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# The discovery of fire by humans: a long and convoluted process

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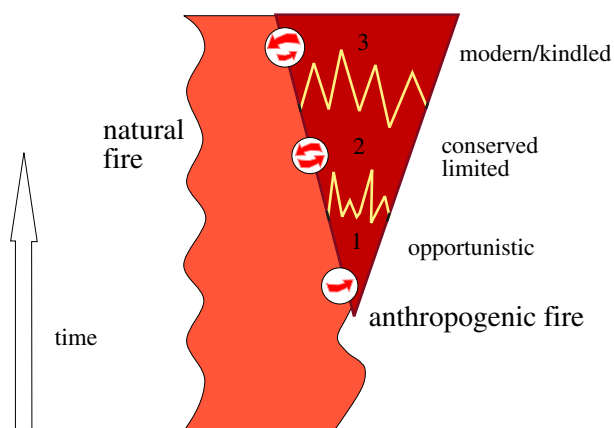
Numbers of animal species react to the natural phenomenon of fire, but only humans have learnt to control it and to make it at will. Natural fires caused overwhelmingly by lightning are highly evident on many landscapes. Birds such as hawks, and some other predators, are alert to opportunities to catch animals including invertebrates disturbed by such fires and similar benefits are likely to underlie the first human involvements with fires. Early hominins would undoubtedly have been aware of such fires, as are savanna chimpanzees in the present. Rather than as an event, the discovery of fire use may be seen as a set of processes happening over the long term. Eventually, fire became embedded in human behaviour, so that it is involved in almost all advanced technologies. Fire has also influenced human biology, assisting in providing the high-quality diet which has fuelled the increase in brain size through the Pleistocene. Direct evidence of early fire in archaeology remains rare, but from 1.5 Ma onward surprising numbers of sites preserve some evidence of burnt material. By the Middle Pleistocene, recognizable hearths demonstrate a social and economic focus on many sites. The evidence of archaeological sites has to be evaluated against postulates of biological models such as the 'cooking hypothesis' or the 'social brain', and questions of social cooperation and the origins of language. Although much remains to be worked out, it is plain that fire control has had a major impact in the course of human evolution.

This article is part of the themed issue 'The interaction of fire and mankind'.

## 1. Introduction

Fire is universally accepted as important to human life, with myriad expressions and uses in the modern world [1–7]. It was regarded by Darwin as the greatest discovery made by humanity, excepting only language [8]. Although open fire tends to be built out of Western technology, it persists in many forms as hidden fire, as in the internal combustion engine. Fire has underpinned the development of all modern technologies—from ceramics, to metal working, to the nuclear industry.

This paper starts with the view that such human fire use is an offshoot or outgrowth of far older natural fire regimes [9–15] (figure 1), and it aims to address two main issues: when and how humans came to be engaged with fire; and what are the main long-term impacts that their fire use has had on the natural environment? In the first place, large numbers of lightning strikes would have made fire evident to early humans in the form of bush fires, even aside from other rarer forms of natural ignition such as volcanic activity [16]. Archaeology and anthropology have often treated fire as a technological 'add on' or invention, but fire awareness must inevitably go back to very early times because of the high visibility of natural fires. The early encounters have been followed by an intensification of use which has had profound impacts on human culture and even biology [17]. Fire has played a major role in transforming human diet [18], and apart from its major impact on environments, it has become socially embedded, even to the point of having religious significance and being incorporated in ritual [1,19,20].



**Figure 1.** A putative general outline for the development of human fire use, showing its emergence from and interchanges with natural wildfire. All boundaries can be regarded as highly fluid: it is highly likely that there are different fire histories on different latitudes and continents.

The evolution of the primates from about 70 Ma [21,22] provides the ultimate background for encounters with fires in landscapes. Their development is largely owed to the ‘angiosperm revolution’ [10,11,23], in which flowering and fruiting trees provided niches for tree-living insectivores and especially frugivores as well as folivores. By 35 Ma ape-like and monkey-like primates had appeared. For more than 20 Myr, recognizable apes were widespread as denizens of forests [24]. Although lightning can on occasion cause tropical forest fires, in general they would not have been considerably exposed to fire in these moist densely vegetated environments [25,26]. Within the last 10 Myr, however, pivotal climate and vegetation changes led to new habitats and new adaptations across the Old World, and in that context the evolution of the hominids [27]. Along with C4 plants such as grasses, mammal groups such as horses were able to disperse through Africa [23,28,29], and tropical forest was replaced over large areas by wooded, bushy or more open habitats.

The earliest hominins probably diverged from apes around 6–8 Ma [30], and their evolution can be seen as a response to these changes—apes who, as the final part of a Miocene ape radiation, adapted to new wooded environments [31]. Rather than apes who came down from the trees, as traditionally seen, our ancestors were the bush country apes, and as such, through the last 3 Myr especially, some of them became exposed to more open habitats where natural fire was much more prevalent and obvious. The period 6–3 Ma, the first half of this evolution—the time of *Ardipithecus* and its relatives [32]—involved adaptations of bipedalism and life in wooded environments, accompanied by features such as reduction of jaws and teeth and lengthening of the thumb [31–33]. The second half indicates, for *Homo* lineages at least, a new complex of adaptation committed to long ranging, open environments, meat eating and other new foods [34–36]. In this context, encounters with fire must have become far more frequent and significant (figure 2).

A series of recent finds has given us a changed deep picture of the hominins, showing that their engagement with technology reaches back as much as 50% of the way to hominin origins. Stone tool finds from Lomekwi 3 at West Turkana in northern Kenya push back the hard record of technology from 2.6 to 3.3 Ma [37]. Such finds are important, because they almost certainly indicate a knowledge of working wood

as well as stone, and hence of properties of friction and heat. At the same time, new finds from northern Ethiopia set the origins of our own genus, *Homo*, as early as 2.8 Ma [38]. These discoveries square with others that indicate a dispersal of hominins across the Old World far earlier than was expected a few years ago—dates of 1.8 Ma in Georgia and eastern Syria, 1.7 Ma in northern China and more than 1.5 Ma in Java are strong indicators that the actual dispersal goes back further, perhaps more than 2 Myr [39–43]. It has the effect of putting hominids as far north as 40°N, at this early date, indicating that unlike the great majority of primates they had evolved means to cope with summer–winter seasonality.

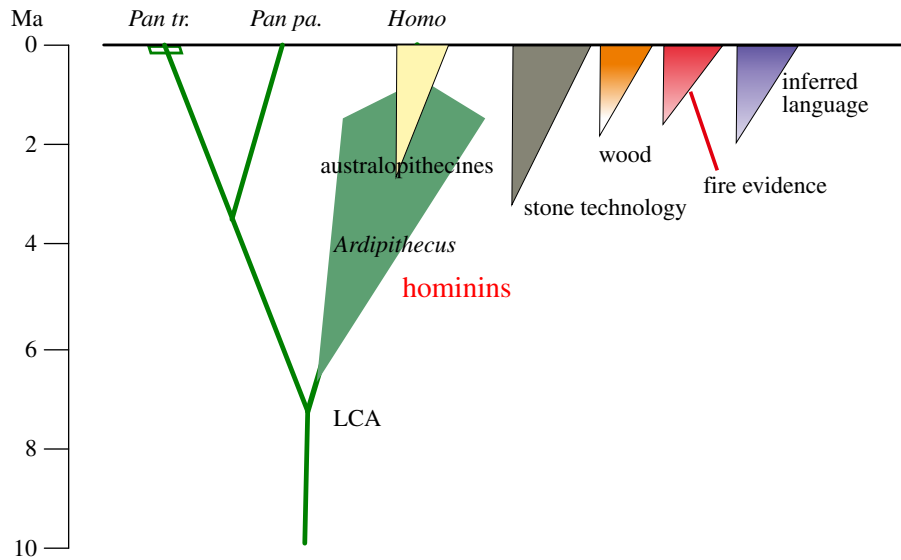
Altogether, a more complex picture of early *Homo* has emerged, with regional diversity, smaller brains than were expected, and coexistence with other hominins such as the robust australopithecines for at least 1.5 Myr. Stone tool transport distances show that these animals ranged over large territories which were often open in character [44,45]. Recent research has also given a broader picture of other primate behaviour. The sophistication of ape behaviour has been recognized, including their technology. In West Africa, Pruett and LaDuke have shown the use of wood weapons by savanna chimpanzees, and their awareness of fire [46]. We must be alert then to possibilities that hominins could have been interacting with fire in simple ways from an early date [47].

## 2. Origins of interactions with fire

Archaeological research has tended to concentrate narrowly on the presence or the absence of hearths, largely because of its own focus on living sites [48]. In broader evolutionary scenarios, it is evident that we have to consider at least three distinct but potentially intergrading forms of fire use: first, fire foraging for resources across landscapes; second, social/domestic hearth fire, for protection and cooking; and third, fires used as tools in technological process, e.g. for firing pottery.

Modern fire use is highly complex, but its origins are likely to have been simple: a common biological rationale is that there is one main selective pressure for a new development of this kind [49]. For humans, fire became important for many reasons, including cooking, protection and warmth, but most of these presuppose some degree of control. Fire foraging, in contrast, demands only an attraction towards fires, in the hope of benefitting from additional resources [17,49]. For hominins, benefits could include retrieval of birds eggs, rodents, lizards and other small animals, as well as of invertebrates. Although fire does not create such resources, it renders them far more visible, and chance cooking might well improve their digestibility.

Support for the primacy of foraging comes from the animal world. Although only humans have full mastery of fire, and it has been said that there is no analogue, there are occasional instances, largely anecdotal, of mammalian predators such as cheetahs positioning themselves to spring on prey fleeing fires. Bird ‘fire followers’ are much better recorded. They amount to many species across continents [50]. They show the availability of resources, the potential selective advantage, and by inference that this kind of fire harvesting would be within the cognitive capabilities of early hominins [51].



