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On the evidence for human use and control of fire at Schöningen

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ABSTRACT

When and how humans began to control fire has been a central debate in Paleolithic archaeology for decades. Fire plays an important role in technology, social organization, subsistence, and manipulation of the environment and is widely seen as a necessary adaptation for the colonization of northern latitudes. Many researchers view purported hearths, burnt wooden implements, and heated flints from Schöningen as providing the best evidence for the control of fire in the Lower Paleolithic of Northern Europe. Here we present results of a multianalytical study of the purported hearths along with a critical examination of other possible evidence of human use or control of fire at Schöningen. We conclude that the analyzed features and artifacts present no convincing evidence for human use or control of fire. Our study also shows that a multianalytical, micro-contextual approach is the best methodology for evaluating claims of early evidence of human-controlled fire. We advise caution with macroscopic, qualitative identification of combustion features, burnt flint, and burnt wood without the application of such techniques as micromorphology, Fourier transform infrared (FTIR) spectroscopy, organic petrology, luminescence, and analysis of mineral magnetic parameters. The lack of evidence for the human control of fire at Schöningen raises the possibility that fire control was not a necessary adaptation for the human settlement of northern latitudes in the Lower Paleolithic.

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1. Introduction

The origins of the use and control of fire is one of the central and most debated topics in Paleolithic archaeology and human evolution (e.g., Goudsblom, 1986; James et al., 1989; de Lumley, 2006; Gowlett, 2006; Wrangham, 2009; Alperson-Afil and Goren-Inbar, 2010; Roebroeks and Villa, 2011a; Sandgathe et al., 2011a; Gowlett and Wrangham, 2013). Fire use and control would have provided several crucial advantages to early humans: it can serve as a light and heating source (Oakley, 1955; Bellomo, 1994; Gilligan, 2010), as a hunting aid (Goudsblom, 1986; Mallol et al., 2007), can be used for cleaning occupation surfaces (Goldberg et al., 2009; Wadley et al., 2011), as protection from predators (Goudsblom, 1986; Brain, 1991), as a means to improve tool technology (Ahlers, 1983; Mallol et al., 2007; Brown et al., 2009), and as a way to increase food range, its nutritional value, and preservation (Stahl et al., 1984; Bellomo, 1994; Wrangham et al., 1999; Wrangham and Conklin-Brittain, 2003; Mallol et al., 2007; Wrangham, 2009; for an overview, see Clark and Harris, 1985). Because of these advantages, archaeologists assign fire use and control an important role in human evolution. Brain (1991) suggests that fire use and control could have increased early humans' competitiveness (Brain, 1991),

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and Gowlett (2006) and Wrangham (2009) amongst others (Rolland, 2004; Pruetz and LaDuke, 2010) suggest that fire use and control impacted the evolution of biological traits, including brain size and cognition.

Furthermore, several researchers see the use and control of fire as a precondition for the first settlement of northern latitudes (Oakley, 1955; Brace et al., 1987; Straus, 1989; Weiner et al., 1998; Wrangham et al., 1999; Klein, 2002; Rolland, 2004; Gowlett, 2006; Preece et al., 2006). The sites at Schöningen are referenced as among the earliest such examples (Mania, 1995; Thieme, 1997, 2005, 2007a, b, c, d; Klein, 2002, 2009; Goren-Inbar et al., 2004; Alperson-Afil and Goren-Inbar, 2006; Gowlett, 2006; Preece et al., 2006; Berna and Goldberg, 2008; Wrangham, 2009; Daniau et al., 2010; Roebroeks and Villa, 2011a; Gowlett and Wrangham, 2013; Shahack-Gross et al., 2014). Northern latitudes present several challenges to their occupants, having shorter duration of daylight in winter, severely cold winters, a variety of large predators, and a scarcity of edible plants during winter, consequently demanding a stronger reliance on animal resources. According to Gilligan (2010), these challenges can be answered through seasonal migration, physical adaptation, or technological improvement in the form of new hunting weaponry, clothing, use of shelters, and use of fire.

Most evidence for early use of fire relies on macroscopic, qualitative identification of residues and objects that appear to have been affected by fire, often described as a change in color (e.g., Purdy and Brooks, 1971; Purdy, 1971, 1975; Shipman et al., 1984). However, macroscopic observations of burning are often misleading and need to be confirmed by specific analyses, such as micromorphology, Fourier transform infrared (FTIR) spectroscopy, organic petrology, analysis of mineral magnetic parameters, and thermoluminescence measurements (e.g., James et al., 1989; Stiner et al., 1995; Shahack-Gross et al., 1997; Richter, 1998; Goldberg et al., 2001; Ligouis, 2006; Hanson and Cain, 2007; Roebroeks and Villa, 2011a). In short, human control of fire is best investigated by employing a micro-contextual approach (e.g., Karkanas et al., 2007).

Several researchers cite hearths, burnt wood, and flint from different localities and find horizons as providing evidence for human use and control of fire at Schöningen (e.g., Klein, 2002; Alperson-Afil and Goren-Inbar, 2006; Berna and Goldberg, 2008; Wrangham, 2009; Weiner, 2010; Roebroeks and Villa, 2011a). However, apart from a preliminary and inconclusive micromorphological investigation of one of the purported hearths (Schiegl and Thieme, 2007), only macroscopic, qualitative observations of fire use and control have been reported at Schöningen (Thieme, 1997, 1999, 2005, 2007b; Schiegl and Thieme, 2007). Here we present the first contextualized, multianalytical study of deposits, materials, and purported hearths at Schöningen and show that claims for human use and control of fire are highly dubious.

1.1. Early evidence for human use of fire

Evidence for fire in the archaeological record can be the result of either human action or natural fire, and it is commonly difficult to separate the two. Therefore, the burden of proof rests on the archaeologists to demonstrate that the evidence for fire clearly represents human action, and not a natural process. Identification of human use of fire is further complicated by the possible human exploitation of natural fire. Archaeologists generally differentiate three stages of anthropogenic fire: (1) the use, (2) control, and (3) production of fire (e.g., Frazer, 1930; Pruetz and LaDuke, 2010; Sandgathe et al., 2011a). Roebroeks and Villa (2011a) and Sandgathe et al. (2011a, b) further differentiate between observations of sporadic fire use—including the use and controlled use of fire from natural, more unreliable sources—and habitual fire use, which infers the production of fire, in the archaeological record (see also Shahack-Gross et al., 2014). In many cases, the stages of fire use can be differentiated from each other and from natural fire by a contextual analysis (e.g., Bellomo, 1994; Weiner et al., 1998; Goldberg et al., 2001; Gowlett et al., 2005; Karkanas et al., 2007; Roebroeks and Villa, 2011a; Berna et al., 2012; Shahack-Gross et al., 2014).

1.1.1. Natural fire The earliest evidence for naturally occurring fire are fragments of charcoal found reported in rocks dating to the Devonian (Scott, 2000). Fires can be caused by lightning strikes (which are the source for the majority of natural fires), volcanic activity, sparks from rock falls, spontaneous combustion, and meteorite impacts (Batchelder, 1967; Tutin et al., 1996; Jones and Lim, 2000; Scott, 2000). Tree-crown fires, volcanic eruptions, and lightning strikes can produce temperatures over 700°C, and tree stumps, burning humus, or peat fires can burn over elongated periods (Davis, 1959; Stach et al., 1975; Isaac, 1982; James et al., 1989; Scott, 1989, 2000; Pyne et al., 1996; DeBano et al., 1998; Buenger, 2003; Christian et al., 2003; Fessler, 2006). Lightning strikes and burning tree stumps can produce local heat-alterations of sediments that mimic anthropogenic combustion features (see also Isaac, 1982; Clark and Harris, 1985; Isaac and Harris, 1997; Scott, 2000).

Evidence that archaeologists assume to be indicative of anthropogenic fire—such as burnt bone or heated flint or sediment—can also be produced naturally. For example, Hendey (1976) reported Miocene burnt bone from the fossil bone bed of Langebaanweg, whereas Avery et al. (2004) mention burnt tortoise bones caused by bush fires in South Africa and Bordes (1957) reported Miocene burnt flint from Thenay, France. Clark et al. (1984) and Clark and Harris (1985) reported Pliocene burnt sediment at Middle Awash, Ethiopia.

1.1.2. Human use of fire Human use or opportunistic use (Clark and Harris, 1985) of fire includes both conceptualization of fire and its collection from natural sources (Pruetz and LaDuke, 2010). Fire use does not represent a unique human behavior, since chimpanzees have been observed to show predictive behavior towards fire, and other species are known to exploit wild fires for warmth and food (Goudsblom, 1986; Wrangham, 2009; Pruetz and LaDuke, 2010). Human knowledge of fire is difficult to identify in the archaeological record, and most hypotheses regarding early human–fire interaction are based on inferences or indirect data (e.g., Berna et al., 2012; Gowlett and Wrangham, 2013). Some of the earliest evidence for knowledge of fire comes from the ca. 1.0 Ma site of Wonderwerk in South Africa. Here, Berna et al. (2012) described ash remains and burnt bone, as identified by micromorphological and FTIR analysis, inside the cave, arguing that one would not expect natural fire in this setting. Gowlett and Wrangham (2013), using observations of changes in human morphology, argue that humans used fire as early as 1.5 Ma, despite the lack of direct archaeological evidence.

1.1.3. Human control of fire Control of fire or predetermined use (Clark and Harris, 1985) means the maintenance of a fire via fuel provisioning and restraint. The control of fire includes preservation and transport of fire from natural sources of ignition and represents a much more complex and unique human behavior, excluding some rehabilitated chimpanzees who are capable of managing campfires (Brewer, 1978). Researchers have argued for indirect evidence for the control of fire, such as selective burning of materials (Gowlett and Wrangham, 2013) and materials heated to high temperatures at archaeological sites (e.g., Brain and Sillen, 1988; Bellomo, 1993, 1994; Preece et al., 2006; Backhouse and Johnson, 2007). The latter arguments assume that high temperatures are only reached within campfires and are not reached by natural fires, which exhibit a shorter

burning time; however, this assumption is questionable (see above and Gowlett and Wrangham, 2013).

Combustion features, in the form of structured hearths, provide the most direct evidence for human control of fire; however, they can be difficult to identify since they are often ephemeral features subject to post-depositional alteration. Micromorphological analysis has proven useful in the analysis of archaeological combustion features (Courty et al., 1989; Goldberg et al., 2001; Karkanas et al., 2007; Wadley et al., 2011; Mentzer, 2012; Shahack-Gross et al., 2014). Localized features consisting of heat-altered sediments that excavators interpreted as the remains of hearths have been reported and subsequently criticized at the Lower Paleolithic sites of Chesowanja (Gowlett et al., 1981, 1982; Isaac, 1982), Gadeb (Clark and Kurashina, 1979; Barbetti, 1986), Koobi Fora (Isaac, 1984; Clark and Harris, 1985; Barbetti, 1986), and Olorgesailie (Isaac, 1977, 1984) in Africa, and Zhoukoudian (Wu, 1985; Binford et al., 1985; Weiner et al., 1998; Goldberg et al., 2001) in Asia (for a critical overview see James et al., 1989). Alperson-Afil (2008) and Alperson-Afil and Goren-Inbar (2006), Alperson-Afil et al. (2007) proposed indirect evidence of hearths at Gesher Benot Ya'aqov, dated to 800,000 BP. They inferred the former presence of hearths using spatial analysis of burnt flint, as verified by thermoluminescence analysis. However, in their discussion of burning by natural fire they only refute the possibility of an *in situ* natural fire. Similarly, they do not discuss the possibility that nodules of raw material had been heat altered before human use.

In Europe, burnt sediment at the Lower Paleolithic sites of Vértesszöllös (Vértes and Dobosi, 1990), Menez-Dregan (Monnier et al., 1994, 2001), and Terra Amata (Villa, 1982, 1983), an accumulation of purported burnt wood at Bilzingsleben (Mania, 1991; Mania and Mania, 2000; but see Steguweit, 2003), and hearths at Schöningen (Thieme, 1997, 2005) have been reported as evidence of human control of fire. However, the researchers at these sites do not demonstrate that the purported heat-altered materials are anthropogenic (see also James et al., 1989; Roebroeks and Villa, 2011a), and the dating of Menez-Dregan is still unclear (Mercier et al., 2004). Gowlett (2006) and Preece et al. (2007) reported on scatters of burnt flint and bone next to possible hearths at Beeches Pit, UK. To date, no data have been published to demonstrate that the supposed hearths were formed through heating, and it is not clear if the heated bones and lithic artifacts were produced by human activities or natural fires (see also Preece et al., 2007).

The most direct and unambiguous evidence for the control of fire and of habitual fire use in the form of hearths and reused hearths comes from Qesem Cave in Israel, dated to 400,000 and 300,000 BP, respectively (Karkanas et al., 2007; Shahack-Gross et al., 2014). In the Middle Paleolithic and Middle Stone Age, evidence for control of fire with discrete hearths is known in Africa from Sibudu (Wadley et al., 2011), in Asia from sites such as Tabun, Kebara, and Hayonim (Goldberg, 2003), and in Europe from sites such as Pech-de-l'Azé, Roc de Marsal (Goldberg, 2004; Aldeias et al., 2012; Goldberg et al., 2012), and Abric Romani (Vallverdú et al., 2010).

