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Geology

On the possible use of fire by *Homo erectus* at Zhoukoudian, China

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Abstract For decades, the so-called Peking Man (*Homo erectus pekinensis*) at Zhoukoudian has been considered to be a hominin that engaged in the controlled production and management of fire. However, relatively recent analyses have cast doubt on this assertion. The most compelling reason for this doubt was the absence of siliceous aggregates in the Zhoukoudian deposits. This study presents evidence establishing the controlled use of fire by *Homo erectus pekinensis* through analyses of four soil samples sourced from Layers 4 and 6 at Zhoukoudian Locality 1. These results demonstrate that all four specimens contain siliceous aggregates as well as elemental carbon, and the potassium content of the insoluble residues of these specimens ranges between 1.21 % and 2.94 %. The analyses provide strong evidence of the in situ use of fire by *Homo erectus pekinensis*.

Keywords *Homo erectus* · Zhoukoudian · Fire use · Middle pleistocene · Siliceous aggregate · Elemental carbon

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1 Introduction

Zhoukoudian (also Choukoutien or Chou-k'ou-tien) Locality 1 (Figs. 1, 2) in northern China has been widely known since the 1920s as the site of the discovery of the Middle Pleistocene human ancestor *Homo erectus pekinensis* [1–3]. The layers 7–10 of this site are dated to 0.77 million years ago [4]. By 1931, the suggestion that the Zhoukoudian hominins could use and control fire had become widely accepted among anthropologists and other scholars [5]. For more than half a century, burned items (including stones, bones and seeds), charcoal, and "ash accumulation" unearthed at the site have been proposed as the earliest evidence of the controlled use of fire by human ancestors. This is supported by chemical analyses which have identified free carbon in the burned fossils and "ash" [6–13].

In 1929, Pei and his colleagues began to collect the stone artifacts and evidence of fire use at the site. In 1931, Pei and his research team discovered large numbers of stone tools made of quartz and other lithic raw materials as well as what they interpreted as abundant evidence of anthropogenic fire in Quartz Horizon 2 (QII), including burned bone and stone, ash, and *Cercis* (redbud) charcoal; thus, further establishing that *Homo erectus pekinensis* was both a tool maker and competent user of fire [11].

Furthermore, in 1935 Pei and other researchers excavated beneath Zhoukoudian Locality 1 Layers 4–5 and discovered abundant stone tools and evidence of anthropogenic fire including burned stone, ash, and numerous *Celtis* (hackberry) seeds [11]. Their excavations were halted by the Japanese invasion of China in 1937 until 1951 when work at the site resumed. Jia has divided the Locality 1 profile into 13 stratigraphic levels which accumulated between roughly 700,000 and 200,000 years ago [13].

Fig. 1 Zhoukoudian Locality 1

Fig. 2 Excavation spot in Locality 1. The excavation has been carried out since 2009

In 2004, Shen and others detected elemental carbon in soil samples from Zhoukoudian Locality 1. Elemental carbon forms a continuum from single-crystal graphite to amorphous carbon, with high chemical inertia and bio-inertia, as a product of incomplete combustion which can be preserved for hundreds of thousands of years in enclosing sediments. Shen and his colleagues analyzed samples taken from deposits in Zhoukoudian Locality 1 Layers 4, 7, and 10 as well as from areas outside the cave and from ash deposits unearthed in the 1930s exhibited in the Peking Man Site Museum. Shen's team discovered that the concentrations of elemental carbon in samples taken from Layer 10 inside the cave were an order of magnitude higher than samples from the others [14], and concluded that the Layer 10 sample locations might have been located near the base of a large, presumably anthropogenic, fire.

The chronology of the use of fire by *Homo erectus pekinensis* was studied using fission-track dating in 1991 to determine that the ash present at Locality 1 was likely deposited 452 ± 45 ka (Layer 10) and 299 ± 55 ka (Layer 4) earlier, with both episodes lasting about 153,000 years [15, 16]. The detailed chronology of Zhoukoudian Locality 1 has been reviewed by Zhao et al. [17, 18] and Goldberg et al. [19].

Shen and colleagues [4] used $^{26}Al/^{10}Be$ dating to determine that the best age estimate for lower cultural layers 7–10 at Zhoukoudian Locality 1 is 0.77 ± 0.08 million years, so *Homo erectus pekinensis* first occupied Locality 1 some 770,000 years ago, when climatic conditions were relatively cold and human ancestors had to create heat more efficiently to defend against the extreme cold.

