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Intensifying Weathering and Land Use in Iron Age Central Africa

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Abstract:

About 3000 years ago, a major vegetation change occurred in Central Africa, when rainforest trees were abruptly replaced by savannas. The consensus is that the forest disturbance was caused by climate change. We show here that chemical weathering in Central Africa, reconstructed from geochemical analyses of a marine sediment core, intensified abruptly at the same period, departing significantly from the long-term weathering fluctuations related to the Late Quaternary climate. Evidence that this weathering event was also contemporaneous with the migration of Bantu-speaking farmers across Central Africa suggests that human land-use intensification at that time already had a significant impact on the rainforest.

A major vegetation change occurred in Central Africa during the third millennium before present, when mature evergreen trees were abruptly replaced by savannas and secondary grasslands (*1-4*). The consensus is that the forest disturbance was caused by a regional climate change (*1-4*). However, this episode of forest clearance occurred contemporaneously with the migration of Bantu-speaking peoples from near the modern Nigeria-Cameroon border (*5-9*). The so-called Bantu expansion led to diffusion of agriculture and iron smelting technology across Central Africa, with potential impacts on the environment (*10*). Whether the Bantu farmers played an active role in the Central African deforestation event remains an open question.

To provide further constraints on this issue, we have reconstructed the late Quaternary history of chemical weathering in Central Africa using a marine sediment record recovered off the mouth of the Congo River (Fig. 1). This core (KZAI-01; 05°42′ S, 11°14′ E), collected at a water depth of 914 m, provides a continuous record of the Congo River sediment discharge for about the last 40,000 years (see supporting online material, SOM). Although changes in chemical weathering intensity on continents are driven primarily by natural factors, such as physical weathering rates, vegetation, rainfall and temperature (*11*, *12*), intensive land-use and accelerated soil denudation, by increasing the surface area of minerals and rocks exposed to weathering, can also dramatically lead to much higher rates of chemical alteration (*13*). The degree of chemical weathering of fine-grained sediments can be inferred from the ratio of aluminium to potassium (Al/K). Potassium is highly mobile during chemical weathering and typically depleted in soils, whereas aluminium is one of the most immobile elements, being incorporated into secondary clay minerals such as kaolinite (see SOM Text). High Al/K ratios in Congo fan sediments are therefore considered to be indicative of periods of intense chemical weathering in the Congo Basin (*14*). Because downcore variations of the bulk chemical composition can also reflect changes in sediment source, we measured neodymium (Nd) and hafnium (Hf) isotopic ratios to discriminate between both weathering and provenance signals in our sediment record. The Nd isotopic signature of terrigenous sediments is retained during continental weathering and subsequent transport, thereby providing direct information on the geographical provenance of sediment (*15*). Hafnium isotopes exhibit globally similar behavior, but are also prone to significant fractionation during chemical weathering, because incongruent dissolution of silicate rocks leads to products of erosion having very distinctive but systematic Hf isotopic signatures (*16*, *17;* see SOM Text).

In this study, the bulk sedimentary major element composition of KZAI-01 was determined quantitatively at a 5-cm sampling interval (Fig. 2), corresponding to a temporal resolution of about 100-400 years. The age model for KZAI-01 is based on accelerator mass spectrometry (AMS) radiocarbon measurements of mixed marine carbonate fractions and tuning to a well-dated nearby sediment record from the Gulf of Guinea (GeoB6518-1; see location in Fig. 1). Additional age constraints were also obtained from ^{14}C-AMS dating of bulk sediment organic carbon (Fig. 2). Figure 3A shows that the Nd isotopic composition of sediments deposited at site KZAI-01 (average ε_{Nd} ~ -15.9 ± 0.6) is almost constant and very similar to that reported for present-day riverine particulates from the Congo Basin (*18*). This indicates that the source of material delivered to the ocean by the Congo River has remained unchanged during the Late Quaternary. By contrast, Hf isotopes display significant downcore variations (from ε_{Hf} ~ -6.8 to -13.9), which correlate well with the Al/K depth-profile (Fig. 3A,B). Because grain-size is homogeneous in this core, with medians ranging from 4 to 6 µm (*17*), the large range of ε_{Hf} values cannot be explained by changes in the relative proportions of mineral phases having distinct Hf isotope signatures. Importantly, therefore, these data show that downcore fluctuations of ε_{Hf} and Al/K ratios at site KZAI-01 both reflect variations in chemical weathering intensity within the Congo River drainage basin, rather than changes in sediment provenance and/or grain-size.