1.1.4. Human production of fire Fire can be artificially produced by wood-on-wood friction or stone-on-stone percussion in addition to a tinder source (Hough, 1926; Weiner, 2003). Direct evidence for this behavior is rare and so far has only been reported from the Upper Paleolithic (e.g., Weiner and Floss, 2005; Sorensen et al., 2014), with one possible exception from the Middle Paleolithic site of Bettencourt, France (Rots, 2011, 2015). Habitual fire use, manifested in the archaeological record as a repetitive pattern of fire control, is often seen as a prelude to the production of fire (Frazer, 1930; Goudsblom, 1986; Gowlett, 2006; Pruetz and LaDuke, 2010). Sandgathe et al. (2011a, b) maintain that habitual fire use presents indirect evidence for fire production. They further argue, based on a lack of evidence for habitual fire use at the sites of Roc de Marsal and Pech-de-l'Azé, that Middle Paleolithic humans in Europe still relied on scarce, natural sources of ignition and that Neanderthals lacked the ability to make fire (Sandgathe et al., 2011a; but see Roebroeks and Villa, 2011b).

1.2. Schöningen

1.2.1. Setting and geology Schöningen lies between the North German Plain to the north and the Harz Mountains to the southeast (Fig. 1) and is situated at the southeastern foot of the Elm, a limestone ridge 25 km long and up to 8 km wide (Elsner, 2003) at an altitude of 114 m above mean sea level.

Schöningen is located on the southwestern syncline of the Offleben salt wall and in the Helmstedt Staßfurt salt structure (Mania, 1995; Brandes et al., 2012). Today the site complex of Schöningen is located in an open-cast lignite mine, which exposes Middle Pleistocene sites sandwiched between glaciogenic deposits of the Elsterian and Saalian glaciations (Urban et al., 1991a; Mania, 1995; Elsner, 2003; Ehlers et al., 2004). The Paleolithic site complex of Schöningen is preserved in an elongated trough, which dissects the underlying Paleogene marine bedrock. Lang et al. (2012, 2015) recently interpreted the trough as a tunnel valley that formed underneath the Elsterian ice shield. Mania (1995, 2007) interpreted the formation of the trough as a result of salt dome solution, which resulted in lowering of the basin. He suggested that recurring fluvial activity at the onset of a warm period would have eroded and infilled the trough during the interglacial following the Elsterian.

1.2.2. Stratigraphy The trough is filled with Elsterian glaciogenic deposits that are unconformably overlain by a sequence of interglacial deltaic and lacustrine deposits. These deposits are in turn capped by Saalian glaciogenic deposits and Weichselian loess

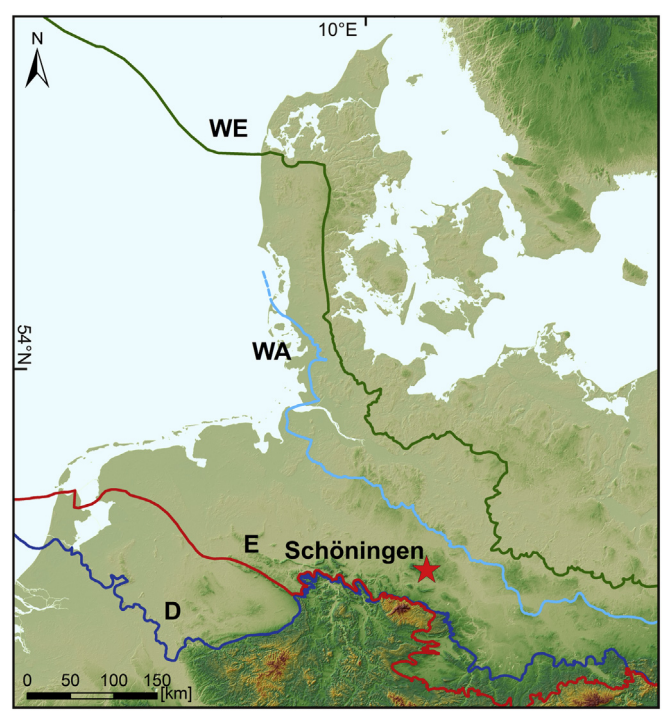

Figure 1. Location of Schöningen in Northern Germany. Green, light blue, red, and dark blue lines indicate the maximum extent of the glacial ice sheets (E = Elsterian; D = Saalian Drenthe; WA = Saalian Warthe; WE = Weichselian; modified from Lang et al., 2012:87).

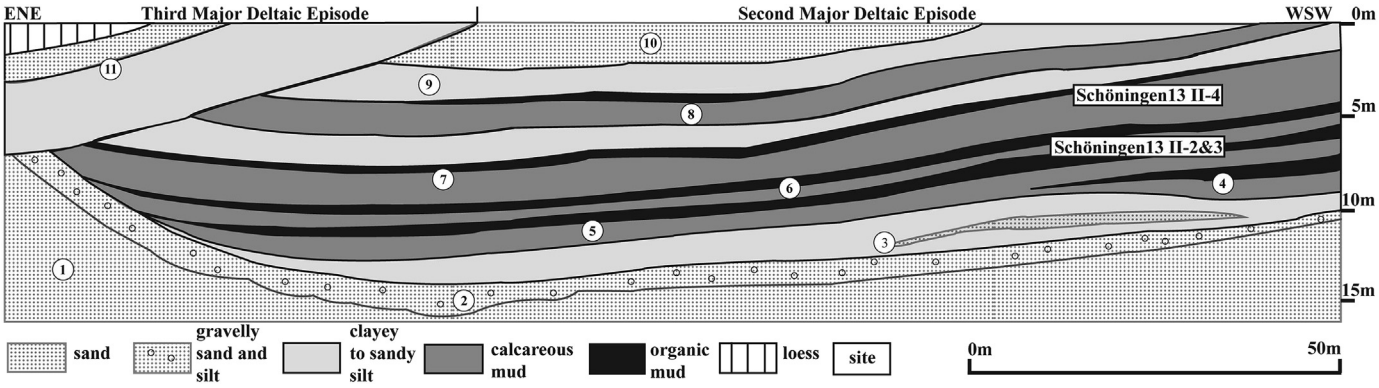

Figure 2. Simplified, schematic sequence at Schöningen 13 II (after Mania [in Thieme, 1999:463 and Urban, 2007], modified according to Lang et al. (2012); see also Stahlschmidt et al., 2015). 1 and 2) Elsterian glaciolacustrine deposits; 3) Lacustrine deposits; 4–7) Reinsdorf Interglacial shallowing cycles of the lake Schöningen 13 II-1 to II-4, with calcareous mud grading into an overlaying dark organic mud: 4) cycle 1; 5) cycle 2; 6) cycle 3; 7) cycle 4; note the location of Schöningen 13 II-4 in cycle 4 and 13 II-2 and II-3 in cycles 2 and 3; 8) 5th shallowing cycle, composed of sandy silt and an overlaying dark organic mud; 9 and 10) Glaciolacustrine deposits; 11) Lacustrine deposits and loess. See Figure 3 for the position of the profile.

(Fig. 2). The interglacial Middle Pleistocene sedimentary sequence, which contains the numerous Paleolithic layers, consists of three major superimposed deltaic systems (Urban, 1995, 2007; Lang et al., 2012; Figs. 2 and 3). Urban (2007) and Van Kolfschoten (2014) assign the first deltaic systems to the Holsteinian interglacial and MIS 11. However, the correlation of the Holsteinian interglacial with MIS 9 or 11 is still under debate (Geyh and Müller, 2005; Ashton et al., 2008; Geyh and Krbetschek, 2012).

The second major deltaic system consists of a series of lacustrine deposits (Figs. 2 and 3; Lang et al., 2012) and contains the materials from sites Schöningen 12 B and Schöningen 13 II analyzed in this study. Biostratigraphic evidence places Schöningen 13 II and 12 B in the Reinsdorf Interglacial, which was most recently dated to MIS 9 (Urban, 2007; Urban and Sierralta, 2012; but see Urban et al., 2015). Some researchers (Litt et al., 2007; Bittmann, 2012; Lang et al., 2012) argue that the Reinsdorf Interglacial is a possible equivalent subset of the Holsteinian Interglacial. The sedimentary sequence at Schöningen 13 II consists of five lacustrine cycles of gray calcareous mud that grade upward into dark brown organic muds (Thieme, 2007c; Urban, 2007; Stahlschmidt et al., 2015). Geological studies (Mania, 2007; Urban, 2007; Lang et al., 2012) interpret the alternation between marl and organic mud at Schöningen 13 II as a result of lake-level fluctuations related to variations in climate. Similarly, the sedimentary sequence at Schöningen 12 B consists of sequences of calcareous muds and organic rich deposits interpreted as the result of lake level changes (Thieme and Maier, 1995).

Urban et al. (1991a) assign the third episode of deltaic infill, which has only been exposed in the northern mine, to the Schöningen Interglacial, which they interpret as an equivalent of marine isotope stage 7 (MIS 7). The same authors (Urban et al., 1991a, b) also report travertine and peat in the northern part of the mine, which they correlate with Eemian MIS 5e and substages 5d and 5c.

1.2.3. Archaeology During the course of mining, which began at Schöningen in the 1970s, the miners artificially lowered the groundwater table through the construction of several deep wells. Starting in 1983 state archaeologist H. Thieme monitored operations at the lignite mine and discovered the first Paleolithic artifacts in 1992 (Thieme, 1997). Additional wells were then constructed to facilitate subsequent archaeological excavation. Twenty-eight Paleolithic sites and find horizons were discovered in association with the mine (Serangeli et al., 2012; Serangeli and Conard,

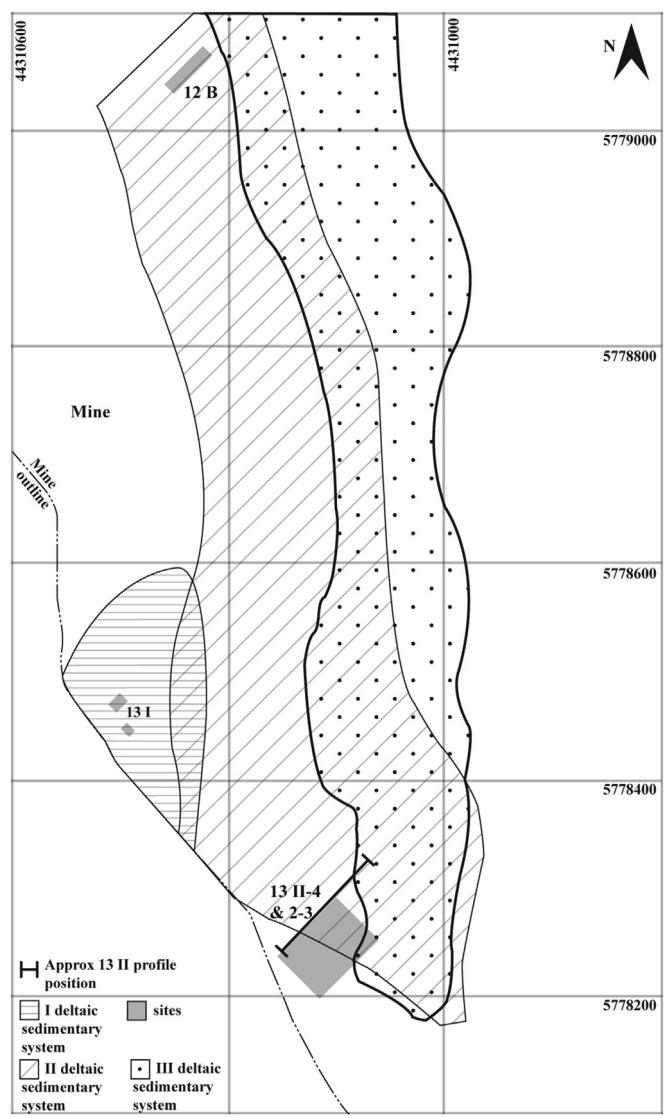

Figure 3. Map of Schöningen sites discussed here (after Mania in Thieme, 1999:457 and Serangeli et al., 2012:14). The Schöningen sites are located in an open-cast mine and the sites Schöningen 13 II and 12 B are associated with sediments from the second major cycle of lacustrine deposition. The approximate 13 II profile position refers to Figure 2.

2015), most of which were excavated as salvage operations. The sites contain lithic material, bone remains, and wooden artifacts, the last being excellently preserved due to the waterlogged state of the deposits. The materials discussed in this study come from Schöningen 12 B and 13 II.

1.2.4. Schöningen 13 II Excavations at Schöningen 13 II began in 1994 and are ongoing. Archaeological artifacts at Schöningen 13 II-4 are mostly found at the contact of layer 4b/c, a calcareous marl, with layer 4b, an organic mud (e.g., Stahlschmidt et al., 2015), and consist of butchered horse remains, wooden spears, and numerous flint artifacts in addition to purported evidence for anthropogenic fire (Thieme, 1997, 2005, 2007b; Voormolen, 2008; Serangeli and Böhner, 2012; Van Kolfschoten, 2014; Schoch et al., 2015; Fig. 4).

At Schöningen 13 II-3 and 13 II-2 bone remains, lithic artifacts, and one wooden artifact were discovered (Thieme, 2002, 2007d; Serangeli and Böhner, 2012). Here, the recent excavation team observed an additional case of possible heat-altered sediment. They noted a vertical crack several meters long through the calcareous marl of 13 II-3 and across layers 13 II-2 that was filled with black sediment (Fig. 5; see below).

1.2.5. Schöningen 12 B Schöningen 12 B was a rescue excavation, and the locality contains two find horizons. Find horizon 1 consists of a sandy mud and find horizon 2 of coarse detrital mud, both containing bone remains and lithic material (Thieme and Maier, 1995). Mania (1995) and Thieme (2007c) reported an accumulation of burnt wood in find horizon 2 and interpreted this accumulation of burnt wood as a possible hearth. The find horizon contained an additional fragment of supposedly burnt wood, the so-called *Fackelkopf* (ID 13325; see below).