Although taphonomic observations and elemental analyses have also strongly suggested anthropogenic fire at Zhoukoudian Locality 1 [4, 19, 20], disputes have still arisen over the past three decades concerning the reliability of evidence for human-caused burning at Zhoukoudian. Binford and Ho [6] confirmed that bones from the site were burned by fire. However, they concluded that the ash deposits inside the cave were not the result of intentional hominin activity, but rather the result of spontaneous combustion of organic material and the so-called "ash layer" was actually composed of the excrement of owls or other raptorial birds and bats. Excrement contains phosphorus and is, thus, susceptible to spontaneous combustion in certain depositional contexts. Binford and Stone [7] concluded that by the late phase of hominin occupation at Zhoukoudian (about 200,000 years ago), *Homo erectus pekinensis* knew how to make and control fire.

Another method for identifying anthropogenic fire is the detection of siliceous aggregates. Schiegl and colleagues [21] reported that large accumulations of fossil siliceous aggregates have been identified in the HaYonim Cave in the Upper Galilee of Israel using optical and scanning electron microscopy together with elemental analyses, and that such aggregates were also present in various hearth features at Kebara Cave, in the Carmel Range, also in Israel [22]. Weiner and his colleagues [23] used infrared spectra (IR) and elemental analysis methods to test a small number of specimens sourced from Layers 10 and 4 at Zhoukoudian Locality 1 and found no evidence of siliceous aggregates which should have been produced during the combustion, and very low potassium content, which is a key element in siliceous aggregates. They pointed out that some mineral clusters resembling siliceous aggregates were identified which were possibly products of the silicification process. They concluded that even though some burned bones similar to those obtained in much younger sites where anthropogenic fire undoubtedly occurred were present at Zhoukoudian, they were probably brought into the cave by fluvial processes rather than by human activity. Their conclusion is that in the absence of ash or ash remnants (such as siliceous aggregates) and the lack of identifiable in situ hearth features means that there is no direct evidence of anthropogenic burning in Layer 4 and Layer 10 at Zhoukoudian. This significant contribution by Weiner and his colleagues spurred intense debate. Soon afterward, the Institute of Vertebrate Paleontology and Paleoanthropology of the Chinese Academy of Sciences organized a special team of scholars to study this issue, focusing on trying to recognize the possibility of the use of fire by *Homo erectus pekinensis* [24]. Wu [25] then used the proportions of large and small bones discovered in Layer 10 at Locality 1 to explain the limitations and deficiencies of the conclusions of Weiner et al. [23].

At present, the focal point of the debate over the intentional use of fire by *Homo erectus pekinensis* at Zhoukoudian is whether or not siliceous aggregate (an insoluble phase of burned ash) is present in ash remains recovered from the site. The present study verified the use of fire by *Homo erectus pekinensis* using four ash samples retrieved from different positions of Locality 1 at Zhoukoudian to examine whether siliceous aggregates and potassium are present in the insoluble phase of the ash, which could prove the use of fire by *Homo erectus pekinensis*. Once the presence of siliceous aggregates and potassium is identified in the ash deposits, the in situ use of fire can be extrapolated. This method has been used to confirm the presence of anthropogenic fire use at other early sites [26].

Fig. 3 Sampling locations. Samples were collected during the excavations carried out in 2009

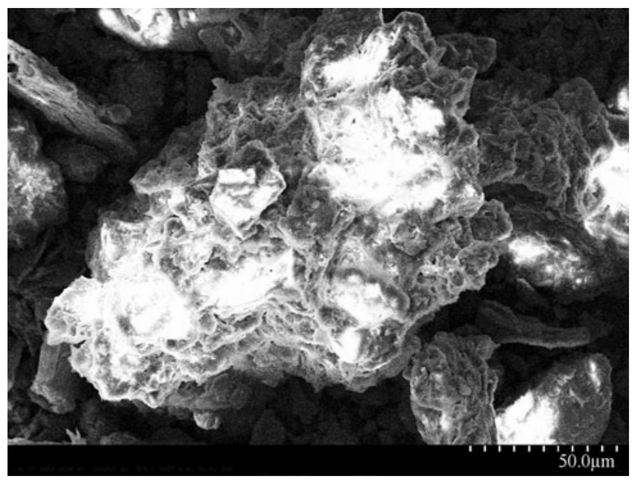

Fig. 4 Photomicrograph of Sample ZKD3. The photo illustrates the sintered agglomerate in the insoluble phase under ×600 magnification, every interval in the *scale bars* represents 50.0 μm

2 Materials and methods

Four samples were collected from different locations at the site with one sample from Layer 6 (ZKD4) and three from Layer 4 (ZKD1, ZKD2, and ZKD3) where excavations in 2009 exposed fresh deposits more suitable for sampling, as shown in Fig. 3.