Comparison of our proxy data with organic geochemical and molecular records from core GeoB6518-1 suggests that much of the weathering signal at site KZAI-01 is driven by continental precipitation. From about 20,000 to 3,500 years ago, our weathering record exhibits strong correlation with the precipitation signal from core GeoB6518-1, inferred from the deuterium composition of plant waxes (*19*, *20*) (Fig. 3C). This observation suggests that chemical alteration in the Congo Basin has responded quickly to regional climatic changes, at least for the time scales being considered here. The trends towards wetter conditions that are visible in the GeoB6518-1 deuterium record, between about 18 to 13 kyr BP and ~12 to 9 kyr BP, coincide well with marked periods of intensifying chemical weathering. Similarly, the progressive onset of dryer conditions since ca. 6 kyr BP, which marks the end of the African Humid period, is accompanied by lower weathering rates. Reduced weathering rates also occurred during the Younger Dryas, between approximately 12.8 and 11.5 kyr BP, a period characterized by lower precipitation levels in Central Africa (*19*). In comparison, the evolution of mean annual temperatures in Central Africa has been very gradual since the last deglaciation, rising smoothly from about 21° to 25°C (*21*). Most probably, this suggests that temperature only played a minor role in controlling past chemical weathering variations in the Congo Basin during the Late Quaternary.

From about 3,500 years BP, an abrupt trend towards higher Al/K and Hf isotope values indicates rapidly intensifying chemical weathering. The weathering peak, centered at around 2,500 years BP, is characterized by the highest Al/K and ε_{Hf} values measured throughout core KZAI-01, indicating that global weathering rates in the Congo Basin during that period were higher than at any other time in the last 40 thousand years. After about 2,000 year BP, chemical weathering intensity values decreased slightly, but still remained at much higher levels than prior to 3,000 year BP. The weathering episode occurred contemporaneously with the major vegetation change that occurred in Central Africa during the third millenium BP, illustrated in Fig. 3E by the sudden increase in the abundance of herbaceous pollen taxa (*Graminaea*) at Lake Barombi Mbo (*3*) (see location in Fig. 1). This event is well-documented in numerous palynological and sedimentological records (*1-4*), from the Equatorial Atlantic coastal region to the eastern border of the Congo Basin, near Lake Tanganyika (Fig. 1). At many sites, proxy records for past vegetation patterns indicate a significant loss of primary forest between ~ 3,000 and 2,200 calendar year BP, and its replacement by savannas and other pioneer formations. To some extent, this large scale deforestation event shaped the African rain forest into its present-day vegetation patterns (*1, 2*). The cause usually invoked for the forest disturbance is a global shift towards seasonally dryer conditions in Central Africa (*1, 4*). This hypothesis is in agreement with the Late Holocene rainfall signals for tropical regions, which indicate reduced precipitation levels from ~ 4,000 years BP (*1, 19*). At that time, one would expect the weathering signal at site KZAI-01 to follow the same way it evolved during the last 40 thousand years when continental climate became dryer, i.e. towards lower intensity levels (lower Al/K ratios). Instead, evidence that chemical alteration strongly intensified during the third millennium BP, departing therefore from the long-term weathering fluctuations related to the Late Quaternary climate, suggests that this weathering event was not triggered by natural climatic factors.

We are confident that this pulse of intense chemical weathering does not reflect reworking of sediments on the shelf, due to sea-level rise for example, or denudation of strongly weathered ancient soils from the Congo Basin. Indeed, at the time of deposition, the global mean sea level in the oceans had already been close to modern values for several millenia at least (*22*). In addition, the calibrated ages for bulk organic matter samples in this part of core KZAI-1, which include a significant continental organic fraction (*23*), agree well with those inferred from our age model (determined from radiocarbon dating of marine carbonate material; see Table S3). Importantly, this suggests that the suspended particles transported by the Congo River during that period were mainly derived from relatively young soils, rather than from older tropical soils. Taken together, these observations clearly show that the anomalously high Al/K values in the upper part of core KZAI-01 correspond to a true contemporaneous signal of chemical weathering from the Congo Basin.

