum quarry, Kuhn quarry, and Arlington quarry (Fig. 1). Samples consisted of bulk soil material with Fe-oxide cement and groundwater crusts. Groundwater crusts were crushed to a grain size of $\sim 200\text{-}500\text{ }\mu\text{m}$. Bulk soil material and crushate was sieved to remove material $<20\text{ }\mu\text{m}$ and $>2\text{ mm}$, and then density separated using a sodium polytungstate (SPT) solution of density $\sim 3050\text{ kg/m}^3$. The material was mixed with the SPT and centrifuged at 3200 rpm for 30 min. The supernatant was discarded, and the settled material was rinsed several times in distilled water. This process removed most of the quartz and other light minerals and left material highly enriched in Fe-oxides. Samples of the Kuhn quarry were treated with 0.1 M hydroxylamine hydrochloride at room temperature for four hours to selectively dissolve Mn-oxide grains (procedure after Chao, 1972).

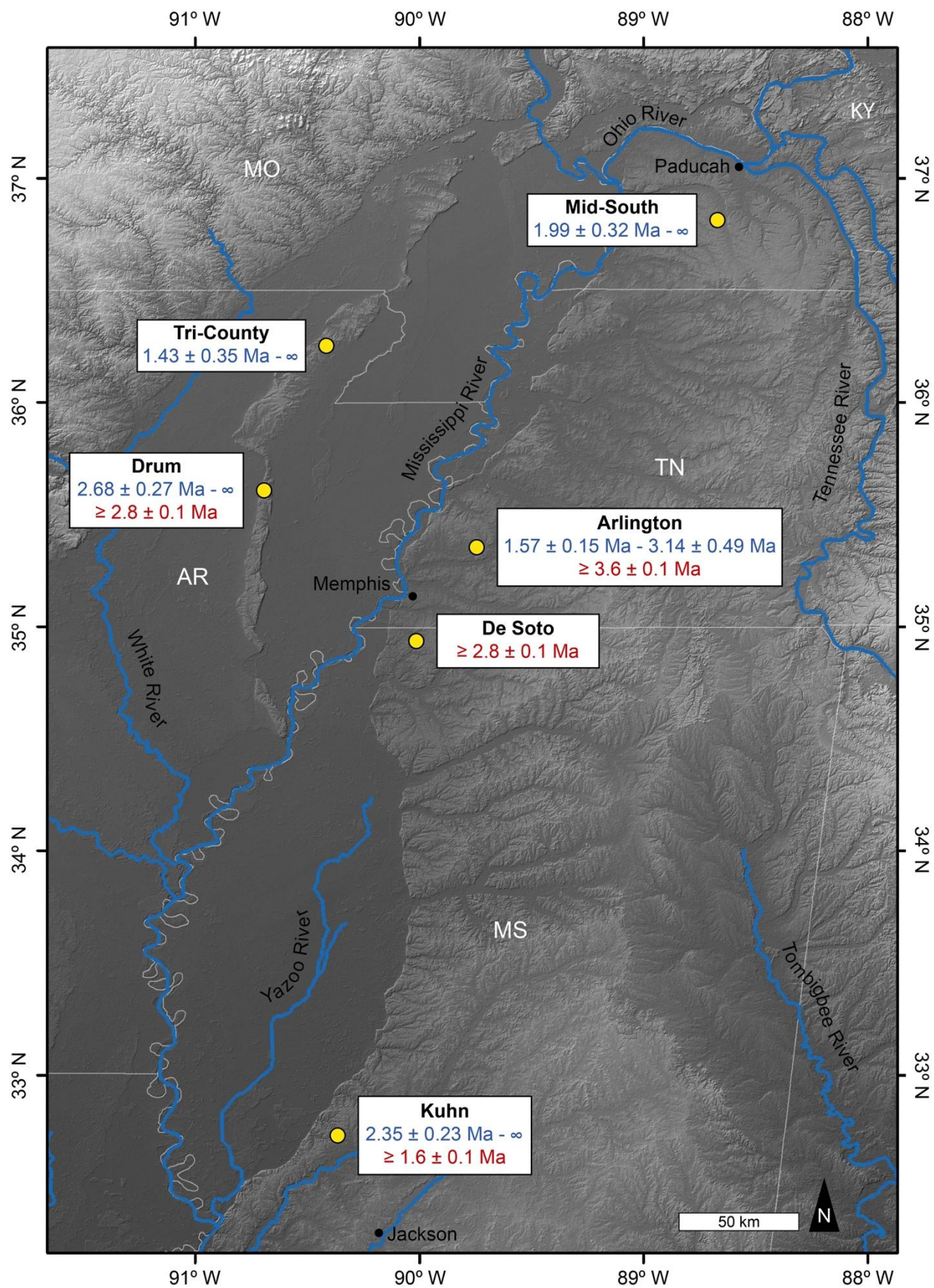


Figure 1. Locations of sites dated with cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He geochronology. Cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ burial ages of terraces are shown above (U-Th)/He ages and represent the 1σ (analytical uncertainty) minimum and maximum ages where available; minimum age constraints derived from the oldest (U-Th)/He ages (with 1σ uncertainty) for each site are shown below burial ages. Note that the Mid-South and Tri-County quarries only have $^{26}\text{Al}/^{10}\text{Be}$ burial ages, whereas the De Soto quarry only has a (U-Th)/He age. ***2-column fitting image***