The analysis method employed in this research consisted of first grinding the ash and then extracting a 10 g sample that passed through a sieve that was treated as follows. The sample was first soaked in 6 N hydrochloric acid for 24 h [5, 26], followed by filtration, scrubbing, drying, and another soaking in 6 N nitric acid for an additional 24 h. After another filtration, scrubbing and drying sequence, the elemental composition and structure of the residual insoluble phase were analyzed. During the elemental composition analysis, a small amount of the residual insoluble phase was taken for making thin sections, followed by elemental scanning of the obvious sintered agglomerates using a Hitachi-S4800 Field-Emission Scanning Electron Microscope with magnifications varying between 30 and 500,000 diameters.

During the X-ray analysis, some of the residual insoluble phase from the acid-soaked and dried ash was extracted to prepare sample wafers, which were then X-rayed to obtain a diffraction spectrum of the substance's constituent components. A comparative analysis of the sample's molecular structure was then conducted to determine the substance's components in the insoluble phase by comparing the diffraction spectrum with those of different substances. This analysis used a Bruker-D8 Advanced X-ray diffractometer.

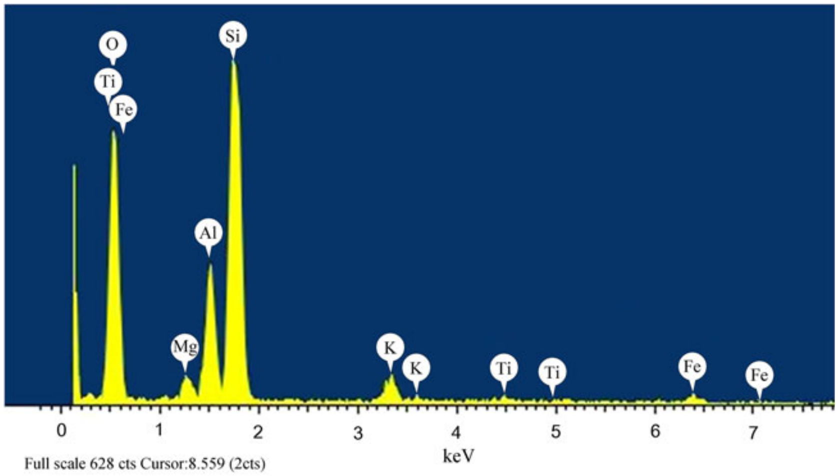

Fig. 5 Peak spectrum of elements contained in the insoluble phase of Sample ZKD3. The peak spectrum shows that the elements Al, Si, K, and Fe are present

Table 1 Element compositions and main substances contained in the insoluble phase of four samples

Samples	Wt%				Main composition of insoluble phase
	Al	Si	K	Fe	
ZKD1	5.88	18.46	1.21	1.07	SiO_2, C, K2($Al_{3.74}Fe_{0.26}$)($Si_6Al_2O_{20}$)$(OH)_4$
ZKD2	6.04	22.21	1.27	3.53	SiO_2, C, K2($Al_{3.74}Fe_{0.26}$)($Si_6Al_2O_{20}$)$(OH)_4$, $KAlSi_3O_8$
ZKD3	8.96	28.94	2.73	3.00	SiO_2, C, $KFe_{0.28}Al_{0.72}Si_3O_8$, K($Al_{1.91}Fe_{0.09}$)($Si_3Al$)$O_{10}$ $(OH)_2$, K2($Al_{3.74}Fe_{0.26}$)($Si_6Al_2O_{20}$)$(OH)_4$
ZKD4	6.61	31.34	2.94	1.89	SiO_2, C, $KFe_{0.28}Al_{0.72}Si_3O_8$, K($Al_{1.91}Fe_{0.09}$)($Si_3Al$)$O_{10}$ $(OH)_2$, K(Si_3Al)O_8, K_2($Al_{3.74}Fe_{0.26}$)(Si_6Al2O_{20}) $(OH)_4$