1.2.6. Evidence for fire Thieme (1997, 1999, 2002, 2005, 2007a, b) and Mania (1995) reported evidence for anthropogenic fire from six sites and find horizons at Schöningen (Table 1). Most of the evidence was based on qualitative, macroscopic observations; however, Richter (1998, 2007) conducted a thermoluminescence study of burnt flint pieces from Schöningen 13 I, and Schiegl and Thieme (2007) conducted an inconclusive micromorphological study of hearth 1 from Schöningen 13 II-4. Most of the arguments for the anthropogenic origin of fire at Schöningen are based on the association of supposedly burnt materials with archaeological remains (e.g., Thieme, 2005).

1.2.7. Evidence for fire – hearths Thieme (1997, 1999, 2005, 2007b) interpreted four features at Schöningen as hearths (see Fig. 4). His interpretation was based on macroscopic observations of localized reddening of the calcareous marl, layer 4b/c, at the contact with the organic mud, layer 4b, and on cracks in the sediment at this contact (Thieme, 1997, 1999, 2005; Schiegl and Thieme, 2007; Fig. 6). Thieme excavated the features only partially and preserved the remaining sediment columns in wooden cases for future analysis. The recent excavation team reopened and excavated the hearth features between 2010 and 2012, noting that they had been affected by bioturbation and drying (Fig. 6). No charcoal, burnt bone, or ash was recovered from the features. Thieme reported that the hearths had a dimension of 1 m^2, whereas upon reopening the wooden cases, the reddened area was up to 3 m^2, thus presenting what would

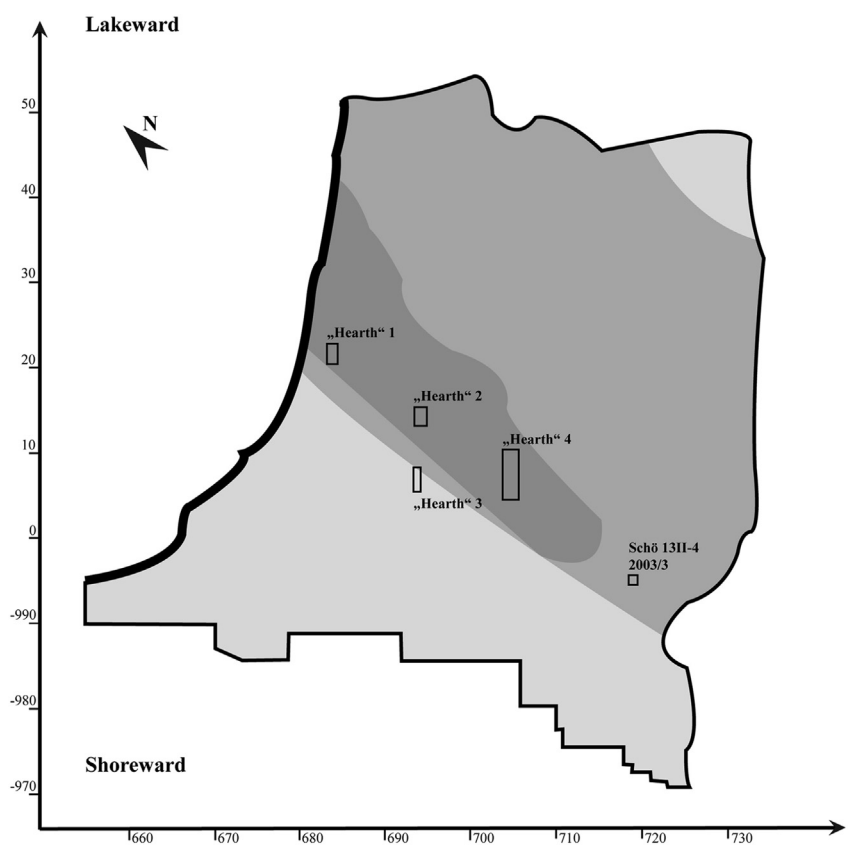

Figure 4. Schematic map of Schöningen 13 II-4 showing find density and the locations of the four purported hearths (modified after Thieme, 2007e:173; see also Stahlschmidt et al., 2015) and the reference sample Schö 13 II-4 2003/3. The excavation area Schöningen 13 II-4 is cut by mining activities to the north, east, and south, and the actual size dimension of the find horizon is therefore not known. Colored in dark gray is the approximate area of highest find density, in medium gray of medium find density, and in light gray of low find density. The schematic sequence depicted in Figure 3 was taken at the northern edge of the excavation area Schöningen 13 II-4 (thick line). Note, however, that the profile in Fig. 2 continues further east.

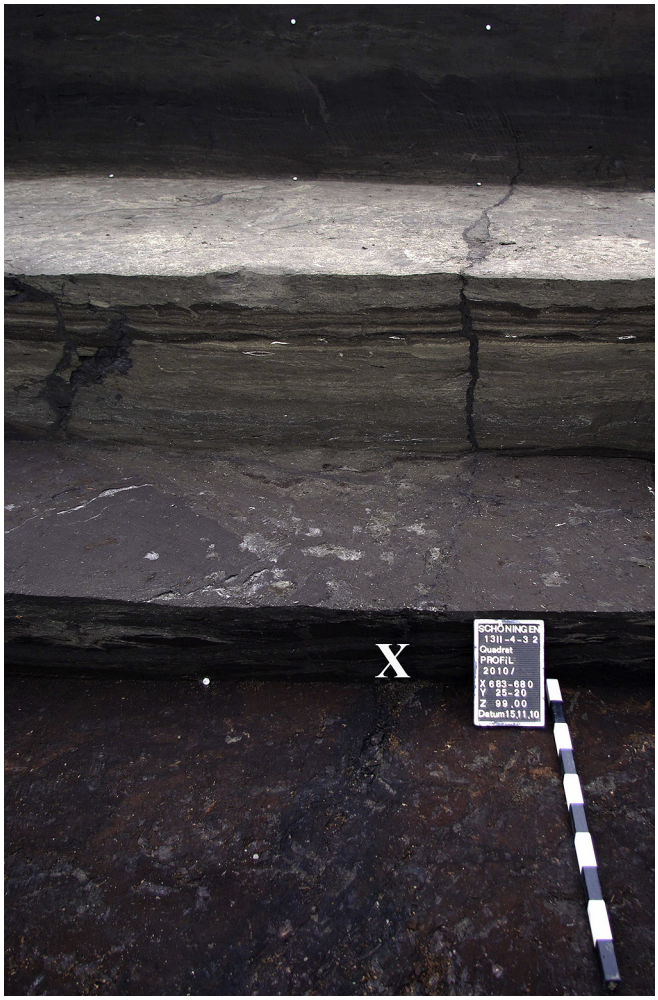

Figure 5. Photo of the crack running through Schöningen 13 II-3 and 13 II-2. The crack runs through the calcareous marl of 13 II-3 and across the organic mud of 13 II-2. The crack was filled with black sediment, which was interpreted as a possible heat-altered sediment. Samples were taken at the contact of Schöningen 13 II-2 with 13 II-3 and the "X" illustrates the approximate location of the samples. Photo by W. Mertens ©NLD.

be unusually large hearths (but see Shahack-Gross et al. [2014] for similarly large hearths). Preliminary micromorphological analysis by S. Schiegl on thin sections from hearth 1 detected the presence of quartz grains with surface cracks, which she suggested could have been caused by heating. However, Schiegl and Thieme (2007) also pointed out that the mollusk shells within the sediment from hearth 1 did not appear altered by heat. The authors reported these results as inconclusive (Schiegl and Thieme, 2007).

1.2.8. Evidence for fire – burnt wood Excavators have described fragments of burnt wood from Schöningen 13 II-1, 13 II-2 Berm, 13 II-4, 12 A find horizon 2, and 12 B (Mania, 1995; Thieme and Maier, 1995; Thieme, 1997, 1999, 2002, 2005, 2007a, b, c, d; W. Schoch, pers. comm.; Table 1). Two accumulations of burnt wood in Schöningen 13 II-2 Berm and 12 A find horizon 2 were reported as hearths, but no details were provided. Thieme (2005) also reported a piece of wood that appeared to be worked by humans and also possibly burnt. He interpreted this as a roasting stick, or *Bratspieß*.

1.2.9. Evidence for fire – burnt flint Richter (1998, 2007), Richter and Thieme (2012), and Richter and Krbetschek (2015) reported 13 burnt pieces of flint from Schöningen 13 I, which was confirmed with thermoluminescence and recently dated to 321 ± 16ka (Richter and Krbetscheck, 2015). None of these pieces show clear characteristics of having been worked or modified by humans (Richter, 1998, 2007; Richter and Thieme, 2012; Richter and Krbetscheck, 2015).

Since its discovery and the reporting of evidence for fire, Schöningen has been cited in almost all of the major reviews of early evidence for fire (Gowlett, 2006; Klein, 2009; Wrangham, 2009; Alperson-Afil and Goren-Inbar, 2010; Daniau et al., 2010; Roebroeks and Villa, 2011a; Gowlett and Wrangham, 2013). Several studies mention fire-hardening of the wooden spears from Schöningen as evidence for human use of fire (Rice, 2007; Berna and Goldberg, 2008; Coolidge and Wynn, 2009; Alperson-Afil and Goren-Inbar, 2010; Weiner, 2010). Neither Thieme (1997, 2005) nor any subsequent studies (Schoch et al., 2015) described the spears as exhibiting evidence for heating.

2. Material and methods

2.1. Materials

Table 2 contains an overview of all samples and the performed analyses.

2.1.1. Hearths All four purported hearths from Schöningen 13 II-4 were sampled in blocks from various locations that encompass the sediments of layer 4b/c, layer 4b, and their contact, where the purported hearths are located (Fig. 6). Hearth 1 was analyzed by all methods, whereas the remaining hearths were investigated only with micromorphology. One bulk sample from layer 4b, two block samples and one bulk sample from layer 4b/c, and one block sample encompassing the contact of layer 4b/c with the overlying sediments, layer 4b, with no reddening in between, were additionally taken outside the hearths to serve as control samples (Table 2). The control bulk samples were used for a heating experiment, studied by micromorphology, FTIR, mineral magnetic parameters, and thermoluminescence, and the control block samples were studied by micromorphology and thermoluminescence.

2.1.2. Burnt sediment Two bulk samples from the black, purportedly burnt sediment from the crack running through Schöningen 13 II-3 and 13 II-2 were taken at the contact of an organic mud from 13 II-2 and studied by organic petrology.

2.1.3. Burnt wood A piece (2 mm^3) of purported carbonized wood from a supposed wooden artifact from Schöningen 12 B and the attached sediment were studied by organic petrology. Sampling here was conducted by the Department of State Heritage Lower Saxony.

2.2. Methods

Both micromorphological and organic petrology analyses were employed to describe microscopic organic constituents. For clarity and consistency between the two methods we employ the term "plant tissue" for organic constituents originating from plants. This term is similar to soil micromorphology terms such as "plant residue" (Stoops, 2003) and organic petrology terms such as "macerals" (Taylor et al., 1998).

2.2.1. Micromorphology Micromorphology is the study of intact blocks of sediment and soils in thin section using a petrographic microscope. It permits identification of the composition, texture, structure, and fabric of the deposits, as well as the observation of pedogenic and anthropogenic features. Since the original integrity of the sediment is conserved it is possible to determine the relative spatial and temporal relationships among materials and voids in the sample (e.g., Courty et al., 1989). The technique of

Table 1
Overview of the Middle Pleistocene purported evidence for anthropogenic fire at Schöningen.[a]

Site/locality	Archaeological remains	Fire evidence	Publication of fire evidence	References of fire evidence	Performed analysis	Results	Interpretation: anthropogenic fire
Schöningen 13 I	Lithics, bone remains	Burnt flint – natural pieces	Richter, 1998, 2007, Richter and Thieme, 2012	Alperson-Afil and Goren-Inbar, 2006; Wrangham, 2009; Roebroeks and Villa, 2011a	Thermoluminescence	Burnt	Fire use: unknown Fire control: no Fire making: no
Schöningen 13 II-1	Bone remains with cutmarks	Burnt wood	Thieme, 2002	–	Organic petrology	Not burnt	–
Schöningen 13 II-2/3	Bone remains, lithics, one wood artefact	Black sediment	–	–			
Schöningen 13 II-2 Berme	Bone remains, two lithics	Accumulation of burnt wood (termed hearth)	Thieme, 2007d	–	–	–	–
Schöningen 13 II-4	Lithics, wooden tools, bone remains with cutmarks	Hearths	Thieme, 1997, 1999, 2005, 2007b; Schiegl and Thieme, 2007	Gaudzinski and Roebroeks, 2000; Alperson-Afil and Goren-Inbar, 2006; Preece et al., 2006; Klein, 2009; Wrangham, 2009; Roebroeks and Villa, 2011a	Micromorphology, FTIR, mFTIR, organic petrology, thermoluminescence, mineral magnetic parameters	Not burnt	–
	Lithics, wooden tools, bone remains with cutmarks	Burnt bone	–	Voormolen, 2008	–	–	–
	Lithics, wooden tools, bone remains with cutmarks	Charred wood – roasting stick (*Bratspieß*)	Thieme, 1997, 1999, 2005, 2007a	Preece et al., 2006; Wrangham, 2009; Roebroeks and Villa, 2011a	–	–	–
	Lithics, wooden tools, bone remains with cutmarks	Burnt wood – Fire-hardened spears	–	Rice, 2007; Berna and Goldberg, 2008; Coolidge and Wynn, 2009; Alperson-Afil and Goren-Inbar, 2010; Weiner, 2010	–	–	–
Schöningen 12 A – find horizon 2	–	Accumulation of burnt wood (termed hearth)	Thieme and Maier, 1995	–	–	–	–
Schöningen 12 B – find horizon 2	Bone remains, lithics	Burnt wood	Mania, 1995; Thieme, 2007c	–	Organic petrology	Not burnt	–

[a] Note that only in one instance (burnt lithics 13 I) were analyses able to confirm the burnt state of the material, while at the same time an anthropogenic involvement is doubtful.

micromorphology has proven to be a powerful tool for detecting early fire by revealing the presence of ash and the *in situ* character of hearth-related features (e.g., at Sibudu [Goldberg et al., 2009], Qesem Cave [Karkanas et al., 2007; Shahack-Gross et al., 2014], Wonderwerk Cave [Berna et al., 2012], Kebara, and Hayonim Cave [Goldberg and Bar-Yosef, 1998]); it was also successfully applied to the correction of claims of fire at Zhoukoudian (Goldberg et al., 2001).