2.2.3. Analysis

Aliquots of Fe-oxide cement free of visible inclusions and intergrowth with other phases were picked from this material and loaded into Pt tubes. Aliquots representing the center of interstitial goethite cement away from neighboring phases were picked to reduce the effect of possible alpha ejection and implantation. Degassing, ^4He measurement, dissolution, and ICP-MS measurement of U, Th, Sm, Fe, Mn, Al, and Si followed the goethite protocol described in Hofmann et al. (2020). Procedural He blanks were around 1 pcc (~ 45 amol) and measured He amounts were at least a factor of three above blank level (>3 pcc). Blanks were interspersed among sets of 6-12 sample measurements. Reported He measurements were blank-corrected using these procedural blank measurements.

Aliquots were screened for being pure Fe-oxide by measuring elemental contributions from substitution for Fe and from other phases. We rejected aliquots based on the following criteria: (1) the Fe-based mass was significantly lower than expected based on the physical dimensions of the aliquot, (2) aliquots with an Al, Si, and Mn content above reasonable limits for goethite stoichiometry, (3) Fe-based mass and trace element concentrations were comparable to other aliquots of the same sample but contained a much higher He concentration and subsequently produced ages that were geologically unreasonable. An elevated He concentration is most likely caused by He implanted from and contained in insoluble mineral inclusions, such

as zircon, and has been observed in previous studies (e.g., Hofmann et al., 2017; Hofmann, 2019).

The mineral phases of samples were identified using Attenuated Total Reflection Fourier-Transform Infrared (ATR-FTIR) spectroscopy by comparing them to known goethite, hematite, and quartz samples. Characteristic peaks for goethite are at 795 cm^{-1} , 899 cm^{-1} , 1662 cm^{-1} , and 1793 cm^{-1} , with an additional broad peak with a center around $3090\text{--}3110\text{ cm}^{-1}$. Quartz peaks are at 1079 cm^{-1} and 453 cm^{-1} , with an additional doublet at 783 cm^{-1} .

3. Results

3.1.1. Initial $^{26}\text{Al}/^{10}\text{Be}$ geochronology

Van Arsdale et al. (2014) previously dated a remnant of the Upland Complex in Arlington, Tennessee, 15 km northeast of Memphis using cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ in two samples from a Memphis Stone and Gravel Company quarry. These samples were collected at a depth of approximately 10 m below the top of the Upland Complex and processed by G. Balco for AMS measurement. Gravel sample 12-GG-UC2 yielded a minimum burial age of $1.35 \pm 0.15\text{ Ma}$ and a maximum burial age of $2.84 \pm 0.52\text{ Ma}$, while sand sample 12-GG-UC1S yielded a minimal burial age of $1.57 \pm 0.15\text{ Ma}$ and a maximum burial age of $3.14 \pm 0.49\text{ Ma}$ (all 1σ analytical uncertainties). These results indicate that this section of the Upland Complex is at least Early Pleistocene in age and may be Pliocene.

3.1.2. New $^{26}\text{Al}/^{10}\text{Be}$ burial ages

Measured ^{26}Al and ^{10}Be concentrations are provided in the supplementary data. The minimum ages were generally Pleistocene, with the exceptions of samples VA-DRUM (sand),

MID-1 (quartz gravel), and VA-TRI-52 (chert). Sample MID-1, a single quartz clast, featured an unusually old age and low $^{26}\text{Al}/^{10}\text{Be}$ ratio relative to its counterparts at the Mid-South quarry, indicating that it experienced previous burial. As such, it was excluded from further calculations. Similarly, the chert clast VA-TRI-52 had an excess concentration of ^{10}Be that lowered its $^{26}\text{Al}/^{10}\text{Be}$ ratio and increased its apparent age. This was attributed to meteoric ^{10}Be contamination that commonly occurs with cherts and led to the sample's exclusion from the final age estimate. VA-DRUM, being a sand fraction, likely contained minimal reworked material and yielded a valid Pliocene minimum age of 2.68 ± 0.27 Ma (1σ analytical uncertainty).