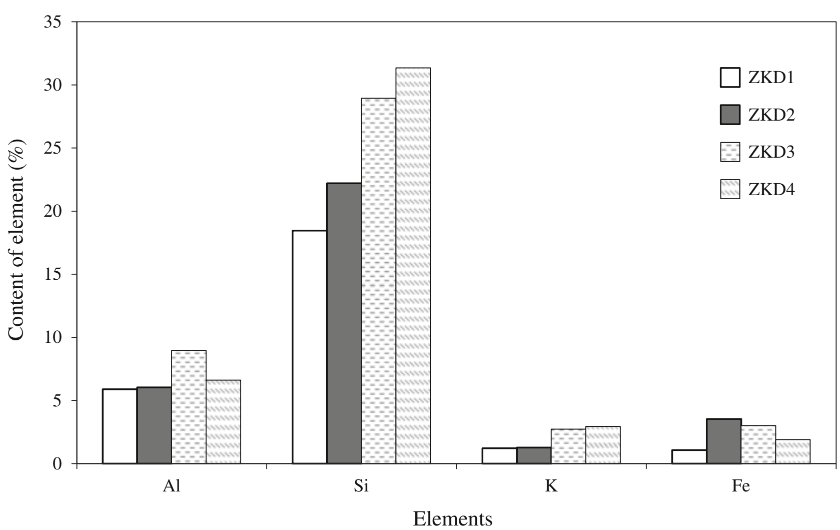

Fig. 6 Si, Al, Fe, and K contents of the insoluble phase of the four ash specimens

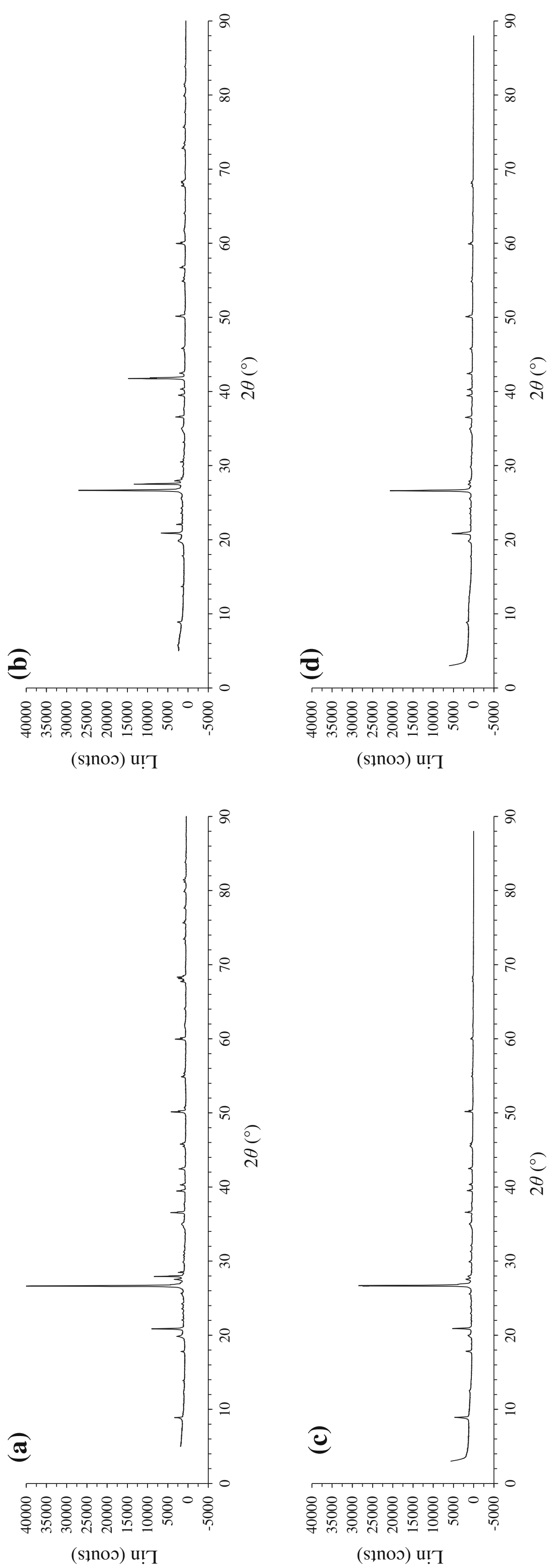

Fig. 7 X-ray diffraction spectra of four specimens from ZKD Locality 1. **a–d** The results of ZKD1 to ZKD4, respectively

3 Results and analysis

The above procedures were used to analyze four samples taken from Locality 1 at Zhoukoudian. The following discussion describes representative results of the entire laboratory analysis. The sample treatment and process of the analysis for all four samples are similar, with the result for the sample ZKD3 presented as an example (as shown in Figs. 4, 5).