For the micromorphological study, oriented blocks of sediment were collected in the field and stabilized by plaster of Paris or wooden containers. Sample preparation was conducted at the Geoarchaeology Laboratory, University of Tübingen. Samples were oven dried at 40°C for 1 day and then impregnated under a vacuum with a 7:3 part mixture of unpromoted polyester resin and styrene, catalyzed with methyl ethyl ketone peroxide (MEKP). After 5–10 days the samples were again heated at 50°C until they had hardened completely. The hardened blocks were then sliced into tiles of 50 × 75 × 10 mm. Thin sections were produced by Spectrum Petrographics, Inc. in Vancouver, Washington, U.S.A., and Th. Beckmann, Braunschweig, Germany. Analysis of the resulting thin sections was conducted with a Zeiss Axio Imager petrographic microscope under plane-polarized (PPL), cross-polarized (XPL), and blue light fluorescence, at magnifications of 20× to 500×. Description and analysis follows Courty et al. (1989), Stoops (2003), and Stoops et al. (2010).

2.2.2. Organic petrology Organic petrology is a branch of earth sciences that is widely used in the study of peat, brown coal, and hard coal properties with reflected light microscopy (Taylor et al., 1998). The study of the reflectance and fluorescence of organic constituents can be informative about the presence of charred plant material (wood, seeds, tissues etc.), which constitutes important evidence for fuel use and combustion conditions (e.g., Schiegl et al., 2004; Ligouis, 2006; Goldberg et al., 2009; Clark and Ligouis, 2010).

Organic petrological investigations are carried out on well-polished surfaces of particulate- or block-samples in reflected white light and in fluorescence mode on organic particles known as "macerals" (see Stahlschmidt et al., 2015:Table 3 for organic petrology terms). Sample preparation for organic petrology was conducted at the Laboratory for Applied Organic Petrology (LAOP) at the University of Tübingen. Polarized light is used to assess the properties (anisotropy, mosaic structure) of the carbon forms, especially if they result from coal carbonization (coke) and from incomplete combustion of fossil fuels (nonburnt carbon in the form of char; Taylor et al., 1998). Analysis was conducted with a Leitz DMRX-MPVSP microscope photometer equipped for reflected white-light and blue-light illumination, and is set up with oil immersion objectives (20× to 50×).

2.2.3. FTIR Fourier-Transform Infrared Spectrometric analysis was performed on thin sections and loose samples. Fourier-Transform Infrared (FTIR) spectroscopy is used in order to determine the characteristic molecular absorptions of infrared radiation by organic and inorganic material. The resulting infrared absorbance spectra are used to understand the composition of archaeological sediments and materials. Furthermore, FTIR spectroscopy is very sensitive to variations in composition (substitutions) and crystallography (atomic order) that result from diagenetic processes such as heat alteration (e.g., Weiner, 2010).

Sample preparation was performed at the MicroStratigraphy Laboratory at Boston University. Powdered aliquots of experimental and archaeological samples were analyzed by FTIR spectroscopy using a Thermo-Nicolet Nexus 470 IR spectrometer. Representative FTIR spectra were obtained by grinding a few tens of micrograms of sample with an agate mortar and pestle. About 0.1 mg or less of the sample was mixed with about 80 mg of KBr (IR-grade). A 7 mm

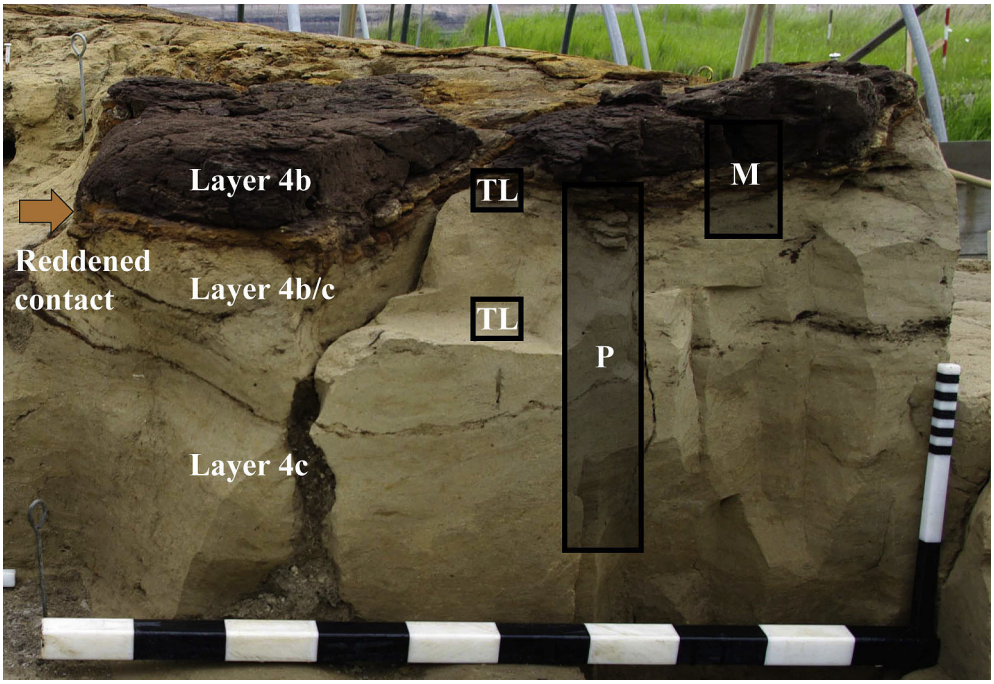

Figure 6. Sedimentary sequence at the purported hearth 1 at Schöningen 13 II-4. The sedimentary sequence at the purported hearths at Schöningen 13 II-4 consists of a calcareous marl, layer 4c, at the base, overlain by a transitional layer, layer 4b/c, exhibiting an increase in organic matter, which in turn is overlain by an organic mud, layer 4b. The contact between layer 4b/c and layer 4b is overprinted by an indurated, reddened crust, which was interpreted as the result of heat alteration (Thieme, 1997, 2005). The squares show the approximate locations of samples for micromorphology, FTIR, and organic petrology (all "M"), for study of mineral magnetic parameters ("P"), and for thermoluminescence analysis ("TL"). Note the recent bioturbation (refilled channel) and drying features (cracks). Photo by J. Lehmann ©NLD.

pellet was made using a hand press (Qwik Handi-Press, Spectra-Tech Industries Corporation) without evacuation. The spectra were collected between 4000 and 400 cm^{-1} at 4 cm^{-1} resolution. The presence of FTIR absorption of organic and inorganic phases was identified by using in-house or ad hoc spectral libraries (i.e., Weiner, 2010).

2.2.4. Mineral magnetic parameters Mineral magnetic properties can reflect changes in iron mineralogy in soils, soft sediments, and

Table 2
Sample list of all block and bulk samples, their location, and employed method.[a]

Site	Sample No/ID	Sample type	Square	Z-value[b]	Feature	Layer	Employed method
Schöningen 13 II-4	Schö 13 II-4 Sch FS1 1	Sediment block sample	683/21	102.44–102.56	hearth 1	4b-red layer-4c	Micromorphology/mFTIR/Organic Petrology
	Schö 13 II-4 Sch FS1 2	Sediment block sample	682/21	102.29–102.40	hearth 1	4b-red layer-4c	Micromorphology/mFTIR
	Schö 13 II-4 Sch FS1 3	Sediment block sample	683/21	102.54–102.80	hearth 1	4b-red layer-4c	Micromorphology/mFTIR/Organic Petrology
	Schö 13 II-4 Sch FS1 4	Sediment block sample	682/21	102.37–102.42	hearth 1	4c	Micromorphology/mFTIR
	Schö 13 II FS1 2010/21.1 BT 1079	Sediment block sample	683/22	102.61–102.05	hearth 1	4c	Thermoluminescence
	Schö 13 II-4 FS 1 2010/22.1	Sediment bulk sample	683/22	102.05–102.62	hearth 1	4c	Mineral Magnetic Parameters
	Schö 13 II-4 FS 1 2010/16	Sediment bulk sample	682/22	102.54	hearth 1	4c	Mineral Magnetic Parameters
	Schö 13 II-4 2010/29	Sediment bulk sample	693/14	102.42	hearth 2	4b-red layer-4c	FTIR
	Schö 13 II-4 2010/30	Sediment bulk sample	693/13	102.46	hearth 2	4b-red layer-4c	Micromorphology/FTIR
	Schö 13 II-4 2011/5	Sediment block sample	694/6	102.73	hearth 3	4c-red layer-4c	Micromorphology
	Schö 13 II-4 2011/08	Sediment block sample	695/7	103.00	hearth 3	4b-red layer-4c	Micromorphology
	Schö 13 II-4 2011/01	Sediment block sample	695/8	102.99–102.74	hearth 3	4b-red layer-4c	Micromorphology
	Schö 13 II-4 2010/23	Sediment block sample	704/9	101.65–102.05	hearth 4	4b-red layer-4c	Micromorphology/FTIR
	Schö 13 II-4 2010/24	Sediment bulk sample	705/9	101.51–102.15	hearth 4	4b-red layer-4c	Micromorphology/FTIR
	Schö 13 II-4 FS1 5	Sediment block sample	684/22	102.17		4c	Micromorphology/mFTIR
	Schö 13 II-4 2003/3.1	Sediment block sample	719/-995	102.16		4b–4c	Micromorphology
	Schö 13 II-4 BT-2011/25 BT 1077	Sediment block sample	776/-949	101.26		4c	Thermoluminescence
	Schö 13 II-4 BrEx 4b/c	Sediment bulk sample			off site marl	4b/c	Heating Experiment
	Schö 13 II-4 BrEx 4b	Sediment bulk sample			off site marl	4b	Heating Experiment
Schöningen 13 II-3/2	Schöningen 13 II-3/2 2010/35	Sediment bulk sample	681/21	98.95		2a	Organic Petrology
Schöningen 13 II-3/2	Schöningen 13 II-3/2 2010/36	Sediment bulk sample	682/21	98.95		2a	Organic Petrology
Schöningen 12 B	ID 13325	Wood and sediment	7/10	Not specified		Not specified	Organic Petrology

[a] Note that some block samples were analyzed by micromorphology, organic petrology, and FTIR.
[b] Z-value relates to block sample and not the actual sample.

Table 3
Micromorphological description of layers 4b and layer 4b/c at the four hearths and the control sample (Schö 13 II-4 2003/3.1).[a]

Sample No.	Layer	Microstructure, aggregates, voids, and ratio coarse to fine fraction	Fine fraction[b]	Coarse fraction[b]	Comments
Schö 13 II-4 sediment hearth 1–4	4b	Homogenous, locally laminated; elongated plant tissue residues with a tendency for horizontal alignment, large fractures, lens structure in one TS	Clay and amorphous organic fine material	Plant issue residues and cells (0.1–0.002 mm, but predominantly ~0.5 to 0.1 mm; fragmented, light brown to brown in color), quartz (rounded, fine sand to silt sized), mica, gypsum, framboidal pyrite, sponge spicules, diatoms, very few rounded charcoal particles	
Schö 13 II-4 sediment hearth 1–4	4b/c	Water escape structures elongated plant tissue residues with a tendency for horizontal alignment, simple packing voids, some large fractures	Dominantly micritic to rarely rhombohedral calcite to clayey and amorphous organic fine material	Plant tissue residues and cells (0.02–0.001 mm, but predominantly around 0.5 to 0.1 mm, fragmented, light brown to brown in color), quartz (rounded, fine sand to silt sized), framboidal pyrite, ostracods and mollusk fragments, charophyte internodia and gyrogonites, gypsum sponge, spicules, diatoms, bone fragments (angular, ~0.5 mm)	Contact with unit 4b clear and with intense iron precipitation Diffuse iron precipitation
Schö 13 II-4 sediment hearth 1, 4	4c	Homogenous, elongated plant tissues residues with tendency for horizontal alignment, simple packing voids, few larger fractures	Dominantly micritic to rarely rhombohedral calcite to slightly clayey	Quartz (rounded, fine sand to silt sized), plant tissue residues and cells (0.01–0.2 mm, fragmented, light brown to brown in color) framboidal pyrite, gypsum, ostracod and mollusk fragments, charophyte internodia and gyrogonites, diatoms sponge spicules	Contact with unit 4b/c gradual Diffuse iron precipitation
Schö 13 II-4 2003/3.1	4b	Elongated plant tissue residue with a tendency for horizontal alignment, large vertical fractures slightly fissural	Clay and amorphous organic fine material	Plant tissue residues and cells (around 0.5 to 0.1 mm; fragmented, light brown to brown in color), gypsum, quartz (rounded, fine sand to sit sized), mica, framboidal pyrite, diatoms, sponge spicules	Fracture and fissure related to recent freezing and defrosting
Schö 13 II-4 2003/3.1	4b/c	Elongated plant tissue residue with a tendency for horizontal alignment, simple packing voids, some large fractures	Dominantly micritic to rarely rhombohedral calcite to clay and amorphous organic fine material	Plant tissue residues and cells (0.5–0.1 mm, fragmented, light brown to brown in color), quartz (rounded, fine sand to silt sized), framboidal pyrite, ostracods and mollusk fragments, charophyte internodia and gyrogonites, gypsum, sponge spicules, diatoms, bone fragments (angular, ~0.5 mm)	Contact with 4b/c clear but fractured Fractures related to recent freezing and defrosting

[a] The variation among the four hearths is insignificant and they are therefore described as one.
[b] Limit fine to coarse fraction at 10 μm.

hard rocks that result from diagenetic redox-processes, pedogenesis, and also thermal alteration. Thermal alteration leads to an enhancement of mineral magnetic parameters caused firstly by the thermal degradation of plant material and secondly by the transformation of para- and/or antiferromagnetic iron minerals to ferrimagnetics. This enhancement of mineral magnetic parameters can be identified by low field susceptibility and concentration of independent interparametric ratios derived from laboratory induced remanences (Dalan and Banerjee, 1998; Evans and Heller, 2003).

