A preliminary study on ochre sources in Southwestern Germany and its potential for ochre provenance during the Upper Paleolithic

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Abstract

The use of mineral pigments, specifically iron-oxide rich mineral pigments called ochre, has been put forward as a key element in the development of symbolic and non-utilitarian behaviors in human evolution. However, the processes of ochre procurement, trade and use are difficult to conceptualize without the identification and characterization of the sources where these materials were acquired. We present the results of geochemical analyses of ochre source samples collected from the Swabian Jura, Black Forest, and other localities in southern and eastern Germany. The goal of this study was to build the groundwork for future investigations on the range of ochre behaviors at archaeological sites in the region. Our aim was to determine whether certain ochre outcrops could be differentiated based on their geochemical signatures. Using data from Neutron Activation Analysis (NAA), we were able to determine that the ochre source regions exhibit greater source inter-variability than intra-variability when observed using a range of statistical techniques, therefore satisfying the *provenance postulate*. Furthermore, the data provide the foundation for a Central European database of ochre sources to allow the comparison of ochres from different regions to archaeological ochres from important nearby and perhaps distant sites.

Mineral pigments, ochre, neutron activation analysis (NAA), Europe, multivariate statistics

1. Introduction

The use and manipulation of earth minerals into usable pigments has long been at the center of models for the emergence of modern behaviors in hominin species (McBrearty and Brooks, 2000, Henshilwood and Marean, 2003, d'Errico and Henshilwood, 2011, Zilhão, 2011, d'Errico, et al., 2003, Nowell, 2010, Wadley, 2001, Wadley, 2003, Wadley, 2006). Of the earth pigments used by hominins, red ochre (a series of rocks, clays, and sediments containing varying amounts and mineral phases of iron oxides/hydroxides) is one of the most frequently reported materials and was perhaps the most widely used pigment producing material in ancient contexts (Dart, 1975, Wreschner, 1981, Velo and Kehoe, 1990, O'Connor and Fankhauser, 2001, Bernatchez, 2008, Henshilwood, et al., 2009, Watts, 2009, Roebroeks, et al., 2012, Salomon, et al., 2012, Hodgskiss, 2012, Dayet, et al., 2016, Zipkin, 2015, Brooks, et al., 2016, Hodgskiss and Wadley, 2017, Rosso, et al., 2017). The presence of ochre in large quantities at African archaeological sites, in addition to insights from ethnographic groups, have spurred investigations into the potential range of uses for this material (Rifkin, 2015a, Rifkin, 2015b, Wadley, 1987, Taçon, 2004, Watts, 1998). These studies have shown the usefulness of ochre for non-symbolic or "functional" applications (Rifkin, 2015a, Rifkin, 2011, Rifkin, et al., 2015, Wadley, 2005, Hodgskiss, 2006).

Though traditional qualitative analyses of archaeological ochre assemblages provide useful insights on the range of colors, textures, and types of ochre artifacts (Watts, 2009, Hodgskiss, 2012, Hodgskiss and Wadley, 2017, Rosso, et al., 2017, Watts, 2010, Rosso, et al., 2014, Velliky, et al., 2018), incorporating geochemical data into this repertoire can supplement hypotheses on aspects of ochre behavior, including mineral selection and exchange (Pradeau, et al., 2014, Anderson, et al., 2018, Bernatchez, 2012, Sajó, et al., 2015, Dayet, et al., 2013, Salomon, 2009, MacDonald, et al., 2013, MacDonald, et al., 2018, Huntley, et al., 2015). Information on the mineralogical aspects can shed light on geological formation, mineralogical composition and the life-history of ochre materials, while ochre geochemical fingerprinting can highlight regional acquisition patterns and the movement of materials in the landscape. Observing these qualitative and quantitative data collectively allows for a holistic approach to investigating the entire process behind mineral pigment behaviors of ancient populations.

In European contexts, much research emphasis is placed on identifying early occurrences of ochre and pigments, specifically regarding Neanderthal symbolic behavioral and cognitive capacities (Roebroeks, et al., 2012, Salomon, et al., 2012, Hoffmann, et al., 2018, Heyes, et al., 2016, Bodu, et al., 2014, Dayet, et al., 2014, Dayet, et al., 2019). Moreover, the use of mineral pigments is well documented for the Upper Paleolithic (UP) (ca. 44-14.5 kcal. BP) of Western (Salomon, et al., 2012, Pradeau, et al., 2014, Bodu, et al., 2014, Dayet, et al., 2014, Guineau, et al., 2001, d'Errico and Soressi, 2002, Soressi and d'Errico, 2007, Zilhão, et al., 2010, Román, et al., 2015, de Lumley, et al., 2016, Couraud, 1983, Couraud, 1988, Couraud, 1991) and Southern Europe (Gialanella, et al., 2011, Peresani, et al., 2013, Cavallo, et al., 2017a, Cavallo, et al., 2017b, Cavallo, et al., 2018, Fontana, et al., 2009). Yet, ochre research in Central Europe remains comparatively understudied, even though some of the most well-known and prominent sites of the Upper Paleolithic in Central Europe, such as Hohle Fels (Velliky, et al., 2018) and Geißenklösterle (Gollnisch, 1988) in southwestern Germany, have also produced extensive evidence of pigment use.

Here, we present the results of an investigation on ochre sources in southern, western, and eastern Germany. Following a series of surveys, we collected modern-day source materials from "local" (<80 km), "regional" (80-300 km), and "distant" (>300 km) ochre sources. These locational classifications are arbitrarily defined based on our investigative epicenter, the archaeological sites of the Swabian Jura (Section 2.2). The samples were then geochemically characterized using Neutron Activation Analysis (NAA) in order to address three questions: 1) what is the degree of inter- and intra-source elemental variability of the ochre source deposits and sub-outcrops?; 2) do the source chemistries satisfy the *provenance postulate* (Weigand, et al., 1977)?; 3) how have environmental and landscape changes possibly impacted collection opportunities during the Late Pleistocene in this region? The results of these investigations allow for a more nuanced approach to exploring potential areas of ochre acquisition throughout southern and eastern Germany and the possible impacts of climate and environment on source availability. They will furthermore contribute towards establishing the necessary groundwork for future ochre comparative studies with archaeological materials.

2. Background

2.1 Previous Geochemical Studies on Ochre

Geochemical research on minerals found in archaeological contexts have explored and reconstructed ancient networks of movement, migration, trade and how people interacted and engaged with these materials. These studies commonly include ceramics, clays, lithic materials, and metals. Included in this suite is ochre, a colloquial term referring to any earth material containing enough Fe-oxide or hydroxide to produce a color streak (Watts, 2002), and has been collected by hominins since at least ca. 270 ka BP (Barham, 2002, McBrearty, 2001). Though ochre can be a difficult material for provenance studies due to its heterogeneity (any clay, sediment, or rock with >3% Fe-oxide) (MacDonald, et al., 2018, Cornell and Schwertmann, 2003, Popelka-Filcoff, et al., 2007), research on the geological and elemental components of ochre sources and their chemistry has been successful in attributing different archaeological materials to certain source areas (Dayet, et al., 2016, Popelka-Filcoff, et al., 2008, MacDonald, et al., 2011). North American researchers have successfully used NAA (MacDonald, et al., 2013, Popelka-Filcoff, et al., 2007, Popelka-Filcoff, et al., 2008, MacDonald, et al., 2011, Kingery-Schwartz, et al., 2013), Particle Induced X-ray Emission (PIXE) (Beck, et al., 2012, Erlandson, et al., 1999), Laser Ablation – Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) (Bu, et al., 2013, Eiselt, et al., 2019) and portable X-ray Fluorescence (Koenig, et al., 2014) to document ochre sources, their associated archaeological components and rock art pigment technologies and characteristics. Similar studies in Africa using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (Dayet, et al., 2016, Moyo, et al., 2016), LA-ICP-MS (Zipkin, et al., 2017) and PIXE (Bernatchez, 2008) documented ochre formations and the interplay between humans, the landscape and ancient acquisition and use of ochre pigments. Several studies in Australasia using a similar suite of analytical methods have revealed the diversity in ochre materials, including those used for rock art pigments (Huntley, et al., 2015, Huntley, 2015, Scadding, et al., 2015, Jercher, et al., 1998). Other studies in this region have furthermore shown ochre pigments in rock art sites that pre-date many European contexts and have expanded our knowledge of the spread and antiquity of this material (Aubert, et al., 2014, Aubert, et al., 2018).

In Europe, much research concerning the Middle and Upper Paleolithic has focused on characterizing types of rock art mineral pigments (Hoffmann, et al., 2018, Gialanella, et al., 2011, Smith, et al., 1999, Chalmin, et al., 2006, Resano, et al., 2007, Chalmin, et al., 2007, Jezequel, et al., 2011, Lahlil, et al., 2012, Roldán, et al., 2013, Bonjean, et al., 2015, Iriarte, et al., 2009), ochres from within archaeological settlement contexts (Salomon, et al., 2012, Pradeau, et al., 2014, Román, et al., 2015, Salomon, et al., 2008), artifacts with ochre residues (Zilhão, et al., 2010, Capel, et al., 2006, Cuenca-Solana, et al., 2016), and identifying evidence of heat treatment of ochres in ancient contexts (Cavallo, et al., 2018, Salomon, et al., 2015). Some recent studies in Italy and Spain have shown promise for a provenance-based analysis of archaeological materials and local and/or distant ochre sources using a combination of methods such as X-ray Diffraction (XRD), Raman Spectroscopy, ICP-MS, XRF, and Scanning Electron Microscopy (SEM-EDX) (Sajó, et al., 2015, Cavallo, et al., 2017a, Cavallo, et al., 2017b, Román, et al., 2019). To date, no provenance-based studies of ochre materials and their archaeological counterparts have taken place in Germany, though one study in Hungary was able to associate a well-known Epi-Gravettian (ca. 14-13 ka BP) hematite source to nearby archaeological sites in Hungary (Sajó, et al., 2015).

2.2 Ochre artifacts from the Ach Valley cave sites

The Ach Valley of the Swabian Jura (Ger. *Schwäbische Alb*), in Southwestern Germany, and has been an area of interest for Paleolithic research since the late 19th century (Fraas, 1872, Riek, 1934, Riek, 1973, Schmidt, et al., 1912). Archaeological excavations conducted in the cave sites of this region have yielded numerous symbolic artifacts from the earliest Aurignacian (ca. 44-34 kcal. BP) sequences in Europe, which include a 'Venus' figurine and other statuettes made from mammoth ivory (Conard, 2003, Conard, 2009, Dutkiewicz, et al., 2018), musical instruments (Conard, et al., 2009), and personal ornaments (Wolf, 2015, Hahn, 1977, Hahn, 1988). Two cave sites in the Ach Valley yielded numerous ochre and ochre-related artifacts dating to the Upper Paleolithic (ca. 44-14.5 kcal. BP), including ca. 900 ochre pieces from Hohle Fels, some with traces of modification (Velliky, et al., 2018). Geißenklösterle contains 278 artifacts with several varieties of hematite and limonite, as well as a supposed ochre layer or *Rötelschicht* in the Aurignacian layers (Hahn, 1988). Several painted limestone pieces bearing parallel rows of painted red dots also come from Hohle Fels (Conard and Malina, 2010, Conard and Malina, 2011, Conard and Malina, 2014, Conard and Uerpmann, 1999), and a painted limestone fragment with traces of pigment have been reported from the Geißenklösterle Aurignacian (Hahn, 1988). These artifacts document the range and wealth of ochre behaviors at these sites, and the presence of numerous other lithic and faunal elements suggest that the two caves were occupied intensively but intermittently throughout the Upper

Paleolithic (Niven, 2003, Conard and Moreau, 2004, Münzel and Conard, 2004, Barth, et al., 2009, Bataille and Conard, 2018, Taller, 2014, Taller and Conard, 2016).

2.3 Regions of study

The goal of our research presented here was to understand the numerous ochre artifacts from the Ach Valley sites (Hohle Fels, Geißenklösterle; Velliky, et al., 2018, Gollnisch, 1988) in the context of regional practices of procurement, use and discard, and to evaluate the potential for future provenance-based studies. With these scopes in mind, we mapped, described, sampled and performed NAA characterization on samples from potential ochre sources located in the region immediately surrounding Hohle Fels and Geißenklösterle caves. We investigated the Black Forest (or *Schwarzwald*), as this area has a known history of hematite mining extending back to the Neolithic *Linearbandkeramik* (LBK) cultural period (Goldenberg, et al., 2003, Schreg, 2009). Lastly, we analyzed ochres from the Harz Mountains and from Geyer-Erzgebirge in Thüringen, which were donated from older geological collections. In this section we provide some background information regarding the geology of these four areas.

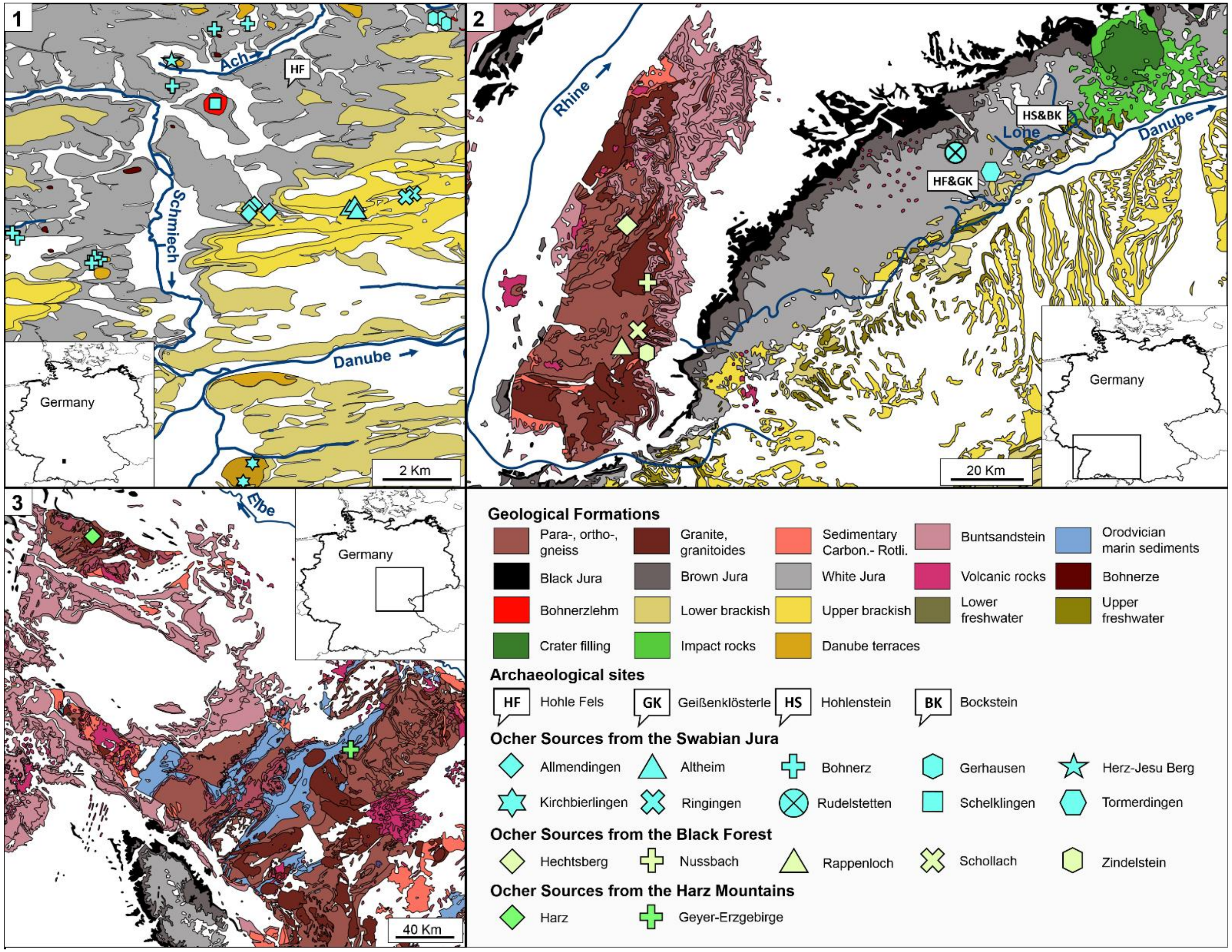

Fig. 1: Geological maps of southern and eastern Germany showing all ochre source areas analyzed in this study. *Sub-figs are as follows: A) Swabian Jura (local) sources, B) Black Forest (regional) ochre sources, as well as two sources (Rudelstetten and Tormerdingen) included in the Swabian Jura sources, C) Harz Mountain and Geyer (distant) ochre sources. Relevant Paleolithic cave sites in the Swabian Jura are also noted. Maps based on published data (Geyer and Villinger, 2001, Szenkler, et al., 2003, BGR, 2003), and field observations of the authors.*

2.3.1 Swabian Jura

The Swabian Jura (Fig. 1, detail A and B) is bounded by the Neckar Valley to the north, the Danube to the south, the Black Forest to the west and the Nördlinger Ries to the east. It is an extension of the larger Jura mountain range which extends into France and Switzerland. Previous geological (Borger, et al., 2001), geomorphological (Barbieri, et al., 2018), and archaeological studies (Schreg, 2009, Reinert, 1956, Reiff and Böhm, 1995), as well as local knowledge (V. Sach and R. Walter, personal communication, 2017) provided information on locations of known and potential sources. The bedrock is composed of Jurassic limestone comprising three main types: black, brown and white (*Schwarzer, Brauner,* and *Weißer Jura*) (Geyer and Gwinner, 1991, Schall, 2002). Marls, mudstones and sandstones also occur, as well as molasse and volcanic rocks formed during the Miocene (Barbieri, et al., 2018, Geyer and Gwinner, 1991). Numerous karstic features are found in the landscape, including the caves, which often hold archaeological materials (Barbieri, et al., 2018, Miller, 2015). Remnants of Tertiary sediments are found throughout the karstic features and dry valleys; of these, the *Bohnerze* and associated *Bohnerzlehm* formations are perhaps the most relevant in regard to possible Fe-oxide sources. *Bohnerze* (sing. *Bohnerz)*, or "bean ore", are highly compacted pebbles of goethite and hematite, formed by iron precipitating through limestone and accumulating in karstic fissures (Borger, et al., 2001, Ufrecht, 2008). *Bohnerzlehm* (bean ore clay) occurs with the *Bohnerze* and is an iron-rich kaolinite clay (Borger, et al., 2001, Ufrecht, 2008). These features once formed a large sheet across the Swabian Jura (Borger, et al., 2001), and remnants of this formation were a focal point for survey in this region. Other geomorphological studies in the Swabian Jura report lateritic materials and hematite-rich lateritic pebbles, limonite crusts and iron concretions in sandstones, and deeper hematite-containing horizons associated with Upper Jurassic deposits (Borger, et al., 2001).

2.3.2 Black Forest

The Black Forest (Fig. 1, detail B) is one of the oldest and most geologically complex regions in Germany with a total area of around 6,000 km^2 (Walter, et al., 2017, Markl, 2016, Murad, 1974, Stober and Bucher, 1999, Brockamp, et al., 2003). The bedrock consists of granite and gneiss formed during the Paleozoic with later Triassic Magmatite inclusions (Stober and Bucher, 1999). The overlying rock is predominantly red sandstone formed during the Rotliegend period, though other metamorphic and sedimentary varieties occur. Here, hematite forms in hydrothermal veins with low contents of non-ferrous metals and Fe-oxides are also found in the exposed red sandstone features (Brockamp, et al., 2003). So far, it has been established that the hydrothermally formed hematite was mined from the Neolithic period to the Middle Ages (Goldenberg, et al., 2003, Schreg, 2009).

Though Alpine Glaciers did not completely cover the Black Forest around the time of the Last Glacial Maximum (LGM), around 30 ka BP, the southern portion saw intermittent glaciation during the Würm stadials and interstadials and thus confirmed our decision to focus on the areas that were accessible before and after the LGM (Ivy-Ochs, et al., 2008, Litt, et al., 2007, Schlüchter, 1986).

2.3.3 Harz Mountains

The Harz Mountain range (Fig. 1, detail C) extends across the German states of Lower-Saxony (*Niedersachen*), Saxony-Anhalt (*Sachsen-Anhalt*), and Thuringia (*Thüringen*). Their formation is the result of intensive folding during the Paleozoic era followed by tectonic uplifting during the Cretaceous. Much of the overlying layers were eroded and the remaining base rock is what forms the mountains today (Sano, et al., 2002, Brink, 2011, Ullrich, et al., 2011). Though it is quite geologically diverse, common rock types include Gabbro (which is still extensively mined today), granite, limestone, and shale, to name a few. The Harz Mountains have a history of ancient mining activities (mainly Pb but also Ni and Fe) extending back to the Iron Age (Ullrich, et al., 2011, Matschullat, et al., 1997, Voigt, 2006, Kaufmann, et al., 2015). The Fe-oxide formations here are varied and include iron-rich sandstones associated with the larger *Buntsandstein* formation, hydrothermal hematite veins occurring along granitic rocks, and early Jurassic ooidal iron stones formed by early marine deposits (Sano, et al., 2002, Ullrich, et al., 2011, Kaufmann, et al., 2015, Nadoll, et al., 2018, Young, 1989, Dreesen, et al., 2016), the latter of which constitute the samples analyzed in this study.

2.3.4 Geyer (Erzgebirge)

Geyer is a town located in the *Erzgebirgekreis* district in Saxony (*Sachsen*), Germany. It is part of a larger formation extending into Bohemia and was formed by the Variscan Orogeny during the late Paleozoic. The geological basement is mainly formed of medium to high-grade mica schists and gneisses (Seifert and Sandmann, 2006, Daly, 2018). The region is well-known for its extensive silver and tin deposits which were mined extensively in the 13th century, but were known as far back as the Bronze Age (Müller, et al., 2000, Scheinert, et al., 2009). These ores are present in hydrothermal polymetallic veins throughout the landscape and include iron, copper, lead, and iron and manganese oxides (Seifert and Sandmann, 2006, Tischendorf and Förster, 1994). It is for these metallic vein formations that the Erzgebirge is also referred to as the "Ore Mountains" (Daly, 2018, Scheinert, et al., 2009). Both the Harz Mountains and Geyer-Erzgebirge were ice-free during the late Pleistocene exhibiting a largely treeless tundra-based environment (Ivy-Ochs, et al., 2008).

3. Materials and methods

3.1 Sample selection and description.

We conducted surveys in Swabian Jura and Black Forest in summer and early autumn of 2017, using archaeological and GPS equipment provided by the University of Tübingen. Ochre samples from the Harz Mountain and Geyer sources (Fig. 1, detail C) were donated from older private collections. As such, no physical surveys were conducted in this region. Fig. 1 displays a map with the source locations.

To clarify terminology, we use *ochre source* and *Fe-oxide source* interchangeably to refer to specific locations where these materials were collected. *Source regions* refer to the large-scale areas where several outcrops were mapped, such as the Black Forest or the Swabian Jura, and *sub-sources* or *outcrops* refer to specific confined points where samples were gathered. The materials that we collected and analyzed in this study are referred to as *ochre samples* or *specimens.*

For the Swabian Jura, we focused our survey on a ca. 20 km radius of Hohle Fels and Geißenklösterle caves (Fig. 1, detail A and B), since this region might have been easily accessed by the hunter-gatherers that populated the Ach Valley during the Pleistocene. Within this area we mapped 17 ochre outcrops, collecting 106 samples. At a further distance from this area (ca. 60 km from Hohle Fels), we analyzed samples from the Rudelstetten (Rudel) ochre source which were generously donated to the study by R. Walter. For the scope of this paper we consider all these sources as "local" (<80 km from the Ach Valley).

Additionally, we surveyed the northern and central areas of the Black Forest (Fig. 1, detail B), due to its proximity to the Swabian Jura (ca. 115 km) and knowledge and advice from geologists working in the region at the University of Tübingen (U. Neuman, personal communication, 2017). In these areas, we collected 46 ochre samples from 5 different outcrops. The amounts we collected from each outcrops varied depending on its size: Rappenloch (Rappen), for example, was a large deposit and we collected 22 different samples from a total area of ca. 400 m. We consider these outcrops as "regional" ochre sources (80-300 km from the Ach Valley).

Lastly, we analyzed two ochre nodules which were donated from older geological collections. The specimens come from two locations: one from the Harz Mountain range, and another from the locality of Geyer-Erzgebirge in Saxony (Fig. 1, detail C). For the aim of this paper we regard these samples as distant ochre sources (>300 km).

All sampled outcrops were photographed and described either during or post-survey. For the fine-fraction we reported color (Munsell Soil Color Book 2009), texture (by "feel" Vos, et al., 2016), and cohesion (USDA-NRCS, 2012). For the coarse fraction we documented shape (Zingg, 1935), roundness (Powers, 1953), and size (ISO 14688-1:2002 standard). We described also cohesion (USDA-NRCS, 2012) and color (Munsell Soil Color Book 2009) of iron nodules and concretions. When possible, we described also stratigraphy and bedding of the sources.

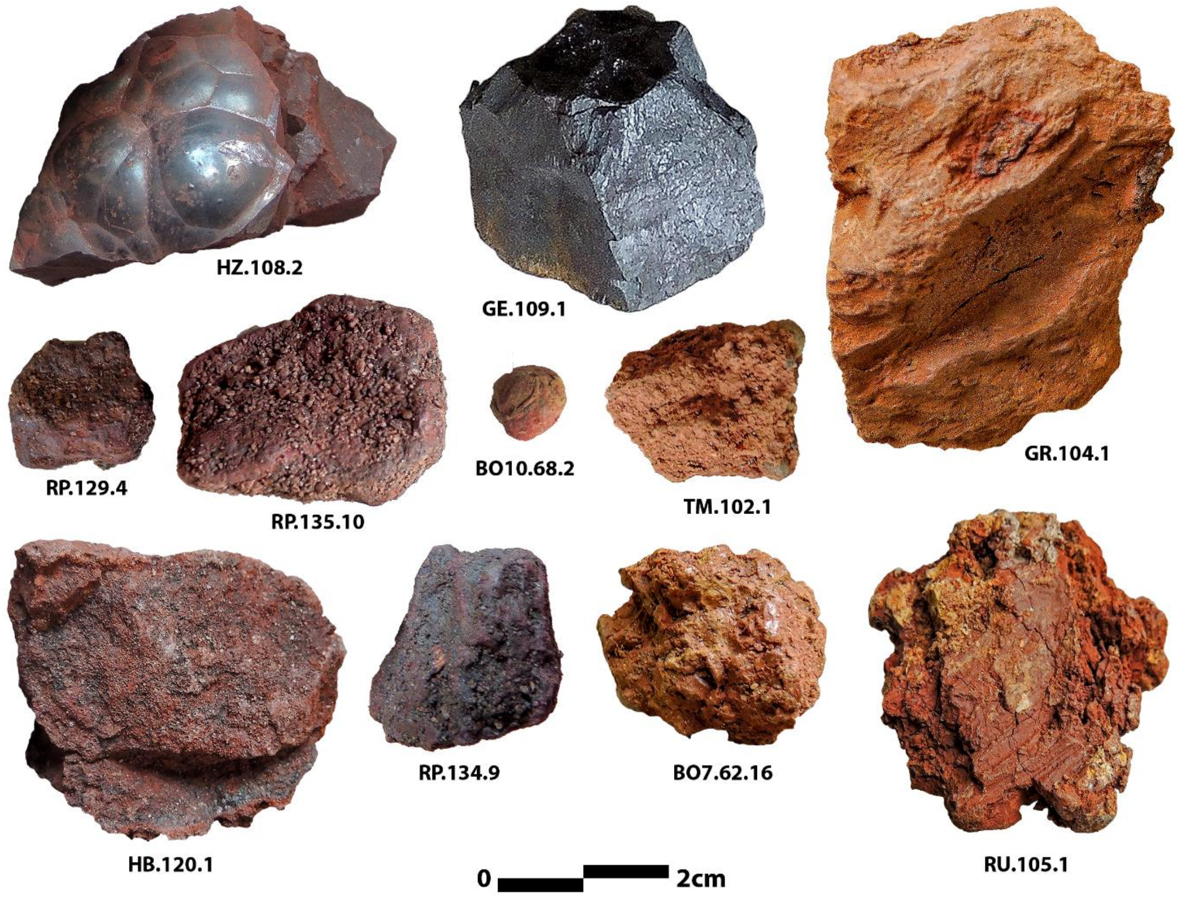

Fig. 2: Ochre samples from each of the regions analyzed. *Selected analyzed samples from all investigated regions. Sample ID's correspond to SI Table C. HZ and GE labels are Harz Mountain samples, RP and HB are Black Forest specimens, and GR, BO, TM, and RU are Swabian Jura samples.*

3.2 Neutron Activation Analysis (NAA)

We characterized the ochre samples from the Swabian Jura, Black Forest, and Harz regions using Neutron Activation Analysis (NAA), with several sub-samples being taken from individual source samples to evaluate intra-source variation. In total, we performed measurements on 83 sub-samples from the Swabian Jura ochres, 46 on the materials from the Black Forest, and 10 on the samples from the Harz region. Table 1 shows a breakdown of the number of NAA measurements sorted per source region and outcrop.

All NAA measurements were conducted at the Archaeometry Laboratory in The University of Missouri Research Reactor (MURR) using standard procedures described in greater detail elsewhere

(MacDonald, et al., 2018, Popelka-Filcoff, et al., 2008, Eiselt, et al., 2011). Two thermal neutron irradiations were conducted to collect data on elements that produce short-, medium-, and long-lived radioisotopes. Ochre samples and standard reference materials in polyvials were irradiated via pneumatic tube system for 10 s at a flux of 8 X 10^{13} n cm^{-2} s^{-1}. Samples were each allowed to decay for 25 minutes, at which point gamma ray energies for elements that produce short-lived isotopes (Al, Ba, Ca, Dy, K, Mn, Na, Ti, and V) were measured by a hyper-pure germanium detector (HPGe) for 12 min. The quartz encapsulated samples were subjected to a 24–hour irradiation at a neutron flux of 6 x 10^{13} n cm^{-2} s^{-1}. After a 7-10 day decay, the radioactive samples were measured for 2000 s to obtain data on medium-lived isotopes (As, La, Lu, Nd, Sm, U, and Yb), and again after 2-3 weeks for 8200 s to measure for long-lived isotopes (Ce, Co, Cr, Cs, Eu, Fe, Hf, Ni, Rb, Sb, Sc, Sr, Ta, Tb, Th, Zn, and Zr). The spectral data were calculated to elemental concentrations using in-house software and calibrated to NIST standard reference materials by comparator method. These analyses generated elemental concentration values for 33 elements in most of the samples analyzed.

Table 1: List of samples measured with NAA sorted by region and ochre source.

Swabian Jura (n = 83) *Local <80 km*		Black Forest (n = 46) *Regional 80-300 km*	Harz Mountains (n = 10) *Distant >300 km*
Allmendingen (n=12)	Kirchbierlingen (n=1)	Hechtsberg (n=9)	Geyer-Erzgebirge (n=5)
Altheim (n=10)	Ringingen (n=5)	Nussbach (n=5)	Harz (n=5)
Bohnerz 1-8 (n=27)	Rudelstetten (n=5)	Rappenloch (n=22)	
Gerhausen (n=5)	Schelklingen (n=8)	Schollach (n=5)	
Herz-Jesu Berg (n=5)	Tormerdingen (n=5)	Zindelstein (n=5)	

4. Results

4.1 Source Description

4.1.1 Swabian Jura

4.1.1.1 Allmendingen

In a section exposed within a quarry located some 5 km south of the town of Schelklingen (Fig. 1, detail A), we distinguished three main sedimentary units (SI Fig. D). The upper most unit corresponds to the modern soil, below this we distinguished a ca. 60 cm thick layer composed of triaxial to oblate, sub-angular to angular, fine gravel- to boulder-sized fragments of limestone embedded in brown silty clay. Underneath this sediment, we documented a possible molasse deposit, which appeared at least 2 m thick and was composed of triaxial to oblate, well-rounded, fine gravel- to cobble-sized fragments of limestone, marls and sandstones. The coarse fraction exhibited upwards fining and often appeared coated with a thin (<1 mm thick) very dusky red to dark red crust of iron--manganese oxides. The fine fraction (clayey sand to silty clay) was very dense and exhibited alternating red and yellowish-brown colors, and cemented the coarse fraction together. Based on the alternating colors of the matrix and difference in grai n size, it was possible to distinguish cross-beds. All over the ground surface within the quarry, we noticed red to yellowish-red sandy clay to clay outcrops. We characterized representative samples of all the “red clays” documented in this source with NAA.

4.1.1.2 .Altheim

In a quarry located about 4 km south from Hohle Fels (Fig. 1, detail A), we documented three sections, each down to ca. 3 m deep. Below the ground surface, the entire exposed sequence consisted of cross-bedded molasse deposits, which are mainly made from loose, dark yellowish-brown to light yellowish-brown sand and silt. Both sand and silt fractions appeared very rich in micas. Coarse fraction appeared rare and was composed of triaxial, sub-rounded to well-rounded, fine to medium gravel of limestone, sandstone, quartz, and dolomite. The Altheim deposits exhibited numerous reddish greygray to strong brown discontinuous laminations. These laminations appeared from only a few millimeters to ca. 20 cm thick, and within the latter we identified prolate, sub-angular, up to medium gravel-sized, very dense and strong brown iron nodules. Furthermore, the sandstone and limestone fragments buried inside these iron-stained laminations appeared extensively impregnated with iron oxides. We also collected and characterized a sample of these sandstones with NAA.

4.1.1.3 Bohnerz (1-8)

On top of the plateau and along the hillsides in the surroundings of Hohle Fels cave w e mapped 8 *Bohnerz* sources (Fig. 1, detail *Bohnerz 1-8*). These sources correspond to *Bohnerz* nodules embedded in various sediments, and were visible in exposures and depressions resulting from forestry road construction, historical mining activities, tree fall, and natural erosion. *Bohnerz* nodules appear as triaxial to equiaxial, sub-angular to sub-rounded, fine gravel- to cobble-sized, very dense iron concretions. Smaller *Bohnerz* (up to medium gravel sized) are usually made from single individual grains, while larger *Bohnerz* can be composed of many individual grains cemented together. The color of *Bohnerz* varies from black, reddish black, very dusky to dark yellowish brown (see Table C in SI).

The loose sediment in which *Bohnerz* nodules are buried displays high variability, even within each single source (SI Fig. E). The fine fraction exhibits discontinuous texture (from clayey silt to clay), and color (from yellowish brown, to dark brown, and red). In most of these sediments, *Bohnerz* nodules occur as the main (or only) coarse fraction components. However, in the source *Bohnerz* 4 we documented the presence of weathered, triaxial, sub-angular, medium to coarse gravel-sized fragments of limestone, and in *Bohnerz* 3 and 5 we identified fresh, triaxial, angular, fine gravel-sized fragments of limestone generally smaller than 1 cm in diameter (this sediment type is also known in the region as *Bergkies*, see Barbieri, 2019).

4.1.1.4 Gerhausen

From this quarry (Fig. 1, detail A) we received a large aggregate of nearly pure, well sorted, compact, red clay, which we subsampled for with NAA. The sample was collected by R. Walter ca. 3 m below surface during mining activities, and appears to be part of a larger *Bohnerzlehm* formation with some larger, sub-rounded *Bohnerz* nodule inclusions (Fig. 5, detail 1).

4.1.1.5 Herz-Jesu Berg

On top of the hill Herz-Jesu Berg (Fig. 1, detail A), located in the town of Schelklingen, we mapped *Bohnerz* outcrops that were visible in exposures resulting from the construction of forestry roads. We decided to consider the *Bohnerz* from Herz-Jesu Berg as a separate source since they display slightly different colors (dark reddish brown to very dark brown) than those from the other *Bohnerz* sources. Furthermore, they have been buried together with weathered, triaxial and oblate, poorly sorted, well-rounded, medium and coarse gravel-sized limestone fragments.

4.1.1.6 Kirchbierlingen

From the Pleistocene-aged terraces located ca. 5 km south from the present day course of the Danube River (Fig. 1, detail A) we report the occurrence of rare, very dense, triaxial, sub-rounded, fine gravel- to medium gravel-sized, very dark gray to black hematite concretions. We investigated one of these concretions with NAA. These hematite fragments were visible as surface finds in recently ploughed fields (yellowish brown, silty clay), where they occur together with triaxial, sub-rounded to well-rounded, poorly sorted fine to coarse gravel of limestone, sandstone, quartz, feldspar and dolomite.

4.1.1.7 Ringingen

In a quarry located some 6 km south east from Hohle Fels cave (Fig. 1, detail A), we investigated two, ca. 8 m deep, exposed sections. These sequences display composition, color, and structure generally comparable to the deposits described at Altheim. However, at Ringingen, reddish grey to strong brown laminations appear more continuous and thicker (up to 50 cm), especially 2 m below the ground surface. We collected well-sorted loose samples from these features for characterization with NAA.

4.1.1.8 Rudelstetten

These samples of compacted dusky-red clay were collected by R. Walter from an exposure located on outskirts of the small town of Radelstetten, located ca. 18 km northeast of Hohle Fels and situated in the larger White Jura formation (Fig. 1, detail B). The sample is a fine-grained clay to silty-clay (Bohnerzlehm) with very few small (< 1 cm) Bohnerz inclusions.

4.1.1.9 Schelklingen

In 2 sections exposed in limestone quarry located ca. 1 km south from the town of Schelklingen we mapped a laterally discontinuous *Bohnerzlehm* deposit composed of triaxial, poorly sorted, angular medium gravel-sized to cobble-sized weathered fragments of limestone embedded in a loose, red to yellowish brown, clayey sand to silty clay (Fig. 1, detail A; Fig. 5, detail 2). This deposit rests in between the modern soil and the limestone bedrock, and it appears up to 2 m thick. Due to the quarrying activity it was not possible to verify further its structure.

4.1.1.10 Tormerdingen

A large clay block was donated to us by R. Walter from this ochre outcrop, which is situated in the larger White Jura formation that extends to the northeast of Hohle Fels (Fig. 1, detail A). As such we do not discuss its original stratigraphic context. The sample itself is a fine-grained clayey sand to silty clay (*Bohnerzlehm*) with <1 cm pebble-sized inclusions of *Bohnerz* nodules (Fig. 2).

4.1.2 Black Forest

4.1.2.1 Hechtsberg

Located in between the towns of Haslach (to the west) and Hausach (to the east), Hechtsberg is an active quarry mainly of biotite-bearing gneisses (Fig.1, detail B). Here, we documented a 4 m deep north-facing granite exposure (ca. 50 m east-west) bearing weathered iron-oxide veins on the profile. From this section, we sampled several triaxial hematite fragments which were generally sub-rounded, showing fine-grained sand to silty textures and ranging from reddish black to very dusky red in color.

4.1.2.2 Nussbach

On a hillside north of Nussbach (Fig. 1, detail B), from where reports cite the occurrence of hematite and quartz associated with granitic porphyries (Leiber, 2000), we identified and sampled a small (ca. 1 x 1.5 m) section exposed due to construction activities. Along this section, ca. 1 m below the modern-day surface, we distinguished a Fe-oxide deposit compared of sub-angular pebble to cobble sized fragments of granite and quartz embedded in a moderately sorted matrix of loose, dark red sand and clay. In this sediment we also identified semi-compacted sub-angular and rounded pebble-sized red to dark red iron-rich nodules. The size of the exposure limited extensive sampling of this source.

4.1.2.3 Rappenloch

The Rappenloch source is a former mine located in the town of Eisenbach in the "Hochschwarzwald" or High Black Forest (Fig. 1, detail B). The area was mined for Fe and Mn deposits in mineralized fissures within granitic outcrops. The mine closed in 1942 and has since experienced significant overgrowth and revegetation (SI Fig. G). In this quarry we sampled several small pits and exposures ranging from depths of ca. 30 cm – 60 cm along the southern and western faces of the hill totaling ca. 400 m in length. These exposures showed mostly dark red to reddish-black medium-densely packed sand with sub-angular and sub-rounded pebble to cobble-sized fragments of granite. We also sampled from an exposed profile (ca. 50 cm - 1.5 m) near the bottom of the former mine, showing a dusky to very dusky red, predominantly clay-based and relatively well-sorted sediment capped with medium to coarse grained sand with some sub-angular and angular sandstone fragments.

4.1.2.4 Schollach

We identified a discontinuous outcrop on a small hillside located ca. 2 km southeast of the town of Schollach (Fig. 1, detail B), which was exposed due to road construction activities. The outcrop (ca. 2 x 1.5 m) consisted of dark reddish brown to weak red loosely compacted and moderately sorted sandy-clay with a low amount of pebble and cobble-sized sub-angular and sub-rounded gravel-sized fragments of calcic silicate rocks (SI Fig. H).

4.1.2.5 Zindelstein

In the Breg valley near the town of Hammereisenbach (Fig.1, detail B), we sampled one exposed outcrop in an abandoned granite and gneiss quarry with hydrothermal veins containing fluorite, graphite, quartz and feldspars. The amount of erosion and overgrowth made it difficult to properly map certain exposures, and we thus focused on one location with a ca. 2 m high wall and

30 m long (east-west) wall. The analyzed samples come from dark reddish-brown well-sorted iron-rich clay aggregates forming in fissures within the granite outcrops.

4.1.3 Harz and Geyer-Erzgebirge

4.1.3.1 Geyer-Erzgebirge

One large densely compacted ironstone was donated to the study from an older geological collection. This single piece from the "Ore Mountain" region near the town of Geyer (Fig.1, detail C) is a silty dark reddish gray and produces a very dusky red streak; though the exact stratigraphical context cannot be described, it was likely formed as a mineral deposit in hydro-thermal veins common to the region.

4.1.3.2 Harz Mountains

Pieces of botryoidal ironstone from the Harz Mountain region (Fig.1, detail C) were donated for the study from older geological collections, one of which we sub-sampled and characterized with NAA. The analyzed piece was a densely compacted silty dark reddish-gray ironstone producing a dark red streak and showing *Glaskopf* or "kidney ore" morphology (Fig. 2).

4.2 NAA results

In total, 139 ochre survey samples were characterized by NAA. Elemental concentration data is provided in SI Table G with means and standard deviations shown in SI Tables A-B, as well as more detailed descriptions of specific elemental characteristics from each ochre source.

4.2.1 Statistical exploration of data

Because the iron content can vary significantly, and that variability can artificially amplify or dilute the presence of other diagnostic trace elements, it is often advantageous to convert all elemental concentration values to a ratio of iron content (Fe-normalization). It is also useful in circumstances where the Fe-oxide deposits may have undergone significant weathering and subsequent elemental substitution. The atomic structural similarity of some transition metals and rare earth elements (REEs) to iron readily permits their substitution into Fe-oxide structures (Cornell and Schwertmann, 2003). Therefore, the data were transformed prior to statistical testing with Fe-normalization and log10. Both of these transformations are used to compensate for the variation in magnitude between major, minor, and trace elements, and are necessary for scale-dependent, multivariate discriminant statistics (e.g. PCA) (Dayet, et al., 2016, MacDonald, et al., 2013, Popelka-Filcoff, et al., 2007, Popelka-Filcoff, et al., 2008, MacDonald, et al., 2011). However, it is important for such data transformations to be assessed for their efficacy before considering those values as statistically representative. In our statistical exploration, including iterative bivariate plotting (element concentrations, log10 Fe-normalized ratios), PCA and CDA, we consistently found that using data transformed to ratios to Fe content, and subsequently transformed to log 10 values generated the clearest separation of source groups.

Element-pair bivariate plotting did not yield clear separation for most ochre source groups and was minimally informative (see supplementary text: Results). Both PCA and CDA showed the same degree of group separation when all sources are plotted together (Fig. 3; SI Fig. C). Here, we show results of CDA, performed on log10 Fe-normalized values for all possible elements (Sm/Fe, Ce/Fe, Sc/Fe, La/Fe, U/Fe, Sb/Fe, Cr/Fe, As/Fe; all others excluded due to excessive zero values). Fig. 3 is a bivariate plot of CD#1 versus CD#2, showing the distribution of sources highlighted by region. CD#1, which accounts for 70.0% of the variance, is driven primarily by elements Sm (-1.36) and Eu (1.36), while elements driving CD#2 (16.1% variance) are Sm (-1.10), Eu (1.39), and Sc (-0.56). Table 2 shows the relevant CDA data for Figs 3 and 4, but all CDA scoring coefficients and discriminant functions are provided in SI Tables E-F. Because CDA tends to maximize inter-group variation, the separation of sources by region is particularly accentuated. The variation in the Swabian Jura sources is significantly minimized, suggesting that all groups share similar geochemical characteristics. The Harz Mountain sources are differentiated from other regions, and the CDA projection shows stronger separation between the Black Forest sources, suggesting a high degree of chemical variability within and between sources in that region. The distant ochre sources consistently associated with each other, and are therefore collectively labeled as the Harz Mountain sources. The Rappenloch source, located in the Black Forest, showed high heterogeneity with certain samples, likely due to their varying Ba content. Based on this, we made the decision to project these as separate “Rappen” and “RappenB” groups in Fig. 3.

To further investigate if the Swabian Jura sources can be differentiated, a subsequent CDA was conducted on a sub-set of only Swabian Jura sources. Fig. 4 is a bivariate plot of CD#1 versus CD#3, showing separation of most Swabian Jura sources. Here, CD#1 accounts for 38.5% of the variance and is driven by Sm (-0.35) and Eu (-0.27). CD#3 accounts for 20.5% of the variance and is driven primarily by elements Sm (1.37), Eu (-0.94) and Nd (-0.53) (SI Table F) These results further highlight regional and sub-regional scale variability in ochre sources. When all sources in all regions were included, Black Forest and Harz Mountain sources could be reasonably differentiated, however, the Swabian Jura samples exhibited consistent overlap (see Fig. 3). When Black Forest and Harz Mountain sources were removed and a new CDA was performed, the Swabian Jura sources were more readily separated. These results suggest the potential for a moderately consistent internal elemental signature, which indicates promise for future local versus non-local artifact provenance investigations.

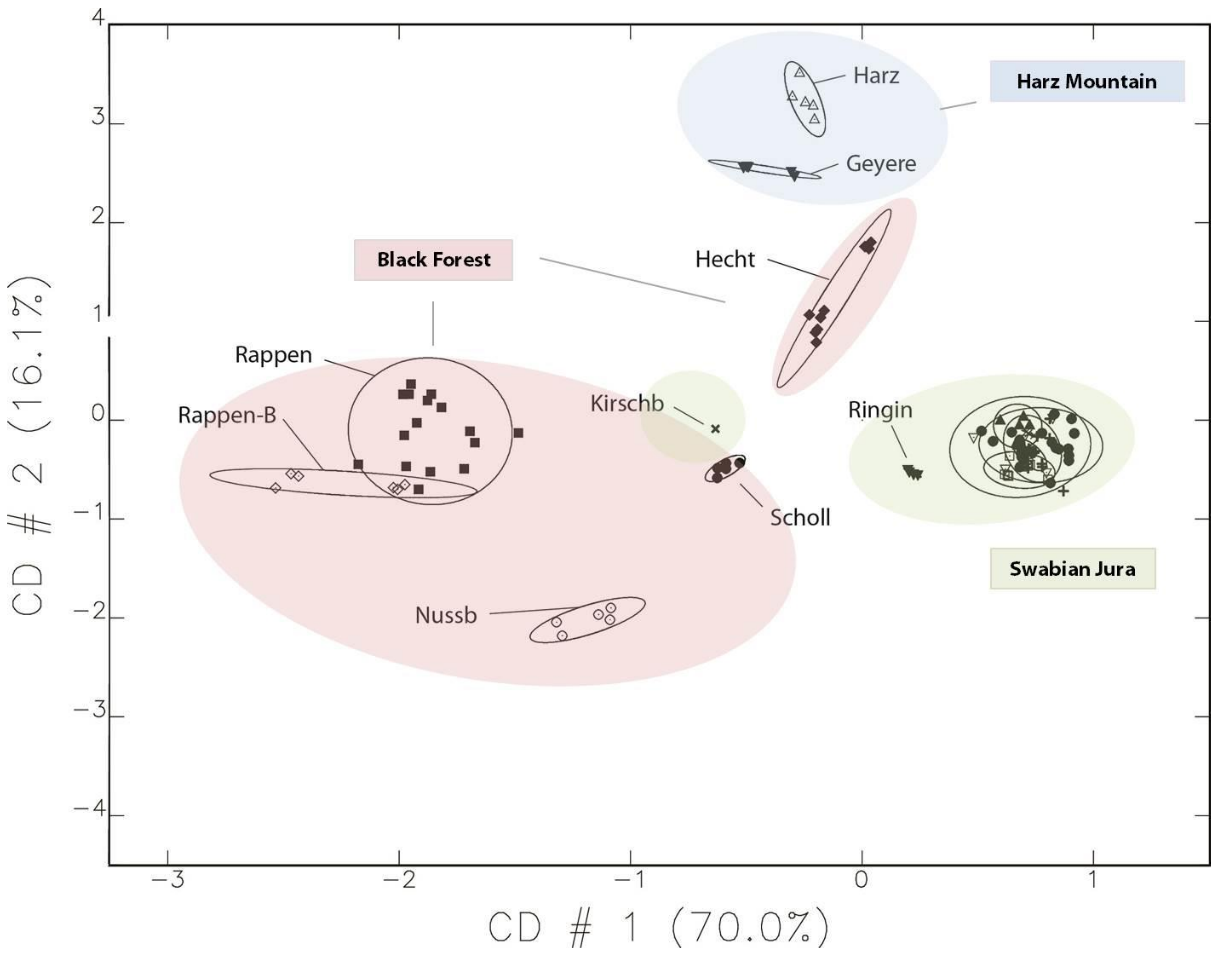

***Fig. 3: Bivariate plot of CD#1 versus CD#2 for all sources, highlighted by region**. Note how most Swabian Jura groups overlap. Harz Mountain sources are significantly different, while Black Forest sources exhibit the widest distribution at both source and sub-source levels. Ellipses are drawn at 90% confidence.*

5. Discussion

5.1 Ochre source characterization

Previous research has demonstrated the potential for ochre provenance by bulk elemental analysis (Dayet, et al., 2016, MacDonald, et al., 2013, MacDonald, et al., 2018, Popelka-Filcoff, et al., 2008, MacDonald, et al., 2011, Kingery-Schwartz, et al., 2013, Zipkin, et al., 2017, Eiselt, et al., 2011, Pradeau, et al., 2015). The results of this study are consistent with other research in demonstrating that it is possible to differentiate ochre sources and sub-sources based on elemental chemistry, when interpreted using a combination of stepwise, multi-element statistical approaches.

From the Swabian Jura, the *Bohnerzlehm* sources of Gerhausen, Rudelstetten, Schelklingen, and Tormerdingen consistently group together in both bivariate (SI Figs. A-B) and multivariate (SI Fig.

C) projections, and exhibit the highest amount of Al (>10%, Table A in SI). This association and elemental composition is likely indicative of clay-based minerals (possibly kaolinite), which are commonly reported from *Bohnerzlehm* deposits (Borger, et al., 2001, Ufrecht, 2008). Most of our *Bohnerz* samples display high variability but, as a whole, tend to overlap with the *Bohnerzlehm* specimens (Fig. 4; SI Figs. A-C). This could be due to the fact these sources formed in the same region and likely in similar environment(s) (Borger, et al., 2001, Ufrecht, 2008). In the field, we distinguished the source of Herz-Jesu Berg from the other *Bohnerz* outcrops as it contained rounded gravel inclusions, indicative of fluvial deposition. By comparing the elevation of this outcrop with river terraces reported from Schmiech, Ach, and Blau valleys, we hypothesize that this sediment accumulated by the Danube River in the Early Pleistocene (Geyer and Villinger, 2001, Szenkler, et al., 2003, Kaufmann and Romanov, 2008). In bi-elemental comparisons (SI Figs. A-B), the Herz-Jesu Berg *Bohnerz* samples tend to plot with the larger *Bohnerz* group. However, when observed using CDA (Fig. 4), Herz-Jesu Berg samples separate from the other *Bohnerz* sources. This difference may be due to the fact that the *Bohnerz* fragments from Herz-Jesu Berg might have been eroded from formations located several tens of kilometers away from the Ach Valley. Samples from the molasse deposits of Allmendingen and Ringingen appear separated and distinct form *Bohnerzlehm* and *Bohnerz* sources when observed with multivariate statistics (Fig. 4). They contain Al (ca. 3%, Table A in SI) and exhibit comparatively high concentrations of K (1.5 % to 3%, Table A in SI). This composition might indicate the presence of kaolinite and illite clays, the latter likely deriving from the weathering of micas that are abundant in molasses deposits. In our bivariate plots, it was not always possible to differentiate Kirchbierlingen from Ringingen, or even from the Black Forest sources. This may be because Kirchbierlingen corresponds to a Pleistocene-aged Danube terrace made from components eroding from granites located in the Alps and molasse deposits located in the Swabian Jura (Geyer and Villinger, 2001, Szenkler, et al., 2003).

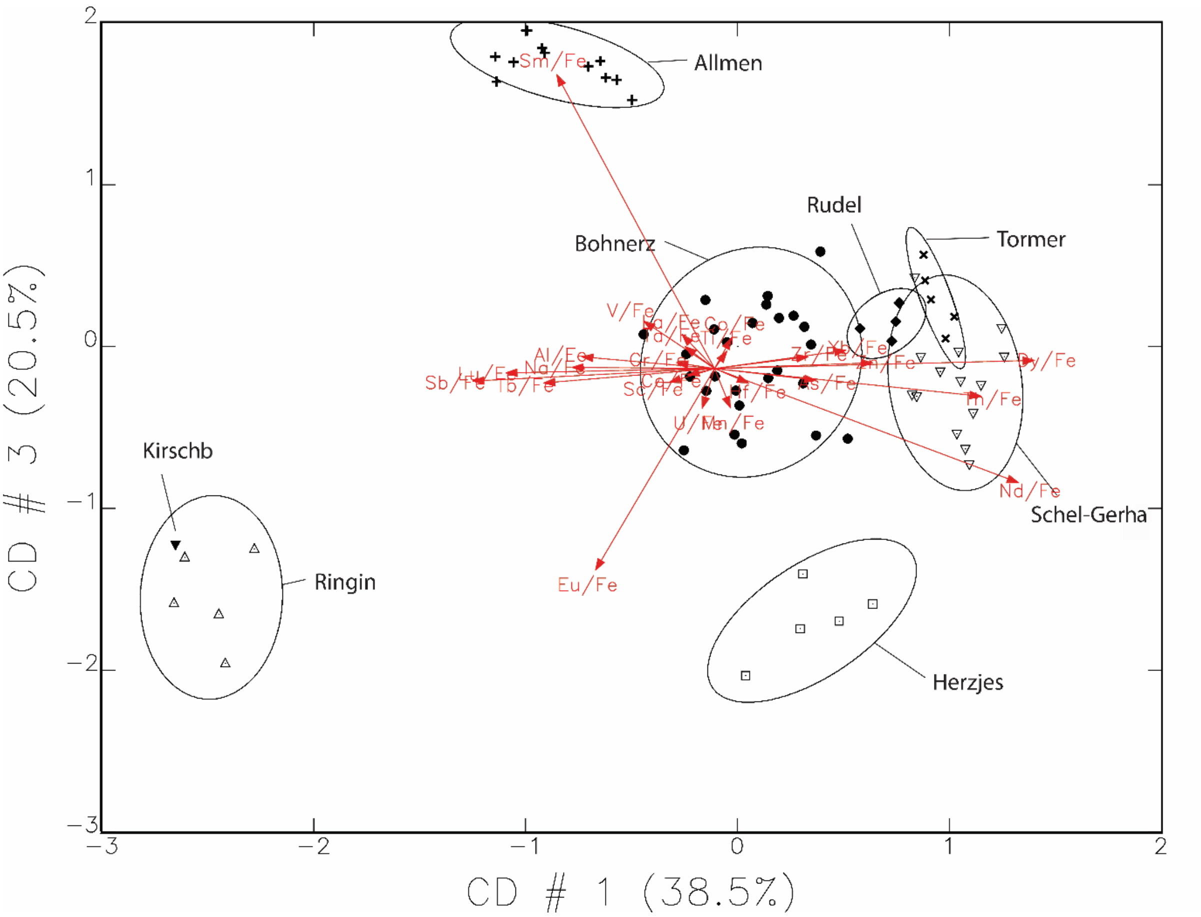

Fig. 4: Bivariate plot of CD#1 versus CD#3 for eight Swabian Jura sources. *Note that while the single Kirchbierlingen (Kirschb) sample falls within the ellipse of Ringingen source in this projection, it separates out in other CDA projections. Also note the similarity of the Bohnerz source group when projected with the other Swabian Jura source samples. Ellipses are drawn at 90% confidence.*

Table 2: Canonical discriminant functions and elemental contributions for CDA plots shown in Figs 3 and 4.

Fig. 3	**CD1**	**CD2**	**Fig. 4**	**CD1**	**CD3**
Variable	**70.08**	**16.10**	**Variable**	-0.351	1.370
Sm/Fe	-1.36	-1.10	**Sm/Fe**	-0.265	-0.939
Eu/Fe	1.36	1.39	**Eu/Fe**	0.677	-0.531
La/Fe	0.39	-0.50	**Nd/Fe**	0.292	0.086
Ce/Fe	0.06	0.35	**Yb/Fe**	0.712	0.038
Tb/Fe	-0.14	0.11	**Dy/Fe**	-0.464	-0.020
Sb/Fe	-0.79	0.61	**Lu/Fe**	-0.538	-0.058
Sc/Fe	-0.34	-0.56	**Sb/Fe**	-0.295	0.056
Cr/Fe	0.54	0.02	**Al/Fe**	0.593	-0.129
As/Fe	-0.07	-0.46	**Th/Fe**	-0.072	0.159
Mn/Fe	-0.16	-0.01	**La/Fe**	-0.100	-0.064
U/Fe	-0.28	0.13	**Sc/Fe**	-0.351	1.370

The Harz Mountain sources (both Harz and Geyer-Erzgebirge) exhibit high Fe and Sb values and separate from all Black Forest and Swabian Jura samples in the bivariate (SI Figs. A and B) and multivariate (Fig. 3; SI Fig. C) projections. Regarding the Black Forest sources, though the Rappenloch samples exhibited high variability due to the high amount of Ba present in some of the samples, they contained above average light REE concentrations. This may be due to the volcanic rock basic of the central Black Forest and the formation of these hematite veins in igneous rock exposures (Fleet, 1984, Humphris, 1984). The elemental heterogeneity of the Rappenloch source in the Black Forest is likely caused by localized instances of element mobility due to weathering (Cornell and Schwertmann, 2003, Pollard, et al., 2007, Shatrov and Voitsekhovskii, 2013, Babechuk, et al., 2014), the relative size of the exposure (ca. 400 m sampled for this project) and the numerous intensive metamorphic events in the geological history of the central Black Forest (Chen, et al., 2000). It should be stressed that the labels of the sources are place-names, and should not necessarily always be treated as the same compositional group when trends in elemental geochemistry strongly suggest otherwise. It is possible to have two different sub-sources (as indicated by the compositional groups, Rappen and RappenB) in one larger geographically confined source. It is also important to note that we were able to identify the variability within the Rappenloch source due to the number of samples we analyzed (n = 22). It is possible that with more extensive sampling of this source, as well as the other source analyzed in this study, other patterns of homogeneity or variability may emerge.

5.2 Further prospects: Investigating the environmental and geological processes responsible for variation in source accessibility

The Swabian Jura has witnessed intense environmental and climatic fluctuations throughout the Pleistocene, which promoted alternating phases of soil formation, river valley incision, hillside erosion and floodplain aggradation (Barbieri, et al., 2018, Barbieri, 2019). In this section, we explore the possibility of a causal link between these events and similar geomorphological processes and how they might have facilitated or impeded humans from accessing potential ochre sources.

Materials exhibiting composition, texture, color, and compaction comparable to the *Bohnerz* and *Bohnerzlehm* formations are common in the deposits preserved inside the cave sites of the Swabian Jura (Fig. 5, detail 2; Miller, 2015, Jahnke, 2013, Barbieri and Miller, 2019a). Micromorphological analyses conducted at Hohle Fels and Geißenklösterle in the Ach Valley revealed that aggregates made from compact, red, iron-stained clay occur with high frequency in deposits dating to the Middle Paleolithic and the late Aurignacian (Miller, 2015, Goldberg, et al., 2003). Results from semi-quantitative analyses conducted at Hohlenstein-Stadel cave in the Lone Valley, approximately 50 km northeast from Hohle Fels (Fig. 1, detail B), show that *Bohnerz* and kaolinite aggregates similar to those documented at Hohle Fels are more frequent in the sediments pre-dating the LGM (Fig. 5, detail 3; Barbieri, et al., 2018, Barbieri, 2019, Barbieri and Miller, 2019a, Barbieri and Miller, 2019b). These observations are in agreement with coring data from the Lone Valley where, from a depth of ca. 6 m, Barbieri (et al 2018, 2019) recovered a deposit (GL 315) made from compact, red kaolinite (with light reddish pale speckles), extensively impregnated with iron oxides (Fig. 5, detail 4). The core GL 315 may correspond to a *Bohnerzlehm* deposit that was reworked downslope into the Lone Valley by colluviation processes, possibly during the Early/Middle Pleistocene (Barbieri, 2019). Subsequently, GL 315 was incised by the Lone River and covered with a ca. 30 cm thick colluvial deposit that was remarkably rich in *Bohnerz* and iron-manganese nodules (GL 37-41, GL 266; Fig. 6, detail 4). This sediment yielded dates ranging between ca. 36-29 kcal. BP (Barbieri, et al 2018, 2019). The sediments resting on top of GL 37-41 and GL 266 contained very rare components which exhibited texture, composition, structure and color comparable with the *Bohnerz* and *Bohnerzlehm* formations (Fig. 6, details 2 and 4). Thus, we conclude that the outcrops of these formations were likely more visible in the landscape of the Swabian Jura (and potentially exploited for ochre use) during their more intensive erosional phase before 29 kcal BP. This hypothesis, though speculative, has the potential to be validated with future analyses.

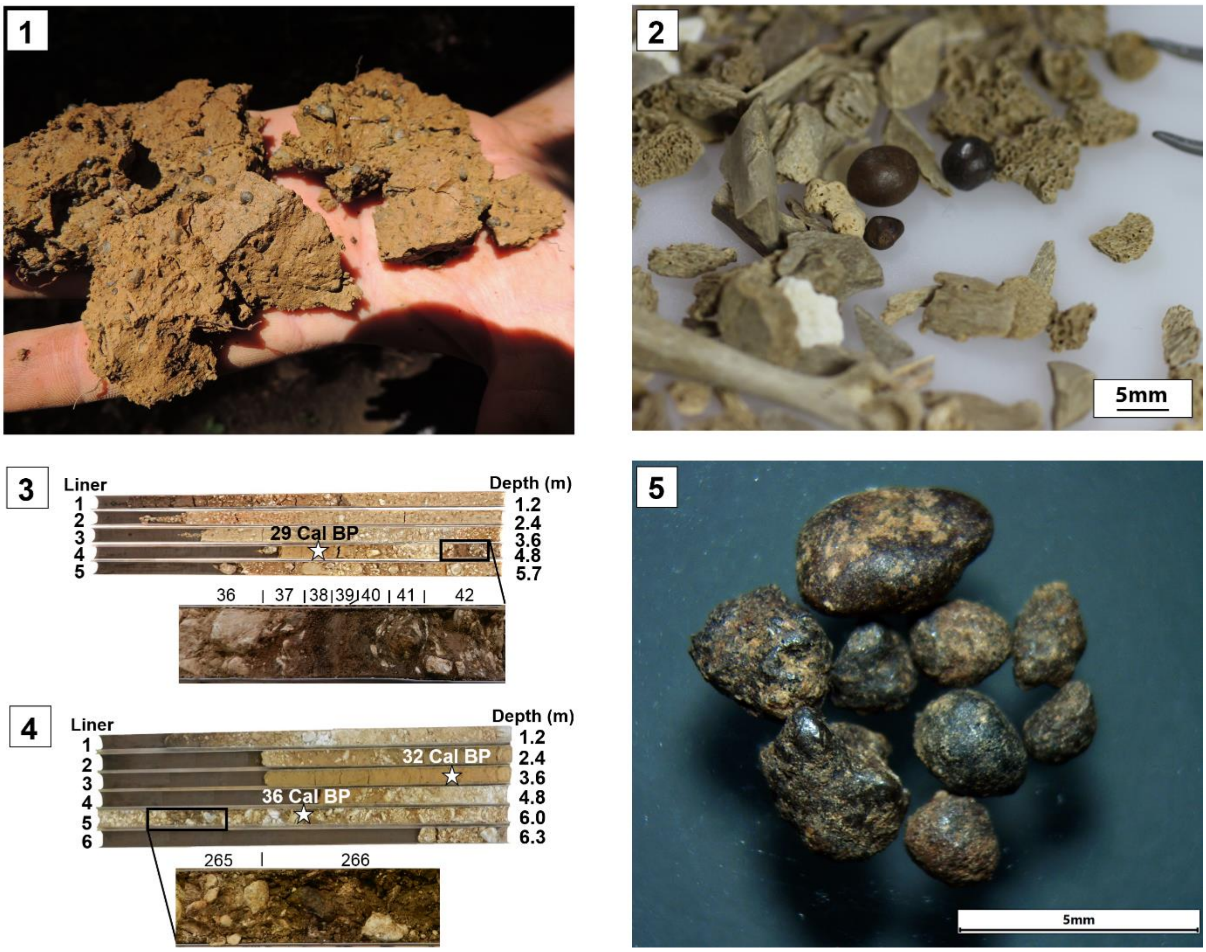

Fig. 5: Bohnerz from the Swabian Jura. *1) Sediment aggregates containing Bohnerz fragments, photo taken during Swabian Jura survey; 2) Larger Bohnerz fragments identified during sorting of archaeological material excavated at Hohle Fels (photo: Maria Malina); 3) Core 12 drilled in the Lone Valley opposite from the Hohlenstein caves. The detail shows the deposits GL36-GL42, which appear rich in Bohnerz and display an extensive iron-manganese impregnation of both fine and coarse fraction; 4) Core 31 drilled in the Lone Valley downslope from the Bockstein caves. The detail show GL 266, which is very close in composition to GL36-42 (modified from Barbieri, et al. 2018, Barbieri, 2019), and; 5) Detail of Bohnerz fragments from GL42.*

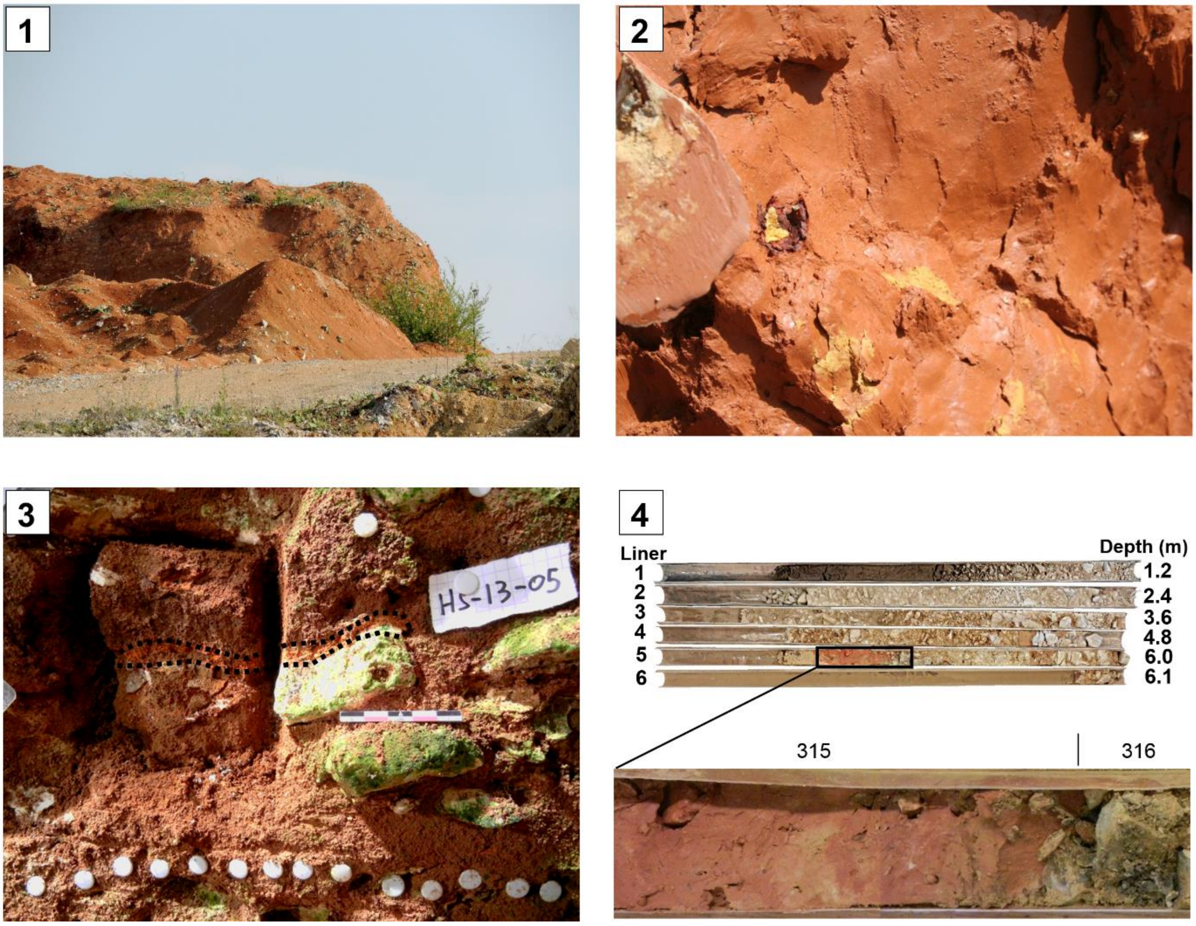

Fig. 6: Clays impregnated with Fe-oxide from the Swabian Jura. *1) Red clay and sand outcropping at Schelklingen, photographed during Swabian Jura survey; 2) Detail of a clay aggregate from Gerhausen (picture width is ca. 10 cm) (photo: Rudolf Water); 3) Aggregate composed of clay, silt and sand within Middle Paleolithic sediment at Hohlenstein-Stadel in the Lone Valley; 4) Core 5 recovered from the Lone Valley opposite from the Hohlenstein caves. The detail shows the deposits GL315, mainly composed of iron stained kaolinite, and GL316, formed from weathered limestone gravel impregnated with iron-manganese oxides. Based on cross-correlation with other coring data, these sediments accumulated before 36 kcal. BP (Barbieri, et al. 2018, Barbieri, 2019).*

Shortly after 30 kcal. BP, the Ach and Lone valleys underwent an intensive erosional phase, which led to the removal of sediments and archaeological materials from the cave sites in the region. Erosion was followed by a phase of floodplain aggradation, in which the Ach and Lone valleys were covered with up to 5 m-thick deposits of reworked loess and frost induced limestone debris (Barbieri, et al., 2018, Barbieri, 2019). These dramatic geomorphological processes may have impacted the local ochre sources by decreasing their visibility and accessibility to groups that inhabited the Swabian Jura after the LGM. On the other hand, the movement of glaciers out of the Black Forest left numerous tarns, deepened valleys, and exposed geological and topographic features which may have facilitated the identification of potential ocher source areas in this region (Ivy-Ochs, et al., 2008, Keller and Krayss, 1993). All of these hypotheses have the potential to be tested in the future with a provenance-based assessment using the data presented here and archaeological remains from the Swabian Jura sites. By first establishing that Fe-oxide materials these respective regions in Germany can be differentiated based solely on their geochemistry, we have provided a platform upon which to conduct future comparisons with ochre artefacts in order to identify their geological source origins. It is ultimately our goal to use our data to explore these hypotheses related to human behavioral complexities surrounding ochre collection, transportation and interaction.

6. Conclusion

Regarding our first research goal, the results presented here show that Fe-oxide sources in Germany can be differentiated by elemental composition. Most sources can be distinguished on a regional and sub-regional scale using stepwise multi-element statistics, indicating the possibility to distinguish local versus non-local and distant ochre artifact provenance. Regarding our second goal, we were able to separate Fe-oxide sources on a regional and partially sub-regional scale though there was some intra-source variability, such as with the Rappenloch source. There was also inter-source grouping as observed with the Schelklingen and Gerhausen sources, though these two outcrops are located within ca. 5 km of each other and are part of the same *Bohnerzlehm* formation. Thus, the provenance postulate (Weigand, et al., 1977) is not supported for all of the sampled outcrops, though was supported on a larger scale with the regional ochre sources. Lastly, we believe that the substantial transportation of the *Bohnerzlehm* features in the Swabian Jura may have impacted the source geochemistry (like with the Herz-Jesu Berg samples, for instance) and may have decreased source visibility and accessibility following 30 kcal BP. Based on the dramatic landscape changes following the LGM, we expect that populations in the Swabian Jura may have sought other areas for their ochre resources, though socio-cultural factors may also have been the primary driver for shifts in collection areas and strategies. Our current data, as it stands, cannot confirm either scenario, though these hypotheses have room for exploration in the future.

Our motive for investigating ochre sources in the region of the Swabian Jura is threefold: 1) the presence of numerous ochre pigment artifacts throughout the entire Upper Paleolithic (ca. 44-14.5 kcal. BP) (Velliky, et al., 2018) suggest an intensive practice of ochre and human interactions, which requires an extensive knowledge of the landscape and where to collect these materials; 2) the results presented here can potentially facilitate a provenance-based analysis of these materials that would be the first of its kind in the Swabian Jura; and 3) the geochemical data of the ochre sources in the sampled regions can provide the groundwork for expanding a European ochre database. Though this preliminary study offers promise, we believe that further and more extensive samples of the sources tested here, as well as other sources within and outside of Germany, may offer more valuable insight into the geological varieties of ochre. It is also our hope that the latter motive will encourage an increased focus on studying the range and depth of ochre behaviors in the Upper Paleolithic of Europe and foster further landscape and provenance-oriented studies on the recognition, collection, and transportation of materials during the late Pleistocene.

7. Acknowledgements

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