The analyses detect a large number of sintered agglomerates in the insoluble residual phases of the samples, as shown in Fig. 4 for ZKD3. Furthermore, the analyses indicate that the elements associated with siliceous aggregates (Al, Si, K, and Fe) are present in all the samples, as illustrated by the peak distributions of the EDS energy-dispersive spectrum for sample ZKD3 in Fig. 5. The element contents in all the samples are listed in Table 1. In all four samples, the Si contents are the highest, followed by Al as shown in Fig. 6. K, which is only preserved in siliceous aggregates and Fe is present in lower concentrations than those of Si and Al.

Figure 7 shows the X-ray diffraction spectra of the four samples from Zhoukoudian Locality 1. The diffraction peaks of the spectra are very similar, indicating that the substances contained in these four samples are also nearly identical. The X-ray diffraction spectra for Sample ZKD3 shown in Figs. 8, 9, 10, 11, and 12 as an example indicate that $KFe_{0.28}Al_{0.72}Si_3O_8$, $K_2(Al_{3.74}Fe_{0.26})(Si_6Al_2O_{20})(OH)_4$, C, $K(Al_{1.91}Fe_{0.09})(Si_3Al)O_{10}(OH)_2$, and SiO_2 are the main constituents of the insoluble phase of the ash.

The material composition analyses show that the substances in the insoluble phases of the ash are mainly SiO_2, elemental C, and silicates. The silicates include $KFe_{0.28}Al_{0.72}Si_3O_8$, $KAlSi_3O_8$, $K(Al_{1.91}Fe_{0.09})$ $(Si_3Al)O_{10}(OH)_2$, $K(Si_3Al)O_8$, and $K_2(Al_{3.74}Fe_{0.26})$ $(Si_6Al_2O_{20})$ $(OH)_4$ (Table 1). Elemental carbon is present in the ash, and the insoluble phases contain 1.21 %–2.94 % by weight of elemental K. Thus, the test results clearly indicate the presence of elemental C, elemental K, and siliceous aggregates in the insoluble phases of the ash from Zhoukoudian Locality 1 Layers 4 and 6.

4 Discussion

The absence of siliceous aggregates and potassium in Layer 10 at Zhoukoudian is the principal reason that Weiner et al. [23] did not support earlier conclusions that *Homo erectus pekinensis* used fire at Zhoukoudian Locality 1. As a corollary, siliceous aggregates are considered to be a definitive indicator of in situ fire use [23, 26]. The current measurements show that the siliceous aggregates of different forms (Table 1) and potassium are

