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Response to Comments on “Intensifying Weathering and Land Use in Iron Age Central Africa”

Germain Bayon*, Bernard Dennielou, Joël Etoubleau, Emmanuel Ponzevera,Samuel Toucanne, Sylvain Bermell

Institut Français de Recherche pour l’Exploitation de la Mer (IFREMER), Unité de Recherche Géosciences Marines, F-29280 Plouzané, France.

*: Corresponding author : Germain Bayon, email address : gbayon@ifremer.fr

Abstract:

Neumann *et al*. argue that terrestrial evidence does not support our interpretation of large-scale human land use in Central Africa about 2500 years ago and that climate was the main driver of the rainforest crisis at that time, and Maley *et al*. raise a number of concerns about our interpretation of data from chemical weathering proxies. Taking into account existing palaeoclimatic data and clarifying some misconceptions, we reassert that humans must also have contributed fundamentally to this large vegetation change.

In our recent paper (*1*), we reported geochemical records from a marine sediment core recovered in the Gulf of Guinea, that allowed the reconstruction of chemical weathering intensity in Central Africa for the last 40,000 years. Our data indicated a pulse of intensified weathering centered around 2500 years ago, contemporaneous with a major vegetation change recorded in terrestrial lake records. Based upon the evidence that this weathering event departed significantly from the long-term weathering fluctuations related to the Late Quaternary climate, we suggested that it was not triggered by natural climatic factors solely. Instead, we proposed that the settlement of Bantu-speaking farmers in Central Africa at that time had a more pronounced environmental impact than initially thought. Our conclusions have been challenged by Neumann et al. (2) and by Maley et al. (3).

In their comment, Neumann et al. (*2*) disagree with our interpretation, arguing that there is no terrestrial evidence for massive forest destruction by humans at that time, and that climate was the sole factor responsible for the vegetation change. Below, we comment on the issues raised by Neumann et al., and reassert that, while climate certainly played a role in the migration of Bantu agriculturalists and the contemporaneous vegetation change, human footprint in the central African rainforest was already significant in the third millenium before present. Neumann et al. provide a detailed and interesting review of the way of life of the Bantu-speaking peoples who immigrated into the central African rainforest about 3000 years ago. As pointed out by the authors, available archaeological data suggest that those early farmers relied on a mixed subsidence system, involving arboriculture and small-scale plant cultivation, taking mainly advantage of secondary forest plant communities, which they could easily clear with presumably minor impact on the environment. Neumann et al. also indicate that iron metallurgy, which developed in Central Africa after ~2500 years before present (BP), is unlikely to have had major influence on the vegetation. Finally, the authors relate the major vegetation change recorded in terrestrial records at that time to an abnormal southward shift of the rainbelt, leading to the onset of marked dry seasons.

Since the end of the African Humid Period, about 6000 years ago, African climate has evolved progressively towards dryer conditions in response to reduced summer insolation and ocean circulation changes (*4, 5*). Surimposed on this gradual drying trend, several centennial- to millenial-scale episodes of low precipitation also occurred during that period. While the onset of those minor climatic deteriorations is attested from a few paleoclimatic archives (*5, 6*), their impact on the rainforest remains unclear.

At present, vegetation patterns in Central Africa match remarkably well annual precipitation rates (*7*). Although the controls on past vegetation are still under debate, the extent of rainforest trees versus savannas (and other secondary formations) in Central Africa during the Late Quaternary correlates well with sea surface temperatures (SST) in the eastern equatorial Atlantic. Tropical SST, in turn, are thought to control continental precipitation in this region (*8-10*). The large vegetation changes that occurred over interglacial/glacial timescales corresponded to SST changes of about 3-5 °C in tropical Atlantic (*8, 9*). A number of minor millenial-scale SST oscillations (about 1°C or less) also took place in the Gulf of Guinea during the Holocene period, including one between about 4000 and 2500 years ago (*11*). These small SST drops were related to periods of lower lake levels and reduced moisture availability in Central Africa (*11*). Most likely, these minor climatic deteriorations, surimposed on the gradually drying trend of the late Holocene African climate, also had some impact on the rainforest.