In fact, recent archaeological surveys showed that the deforestation event in the third millennium BP coincided with the large-scale settlement of Bantu-speaking farmers in sub-Equatorial Africa (*4*, *10*, *24*). The first Bantu speakers were cultivators in the eastern Nigeria and western Cameroon area, who began to spread eastward and southward about 4,000 years ago (*5*-*9*). From the third millennium BP, a major expansion wave was associated with the introduction of agriculture into the central African rainforest (*5*, *10*, *24*). This period coincides with marked increases in the abundance of oil palm pollen at numerous sites across west and central Africa, interpreted as evidence for intensifying plant cultivation (*25*). In this region, numerous archeological sites containing ceramics, domesticated crop remains, oil palm nuts, stone tools were dated between about 3,000 and 2,000 years ago (*24*, *26*-*29*). At that time, the cultivation of savanna crops, such as pearl millet and yams, was made possible by the onset of seasonality alternance between wet and dry seasons (*4, 24*). The discoveries of several iron-working furnaces and smelted iron artefacts in Cameroon, Gabon, Central African Republic and Congo, dating from the same period or even older, also indicated that the Bantu farmers were carrying the technology for iron metallurgy (*29*-*33*).

One hypothesis to link the rainforest crisis to intensifying human activities in Central Africa during the third millennium BP has been to propose that the deforestation event created favorable conditions for the settlement of Bantu farmers across Central Africa, through opening of savanna corridors (*4, 34*). Alternatively, the introduction of novel agricultural practices and iron smelting technology could also have led to intensive land clearance for shifting cultivation and charcoal production, thereby being partly responsible for the major vegetation change about 2,500 years ago (*10*). Because all of land-use, anthropogenic deforestation, and agriculture would have significantly increased rates of soil erosion and, as a consequence, chemical weathering, intensifying human activities in sub-Equatorial Africa hence represent a plausible explanation for the third millennium BP weathering episode. Based upon our results, it is difficult to assess the degree to which human land-use and/or climate change played a role during this Late Holocene deforestation event. However, evidence from our proxy record that chemical weathering rates at that time were unprecedented during the last 40 thousand years clearly suggest that the environmental impact of human population in the central African rainforest was already significant about 2,500 years ago, at least greater than that induced by the Late Quaternary climatic oscillations.

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Figure legends

Figure 1: African satellite map with location of the studied core (KZAI-01). A major vegetation change was reported at a number of sites in Central Africa between about 3,000 and 2,000 years ago (yellow stars; see SOM Fig. S1), with evidence for a significant loss of primary forest and expansion of savannas and other pioneer formations. This deforestation event was contemporaneous with the migration of Bantu-speaking agriculturalists originating from the Nigeria-Cameroon area. During the third millennium before present, Bantu farmers spread both southward, across Atlantic Equatorial Africa, and eastward, through the Congo watershed, reaching Angola and the Great Lakes region by around 2,500 yr BP, respectively (thick orange

arrows). Thin yellow arrows represent subsequent migration waves towards southern Africa. CAR: Central African Republic; DRC: Democratic Republic of the Congo.

Figure 2: CaO concentrations (wt%) and Al/K ratios versus core depth (m) in core KZAI-01. The triangles indicate the position of AMS ^{14}C dates for mixed marine carbonate fraction (black) and bulk organic matter (grey), and the age control points tuned to the well-dated nearby core GeoB6518-1 (white). The upper right inset shows the depth versus calendar age plot for KZAI-01.

Figure 3: Proxy records for source provenance and chemical weathering intensity in core KZAI-01, and comparison with paleoclimatic and paleovegetation records. A) Neodymium and Hafnium isotopic composition in core KZAI-01 (expressed as ε_{Nd} and ε_{Hf}, respectively), as proxies for sediment provenance and chemical weathering intensity. B) The Al/K record from core KZAI-01 indicating variations of chemical weathering intensity in Central Africa. C) Plant-wax δD values (‰) in core GeoB6518-1, as an index of precipitation changes in Central Africa (*19*). D) The annual Mean Annual Temperature (MAT) record of the Congo Basin in core GeoB 6518-1 based on biomarkers (*21*). E) Abundance of pollen from herbaceous plants (mainly *Graminaea*) at the Lake Barombi Mbo (Cameroon), reflecting the relative presence of savannas versus forests in western Equatorial Africa (*3*).