Pre-burial erosion rates were generally low but can be difficult to quantify when significant post-burial production has occurred. If post-burial production of $^{26}\text{Al}/^{10}\text{Be}$ is unaccounted for, the calculated pre-burial erosion rates will likely overestimate the true values. Conversely, accounting for maximum post-burial production will potentially yield underestimates of pre-burial erosion rates (see Fig. 2). Nonetheless, the pre-burial erosion rates that ignore post-burial production are useful for placing bounds on maximum erosion rates prior to sediment burial (see supplementary table). Sand fractions yielded generally slow pre-burial erosion rates, ranging from 6.6-21.8 m/My. Gravel fractions and individual clasts yielded somewhat higher pre-burial erosion rates, ranging from 7.0-33.9 m/My when the ^{10}Be -contaminated chert clast was ignored.

Although minimum burial ages for the remaining samples were generally Early Pleistocene and featured low uncertainties, the maximum burial ages were more widely distributed. In most cases, maximum ages were unconstrained toward infinity. These partial maximum burial ages aid in identifying more likely burial ages but leave open the possibility of infinite burial ages. Samples 12-GG-UC2 and 12-GG-UC-1S, both from the Arlington quarry, produced the only completely constrained maximum burial ages. Their respective burial ages permit either a

Pleistocene or Pliocene burial age for the Upland Complex at the Arlington quarry. This wide span of possible ages motivates an additional constraint – (U-Th)/He geochronology – on the true age of the Upland Complex. The high precision of (U-Th)/He dating on goethite cements allows a further constraint on the minimum age of Upland Complex deposits.

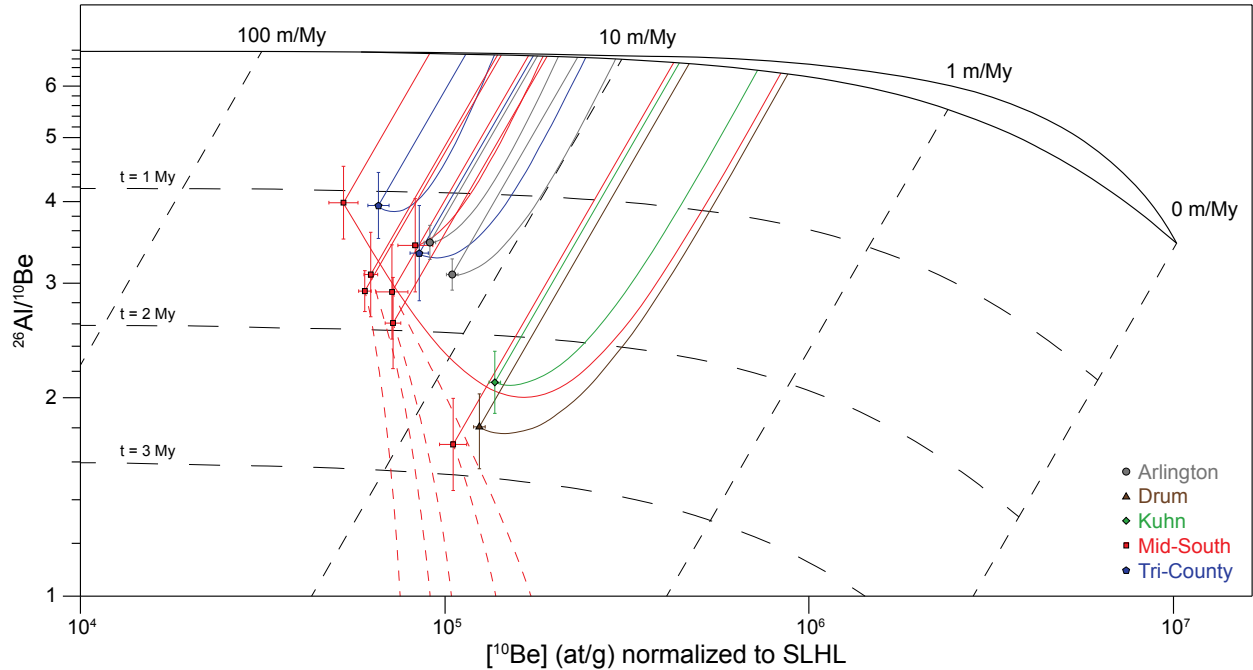


Figure 2. Measured samples and their projected pre-burial histories are shown on the exposure-burial diagram. Simple burial histories that do not account for post-burial production (minimum ages) are represented by straight lines; burial histories that do account for post-burial production (maximum ages) are represented by curves. Samples that yielded indefinite maximum ages have unconstrained burial histories represented by dashed lines. Note that pre-burial erosion rate estimates are lower when post-burial production is incorporated into sample histories.

3.2.1. (U-Th)/He Results

We acquired (U-Th)/He formation ages of a total of 102 individual aliquots, of which 18 were rejected based on the criteria outlined in the methods section. The ATR-FTIR spectra (Fig.

