Identifying diachronic changes in ochre behaviours throughout the Upper Palaeolithic (ca. 44-12.5 kya) of Southwestern Germany

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Elizabeth C. Velliky
aus Warren, MI, USA

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This thesis contains work that has been published and/or prepared for publication.

Accepted publications

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Submission-ready Manuscripts

3. Velliky, Elizabeth C., Brandi L. MacDonald, Martin Porr and Nicholas J. Conard (in prep) Evidence for long-term symbolic behavioural continuity through pigment use from three Upper Palaeolithic cave sites in the Swabian Jura.

Note: *One of the paper manuscripts (referred to as Paper 1, 2, and 3 throughout this document) have been formatted specifically for this dissertation (Paper 3). This has been done to maintain the structure, clarity and cohesion of this dissertation document. Section numbers, figure and table numbers and titles follow the numerical order of this thesis, with references shown in a combined section at the end of this thesis document. Paper 1 is presented in its original published format. Paper 2 is presented in its publication-accepted format.*

Personal Contribution

Description of the extent and significance of the personal contribution according to § 6,2 PromO of the University of Tübingen. Numbers correspond to **List of Publications**.

1. I was first and corresponding author, as well as the main person responsible for conceiving the study design, undertaking the proposed research and data collection, analysing the data, and writing the manuscript. The co-authors (Martin Porr, Nicholas Conard) assisted with the writing and editing of the manuscript and oversaw the study as doctoral supervisors. Nicholas Conard is the director of the site in focus assisted with collections access.

2. I was first and corresponding author and was responsible, along with Alvise Barbieri, for conceiving the study design, undertaking the proposed research, data collection and data analysis. I wrote the majority of the manuscript along with Alvise Barbieri. Brandi L. MacDonald assisted with data analysis and manuscript comments and editing. Martin Porr and Nicholas J. Conard assisted with manuscript edits and doctoral supervisors.

3. I was first and corresponding author, as well as the main person responsible for conceiving the study design, undertaking the proposed research and data collection, analysing the data, and writing the main portion of the manuscript. Brandi L. MacDonald assisted with data analysis, data conceptualisation, and research design. Martin Porr and Nicholas J. Conard assisted with manuscript edits and doctoral supervision. Nicholas J. Conard is the director of the sites in focus and assisted with collections access.

Abstract

The archaeological assemblage from the Upper Palaeolithic levels (ca. 44-14.5 kya) of Hohle Fels cave in southwestern Germany is central to our understanding of the beginnings of anatomically modern humans (AMHs) in Europe and their behaviours, including the capacity for symbolic mediation. The use and manipulation of mineral pigments is understood to be one of the earliest forms of symbolic expression and plays a pivotal role in our understanding of behavioural modernity. Of the mineral pigments, a series of Fe-oxide based materials colloquially referred to as "ochre" are the oldest and most widespread pigment found at archaeological sites worldwide. Understanding its role in human behaviours, the intricacies surrounding its collection and use, and the lasting imprint it left is thus of utmost relevance in order to investigate the behavioural evolution of our hominin lineage.

The goal of my dissertation is to use a holistic approach to conduct a diachronic study of the ochre assemblage from Hohle Fels cave in southwestern Germany. Ultimately, my aim is to investigate the ways in which humans interacted with ochre in order to expand our understanding of their behavioural complexity during the earliest onset of the Aurignacian (ca. 44kcal. BP) and how these changed over time. Since ochre is a multi-faceted item with a range of uses and occurs in a variety of geological contexts, a diverse approach is best suited to explore its life-cycle and in what ways humans shaped and were impacted by their interactions with ochre. I present my thesis results in three stages, represented by three papers that are either published or ready for peer-review publication.

The first stage used previously established categorical or qualitative methods to document the size, types, and overall presence of ochre artefacts at Hohle Fels. This investigation allowed observation of temporal patterns in visual and textural characteristics of ochres. It furthermore demonstrated that there are significant differences in the types of ochre collected during the Aurignacian (ca. 44-34 kcal. BP) and later time periods, namely, that ochre colours and textures were more varied during the Aurignacian which narrowed to a preference for purple, silty and micaceous ochres during the Gravettian (34-30.5 kya) and Magdalenian (16.5-14.5 kya). The traces of anthropogenic

use during the later time periods are more in line with pigment powder production, while in the Aurignacian only a stylised motif is present.

The second stage involved conducting a survey nearby Hohle Fels as well as in other areas, in order to locate Fe-oxide sources which could have provided the ochre materials to cave inhabitants. This also ties into the third stage, which aimed to geochemically characterize a selection of ochre artefacts from Hohle Fels using neutron activation analysis (NAA) and compare these with the source materials to conduct a provenance-based analysis. These two stages revealed that there are several compositional groups acquired from different sources represented in the ochre assemblage, most of which were locally-based. However, two compositional groups showed that ochre acquisition was not only restricted to local areas, and even during the Aurignacian ochre was transported over great distances (ca. 300 km). Furthermore, several of these sources were accessed throughout the entire Upper Palaeolithic, showing that groups of people were sharing knowledge through generations and were remaining loyal to certain source areas during a vastly changing environment and climate. The last aspect of the third stage involved the incorporation of ochres from the nearby cave sites of Geißenklösterle and Vogelherd, in order to explore whether ochre behaviours were shared between the cave sites. The results showed that people were indeed sharing or accessing the same ochres, but some were kept exclusive to certain groups as is seen with the ochre from Hohle Fels and Geißenklösterle.

The data on the ochre materials, both archaeological and modern, coupled with environmental and climatic data, revealed that people were adapting when necessary, but also maintaining behaviours over time. Overall, the combination of all of these methods and techniques allowed for new and unique insights into the ways that people communicated with each other, interacted with their landscape, and how ochre formed a part of their lives throughout the Upper Palaeolithic.

Keywords: Ochre; mineral pigments; symbolic behaviours; Upper Palaeolithic; provenance analysis; behavioural modernity.

Zusammenfassung

Die archäologischen Inventare aus den jungpaläolithischen Schichten (ca. 44–14,5 kya) der Hohle Fels-Höhle im Südwesten Deutschlands sind zentrale Bestandteile unseres Verständnisses der Anfänge des anatomisch modernen Menschen (AMHs) in Europa und seines Verhaltens, einschließlich seiner Kapazität zur symbolischen Vermittlung. Die Verwendung und Manipulation von Mineralpigmenten wird als eine der frühesten symbolischen Ausdrucksformen verstanden und spielt eine entscheidende Rolle in unserem Verständnis modernen Verhaltens (*behavioural modernity*). Mineralische Pigmente auf Eisenoxid-Basis, die umgangssprachlich als „Ocker“ oder „Rötel“ bezeichnet werden, sind die ältesten und am weitesten verbreiteten Mineralpigmente, die weltweit an archäologischen Stätten gefunden werden. Das Verständnis ihrer Rolle im menschlichen Verhalten und der Komplexität der Beschaffung und Verarbeitung sowie der bleibende Eindruck, den diese Mineralien hinterlassen, sind daher von größter Bedeutung, um die Verhaltensentwicklung der Hominin-Linie zu untersuchen.

Das Ziel meiner Dissertation ist es, mit einem ganzheitlichen Ansatz eine diachrone Untersuchung der Ocker- und Rötelinventare vom Hohle Fels durchzuführen. Letztendlich ist mein Ziel zu untersuchen, wie Menschen mit Ocker interagierten, um unser Verständnis der Komplexität ihres Verhaltensweisen am Beginn des Aurignacien (ca. 44 kya) zu erweitern und zu untersuchen, wie sich diese im Laufe der Zeit verändert haben. Da es sich bei Ocker um ein Material mit einer Vielzahl von Verwendungsmöglichkeiten handelt und es in verschiedenen geologischen Kontexten vorkommt, ist ein breit gefächerter Ansatz am besten geeignet, seinen Lebenszyklus und die Art und Weise, wie der Mensch durch die Wechselwirkung mit Ocker beeinflusst wurde, zu untersuchen. Ich lege die Ergebnisse meine Dissertation in drei Phasen vor, die durch drei Artikel repräsentiert werden oder eingereicht sind beziehungsweise sich im Review-Prozess durch Fachkollegen befinden.

In der ersten Stufe wurden zuvor festgelegte kategoriale oder qualitative Methoden verwendet, um die Größe, die Art und das gesamte Vorhandensein von Ocker- und Rötelartefakten im Hohle Fels zu dokumentieren. Diese

Untersuchung ermöglichte die Beobachtung von Mustern in visuellen und texturellen Merkmalen von Ocker im Lauf der Zeit. Es zeigte sich weiterhin, dass es größere Unterschiede bei den Ockertypen im Aurignacien (ca. 44-34 kya) als in späteren Zeiträumen gibt. Diese variieren in Farbtönen und Texturen viel stärker als in späteren Zeitabschnitten, wo es eine Präferenz für lilafarbenen, feinkörnigen und glimmerhaltigen Ocker im Gravettien (34-30,5 kya) und im Magdalénien (16,5-14,5 kya) gibt. Die Spuren des anthropogenen Gebrauchs in den beiden letzteren Zeitstufen entsprechen eher Spuren der Pigmentpulverproduktion, während in der Aurignacien nur ein stilisiertes Motiv vorhanden ist.

Die zweite Phase umfasste die Durchführung einer Geländebegehung in der Nähe des Hohle Fels sowie in anderen, weiter entfernten Gebieten, um Eisenoxid-Quellen zu lokalisieren, die die Mineralische Pigmente hätten liefern können. Dies knüpft auch an die dritte Stufe an, die darauf abzielte, eine Auswahl von Ockerartefakten vom Hohle Fels mithilfe der Neutronenaktivierungsanalyse (NAA) geochemisch zu bestimmen und diese mit den aufgesammelten Materialproben zu vergleichen, um eine Herkunftsanalyse durchzuführen. Diese beiden Stadien ergaben, dass es mehrere Kompositionsgruppen im Ockerinventar gibt, die aus verschiedenen Quellen stammen, und von denen die meisten lokal vorkommen. Zwei Kompositionsgruppen zeigten jedoch, dass die Beschaffung von Ocker nicht nur auf lokale Gebiete beschränkt war, sondern dass Ocker im Aurignacien auch über große Entfernungen (ca. 300 km) transportiert wurde. Darüber hinaus wurde auf mehrere dieser Lagerstätten im Verlauf des gesamten Jungpaläolithikums zugegriffen, was zeigt, dass Gruppen von Menschen über Generationen hinweg Wissen austauschten und bestimmten Quellen von Ressourcen auch in einem sich stark verändernden Umfeld und Klima treu blieben. Der letzte Aspekt der dritten Stufe umfasste die Einbeziehung von Ocker- und Rötelartefakten aus den nahe gelegenen Höhlenstandorten Geißenklösterle und Vogelherd, um zu untersuchen, ob sich die Nutzung von Ocker innerhalb der verschiedenen Höhlenstationen veränderte . Die Ergebnisse zeigen, dass die Menschen tatsächlich auf dieselben Ockerquellen zurückgriffen; manche Ockersorten aber traten in bestimmten Gruppen exklusiv auf, wie dies bei einigen Ockersorten von Hohle Fels und Geißenklösterle der Fall ist.

Die archäologischen und naturwissenschaftlichen Daten zu den Mineralische Pigmente sowie die Umwelt- und Klimadaten zeigen, dass sich die Menschen bei Bedarf anpassten und ihr Verhalten im Laufe der Zeit beibehielten. Insgesamt ermöglichte die Kombination all dieser Methoden und Techniken neue und einzigartige Einblicke in die Art und Weise, wie Menschen miteinander kommunizierten, mit ihrer Landschaft interagierten und auf welche Weise Ocker und Rötel einen Teil ihres Lebens im gesamten Jungpaläolithikum bildeten.

Schlagwörter: Ocker, Rötel; Mineralpigmente; symbolisches Verhalten; Jungpaläolithikum; Herkunftsanalyse; modernes Verhalten.

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Dedication

I dedicate this thesis to my parents, Michele Velliky and John Velliky, for I would not be where I am without their endless love and support.

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List of Acronyms

UWA	University of Western Australia
BP	Before present
AMHs	Anatomically modern human(s)
mya	Millions of years ago
kcal	Thousands of years calibrated
kya	Thousand years ago
HF	Hohle Fels Cave
GK	Geißenklösterle Cave
VH	Vogelherd Cave
PCA	Principal Components Analysis
CDA	Canonical Discriminant Function Analysis
MURR	University of Missouri Research Reactor
NAA	Neutron Activation Analysis
XRD	X-ray Diffraction
SEM-EDS	Scanning Electron Microscope with Energy Dispersive Spectroscopy

Chapter 1. Introduction

> *My attention has, by sheer chance, been drawn recently to that peculiar substance – red ochre. The responses it evoked from humanity, have caused it to be of unusual, if not pre-eminent importance for localizing temporally and spatially the dawn of symbology.*
>
> *Raymond Dart, 1968:20*

One of the most significant questions in archaeological research asks when hominins started to exhibit characteristics of “modern” behaviour, such as complex syntactical language, abstract thinking, planning depth, behavioural, technological and economic innovativeness, and symbolic behaviour. The pursuit of this question has led an inquiry into how hominins interacted with materials and their methods and motives behind acquiring and utilising them. One such material is a mineral pigment called ochre, which is often proposed to be one of the oldest pieces of material evidence that indicate behavioural modernity in our shared lineage (Barham 1998; 2002; Brooks et al. 2016; Brooks et al. 2018; McBrearty and Brooks 2000; Watts 1999; Watts et al. 2016). The manipulation of ochre has been used as a proxy for the emergence of language (d'Errico and Henshilwood 2011b; d'Errico et al. 2009; Henshilwood and Dubreuil 2009; Watts 2009; Zilhão 2011) and advanced cultural cognition (Henshilwood et al. 2011; Hodgskiss 2014b; Nowell 2010; Rosso et al. 2016; Wadley 2010; 2011; Wadley et al. 2009), as evidence of long-distance trade and social networks (Bouillot et al. 2017; Brooks et al. 2018; Dayet et al. 2016; Dayet et al. 2013) and is often interpreted as an artistic and/or symbolic component in ancient contexts (d'Errico et al. 2003; Gravel-Miguel et al. 2017; Henshilwood 2004; Henshilwood et al. 2011; Henshilwood et al. 2009; Henshilwood et al. 2002; Hovers et al. 2003b; Knight 2010; Román et al. 2019; Watts 2002; 2009; Watts et al. 2016; Wolf et al. 2018; Zilhão et al. 2010; Zipkin 2015).