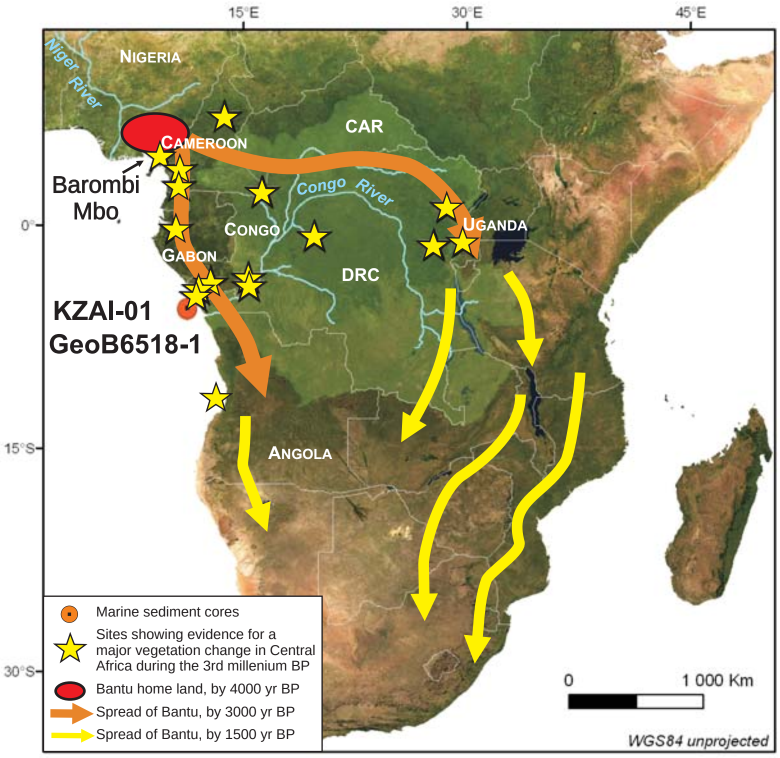
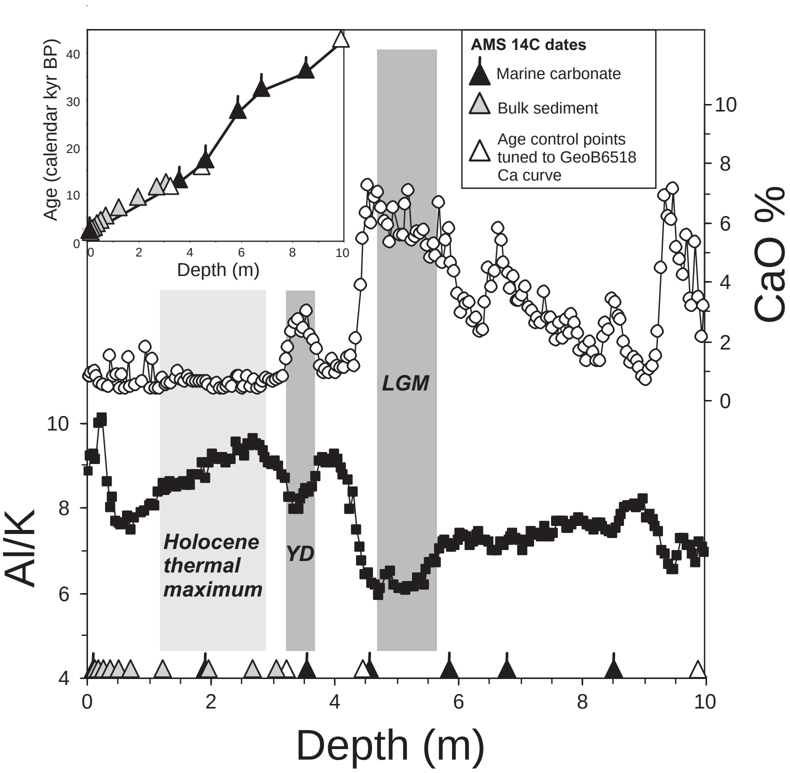
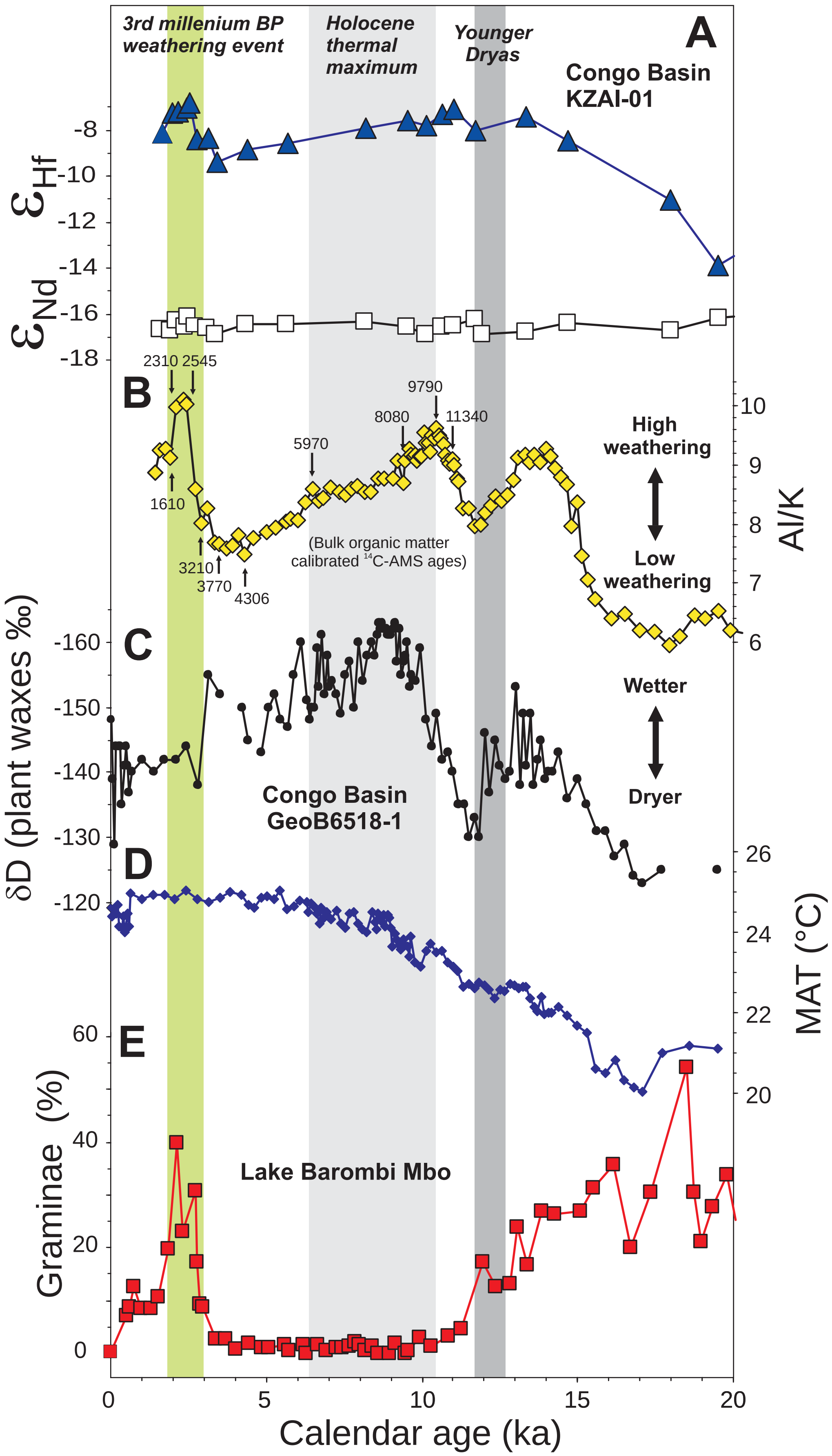