3) of samples analyzed for (U-Th)/He dating show that they mainly consist of goethite. The spectra also show a minor contribution of quartz in the bulk samples used for ATR-FTIR analysis. The aliquots picked from this material for (U-Th)/He dating were single grains of pure goethite with diameters of several hundred micrometers and did not contain any quartz. Since they are much larger than the mean alpha ejection distance ($\sim 20 \mu\text{m}$), no correction for alpha ejection or implantation was applied. A correlation between age and effective uranium concentration (eU), which would indicate detectable loss of U because of sample heating (see Hofmann et al., 2020), was not observed.

(U-Th)/He formation ages of goethite cements from the Upland Complex taken on depth profiles starting just below the “clay gravel” paleosol in the De Soto and Arlington quarries decline with depth (Fig. 4). All (U-Th)/He dates are given with analytical uncertainties to the 1σ level. The oldest ages (2-3.5 Ma) occur close to the contact with the well-developed paleosol. About 0.5 m below the contact, ages range from 0.5 Ma to 2 Ma. Ages are <1 Ma at ~ 1 m below the contact. A sample of a groundwater crust just above the modern groundwater table (Arlington-D) yielded a near-zero age.

Groundwater crusts from the Drum quarry yielded ages between 0.4 Ma and 3 Ma. A goethite cemented boulder from a depth of approximately 15 m beneath the top of the Upland Complex from the Kuhn quarry yielded ages of 0.1-1.5 Ma, with most ages between 0.2 Ma and 0.4 Ma, and only two aliquots >0.6 Ma.

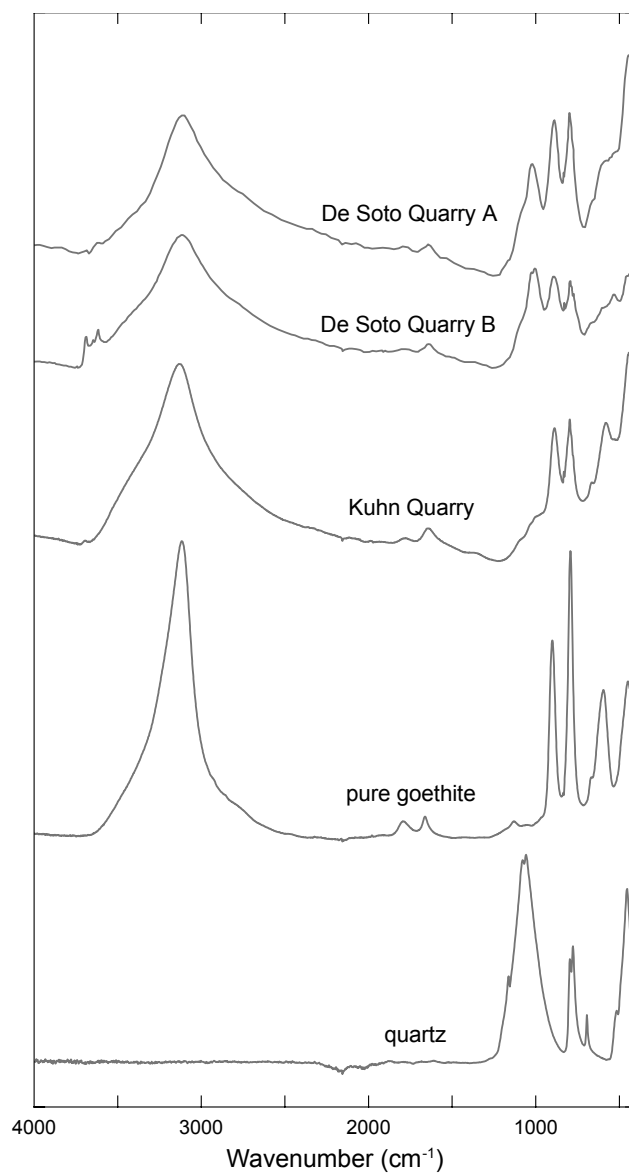


Figure 3. ATR-FTIR spectra of separates from the De Soto and Kuhn quarries compared against pure goethite and quartz. Separates are mostly composed of goethite, with a small amount of quartz present in the bulk material (only goethite was selected for (U-Th)/He dating). Samples from De Soto quarry also show a minor contribution from kaolinite (peaks at 3635 and 3730 cm^{-1}). ***1-column fitting image***