The rainforest crisis that took place in Central Africa between 3000 and 2000 years ago is much greater, however, than what would be expected from the small SST variations recorded in sediment records from the Gulf of Guinea. At some sites (*12*), the disturbance inferred from palynological records for the third millenium BP is even comparable in magnitude to the major vegetation changes that acccompanied the last deglaciation period. At first glance, this apparent discrepancy may seem hard to reconcile with a 'simple' climatic hypothesis, and could indicate that another factor came into play. However, as mentioned by Neumann et al., the scarse archaeological data available do not support large-scale human impact at that time, which could possibly account for the rainforest crisis. In addition, palaeoenvironmental data acquired from scattered terrestrial records do not generally allow clear distinction between climate-induced vegetation changes and anthropogenic disturbances.

Our chemical weathering proxy records overcome some of those difficulties. First, in contrast with vegetation-based proxies, weathering tracers respond in opposite directions to reduced precipitation levels (which induce lower chemical weathering intensity) and increasing human activities (which lead to both enhanced soil denudation and chemical weathering). This makes them particularly well suited for discriminating between climate- versus human-driven changes in past environmental records. Second, our marine sediment core (KZAI-01) provides an integrated record of Late Quaternary environmental conditions at the scale of the whole Congo Basin, something that is not attainable with terrestrial records. We estimate that the achievable temporal resolution in core KZAI-01, inferred from the combined effects of sediment transfer time from continent to ocean, bioturbation and sedimentation rates, is about 600 years. To some extent, this relatively low temporal resolution (compared to terrestrial records) probably accounts for the smooth geochemical profiles in our core (*1*), possibly explaining why the minor millenial-scale events, which punctuated the central African climate during the Late Quaternary (e.g. at ~8.2 kyr and 4 kyr BP), were not recorded at site KZAI-01. In this context, the sudden pulse of intensifying chemical weathering inferred from our sedimentary record after 3000 years BP, and its complete decoupling from the long-term weathering signal of the last 40,000 years, is also hard to reconcile with a 'simple' climatic hypothesis.

So why did weathering rapidly intensify at that time, when it had previously always decreased during dry episodes? We believe that the answer is related to the introduction of agriculture by the Bantu-speaking immigrants.

There is increasing evidence that humans have strongly altered their landscapes since the advent of agriculture (*13-15*). In every part of the world, diffusion of agriculture led to rapidly growing population, with increasing impacts of the environment. Early farmers practised slash-and-burn cultivation for clearing plots for agriculture. Even if they abandonned or rotated among previously farmed plots, the Bantu-speaking agriculturalists would have left behind a lingering footprint on the land that was not reforested for several decades or centuries, thereby being subject to intense soil denudation and chemical weathering. Current estimates actually suggest that humans became the dominant agents of soil erosion (over natural causes) as early as the third millenium before present (*16*). Based on the above considerations, therefore, and although we fully understand that clear archaeological evidence may be still lacking, we reiterate our conclusion that the early farmers who immigrated into the central African rainforest about 3000 years ago already had a significant impact on their environment.

Maley et al. (*3*) criticize our interpretations of Al/K data, raising a number of concerns about their reliability for tracing past changes in chemical weathering intensity. They also disagree with our conclusions, and argue that the third millenium BP crisis of the central African rainforest can be unambiguously related to a large climatic change. Below, we address each of the issues raised by the authors about the interpretation of our data. Our views on the 'climatic' hypothesis proposed by the authors are expressed in the response to Neumann et al.'s technical comment on our paper.

First, Maley et al. point out that the absence of mineralogical data for the detrital phases analyzed in our study strongly limits the relevance of our conclusions. This seems largely overstated, because it is well known that K is predominantly contributed by feldspars in Congo River-borne sediments, and Al by both feldspars and kaolinite (*17*).