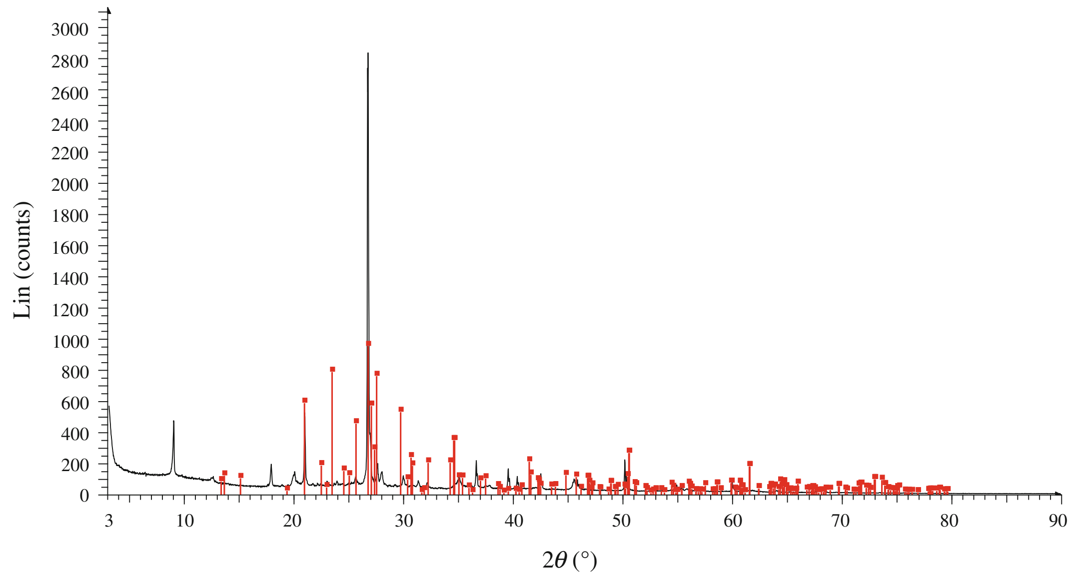

Fig. 8 X-ray diffraction spectrum of $KFe_{0.28}Al_{0.72}Si_3O_8$. The *black curve* is X-ray diffraction spectrum of insoluble phase in Sample ZKD3, the *red square* and *line* represent the intensity and position of diffraction peak of $KFe_{0.28}Al_{0.72}Si_3O_8$

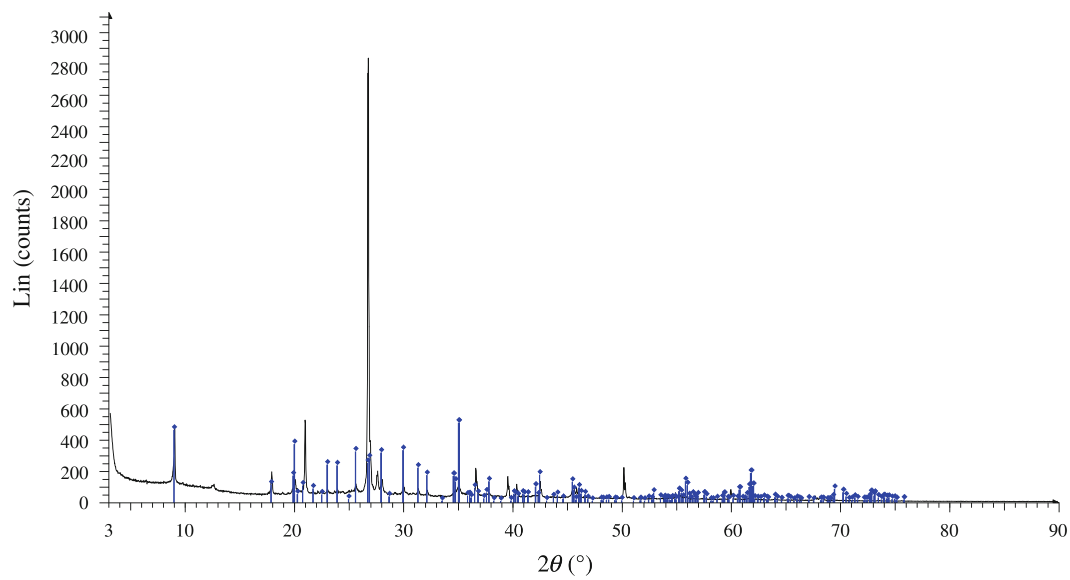

Fig. 9 X-ray diffraction spectrum of $K_2(Al_{3.74}Fe_{0.26})(Si_6Al_2O_{20})(OH)_4$. The *black curve* is X-ray diffraction spectrum of insoluble phase in Sample ZKD3, the *blue rhombus* and *line* represent the intensity and position of diffraction peak of $K_2(Al_{3.74}Fe_{0.26})(Si_6Al_2O_{20})(OH)_4$

present in sediment samples from Zhoukoudian Layers 4 and 6, although the weight percentages of Al, Fe, K, and Si in the insoluble phases of the four samples differ slightly as shown in Table 1. The samples sourced from the various layers at the site have produced different results which, in turn, may have led to different conclusions concerning fire use. The samples in this research are from Layers 4 and 6, which are both younger than Layer 10, where the samples analyzed by Weiner and his colleagues were sourced, which also contained ash layer in earlier reports [1, 11].

In Samples ZKD1 and ZKD2, the potassium content is comparatively low as shown in Table 1. Thus, by comparison with the results of Weiner et al. [23], another possible presumption is that the samples analyzed by Weiner et al. from Layer 10 might have been the burned products of one or more arboreal species that contained lower amounts of siliceous aggregates and elemental K.