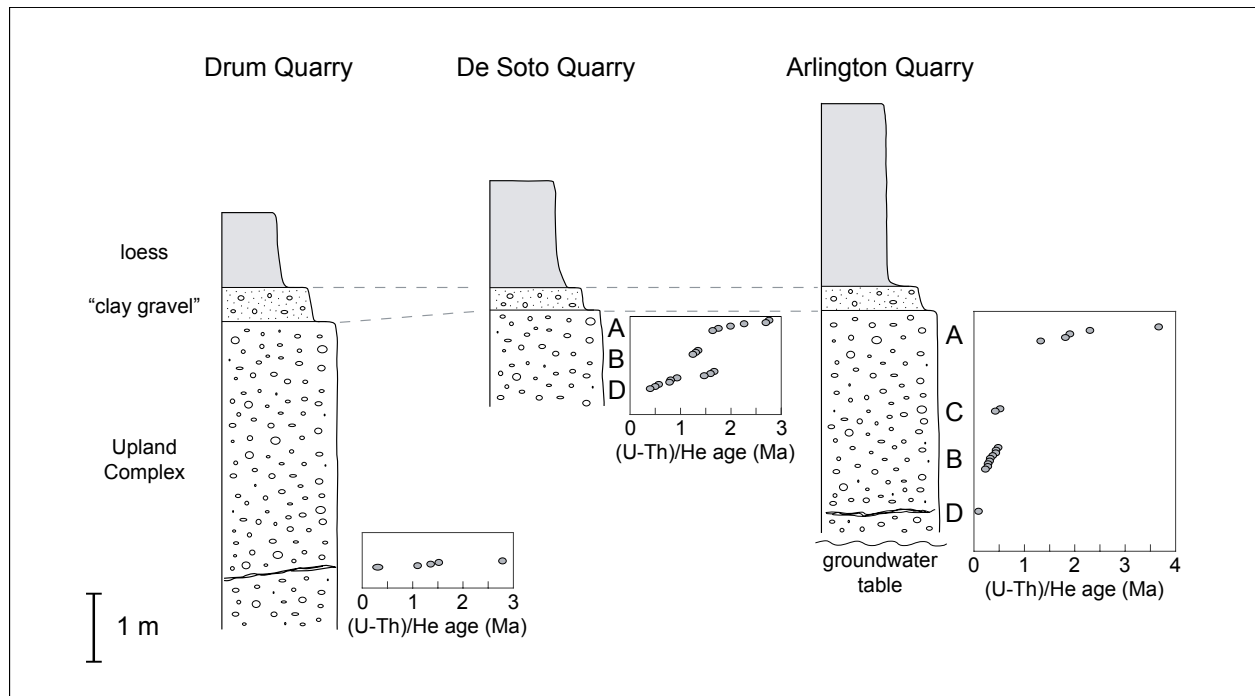


Figure 4. (U-Th)/He dates of goethite cements from the Upland Complex, which is capped by a paleosol (“clay gravel”), and Pleistocene loess. Ages are oldest close to the bottom of the paleosol and decline with depth. Groundwater crusts (indicated by black streaks in the stratigraphic sections) near the modern groundwater table (Arlington quarry) have a near-zero age.

4. Discussion

4.1. Implications of $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He results

Taken together, the $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He geochronology reveal a Late Neogene history of floodplain and terrace formation followed by post-depositional weathering. Based on $^{26}\text{Al}/^{10}\text{Be}$ ages alone, it appears likely that the Upland Complex formed during the Pliocene or Pleistocene; however, it is not possible to determine whether all dated terraces are the same age. The best $^{26}\text{Al}/^{10}\text{Be}$ constraints on the age of the Upland Complex were sourced from the Arlington quarry, but even these results cannot resolve the Pliocene or Pleistocene age of the Upland Complex. Our estimates of pre-burial erosion rates from sands indicate generally slow

erosion rates that support a pre-glacial origin, but do not conclusively demonstrate a Pliocene age.

The (U-Th)/He ages resulting from this study place basic constraints on the minimum ages of the dated sites, as in-place goethite formation must have postdated the formation of the Upland Complex. The similar distributions of (U-Th)/He ages from the Arlington and Kuhn quarries – mostly Late Pleistocene with rare Early Pleistocene to Pliocene ages – reflect the likelihood that older goethite deposits have likely been dissolved and reprecipitated, skewing the distributions toward younger ages (Fig. 5). An additional indication for this process is that the youngest ages are found close to the modern groundwater table, whereas the oldest ages are found well above the groundwater table. Some young ages may also be the result of intergrowth between older and younger material at length scales below that of an individual aliquot or partial helium-loss in the case of very fine-grained material. This could potentially lead to an underestimation of the minimum age. Though less evident at the DeSoto and Drum quarries, skewed age distributions demonstrate a potential limitation of using goethite formation ages as minimum bounds on the true age of a deposit. Even so, incorporating each site's oldest (U-Th)/He age significantly improved age estimates for three of the four sites dated with (U-Th)/He that featured Pliocene (U-Th)/He ages: De Soto quarry (2.8 ± 0.1 Ma), Drum quarry (2.8 ± 0.1 Ma), and Arlington quarry (3.6 ± 0.1 Ma). Based on (U-Th)/He data alone, it appears that the Upland Complex is a pre-glacial unit as these ages significantly predate the first major Pleistocene glaciation at 2.42 ± 0.14 Ma (Balco and Rovey, 2010).