Second, the authors raise important concerns about possible time-lags between soil erosion, river transport and deposition of sediments on the ocean floor. They also question whether chemical weathering processes could react as quickly as we suggest to past environmental changes. Based upon these considerations, Maley et al. argue that the elevated Al/K ratios determined in our core after 3000 year before present (BP) could reflect the erosion of deeper (more ancient) soil horizons, rather than any contemporaneous weathering signal.

Although the global relationship between chemical weathering and environmental parameters such as temperature and precipitation is well-established, there are still large uncertainties on the sensitivity of weathering rates and intensities to these climatic variables, mostly because results obtained from laboratory experiments are difficult to reconcile with natural field-based approaches (*18*). Clearly, the time over which natural chemical weathering occurs cannot be reproduced by experimental studies. So the strongest evidence that chemical weathering in Central Africa reacted quite rapidly (within about 500 years) to past environmental changes actually comes from the application of various weathering proxies to eastern Atlantic sedimentary records. In addition to our work, several investigations based on clay mineralogy or major element geochemistry already suggested that past variations in chemical weathering intensity in the Congo Basin were tightly coupled with climate change (*17, 19*).

There is also significant uncertainty in how much time is needed for sediment in a river basin to reach the ocean. The residence time of sediments on continents can vary drastically from a few years to many thousands of years, though clays are expected to be exported much more rapidly than coarser fractions. In our paper, we addressed this important issue by dating the organic fraction of several bulk sediment samples, in addition to the marine carbonate material used for establishing the age model for core KZAI-01. Because marine sediments deposited off the Congo River contain a significant fraction of continental organic matter (*20*), radiocarbon dating of bulk organic compounds can be used to calculate the age of river-borne particles at any sediment depth, and hence to provide an estimate for past sediment transport times within the drainage basin. In our study, the transport times inferred from those radiocarbon dates were generally lower than 600 years (*1*). This provided reassuring evidence that the suspended particles delivered by the Congo River during the last few millenia were mainly derived from relatively young soils, and hence that the elevated Al/K determined after 3000 years ago were not derived from the erosion of older tropical soils.

Another, perhaps stronger, evidence against the possible contribution of fossil soils to our Al/K signal comes from results obtained during soil investigations. Typical weathering sequences in soil/regolith profiles from tropical environments show that Al/K ratios generally decrease gradually from the topsoil layers to the deeper lateritic horizons (*21, 22*); a consequence of progressive K-depletion by leaching and accumulation of Al in secondary weathering products. Importantly, this suggests that erosion of deep (ancient) soil horizons in the Congo Basin would have led to export of clays characterized by lower Al/K ratios, hence being incompatible with the trend shown by our data.

Maley et al. also argue that increasing human activities during the third millenium BP should have led to less intense chemical weathering in soils (and hence to clays having lower Al/K ratios), rather than, as we suggested, enhanced weathering processes. This claim is based on results obtained during a geochemical survey of suspended sediments from the world's largest rivers (*23*). In that study, the proposed relationship between high physical denudation rates and low chemical weathering intensities was established to account for the large differences observed between rivers draining a wide range of geologic, climatic and tectonic settings. Lowland tropical and soil-mantled regions, such as the Congo Basin, are indeed characterized by low denudation rates and intense weathering processes, while mountaneous areas and volcanic islands exhibit the highest rates of mechanical erosion, but the least weathered sediments (because thin soil covers in these regions generally prevent intense mineral-water reactions to occur). Out of this global context, however, at the scale of individual drainage basins, this relationship is largely obscured by other parameters such as regional precipitation, temperature, and/or vegetation.