Sample preparation was conducted at the Laboratory for Palaeo- and Environmental Magnetism, Bayreuth University, Germany. The low field magnetic susceptibility was determined with a MAGNON Susceptibility Bridge (MAGNON, Dassel, Germany) at AC-fields of 300 A/m at 0.3 and 3 kHz, respectively, and is given as mass specific susceptibility (χ). The frequency dependence of susceptibility (χfd) ($\chi fd\% = [\chi(0.3\ kHz) - \chi(3\ kHz)]/\chi(0.3\ kHz) \times 100$ in %) is a measure of the relative contribution of SP-ferrimagnetica close to the SP-SD threshold. χ reflects concentration of ferrimagnetic minerals and also grain size distribution. Fine-grained superparamagnetic (SP) ferrimagnetica (<0.03 μm) have a 2–3 times higher χ than stable single-domain, pseudosingle-domain (SSD, PSD; ~0.03–10 μm), and multidomain ferrimagnetica (MD, >~10 μm; Evans and Heller, 2003). Induced isothermal remanent magnetizations (IRMs) were determined after exposing the samples to a pulsed field of 2000 and 200 mT (back field), respectively, along one spatial axis. Magnetization was produced using a MAGNON PM II pulse magnetizer and measured via an AGICO JR6-spinner magnetometer (AGICO, Brno, Czech Republic). The IRM acquired in the 2 T field is regarded as saturation isothermal remanent magnetization (SIRM). As the SP-size fraction is defined by the absence of magnetic remanence under room temperature, IRMs are essentially controlled by the concentration of SSD to MD-ferrimagnetica. Furthermore, IRMs depend on the mineralogical composition with ferrimagnetica (magnetite, maghemite) being more easily magnetized than antiferromagnetica (goethite, hematite; Maher, 1986). Therefore, the modified S-ratio (= ((IRM200mT/IRM2000mT) + 1)/2) is indicative of the relative abundance of ferrimagnetica to antiferromagnetica and a concentration-independent proxy (Walden et al., 1999; van Velzen and Deckers, 1999).

Anhysteretic remanent magnetizations (ARMs) were induced with a 50 μT static field and 100 mT alternating field (AF) amplitude using a Magnon AFD 300 demagnetizer. The ARM was produced along one spatial axis, and remanent magnetization was measured via the AGICO JR6-spinner magnetometer. Similar to the IRM, the ARM reflects the concentration of remanence carrying magnetic phases. However, the ARM decreases more strongly from the SSD to the MD-fraction than does the SIRM. Therefore, the IRM/ARM ratio is a useful concentration-independent proxy for detecting changes in the ratio of SSD-MD fraction versus SSD fraction (Maher, 1986; Evans and Heller, 2003).

2.2.5. Thermoluminescence Thermoluminescence (TL) analysis can determine if sediment has been exposed to heating in the past by analyzing the TL glow curve shapes and TL sensitivities. Luminescence has been frequently used to examine the presence of temperature-induced changes in sediment and subsequently to determine the age of heated sediment from archaeological contexts (Aitken, 1985; Alperson-Afil et al., 2007). Verification of prehistoric heating is usually done by the heating plateau test (Aitken, 1985), where a flat ratio of TL induced by artificial irradiation versus the natural TL signal provides evidence of the heating in the past. However, the material under study here is sediment, and bleaching of the signal during deposition or sampling could induce results comparable to heating. Therefore

Table 4
Optical properties of plant tissues of the liptinite group (spores, pollen, algae, bark- or cork-derived tissue) in the samples Schö 13 II-4 FS 1 1a, 1b, 3a, and 3b.

Schö 13 II-4 FS1 1a&b						Schö 13 II-4 FS1 3a&b					
Lithological units and thickness (cm)	Huminite (telohuminite) reflectance			Fluorescence properties of organic particles		Lithological units and thickness (cm)	Huminite (telohuminite) reflectance			Fluorescence properties of organic particles	
	Mean value %Rr	Standard deviation	Number of measurements	Huminite	Liptinite		Mean value %Rr	Standard deviation	Number of measurements	Lithological units and thickness (cm)	Huminite (telohuminite) reflectance
4b >1.8	0.21	0.039	100	non-fluorescing to brown fluorescing	brightly yellow and green fluorescing	**4b** >6.3	0.17	0.028	100	non-fluorescing to brown fluorescing	yellow and brightly green fluorescing
Red contact upper part 0.4–0.8	0.19	0.048	23	non-fluorescing to brown fluorescing	brightly yellow and brightly green fluorescing	**Red contact upper part** 0.3–0.5	0.13	0.031	40	non-fluorescing to brown fluorescing	yellow and brightly green fluorescing
Red contact lower part 1.0–1.5	0.17	0.054	10	non-fluorescing to brown fluorescing	yellow and brightly green fluorescing	**Red contact lower part** 2.0–2.5	0.15	0.042	47	non-fluorescing to brown fluorescing	yellow and green fluorescing
4c >5.8	0.22	0.030	20	non-fluorescing to brown fluorescing	yellow and green fluorescing	**4c** >1.3	0.15	0.051	34	non-fluorescing to brown fluorescing	brightly yellow and brightly green fluorescing

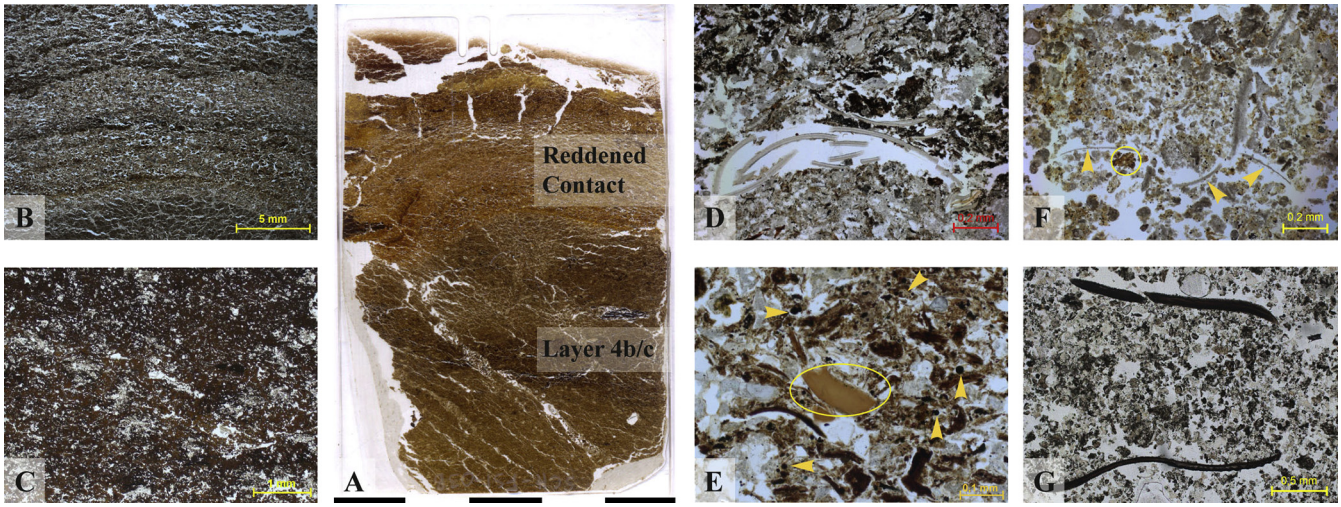

Figure 7. Thin section analyses in layer 4b/c, the reddening and the heating experiment. A: Scan of thin section Sch FS 1 03B showing the reddening and the lower layer 4b/c. Note the laminated appearance of the reddening. B: Microphotograph of reddening. Note again the laminated appearance of the reddening. Scale lower right 5 mm, Plane-polarized light (PPL). C: The reddening at higher magnification showing the impregnation of layer 4b/c by amorphous iron. Scale at lower right 1 mm, PPL. D: Microphotograph of shell fragments in layer 4b/c directly below the reddening. Note that the shell fragments show no evidence for heat alteration contrary to what was replicated by the heating experiment (see F and G). Scale at lower right 0.2 mm, PPL. E: Microphotograph of layer 4b/c below the reddening. Note the abundance of pyrite (yellow arrows), brown plant tissues, and a bone fragment (yellow circle). None of these components show evidence for heat alteration. Scale at lower right 0.1 mm, PPL. F: Microphotograph of the calcareous marl heated to 500°C. Note the gray coloring of the shell fragments (yellow arrows) and localized red staining (yellow circle). Scale at lower right, 0.2 mm, PPL. G: Microphotograph of the calcareous marl heated to 800°C. Calcite depletion is visible here and hematite (pinkish color) formation. Note also the black color of the two shell fragments. Scale at lower right 0.5 mm, PPL.

the heating plateau test alone is not proof of a prehistoric firing event. However, heating of minerals changes the sensitivity of the TL-signal and results in different shapes of the TL-glow curves, which can indicate prehistoric heating.

Sample preparation was conducted at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. TL measurements were performed on a Risø Da-15 luminescence reader at 5 K s^{-1} to 450°C with immediate background subtraction. Luminescence detection with an EMI 9236QA photomultiplier was restricted to the UV-blue wavelength range by Corning 5-58 and KG-5 glass filters. Irradiations were performed with a calibrated external $^{90}Sr/^{90}Y$-source, and samples were stored at 50°C for one week before measurement. Prior to the luminescence study, the organic and carbonate content of this fine grained sediment was removed and the fine grain fraction (4–11 μm) was extracted according to Stokes law.

2.2.6. Heating experiment Sample preparation and the heating experiment itself were performed at the Geoarchaeology Laboratory, University of Tübingen. Sediment samples from layer 4b/c and layer 4b from Schöningen 13 II-4 were subjected to a stepwise heating experiment. The samples were heated for 4 h in a muffle furnace to temperatures of 100°C, 200°C, 300°C, 400°C, 500°C, 700°C, 800°C, 900°C, 1000°C, and 1100°C, and subsequently cooled down for at least 24 h in a desiccator. In a second run, no desiccator was employed to account for possible variance, but none was observed and only some test analyses of the mineral magnetic parameters were carried out on these. Color change and weight loss were recorded and further analyses were chosen based on these observations. The samples of layer 4b were only studied macroscopically. For the samples of layer 4b/c, study of the mineral magnetic parameters was conducted on the whole temperature range. Micromorphological analyses and FTIR spectroscopy were also performed on the samples from layer 4b/c between temperatures of 400°C–1100°C. Thermoluminescence analyses were conducted on samples from layer 4b/c heated to 400°C, 700°C, and 900°C. A non-heated sample from layer 4b/c was analyzed with micromorphology, FTIR, by study of the mineral magnetic parameters, and by thermoluminescence analyses.

3. Results

3.1. Hearths at Schöningen 13 II-4

Stahlschmidt et al. (2015) present a detailed analysis of the geological context of the purported hearth features and the following includes a short review of the geological context.

3.1.1. Geological context – layer 4b Layer 4b is composed of dark brown (Munsell Soil Color Chart 7.5YR 3/2) organic silt, which locally exhibits laminations. Layer 4b has a variable but maximal thickness of 35 cm. Under the microscope, layer 4b is composed mostly of small (<0.3 mm), slightly humified fragments of plant tissue, with a minor portion of rounded, sand- to silt-sized grains of quartz and mica (Tables 3 and 4). Framboidal pyrite, diatoms, sponge spicules, and secondary nodules of gypsum were additionally noted in thin section. The microstructure is massive with some lamina distinguished by increased silt-sand-sized quartz and clay content. No evidence for heat alteration was found in this layer (Table 3).

3.1.2. Geological context – layer 4b/c Macroscopically, layer 4b/c is a calcareous mud with some mollusks that represent the only macroscopically identifiable materials in addition to the archaeological remains. Layer 4b/c exhibits minor soft sediment deformation, and it varies in color from brownish gray to gray (Munsell Soil Color Chart 2.5YR 6/3, 5/4, 6/1, and 10YR 5/8 to 4/6), which results from variable content of plant material, pyrite, and iron precipitations (see Stahlschmidt et al., 2015). Microscopically, layer 4b/c consists of small (<0.3 mm), slightly humified fragments of plant tissue, pyrite, silt- to sand-sized quartz grains, diatoms, and shell fragments in a calcareous matrix (Fig. 7d, e; Table 3).