**Figure 2.** The emergence of the hominins: chart indicating the relationships with chimpanzees and bonobos (*Pan troglodytes* and *Pan paniscus*), and the staging of the major hominin adaptations and culture. Of these, hard technology, fire and language can be seen as ‘the big three’, deeply connected in the end and perhaps at earlier stages. LCA, last common ancestor of hominins and *Pan*.

From simple interactions, the challenge to hominins would be to stretch fire, both in space and time, to enhance its utility. In Alaska—a reasonable proxy for parts of ice age Europe—the fires burn largely from June to September. Thus, fire would not be available through the cold parts of the year, unless it could be maintained effectively. In Africa, the challenge might be to maintain fires through the wet seasons. Any such efforts, indeed almost all fire management, pushes towards a division of labour. Slow-burning materials such as animal dung or plant material tapers need to be selected and guarded, while other subsistence activities go on.

Without doubt, natural fire was available on the landscapes inhabited by hominins. Of the millions of lightning strikes that are recorded each year [16], many lead to bush and forest fires, especially at the start of a rainy season: then lightning from the first thunder storms often strikes when much of the vegetation remains dry [52–58]. Most of the instances of relevance are in forest, woodland and savanna, but the fire regimes operate surprisingly far north. Farukh & Hayasaka [59] give the example of Alaska, where up to 100 fires are burning on a given day in the summer season, and important for hominins, they have an average duration of more than 20 days.

### 3. Sampling the record of early fire

In total, the early archaeological record documents many thousands of events of hominin activity, but the chances of fire being preserved are exceptionally small. This is in part because of its ‘disappearing act’—there remain scant traces of burning, rather than the fire itself [5]—and partly because of the overall low density of sampling. As stone tools endure far better, their record is full enough to give some insights into sampling. When the Lomekwi 3 site at West Turkana in Kenya was published it took the record back from 2.6 to 3.3 Ma [37]—amounting to one sampling of the ‘new’ 700 000 years. If hominins had actually made tools (say) 10 times a year, then with a population of (say) 10 000, current sampling would give a 1 in 70 billion chance of recovery. If that seems excessively hypothetical, we can come forward to the period 2–1 Ma: there are some hundreds of

archaeological occurrences in total, but currently a maximum of five preserving evidence of burning (mentioned below). Fire is therefore about 10–100 times less likely to feature than hard artefacts. In that light, it seems remarkable that overall we do have so much fire in the record.

### 4. Major biological models

Fire foraging would lead inevitably to consumption of foods cooked accidentally, including the ‘roots made digestible’ mentioned by Darwin. The basis of the cooking hypothesis as set out by Wrangham and colleagues is that hominins living in more open environments would be unable to feed through the year from the fruit and herb resources which sustain apes in tropical forest. They would need to adopt other foods, particularly during dry seasons [34]. Extending their use of meat and particularly of carbohydrates in the form of roots and tubers would be necessary for filling this gap [35,36,60]. Large teeth—megadonty—hint at dietary stress in the period before 3 Ma, and isotopic studies at the incorporation of new foods such as grasses and sedges [61,62]. From as early as 2.6 Ma, increased meat eating is well attested by archaeological sites that link stone tools and cut-marked bones [44,63].

But the new foods are hard to digest. Cooking greatly increases their digestibility: in the view of Wrangham and colleagues, this would have come with *Homo erectus* at about 1.7 Ma [64–66]. Part of the evidence advanced is that a modern human body plan emerges at this time, with features including lengthened hindlimbs [67], and reduction of sexual dimorphism [68]. In particular, the teeth of *Homo erectus* are reduced in size, sometimes as much as those of modern humans making allowance for body size ([68], cf. [69]).

In a sense, the cooking hypothesis is proved, in that all modern humans need cooked food [66]: the question therefore is whether the hypothesis can be locked into a fixed position in the past, a rapid switch of adaptation. This is far harder to demonstrate, given our inadequate picture of early hominin species variation, and the variety of environments which they inhabited. As a working hypothesis,

however, this set of ideas brings to life the problems that early hominins were working against in terms of processing foods, and living alongside large predators.

A striking increase in human brain size is also one of the major developments in *Homo*. It has risen from an average *ca* 600 to 1300 cc in the course of the Pleistocene [70,71]. As a larger brain is costly in energy, it needs explanation. The social brain hypothesis aims to explain the phenomenon in terms of increases in group size and pressures towards social cognition [72–74]. High-quality diets are a necessity of fuelling the larger brain, from early times and especially from half a million years ago [68,72,75]. Social brain calculations suggest rapid change at this stage, and a link with language origins [71,76].

These hypotheses can be seen as promoting ‘step changes’ in hominin evolution—but the genetic comparisons now possible from whole genome studies indicate a steady progression of many complex changes, rather than any Rubicon [77].

## 5. Recognizing fire in the record

Fire on landscape is of deep interest, but it is practically impossible to distinguish between wildfires and similar fires that may have been started by humans. Some of our best clues as to how this might be done come from Australia. In a modern instance, the Martu people of the western desert only gave up their traditional fire stick farming methods in the 1960s. The change led to a great rise in the size of individual fires [78,79]. Through the systematic use of small fires the aborigines had habitually managed small mammal communities in a way that appears to enhance resources [80]; other hunter–gatherer studies imply also a concern for enhancing vegetation [54].

More generally, archaeological methodology has to focus on the restricted domains of sites where there has been notable human activity—possible home bases. The idea of the home base has been much debated [80–82], but dense concentrations of stone tools as much as 2.5 Ma show that hominins remained in one place long enough or frequently enough that overnight stays were likely [83,84]—and if fire was in use it was likely to be employed on some of these, although the chances of preservation are very slight.

On occasion archaeology is capable of recognizing artefact evidence of fire beyond all doubt. One case is a preserved wooden fire ‘hearth’ from Guitarrero Cave in Peru, directly dated by radiocarbon to around 2000 years BP; cord and dowels from the site date to *ca* 10 ka [85,86]. The sockets where the fire drill was inserted are plainly visible.

Another is lumps of pitch preserved from a Neanderthal site at Königsau in the foothills of the Harz Mountains in Germany [87]. Pitch, probably used as a fixative in hafting, can be made from tree bark only by maintaining high temperatures in a controlled fire for several hours. This can be regarded as almost the ideal case of fire documentation, since one piece of pitch retained a human fingerprint, and direct radiocarbon dating gave an age of *ca* 48 000 BP, on the limits of the technique, and compatible with a geological age of approximately 80 000 years. The use of gypsum plaster for hafting in the Middle East also implies the use of fire [88].

Occasionally, elsewhere, wooden artefacts may be part burnt or burnt. At Kalambo Falls in Zambia burnt wooden artefacts were found on Acheulean sites dating to *ca* 0.5 Ma

[89,90]. At Beeches Pit, mentioned below, a refitting flint artefact set included two burnt specimens in the set of 27, a circumstance not readily consistent with natural fire [91,92].

Such examples emphasize the importance of context, and the point that an organized methodology is necessary for fire enquiries. In archaeology, a first general treatment was provided by Bellomo in the 1990s [93,94]; subsequently, micromorphological studies of sediments, magnetic methods—including magnetic susceptibility and palaeomagnetic techniques—and thermoluminescence measurements have all proved highly useful [95,96].

No technique on its own completely addresses the problems of enquiry. The strength of micromorphology is obviously its ability to look at the small scale. The scaling up to provide evidence of specific human actions is therefore more likely to come from archaeology; but multiple techniques are necessary for any full picture. Thermoluminescence and magnetic methods can provide estimates of critical factors such as temperatures and duration of burning [97].

## 6. Fire origins in the archaeological record

The two earliest sites are in Kenya: FxJj20 at East Turkana, and site GnJi 1/6E in the Chemoigut Formation at Chesowanja near Lake Baringo (figure 3). These are both open sites. According to the original publications, FxJj20 preserves burned sediments and some heat-altered stone tools [98,99]. The site remains a strong candidate for early fire use and is currently under complete reinvestigation (S. Hlubik 2015, personal communication). Chesowanja preserves somewhat similar information, but the burnt material at the centre of the site consists not of a burnt patch, but of a few large clasts of baked clay [100,101]. The possibility that they could come from an adjacent (but lost) natural burning feature is difficult to exclude on present evidence, although the clasts are directly associated with numerous stone tools and faunal remains. A site at Gadeb in Ethiopia is also of similar age [102].

Several sites then range through the period approximately 1.0–0.5 Ma. They include the very different cave sites of Swartkrans and Wonderwerk in southern Africa, and the open site of Kalambo Falls in Zambia (mentioned above). At Swartkrans, in Member 3, described as a roofed gully, fragments of burnt bone were found in 17 excavation squares, arguing against their creation by occasional savanna fires sweeping up to the site [103–107]. They include several specimens also showing cutmarks from butchery. At Wonderwerk Cave, micromorphology studies in stratum 10, dating to approximately 1 Ma, indicate that quantities of grass and other vegetation were introduced far into the cave and became burnt along with bone preserved as microscopic fragments [108,109]. The important site of Gesher Benot Ya’aqov in Israel preserves burnt materials at numerous levels in a 30 m sequence dating to *ca* 700 000 years [110–112]. Charcoal was identified at 10 levels, and burnt wood at 4. Most specifically, burnt flint microartefacts were found in clusters which mark out ‘phantom hearth’ areas [110,112]. Macroscopic burnt flints and burnt pebbles have also been found, for example, 24 in total from the layer I1–6 L-7 [112].

Zhoukoudian near Beijing in China has been known for more than 80 years as a fire site [113,114]. Critiques have been made of its context, and on the nature of the ‘burnt’ material [115–118], much of which resulted from other



**Figure 3.** Some major Pleistocene sites with traces of fire. Following earliest traces at Koobi Fora and Chesowanja, *ca* 1.5 Ma, the ovoids indicate the biases in representation: centre, occurrences *ca* 0.7–1.0 Ma; Europe/Mediterranean, 400 000 years onward; southern African: *ca* 0.5 Ma onwards. In the Far East, Zhoukoudian (*ca* 0.7 Ma) is followed by other sites with fire traces.

natural processes. Nonetheless, the site is a record of the activities of *Homo erectus* in the period 0.4–0.7 Ma, with more than 100 000 artefacts, and preserving burnt bone [117,119,120]. The repeated associations argue for controlled fire [120].