15°E
30°E
45°E
0°
15°S
30°S
Niger River
NIGERIA
CAR
CAMEROON
Barombi
Mbo
Congo River
CONGO
UGANDA
GABON
DRC
KZAI-01
GeoB6518-1
ANGOLA
Marine sediment cores
Sites showing evidence for a major vegetation change in Central Africa during the 3rd millenium BP
Bantu home land, by 4000 yr BP
Spread of Bantu, by 3000 yr BP
Spread of Bantu, by 1500 yr BP
0
1 000 Km
WGS84 unprojected

Fig 1



AMS 14C dates
Marine carbonate
Bulk sediment
Age control points tuned to GeoB6518 Ca curve
Age (calendar kyr BP)
Depth (m)
CaO %
Al/K
Holocene thermal maximum
YD
LGM
Depth (m)

Fig 2



3rd millenium BP weathering event
Holocene thermal maximum
Younger Dryas
A
Congo Basin KZAI-01
εHf
εNd
B
2310 2545
1610
3210
3770
4306
5970
8080
9790
11340
(Bulk organic matter calibrated 14C-AMS ages)
High weathering
Low weathering
Al/K
C
δD (plant waxes ‰)
Wetter
Dryer
Congo Basin GeoB6518-1
D
MAT (°C)
E
Graminae (%)
Lake Barombi Mbo
Calendar age (ka)

Fig 3