Below the strongly reddened features interpreted as hearths, layer 4b/c appears slightly more red than the marls outside the

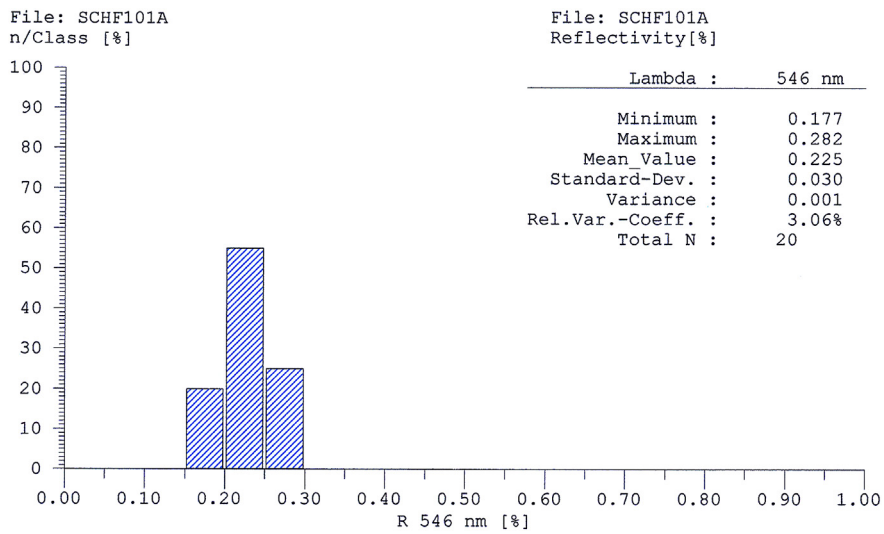

Figure 8. Huminite reflectance histogram of layer 4c/b in sample Schö 13 II-4 FS11a. The reflectance values range from 0.17%Rr to 0.28%Rr, which indicates low humification of the plant tissue and not carbonization.

purported hearth areas (Munsell Soil Color Chart 2.5YR 5/3). Excavators initially thought that this was also a result of heat alteration. However, the micromorphological analyses revealed the reddish colorations result from localized iron oxidation associated with microscopic plant tissues and oxidation of the ubiquitous pyrite (see above). The general reflectance value of the plant tissue from layer 4b/c (0.17%Rr to 0.22%Rr) indicates humification and gelification, not charring (Fig. 8). Only very few, dispersed fragmented pieces of charred plant tissue were observed (Fig. 9). The recorded fluorescence color and intensity of the plant tissue are typical for the peat stage of plant tissue and corroborate the reflectance values. Micromorphological analyses on layer 4b/c from outside the hearths showed no difference in components or structures from within the four hearths. Similarly, thermoluminescence analysis showed no difference in the glow curve shape and sensitivity in the sample from layer 4b/c from hearth 1 (Schö 13 II-4 FSI 2010/21 BT-1079; Fig. 10a and b) to that from outside the purported hearths (Schö 13 II-4 2011/25 BT-1077; Fig. 10c and d). The heating plateau test indicates an apparent zeroing of the sample from hearth 1 (Fig. 10b), but the plateau is even more pronounced in the sample outside the hearths (Fig. 10d). Furthermore, heating as a single cause is revoked by bleaching experiments that showed the bleachability of the TL signal. Consequently, the presence of a plateau is not suited here for testing the occurrence of heating. A heating plateau is expected for luminescence not in saturation, but changes in sensitivities and especially glow curve shapes have to occur when sediment is heated. The sediment from layer 4b/c from outside the hearths was experimentally heated in the laboratory and shows an entirely different sensitivity and rather different glow curve shapes (Sch 13 II-4 Br Ex 4b/c LS 39 BT-1080; Fig. 10e) compared to the samples obtained from the Schöningen site (Fig. 10a and c). Taken together, these results suggest that the samples from hearth 1 and outside the hearths did not experience different temperatures.

3.1.3. Results of the heating experiment Table 5 provides an overview of the results of the heating experiment. The heated samples from layer 4b/c show a range of reactions starting from 100° to 300°, at which point destruction of ferromagnetic Fe-sulfides occurs and neo-formation of para- and supermagnetic phases (SP) takes place (Fig. 11). Stable single domain (SSD) magnetite/maghemite forms at 400°C (Fig. 11). A macroscopic color change from greyish brown to pale brown was first observed at 500°C (Fig. 7f). The color change continues to reddish yellow (Munsell Soil Color 7.5YR 7/4-6/4) from 700 to 800°C and to light gray (Munsell Soil Color 10YR 7/2) at 900°C. The change in color noticed in our experiments is likely a result of 1) gray shell fragments and orange staining by iron oxidation at 500°C, 2) blackened shell fragments and an increase in dark red and orange staining from 800°C onwards, 3) calcite depletion from 700 to 800°C, and 4) destruction of magnetite/maghemite from 700 to 900°C with hematite formation at 800°C and 900°C (Figs. 7g and 11). Furthermore, we observed that kaolinite is absent from samples heated to 400°C, and that portlandite first appears at 700°C (Fig. 12) as a result of CaO re-hydration (Weiner, 2010). Finally, at 1000°C all Fe-bearing phases are transformed to magnetite/maghemite (Fig. 11). The shape of the TL signal changes as a result of laboratory heating as observed in the samples heated to 400°C, 700°C, and 900°C (Fig. 10e). Additionally, for an identical dose the sensitivity is raised by a

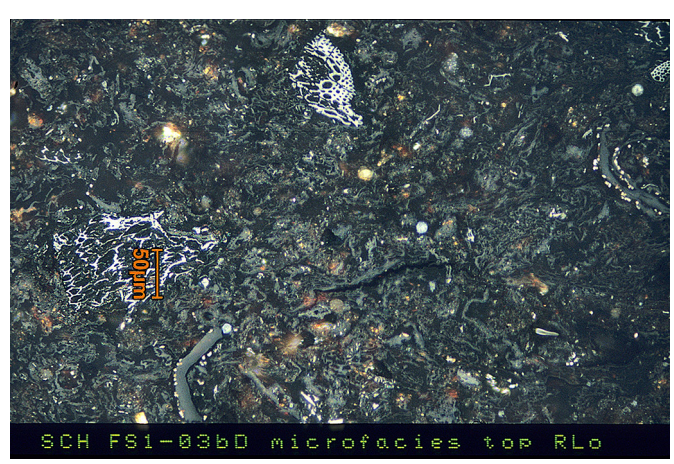

Figure 9. Microphotograph in reflected light of a polished block from layer 4b at hearth 1. Two fragments of charred herbaceous-derived tissue (white) occur next to numerous fragments of mixed, not burnt huminitic herbaceous-derived tissues. Scale at the left 50 µm.

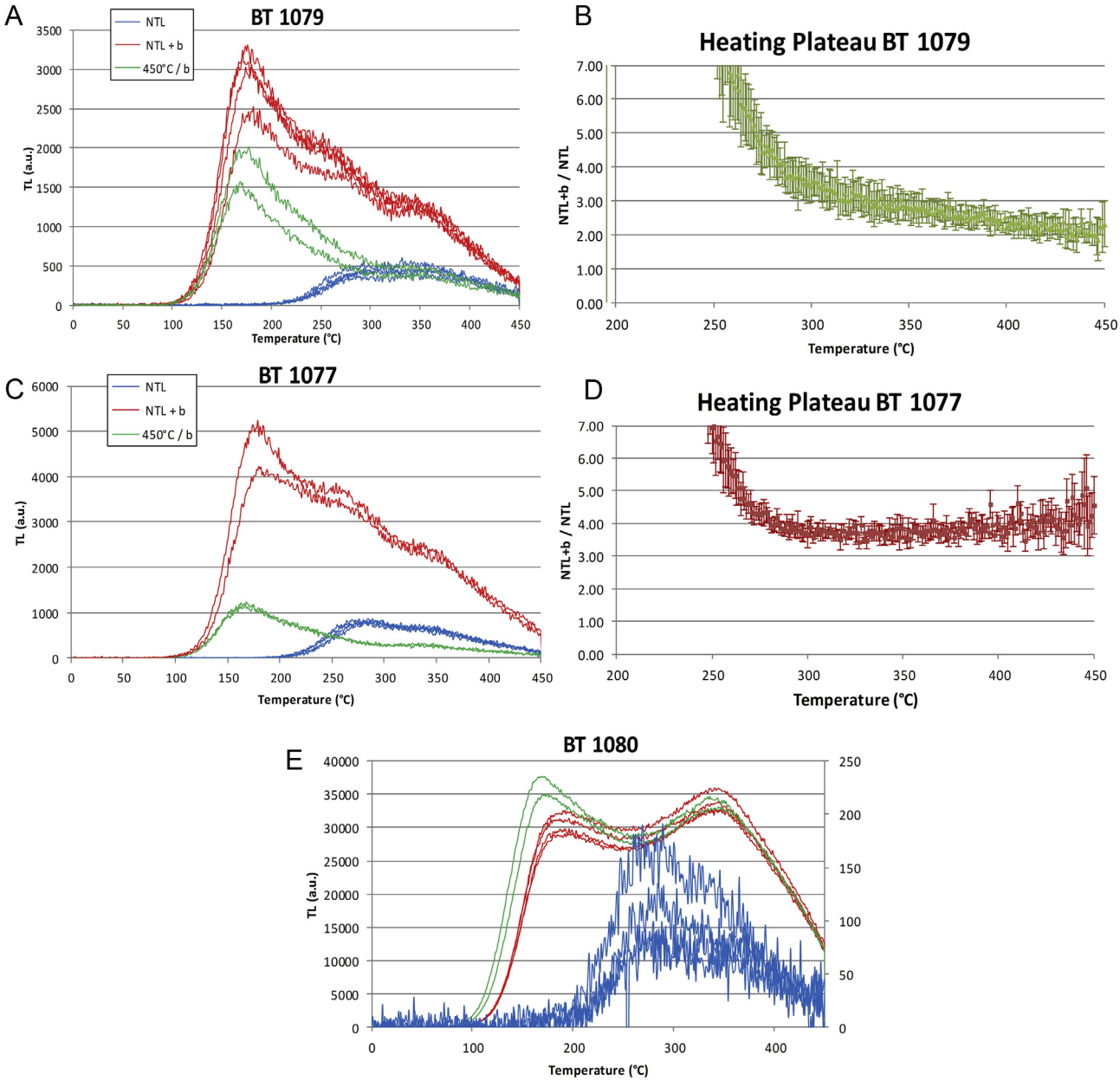

Figure 10. A and B: TL glow curves of sample Schö 13-II FS1 2010/21.2 (BT-1079) from layer 4b/c in hearth 1. A: The blue curves (NTL) show the natural TL, the red lines (NTL+b) the TL signal produced by an additional artificial irradiation (200 Gy), and the green lines (450°C/b) the TL-signal after identical irradiation of the sample after measurement of the NTL. B: Ratio of NTL+b over NTL (heating plateau test) shows apparent zeroing. C and D: TL glow curves of sample Schö 13 II-4 2011/25 BT-1077 from layer 4b/c outside the hearths. C: The blue curves (NTL) show the natural TL, the red lines (NTL+b) the TL signal produced by an additional artificial irradiation (200 Gy), and the green lines (450°C/b) the TL-signal after identical irradiation of the sample after measurement of the NTL. Note the similar shape of the glow curves attained in the hearth 1 sample, Figure 10A. D: the ratio of NTL+b over NTL (heating plateau test) shows apparent zeroing. E: TL glow curves of sample Schö 13-II BrEx 4b/c LS 39 (BT-1080) which is layer 4b/c heated to 400°C. The blue curves (400°C) show the residual TL after heating, the red lines (400°C+b) show the TL signal produced by an artificial irradiation (200 Gy), and the green lines the TL-signal after identical irradiation of the sample after measurement of the residual. Note the clear difference in sensivity and shape of glow curves compared to the samples from hearth 1 and outside the hearths in Figure 10A and C.

factor of seven compared to the regeneration of the sample from the purported hearths.

3.1.4. The reddening/purported hearth features The reddened contact between layers 4b/c and 4b occupied horizontal spaces of 1–3 m^3, varying among the four hearths. The reddened contact consists of a consolidated hard crust with a thickness of 2–3 cm and a brownish yellow to reddish yellow color (Munsell Soil Color 10YR 6/8- 7.5YR 6/6). Microscopically, the reddening is composed of amorphous iron that impregnated the groundmass of layers 4b and 4b/c. This reddening is in fact composed of several microlayers, which indicates multiple episodes of formation (Fig. 7a–c). Oxygen-rich water in combination with a redox (reduction/oxidation) boundary at the contact of the two layers brought about the massive precipitation of iron at the contact. Other spatially extensive iron oxidation features at similar sedimentary contacts were observed in the excavation area at Schöningen 13 II (Fig. 13). Moreover, the observation by the excavators that the reddened contact has grown vertically and horizontally over the years supports the assumption that the reddening represents a recent, on-going process, likely related to the recent groundwater lowering at the mine.