From around 400 000 years ago, traces of fire become much more numerous on many sites, including numbers in Europe and the Middle East as well as Africa and Asia [80,121,122]. Qesem in Israel preserves a large hearth maintained over a period [123,124]; fire traces also appear regularly at nearby Tabun Cave at about the same time [125]. In northwest Europe, Beeches Pit, a 400 000 year old interglacial site in eastern England, has various traces of fire, suggesting that large hearths were maintained by the side of a creek. The traces include burnt bone, shells, combustion features, and most particularly the evidence of a refitting set of flint artefacts [91,92,122]. Of 27 flakes discarded in the process of shaping an intended handaxe, only two became heated and reddened, indicating highly localized burning.

Despite the increasing numbers of fire sites, their *relative* scarcity is still notable [126], as is the fact that some very major sites in Europe are totally lacking in fire evidence. These include lower levels at the Caune d’Arago at Tautavel in southern France, where among more than half a million finds of flints and bone there are no burnt traces older than 400 000 years [121]. At a later date, too, there are significant gaps in the fire representation in Mousterian sites [127]. By contrast, at approximately 300 000 years ago, Vertesszollos in Hungary, Terra Amata and Menez Dregan in France and Bolomor in Spain show frequent evidence of fire [121,128–131], continued in Spain on later Neanderthal sites such as Abric Romani [132].

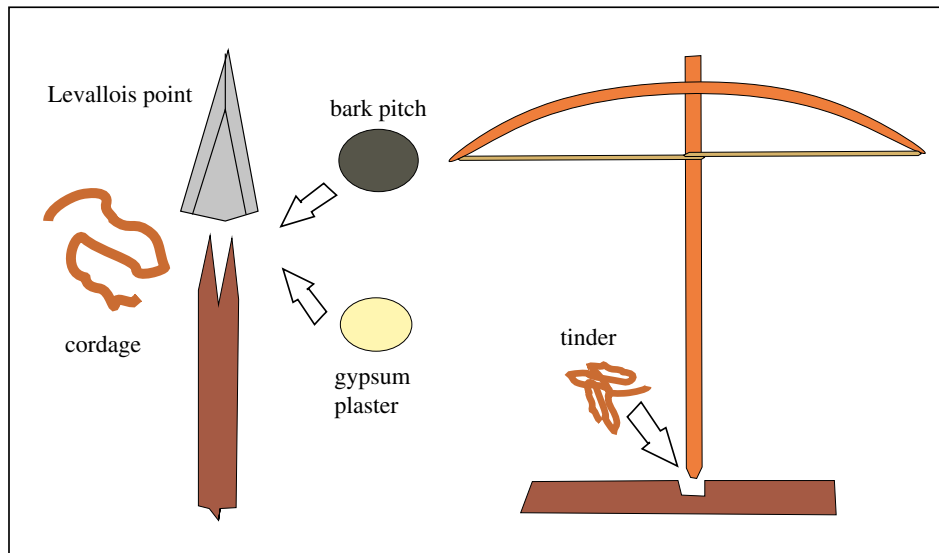
It has been argued a number of times that fire management may have improved markedly around 400 000 years ago [81,121–123,126]. The Levallois technique of stone working

originates around the same period, and gives strong indications of the beginnings of hafting [133–135] (figure 4). This is also implied at two German sites, notably Schöningen, where short wooden staves are preserved with deep notches in the ends [136]. Effective hafted systems require glue or twine—it may be highly significant that two of the main glues require heat treatment for their production [87,88].

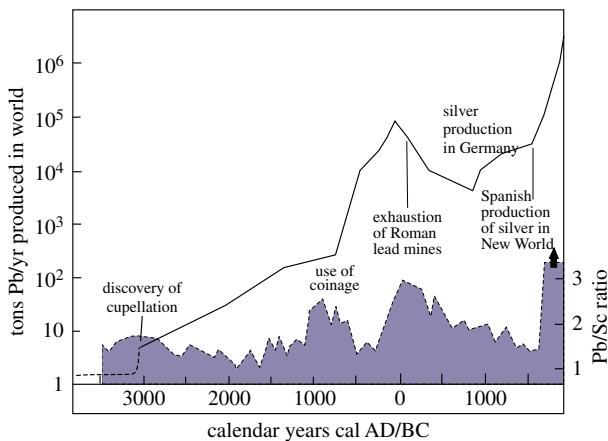
The question of ignition is an important one [127,137], but perhaps less crucial to effective fire use than often assumed. If hominins could not ignite fire, however, they would need to be able to maintain it robustly, and hence probably be reliant on a strong social network allowing its replacement [138]. They would need good knowledge of slow-burning materials, although field studies show that animal dung is useful in this respect. Ignition is often assumed to have required a cognitive advance. Yet the simplest kindling technique of rubbing a stick in a groove in a wooden ‘hearth’ requires no more than power and basic skill. It does not seem a more complex process than hafting, which it closely resembles in that two component parts require understanding and use of an intermediary: fixative in the one, and tinder in the other (figure 5).

By 120 000 years ago, pierced shell beads [141] indicate a knowledge of twine or leather cord, which would have been necessary for operating a fire drill. Before this date at Pinnacle Point in South Africa, stone was being warmed to improve its working qualities [142]. Such finds are a further early indication of the use of fire in technological processes: with its need for fuelling and maintenance domestic fire becomes a firm stimulus towards division of labour, planning and focusing of attention [17].

From this point, fire use can be seen as almost universal, as it is among living modern humans (e.g. [143–145]). Even so, there are puzzles in the record, where fire is



**Figure 4.** Hafting of a Levallois point: the implicit connections with fire. Hafting of Levallois may occur as early as 500 000 years ago [133–135]. Two glues in use by 50–100 ka require fire for preparation; twine, implied to be in use by 120 ka [123] is a requisite for working a fire drill. Hafting and the use of a fire drill involve a similar conceptual mastery of bringing together two components via a vital intermediary—fixative in the one and kindling in the other.



**Figure 5.** Full impact of fire use may come only when agricultural economies are followed by industrial ones. Here evidence of two records of metal exploitation demonstrates effects through the last 5000 years. The lead aerosol record of Arctic ice cores gives a dated index to production of lead and silver through the last 5000 years [139], and as such may provide an effective guide to the relative scales of burning of wood in industrial processes through that period, long before the atmospheric effects of fossil fuel burning are seen. Through the same period, lead/scandium ratios from a peat bog in the Basque country give indications of the local peak mining period which are sometimes also marked by signs of deforestation [140].

seemingly inexplicably absent (as in some parts of the record in Middle Palaeolithic France [127]), and it remains possible—balanced against the vicissitudes of sampling and preservation—that the costs and risks of using it sometimes outweighed the benefits.

## 7. The impact of fire

Over a long period, human interventions have grown to the point that in the modern world fires started by humans usually vastly outnumber those started by nature. Even so, in areas such as the Great Basin of the southwest USA, lightning-started fires still outnumber anthropogenic fires by a

factor of 2 or 3 to 1 [146]. In general, however, longstanding natural fire regimes have been interrupted and superseded. Recent syntheses make plain the importance of knowing when that becomes true in terms of landscape, and it is evident that geographical, ecological, archaeological and anthropological studies can come together far more effectively (e.g. [147]). The issues are complex for three main reasons which have to be meshed with the studies of natural fire regimes [10,12,15,149–171]. First, the dispersal of modern humans is marked by different arrival times in different regions—of the order of 50–60 ka for Australia and 40 ka for Europe [172,173], and 10–20 ka for the Americas [174], far later again for New Zealand and the Pacific [175]. Second, the arrivals and recolonizations sometimes cut across the immense climate changes involved in the transition from the last glacial maximum to the Holocene. A third key factor is that hunting and gathering economies began to be replaced by agricultural and pastoralist economies from about 10 000 years ago [176]. Until then, populations were relatively low, of the order of 1 person km<sup>-2</sup>, but farming raised population densities by at least 10 or 100 times: the significance of this is that most major human impacts are likely to be relatively recent, occupying less than 0.5% of the Pleistocene.

Modern hunter-gatherers do however demonstrate that people in small numbers can have significant effects [78,79]. Humanly influenced regimes are found across the world of hunter-gatherers [54,78,79,177–181], but to varied and debated extents. Principal questions are how far back they go in time, and how great their influence was. For Africa, Archibald *et al.* [54] have argued for a potentially greater influence through the last approximately 100 000 years, as early modern human populations increased. The main archaeological evidence comes from the shaping of the African Middle Stone Age (MSA), including greater transport distances for artefacts, and the eventual dispersal out of Africa [182,183]. The other signs of complex fire management, mentioned above [87,88,142] also suggest the possibility that the landscape scale interventions may extend back to 100–200 000 years ago, if not further. A rare study based on elemental carbon in a deep sea core indicates an increase in fire at about 400 000 years

ago [184], but in the view of its specific association with interglacial to glacial transitions, there may be no anthropogenic implications.

As has been seen, in many parts of the world first interventions by colonizing modern humans would occur only at more recent dates. Accordingly, local fire histories may have far greater validity than global ones, and the time differences in human occupation give scope to compare records, especially across the southern continents.

Within the last 20 000 years, there came major new fire interactions, the first associated with pottery, which appears to have originated in China [185,186]. From around 10 000 years ago, agriculture would potentially have widespread effects. Fixed Neolithic settlements, such as Çatalhöyük, would have required wide-ranging foraging for firewood [187], but there are indications in the Levant that woodland was sometimes managed [188]. Soon afterwards, from roughly 5000 years ago come the beginnings of metalworking, first copper and bronze, and then iron. Such interventions involve the raising of temperatures far above those of open fires—the development of a true pyrotechnology [189]. Lead aerosols from arctic ice cores provide an index of lead and silver production through the last 5000 years [139], and can perhaps also be used as a rough proxy for the scale of burning across the Northern Hemisphere through the last 5000 years. They are consonant with local records of mining evidence, e.g. from the Basque country [140], where there are signs of periodic deforestation. The main impact came from the time of the Roman Empire onwards (figure 5).