Finally, Maley et al. comment on a presumed discrepancy between the timing of our Al/K weathering episode (centered around 2500 years ago) and subsequent intensification of human activities in Central Africa. Although the rise of Al/K ratios in core KZAI-01, initiated about 3000 years ago, coincided well with the arrival of the first Bantu-speaking farmers in Central Africa (*24*), we agree with Maley et al. that the Al/K decrease after 2000 year BP may seem, at first glance, rather peculiar. One possible explanation for this trend actually also involves humans. Indeed, current archaeological evidence suggests that human populations in the Congo Basin crash relatively abruptly ~1500 years ago, resulting in widespread forest regeneration (*25, 26*). The observed hiatus lasted for about six centuries, before human activities re-started again after ~1200 A.D. If correct, these observations would hence be coherent with the observed decrease of Al/K ratios at site KZAI-01 between ~2000 and 1400 years ago (i.e. the sediment age for the core-top), implying that forest regrowth at that time led to a decrease of soil erosion rates and chemical weathering processes in soils. Therefore, to conclude in response to Maley et al.'s comments, we are still confident that the Al/K profile for core KZAI-01 represents a reliable indicator of past chemical weathering in Central Africa, and that its deviation from the long-term climatic signal after 3000 year BP reflects the rapid development of agriculture at that time.

References

1. G. Bayon *et al.*, *Science* **335**, 1219 (2012).
2. K. Neumann *et al.*, *Science* **337**, 1040-e (2012).
3. J. Maley et al., *Science* **337**, 1040-e (2012).
4. F. A. Street-Perrot, R. A. Street-Perrot, *Nature* **343**, 607 (1990).
5. F. Gasse, *Quat. Sci. Rev.* **19**, 189 (2000).
6. L. G. Thompson *et al.*, *Science* **298**, 589 (2002).
7. J. A. Collins *et al.*, *Nat. Geosci.* **4**, 42 (2011).
8. J. W. H. Weijers, E. Schefuß, S. Schouten, J. S. Sinninghe Damsté, *Science* **315**, 1701 (2007).
9. E. Schefuß, S. Schouten, J. H. F. Jansen, J. S. Sinninghe Damsté, *Nature* **422**, 418 (2003).
10. S. Weldeab, D. W. Lea, R. R. Schneider, N. Andersen, *Science* **316**, 1303 (2007).
11. S. Weldeab, R. R. Schneider, M. Kolling, G. Wefer, *Geology* **33**, 981 (2005).

12. J. Maley, P. Brenac, *Rev. Palaeobot. Palynol.* **99**, 157 (1998).
13. S. L. O'Hara, F. A. Street-Perrott, T. P. Burt, *Nature* **362**, 48 (1993).
14. W. F. Ruddiman, *Clim. Change* **61**, 261 (2003).
15. E. C. Ellis, N. Ramankutty, *Front. Ecol. Environ.* **6**, 439 (2008).
16. B. H. Wilkinson, *Geology* **33**, 161 (2005).
17. R. R. Schneider, B. Price, P. J. Müller, D. Kroon, I. Alexander, *Paleoceanography* **12**, 463 (1997).
18. A. F. White, S. L. Brantley, *Chem. Geol.* **202**, 479 (2003).
19. F. X. Gingele, P. M. Muller, R. R. Schneider, *Palaeogeog. Palaeoclimatol. Palaeoecol.* **138**, 17 (1998).
20. J. W. H. Weijers, S. Schouten, E. Schefuß, R. R. Schneider, J. S. Sinninghe Damsté, *Geochim. Cosmochim. Acta* **73**, 119 (2009).
21. H. W. Nesbitt, G. Markovics, *Geochim. Cosmochim. Acta* **61**, 1653 (1997).
22. A. F. White et al., *Geochim. Cosmochim. Acta* **62**, 209 (1998).
23. J. Gaillardet, B. Dupré, C. J. Allègre, *Geochim. Cosmochim. Acta* **63**, 4037 (1999).
24. K. Neumann *et al.*, *Science* (Comment) (2012).
25. K. J. Willis, L. Gillson, T. M. Brncic, *Science* **304**, 402 (2004).
26. R. Oslisly, in *African Rain Forest Ecology and Conservation*, B. Weber, L. J. T. White, A. Vedder, L. Naughton-Treves, Eds. (Yale Univ. Press, New Haven, CT, 2001), p. 101 p.

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