Table 5
Overview of the results from the heating experiment.[a]

Temperature	Color Macroscopic (Munsell color Chart)	Microstructure	Components and their alterations	Red staining	Mineral phases (present after cooling-down to ambient temperatures)
0°C	10YR 5/2 grayish brown	Massive	Shells, diatoms, quartz grains, plant tissue residues and cells, bone, calcite, clay	None	Calcitic crystallitic b-fabric, Kaolinite present
up to 300°C	10YR 5/2 grayish brown	–	Shells, diatoms, quartz grains, plant tissue residues and cells, calcite, clay	–	Destruction of ferrimagnetic Fe-sulfides, neo-formation of para- and superparamagnetic (SP; Fe-oxide?) phases
400°C	10YR 5/2 grayish brown	Massive to granular	Shells grayish, diatoms and quartz unaltered, charred plant tissue residues and cells, calcite, clay	Many dark red spots	Calcitic crystallitic b-fabric, no Kaolinite, neo-formation of SP Fe-oxide-phases and of stable single domain (SSD) magnetite/maghemite
500°C	10YR 6/3 pale brown	Granular to dense massive	Shells grayish, diatoms and quartz unaltered, charred plant tissue residues and cells, calcite, clay	Many dark red spots	Calcitic crystallitic b-fabric, magnetic phases as above, no Kaolinite
700°C	7.5YR 7/4-6/4 reddish yellow	Granular to dense massive	Shells dark gray to black, diatoms and quartz unaltered, calcite, clay altered, portlandite	Many dark red spots and some orange red staining	Calcite depletion zones visible, beginning hematite formation, destruction of magnetite/maghemite, no Kaolinite
800°C	7.5YR 7/4-6/4 reddish yellow	Dense massive, locally granular	Very few diatoms and few brown to black colored shells observed, quartz grains unaltered, portlandite	Many dark red spots and some orange red staining	Calcite dissolved, increasing hematite formation, destruction of magnetite/maghemite continues, no Kaolinite
900°C	10YR 7/2 light gray	Dense massive, locally granular	Very few diatoms and brown shells, quartz grains unaltered, portlandite	Many dark red spots and some orange red staining	Hematite present, no Kaolinite
1000°C	10YR 7/2 -7/3 light gray to very pale brown	Dense massive	Very few diatoms and no shells observed, quartz grains unaltered, portlandite	Many dark red spots and some orange red staining	Transformation of all Fe-bearing phases to magnetite/maghemite, no Kaolinite
1100°C	10YR 7/2 light gray	Granular to massive	No diatoms observed neither shells, quartz grains unaltered, portlandite	Locally dark red spots	Magnetite/Maghemite, no Kaolinite

[a] The sediment samples exposed to heating show a range of reactions (charring of plant tissue, color change of shell fragments, formation of portlandite, hematite, and magnetite, calcite depletion, local red staining) at the different temperature intervals, which was not replicated in the samples from the purported hearths.

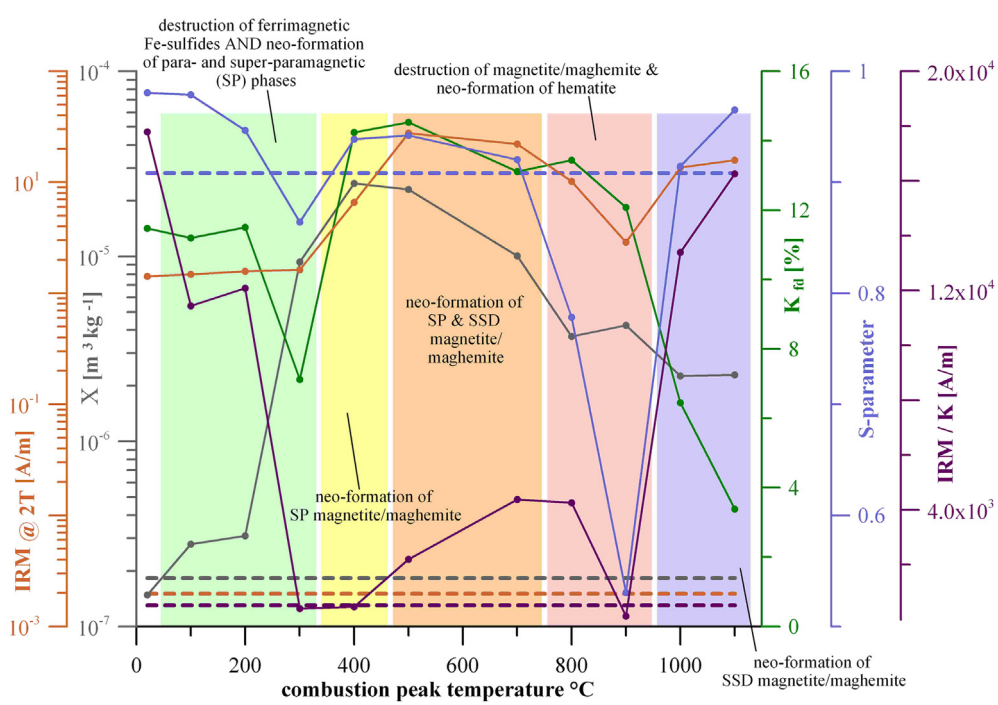

Figure 11. Changes of mineral magnetic parameters with heating up to 1100°C. Concentration-dependent parameters are plotted at the left (orange = IRM@2T [A/m] value, gray = X [m^3kg^{-1}] value), and mineral and grain size indicative inter-parametric ratios are shown at the right (green = K_{fd}[%] value, blue purple = S-parameter, red purple = IRM/K[A/m] ratio). The dashed lines mark the respective values of the reddened layer at the purported hearth. Note that there is no temperature interval where the magnetic characteristics of the reddened layer correspond to the experimental results. Several magneto-mineralogical changes were observed with increasing temperatures: ≤300°C destruction of ferrimagnetic Fe-sulfides and neo-formation of para- and superparamagnetic (SP) phases occurs; ≤700°C neo-formation of SP phases AND of stable single domain (SSD) magnetite/maghemite can be observed; ≤900°C: increasing neo-formation of hematite occurs; up to 1100°C transformation of all Fe-bearing phases to SSD magnetite/maghemite occurs.

Micromorphological analyses did not detect ash remains or phytoliths associated with the reddening and revealed only a few, isolated charcoal fragments. Reflectance values indicate generally low humification of the plant tissues. Organic petrology analysis observed very few, small (<0.3 mm) fragmented, charred particles and showed that the charred plant tissues are herbaceous (Table 4; Fig. 14). Accordingly, they most likely derive from natural peat fires. Bone, ostracod, and mollusk shell fragments in thin section show no evidence for heat alteration (Fig. 7d, e; Table 3). Furthermore, FTIR analyses demonstrated the presence of kaolinite, which is not stable above temperatures of 400°C (Fig. 12). None of the experimentally produced heat alterations (charring of plant tissue, color change of shell fragments, formation of portlandite, hematite, magnetite, or calcite depletion) were observed on the material obtained from the purported hearths, and the local red staining observed in the heating experiment is unlike the reddening at the purported hearths (see above).

3.2. Burnt sediment from Schöningen 13 II-2 and 13 II-3

The reflectance values of the two sediment samples from Schöningen 13 II-2 and 13 II-3 show a mean value of 0.25%Rr and a range from 0.10%Rr to 0.45%Rr (Fig. 15). These reflectance values are indicative of humification and not carbonization (which results in values greater than ~0.6%Rr). Charred plant tissues (fusinites) are a rare occurrence in the sediment sample and are dominantly herbaceous and highly fragmented.

3.3. Burnt wood and sediment from Schöningen 12 B

The presumed burnt piece of wood is very well preserved and shows low reflectance values, 0.11%Rr to 0.16%Rr (Fig. 16), which are indicative of humification and not carbonization. No part of the wood piece showed reflectance values that indicate combustion (which would be >0.6%Rr). Brown fluorescence of the cell walls shows that the wood sample is composed of humic substances in addition to lignin and cellulose.

4. Discussion

4.1. No evidence for human use or control of fire at Schöningen

Our results show that the reddening at the purported hearths at Schöningen 13 II-4 did not result from heating but instead represents a natural, recent post-depositional process of iron precipitation and oxidation. Such reddened contacts of two overlying sedimentary layers are widely known features in lacustrine sequences (e.g., Deike et al., 1997; Kaczorek and Sommer, 2003). A few transported, charred plant tissues probably resulting from natural fires are the only evidence for fire at Schöningen 13 II (see also Urban et al., 2015). Palynological analyses (Stahlschmidt et al., 2015; Urban et al., 2015) document an increase in microcharcoal at several erosional contacts in the profile section 12 II and 13 II, which may indicate a change in frequency of natural fires resulting from shifts in climate or changing seasonality.

Furthermore, the organic petrology analyses show that the presumably burnt sediment from Schöningen 13 II-3 and purported burnt wood from Schöningen 12 B have not been exposed to heat. These results highlight the difficulty of using macroscopic identification of burnt sediment and charcoal without further verification, and call into question other burnt wood claimed as evidence for fire at Schöningen, such as the *Bratspieß* (e.g., Thieme, 2005; Schoch et al., 2015).

Lithic artifacts from Schöningen 13 I had been exposed to fire, as demonstrated by thermoluminescence analysis (Richter, 1998, 2007; Richter and Thieme, 2012; Richter and Krbetschek, 2015). This being said, the association of burnt, possibly natural pieces of flint with archaeological remains does not demonstrate human use of fire (e.g., James et al., 1989; Roebroeks and Villa, 2011a). This particularly applies to burnt wood, which occurs naturally and is frequently preserved in lacustrine deposits (e.g., Power et al., 2010).

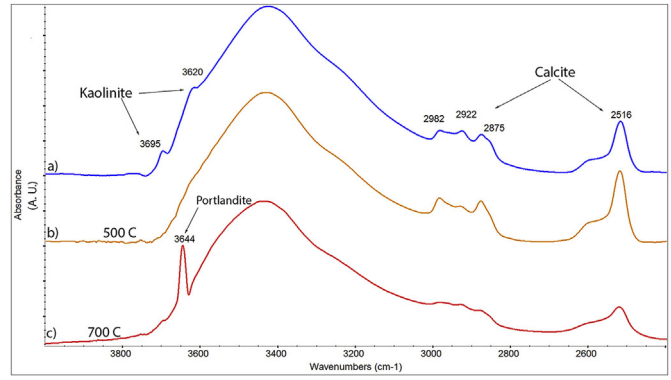

Figure 12. a) Representative FTIR spectrum of local marl sediment showing the IR absorptions of kaolinite (3620 and 3695 cm^{-1}) and calcite (2516 and 2875–2982 cm^{-1}); b) Representative FTIR spectrum of local marl sediment heated to 500°C showing the abatement of kaolinite IR absorptions (3620 and 3695 cm^{-1}); c) Representative FTIR spectrum of local marl sediment heated to 700°C showing the IR absorption of portlandite [Ca(OH)2](3644 cm^{-1}) and the abatement of kaolinite IR absorptions (3620 and 3695 cm^{-1}).

4.2. Implications for the archaeological record in northern latitudes

Schöningen does not contain evidence for controlled or habitual use of fire. The results of our study on the reddened and black sediments at Schöningen call into question similar claims for human control of fire that are solely based on macroscopic, visual

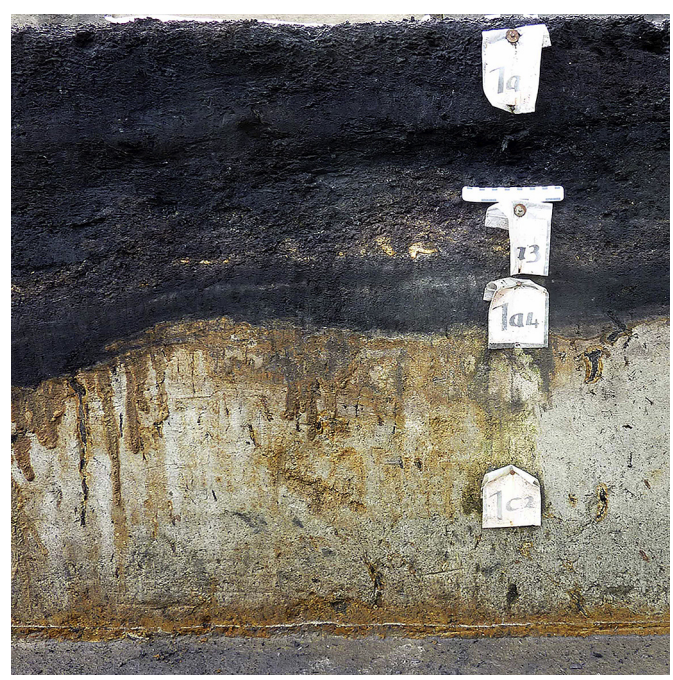

Figure 13. Photograph of the contact of a lower calcareous marl with an upper organic mud/peat deposit at Schöningen 13 II-1. Note the iron precipitation at this contact, which is similar to the purported hearth features in 13 II-4. Height of profile about 1.20 m.

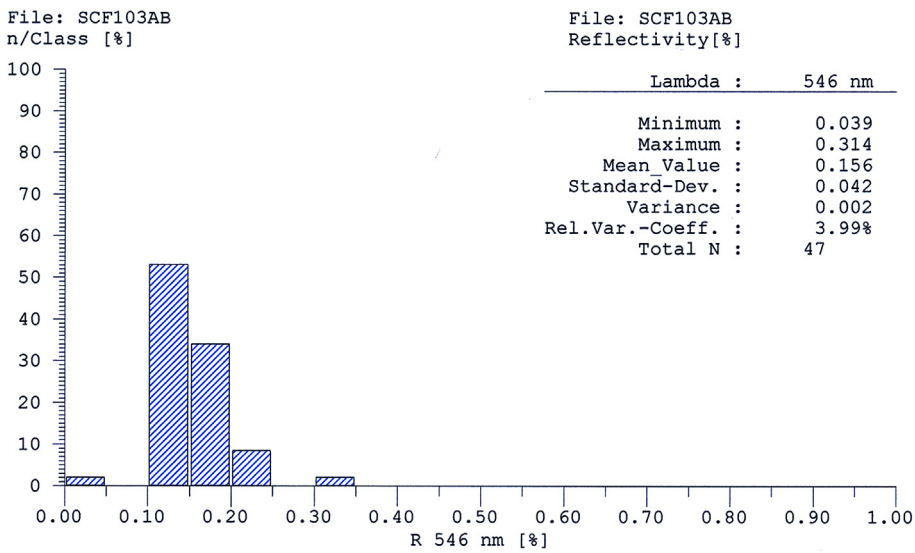

Figure 14. Huminite reflectance histogram of the reddening in sample Schö 13 II-4 FS 13a and 13b. The reflectance values range from 0.03%Rr to 0.31%Rr, which indicates low humification of the plant tissue and not carbonization.

identification of reddened or dark-colored sediments. At Beeches Pit, Gowlett et al. (2005) identify hearths based on the presence of oxidized sediments overlain by dark-colored deposits. They note the spatial association of these features with clusters of burnt flint and bone. However, the inferred temperature of 350–800°C for the bones and lithic material does not exclude natural fires, and no analysis of the purported hearth sediments has yet been presented. A detailed micro-contextual analysis of the purported hearths, as also proposed by Gowlett et al. (2005), would potentially be able to differentiate between natural and anthropogenic fire.