It remains to consider the impact of fire on human biology and sociality. The change in the genus *Homo* over 2 Myr has been remarkable. There are signs that a considerable part of this can be put down to the influence of fire. Particularly striking is that modern adult humans have an exceptionally long waking day, of 16 h or more, compared with 8 h in many mammal species [190,191]. Whereas other primates such as chimpanzees and gorillas rise with the dawn and go to sleep around sundown [192], humans have peak alertness in the early evening [13,193,194]. The several additional hours of wakefulness appear to have been made possible by fire and its ‘daylight extension’. The reasons appear to have been for social time (hence a probable link with language: [49,71,72,138,195]), as well as protection against predators. Changes in the size and proportion of stomach, small intestine and large intestine may be part of the same complex—owed to changed diet, necessary for sustained movement on the ground, and following the expensive tissue hypothesis a possible co-requisite of the large human brain [75].

It is probably not an exaggeration to say that there was also a re-organization of human sociality focused on fire and the hearth. Earlier mention was made of the needs for division of labour. Costs of fire can be high, too: the longer a settlement is inhabited, often the greater the distances covered in fuel-foraging. Such aspects can probably be related to the emergence of larger group sizes, these also entailing the active support of a post-mature generation—grandfathers and grandmothers [196,197]—and of children [20].

From all this, it is clear that fire has had both direct and indirect impacts. Apart from its effects on the environment and human sociality, its influence has reached in some way into the human psyche, expressed in religion, in ritual, in ceremony [198] and through ubiquitous myths about fire origins [149,199].

## 8. Conclusion

The deep importance of fire, and the longstanding nature of human interactions with it in the past, are both beyond doubt. The vanishing act of early fire ensures that it remains difficult to investigate, so that widely varying views remain both about its first take-up and subsequent use, but recently a changed perception has emerged. First, there is an increasing recognition of a need to move beyond simple ‘presence/absence’ judgements about archaeological hearths as an index for the ‘when’ of human fire use. Regular human–fire interactions could long precede fixed hearths in settlements. Second, an understanding is emerging that fire use is not a single technology or process, but that several scales of use, and probably several intensifying technologies, evolved over a long period, intertwined, and sometimes eventually became bound together.

In total, we know a good deal, if much remains to be found out of the ‘why and when?’. We know that our nearest relatives, the chimpanzees, are not intimidated by fire, but behave sensibly in relation to it; that humans were exposed to fire frequently from the time that they moved into open savanna environments more than 2 Ma; from isotopic evidence and changes in teeth, that their diet altered considerably around this time. We know that burning evidence occurs on numbers of archaeological sites from about 1.5 Ma onwards (there is evidence of actual hearths from around 0.7 to 0.4 Ma); that more elaborate technologies existed from around half a million years ago, and that these came to employ adhesives that require preparation by fire. We know that both early modern humans and Neanderthals had sophisticated fire technologies, at least some of the time. Despite the huge biases of disappearance and preservation, a new phase of early fire research is emerging in which interdisciplinary approaches offer the chance of addressing questions with increased success. In the grand sweep of human evolution, ‘intensification’ is a dominant theme in the practices and culture of *Homo*: fire use is entirely in step with other lines of evidence.

## 9. Meeting discussion

*N. Roberts* (University of Edinburgh). What information is available regarding the size of the groups that would congregate around and use fires across archaeological times and in different regions of the world? Is there a latitude dependence perhaps relating to the need to provide warmth?

*J. Gowlett*. It is an important question, but up to 400 000 years ago any information we have relates to site size and group size, rather than how many congregated around a hearth. From around 400 000–300 000 years ago when numbers of structured hearths can be seen, they appear to include both large and small in different contexts. Size may depend on immediate purpose and available fuel more than climate. Social factors are also likely to determine whether fires are communal, or specific to nuclear families. We have Late Pleistocene sites such as Meer in Belgium where there are numbers of hearths of different sizes in a small settlement.

*C. Roos* (Southern Methodist University, USA). I appreciate your recommendation that we look to non-human animal analogies for how our hominin ancestors may have seen fire as an opportunity. Do you think that opportunistic fire-margin hunting or scavenging might account for the evidence

for increased meat consumption around the time of early encephalization (instead of the cooking hypothesis)?

*J. Gowlett.* The analogy with other animals might suggest that in the first instance early hominins would go to fires simply to take advantage of any additional opportunities of gaining prey, regardless of whether the resources were cooked. For example, fire may reveal a clutch of eggs—so much the better if it has baked them. For encephalization, new cranial finds are altering the figures rapidly, but at the moment it would seem that the average cranial capacity for early *Homo* at 1.8 Ma is 600–650 cc, 40–50% greater than for most apes and australopithecines—and yet this is earlier than Richard Wrangham's postulated date of 1.7 Ma for applying the cooking hypothesis. Perhaps the fire foraging is one important element, and the cooking hypothesis comes into play more strongly later, but other factors operate alongside both.

## References

- Clark JD, Harris JWK. 1985 Fire and its roles in early hominid lifeways. *Afr. Archaeol. Rev.* **3**, 3–27. (doi:10.1007/BF01117453)
- Goudsblom J. 1992 *Fire and civilization*. London, UK: Penguin.
- Scott AC, Bowman DMJS, Bond WJ, Pyne SJ. 2014 *Fire on Earth: an introduction*. London, UK: Wiley-Blackwell.
- Pyne SJ. 2001 *Fire: a brief history*. London, UK: British Museum Press.
- Perlès C. 1975 L'homme préhistorique et le feu. *La Recherche* **6**, 829–839.
- Perlès C. 1977 *La préhistoire du feu*. Paris, France: Masson.
- Frazer JG. 1922 *The golden bough*. London, UK: Macmillan.
- Darwin C. 1871 *The descent of man*. London, UK: John Murray.
- Whelan RJ. 1995 *The ecology of fire*. Cambridge, UK: Cambridge University Press.
- Bond WJ, Keeley JE. 2005 Fire as a global 'herbivore': the ecology and evolution of current flammable ecosystems. *Trends Ecol. Evol.* **20**, 387–394. (doi:10.1016/j.tree.2005.04.025)
- Belcher CM, Collinson ME, Scott AC. 2013 A 450 million year record of fire. In *Fire phenomena in the earth system—an interdisciplinary approach to fire science* (ed. CM Belcher), pp. 229–249. London, UK: John Wiley and Sons.
- Bowman DMJS *et al.* 2011 The human dimension of fire regimes on Earth. *J. Biogeogr.* **38**, 2223–2236. (doi:10.1111/j.1365-2699.2011.02595.x)
- Scott AC. 2009 Forest fire in the fossil record. In *Fire effects on soils and restoration strategies* (eds A Cerdà, P Robichaud), pp. 1–37. Enfield, NH: Science Publishers Inc.
- Scott AC. 2000 The pre-quaternary history of fire. *Palaeogeogr. Palaeoclimatol.* **164**, 281–329. (doi:10.1016/S0031-0182(00)00192-9)
- Roos CI *et al.* 2014 Pyrogeography, historical ecology, and the human dimensions of fire regimes. *J. Biogeogr.* **41**, 833–836. (doi:10.1111/jbi.12285)
- Christian HJ *et al.* 2003 Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.* **108**, ACL1–AC15. (doi:10.1029/2002JD002347)
- Gowlett J. 2010 Firing up the social brain. In *Social brain and distributed mind* (eds R Dunbar, C Gamble, J Gowlett), pp. 345–370. London, UK: The British Academy.
- Gowlett JAJ, Wrangham RW. 2013 Earliest fire in Africa: the convergence of archaeological evidence and the cooking hypothesis. *Azania: Archaeol. Res. Africa* **48**, 5–30. (doi:10.1080/0067270X.2012.756754)
- Barnard A. 1992 *Hunters and herders of southern Africa: a comparative ethnography of the Khoisan peoples*. Cambridge, UK: Cambridge University Press.
- Sanders T. 1999 'Doing gender' in Africa: embodying categories and the categorically disembodied. In *Those who play with fire: gender, fertility and transformation in east and southern Africa* (eds HL Moore, T Sanders, B Kaare), pp. 41–82. London, UK: Athlone Press.
- Bloch JL, Silcox MT, Boyer DM, Sargis EJ. 2007 New Paleocene skeletons and the relationship of plesiadapiforms to crown-clade primates. *Proc. Natl Acad. Sci. USA* **104**, 1159–1164. (doi:10.1073/pnas.0610579104)
- Williams BA, Kay RF, Kirk EC. 2010 New perspectives on anthropoid origins. *Proc. Natl Acad. Sci. USA* **107**, 4797–4804. (doi:10.1073/pnas.0908320107)
- Bond WJ, Midgley JJ. 2012 Fire and the angiosperm revolutions. *Int. J. Plant. Sci.* **173**, 569–583. (doi:10.1086/665819)
- Stevens N *et al.* 2013 Palaeontological evidence for an Oligocene divergence between Old World monkeys and apes. *Nature* **497**, 611–614. (doi:10.1038/nature12161)
- Tutin CEG, White LJT, Mackangamissandzou A. 1996 Lightning strike burns large forest tree in the Lopé Reserve, Gabon. *Glob. Ecol. Biogeogr. Lett.* **5**, 36–41. (doi:10.2307/2997469)
- Stott P. 2000 Combustion in tropical biomass fires: a critical review. *Prog. Phys. Geogr.* **24**, 355–377. (doi:10.1177/030913330002400303)
- Crompton RH. 2015 The hominins: a very conservative tribe? Last common ancestors, plasticity and ecomorphology in Hominidae. Or, What's in a name? *J. Anat.* **228**, 686–699. (doi:10.1111/joa.12424)
- deMenocal PB. 2004 African climate change and faunal evolution during the Pliocene-Pleistocene. *Earth Planet. Sci. Lett.* **220**, 3–24. (doi:10.1016/S0012-821X(04)00003-2)
- deMenocal P. 2011 Climate and human evolution. *Science* **331**, 540–541. (doi:10.1126/science.1190683)
- Langergraber KE *et al.* 2012 Generation times in wild chimpanzees and gorillas suggest earlier divergence times in great ape and human evolution. *Proc. Natl Acad. Sci. USA* **109**, 15 716–15 721. (doi:10.1073/pnas.1211740109)
- White TD, Lovejoy CO, Asfaw B, Carlson JP, Suwa G. 2015 Neither chimpanzee nor human, *Ardipithecus* reveals the surprising ancestry of both. *Proc. Natl Acad. Sci. USA* **112**, 4877–4884. (doi:10.1073/pnas.1403659111)
- White TD, Asfaw B, Beyene Y, Haile-Selassie Y, Lovejoy CO, Suwa G, WoldeGabriel G. 2009 *Ardipithecus ramidus* and the paleobiology of early hominids. *Science* **326**, 75–86. (doi:10.1126/science.1175802)
- Crompton RH, Sellers WI, Thorpe SKS. 2010 Arboreality, terrestriality and bipedalism. *Phil. Trans. R. Soc. B* **365**, 3301–3314. (doi:10.1098/rstb.2010.0035)
- Laden G, Wrangham RW. 2005 The rise of the hominids as an adaptive shift in fallback foods: plant underground storage organs (USOs) and australopithecine origins. *J. Hum. Evol.* **49**, 482–498. (doi:10.1016/j.jhevol.2005.05.007)