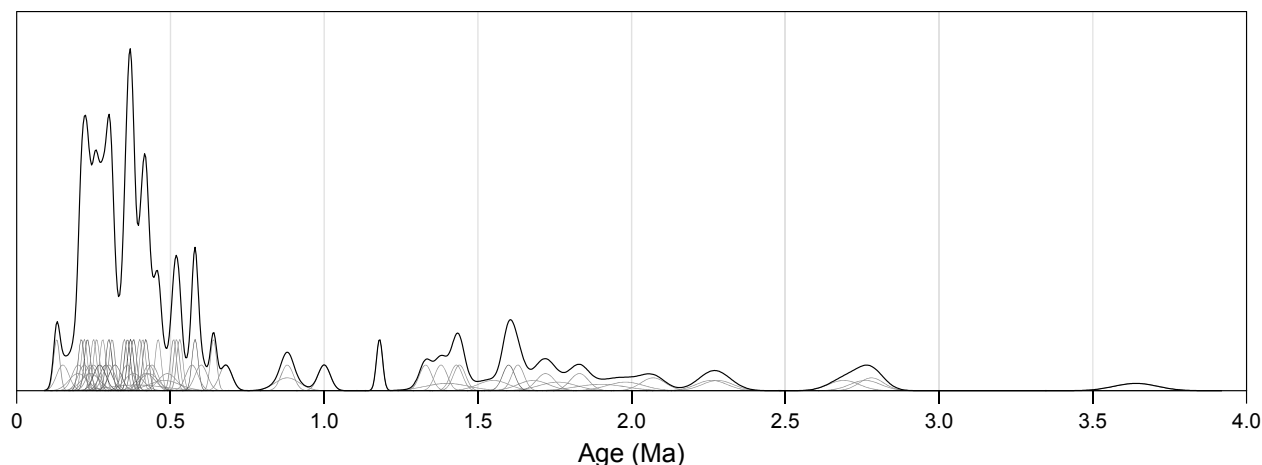


Figure 5. Normal kernel density estimates of (U-Th)/He ages of goethite cements. Individual ages are shown in gray; overall age distribution is shown in black. Note that the age distribution is skewed toward ages <0.5 Ma, reflecting the likely dissolution and reprecipitation of older Fe-oxide deposits. Plot created using camelplot.m

MATLAB code by G. Balco, available at http://depts.washington.edu/cosmolab/pubs/gb_pubs/camelplot.m ***2-

column fitting image***

4.2. Generating relative likelihood functions for dated deposits

To calculate the permissible range of $^{26}\text{Al}/^{10}\text{Be}$ ages for each sample, we solved Eqs. (3) and (4) for measured concentrations of ^{26}Al and ^{10}Be . Uncertainties were propagated numerically assuming normal distributions for the isotope measurements. We constructed a likelihood function for the total permissible age distribution of each sample by taking the minimum age from the left (younger) side of the minimum age likelihood function, and the maximum age from the right (older) side of the maximum age likelihood function. For cases with minor post-burial production, this approach yielded closed likelihood functions. In cases where the theoretical post-burial production calculated with Eq. (4) yielded greater concentrations than actually measured, the maximum age likelihood function was unconstrained on the high end.

To generate overall age estimates for individual quarry sites with multiple samples, we

assumed that (1) all sands and gravels of a given terrace deposit were the same age and (2) all (U-Th)/He ages represented minimum ages for the deposit, since goethite formation post-dated terrace deposition. We generated a likelihood function for the oldest (U-Th)/He age at each location that featured constant likelihood for all ages exceeding the (U-Th)/He age. This likelihood function was then multiplied by all of the $^{26}\text{Al}/^{10}\text{Be}$ likelihood functions at that location to generate an overall likelihood function for the site. We opted to multiply, rather than add, likelihood functions to set likelihood to zero in age ranges forbidden by any sample. At locations where only $^{26}\text{Al}/^{10}\text{Be}$ measurements were available (i.e., Mid-South and Tri-County quarries), we multiplied all $^{26}\text{Al}/^{10}\text{Be}$ likelihood functions. This yielded one final likelihood function of permissible ages per quarry, six in total. These likelihood functions were then normalized for each site to generate relative likelihood functions (Fig. 6).