The lack of evidence for human induced fire at Schöningen, and the questionable evidence at Beeches Pit, leaves archaeologists with no conclusive evidence for human control of fire in northern latitudes during the Lower Paleolithic (Roebroeks and Villa, 2011a). This stands in contrast to the evidence for human occupation as early as 800,000 years ago above the 50th degree of latitude in Europe (Parfitt et al., 2010). The lack of evidence for human use and control of fire could be either a result of poor preservation, human behavior, or both.

4.2.1. Preservation Surovell and Brantingham (2007) argue that the archaeological record is subject to taphonomic biases, which cause overrepresentation of younger periods relative to older periods (but see Surovell et al., 2009). The lack of early evidence for human use and control of fire in northern latitudes might also be a result of taphonomic processes erasing the evidence (Sandgathe et al., 2011b). Hearths and burnt materials can be subject to destructive processes, such as bioturbation, erosion, and chemical alterations (e.g., Sergant et al., 2006; Mallol et al., 2007; Braadbaart et al., 2009; Mentzer, 2012). Combustion features can also be influenced by geochemical conditions and modifications of the depositional environment (e.g., Shahack-Gross et al., 2004, 2014). For example, in northern latitudes acidic soils predominate (e.g., Jones et al., 2010), which negatively affects ash preservation. However, charcoal shows better preservation under acidic, rather than alkaline conditions (Braadbaart et al., 2009). Caves and rockshelters exhibit very good preservation properties, as shown by the rich record of well-preserved hearth features in Middle Paleolithic sites in Europe,

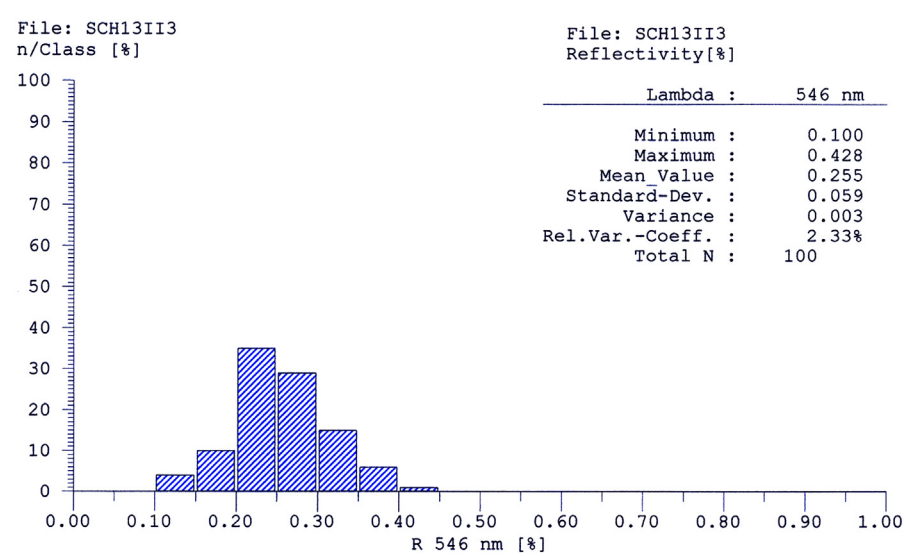

Figure 15. Huminite reflectance histogram of the purported burnt sediment Schö 13 II-2/3 2010/35&36. The reflectance values show a mean value of 0.25%Rr and a range from 0.10%Rr to 0.4%Rr, which is indicative of humification and not carbonization.

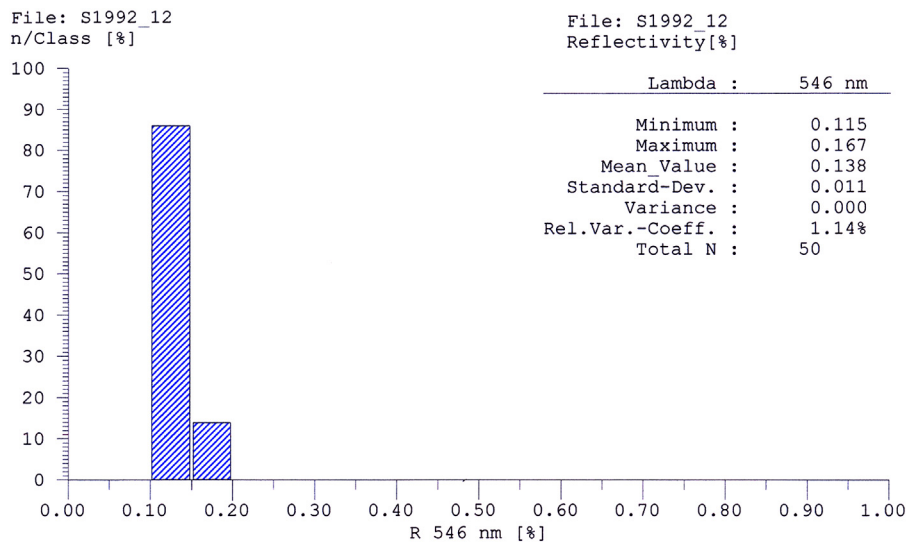

Figure 16. Huminite reflectance histogram of the purported burnt wood ID 13325. The reflectance values range from 0.11%Rr to 0.16%Rr. These values indicate humification and not carbonization.

the Near East, and Africa (e.g., Goldberg and Bar-Yosef, 1998; Goldberg et al., 2009; Wadley et al., 2011). However, Lower Paleolithic sites in caves and rock shelters in Europe have not been reported to contain any evidence for human use of fire (e.g., Atapuerca Gran Dolina and Sima del Elefante, Arago, Treugol'naya, and Visogliano; Roebroeks and Villa, 2011a).

Most Lower Paleolithic sites in northern latitudes are located in open-air settings (e.g., Pakefield, Boxgrove, Happisburgh, Schöningen, Bilzingsleben), and sites in open-air settings are subject to more pronounced post-depositional alterations, such as bioturbation, erosion, and subaerial weathering (Goldberg and Sherwood, 2006). Sergant et al. (2006), in their investigation of a lack of Mesolithic hearths in the NW European plain, argue that unstructured hearths rarely preserve in this type of setting, since they are erased by bioturbation and erosion. Mallol et al. (2007) in an ethnographic study on the use of fire by the Hadza observed that taphonomic processes, such as root invasion and erosion, can erase hearths in open-air settings, but that microscopic traces are often preserved depending on sedimentation rate. Supporting those observations, Friesem et al. (2013) report on a Middle Paleolithic hearth in an open-air setting, noting that it was likely preserved because of rapid burial.

4.2.2. Human behavior Gowlett and Wrangham (2013) argue that a lack of natural fire in northern latitudes presented a limiting factor for human settlement there. However, whereas most of the Lower Paleolithic sites in Europe date to interglacials (e.g., Boxgrove, Bilzingsleben, Pakefield, Schöningen), there are sites occupied during unfavorable climatic conditions, such as Happisburgh (Parfitt et al., 2010). Sandgathe and colleagues (2011a, b) claim that Neanderthals did not practice habitual fire use and that they depended on natural sources of fire. However, contradicting Sandgathe et al.'s claim, Rots (2011, 2015) presents evidence for ignition activities on a Levallois point at the site of Bettencourt, France. The current state of evidence strongly suggests that the first inhabitants of northern Europe did not habitually use and control fire (Roebroeks and Villa, 2011a).

An independence from fire seems odd in the face of data indicating that modern humans cannot survive, even if fully acclimatized, to temperatures below −5°C without some kind of protection against the cold in the form of clothing, fire, or shelter (Hardy et al., 1971; Gilligan, 2010). However, it is possible that archaic humans might have had a different temperature tolerance. In this context, providing warmth seems the most important application of fire next to providing nutritional improvement and light. Use of shelters, seasonal migration, a stronger reliance on animal food resource, clothing, and physical and nutritional adaptation present further strategies to cope with a colder environment (Gilligan, 2010).

Some Lower Paleolithic sites in Europe are situated in rock shelters and caves that could have provided protection. However, most of the known Lower Paleolithic record consists of open-air sites. The analysis of sites in open-air settings have not yet yielded reliable evidence for the construction of shelters in the Lower and Middle Paleolithic (cf. the controversial cases of Terra Amata [de Lumley, 1969], Chichibu [Hadfield, 2000], and Bilzingsleben [Mania and Mania, 2000]). Constructed shelters become a common feature of archaeological sites only in the Upper Paleolithic (Iakovleva and Djindjian, 2005; Svoboda et al., 2005).

Seasonal migration in winter to areas with less harsh climate or only ephemeral occupation have been suggested for Early Pleistocene occupation in northern latitudes (e.g., Roebroeks, 2001; Dennell, 2003, 2013), but high resolution data on seasonal signals and cold or warm phase occupation is often lacking. So far this option has been explored in detail only from the later Middle Paleolithic onward (e.g., Féblot-Augustins, 1993). Similarly, the fossil record of the Middle Pleistocene in northern latitudes is too sparse to ascertain a physical adaptation to colder climates, whereas with the Middle Paleolithic a cold-adapted species—the Neanderthals—appears in Europe (Sergi, 1944; Churchill, 1998; Steegmann et al., 2002; Snodgrass and Leonard, 2009; but see Rae et al., 2011).

Some researchers suggest that an increase in the consumption of animal resources is a necessary adaptation in order to maintain a high metabolic rate when confronted with the rarity of plant food in northern latitudes (Snodgrass and Leonard, 2009; but see Speth, 2010). However, more detailed studies of edible plants in northern latitudes are still in progress (Bigga et al., 2015). The lack of vitamin C caused by the scarcity of plant food could have been answered with an increase of raw—not cooked—meat, especially liver, as is practiced by the Inuit (Höygaard, 1940; Draper, 1977). The spears from Schöningen are an excellent example of an improved hunting technology, and the richness of butchery remains at the site shows

good access to animal resources (see also Dennell, 2013). Horsehide might also have been exploited as protection against the cold (Voormolen, 2008), and it is generally assumed that Neanderthals (e.g., Wales, 2012) depended on clothing to survive winter. The origin of clothing is still an open question since its preservation in Paleolithic context is very improbable. However, studies of needles, depictions, textile impressions, and the evolution of lice have provided some indirect evidence for Paleolithic clothing (e.g., Adovasio et al., 1996; Soffer et al., 1998; Soffer, 2004).

5. Conclusion

Since James et al.'s (1989) early critique on the various claims for human use and control of fire in the Paleolithic literature, the evaluation of evidence for fire has been approached in a much more circumspect manner and the associated human behavior is carefully classified into fire use, control, sporadic use and control, habitual use and control, and fire production. However, many claims for early use of fire still rest on unsubstantiated assumptions and "intuitive" claims. Our multianalytical, contextualized study at Schöningen is an example of a refutation of such types of unsupported claims. Our analysis on purported hearths, burnt sediment, wood, and lithic material, along with a critical reassessment of other claims for fire at Schöningen, clearly show that the site complex does not serve as an example of human use or control of fire in the Lower Paleolithic.

In order to investigate the human mastery of fire, archaeologists must conduct a three-step evaluation of their data. First, the researcher must demonstrate that the material evidence was either produced or altered by fire. As shown in this study, macroscopic, qualitative evidence for heat alteration is often ambiguous but can be verified with such techniques as micromorphology, Fourier transform infrared (FTIR) spectroscopy, organic petrology, luminescence, and analysis of mineral magnetic parameters. Second, the researcher must demonstrate that the heat alteration is related to human activity and is not the result of a natural process (e.g., forest fire or lightning strike); a micro-contextual approach presents the most promising tool. Third, the researcher must evaluate whether the evidence suggests use of fire, control of fire, production of fire, or habitual use of fire.

The lack of direct evidence for human use and control of fire in northern latitudes does not serve as evidence for absence of such behavior, and it is still debatable if this lack of evidence is related to poor preservation or to human behavior. Accepting the null hypothesis would mean that unless material is proven to be burnt, it is not burnt, and that unless human fire use can be proven, humans did not use fire. Accordingly, the present data set in Europe suggests the absence of fire use and control in the Lower Paleolithic. More in-depth research along the lines used in this study is needed to find and evaluate evidence for early fire use in northern latitudes.

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C.E.M., P.G., J.S., and N.J.C. conceived the project; M.C.S., C.E.M., and J.S. performed sampling and field analysis; M.C.S., C.E.M., P.G., and F.B. performed micromorphological analysis; B.L. performed organic petrology; U.H. performed mineral magnetic parameters studies; D.R. performed thermoluminescence studies; F.B. performed FTIR and mFTIR analyses; M.C.S. and C.E.M. designed the heating experiment, and M.C.S. wrote the paper.

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