35. Stiner M. 2002 Carnivory, coevolution, and the geographic spread of the genus *Homo*. *J. Archaeol. Res.* **10**, 1–63. (doi:10.1023/A:1014588307174)
36. Milton K. 1999 A hypothesis to explain the role of meat-eating in human evolution. *Evol. Anthropol.* **8**, 11–21. (doi:10.1002/(SICI)1520-6505(1999)8:1<11::AID-EVAN6>3.0.CO;2-M)
37. Harmand S *et al.* 2015 3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya. *Nature* **521**, 310–315. (doi:10.1038/nature14464)
38. Villmoare B *et al.* 2015 Early *Homo* at 2.8 Ma from Ledi-Geraru, Afar, Ethiopia. *Science* **347**, 1352–1355. (doi:10.1126/science.aaa2397)
39. Gabunia L, Antón SC, Lordkipanidze D, Vekua A, Justus A, Swisher III CC. 2001 Dmanisi and dispersal. *Evol. Anthropol.* **10**, 158–170. (doi:10.1002/evan.1030)
40. Ferringer R *et al.* 2011 Earliest human occupation at Dmanisi (Georgian Caucasus) dated to 1.85–1.78 Ma. *Proc. Natl Acad. Sci. USA* **108**, 10 432–10 436. (doi:10.1073/pnas.1106638108)
41. Le Tensorer J-M, Le Tensorer H, Martini P, von Falkenstein V, Schmid P, Villalain JJ. 2015 The Oldowan site Ain al Fil (El Kowm) Syria. *L'Anthropologie* **119**, 581–594. (doi:10.1016/j.anthro.2015.10.009)
42. Zhu RX *et al.* 2004 New evidence on the earliest human presence at high northern latitudes in northeast Asia. *Nature* **431**, 559–562. (doi:10.1038/nature02829)
43. Zaim Y *et al.* 2011 New 1.5 million-year-old *Homo erectus* maxilla from Sangiran (Central Java, Indonesia). *J. Hum. Evol.* **61**, 363–376. (doi:10.1016/j.jhevol.2011.04.009)
44. Semaw S *et al.* 2003 2.6-Million-year-old stone tools and associated bones from OGS-6 and OGS-7, Gona, Afar, Ethiopia. *J. Hum. Evol.* **45**, 169–177. (doi:10.1016/S0047-2484(03)00093-9)
45. Féblot-Augustins J. 1999 Raw material transport patterns and settlement systems in the European Lower and Middle Palaeolithic: continuity, change and variability. In *The Middle Palaeolithic occupation of Europe* (eds W Roebroeks, C Gamble), pp. 193–214. Leiden, The Netherlands: European Science Foundation and University of Leiden.
46. Pruetz JD, LaDuke TC. 2010 Reaction to fire by savanna chimpanzees (*Pan troglodytes verus*) at Fongoli, Senegal: conceptualization of 'fire behavior' and the case for a chimpanzee model. *Am. J. Phys. Anthropol.* **141**, 646–650. (doi:10.1002/ajpa.21245)
47. Burton FD. 2009 *Fire: the spark that ignited human evolution*. Albuquerque, NM: University of New Mexico Press.
48. James SR. 1989 Hominid use of fire in the Lower and Middle Pleistocene: a review of the evidence. *Curr. Anthropol.* **30**, 1–26. (doi:10.1086/203705)
49. Dunbar RIM, Gowlett JAJ. 2014 Fireside chat: the impact of fire on hominin socioecology. In *Lucy to language: the benchmark papers* (eds RIM Dunbar, C Gamble, JAJ Gowlett), pp. 277–296. Oxford, UK: Oxford University Press.
50. Berthold P, Bauer HG, Westhead V. 2001 *Bird migration: a general survey*. Oxford, UK: Oxford University Press.
51. Twomey T. 2013 The cognitive implications of controlled fire use by early humans. *Camb. Archaeol. J.* **23**, 113–128. (doi:10.1017/S0959774313000085)
52. Mondal N, Sukumar R. 2013 Characterising weather patterns associated with fire in a seasonally dry tropical forest in southern India. *Int. J. Wildland Fire* **23**, 196–201. (doi:10.1071/WF13002)
53. Uhl C, Kauffman JB, Cummings DL. 1988 Fire in the Venezuelan Amazon. 2. Environmental conditions necessary for forest fires in the evergreen forest of Venezuela. *Oikos* **53**, 176–184. (doi:10.2307/3566060)
54. Archibald A, Staver AC, Levin SA. 2012 Evolution of human-driven fire regimes in Africa. *Proc. Natl Acad. Sci. USA* **109**, 847–852. (doi:10.1073/pnas.1118648109)
55. Huffines GR, Orville R. 1999 Lightning ground flash density and thunder-storm duration in the continental U.S. *J. Appl. Meteorol.* **38**, 1013–1019. (doi:10.1175/1520-0450(1999)038<1013:LGFDAT>2.0.CO;2)
56. Mitchener LJ, Parker AJ. 2005 Climate, lightning, and wildfire in the National Forests of the southeastern United States, 1989–1998. *Phys. Geogr.* **26**, 147–162. (doi:10.2747/0272-3646.26.2.147)
57. Wierzchowski J, Heathcott M, Flannigan MD. 2002 Lightning and lightning fire, central cordillera, Canada. *Int. J. Wildland Fire* **11**, 41–51. (doi:10.1071/WF01048)
58. Johnson EA. 1992 *Fire and vegetation dynamics: studies from the North American boreal forest*. Cambridge, UK: Cambridge University Press.
59. Farukh MA, Hayasaka H. 2012 Active forest fire occurrences in severe lightning years in Alaska. *J. Disaster Sci.* **33**, 71–84. (doi:10.2328/jnds.33.71)
60. Peters CR, O'Brien EM. 1981 The early hominid plant-food niche: insights from an analysis of plant exploitation by *Homo*, *Pan* and *Papio* in eastern and southern Africa. *Curr. Anthropol.* **22**, 127–140. (doi:10.1086/202631)
61. Sponheimer A *et al.* 2013 Isotopic evidence of early hominin diets. *Proc. Natl Acad. Sci. USA* **110**, 10 513–10 518. (doi:10.1073/pnas.1222579110)
62. Lee-Thorp JA, Sponheimer M, Passey BH, De Ruiter D, Cerling TE. 2010 Stable isotopes in fossil hominin tooth enamel suggest a fundamental dietary shift in the Pliocene. *Phil. Trans. R. Soc. B* **365**, 3389–3396. (doi:10.1098/rstb.2010.0059)
63. Bunn HT. 2007 Meat made us human. In *Evolution of the human diet: the known, the unknown, and the unknowable* (ed. PS Ungar), pp. 191–211. New York, NY: Oxford University Press.
64. Wrangham RW, Jones JH, Laden G, Pilbeam D, Conklin-Brittain N. 1999 The raw and the stolen: cooking and the ecology of human origins. *Curr. Anthropol.* **40**, 567–594. (doi:10.1086/300083)
65. Wrangham RW. 2007 The cooking enigma. In *Evolution of the human diet: the known, the unknown and the unknowable* (ed. PS Ungar), pp. 308–323. New York, NY: Oxford University Press.
66. Wrangham R. 2009 *Catching fire: how cooking made us human*. New York, NY: Basic Books.
67. Pontzer H, Rolian C, Rightmire GP, Jashashvili T, Ponce de León MS, Lordkipanidze D, Zollikofer CPE. 2010 Locomotor anatomy and biomechanics of the Dmanisi hominins. *J. Hum. Evol.* **58**, 492–504. (doi:10.1016/j.jhevol.2010.03.006)
68. Wrangham RW, Carmody R. 2010 Human adaptation to the control of fire. *Evol. Anthropol.* **19**, 187–199. (doi:10.1002/evan.20275)
69. Organ CL, Nunn CL, Machanda Z, Wrangham RW. 2011 Phylogenetic rate shifts in chewing time during the evolution of *Homo*. *Proc. Natl Acad. Sci. USA* **108**, 14 555–14 559. (doi:10.1073/pnas.1107806108)
70. Tobias PV. 1981 The emergence of man in Africa and beyond. *Phil. Trans. R. Soc. Lond. B* **292**, 43–56. (doi:10.1098/rstb.1981.0012)
71. Aiello LC, Dunbar RIM. 1993 Neocortex size, group size, and the evolution of language. *Curr. Anthropol.* **34**, 184–193. (doi:10.1086/204160)
72. Dunbar RIM. 1998 The social brain hypothesis. *Evol. Anthropol.* **6**, 178–190. (doi:10.1002/(SICI)1520-6505(1998)6:5<178::AID-EVAN5>3.3.CO;2-P)
73. Dunbar RIM, Shultz S. 2007 Evolution in the social brain. *Science* **317**, 1344–1347. (doi:10.1126/science.1145463)
74. Dunbar RIM, Gamble C, Gowlett JAJ (eds). 2014 *Lucy to language: the benchmark papers*. Oxford, UK: Oxford University Press.
75. Aiello LC, Wheeler P. 1995 The expensive tissue hypothesis: the brain and the digestive system in human and primate evolution. *Curr. Anthropol.* **36**, 199–221. (doi:10.1086/204350)
76. Aiello LC. 1996 Hominine preadaptations for cognition and language. In *Modelling the early human mind* (eds P Mellars, K Gibson), pp. 89–99. Cambridge, UK: McDonald Institute.
77. Green RE *et al.* 2010 A draft sequence of the Neandertal genome. *Science* **328**, 710–722. (doi:10.1126/science.1188021)
78. Bliege Bird R, Coding BF, Kauhainen PG, Bird DW. 2012 Aboriginal hunting buffers climate-driven fire-size variability in Australia's spinifex grasslands. *Proc. Natl Acad. Sci. USA* **109**, 10 287–10 292. (doi:10.1073/pnas.1204585109)
79. Jones R. 1969 Firestick farming. *Aust. Nat. Hist.* **16**, 224–228.
80. Rolland N. 2000 Cave occupation, fire-making, hominid/carnivore coevolution, and Middle Pleistocene emergence of home-base settlement systems. *Acta Anthropol. Sin.* **19**, 209–217.
81. Rolland N. 2004 Was the emergence of home bases and domestic fire a punctuated event? A review of the Middle Pleistocene record in Eurasia. *Asian Persp.* **43**, 248–280. (doi:10.1353/asi.2004.0027)
82. McGrath GS. 2014 *Before modern humans: new perspectives on the African Stone Age*. Walnut Creek, CA: Left Coast Press.
83. Roche H, Delagnes A, Brugal J-P, Feibel C, Kibunjia M, Mourre V, Texier J-P. 1999 Early hominid stone tool production and technical skill 2.34 Myr ago in West Turkana, Kenya. *Nature* **399**, 57–60. (doi:10.1038/19959)
84. Isaac GL, Harris JWK. 1997 The stone artefact assemblages: a comparative study. In *Koobi Fora*