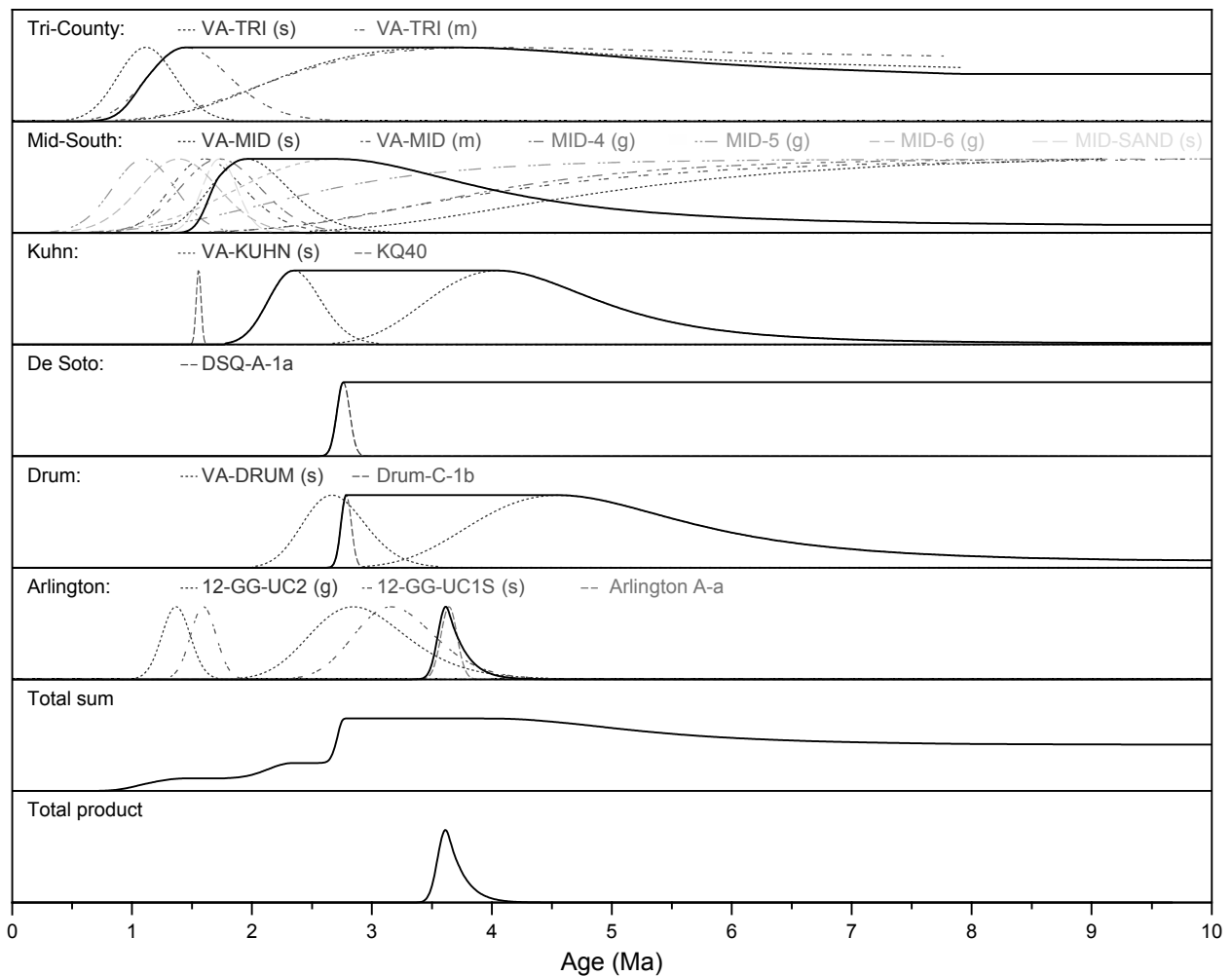


Figure 6. Relative likelihood functions for all sites and the Upland Complex as a whole. Each site's most likely age is represented by a solid line and was calculated by multiplying the normalized likelihood functions for the $^{26}\text{Al}/^{10}\text{Be}$ minimum/maximum ages and the oldest (U-Th)/He age at each site, where available. Dashed lines represent minimum and maximum ages from $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He dating; individual likelihood functions are available in the supplementary figure. The total sum represents the normalized sum of relative likelihood functions from all sites, whereas the total product assumes coeval deposition and was calculated from the normalized product of all relative likelihood functions. ***2-column fitting image***

4.3. Confirming a Pliocene age for the Upland Complex

By combining $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He geochronology, new age estimates emerge for several sites. Kuhn, Mid-South, and Tri-County quarries may still be Pleistocene in age, given

their distributions of $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He ages. It is clear, however, that the deposits at the Arlington, DeSoto, and Drum quarries date to at least the Late Pliocene. Summing all of the likelihood functions yields a curve that sharply increases during the Late Pliocene and reaches a maximum value at 3.61 Ma. Given the high uncertainty of most maximum ages, the relative likelihood function gradually tapers as age increases. If it is assumed that all deposits must be the same age, multiplying the relative likelihood functions for each site yields a well-constrained likelihood function for the age of the Upland Complex. This function is strongly controlled by the likelihood function for the Arlington quarry and also yields a most likely age of 3.61 Ma, with potential ages ranging from 3.40-4.29 Ma (Fig. 6). Whether or not the deposits were coevally formed, these models indicate that the Upland Complex is likely a Pliocene deposit.