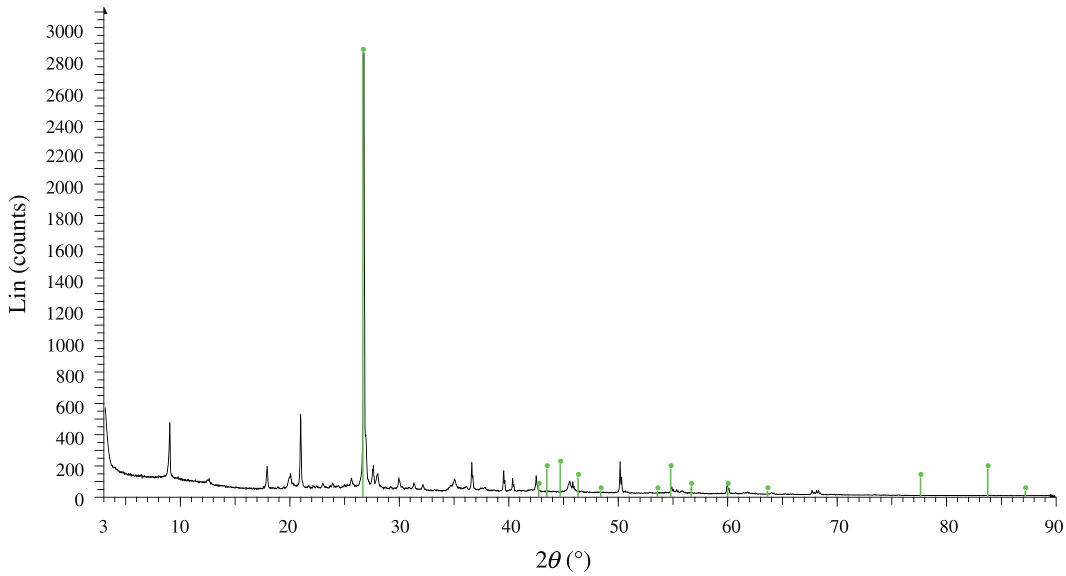

Fig. 10 X-ray diffraction spectrum indicating the presence of carbon. The *black curve* is X-ray diffraction spectrum of insoluble phase in Sample ZKD3, the *green circle* and *line* represent the intensity and position of diffraction peak of carbon

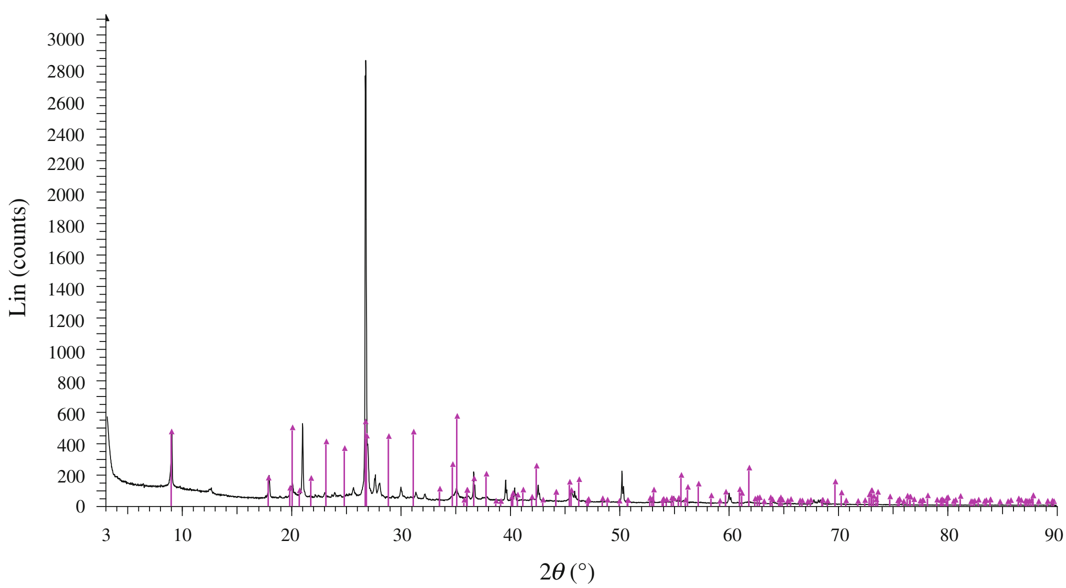

Fig. 11 X-ray diffraction spectrum of $K(Al_{1.91}Fe_{0.09})(Si_3Al)O_{10}(OH)_2$. The *black curve* is X-ray diffraction spectrum of insoluble phase in Sample ZKD3, the *pink regular triangle* and *line* represent the intensity and position of diffraction peak of $K(Al_{1.91}Fe_{0.09})(Si_3Al)O_{10}(OH)_2$