- research project volume 5: Plio-Pleistocene Archaeology (eds GLL Isaac, B Isaac), pp. 262–362. Oxford, UK: Clarendon Press.
85. Lynch TF (ed.). 1980 *Guitarrero cave: early man in the Andes*. New York, NY: Academic Press.
  86. Lynch TF, Gillespie R, Gowlett JAJ, Hedges REM. 1985 Chronology of Guitarrero Cave, Peru. *Science* **229**, 864–867. (doi:10.1126/science.229.4716.864)
  87. Koller J, Baumer U, Mania D. 2001 High-tech in the Middle Palaeolithic: Neandertal-manufactured pitch identified. *Eur. J. Archaeol.* **4**, 385–397. (doi:10.1179/eja.2001.4.3.385)
  88. Friedman E, Goren-Inbar N, Rosenfeld A, Marder O, Burian F. 1995 Hafting during Mousterian times—further indication. *Mitekufat Ha'even* **26**, 8–31.
  89. Clark JD (ed.). 2001 *Kalambo Falls prehistoric site, vol. 3: the earlier cultures: Middle and Earlier Stone Age*. Cambridge, UK: Cambridge University Press.
  90. Duller GAT, Tooth S, Barham L, Tsukamoto S. 2015 New investigations at Kalambo Falls, Zambia: luminescence chronology, site formation, and archaeological significance. *J. Hum. Evol.* **85**, 111–125. (doi:10.1016/j.jhevol.2015.05.003)
  91. Gowlett JAJ, Hallos J, Hounsell S, Brant V, Debenham NC. 2005 Beeches Pit – archaeology, assemblage dynamics and early fire history of a Middle Pleistocene site in East Anglia, UK. *Eurasian Prehistory* **3**, 3–38.
  92. Preece RC, Gowlett JAJ, Parfitt SA, Bridgland DR, Lewis SG. 2006 Humans in the Hoxnian: habitat, context and fire use at Beeches Pit, West Stow, Suffolk, UK. *J. Quat. Sci.* **21**, 485–496. (doi:10.1002/jqs.1043)
  93. Bellomo RV. 1993 A methodological approach for identifying archaeological evidence of fire resulting from human activities. *J. Archaeol. Sci.* **20**, 525–555. (doi:10.1006/jasc.1993.1033)
  94. Bellomo RV. 1994 Methods of determining early hominid behavioural activities associated with the controlled use of fire at FxJ20 Main, Koobi Fora, Kenya. *J. Hum. Evol.* **27**, 173–195. (doi:10.1006/jhev.1994.1041)
  95. Gedye SJ, Jones RT, Tinner W, Ammann B, Oldfield F. 2000 The use of mineral magnetism in the reconstruction of fire history: a case study from Lago di Origlio, Swiss Alps. *Palaeogeogr. Palaeoclimatol.* **164**, 101–110. (doi:10.1016/S0031-0182(00)00178-4)
  96. Goldberg P, Berna F. 2010 Micromorphology and context. *Quat. Int.* **214**, 56–62. (doi:10.1016/j.quaint.2009.10.023)
  97. Stahlschmidt MC *et al.* 2015 On the evidence for human use and control of fire at Schöningen. *J. Hum. Evol.* **89**, 181–201. (doi:10.1016/j.jhevol.2015.04.004)
  98. Bellomo RV, Kean WF. 1997 Evidence of hominid controlled fire at the FxJ20 site complex, Karari escarpment. Appendix 4A. In *Koobi Fora research project volume 5: Plio-Pleistocene Archaeology* (eds GL Isaac, B Isaac), pp. 224–233. Oxford, UK: Clarendon Press.
  99. Rowlett RM. 2000 Fire control by *Homo erectus* in East Africa and Asia. *Acta Anthropol. Sin.* **19**, 198–208.
  100. Gowlett JAJ, Harris JWK, Walton D, Wood BA. 1981 Early archaeological sites, hominid remains and traces of fire from Chesowanja, Kenya. *Nature* **294**, 125–129. (doi:10.1038/294125a0)
  101. Gowlett JAJ. 1999 Lower and Middle Pleistocene archaeology of the Baringo Basin. In *Late Cenozoic environments and hominid evolution: a tribute to Bill Bishop* (eds P Andrews, P Banham), pp. 123–141. London, UK: Geological Society.
  102. Barbetti M. 1986 Traces of fire in the archaeological record, before one million years ago? *J. Hum. Evol.* **15**, 771–781. (doi:10.1016/S0047-2484(86) 80009-4)
  103. Brain CK. 1981 *The hunters or the hunted? An introduction to African Cave Taphonomy*. Chicago, IL: University of Chicago Press.
  104. Brain CK. 2005 Essential attributes of any technologically competent animal. In *From tools to symbols: from early hominids to modern humans* (eds F d'Errico, L Backwell), pp. 38–51. Johannesburg, South Africa: Witwatersrand University Press.
  105. Brain CK, Sillen A. 1988 Evidence from the Swartkrans cave for the earliest use of fire. *Nature* **336**, 464–466. (doi:10.1038/336464a0)
  106. Pickering TR. 2012 What's new is old: Comments on (more) archaeological evidence of one-million-year-old fire from South Africa. *S. Afr. J. Sci.* **108**. (doi:10.4102/sajs.v108i5/6.1250)
  107. Pickering TR, Dominguez-Rodrigo M, Egeland BCP, Brain CK. 2005 The contribution of limb bone fracture patterns to reconstructing early hominid behaviour at Swartkrans Cave (South Africa): archaeological application of a new analytical method. *Int. J. Osteoarchaeol.* **15**, 247–260. (doi:10.1002/oa.780)
  108. Berna F, Goldberg P, Horwitz LK, Brink J, Holt D, Bamford M, Chazan M. 2012 Microstratigraphic evidence of *in situ* fire in the Acheulean strata of Wonderwerk Cave, Northern Cape province, South Africa. *Proc. Natl Acad. Sci. USA* **109**, E1215–E1220. (doi:10.1073/pnas.1117620109)
  109. Goldberg P, Berna F, Chazan M. 2015 Deposition and diagenesis in the Earlier Stone Age of Wonderwerk Cave, Excavation 1, South Africa. *Afr. Archaeol. Rev.* **32**, 613–643. (doi:10.1007/s10437-015-9192-9)
  110. Goren-Inbar N, Alpers N, Kislev ME, Simchoni O, Melamed Y, Ben-Nun A, Werker E. 2004 Evidence of hominin control of fire at Geshen Benot Yaaqov, Israel. *Science* **304**, 725–727. (doi:10.1126/science.1095443)
  111. Alpers-Afil N. 2008 Continual fire-making by hominins at Geshen Benot Ya'aqov, Israel. *Quat. Sci. Rev.* **27**, 1733–1739. (doi:10.1016/j.quascirev.2008.06.009)
  112. Alpers-Afil N, Goren-Inbar N. 2010 *The Acheulean site of Geshen Benot Ya'aqov, Volume II. Ancient flames and controlled use of fire*. Vertebrate Paleobiology and Paleoanthropology series. Dordrecht, The Netherlands: Springer.
  113. Black D. 1934 Recent discoveries at Choukoutien [China]. *Nature* **133**, 89–90. (doi:10.1038/133089a0)
  114. Oakley KP. 1956 Fire as Palaeolithic tool and weapon. *Proc. Prehist. Soc.* **21**, 36–48. (doi:10.1017/S0079497X00017382)
  115. Binford LR, Ho CK. 1985 Taphonomy at a distance; Zhoukoudian, the cave home of Beijing man? *Curr. Anthropol.* **26**, 413–442. (doi:10.1086/203303)
  116. Binford LR, Stone N. 1986 Zhoukoudian: a closer look. *Curr. Anthropol.* **27**, 453–475. (doi:10.1086/203469)
  117. Weiner S, Xu Q, Goldberg P, Liu J, Bar-Yosef O. 1998 Evidence for the use of fire at Zhoukoudian, China. *Science* **281**, 251–253. (doi:10.1126/science.281.5374.251)
  118. Goldberg P, Weiner S, Xu Q, Liu J. 2001 Site formation processes at Zhoukoudian, China. *J. Hum. Evol.* **41**, 483–530. (doi:10.1006/jhev.2001.0498)
  119. Boaz NT, Ciochon RL, Xu Q, Liu J. 2004 Mapping and taphonomic analysis of the *Homo erectus* loci at Locality 1 Zhoukoudian, China. *J. Hum. Evol.* **46**, 519–549. (doi:10.1016/j.jhevol.2004.01.007)
  120. Zhong M, Shi C, Gao X, Wu X, Chen F, Zhang S, Zhang X, Olsen JW. 2014 On the possible use of fire by *Homo erectus* at Zhoukoudian, China. *Chinese Sci. Bull.* **59**, 3, 335–343. (doi:10.1007/s11434-013-0061-0)
  121. Lumley H. 2006 Il y a 400,000 ans: la domestication du feu, un formidable moteur d'homínisation. In *Climats, Cultures et sociétés aux temps préhistoriques, de l'apparition des Hominidés jusqu'au Néolithique* (ed. H de Lumley). *C. R. Palevol.* **5**, 149–154. (doi:10.1016/j.crpv.2005.11.014)
  122. Gowlett JAJ. 2006 The early settlement of northern Europe: fire history in the context of climate change and the social brain. In *Climats, Cultures et sociétés aux temps préhistoriques, de l'apparition des Hominidés jusqu'au Néolithique* (ed. H de Lumley). *C. R. Palevol.* **5**, 299–310. (doi:10.1016/j.crpv.2005.10.008)
  123. Karkanas P, Shahack-Gross R, Ayalon A, Bar-Matthews M, Barkai R, Frumkin A, Gopher A, Stiner MC. 2007 Evidence for habitual use of fire at the end of the Lower Paleolithic: site-formation processes at Qesem Cave, Israel. *J. Hum. Evol.* **53**, 197–212. (doi:10.1016/j.jhevol.2007.04.0)
  124. Shahack-Gross R, Berna F, Karkanas P, Lemorini C, Gopher A, Barkai R. 2014 Evidence for the repeated use of a central hearth at Middle Pleistocene (300 ky ago) Qesem Cave, Israel. *J. Archaeol. Sci.* **44**, 12–21. (doi:10.1016/j.jas.2013.11.015)
  125. Shimelmitz R, Kuhn SL, Jelinek AJ, Ronen A, Clark AE, Weinstein-Evron M. 2014 'Fire at will': the emergence of habitual fire use 350,000 years ago. *J. Hum. Evol.* **77**, 196–203. (doi:10.1016/j.jhevol.2014.07.005)
  126. Roebroeks W, Villa P. 2011 On the earliest evidence for habitual use of fire in Europe. *Proc. Natl Acad. Sci. USA* **108**, 5209–5214. (doi:10.1073/pnas.1018116108)
  127. Sandgathe DM, Dibble HL, Goldberg P, McPherron SP, Turq A, Niven L, Hodgkins J. 2011 Timing of the appearance of habitual fire use. *Proc. Natl Acad. Sci. USA* **108**, E298. (doi:10.1073/pnas.1106759108)