The strong dependence of our age estimate on the ages from Arlington quarry is an important consideration when estimating the overall age of the Upland Complex. If the $^{26}\text{Al}/^{10}\text{Be}$ and (U-Th)/He ages from Arlington are discarded when estimating the Upland Complex's age, a slightly different age distribution is revealed. Because of the Pliocene (U-Th)/He ages for goethite deposits at the DeSoto and Drum quarries, it remains likely that the Upland Complex is indeed at least Pliocene in age. The lack of Pliocene goethite at the Kuhn, Mid-South, and Tri-County quarries may reflect dissolution of older generations of cement at those sites and does not preclude a Pliocene minimum age for those locations. Although the uncertainties of $^{26}\text{Al}/^{10}\text{Be}$ maximum ages at the remaining sites remain high, the maximum age distributions for the Drum, Kuhn, and Mid-South quarries all indicate a likely Messinian – but possibly Tortonian – maximum age (Fig. 6). As such, it appears likely that the Upland Complex is at least Pliocene in age and no older than Late Miocene, even in the absence of the measurements at the Arlington quarry.

These age ranges overlap within uncertainty with cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ burial ages for the Grover Gravel deposits in southern Missouri (Rovey et al., 2016) that have been argued to represent the transition from the late Pliocene to the early Pleistocene (Rovey and Spoering, 2020). Our age estimate could correspond to a period of normal or reverse magnetic polarity (Cande and Kent, 1995), so it is not possible to compare with the observation of Rovey and Spoering (2020) that the Grover Gravel was deposited during a period of normal polarity. Our evidence is compatible with the Grover Gravel and Upland Complex being equivalent but does not unequivocally demonstrate this hypothesis.

4.3. The Upland Complex floodplain and Pliocene sea level

Prior to the formation of the Upland Complex, a higher elevation Mississippi River deposited a floodplain mapped as the Citronelle Formation (Dockery and Thompson, 2016), preserved in southern Mississippi. Dockery and Thompson (2016) report that the Citronelle Formation is the remnant of a vast fluvial deposit preserved on drainage divides and is probably Pliocene in age. Near Crystal Springs, Mississippi, the base of the Citronelle is 141 m above msl and slopes south at ~ 1 m/km. The top of the Upland Complex at the latitude of Crystal Springs is ~ 115 m amsl, thus illustrating that these do not represent the same level of the ancestral Mississippi River. We hypothesize that incision through the Citronelle Formation and establishment of an Upland Complex floodplain may have been controlled by an Early Pliocene base level drop, perhaps coincident with a currently unidentified continental glaciation.

Our range of possible Pliocene burial ages for different deposits of the Upland Complex may reflect its gradual formation during a prolonged period of base level stability. At the De Soto, Drum, Kuhn, Mid-South, and Tri-County Quarries, we observed overlapping age

distributions during the mid-to-late Pliocene that postdate the Arlington Quarry deposit's formation at ~3.6 Ma. We propose that, given its broad areal extent and thickness, the Upland Complex was gradually deposited during the Pliocene. This gradual mechanism of formation yields similar yet asynchronous age distributions for different dated sites of the Upland Complex, as represented by a broad plateau on the sum of likelihood distributions for all quarries (Fig. 6).

The late Pliocene featured generally high sea levels (Miller et al., 2020) and included the mid Piacenzian Warm Period (mPWP), a well-documented period of elevated temperatures and high sea level (Robinson et al., 2018). Similar conditions were likely responsible for the formation of numerous erosional and aggradational features in North America. Along the east coast of North America, widespread wave-cut shorelines provide evidence of a sea level high stand from ~3.3-2.9 Ma (Rovere et al., 2015). In the Shenandoah Valley, Virginia, $^{26}\text{Al}/^{10}\text{Be}$ dating of alluvial fans and terraces has revealed widespread aggradation at ~3.3 Ma followed by gradual incision (Odom et al., 2019). It appears likely that the Upland Complex also formed as a result of Pliocene aggradation resulting from prolonged base level stability and a high sea level.

5. Conclusion

The age of the Upland Complex has been debated for decades. Previous efforts to date the Upland Complex with cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ improved age constraints but were unable to discern a Pliocene or Pleistocene age. Our combination of $^{26}\text{Al}/^{10}\text{Be}$ burial dating with (U-Th)/He dating of goethite cements demonstrates that the Upland Complex predates the Pleistocene and is very likely Pliocene in age. This supports the hypothesis that the Upland Complex was deposited prior to Pleistocene glaciation.

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7. Data availability

A complete dataset of (U-Th)/He ages, goethite compositions, and related data are included in the supplementary spreadsheet. This document also includes $^{26}\text{Al}/^{10}\text{Be}$ data, burial ages, and non-blank-corrected AMS data for $^{26}\text{Al}/^{27}\text{Al}$ and $^{10}\text{Be}/^9\text{Be}$ measurements. MATLAB code for likelihood function calculations is included in supplementary documentation.

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