Ochre is a mineral pigment with many faces, forms, and colours; it was collected and manipulated from possibly 500 kya onwards by different types of hominins (Watts et al. 2016). Though it is arguably one the earliest pieces of evidence supporting symbolic behaviours, it may have also served a variety of both functional and non-functional uses (Henshilwood et al. 2009; McBrearty and Brooks 2000; Watts 1999; 2009). It appears as a residue on lithics (Lombard 2006; 2007; Villa et al. 2015; Wojcieszak and Wadley 2018), bones (Darchuk et al. 2009; Román et al. 2015; Velliky et al. 2018), shells (d'Errico et al. 2005; Peresani et al. 2013; Velliky et al. 2018; Zilhão et al. 2010), ornaments (d'Errico et al. 2005; Dayet et al. 2017; Henshilwood et al. 2004), and rock walls (Aubert et al. 2014; Aubert et al. 2018; Clottes 2008; Cuenca-Solana et al. 2016; d'Errico et al. 2016; Huntley et al. 2015; Rifkin et al. 2016). It was likely used as body paint by ancient societies (Fiore 2018b) and is recently still in use by some indigenous cultures (Bouchard and Kennedy 1986; Matthews and Khahtsahlano 1955; Noetling 1909; Rifkin 2015a; 2015b; Taçon 2004). It has been used it as a medicine (Velo 1984; 1986), as a nutritional supplement (Abrahams 2010; Macintyre and Dobson 2017), as a component in ceramic vessels (Capel et al. 2006; Eiselt et al. 2019), as a ritual offering in burials and ceremonies (Hovers et al. 2003b; Pettitt et al. 2003; Román et al. 2015; Román et al. 2019). It was collected in specific areas and transported over great distances (Brooks et al. 2018); its use and recognition as an essential and valuable item have persisted throughout time and space. From an archaeological perspective, it has a broad temporal, geographic, and application range. Ochre is unique; studying the impact it had on the lives of ancient hominins is thus pivotal to understand how they interacted with the material world around them and how these interactions shaped their cultural, social, and behavioural structures over time.

Though ochre as a material item was recognised relatively early on by some researchers as an important cultural material (Couraud 1983; Dart 1924; 1968a; 1968b; 1969; 1975; Dart and Beaumont 1967; Wreschner 1975; 1976; Wreschner et al. 1980), it was known mainly as a paint in cave art for most of the later 20th century. Up until the turn of the 21st century, human cultural evolution was thought to have arisen and flourished in the European Upper Palaeolithic beginning at ca. 40 kya and peaking during the Magdalenian (ca. 16-12 kya). The “Cultural Revolution” belonged to anatomically modern humans as they entered into the European continent, where they created a wealth of innovative, artistic, and technologically advanced artefacts (Bar-Yosef 2002; Mellars and Stringer 1989). A critical review by McBrearty and Brooks (2000) deconstructed the Cultural Revolution as being the by-product of Eurocentric and Westernist perspectives, which largely ignored archaeological evidence in other parts of the globe. Attention then shifted to the African continent, where an equally abundant and ancient archaeological record was expanding what was previously known about human evolution. Advanced stone tool technology, innovative resource gathering strategies, forms of personal ornamentation and decoration and other symbolic items were equal to and exceeded some European assemblages in age and abundance (Barham et al. 2002; Barham 1998; 2002; Clark 1999; d'Errico et al. 2003; Deacon and Wurz 2001; Henshilwood et al. 2004; Henshilwood et al. 2002; Henshilwood and Marean 2003; Henshilwood et al. 2001; McBrearty et al. 1996; McBrearty and Brooks 2000; Wadley 2001; 2003; 2006; Watts 1999; 2009; 2010; Wurz 1999; 2002). Increasing attention was placed on ochre assemblages in African contexts due to the association of pigment use to symbolic behavioural capacities (Knight et al. 1995; McBrearty and Brooks 2000; Watts 1999; 2002; 2009; Watts et al. 2016). Furthermore, the prevalence of ochre artefacts at some archaeological sites led to hypotheses on the variety of possible applications of ochre outside of the “symbolic” realm (Rifkin 2011; 2015a; Rifkin et al. 2015; Wadley 2005b; 2011; Watts 1998a). Studying pigment use is now at the forefront of investigating a range of behaviours and the role it played in human evolution (d'Errico 2008; Henshilwood et al. 2009; Roebroeks et al. 2012; Wadley 2006; Watts et al. 2016; Zilhão 2007; Zilhão et al. 2010).

Though researchers often cite ochre and pigment use in African archaeology as an indicator for evaluating symbol use, advanced cognition and behavioural modernity more generally, comparable research on European ochre and pigment contexts are comparatively limited. Though numerous Upper Palaeolithic sites report or mention ochre and pigment assemblages, few integrative analyses (except for de Lumley et al. 2016; Pradeau et al. 2014) have focused on ochre, apart from older studies (Couraud 1983; 1988; Gollnisch 1988) or reports of artefacts containing ochre residues (Marshack et al. 1979). Furthermore, after the 1980s (Audouin and Plisson 1982), little experimental work focused on ochre and pigments in European archaeological assemblages. Instead, researchers place more attention on expanding symbolic behavioural capacities to European Neanderthals through studying their pigment use (Bodu et al. 2014; Dayet et al. 2014; Heyes et al. 2016; Hoffmann et al. 2018; Roebroeks et al. 2012; Salomon et al. 2012a; Salomon et al. 2008; Soressi and d'Errico 2007), leaving a gap in knowledge on the behavioural intricacies surrounding an otherwise important material item.

I am to rectify this disparity and shed light on ochre use from Upper Palaeolithic cave sites in the Swabian Jura of Central Europe, specifically the site of Hohle Fels. My research focuses on the types of ochre found at the site and how this reflects material preferences over time, how the inhabitants were processing and using ochre and where they were collecting it. The examination of the Hohle Fels ochre assemblage not only contributes to the extensive research previously conducted on other forms of material culture found at the site but also contributes towards expanding our knowledge of ochre behaviours during the Upper Palaeolithic in Europe. Specifically, I will incorporate an operational chain-, or *chaîne opératoire*, based approach focusing on the major stages of human interaction with ochre materials, from collection to processing to deposition. This approach integrates traditional qualitative artefact analyses with geochemical characterisation, geological source identification, and the impact of climate and environment on collection strategies and behaviours. This robust and holistic assessment is necessary to establish the life-cycle of ochre materials, including the particularities of the physical materials, the activities involved in its use, and the fundaments of the engagements between ancient people and their material world.

1.1. Project goal and research objectives

I first came to excavate at the site of Hohle Fels in southwestern Germany in the summer of 2014. The site is already well-studied, as its deep and intact archaeological stratigraphy, which spans the entire Middle to Upper Palaeolithic, allows for a detailed introspection on diachronic changes in behaviours over time. Ivory figurines (Conard 2009; Dutkiewicz et al. 2018; Hahn 1986), personal ornaments (Wolf 2015b), musical instruments (Conard et al. 2009), faunal elements and osseous artefacts (Conard and Malina 2015; Münzel and Conard 2004a; 2004b), and tens of thousands of lithic artefacts (Bataille and Conard 2018; Floss and Kieselbach 2004; Taller 2014; Taller and Conard 2016; Taller et al. 2019) had already been studied and offered insights into site occupation patterns, seasonal migrations and symbolic behaviours throughout the late Pleistocene. Though the site is thoroughly documented and plays a vital role in investigating the earliest anatomically human movements into the European continent, the ochre artefacts were receiving little post-excavation attention. The presence of painted limestone artefacts from the Magdalenian (Conard and Floss 1999; 2001; Conard and Malina 2010; 2011; Conard and Uerpmann 2000; Floss and Conard 2001), which are some of the only examples of portable painted art in Germany, provided further evidence that pigment behaviours were in place at the site of Hohle Fels. Though the artefacts themselves are valuable specimens for artistic and symbolic capacities during the Upper Palaeolithic, currently no connections have been made between the ochre pieces and the objects with pigment residues, let alone resource collection strategies in the landscape. I, therefore, realised that an essential part of the puzzle was missing and that a diachronic assessment of the Hohle Fels ochre assemblage could offer insights into an understudied behaviour in this region.

At the time of writing, there has not been a comprehensive analysis conducted on an Upper Palaeolithic ochre assemblage in Central Europe. Some short reports and isolated geochemical studies exist (Sajó et al. 2015b). Still, nothing describes a detailed assessment of ochre types, geological varieties, or a holistic evaluation of behaviours evidenced by archaeological ochre materials. There have been some studies on Upper Palaeolithic ochres in France (Couraud 1991; Pradeau et al. 2014), but the majority have been on *Châtelperronian* contexts (Bodu et al. 2014; Dayet et al. 2014; Salomon et al. 2012a), which is a transitional industry ascribed to Neanderthals dating from ca. 45-36 kya, and found only in Western Europe. Thus, a large void in knowledge exists on ochre varieties, geological types, and behaviours for this region and period. My goal is to rectify this by conducting the first comprehensive and systematic assessment of an ochre assemblage in the Upper Palaeolithic of Central Europe, in order to explore change and continuity in ochre behaviours in the Swabian Jura and what these can tell us about cultural evolution. My more research specific objectives are:

- To investigate the nature of ochre material varieties at Hohle Fels cave, how people used ochre, and whether their preferences or ways they used it changed over time.

- To identify where in the landscape ochre was collected from and whether collection behaviours were impacted by environmental and climatic changes throughout the Upper Palaeolithic.

- To determine if the *provenance postulate* (Weigand et al. 1977) can be satisfied for German ochre sources, and whether or not the ochre artefacts from Hohle Fels can be attributed to specific outcrops or sub-outcrops.

Previous comprehensive studies on ochre assemblages conducted in other regions often include either a more site-focused and artefact specific behavioural approach (Bernatchez 2012; Dayet et al. 2013; Hodgskiss 2014b; Rifkin 2012b; Rosso et al. 2014), or a more regional approach focusing on comparing ochre artefacts from certain sites (Watts 1998b), their provenance (MacDonald 2008; 2016), and how these reflect on ochre behaviours (Dayet et al. 2016; Rosso et al. 2017; Zipkin 2015). I will build upon these previous studies to include a site-focused assessment of the Hohle Fels ochre assemblage, as well as discuss ochre sources and acquisition strategies from a more regional perspective and incorporate some ochre assemblages from neighbouring sites in the region. I aim to maintain consistency with previous research on ochre artefacts in order to work towards building a systematic protocol for researching ochre assemblages that can function throughout different sites, periods, regions, and technocomplexes.

The topic of provenance plays an important role in ochre research as well as archaeological material studies more generally. Provenance, in its original definition, refers to the discovery place or the manufacture location of an object (Joyce 2012). In more recent years, due to advances in geochemical analyses in archaeometry, it has come to refer to the geographic location of the geological origin of a material (Pollard et al. 2014; Wilson and Pollard 2001). In order to attribute archaeological samples to their source locations, outcrops must exhibit some level of geochemical homogeneity. Samples from one source location must be more chemically similar to each other than samples from another outcrop; otherwise, artefacts cannot be assuredly attributed to that source. This concept, that inter-source variation must be greater than intra-source variation, formulates the basis of the *provenance postulate* or the *provenance hypothesis* (Pollard et al. 2014; Weigand et al. 1977; Wilson and Pollard 2001). Ochre provenance studies have previously supported this postulate (Eiselt et al. 2011;

Kingery-Schwartz et al. 2013; MacDonald et al. 2018; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007), and thus offer promise for conducting a similar study in a Central European context. Determining the origin of ochre artefacts can shed light on movement and interaction in ancient populations and, and coupled with the physical characteristics of ochre (e.g. deeper red hues, micaceous inclusions, silty textures), can offer insight into behaviours an and practices and how these develop over time.

1.2. Methods and the *chaîne opératoire*

To address and explore my research goal, I formulated corresponding methods to examine the archaeological material from primarily Hohle Fels cave, but also Geißenklösterle and Vogelherd caves on a smaller scale. These methods are:

1. To catalogue and describe the ochre assemblage from Hohle Fels cave, including their physical (qualitative) and geochemical (quantitative) characteristics;

2. To locate and sample potential sources where ancient populations may have collected ochre materials, and to document their geological and chemical components;

3. To compare the modern-day source samples and the archaeological materials for a provenance analysis of the ochre artefacts from the Swabian Jura caves;

4. Based on the three points above, to conduct a holistic analysis of the ochre materials from Hohle Fels to interpret the operational chain of ochre behaviours at the site and to investigate how people interacted with ochre, and its role in socio-cultural constructs of the Swabian Jura during the Upper Palaeolithic.

These methods incorporate a sequence of investigative techniques, focusing first on describing the specific ochre pieces and their context within the cave site. Each ochre artefact was measured and described, then studied for evidence of anthropogenic modification. In some cases, streaks were obtained from the objects to evaluate the “pigment” colour of the ochre. Some more detailed qualitative information on the chemical and mineralogical data of selected ochre pieces was obtained using neutron activation analysis (NAA), X-ray diffraction (XRD), and scanning electron microscopy (SEM).

I then shift my focus outward to identifying ochre sources nearby and from more distant regions that could have been accessible during the late Pleistocene. I discuss these sources in relation to the archaeological ochre assemblage and regional geomorphological data. Considering the changes and fluctuations in landscape erosion and climate is relevant as these may have impacted ochre collection strategies by increasing or decreasing the accessibility or visibility of particular sources.

Lastly, I tie these two investigations together by comparing the geochemistry of the identified sources and the ochre pieces, in order to examine whether German ochre sources can satisfy the *provenance postulate,* and whether the archaeological ochres can be attributed to any of the identified sources. I furthermore outline and discuss any trends or patterns within the data, whether people may have selected certain sources over others, any diachronic patterns or trends in the ochre assemblage and how combined, this data constructs the narrative of ochre behaviours at the site of Hohle Fels. The results of this study, as well as each of the aims and the objectives used to address them, correspond to specific stages in the *chaîne opératoire* of ochre use as initially outlined by Couraud (1983), but slightly modified for this thesis and research area. The stages, as I define them, are:

Table 1.1: ***Chaîne opératoire*** **outlined as a step-by-step process, with each stage relying on the completion of the previous step.**

Operational stage
1. Desire to utilise ochre
2. Desire to collect
3. Location of collection
4. Selection
5. Movement/transportation
6. Collection
7. Preparation station
8. Processing
9. Pigment powder
10. Application of pigment
11. Deposition

Overall, my intention is to construct a holistic framework to observe the relationship and entanglements between human behaviours, mineral pigments, and the landscape and environment in which they live. Ochre as an artefact does not occur in a vacuum, and neither do the sequences of actions and events that brought them to a place where people used and deposited them. Studying the life-cycle of ochre will illuminate each step as a pivotal point of interaction with humans, and offer a more in-depth insight into the mechanisms that drive changes and adaptations that manifest in the archaeological assemblage. I discuss all of these topics in the context of my results in Chapter 8.

1.3. Thesis structure

This thesis is submitted in a cumulative format, incorporating three papers that are either published **(Paper 1, Paper 2)** or are a submission ready manuscript **(Paper 3)**. The thesis structure is in accordance with the guidelines provided by the Graduate Research School at the University of Western Australia and the Mathematisch-Naturwissenschaftliche Fakultät at the University of Tübingen for the submission of a

PhD thesis by publication (or a “cumulative thesis”). These papers are presented as three individual chapters. As for the chapters and sections:

- In **Chapter 2,** I cover the archaeological context and background in detail, first by discussing the ochre from both geological and archaeological perspectives, followed by reviewing the archaeological occurrences of ochre from a global standpoint. I then describe the research history in the Swabian Jura, the archaeological context of Hohle Fels, and a review of previous studies of ochre and ochre-related materials in the region.