128. Kretzoi M, Vertes L. 1965 Upper Biharian (Intermindel) pebble-industry occupation site in Western Hungary. *Curr. Anthropol.* **6**, 74–87. (doi:10.1086/200558)
129. Lumley H. 2009 *Terra Amata, Nice, Alpes-Maritimes, France*, vol. 1. Paris, France: CNRS.
130. Fernández-Peris J. 2007 *La Cova del Bolomor (Tavernes de la Valldigna, Valencia): las industrias líticas del Pleistoceno medio en el ámbito del Mediterráneo peninsular*. Valencia, Spain: Servicio de Investigación Prehistórica.
131. Gowlett JAJ. 2015 Les origines de l'utilisation du feu par les hommes: hypothèses actuelles et indices les plus anciens. In *Sur le chemin de l'humanité. Via humanitatis: les grandes étapes de l'évolution morphologique et culturelle de l'Homme: émergence de l'être humain. Colloque international de l'Académie Pontificale des Sciences, Cité du Vatican avril 2013* (ed. H de Lumley), pp. 171–197. Paris, France: Académie Pontificale des Sciences/CNRS.
132. Pastó IE, Allué E, Vallverdú J. 2000 Mousterian hearths at Abric Romani, Catalonia (Spain). In *Neanderthals on the edge: papers from a conference marking the 150th Anniversary of the Forbes' Quarry discovery, Gibraltar* (eds CB Stringer, RNE Barton, JC Finlayson), pp. 59–68. Oxford, UK: Oxbow Books.
133. Wilkins J, Chazan M. 2012 Blade production approximately 500 thousand years ago at Kathu Pan 1, South Africa: support for a multiple origins hypothesis for early Middle Pleistocene blade technologies. *J. Archaeol. Sci.* **39**, 1883–1900. (doi:10.1016/j.jas.2012.01.031)
134. Wilkins J, Schoville BJ, Brown KS, Chazan M. 2012 Evidence for early hafted hunting technology. *Science* **338**, 942–946. (doi:10.1126/science.1227608)
135. Barham L. 2013 *From hand to handle: the first industrial revolution*. Oxford, UK: Oxford University Press.
136. Thieme H. 1998 The oldest spears in the world: Lower Palaeolithic hunting weapons from Schöningen, Germany. In *Los primeros pobladores de Europa/The first Europeans: recent discoveries and current debate* (eds E Carbonell, JM Bermudez de Castro, JL Arsuaga, XP Rodriguez), pp. 169–193. Burgos, Spain: Aldecoa.
137. Sorensen A, Roebroeks W, van Gijn A. 2014 Fire production in the deep past? The expedient strike-a-light model. *J. Archaeol. Sci.* **42**, 476–486. (doi:10.1016/j.jas.2013.11.032)
138. Gowlett J, Gamble C, Dunbar R. 2012 Human evolution and the archaeology of the social brain. *Curr. Anthropol.* **53**, 693–722. (doi:10.1086/667994)
139. Settle DM, Patterson CC. 1980 Lead in Albacore: guide to lead pollution in Americans. *Science* **207**, 1171. (doi:10.1126/science.6986654)
140. Monna F, Galop D, Carozza L, Tual M, Beyrie A, Marambert F, Chateau C, Dominik J, Grousset FE. 2004 Environmental impact of early Basque mining and smelting recorded in a high ash minerogenic peat deposit. *Sci. Total Environ.* **327**, 197–214. (doi:10.1016/j.scitotenv.2004.01.010)
141. Vanhaeren M, Stringer C, James SL, Todd JA, Henk KM. 2006 Middle Paleolithic shell beads in Israel and Algeria. *Science* **312**, 1785–1788. (doi:10.1126/science.1128139)
142. Brown KS, Marean CW, Herries AIR, Jacobs Z, Tribolo C, Braun D, Roberts DL, Meyer MC, Bernatchez J. 2009 Fire as an engineering tool of early modern humans. *Science* **325**, 859–862. (doi:10.1126/science.1175028)
143. Henderson Z. 2001 The integrity of the Middle Stone Age horizon at Florisbad, South Africa. *Navorsing van die nasionale Museum Bloemfontein* **17**, 26–52.
144. Hérisson D, Locht J-L, Auguste P, Tuffreau A. 2013 Néandertal et le feu au Paléolithique moyen ancien. Tour d'horizon des traces de son utilisation dans le Nord de la France. *L'Anthropologie* **117**, 541–578. (doi:10.1016/j.anthro.2013.10.002)
145. Julien M. 2003 A Magdalenian base camp at Pincevent (France). In *Perceived landscapes and built environments. The cultural geography of late Palaeolithic Eurasia* (eds SA Vasil'ev, O Soffer, J Kozłowski), pp. 105–111. Actes XIV Congrès UISPP. Bar International Series 1122. Oxford, UK: Archaeopress.
146. Griffin D. 2002 Prehistoric human impacts on fire regimes and vegetation in the northern intermountain West. In *Fire, native peoples and the natural landscape* (ed. TR Vale), pp. 77–100. Washington, DC: Island Press.
147. Scherjon F, Bakels C, MacDonald K, Roebroeks W. 2015 Burning the land: an ethnographic study of off-site fire use by current and historically documented foragers and implications for the interpretation of past fire practices in the landscape. *Curr. Anthropol.* **56**, 299–326. (doi:10.1086/681561)
148. McWethy DB *et al.* 2013 A conceptual framework for predicting temperate ecosystem sensitivity to human impacts on fire regimes. *Glob. Ecol. Biogeogr.* **22**, 900–912. (doi:10.1111/geb.12038)
149. Pyne SJ. 2016 Fire in the mind: changing understandings of fire in Western civilization. *Phil. Trans. R. Soc. B* **371**, 20150166. (doi:10.1098/rstb.2015.0166)
150. Martin DA. 2016 At the nexus of fire, water and society. *Phil. Trans. R. Soc. B* **371**, 20150172. (doi:10.1098/rstb.2015.0172)
151. Swetnam TW, Farella J, Roos CI, Liebmann MJ, Falk DA, Allen CD. 2016 Multi-scale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. *Phil. Trans. R. Soc. B* **371**, 20150168. (doi:10.1098/rstb.2015.0168)
152. Doerr SH, Santin C. 2016 Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Phil. Trans. R. Soc. B* **371**, 20150345. (doi:10.1098/rstb.2015.0345)
153. Scott AC, Chaloner WG, Belcher CMJ, Roos CI. 2016 The interaction of fire and mankind. *Phil. Trans. R. Soc. B* **371**, 20160149. (doi:10.1098/rstb.2016.0149)
154. Scott AC, Chaloner WG, Belcher CMJ, Roos CI. 2016 The interaction of fire and mankind: Introduction. *Phil. Trans. R. Soc. B* **371**, 20150162. (doi:10.1098/rstb.2015.0162)
155. Belcher CM. 2016 The influence of leaf morphology on litter flammability and its utility for interpreting palaeofire. *Phil. Trans. R. Soc. B* **371**, 20150163. (doi:10.1098/rstb.2015.0163)
156. Power MJ, Whitney BS, Mayle FE, Neves DM, de Boer EJ, Maclean KS. 2016 Fire, climate and vegetation linkages in the Bolivian Chiquitano seasonally dry tropical forest. *Phil. Trans. R. Soc. B* **371**, 20150165. (doi:10.1098/rstb.2015.0165)
157. Hardiman M, Scott AC, Pinter N, Anderson RS, Ejarque A, Carter-Champion A, Staff RA. 2016 Fire history on the California Channel Islands spanning human arrival in the Americas. *Phil. Trans. R. Soc. B* **371**, 20150167. (doi:10.1098/rstb.2015.0167)
158. Bowman DMJS, Perry GLW, Higgins SI, Johnson CN, Fuhlendorf SD, Murphy BP. 2016 Pyrodiversity is the coupling of biodiversity and fire regimes in food webs. *Phil. Trans. R. Soc. B* **371**, 20150169. (doi:10.1098/rstb.2015.0169)
159. Bond W, Zaloumis NP. 2016 The deforestation story: testing for anthropogenic origins of Africa's flammable grassy biomes. *Phil. Trans. R. Soc. B* **371**, 20150170. (doi:10.1098/rstb.2015.0170)
160. Santin C, Doerr SH. 2016 Fire effects on soils: the human dimension. *Phil. Trans. R. Soc. B* **371**, 20150171. (doi:10.1098/rstb.2015.0171)
161. Johnston FH, Melody S, Bowman DMJS. 2016 The pyrohealth transition: how combustion emissions have shaped health through human history. *Phil. Trans. R. Soc. B* **371**, 20150173. (doi:10.1098/rstb.2015.0173)
162. Mistry J, Bilbao BA, Berardi A. 2016 Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. *Phil. Trans. R. Soc. B* **371**, 20150174. (doi:10.1098/rstb.2015.0174)
163. Page SE, Hooijer A. 2016 In the line of fire: the peatlands of Southeast Asia. *Phil. Trans. R. Soc. B* **371**, 20150176. (doi:10.1098/rstb.2015.0176)
164. Balch JK, Nagy RC, Archibald S, Bowman DMJS, Moritz MA, Roos CI, Scott AC, Williamson GJ. 2016 Global combustion: the connection between fossil fuel and biomass burning emissions (1997–2010). *Phil. Trans. R. Soc. B* **371**, 20150177. (doi:10.1098/rstb.2015.0177)
165. Westerling ALR. 2016 Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B* **371**, 20150178. (doi:10.1098/rstb.2015.0178)
166. Blietge Bird R, Bird DW, Coddling BF. 2016 People, El Niño southern oscillation and fire in Australia: fire regimes and climate controls in hummock grasslands. *Phil. Trans. R. Soc. B* **371**, 20150343. (doi:10.1098/rstb.2015.0343)
167. Archibald S. 2016 Managing the human component of fire regimes: lessons from Africa. *Phil. Trans. R. Soc. B* **371**, 20150346. (doi:10.1098/rstb.2015.0346)
168. Davies GM *et al.* 2016 The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Phil. Trans. R. Soc. B* **371**, 20150342. (doi:10.1098/rstb.2015.0342)

169. Carroll M, Paveglio T. 2016 Using community archetypes to better understand differential community adaptation to wildfire risk. *Phil. Trans. R. Soc. B* **371**, 20150344. (doi:10.1098/rstb.2015.0344)
170. Gazzard R, McMorrow J, Ayles J. 2016 Wildfire policy and management in England: an evolving response from Fire and Rescue Services, forestry and cross-sector groups. *Phil. Trans. R. Soc. B* **371**, 20150341. (doi:10.1098/rstb.2015.0341)
171. Roos CI *et al.* 2016 Living on a flammable planet: interdisciplinary, cross-scalar and varied cultural lessons, prospects and challenges. *Phil. Trans. R. Soc. B* **371**, 20150469. (doi:10.1098/rstb.2015.0469)
172. Mellars P, Boyle K, Bar-Yosef O, Stringer C (eds). 2007 *Rethinking the human revolution*. Cambridge, UK: McDonald Institute for Archaeological Research.
173. Smith FH, Ahern JCM (eds). 2013 *The origins of modern humans: biology reconsidered*. Hoboken, NJ: John Wiley and Sons.
174. Dillehay TD *et al.* 2015 New archaeological evidence for an early human presence at Monte Verde, Chile. *PLoS ONE* **10**, e0141923. (doi:10.1371/journal.pone.0141923)
175. Perry GLW, Wilmshurst JM, McGlone MS, Napier A. 2012 Reconstructing spatial vulnerability to forest loss by fire in pre-historic New Zealand. *Global Ecol. Biogeogr.* **21**, 1029–1041. (doi:10.1111/j.1466-8238.2011.00745.x)
176. Harris DR. 2010 *Origins of agriculture in Western Central Asia: an environmental archaeological study*. Philadelphia, PA: University of Pennsylvania Museum of Archaeology and Anthropology.
177. Gould RA. 1971 Uses and effects of fire among the western desert Aborigines of Australia. *Mankind* **8**, 14–24. (doi:10.1111/j.1835-9310.1971.tb01436.x)
178. Lewis HT. 1977 Maskuta: the ecology of Indian fires in northern Alberta. *West. Can. J. Anthropol.* **7**, 15–52.
179. Vale TR. 2002 The pre-European landscape of the United States: pristine or humanised? In *Fire, native peoples and the natural landscape* (ed. TR Vale), pp. 1–39. Washington, DC: Island Press.
180. Parker KC. 2002 Fire in the Pre-European lowlands of the American southwest. In *Fire, native peoples and the natural landscape* (ed. TR Vale), pp. 100–141. Washington, DC: Island Press.
181. Laris P. 2011 Humanizing savanna biogeography: linking human practices with ecological patterns in a frequently burned savanna of Southern Mali. *Ann. Assoc. Am. Geogr.* **101**, 1067–1088. (doi:10.1080/00045608.2011.560063)
182. McBrearty S, Brooks AS. 2000 The revolution that wasn't: a new interpretation of the origin of modern human behavior. *J. Hum. Evol.* **39**, 453–563. (doi:10.1006/jhev.2000.0435)
183. Basell LS. 2008 Middle Stone Age (MSA) site distributions in eastern Africa and their relationship to Quaternary environmental change, refugia and the evolution of *Homo sapiens*. *Quat. Sci. Rev.* **27**, 2484–2498. (doi:10.1016/j.quascirev.2008.09.010)
184. Bird MI, Cali JA. 1998 A million-year record of fire in sub-Saharan Africa. *Nature* **394**, 767–769. (doi:10.1038/29507)
185. Wu X, Zhang C, Goldberg P, Cohen D, Pan Y, Arpin T, Bar-Yosef O. 2012 Early pottery at 20,000 years ago in Xianrendong Cave, China. *Science* **336**, 1696–1700. (doi:10.1126/science.1218643)
186. Cohen DJ. 2013 The advent and spread of early pottery in East Asia: new dates and new considerations for the world's earliest ceramic vessels. *J. Austronesian Stud.* **4**, 55–90.
187. Asouti E. 2013 Woodland vegetation, firewood management and woodcrafts at Neolithic Çatalhöyük. In *Humans and landscapes of Çatalhöyük: reports from the 2000–2008 seasons* (ed. I Hodder), pp. 129–162. Los Angeles, CA: Cotsen Institute of Archaeology, UCLA.
188. Asouti E, Kabukcu C, White EC, Kuijt I, Finlayson B and Makarewicz C. 2015 Early Holocene woodland vegetation and human impacts in the arid zone of the southern Levant. *The Holocene* **25**, 1565–1580. (doi:10.1177/0959683615580199)
189. Wertime TA, Wertime SF (eds). 1982 *Early pyrotechnology: the evolution of the first fire-using industries*. Washington, DC: Smithsonian Institution Press.
190. Anderson JR. 1984 Ethology and ecology of sleep in monkeys and apes. *Adv. Stud. Behav.* **14**, 166–229.
191. Burazeri G, Gofin J, Kark JD. 2003 Over 8 hours of sleep—marker of increased mortality in Mediterranean population: follow-up population study. *Croatian Med. J.* **44**, 193–198.
192. Schaller GB. 1963 *The mountain gorilla: ecology and behavior*. Chicago, IL: University of Chicago Press.
193. Conroy DA, Spielman AJ, Scott RQ. 2005 Daily rhythm of cerebral blood flow velocity. *J. Circ. Rhythms* **3**, 3. (doi:10.1186/1740-3391-3-3)
194. Schmidt C, Collette F, Cajochen C, Peigneux P. 2007 A time to think: circadian rhythms in human cognition. *Cogn. Neuropsychol.* **24**, 755–789. (doi:10.1080/02643290701754158)
195. Ronen A. 1998 Domestic fire as evidence for language. In *Neanderthals and moderns in Asia* (ed. T Akazawa), pp. 439–445. New York, NY: Plenum Press.
196. O'Connell JF, Hawkes K, Blurton-Jones NB. 1988 Hadza hunting, butchering and bone transport and their archaeological implications. *J. Anthropol. Res.* **44**, 113–161. (doi:10.1086/jar.44.2.3630053)
197. O'Connell JF, Hawkes K, Blurton-Jones NB. 1999 Grandmothering and the evolution of *Homo erectus*. *J. Hum. Evol.* **36**, 481–485.
198. James W. 2003 *The ceremonial animal: a new portrait of anthropology*. Oxford, UK: Oxford University Press.
199. Frazer JG. 1930 *Myths of the origin of fire. An essay*. London, UK: Macmillan.