Therefore, the location and quantities of the samples analyzed by Weiner et al. might have been insufficient to draw overall conclusions about the site as a whole. Siliceous aggregates and elemental C [14] have been identified as definitive indicators of in situ fire considering the doubts raised by studies that followed that of Weiner and his colleagues [23]. The results of the present experimental studies have proven the presence of siliceous aggregates and potassium as well as elemental C in the insoluble phase of the ash. These results should spur reconsideration of the conclusions drawn by Weiner and his colleagues and provide additional supporting evidence of in situ controlled use of fire by *Homo erectus pekinensis* at Zhoukoudian Locality 1.

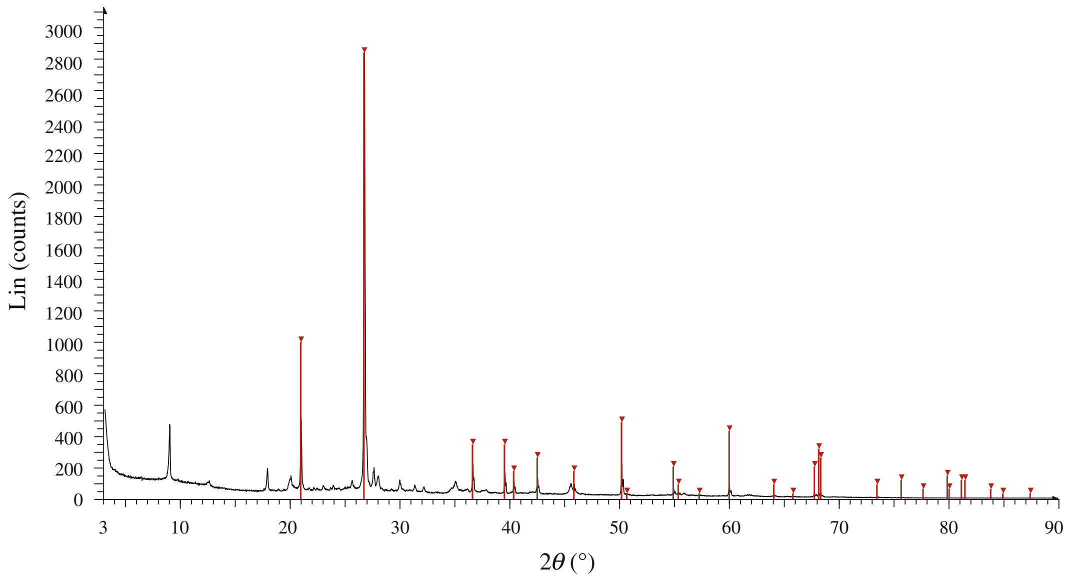

Fig. 12 X-ray diffraction spectrum indicating the presence of silicon dioxide (SiO_2). The *black curve* is X-ray diffraction spectrum of insoluble phase in Sample ZKD3, the *wine-colored inverted triangle* and *line* represent the intensity and position of diffraction peak of silicon dioxide

5 Conclusions

Analyses of the elemental composition and substance components of four ash samples from Zhoukoudian Locality 1 show the presence of siliceous aggregates and potassium as well as elemental C in the insoluble phase of the ash. These test results provide strong evidence supporting the use of fire by *Homo erectus pekinensis* in the time periods related to Layers 4 and 6.

Previously reported age determinations for the Zhoukoudian sequence have shown that *Homo erectus pekinensis* seems to have first occupied Locality 1 some 770,000 years ago, when climatic conditions in North China were relatively cold, perhaps prompting *Homo erectus pekinensis* to obtain more reliable sources of heat to defend against the extreme cold, and implying that through the production and management of fire, Middle Pleistocene hominins in North China survived conditions colder and less conducive to human occupation than at present.

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