- In **Chapter 3,** I provide an overview of the broader discussion surrounding ochre and its role in signifying behavioural modernity in ancient contexts. I address how these concepts are entrenched in the debate of how we define symbolism and symbolic behaviour, and I critique how ochre is often assumed to be representative of symbolic intentions without proper investigative discourse. I situate this within the discussion of what we consider functional and symbolic behaviours, how these two concepts might not be so mutually exclusive and offer my motives for incorporating a holistic approach for investigating the Hohle Fels ochre assemblage.

- In **Chapter 4,** I provide a brief background on different approaches used to study ochre assemblages, their research structures, and what levels of insight they can offer. I then describe the methods I implement in this thesis and my anticipated outcomes and describe each of the techniques and their specific attributes. Some aspects of these are also discussed in the individual papers, but this chapter provides more detailed information on the research methods.

- In **Chapter 5,** I present the first of my three thesis papers:

  Paper 1: Velliky, E.C., M. Porr and N.J. Conard 2018 Ochre and pigment use at Hohle Fels cave: Results of the first systematic review of ochre and ochre-related artefacts from the Upper Palaeolithic in Germany. PLOS ONE 13(12):e0209874.

  The focus of this paper is on the qualitative characteristics of the ochre and ochre-related artefact assemblage of Hohle Fels cave. I provide a detailed assessment of total artefact numbers, colour and textural varieties, rock types, artefacts with ochre residues, modified ochre artefacts, and how these relate to ochre behaviours at Hohle Fels cave. I discuss these artefacts in the context of the internal cave stratigraphy as well as within a regional context of the Swabian Jura in the Upper Palaeolithic, as well as how the artefacts show diachronic changes and patterns in ochre behaviours.

- In **Chapter 6**, I present my second paper:

  Paper 2: Velliky, E.C., A. Barbieri, M. Porr, N.J. Conard, and B.L. MacDonald (2019, in press) A preliminary study on ochre sources in Southwestern Germany and its potential for ochre provenance during the Upper Palaeolithic.

  In this paper, I present the results of a series of surveys I conducted alongside volunteers in the summer and autumn of 2017. We located several Fe-oxide outcrops in the Swabian Jura and the Black Forest. We sampled these in order to determine whether ochre deposits in Germany could satisfy the *provenance postulate*, thus assessing the possibility for a provenance-based analysis of the Hohle Fels ochre assemblage. In addition to the sources, we analysed ochres from donated samples located in distant areas of Central and Eastern Germany. Using Neutron Activation Analysis (NAA), we were able to establish that inter-source variation was greater than intra-source variation, thus providing the groundwork for investigating the potential origins of the ochre artefacts from Hohle Fels.

- In **Chapter 7**, I present the third and final paper of my thesis papers:

  Paper 3: Velliky, E.C., B.L. MacDonald, M. Porr, and N.J. Conard (submission-ready manuscript) Evidence for long-term symbolic behavioural continuity through pigment use from three Upper Palaeolithic cave sites in the Swabian Jura.

  My final dissertation paper presents an accumulation of the ochre source elemental data, as well as the results from NAA characterisation of 183 ochre samples from Hohle Fels, Geißenklösterle and Vogelherd caves. I compare the data from both the archaeological samples and the modern-day source samples using a variety of multivariate statistical techniques in order to determine if the archaeological ochres could be attributed to the sampled Fe-oxide outcrops. The results show that not only were many of the ochres from all three caves collected from local areas, but one ochre compositional group from Hohle Fels was most closely associated with a distant ochre source in Eastern Germany (ca. 300 km away). Other trends show continuity in ochre collection strategies throughout the entire Upper Palaeolithic, as well as shared knowledge of ochre sources between the three cave sites. The results outline an extensive understanding of the landscape and the sharing of knowledge between caves and over 29 millennia in the Swabian Jura.

- **Chapter 8**, I provide a summary of my results and a discussion of the ochre assemblage within a site-based perspective, including both temporal and spatial implications, as well as a regional perspective incorporating data from the ochre survey and the analyses of the three cave sites. I present how the Hohle Fels ochre assemblage and the techniques used to investigate it fit into the larger cultural process of ochre behaviours at the site by situating the results within a *chaîne opératoire* framework. I discuss each of the stages as they relate to the results and their associated behavioural and cognitive implications. I offer an evaluation of how ochre behaviours emerged, evolved, and flourished during the Upper Palaeolithic of the Swabian Jura, and how this dissertation offers promise for future studies focusing on Central European ochre assemblages. Lastly, I discuss the value of using this type of holistic approach, and I identify future research possibilities that stem from this work.

- In **Chapter 9,** I provide concluding remarks on my dissertation and how we can use the results to interpret how and why humans interacted with ochre materials in this time and place. Lastly, I discuss the role of ochre in the behavioural evolution of hominins and the contribution of the Swabian Jura assemblage to this wider debate.

Chapter 2. Background and review of literature

> *For we are still confronted by the primary issues of where and why it all began. Did it arise in Europe with Homo erectus, 500,000 years ago, because his (or her) attention had already become concentrated upon it…? Or did the fascination of the blood-red and glittering black specularite substance that frequently accompanied haematite simply spread along the coastline and rivers of the Mediterranean Area to reach with the inevitability of fate and time into southernmost Africa and incidentally percolate coastal Asia and Indonesia into Australia and Tasmania? Or did the dedication to colour originate in the Near East or in India and radiate from there?*
>
> *Raymond Dart, 1977:208*

2.1. Ochre: A Broad Review

Red ochre is a general term used to describe a series of ferruginous rocks that can be used to produce a variety of shades of coloured powder. The word ochre, when used in archaeological, academic, or colloquial contexts, generally refers to any sediment or rock containing varying amounts of iron oxide and oxyhydroxide (generally, $2Fe_2O_3$ and FeO) minerals (Cornell and Schwertmann 2003). It appears in sedimentary, metamorphic, and igneous contexts as most rock types contain varying amounts of Fe that are oxidized at different rates in many geological settings (Singh et al. 1978). Because of the different amounts of iron content in materials, the colours expressed vary from yellow to red to purple to brown. There are 16 known types of iron oxides and oxyhydroxides, the most widespread and well-known being Hematite (α-Fe_2O_3, red to purple) and Goethite (α-FeOOH, yellow to orange). Other forms include Wüstite (FeO, red to purple), Magnetite (Fe_3O_4, black), Maghemite (γ-Fe_2O_3, dark red to brown), Akagenéite (β-FeOOH, yellow to brown), Lepidocrocite (γ-FeOOH, dark yellow to brown), Feroxyhyte (δ-FeOOH, yellow), Schwertmannite ($(Fe^{3+}_{16}O_{16}(OH,SO_4)_{12\text{-}13}\cdot 10\text{-}12H_2O$, orange to red), Ferrihydrite ($Fe^{3+}_2O_3 \bullet 0.5(H_2O)$, yellowish-brown), to name a few (Cornell and Schwertmann 2003). Lighter shades of red can be heated, thereby altering their colour by the process of calcination, a thermal treatment process that decomposes the mineral (Schmandt-Besserat 1980). This colouration is why it may be difficult for researchers to distinguish ochre found at archaeological sites as a manuport, or as a by-product of hearth features, as it is often the case that layers of red sediment encompass areas altered by heat (Salomon et al. 2012b).

Apart from stone tools, ochre is one of the oldest materials found in archaeological contexts, and as such has been a topic of inquiry for decades. It has been present in ancient and ethnographic contexts throughout virtually the entire duration of human history (Roper 1992; Schmandt-Besserat 1980). Historically, it has been found in a range of settings, including in artistic avenues as a pigment in rock art (Huntley et al. 2015; Tournié et al. 2011), frescos (Bikiaris et al. 2000), ceramics (Capel et al. 2006) and other painted objects (Hradil et al. 2003), in house floors (Schmandt-Besserat 1980), in prehistoric hominin and human burials (Hovers et al. 2003a; Pettitt et al. 2003), and a vast array of other avenues both symbolic and functional (Hodgskiss 2010; Marshack 1981; Wadley 2005b; Watts 2002; Wreschner et al. 1980). Ochre arguably represents some of the earliest evidence regarding symbolic behaviours in ancient hominins, though it likely served as a material component in a variety of both functional and symbolic contexts (Henshilwood et al. 2009; Hovers et al. 2003a; Marshack 1981; Wadley 2005b; Wadley et al. 2004; Watts 2002). The distinction between functional and symbolic (non-functional) uses is not always straightforward to identify archaeologically and thus is an on-going topic of debate. This dichotomy has spurred diverse research trajectories exploring the possible practical applications of ochre, as well as more theoretical fields investigating its relation to the early onset of modern behaviours in hominin populations. Regardless of this separation of research interests, ochre as an archaeological material has a long research history and has appeared in every continent inhabited by humans.

2.1.1. Ochre in Archaeological Contexts

Ochre in the African Record

The earliest ochre finding comes in an almost black form of specular hematite, or Specularite (Fe_2O_3), found in layers dating to ~ca. 500-300 kya at Wonderwerk Cave in the Northern Cape of South Africa (Watts et al. 2016). Specularite is a particularly "sparkly" or "glittery" material, which is a primary reason that Watts and colleagues (2016) propose its use for ritualistic purposes, even at such early dates. Overall, from ~500-300 kya, there are eight known sites in Africa which record finding ochre pieces at the site. These include site GnJh-15 in the Kapthurin Formation, Kenya, from around 285 kya (McBrearty and Brooks 2000), Twin Rivers in Zambia, dating to ~250 kya (Barham 1998; 2002), and at Sai Island, Sudan, dated to 200 kya (Van Peer et al. 2003). It was during the African MSA, from roughly 280-25 kya, that ochre acquisition and exploitation became a regularly practised behaviour amongst *H. sapiens* (Wadley 2005a; Watts 1999). The first sites in the later Middle Pleistocene with anthropogenically modified ochre artefacts include Border Cave (Watts 2002) and Pinnacle Point Cave in South Africa (ca. 164 kya) (Marean et al. 2007; Watts 2010). It is this early appearance of anthropogenically modified red ochre, followed by a sudden explosion of modified ochre appearing at archaeological sites, are the reason that such attention is placed on the origins of symbolic behaviours as they relate to ochre in Africa, and more specifically Southern Africa. Following the discoveries at these locations, during the Late Pleistocene ochre use becomes a common behaviour at the majority of Middle Stone Age (MSA) sites. Ochre pieces with evidence of grinding striations, traces of ochre powder on stone tools and possible ochre grindstones were found at sites Apollo 11 (Watts 2002), Blombos Cave (Henshilwood et al. 2011; Henshilwood et al. 2001), Die Kelders Cave (Thackeray 2000), Diepkloof Cave (Dayet et al. 2013), Hoedjiespunt 1 (Will et al. 2013), Hollow Rock Shelter (Evans 1994), Klasies River Mouth (d'Errico et al. 2012), Klipdrift Cave (Henshilwood et al. 2014), Rose Cottage (Gibson et al. 2004), and Sibudu Cave (Hodgskiss 2013), and at numerous smaller rock shelters and caves (Watts 1998b). One common observation regarding the ochre behaviours in the MSA is that ochre powder extraction becomes a habitual practice from approximately 160 kya onwards (d'Errico 2008; Wadley 2001; Watts 1999; 2002). This observation is accompanied by a spread of innovative lithic technologies and an intensification of resource gathering and region-focused social and cultural structures based on artefact typologies (Deacon and Wurz 2001; Henshilwood 2004; 2007; Wurz 1999).

Ochre use in the African MSA is often used as direct evidence to explore early hominin behaviours, such as the emergence of language that is frequently justified by the presence of ochre pigment (d'Errico et al. 2003; Watts 1999; 2009). Wreschner

(1976) argues that ochre powder was undoubtedly used as body paint to signify different social status and cultural groups. The use of colour is perceived as a crucial piece for solving the puzzle of the emergence of language. Whether or not hominins were forming precise syntactical language at such an early date is perhaps not the primary question; it is the use of colour as a direct message conveying information linked to cultural identities beyond functional necessities.

Ochre and the European Palaeolithic

The use of symbols and symbolic expression on material objects is widely associated with the European Upper Palaeolithic period (ca. 45-10 kya), where the regular use of red ochre as a pigment is considered to be one of the benchmarks of this time (White et al. 1982). It is in Europe where early theories regarding behavioural modernity flourished and is the location where the proposed first “cultural revolution” occurred (Bar-Yosef 2002; Mellars and Stringer 1989). In 1988, during the “The Human Revolution: Behavioural and Biological Perspectives on the Origins and Dispersal of Modern Humans” conference in Cambridge (Mellars and Stringer 1989), the concept of behavioural modernity was widely regarded first to appear in Europe with the arrival of anatomically modern humans into the continent, around 45 kya (see McBrearty and Brooks 2000; Stringer 2007). Accompanied by the presence of *H. sapiens sapiens* in Europe was an abundance of symbolic material such as cave paintings, carved figurines, sophisticated organic and stone tool technology, and the first known musical instruments (Backwell and d’Errico 2005; Conard 2003; Conard et al. 2009; Zilhão 2011). This material culture was labelled as the standard of measure for behavioural modernity, much of which was derived from the comparison between the Middle Palaeolithic techno-complex and *Homo neanderthalensis* populations, and subsequent Upper Palaeolithic cultures belonging to *H. sapiens* (Henshilwood and Marean 2003; Hopkinson 2013). Based on these assumptions, the development of “fully symbolic *sapiens* behaviour” was perceived as a punctuated event, beginning abruptly with *H. sapiens* and thus discrediting the integrity of archaeological assemblages elsewhere. Even though the immediacy and abundance of materials remain unique to Europe (Conard 2008; d'Errico 2003), the concept of the Cultural Revolution having a European epicentre has now become largely discredited within the last two decades. This was preceeded by the discovery of much earlier evidence of similar material culture in other regions, such as southern Africa (Henshilwood et al.

2002; Wadley 2003; Wurz 1999) and the Levant (Bar-Yosef and Vandermeersch 1993; Hovers et al. 2003b; Zilhão 2007).

In Europe, the earliest evidence for ochre use are from Middle Pleistocene sites Terra Amata near Nice (France), Bečov (Czech Republic), and Ambrona (Spain). Terra Amata was originally excavated by de Lumley in 1966 (de Lumley and Boone 1976), and dated to 400 kya. Around 75 pieces of ochre in varying shades of yellow, brown and red were recovered from a supposed hearth context and were thought to be an early instance of colour manipulation by archaic hominins during the Acheulean (Marshack 1981). The stratigraphic integrity of the site and the manipulation of fire by hominins has since been questioned (Roebroeks and Villa 2011; Villa 1983), with suggested dates of 350-280 kya instead of 400 kya. The ochre assemblage is only briefly mentioned as having "…marks of wear on the ends of the pieces evidence their use," which Schmandt-Besserat claims may suggest "…body paint…either way, early humans may have conferred a special meaning on it" (1980127). A recent reassessment has shown a range of ochre types were collected and brought back to the site from up to 50 km away, provided evidence of anthropogenic modification on nine pieces and identified the possible heat-alteration of one hematite nodule (de Lumley et al. 2016).

The Bečov site in the Czech Republic dates to ca. 250 kya, and contains artefacts attributed to Neanderthals. One piece of red ochre showing striations on two surfaces and a flat "rubbing" stone showing signs of abrasion in the centre were found (Fridrich 1976). Of the "grinding" stone, Marshack (1981) claims it was ground "…clearly in the preparation of ochre" (1981188). However, there are no traces of ochre on the supposed grinding stone, though it was recovered in the same context as the ochre piece. This grinding stone remains the only definite ochre artefact found at the site and has not been reexamined since Marshack's initial evaluations (Marshack 1981; Marshack et al. 1979). At Ambrona in Spain, also 250 kya, excavators recovered a single large slab of red ochre that exhibited possible shaping by the removal of some corners of the stone (Howell 1966). These early reports, no matter how sceptical or ephemeral, were lifted by the direct association of ochre to symbolic behaviour. However, their contexts and stratigraphies were circumspect and were not convincing evidence of pigment manufacture. A more systematic approach assessing the setting of these earlier finds, and when and where definite ochre use occurred, might bypass previous misinterpretations, and perhaps let the archaeological material speak for itself.

The oldest reliable evidence for ochre use by Neanderthals in Europe comes from Maastricht-Belvédère, dated to around 250-200 kya, where several discrete hematite concretions were recovered from sediments (Roebroeks et al. 2012). Following this, there was a ca. 100,000-year gap of relatively little evidence. Then, large ochre assemblages were found at Neanderthal sites in France dating to ca. 100-60 kya. These sites are Grotte du Renne (Beck et al. 2012), Pech de l'Azé I and IV (d'Errico 2008; Soressi et al. 2008), Ormesson (Bodu et al. 2014) and Roc-de-Combe (Dayet et al. 2014). During the Mousterian cultural sequence, more than 40 different archaeological sites are reported to contain some evidence for ochre collection, most dating to the very end of the Mousterian at 60-40 kya (Soressi et al. 2008). However, the majority report the presence of ochre materials and not necessarily modified artefacts. The use of manganese oxides, found at numerous Middle Palaeolithic sites, seems to be the preferred material utilised by Neanderthals (d'Errico 2008; d'Errico and Soressi 2002; Dayet et al. 2019; Roebroeks et al. 2012). It is possible that manganese was used functionally, as recent experiments have shown that manganese dioxide provides an excellent combustion agent to help to start fires (Heyes et al. 2016).

Regarding archaic humans, ochre appears in human depositional contexts from as early as 100 kya in the Levant at pivotal sites such as Skhul cave and Qafzeh terrace cave (d'Errico et al. 2010; Hovers et al. 2003a; Salomon et al. 2012b). Skhul cave contained many small (>1 mm) fragments of yellow-red ochre in the breccia deposits from layer B, where ten remains of archaic humans were also found. At Qafzeh, around five ochre pieces with different use-traces such as striations, micro-striations, scoring grooves, and flaking were found from layers dating to ca. 100 kya (Hovers et al. 2003b). Several lithics with traces of ochre on the hafting and working edge as well as cores with traces of ochre on the cortex and flake scars were also found (Hovers et al. 1997; Nowell et al. 2001).

The ochre contexts at Skhul and Qafzeh present evidence for the intentional heat treatment of ochre pieces (Salomon et al. 2012b; Watts 1999). The heating of ochre to temperatures surpassing 200°C can alter its colour, thereby increasing the range of colours available (Schmandt-Besserat 1980; Watts 1999; 2002). This active process of colour recognition and colour manipulation provides evidence for advanced cognition and the emergence of language surrounding the controlled transformation of material items (d'Errico et al. 2003; Watts 2009). However, the deliberate heat treatment of ochres is challenging to confirm archaeologically and can be problematic for the interpretation of such materials. This is particularly relevant in earlier reports, which have interpreted the presence of yellow and red ochres recovered near hearth features in Middle Palaeolithic and Middle Pleistocene sites as evidence for heat treatment, even if there are no other recovered ochre contexts (Leroi-Gourhan 1961; Marshack 1981; Wreschner 1985; Wreschner et al. 1980).

During the Upper Palaeolithic, there is a higher frequency of pure red ochre that is not restricted solely to hearth contexts. The problem lies in whether the heat treatment of ochres was so commonplace by the Upper Palaeolithic that the majority of red ochre pieces are the product of heat treatment, or perhaps research conclusions are too premature in the initial assessments of colourants located near hearth features. Salomon et al. (2012b) conducted numerous analyses on ochre artefacts from Skuhl Cave in Israel, dated to around 100 kya. She found that while in some contexts the heat treatment of ochres was not direct (and thus colour change was in isolated areas on the ochre piece), in others the pieces had undergone a thorough chemical and physical change in their colour and iron oxide content (Salomon et al. 2012b). She also noted that the heat-treated yellow ochres were gathered from sources around 80 km away, indicating preferential sources and a *chaîne opératoire* of ochre acquisition and processing. However, the presence of only one possibly anthropogenically modified ochre piece suggests that there may have been other reasons for this process than simply pigment or powder extraction (2012b719).

Ochre in Oceania

Ochre use in Australia was in place by at least ca. 42 kya (Bowler et al. 2003), but it may extend as far back as ca. 50-60 kya when humans were first believed to populate the continent (Clarkson et al. 2015; Malaspinas et al. 2016; Roberts et al. 1990). The Lake Mungo site in New South Wales yielded the oldest known burial site in Australia, where two individuals, Lake Mungo I and Lake Mungo III, were found (Thorne et al.

1999). Of particular interest is Lake Mungo III, where an interred male was sprinkled with ochre powder before the grave was filled in (Thorne et al. 1999). Elsewhere in Australia, 52 pieces of hematite fragments were recovered from levels dating to 50-60 kya at the Madjedbebe site in Arnhem Land, with over 5 kg of modified and un-modified pieces found in later (ca. 30-40 kya) levels (Clarkson et al. 2015; Roberts et al. 1990). Ochre pieces with signs of grinding striations were found at Sandy Creek 1 in the Cape York Peninsular, dated to 31,900 +7/-600 BP (Cole et al. 1995). Aside from physical ochre pieces, red pigment with no discernible design was found on a limestone slab at Carpenter's Gap in the Kimberley, dated to around 43 kya (O'Connor and Fankhauser 2001), and numerous *in-situ* rock paintings throughout the continent are present from 28 kya and onward (though the current oldest dated rock art has charcoal pigments and not red ochre) (David et al. 2013). The discovery of rock art dating to almost 50 kya at the Sulawesi site in Indonesia (Aubert et al. 2014; Aubert et al. 2018) further suggests that the use of ochre as a pigment in rock art is likely an ancient activity in Australia and Southeast Asia (Aubert et al. 2014; Aubert et al. 2018). This evidence, along with occurrences of red ochre at rock shelter sites in India (Petraglia et al. 2007), Southeast Asia (Langley and O'Connor 2019; Langley et al. 2016) and Australia (Clarkson et al. 2015; McDonald et al. 2018; O'Connor and Fankhauser 2001; Thorne et al. 1999) support the view that "…the first Australians brought pigment usage with them as part of their cultural experience and knowledge. In other words, ochre use was something they and their ancestors had engaged in before they arrived in Australia" (Taçon 200432-33).

Ochre in the Americas

Earth pigments also featured in both ancient and contemporary contexts amongst Indigenous groups in the United States of America (Eiselt et al. 2011; Koerper and Mason 1998; Roper 1992; Stafford et al. 2003), Canada (Bouchard and Kennedy 1986; MacDonald 2008; Teit 1930; York et al. 1993), and Central and South America (Darchuk et al. 2009; Fiore et al. 2008). Similar to Australia, ochre appears as a pigment for rock paintings, or pictographs, throughout the majority of North, Central, and South America (Chippindale and Nash 2004; Corner 1968; Gallardo et al. 1999; Gallardo and Yacobaccio 2005; Keyser 1992; Lundy 1974; Velliky and Reimer 2013; Velliky 2013; Whitley 2014; York et al. 1993). It was also found associated with burial contexts in some of these places (Ames 2005; Cooke 1998; Darchuk et al. 2009;

Darchuk et al. 2010; Matthews and Khahtsahlano 1955; Wise et al. 1994) and operated as a ceremonial and ritual item from ethnographic accounts in modern-day Canada (Bouchard and Kennedy 1986; Schaepe and Miller 2007; Teit 1930; York et al. 1993). Additionally, ochre was likely an important and valuable item for early Clovis groups in the USA, as a recent study shows transport distances of hematite nodules ranging up to 100 km in the Rocky Mountain region(Zarzycka et al. 2019). Red ochre is also a common feature in burials (Erlandson et al. 1999; Morrow and Trubitt 2016; Roper 1992), especially during the "red ochre burial complex" of the late Archaic to early Woodland period (3,000 – 150 BCE) in the Plains and Midwestern region of the USA (Cole and Deuel 1937; Esarey 1986; Ritzenthaler and Quimby 1962), as well as domestic spaces (Ruth 2013; Tankersley et al. 1995; Zoch et al. 1999) and other forms of artistic expression, such as painted bone artefacts (Frison et al. 2018; Roper 1992; Ruth 2013; Stafford et al. 2003; Tankersley et al. 1995).

In South America, the systematic mining of ochre took place as far back as 12,000 BP in Peru (Salazar et al. 2011) and continued throughout the remainder of the Holocene (Scalise and Di Prado 2006; Vaughn et al. 2007). From then on, its presence on the continent is vast, appearing as a pigment in rock paintings (Brook et al. 2018; Fiore 2018a; Fiore et al. 2008; Gallardo et al. 1999; Gallardo and Yacobaccio 2005; Sepulveda et al. 2012) and burial contexts (Darchuk et al. 2009; Darchuk et al. 2010; Villagran and Gianotti 2013; Wise et al. 1994), as well as artefact manuports at archaeological sites (Borrero et al. 1998; Cooke 1998). Ochre was still used by various indigenous populations when the continent was first visited by European colonists, specifically as body paint for marking social and group identity (Fiore 2008; 2018b).

Experimental Archaeology

Researchers have used experimental approaches to investigate ancient uses of ochre (Audouin and Plisson 1982; Hodgskiss 2010; Rifkin 2015a; Rifkin et al. 2015; Wadley 2005a; 2005b). A primary purpose of these studies was to exemplify the applicability of ochre as a functional material, as it is often categorised as ritual or symbolic. This categorisation is likely because ochre as a symbolic component is more observable archaeologically through the mediums of rock art, burial contexts, and paint on portable art and ornamental objects. The archaeological experiments on ochre have demonstrated its use as a hide tanning agent (Audouin and Plisson 1982; Wadley

2005b), as a hafting adhesive for stone tools (Lombard 2007; Lombard and Parsons 2011; Wadley 2005b; 2009; Wadley et al. 2004), as a textured medium to grind and polish objects (White 1997), as a preservative or drying agent (Bahn and Vertut 1988; Marshack 1981), and for various medicinal purposes (Velo 1984; Velo and Kehoe 1990).

For hide-tanning, red ochre effectively preserves the suppleness of organic tissues, prevents them from putrefaction and decomposition, and can reduce collagenase or enzymes that contribute to the decomposition process (Bahn and Vertut 1988; Velo 1984; Wadley 2005b). As an adhesive for weaponry, Wadley (2005b11) states that ochre provides an efficient filler for a plant resin-based adhesive, as it "dries faster than unloaded resin" and "looks stronger, more homogeneous, and less brittle" than pure resin-based adhesives. The ochre-loaded resin was more easily attached to a tool and was more likely to succeed during the drying process than unloaded resin. Rifkin et al. (2015) conducted experiments on the efficacy of red ochre as a protectant against UVR exposure. He justified these experiments by the potential adaptability to a changing climate, as well as the persistence of applying red ochre to the body in modern-day groups in Angola, Namibia, and Ethiopia (Rifkin 2015b). He found that ochres with smaller grain sizes and a higher iron oxide content contained the highest SPF factor of around 10, without preventing the absorption of vitamin D. However, he also noted that while the protective factor of ochre may have been advantageous during a fluctuating climate, the Ovahimba tribe in Namibia who still routinely cover their bodies with red ochre (*otijse*) only noted this functional capacity as a supplementary benefit to their primary ritual use (Rifkin et al. 2015).

Some of these more utilitarian-focused experiments were met with critique. In response to Wadley’s (2001) suggestions that ochre could have been used for practical tasks, which may explain the large amounts of ochre materials found at MSA sites, Watts (2002) argues that practical experiments do not provide sufficient evidence to suggest that ochre has a preservative effect. Therefore, ochre use in hide-tanning was exclusive to the end stage of decoration for its colour, which he supports with ethnographic data (see Watts 1998b). He also states that ochre use for sun protection and for repelling insects are questionable until it is proven that no other clay or mud sediments are shown to provide a similar amount of protection (Watts 20024).

Though Watts raises several important points, he presents somewhat contradictory arguments. Watts' has suggested and supported several possible theories regarding ritual ochre use, such as the Female Cosmetic Coalition hypothesis (FCC) (Watts 2002; Watts et al. 2016) and the association of ancient ochre use to present-day cultural rites such as in the Khoisan of South Africa (Watts 2002). He claims that in many of the South African sites where ochre was found, there is little evidence for functional use, yet states that the presence of ground ochre stones provides direct proof of symbolic uses. He is quick to compare Khoe-San ochre use during menarcheal initiation ceremonies to hypothetical social structures during the MSA (Watts 2002147), thus spurring the FCC theory and negating potential practical uses for ochre, or at least suggesting practical uses were secondary to ritual ones. Instead of trying to find convenient connections between cultural groups separated by over 80,000 years, we should perhaps consider the available evidence on ochre holistically and work towards uncovering the entire range of uses based on testable hypotheses.

Other avenues of experimental archaeological research have explored the use-traces left behind on ochre materials by ancient humans, and to what extent these occur as a by-product of pigment acquisition versus post-depositional processes. Hodgskiss' experimental work (2010) on modern ochre pieces provides a framework to properly identify use-traces resulting from grinding, scoring, and rubbing activities on archaeological ochre pieces. She then applied the results to archaeological ochres from MSA layers at Sibudu Cave (KwaZulu-Natal, South Africa) (Hodgskiss 2013). Using her reference collection, she observed various nuances related to use-traces on ochre, such as that grinding is the only form of modification which greatly alters the shape of the ochre piece, and that scoring produces the least amount of pigment powder compared to grinding and rubbing. She has also suggested that non-visual qualities, such as texture, grain size, iron content and friability, might have driven preference over colour. One significant result of these demonstrations is the variability in the uses of ochre outside of what we consider to be artistic or symbolic contexts. These studies do not imply ochre was never used in symbolic or ritual contexts, but the experimental results show that ancient uses of archaeological materials should not be assumed, and rather tested, explored, and expanded.

Ethnographic Research

Ethnographic investigations with contemporary indigenous groups have provided evidence for the customary use of ochre in Australia, throughout Africa, and in North and South America. In these present-day contexts, researchers reported that ochre operates not only as a functional material (Rifkin 2015a; Rifkin et al. 2015), but also as a pigment for rock art and in symbolic, ritual, and ceremonial contexts, both historically and today (Gould 1968; Huntley et al. 2015; Huntley 2015; Rifkin 2015b; Rudner 1982; Smith et al. 1998; Taçon 2004).

Red ochre was reportedly used primarily for ritual and ceremonial purposes from the onset of human occupation in Australia, as it is widespread as a portable and parietal art pigment. During the first records of European arrival to the continent, the use of ochre by Aboriginal Australians was noted by several explorers, one stating "…all of them with bodies daubed over with red," (Taçon 2004, referencing Macknight 1969:43). Red pigments were regularly used as body paint, to signify different features on the landscape, on rock walls as rock paintings, on personal objects and ornaments, ceremonial and even functional objects (Taçon 2004). Taçon also discusses an experience at a series of funerals in Kakadu National Park, where "Red pigment mixed with water was routinely smeared on the upper arms of all attending in order to protect mourners from evil spirits thought to be lurking nearby" (2004:35). He describes how the surrounding houses, trees, and cars from the deceased were all adorned with red or yellow lines. Mineral pigments are found in high quantities at archaeological sites throughout the Pleistocene and Holocene, which suggest widespread use of red ochre at the onset of human occupation in Australia and continuation to modern-day indigenous groups (Balme et al. 2009; Clarkson et al. 2017; Mulvaney 1978; Noetling 1909; White et al. 1982).

In North America, the ethnographic documentation of ochre is well represented in Canadian First Nations groups, where red ochre was a common cultural material used in potlatches, ceremonies, and ritual contexts, and as such, it was a valuable trade item (Keyser 1992; Matthews and Khahtsahlano 1955; Teit 1896; Teit 1930). In Canada, and specifically the Pacific Northwest, recent research incorporating geochemical techniques has suggested that local sources of ochre were accessed extensively, and perhaps preferentially, over time (MacDonald 2008). Ethnographic insight in the region has revealed that mineral sources, including ochre and obsidian, were preferred based on their proximity to spiritually significant places, and thus were also symbolically charged by their geographical and ritual association to certain place-names (Bouchard and Kennedy 1986; Reimer 2012; Velliky and Reimer 2013). The use of ochre was not transient and ephemeral, rather, sources were known, sought after, and use was based on a specific range of attributes. The acquisition and subsequent use of ochre need not always be as simple as accessing a nearby source; rather, specific attributes, such as colour, texture, friability, and spiritual potency are often important factors in regards to source preference (Lewis-Williams and Pearce 2004; MacDonald 2008; Reimer 2012).

Amongst the Coastal and Interior Salish groups of Western Canada, the colour red held special spiritual significance and was almost always used for paint in ceremonial practices (Leechman 1937; Teit 1930; York et al. 1993). Throughout James Teit's extensive ethnographic work with Salish bands, he notes that the colour red was perceived as "good" and that it "…expressed life, existence, blood, heat, fire, light, day. Some say it also meant the earth. It also appears to have had the meaning self, friendship, success…" (Teit 1930418). A more recent ethnographic interview with Annie York of the Nlaka'pamux people expressed the use of red ochre as a symbol of life and for the protection of life (York et al. 1993). Ochre, and specifically red ochre, is the most abundant rock art pigment used throughout Canada, with rare exceptions of black and white (Keyser 1992). The range of ochre uses in North America mirrors that of Australia; it was employed in burials, as a trade item, for ceremonial and ritual events, and as a frequent pigment in rock paintings throughout the country (Ames 2005; MacDonald 2008; Matthews and Khahtsahlano 1955; Mitchell and Donald 1988; York et al. 1993).

In the United States, ethnographic data are scarcer, but the tradition of rock art is prevalent throughout the entire country (Chippindale and Nash 2004; Loendorf et al. 2005; Whitley 2014). Different shades of ochre (dark red, red, orange, yellow) were extensively used as rock art pigments in the American Southwest and Great Basin (Keyser 1992; Keyser and Poetschat 2004; Quinlan and Woody 2003; Schaafsma 1986; Whitley 1998; 2000), but is also found as a pigment in the Southeast (Faulkner et al. 2004; Simek et al. 2013), Great Plains of the USA and Canada (Keyser 2004;

Keyser and Klassen 2001); Northeastern Woodlands of the USA and Canada (Brown 1997; Lenik 2002; 2010), the Canadian Shield (Arsenault and Zawadzka 2014; Rajnovich 2002) and Pacific Northwest (Lundy 1974; Teit 1896; York et al. 1993).

Analytical research has been conducted on rock paintings in North America (Bu et al. 2013; Edwards et al. 1998; Newman and Loendorf 2005; Velliky and Reimer 2013) and South America (Sepulveda et al. 2012) to identify their specific chemical constituents and to promote scientific dating of rock art sites (though this relies primarily on the presence of organic binders and charcoal pigments) (Rowe 2009; Steelman and Rowe 2012; Steelman et al. 2002). Similar studies have also been conducted on ochre nodules at North American sites, in attempts to identify trade and migration patterns throughout the landscape (Eiselt et al. 2011; Erlandson et al. 1999; Kingery-Schwartz et al. 2013; MacDonald 2008; 2016; MacDonald et al. 2018; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007; Zarzycka et al. 2019). This emphasis on using analytical techniques to approach rock art pigments, and ochre materials more generally, is not a new approach (Erlandson et al. 1999; Jercher et al. 1998; Kukkonen et al. 1997; Singh et al. 1978; Smith et al. 1998). However, due to recent advancements in analytical technology, new techniques have emerged, and the range of testable hypotheses on ochre use and procurement have broadened.

Geochemical Studies

Geochemical techniques, including Instrumental Neutron Activation Analysis (INAA), X-ray diffraction (XRD), X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and Raman Spectroscopy, to name a few, have been used to explore questions related to locating the origin of ochre materials at archaeological sites and their movement in the landscape. Such research projects include assessing the geochemical variability of archaeological ochres (Bernatchez 2008; MacDonald 2008), comparing the physical properties of source material (Erlandson et al. 1999; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007), and analysing rock art pigments to gain insights into behaviours surrounding rock art creation, ochre acquisition, and dating potentiality (Bu et al. 2013; Koenig et al. 2014; Newman and Loendorf 2005; Rowe 2009; Velliky and Reimer 2013).

Geochemical characterisation and provenance studies offer another line of insight into ochre use patterns and can highlight spatial and regional trends of ochre acquisition. Studies in North America (Eiselt et al. 2011; Kingery-Schwartz et al. 2013; MacDonald et al. 2018; MacDonald et al. 2013; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007) suggest that early humans selected types of ochre for certain visual and physical qualities (MacDonald 2008) and that certain ochres were transported up to 100 km in the landscape (Zarzycka et al. 2019). The proximity association of minerals to symbolically laden areas in the landscape (Reimer 2012) and the preference of one ochre source over time were also selection factors for ancient groups (Popelka-Filcoff et al. 2008; Sajó et al. 2015a). Similar studies in southern Africa have explored the geochemical variability of regional ochre outcrops (Dayet et al. 2016; Dayet et al. 2013; Hughes and Solomon 2000) and identified organic binders in ochre mixtures, suggesting its use as a paint (Villa et al. 2015). Similar studies characterised ochre paint and pigment sequences in rock paintings using non-destructive techniques (Rifkin et al. 2016; Tournié et al. 2011). Other research focused on identifying the natural or human origin of ochres at archaeological sites (Gialanella et al. 2011), evaluating different analysis techniques (Popelka-Filcoff et al. 2008; Sajó et al. 2015a; Zipkin et al. 2015), assessing the presence of heat-altered ochres (Salomon et al. 2012b) and different mineralogical varieties (Dayet et al. 2016; Iriarte et al. 2009). Thus, it is apparent that geochemical techniques provide a valuable outlet for exploring the physical properties of ochre, meanwhile enhancing symbolic inference and ethnographic associations.

Though these methods have been applied across the globe, systematic studies characterising ochres are so far lacking in comparison in central Europe and southern Germany. Furthermore, many of the existing studies focus on the analytical aspects without using these lines of inquiry to support larger theories on the behaviours surrounding ochre acquisition and use (Gialanella et al. 2011; Iriarte et al. 2009; Popelka-Filcoff et al. 2008). Thus, there is potential for this approach, and specifically in the German Swabian Jura given the importance of this region for early symbolic behaviours in the Middle and Upper Palaeolithic periods (Conard 2009; Conard et al. 2009; Hahn 1986). A more in-depth and holistic study of the ochre materials from the Swabian Jura, including a characterization of their chemical properties, should provide a more inclusive perspective on the milieu of early symbolic behaviour and the ways in which hominins interacted with and experienced ochre materials.

2.2. Southern Germany and the Swabian Jura

The Swabian Jura (German: *Schwäbische Alb*) is a mountain range bordering the Danube River, located in the modern-day state of Baden-Württemberg, Germany. This region is situated in a greater geological complex of the Jura Mountain range in Europe (Schiegl et al. 2003). The Swabian Jura forms the highest ridge of the Swabian-Franconian terrace country, which runs south-west to the northeast and rises from the Danube gradually, extending to the Neckar Valley.

This region is regarded as a key area in the early development of cultural and symbolic behaviours in humans and contains numerous Middle and Upper Palaeolithic sites (Conard 2003; 2011; Conard and Bolus 2003). The main areas of interest are two tributary valleys of the Danube (German: *Donau*), the Ach and Lone (German: *Achtal* and *Lonetal*). The known sites in the region are Sirgenstein, Brillenhöhle, Hohle Fels and Geißenklösterle in the Ach Valley, and Vogelherd, Bockstein (Bockstein-höhle and Bockstein-Törle), and Hohlenstein (Stadel and Bärenhöhle) in the Lone Valley (Figure 2.1). The Swabian Jura has a history of archaeological interest that extends back to the late 19th century, beginning with Oscar Fraas' excavations of Hohle Fels with Theodor Hartmann in 1870/71 (Fraas 1872; Hahn 1977; 1986; Riek 1934). However, many of the original finds were lost in World War II. In 1906, R.R. Schmidt excavated Sirgenstein Cave (Schmidt et al. 1912), which was the last major excavation in the Ach Valley until the 1950's when Gustav Riek and Gertrud Matschak opened a *sondage* in Hohle Fels (Blumentritt and Hahn 1991; Riek 1973; Wagner 1983). Following this, in the 1960s excavations were conducted at the nearby Brillenhöhle (Riek 1973) and Grosse Grotte, a large cave with Middle Palaeolithic deposits (Wagner 1983). Joachim Hahn and colleagues resumed research in the Ach Valley in 1973 with excavations at Geißenklösterle and Hohle Fels and were the first archaeologists to implement a systematic course of excavation following the French style (Hahn 1977). This work was continued upon his death in 1997 by Nicholas Conard and Hans-Peter Uerpmann with the University of Tübingen (Conard and Uerpmann 1999). At the time of writing, Nicholas Conard has continued excavations through 2019, focusing on the front apse of the cave, as well as deepening the active excavation units to Middle Palaeolithic contexts, and bedrock has still not been reached. Additionally, the Department of Ur- und Frühgeschichte in Tübingen conducts regular surveys each year in the Ach, Lone, and Lauchert Valleys, and will continue to excavate the sites alongside promoting archaeological research in the area.

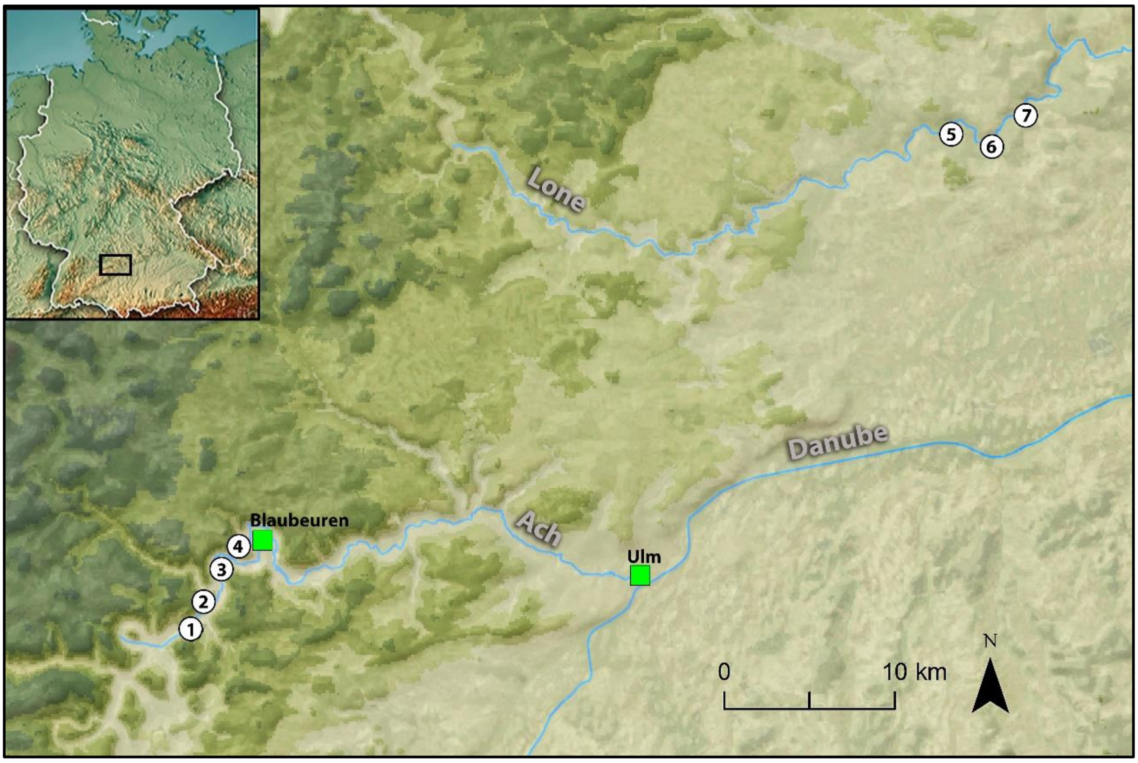

Figure 2.1: Map of southwestern Germany with the principal sites of archaeological interest. Ach Valley: 1 - Sirgenstein, 2 - Hohle Fels, 3 – Geißenklösterle, 4 - Brillenhöhle; Lone Valley: 5 - Bocksteinhöhle and Bockstein-Törle, 6 - Hohlenstein-Stadel and Hohlensteinhöhle, 7 – Vogelherd.

The assemblages from some of these sites characterise part of the earliest known emergence of the Aurignacian cultural sequence at ca. 42 kya, heretofore called the Swabian Aurignacian (Conard and Bolus 2006; Hahn 1986; 1988). The Swabian Aurignacian is unique in Europe for its distinctive specimens of figurative art, musical instruments, and lithic and osseous tools. It is because of these artefacts as well as their antiquity that the Swabian Jura, and more generally the Upper Danube, is considered a central region of cultural and technological advancement during the earliest part Upper Palaeolithic (Conard and Bolus 2006). Due to the wealth of organic and lithic artefacts and their age, several hypotheses were formulated to explain the emergence of such materials. The “Danube Corridor Hypothesis” (Conard and Bolus

2003) proposes that early anatomically modern humans migrated into eastern and central Europe via the Danube River Valley, likely due to it being a major waterway with a hospitable climate and an abundance of resources. This proposed trajectory of anatomically modern humans is supported by radiocarbon dates from archaeological sites in the region (Higham et al. 2012; Richter et al. 2000) as well by the movement of lithic raw materials across the landscape following major water routes (Burkert and Floss 1999; Conard and Bolus 2003).

While establishing the processes of the initial and ongoing settlement of the Swabian Jura is one crucial aspect of research, another is developing an understanding for the people responsible for the creation of the Aurignacian archaeological assemblage. This sudden and focused emergence of such archaeological material was justified under a proposed theory dubbed the *Kulturpumpe* model. In brief, the *Kulturpumpe* model offers three working hypotheses that account for the early onset of technological, symbolic, and artistic material culture found in the Swabian Jura. First, the cultural fluorescence that facilitated advanced stone tool technology and symbolic expression is the result of direct competition between modern humans and Neanderthals after entering the region via the Danube Corridor ca. 40 kya. Second, these cultural innovations are the response of severe climatic stress and fluctuations within a short time-frame during OIS 3; and lastly, none of these cultural innovations are the result of competition with Neanderthals in the region and are the result of socio-cultural and demographic shifts during the Aurignacian and Gravettian (Conard 2002; Conard and Bolus 2003).

Though these hypotheses are not mutually exclusive, it is unlikely that there was direct competition between anatomically modern humans (AMHs) and archaic humans (Neanderthals), as several sites (Hohle Fels, Geißenklösterle, Sirgenstein and Vogelherd) in the region report a stratigraphic hiatus between Middle and Upper Palaeolithic deposits. These hiatus periods lead to the formation of another hypothesis, the *Population Vacuum model*, which proposes that AMHs migrated into the Swabian Jura after the departure of Neanderthals from the region following a dramatic cold snap (Conard 2011; Conard et al. 2006). The proposed lack of cultural mixing between Neanderthal and human populations in the Swabian Jura is also supported by the absence of transitional material culture, such as the Châtelperronian, in the region. Furthermore, there are few consistencies between the lithic technocomplexes of these two populations (Conard and Bolus 2003; Conard et al. 2006).

2.2.1. Hohle Fels in Focus

Hohle Fels cave (also written as Hohler Fels) sits on an eastern expansion of the Swabian Jura, which belongs to the larger European geological formation of the Jura Mountain range. The European Jura consists of Jurassic limestones and houses numerous characteristic karstic landscape features such as caves, dry valleys, underground watercourses, and sinkholes (Geyer and Gwinner 1991; Goldberg et al. 2003; Miller 2015; Schiegl et al. 2003). The landscape and geology of the Swabian Jura and specifically the region near Hohle Fels is the result of extensive erosional processes and weathering since the Cretaceous period due to severe climatic fluctuations (Borger et al. 2001). Of particular note are the characteristic *Bohnerze,* or pebbles of iron ore consisting of limonite or goethite (Reiff 1993; Schall 2002). These mineral formations are found embedded in kaolinite clay and quartz sand in karstic fissures and solution pits, and represent a formerly widespread *Bohnerz* sheet across southern Germany (Ufrecht 2008). Alongside with the *Bohnerze* deposits is *Bohnerzlehm*, an iron-rich silty clay consisting of mostly kaolinite. Both of these features are the result of the weathering and dissolution of transported foreign sediments through the limestone bedrock. Similar erosional and uplift effects during the Pliocene and Pleistocene caused karstic pits in the region to fill with lateritic materials and hematite-rich laterite pebbles (Borger et al. 2001). Other geomorphological studies in the area have found patches of red clay and hematite layers throughout the limestone beds, and also iron-oxide enriched sediments (Koch et al. 1994). The presence of red clay and hematite layers in the limestone, along with patches of weathered lateritic sediments, are strong indicators that there are many red ochre and hematite sources in and around the Swabian Jura.

As of 2019, the only ongoing excavation in the Ach Valley (German: *Achtal*) is at Hohle Fels. It is approximately 534 m above sea level, with a north-facing entrance. It lies between the towns of Blaubeuren and Schelklingen (48.379250N, 9.755528E) within a tor (German: *Felsen*) of Jurassic limestone, and at more than 6000 m^3, is one of the largest caves in the Swabian Jura (Miller 2015). The excavation strategy organises the sediment layers into different Geological Horizons (GH), containing Archaeological Horizons (AH) corresponding to specific Upper Palaeolithic techno-complexes (Figure 2.2).

The stratigraphy in Hohle Fels extends to the Middle Palaeolithic (>44,000 cal yr. BP), followed by an early presence of the Aurignacian (ca. 44,200-34,280 cal yr. BP) (Conard 2009; Conard and Bolus 2008; Riehl et al. 2015). Following these contexts are Gravettian (ca. 34,400-32,000 cal yr. BP) and Magdalenian layers (ca. 16,700-13,500 cal yr. BP) (Riehl et al. 2015). The cultural stratigraphy begins with the uppermost Magdalenian layers AH I and AH IIa, dated to around 13 kya (Taller 2014). Directly below the Magdalenian are the Gravettian layers AH IIb (though IIb might be a transitional layer between the Magdalenian and Gravettian), IIc, IIcf, and layers IId and IIe which chronicles a transitional layer between the Gravettian and Aurignacian (ca. 34,500-32,500 cal yr. BP). The Aurignacian complex contains the sequences AH IIIa, IV, and V, which have yielded many of the figurative art and symbolic artefacts (44,200-34,280 cal yr. BP). Between the Aurignacian and Middle Palaeolithic layers, there is a ca. 30 cm sterile layer suggesting an unoccupied cave during this transition. Hohle Fels is currently still being excavated in the front portion of the cave, and excavations will likely continue through the Aurignacian and Middle Palaeolithic layers until bedrock is reached.

The Magdalenian of Hohle Fels (16.5-14.5 kcal. BP)

The Magdalenian layers are 20-60 cm thick and comprise a total area of ca. 40 m^2. Sediment redistribution caused by cryoturbation has prevented the formation of a detailed stratigraphy (Conard and Floss 2001). These geogenic processes further complicate dating the Magdalenian sequences, as much of the stratigraphy was mixed or eroded out of the cave. Stratigraphic mixing is apparent in the topmost horizon, which contains Neolithic and metal age ceramic pieces along with Magdalenian artefacts. Mixing may also have resulted from disturbance during the Holocene, as the cave was often used as a social space as well as serving as an army bunker during WWII. Even so, the layers have yielded numerous lithic and organic tools, as well as a significant faunal record displaying the diet of the occupants during the Magdalenian (Münzel et al. 2001).

Typical of the Magdalenian culture throughout Europe, numerous bone and reindeer antler tools, such as harpoons and projectile points, characterise the sequence. A number of the lithic artefacts were made with local *Jurahornstein* (a type of chert) and radiolarite, though non-local raw materials also frequently occur (Burkert and Floss 1999). Worked pieces of ivory, perforated fox and badger teeth, freshwater snail shells and transported saltwater shells display evidence for personal ornamentation and long-distance transportation (Rähle 1994). Horse and reindeer provided a significant portion of the Magdalenian diet, as well as fox and hare (Münzel and Conard 2004b). Cave bear bones frequently occur in the Magdalenian, though they likely did not form a substantial part of the overall diet.

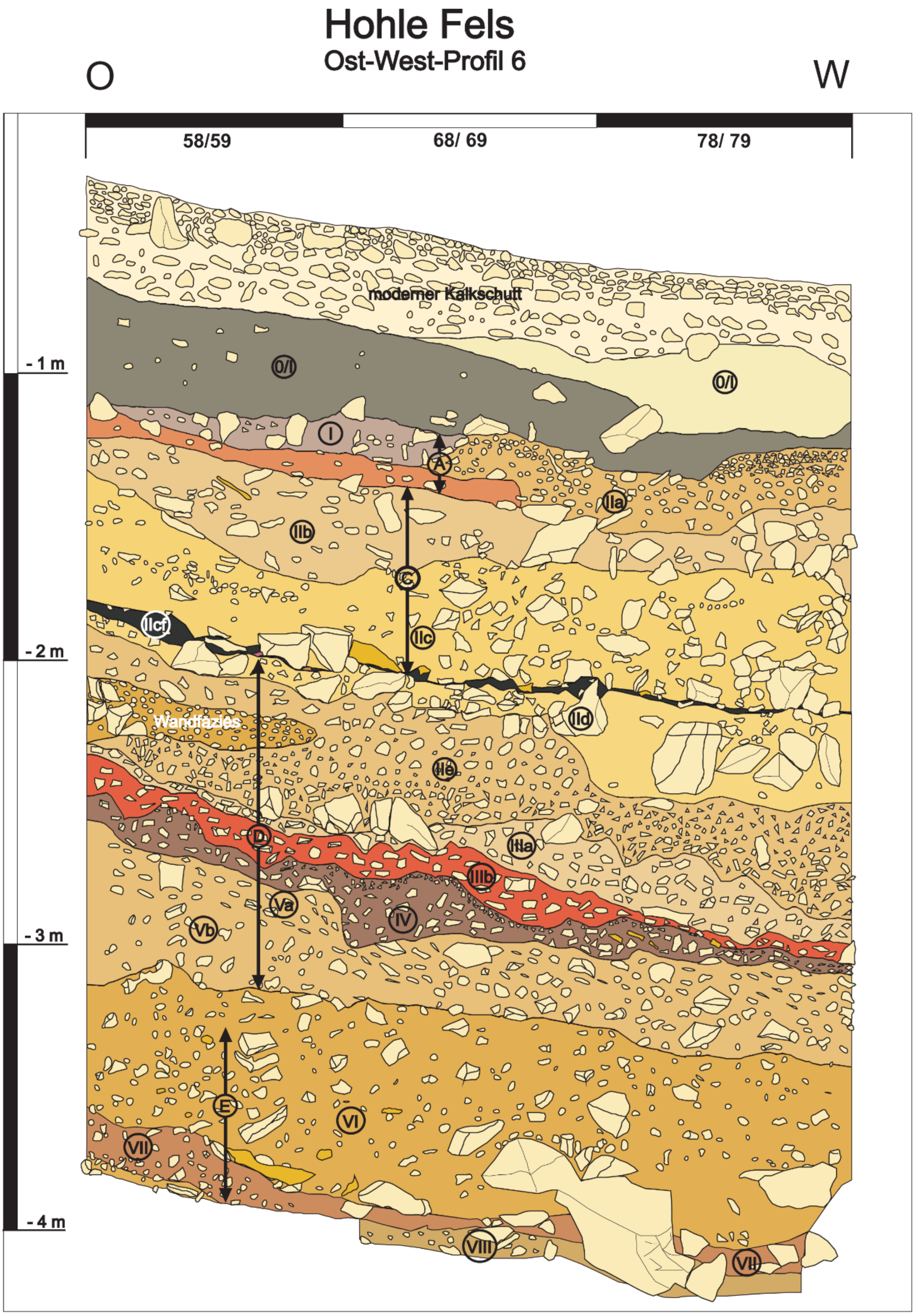

Figure 2.2: Detailed schematic of Hohle Fels cultural stratigraphy (AH). AH's A = Magdalenian, C = Gravettian, D = Aurignacian, E = Middle Palaeolithic.

Ochre artefacts from the Magdalenian

In total, six painted rocks, including limestone and dolomite materials, have been found in the Magdalenian layers (Conard and Floss 1999; Conard and Malina 2010; 2011; 2012; Conard and Uerpmann 2000; Floss and Conard 2001). All of these pieces contain traces of red ochre arranged in a series of painted rows of dots. The rows occur in pairs and range from 1-3 pairs on each stone (Figure 2.3). One piece, uncovered in 1998, is made of the same Jurassic limestone in which the cave is situated. This piece might have originally been attached to the cave wall (Conard and Floss 1999). Two of the limestone fragments (b and c, in Figure 2.3) are rounded and do not refit with any of the other pieces or the cave wall. Their material and lack of refit suggest that instead of sourcing from the interior of the cave, it is possible that they are river cobbles from the Ach (located directly outside of the cave) or the Danube rivers. The stones come from layers AH I and IIad and contain some of the better-preserved series of rows of dots on the painted stone assemblage. It is likely that the overall designs were larger and contained numerous designs, whether they were stylistically similar or not. The lack of preservation of painted stone fragments is probably due to the deterioration of the cave walls in this Karstic region, which are subject to expansion and retraction during the warming and cooling phases of the climate, as well as erosional processes (Conard and Uerpmann 2000).

The patterns on these painted rock fragments are similar to other painted stones from southern Germany, which collectively seem to display some cultural or artistic trend. The painted limestone pieces recovered from the Klausenhöhlen (a series of cave sites located in Bavaria near Essing) also contain several pairs of rows and groups of painted red dots, which are almost identical in style and form to the Hohle Fels samples. The five different artefacts are of limestone, some with rounded edges which may be flow-stones. Others are flat and referred to as *Platten*, or plates or sheets. They were recovered from different caves within the compound area, yet all date from the Magdalenian. A similarly painted limestone artefact was retrieved from another site in Bavaria, Kleine Scheuer, also dating from the Magdalenian and also featuring three rows of small red dots in pairs (Huber and Floss 2014). As of yet in Germany, no other painted designs have been found in any cave interior or open-air site, though rock engravings were recently described along the Rhine and stylistically dated to the Palaeolithic (Welker 2016).

Other rounded stone pieces, called *Gerölle,* bearing traces of red colourant are documented from the earlier excavations at Hohle Fels. In her unpublished MA thesis, Saier (1994) describes five *Gerölle* with red pigments in different arrangements, mostly on the broken surfaces. She notes their similarities with the types of painted patterns on previously studied Azilian pebbles in France, Spain, Italy and Switzerland (Couraud 1985). Similar artefacts in Italy have been suggested to be associated with funerary rites, specifically in "breaking" the pebbles on their painted surfaces (Gravel-Miguel et al. 2017).

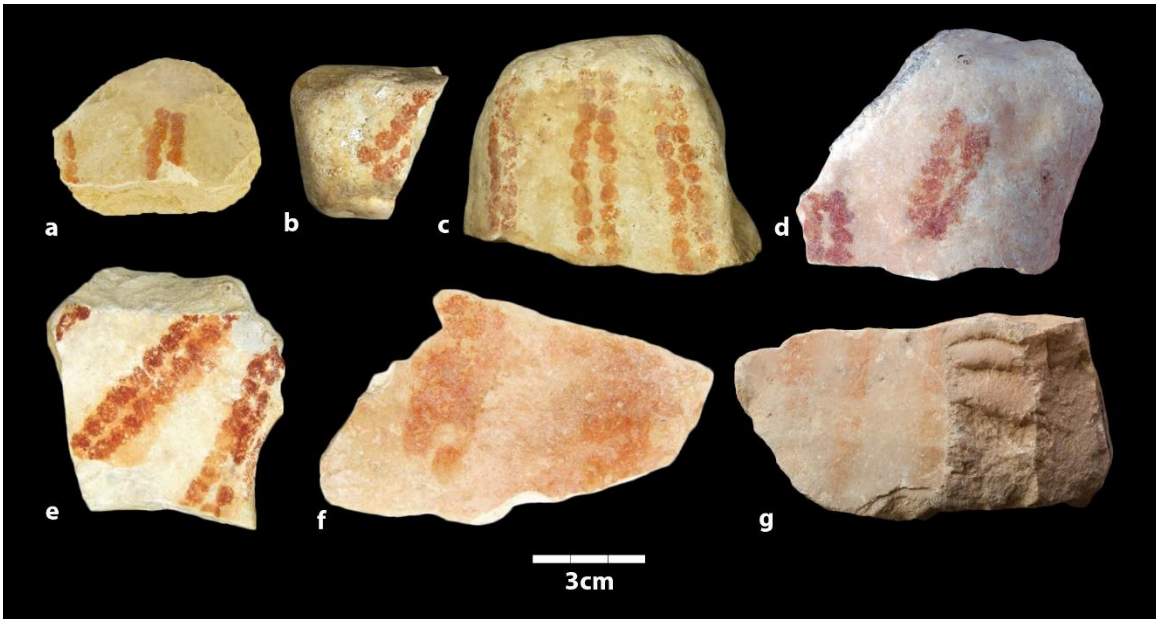

Figure 2.3: Painted limestone fragments from the Magdalenian of Hohle Fels. Find numbers: a) limestone, #44.92 b) limestone, #110.985, c) limestone, #135.197, d), limestone, #55.253, e) dolomitic limestone, #102.487, f) dolomitic limestone, #102.495, g) dolomite, unknown provenience, From Conard and Uerpmann, 1999; Conard and Floss, 1999; Conard and Malina, 2010; 2011.

Faunal elements with traces of ochre are also reported from the Magdalenian levels of Hohle Fels (Floss and Conard 2001). In total, three specimens have been identified, each of a different species. One long-bone recovered from AH Ib displays two large oblong smudges of red ochre (Figure 2.4a). A fragment of a reindeer cranium contains traces of red ochre powder on the interior (Figure 2.4b), from layer AH Ia. A cave bear temporal fragment (Figure 2.4c) from AH IV contains traces of red residues in the concavity of the fragment and provides possible evidence for ochre use in the Aurignacian. The other faunal elements exemplify the potential use of ochre for a variety of purposes at Hohle Fels during the Magdalenian.

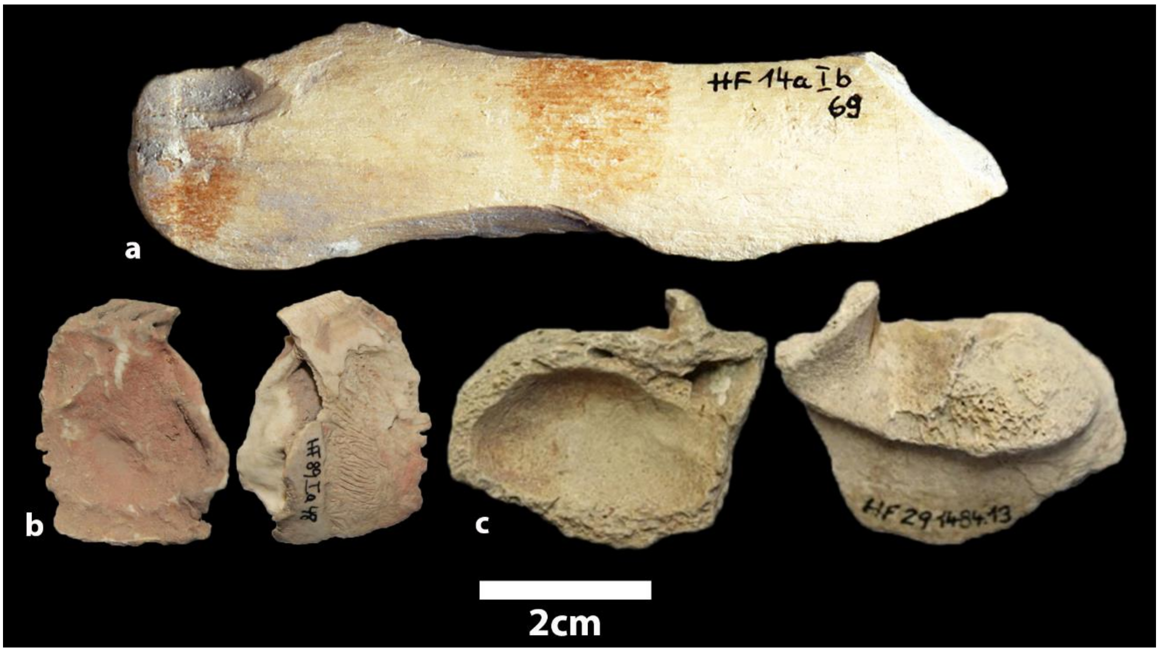

Figure 2.4: Previously reported faunal elements with traces of red residues. Artefacts are: a) Artefact #14.Ib.69, unidentifiable long bone fragment (original photo by H. Jensen, University of Tübingen), b) Artefact #89.Ia.48, reindeer cranium fragment, c) Artefact #29.IV.1484.1, cave bear temporal fragment (photos by A. Blanco, University of Tübingen).

The excavations of Hohle Fels in previous years revealed several anthropogenically modified ochre artefacts. In the years 2009 and 2010, five different pieces were recovered from Magdalenian contexts. Four of the five pieces are hematite with one likely being specular hematite (due to its glittery appearance), and the other piece is classified as “red chalk” (Figure 2.5b). The red chalk piece was recovered from AH Ib and contains deep striations on all four of its surfaces, and forms a “pencil” or “crayon” shape (though the tip of this piece does not seem to contain any evidence of modification that would suggest its use as a “crayon”). The specular hematite artefact is from AH Ic (Figure 2.5a) and has been burnished on two of its sides forming two faceted surfaces. The remaining three pieces appear to be of the same hematite material and were rounded into a circular shape with a perforation in the centre (German: *Rondelle*). Two of these pieces refit together, and it is possible that the third piece could be part of the same or another similar artefact. The exact purpose of this worked piece is unknown, though some hypotheses are that it served as some form of personal ornamentation, decoration, or a pigment source. Further analyses might reveal the exact nature of its unique shape (Figures 2.5c-d).

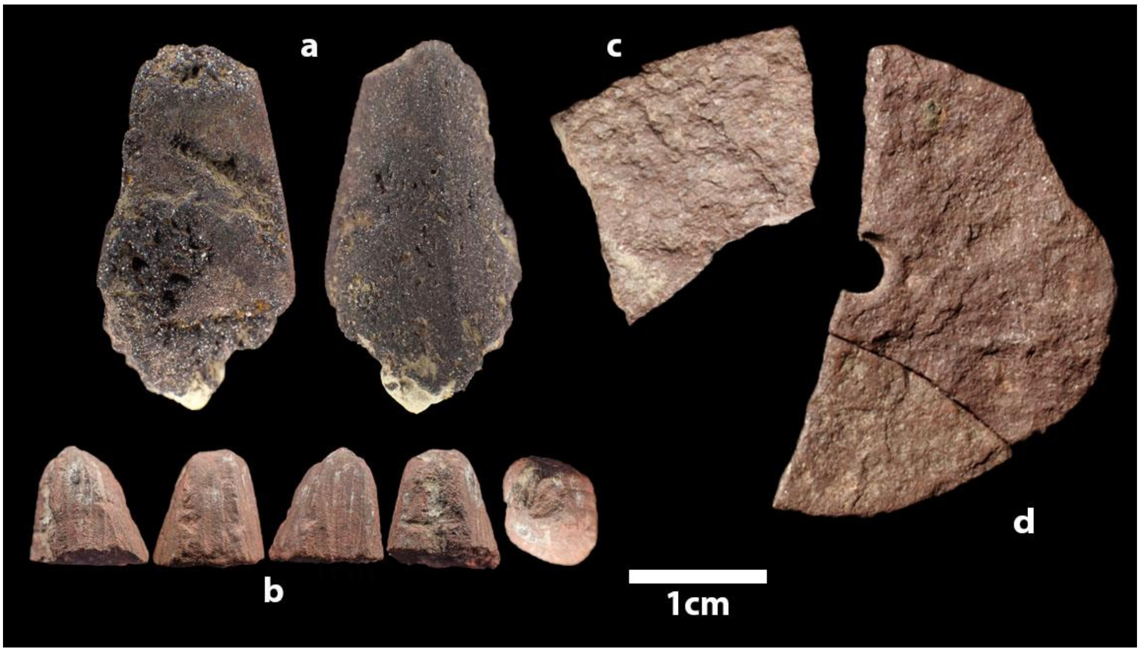

Figure 2.5: Previously found Hohle Fels ochre artefacts. From Conard and Malina, 2010; 2011: a) Specular hematite piece with two facets, #102.630.1; b) Red chalk "crayon" piece with four striated surfaces, #102.555.1; c) Rounded *rondelle*-shaped fragment, #110.434.1; d) Two refitted *rondelle* artefacts from hematite, #110.1104.1 & #110.992.

The Gravettian of Hohle Fels (34-30 kcal. BP)

The Gravettian layers at Hohle Fels are ca. 60-80 cm thick and so far amount to an area of 30 m^2 (Schiegl et al. 2003). The main occupational complex of the Gravettian dates to ca. 29 kya, and was a brief yet intense occupational period during the Upper Palaeolithic (Conard and Moreau 2004).

More than 90% of the lithic assemblage comes from local material sources, including *Jurahornfels* and *Bohnerzhornstein* from the Swabian Jura. Furthermore, 90% of these recovered lithics are unmodified debitage (Schiegl et al. 2003). Of the modified *débitage*, lithic cores, backed knives, burins, Gravette points, microgravette points, *fléchettes*, and end scrapers dominate (Conard and Moreau 2004). The organic tool sequence includes mammoth ivory projectile points, worked bone points, and bone *Lochstäbe* and burnishers. Ornamental tooth pendants, often canines but also incisors, from such species as fox, ibex, cave bear, and badger further characterise the assemblage. Pendants from snail shells, marine shells, and long bones with incision patterns are common (Conard 2003; Conard and Moreau 2004). The discovery of what is argued to be a phallus made from siltstone in the layer AH IIcf (a "dump" layer high in burnt bone and lithic debitage) appears to reflect a rare example of male sexual imagery during the Gravettian (Conard and Kieselbach 2006). It was also believed to have worked as a hammerstone and exemplifies the shift away from animal imagery in the Aurignacian to more anthropogenic imagery during the Gravettian. Male representations are generally less common in the Gravettian, which is characterised by female or "Venus" figurines throughout most of Western and Eastern Europe during this period (Conard and Moreau 2004; Hoffecker 2002; Soffer et al. 2000; Tripp 2016; White 1997).

In 2000, a cave bear vertebra with a lithic fragment of chert embedded in the bone was found. This artefact provides direct evidence that cave bears were actively hunted by the Gravettian occupants of the cave, though they were not likely the most prominent game animal. This was wild horse, followed by reindeer (Münzel and Conard 2004b). Much of the leftover fauna was used as fuel for fires and hearths, as evidenced by a large amount of burnt faunal remains in layer AH IIcf (Schiegl et al. 2003) as well as the noted decrease in woody flora which accompanied a cold snap following the Aurignacian (Miller 2015; Riehl et al. 2015). No ochre or ochre-related artefacts were previously reported from the Hohle Fels Gravettian.

The Aurignacian of Hohle Fels (44-34 kcal. BP)

Hohle Fels is particularly well known for its extensive and detailed Aurignacian cultural sequence. It is perhaps most well-known for the female figurine, the so-called "Venus of Hohle Fels" (~38 kya), which is currently the earliest known example of human representation in the form of a statuette worldwide (Conard 2009). A wealth of lithic and organic artefacts, three mammoth ivory figurines and three flutes out of bone and mammoth ivory were also recovered from Aurignacian contexts (Conard 2003; 2009; Conard et al. 2009). The Aurignacian layers at Hohle Fels consist of geological strata (GH) 5-8, archaeological horizons (AH) IIe-IV, and have so far yielded 6 m^3 of excavated sediment. A primary feature of the lithic assemblage is the predominance of *Jurahornstein* or the local Jurassic chert found throughout the Swabian Jura. The abundance (ca. 94% of the lithic assemblage) of this single material type points to evidence of strictly local procurement of mineral sources. There is a distinct lack of lithic debitage and cores, suggesting other locations for the knapping of raw materials (Schiegl et al. 2003). Ivory working debris and ivory artefacts are abundant throughout the Aurignacian and are characterised by exquisite figurines such as the *Wasservogel* (water bird), *Kleine Löwenmensch* (little Lion-man), and *Pferdkopf* (horse head)

(Conard 2003). In 2015, a perforated ivory baton, or *Lochstab*, was uncovered, providing evidence for rope manufacturing at the site (Conard and Malina 2015). Of the ochre and ochre-related assemblage from the Aurignacian, one temporal fragment of a cave bear was found with traces of red ochre residue on the interior (Figure 2.4c).

2.2.2. Ochre artefacts from other Ach and Lone sites

During his synthesis of ivory figurines from the Swabian Jura sites, Joachim Hahn claimed that several of the figures recovered from Vogelherd (Lone Valley) displayed traces of red powder (Hahn 1977). He suggested this may have been due to sedimentary processes, or perhaps from direct application. He also notes the possibility of ochre residues being used for tanning leather and hides. Additionally, several ochre pieces were found during the Vogelherd excavations and are currently on display at the Urgeschichtliches Museum in Blaubeuren.

The cave site of Geißenklösterle, located in the Ach Valley near Hohle Fels, contained Aurignacian layers that yielded many different and unique objects, including the oldest (40-42 kcal. BP) known musical instrument in Europe, a flute(Conard et al. 2009). Numerous lithic artefacts, faunal remains, and mammoth ivory figurines, such as the famous "*Adorant"*, were also found (Hahn 1988). One piece of limestone with traces of black, yellow, and red pigment was uncovered from the Aurignacian (Figure 2.6) (ca. 40 kya) (Hahn 1986). This piece has not been cleaned or studied extensively, though numerous similar artefacts were recovered from Hohle Fels. Moreover, in Hahn's volume on the excavations at Geißenklösterle cave (Hahn 1988), H. Gollnisch provides a short report on some 134 red and yellow ochre artefacts, including spatial and stratigraphic orientation, colour, and potential source locations (Gollnisch 1988). However, no collective synthesis of this material, from either the Ach or Lone Valleys, has yet been made.

Figure 2.6: Painted limestone piece from the Geißenklösterle Aurignacian. Artefact bears three different colours of pigment: red, yellow, and black.

2.3. Summary

The review of the literature and previously conducted studies provided in this chapter show the geographic and temporal breadth of ochre use in the hominin lineage. The current research history on the relationship between ochre and hominin populations is complex and multi-faceted. However, the appearance of ochre in early archaeological contexts is perhaps taken for granted, considering the intricacies of the definition of symbolism and modern behaviours, and how the manipulation of mineral pigments fits into this paradigm. In some cases, the presence of ochre pieces in ancient contexts is immediately regarded as symbolic. Without a robust assessment of the nature, context, and deposition of these artefacts, it is likely that some aspects of ochre behaviours are being overlooked or are remaining unobserved. This may in part be due to the close association of ochre by researchers to symbolism, complex cognition, and language development, and thus behavioural modernity. Regardless of the exact definition of cultural modernity, whether it is a human (Henshilwood and Marean 2003) or hominin (Zilhão 2007; 2011) trait, or even if it is discernable in archaeological assemblages (McBrearty and Brooks 2000), it is for certain that ochre was recognised and experienced by ancient hominin populations and possibly Neanderthals in a manner that suggests something more than ephemeral and transient behaviours.

Chapter 3. Theoretical Justification

> *It is significant that man in his early stages of biological or cultural development was attracted by ochre. H. presapiens, H. sapiens neanderthalensis, and H. sapiens sapiens have incorporated ochre into their social and cultural behaviour. Thus the long history of ochre in the evolution of man, besides expressing cultural activities, can be seen as a sociobiological element.*
>
> *Ernst Wreschner, 1976:718*

One of the most debated topics in archaeology and human evolution is the use of earth pigments as an indicator of symbolic behaviours. Symbolism and symbolic behaviours are regarded by many as the defining feature of behavioural modernity (d'Errico et al. 2003; d'Errico and Henshilwood 2011b; Henshilwood and Marean 2003; McBrearty and Brooks 2000; Nowell 2010). Behavioural modernity is the condition of resembling modern humans both cognitively and culturally; simply put, it seeks to answer the question of when did we begin to behave like we do today? Identifying behavioural modernity in the past is problematic, as issues of interpretation and identifying the exact nature of specific behaviours through limited material evidence present a considerable challenge and run the risk of being influenced by bias and subjectivity (d'Errico 2003).

Because of this ambiguity, research effort worked towards outlining a list of pieces of evidence that can assist in recognising modern behaviours archaeologically (Henshilwood and Marean 2003; McBrearty and Brooks 2000). Though the list varies depending on region and theoretical perspectives, the regular and consistent use or manipulation of earth pigments (specifically red ochre) is unanimously accepted as evidence for symbolic mediation, a defining feature of behavioural modernity. Therefore, it is necessary to provide a background on the theoretical origins on models of behavioural modernity and to discuss the role that ochre has played in discussions about symbolism, cognitive and cultural capacities, and how we identify and define modern human behaviour.

3.1. Behavioural Modernity: Competing models

The term modern human behaviour was first discussed by Noble and Davidson (1991) in reference to the emergence of language and how it impacted social structures, biology, and cognitive capacities. Modern human behaviour, or behavioural modernity, has since been extended to the point in which hominins became cognitively, socially, and behaviourally equivalent to the present-day human population (see d'Errico 2003; Henshilwood and Marean 2003; McBrearty and Brooks 2000; Nowell 2010; Wadley 2001). This concept is theoretically easy to grasp ("when did they become like us?"), however, defining precisely what modernity is and how we can identify aspects of it in the archaeological record entails a range of discussion topics between different schools of research including archaeology, primatology, linguistics, biology, palaeoanthropology, and cognition studies (d'Errico and Stringer 2011). The definition of behavioural modernity, and indeed the methods for identifying and describing this definition, is not unanimous; and in general, there exists an "…absence of a coherent body of theory defining modern human behaviour," (Henshilwood and Marean 2003:627). This lack of an established methodology to detail this definition is due to ambiguity in the theoretical development of modernity and how this transcends into physical traits and characteristics represented archaeologically.

Here, I will focus exclusively on behavioural modernity represented by cognitive, social, and cultural traits inferred from archaeological materials. Though researchers established early on the separation of biological anatomy and behavioural practices in regards to modernity (Mellars and Stringer 1989), some past theoretical models have incorporated anatomical modernity into this repertoire (Klein 1998; 2000). Other authors heavily critiqued this inclusion and questioned to what extent biological factors should influence our perception of modernity and whether anatomy can be modern without matching behavioural patterns and vice versa (Mellars 2006; Tattersall 2009). This critique centred on the noticeable delay between behavioural and anatomical modernity (Nowell 2010; Porr and Matthews 2017), as the physical evidence for certain behaviours is not as easily discernible as diagnostic features in the fossil evidence (Henshilwood et al. 2004) and is perhaps insufficient to what archaeologists consider behavioural modernity.

Of the models on the emergence and spread of behavioural modernity, the *Cultural Revolution model* (Bar-Yosef 2002; Mellars 1989; 2005; Mellars and Stringer 1989) was the first and persisted for quite some decades. It is, however, no longer considered valid due to its Eurocentric perspective as well as the emergence of older archaeological material elsewhere (Aubert et al. 2014; Aubert et al. 2018; Henshilwood et al. 2011; Henshilwood et al. 2009). In this model, behavioural modernity was a phenomenon first appearing in Europe with the arrival of anatomically modern humans (AMHs), ca. 43 kya (McBrearty and Brooks 2000; Stringer 2007). Archaeologists long supported this “cultural revolution” because of the immediacy and abundance of innovative and intricate cultural material found during the initial onset of the Upper Palaeolithic (d'Errico 2003; 2007). The artistic artefacts of the European Upper Palaeolithic, such as cave paintings, personal ornaments, figurines, and complex bone and stone tool technology thus became the benchmark that constructed the behavioural modernity technocomplex. Numerous authors have since criticised the *Cultural Revolution model* as Eurocentric, noting that it likely reflects a discontinuous archaeological record as opposed to an explosion of cultural innovation that accumulated at different speeds in different areas at different times (McBrearty and Brooks, 2000:454-456). Furthermore, it perpetuated the notion of behavioural modernity as belonging exclusively to *H. sapiens sapiens*, using certain traits and artefacts to further separate the record of Neanderthal and human behaviours (Hopkinson 2013; Nowell 2010; Speth 2004).

With the expansion of competing models (*Late Middle Pleistocene, Early Upper Pleistocene, and Gradualist*), the description of what constitutes modern traits have shifted to incorporate African archaeological materials. These models developed out of increasing awareness of the early age and abundance of archaeological materials in Africa, which were, in many cases, comparable and predated European assemblages (McBrearty and Brooks 2000). Of the African models for behavioural modernity, the larger and more widely accepted of these entail an African origin and subsequent spread through the Levant and into Europe. These are the *Early Upper Pleistocene model* (Deacon 2001; Deacon and Wurz 2001), the *Late Middle Pleistocene model* (Mellars 2006, 2007; Tattersall 2009) and the *Gradualist model* (McBrearty and Brooks 2000; McBrearty 2007). Not mentioned are the *Late Upper Pleistocene* and the *Late Middle Pleistocene* models (Mellars 2006; Tattersall 2009), which both include aspects of anatomical changes in brain capacity and are generally seen as an African version of the *Cultural Revolution* model. The wealth of organic artefacts, engraved objects, ochre pigments, personal ornaments, innovative lithic technology, and evidence for coastal adaptations from sites like Klasies River Mouth (Singer and Wymer 1982; Wurz 2002), Klein Kliphuis (Mackay and Welz 2008), Pinnacle Point (Marean et al. 2007), Blombos Cave (Henshilwood 2007; Henshilwood et al. 2002), and Diepkloof (Parkington et al. 2005; Porraz et al. 2013; Texier et al. 2010) all support an African origin of behavioural modernity during the Middle Stone Age (MSA).

However, the coherence of some aspects of these models, as well as the recognition of Africa as the birthplace of modern behaviours, has not been met without critique. The *Saltation model*, presented by d'Errico and Stringer (2011), acknowledges the large gaps in the African archaeological record, notably during the period in between the Still Bay (ca. 77-70kya) and Howieson's Poort (ca. 66-58kya) cultural sequences, as well as in between the Howieson's Poort and the Later Stone Age (LSA, beginning ca. 40kya BP; Lombard et al. 2012). Instead, d'Errico and Stringer argue for the influence of local conditions and demographics in the emergence, spread, and fluctuations of certain populations in different regions (d'Errico and Stringer 2011:1066). In a similar trajectory, Conard (2008) proposes the *Mosaic Polycentric Modernity* (MPM) model, which "…predicts that the spatiotemporal pattern of the evolution of cultural modernity is neither monocentric nor globally contemporaneous," and he urges us to shed the pursuit for a single origin of modern behaviours (2008:177). Modern behaviour and its encompassing traits are perhaps better viewed as individual parts in a spectrum which operate independently in various contexts, both temporally and geographically. What is optimal or preferred in one geographic setting may not be in another, and to inject a list of constructed traits into ancient contexts, only to find some rising to the top and others falling short, could be blocking other investigations in fully realizing the complexity and variability of hominin behaviours.

Ascribing modernity to specific periods or geographic regions is based on the theory that certain traits are indicative of modern behaviours and that these traits can be made visible by studying archaeological remains. Henshilwood and Marean (2003:628) describe the identification of these traits:

> *"The collective idea appears to be that we can develop a litmus test for modern human behaviour grounded in material correlates of specific behaviours considered to be unique to or indicative of a modern human intellect."*

This litmus test they describe is a list of such traits originally outlined by Mellars (1973) but has since undergone numerous revisions. The specifics of these collective lists are not essential to this dissertation, but in order to maintain consistency and provide clarification, I use the "Traits Used to Identify Modern Human Behaviour" list as outlined by Henshilwood and Marean (2003:628):

- Burial of the dead
- Art, ornamentation, and decoration
- Symbolic use of ochre
- Worked bone and antler
- Blade technology
- Standardisation of artefact types
- Artefact diversity
- Complex hearth construction
- Organised use of domestic space
- Expanded exchange networks
- Effective large-mammal exploitation
- Seasonally focused mobility strategies
- Use of harsh environments
- Fishing and fowling

However, calibrating behavioural modernity by archaeological materials contains several issues. First, it establishes a presentist measuring construct to quantify ancient behaviours (Ames et al. 2013). It is difficult to measure such complex interactions solely by preserved remains, which therefore presents an interpretive bias toward what has managed to survive the elements of time. It furthermore minimises the role of individual agency in the formation of artefacts and contexts and instead focuses on larger behavioural trends and patterns (Ames et al. 2013). Secondly, using these traits as an operational construct, one could conclude that some semi-nomadic indigenous groups, such as the Khoisan in parts of southern Africa (Watts 1998b), were and are not behaviourally modern, or at least only partially so. The absence of certain artefacts at archaeological sites should not be synonymous with a lack of complex behaviours (d'Errico et al. 2003). As Speth (2004) points out, though Paleoindian and Middle Palaeolithic material cultures boast numerous similarities, it would never be assumed that Paleoindians were not cognitively equal to human populations in Palaeolithic Europe. The presence of anatomically modern humans in Sahul and Australia at ca. 50 kya presents a similar argument, where behavioural modernity is in place even though the archaeological assemblages lack the complete “package” of modern traits due to cultural preferences and differences in material culture (Balme et al. 2009; Balme and O’Connor 2014; Clarkson et al. 2015; Habgood and Franklin 2014; Hiscock et al. 2016; McDonald et al. 2018; Mulvaney and Kamminga 1999).

This line of reasoning extends to whether archaic hominins also had the cognitive capabilities for modernity and is a central theme in work from authors including Zilhão and d’Errico, amongst other researchers (d'Errico 2003; Dayet et al. 2014; Hovers and Belfer-Cohen 2006; Roebroeks et al. 2012; Zilhão 2007; 2011; Zilhão et al. 2010); all of whom provide evidence for symbolic pigment use, personal ornamentation, and to a lesser extent, complex multi-component tools amongst European Neanderthals (Pawlik and Thissen 2011). Though others have minimised these arguments (Klein 2000; 2008; Mellars 2005), the presence of some “modern” traits in Neanderthal contexts still needs to be accounted for. This is often accomplished by referring to transitional sequences, such as the Châtelperronian, where Neanderthals are described as possessing the cognitive capacity to adopt modern behavioural traits while simultaneously not being able to develop them independently (Ames et al. 2013). Other authors have argued that the real issue is that behavioural modernity is restricted only to *H. sapiens sapiens*. Thus, definitions of modern traits have had to fluctuate in order to accommodate *H. sapiens* being the sole proprietors of modern behaviours, which has brought an increased reliance on symbolic artefacts and behaviours (Hopkinson 2013). Others speculate that perhaps symbolism and cultural modernity are not mutually exclusive, and may have developed independently of each other in different places and times by various hominin species (d'Errico et al. 2003; d'Errico et al. 1998; Zilhão and d'Errico 1999). There are also those who argue for increased awareness of evidence for social and cultural memory, such as studying the symbolic use of space as well as individual and group memory storage (Wadley 2001; 2010). This approach allows for a more nuanced interpretation of artefacts that represent actions by individuals or groups within a sphere of time, space and interaction. Others call for an abandonment of the search for behavioural modernity altogether, due to the problems of rectifying terminology and classifications with actual behavioural observations (see Chase 2003; Shea 2011).

The collection and manipulation of pigments are often cited as a central feature in symbolism and symbolic mediation (Knight et al. 1995; Power 2009; Watts 1999; 2002; Watts et al. 2016). This is due to the association of pigment use and syntactical language, as the use of colour has been suggested to indicate the use of arbitrary symbols and the creation of meaning for linguistic capacities (Wadley 2003). However, preservation issues and taphonomic processes may bias assemblages and interpretations. Furthermore, assigning pigments to only one behavioural role (symbolism) may not account for the complexity of these materials and the multitude of roles they filled in ancient contexts. Pigments were indeed part of practices that could be considered symbolic, but as with many tangible objects, there is much more lying beneath the surface that can be difficult to reach.

3.2. The definition of symbols and symbolic behaviour

Within the last two decades, the discussion surrounding symbolism has extended to Neanderthals and their cultural behaviours (d'Errico, et al. 1991; Dayet, et al. 2014; Heyes, et al. 2016; Zilhão, et al. 2010). As this is contrary to the long-held belief that symbolism was exclusively a modern human trait associated with *H. sapiens sapiens*, what it means to exhibit symbolic behaviour needs to be redefined, as well as how to interpret such concepts through material culture.

The concept of a symbol originates from linguistics, which defines it as an intangible representation of an external reality. A symbol can, therefore, operate as a construct for language comprehension as it does not necessarily need to have a tangible or physical referent. The idea that symbols can be attached to a physical referent was first explored by Ferdinand de Saussure, who classified the distinction between symbols and signs (de Saussure 1916). Louwerse (2007) builds upon this and suggests

> *"Symbols are…interdependent abstract systems of meaning that are occasionally grounded in the comprehender's iconic experience of the world, and symbolic systems are structured after these iconic relations." (2007:116)*

By this interpretation, symbols cannot exist without an active creator and real-world object or concept which it refers to. