A million-year record of fire in sub-Saharan Africa

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Biomass burning today constitutes approximately one-third of annual anthropogenic CO_2 emissions, and there is a sound theoretical base for expecting fire-related changes in vegetation patterns to affect climate, at least on a regional scale[1–3]. But despite the central role that fire has played in moulding many modern ecosystems, there is little information on the incidence of fire before the earliest time at which anthropogenic burning may have significantly affected natural fire regimes. Here we present a million-year record of elemental carbon abundance from marine sediments on the Sierra Leone rise, 'downwind' of sub-Saharan Africa. Elemental carbon serves as a proxy for wind-blow debris derived from the combustion of sub-Sahara vegetation. The inferred fire incidence in the region was low until about 400,000 years ago, but since that time intense episodes of vegetation fires have occurred during periods when global climate was changing from interglacial to glacial mode. The occurrence of a peak in elemental carbon abundance within the present interglacial is unique in the past million years, suggesting that this peak is anthropogenic in origin, and that humans have exercised significant control over fire regimes in the region at least since Holocene times.

Combustion has underpinned the technological ascent of the genus *Homo*, and lies at the core of current concerns over global change, both through biomass burning, and combustion associated with the production of energy. The potency of fire as an agent of environmental change has led to speculation that prehistoric humanity may have been actively engaged in modifying vegetation patterns, regional climate and atmospheric trace-gas concentrations since long before the advent of modern concerns over global change[4]. For example, it has been suggested that prehistoric human use of fire, coupled with domestication of livestock, has led to the expansion of the Sahel in the past few thousands years, and an increase in recent desertification rates in the region[5–7]. But such a view is not universally held, and others favour natural mechanisms[8,9].

Long records of fire frequency, integrated over a large continental area and spanning several glacial–interglacial cycles, can provide a baseline for natural variability and long-term trends in fire incidence. Deep-sea sediments are particularly suited to this kind of study because they can provide relatively undisturbed, continuous records of large-scale phenomena which are readily dated using oxygen-isotope stratigraphy.

Several chemical techniques have been proposed to quantify the abundance of elemental carbon in marine sediments[10–14], and these techniques have been used to isolate elemental carbon at the K/T boundary[15], and to estimate its abundance in marine sediments of pre-industrial, Quaternary and Tertiary age[11,16,17].

We have modified methods developed by Wolbach and Anders[12] and Emiliani *et al.*[13], and use two oxidative degradation steps to destroy organic carbon leaving a residue composed entirely of oxidation-resistant elemental carbon (OREC; see Fig. 1 legend). The OREC abundance in a sample is then determined manometrically after combustion to CO_2; this has the advantage that the carbon-isotope composition ($\delta^{13}C_{OREC}$ value) of the gas can be determined, providing information on the type of vegetation being burnt[18,19]. Carbonate, aeolian dust, and amorphous silica contents, as well as organic carbon content and organic carbon $\delta^{13}C_{OC}$ value are also determined for each sample (Fig. 1).

Core ODP-668B from the Sierra Leone rise[20], in the equatorial eastern Atlantic Ocean, was chosen for analysis. The core-site is 'downwind' of sub-Saharan Africa, a region likely to have experienced large changes in fire incidence in response both to large-scale global climate changes and the more recent imposition of anthropogenic fire regimes. The products of modern biomass burning in sub-Saharan Africa have been detected as far west as Barbados, and a surface grab sample from the Sierra Leone rise has been reported to have 'clearly noticeable amounts of (elemental) carbon'[21]. Palaeoenvironmental reconstructions based on the aeolian dust content of marine sediments off sub-Saharan Africa suggest that the location

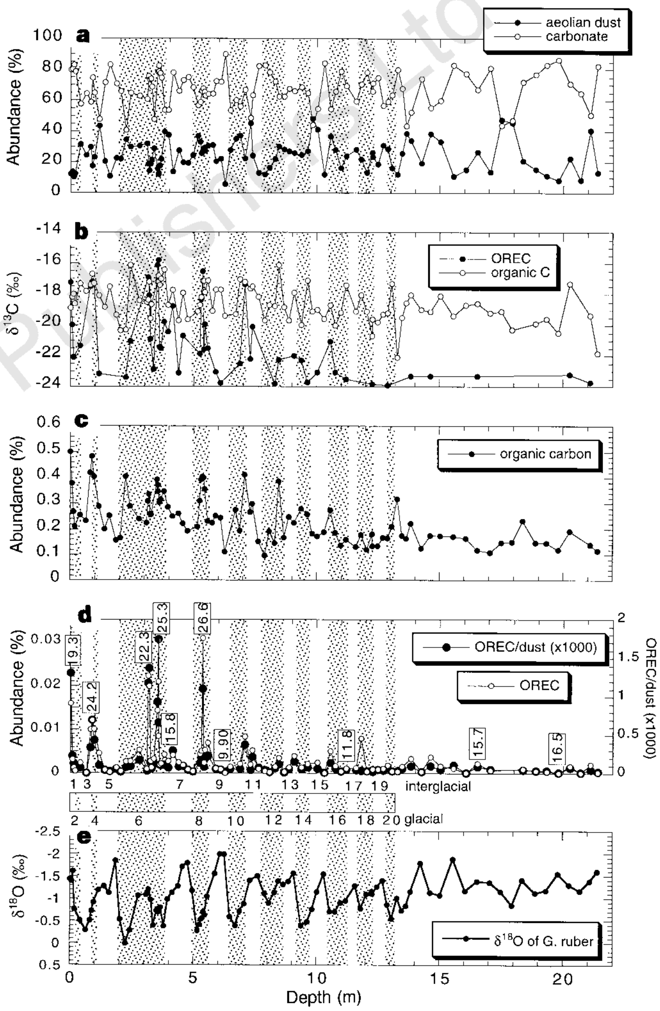

Figure 1 Sedimentological and isotopic results for ODP-668B, Sierra Leone rise. The site is located at 4° 46.23′ N, 20° 55.62′ W in 2,693 m of water[22]. The hole had a total length of 31.3 m with 100% recovery. Samples were prepared using the techniques discussed by Bird and Grocke[20]. Shaded regions represent glacial intervals. **a**, Abundance of carbonate and aeolian dust as a percentage of dry weight. **b**, $\delta^{13}C$ value of OREC (oxidation-resistant elemental carbon) and bulk organic carbon $\delta^{13}C_{OC}$ (±0.1‰). **c**, Abundance of bulk organic carbon as a percentage of dry weight (±2%). **d**, Abundance of OREC (±10%), given both as a percentage of dry weight, and as a ratio of the aeolian dust content of the same sample. Also shown (in boxes) are the C/N ratios of bulk organic matter for selected intervals. **e**, $\delta^{18}O$ value (±0.1‰) of the planktic foraminifer *G. ruber* relative to VPDB. Oxygen-isotope stage assignments are based on comparison with a nearby high-resolution stratigraphy for Meteor 13519 (ref. 25). The stage assignments yield an approximately linear sedimentation rate for the entire sequence of 1.7 cm kyr^{-1} compared with a slightly lower (1.4 cm kyr^{-1}), but also linear, rate of sediment accumulation in Meteor 13519. The Bruhnes–Matuyama boundary[20] occurs at ~13.3 m depth in ODP-668B, also consistent with the stage assignments.

has been in the path of winds emanating from the sub-Saharan region since at least the last interglacial period[22–24]. The location is on a topographic high, and sufficiently far from the coast to ensure that any signal is integrated over a large continental area and thus will not be sensitive to latitudinal shifts in vegetation type in response to climate changes.

The sediment is a muddy foraminiferal ooze containing 40–90% carbonate (Fig. 1a) and <5% amorphous silica (values not shown in Fig. 1), with the balance comprising aeolian dust. The upper 21 m of the core was sampled at an interval of 20 cm (5 cm over important intervals); representing over one million years of sediment accumulation. A study of a nearby core (Meteor-13519) by Sarnthein *et al.*[25] concluded that dust fluxes to the Sierra Leone rise have not varied greatly in the past.

Organic carbon contents in the core studied here are generally low, between 0.1% and 0.3% (Fig. 1c), gradually decreasing down the core as a result of diagenetic loss of labile carbon species[26]. Several peaks in organic carbon abundance (up to 0.5%) occur in the upper half of the core, and similar peaks in other cores from the region have been related to increases in palaeoproductivity[27]. $\delta^{13}C_{OC}$ values generally vary between −17‰ and −20‰ (Fig. 1b), and again such variations have been related to changes in productivity in the area in the past[26]. The chronology for the core is based on the oxygen-isotope composition of the planktic foraminifer *Globigerinoides ruber* (Fig. 1e).

OREC abundances are expressed both as a raw percentage of dry weight, and as a ratio to the aeolian dust fraction. The second measure is the more informative, as it circumvents the potential problem of apparent changes in abundance being due to changes either in wind strength (particulate transport efficiency) or mass accumulation rate. Nevertheless, the general trends are the same using either measure (Fig. 1d) as OREC abundances vary by two orders of magnitude, far in excess of the variations in bulk sediment mass accumulation rate (1.1–2.3 g cm^{-2} kyr^{-1}). Apparent OREC accumulation rates vary from 2–10 μg cm^{-1} kyr^{-1} for periods when OREC deposition rates were low, up to 200–400 μg cm^{-1} kyr^{-1} at times of high OREC deposition.

The abundances of OREC were generally low before the beginning of the stage 10 glacial. Following the small peak at the beginning of stage 10 (~400,000 years before present) there are large peaks in abundance in stages 8, 6, 3–4 and 1. The early peaks are particularly sharp, occurring over intervals of 5–10 cm in the core; assuming a bioturbation depth of 5 cm (ref. 25), these peaks could represent short-duration intense events. The peak in stage 3–4 is lower, and occurs over a thicker sediment interval (~60 cm). Between the peaks, OREC abundances return to comparatively low levels. $\delta^{13}C_{OREC}$ values vary widely in the upper half of the core, from −25‰ when OREC abundances are low, to −15.8‰ when OREC abundances are high (Fig. 1b). This range of values is outside the range normally encountered for marine organic carbon in tropical regions, and well outside the range of $\delta^{13}C_{OC}$ values in the core.

Two additional lines of evidence suggest that the material being analysed is indeed elemental carbon, and not a resistant component of marine organic carbon.

First, the C/N ratios of organic carbon in samples from the intervals containing the OREC peaks are elevated above 20, while other samples from the core exhibit values as low as 9.8, similar to living marine organic matter (Fig. 1d). This suggests that a source high in carbon and low in nitrogen forms a significant component of the bulk organic carbon, consistent with that component being OREC.

Second, there is no relationship between the abundance or $\delta^{13}C$ value of OREC in a sample and either the percentage of organic carbon or the $\delta^{13}C_{OC}$ value of the same sample, as would be expected if the carbon being analysed were a resistant component of marine organic carbon. However, there is a strong relationship between the abundance of OREC and the $\delta^{13}C_{OREC}$ value (Fig. 2). This would be expected if the carbon were indeed elemental carbon, as the incidence of fire in tropical regions is related to the distribution of savannah regions and hence to the distribution of C_4 grasses with high $\delta^{13}C$ values of ~−12‰. Thus low fire incidence implies wet conditions and extensive C_3-dominated forests ($\delta^{13}C$ values of ~−27‰), and hence low $\delta^{13}C_{OREC}$ values. With the expansion of savannahs in drier conditions, fire incidence will increase, as will the proportion of C_4 grasses in the biomass being burnt, and hence $\delta^{13}C_{OREC}$ values will also increase.

The distribution of OREC peaks in the core is significant. The absence of significant peaks in OREC abundance before stage 10 suggests that either fire was not a common phenomenon in sub-Saharan Africa before this time, or that a shift in atmospheric circulation at this time first brought particulates emanating from the sub-Saharan region over the core location. Given that there are no large changes in the dust flux to the Sierra Leone rise[25], the former interpretation is preferred.

With the exception of the most recent peak, no OREC peaks occur either at glacial or interglacial maxima. Given that the sample interval was 20 cm, consideration should be given to the possibility that additional OREC 'peaks' were missed in the sampling. Visual inspection of the OREC-rich samples indicated that these samples had a distinctive greyish colour. Inspection of the core itself revealed no additional 'greyish sediments' which were not sampled.

The OREC peaks occurred solely during periods when climate was changing from interglacial to glacial. In sub-Saharan Africa, previous interglacials are thought to have been characterized by warm, wet conditions and the northward expansion of forest over savannah regions, whereas glacials are characterized by comparatively cool, dry conditions and the southward expansion of desert[22,24]. Neither is conducive to high fire incidence. Large shifts in wind patterns, and hence source regions, could also produce large changes in OREC flux to the site, but, as discussed above, the absence of large changes in dust flux argues against such an interpretation.

These results differ dramatically from those of Verardo and Ruddiman[17], who have presented a 200-kyr charcoal record for a core from the eastern equatorial Atlantic (RC24-07), 2,000 km southeast of ODP-668B. Their results suggests that charcoal abundances peaked in glacial times, with charcoal comprising up to 90% of the total (1–2%) organic carbon in the samples. These results are questionable on two grounds.

First, such a high proportion of elemental carbon in the samples should lead to a dramatic increase in the C/N ratio of organic carbon in the samples, possibly as high as 50 or more. The C/N ratios presented for the same core[27] generally range from 5 to 14,

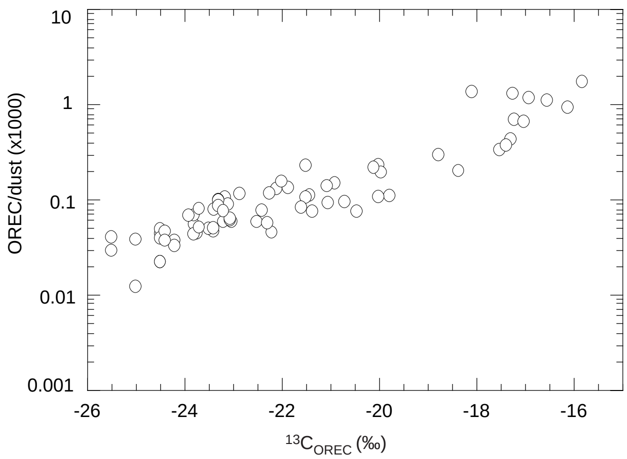

Figure 2 Relationship between the $\delta^{13}C$ value of oxidation-resistant elemental carbon (OREC) and its abundance as a ratio of the aeolian dust component in ODP-668B.

with occasional peaks up to 17. Furthermore, the peak in charcoal abundance inferred by Verardo and Ruddiman[17] at the Last Glacial Maximum corresponds to samples with a very small range of C/N ratios between 8 and 12, suggesting that these samples are predominantly composed of marine-derived carbon. Isolated peaks in C/N ratio up to 18 in some samples may correspond to events similar to those identified in ODP-668B.

Second, the flux rates of elemental carbon calculated by Verardo and Ruddiman[17] range as high as 50,000 $\mu g\,cm^{-1}\,kyr^{-1}$, which is two orders of magnitude higher than calculated for a range of recent, Quaternary and Tertiary marine sediments by other researchers. Smith *et al.*[16] calculated an average pre-industrial flux rate for Pacific and Atlantic sediments of 100 $\mu g\,cm^{-1}\,kyr^{-1}$, whereas Herring[11] calculated Quaternary fluxes of 3–600 $\mu g\,cm^{-1}\,kyr^{-1}$ and Tertiary fluxes of 0.3–10 $\mu g\,cm^{-1}\,kyr^{-1}$ for Pacific Ocean sediments remote from coastal regions. These values agree well with the OREC fluxes calculated for ODP-668B (1–400 $\mu g\,cm^{-1}\,kyr^{-1}$), despite the fact that the data were generated by different techniques.

A sample of Antarctic marine sediment previously shown by Bird and Gröcke[28] to contain <1% elemental carbon was analysed in triplicate using the Verardo and Ruddiman[17] technique. The results indicate that only 49 ± 5% of the carbon in this sample was removed by *in situ* nitric acid oxidation, implying an elemental carbon content of around 50%. It is possible that, whereas some organic carbon is oxidized directly to CO_2, a considerable quantity of more refractory organic carbon is only partly oxidized and solubilized by the treatment but not removed, leading to an overestimate of 'charcoal' abundance using the Verardo and Ruddiman technique.

The OREC results from our study suggest that during the transition from interglacial to glacial mode the regional climate may have been destabilized and highly variable, leading to the build-up of fuel loads during wet periods followed by intense biomass burning in subsequent dry periods. In addition, biomass burning may be one mechanism by which high terrestrial organic carbon stocks built up during interglacials are shed at the onset of the subsequent glaciation.

The most recent peak in OREC abundance is unique in the past million years, in that it has occurred during an interglacial period. Anthropogenic biomass burning is considered the likely cause of this peak. Given that the current conditions of interglacial aridity in the region are also considered by some to be unusual[5–7,22], further consideration should be given to the possibility that a range of human activities in sub-Saharan Africa may have resulted in regional modifications to 'natural' vegetation patterns and climate. □

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Diachronous uplift of the Tibetan plateau starting 40 Myr ago

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The uplift of the Tibetan plateau is generally regarded as a response to the convective removal of the lower portion of the thickened Asian lithosphere[1]. This removal is also thought to be responsible for the east–west extension[2] that took place during the India–Asia collision. The timing of these events has been a subject of great interest for understanding mountain-building processes, collisional tectonics and the influence of these processes on climate change[3,4]. In western Tibet, potassic lavas related to east–west extension were found to have been extruded over the past 20 Myr (refs 5, 6). Here we report the widespread occurrence of magmas in eastern Tibet which show similar geochemical signatures to the potassic lavas to the west but formed 40–30 Myr ago. These magmatic activities suggest a diachronous uplift history for the Tibetan plateau, with the convective removal of the lower lithosphere inducing rapid uplift in the east beginning some 40 Myr ago and in the west about 20 Myr later. This observation is consistent with sedimentation records from the Ganges–Brahmaputra delta to the Bengal fan[7,8] and can better account for the tectonically driven models for strontium isotope evolution in the ocean[9] and global cooling[10] over the past 40 Myr.

The collision of India with Asia since early Cenozoic time has created the Tibetan plateau. The widespread occurrence of north–south-striking normal faults in Tibet (Fig. 1), starting before 14 Myr ago[2], suggests a switch of the tectonic regime from north–south convergence to east–west extension that could have resulted from convective removal of the lower part of lithospheric mantle by hotter and lighter asthenosphere[1]. The latter process may furthermore have caused a sudden increase in the surface elevation and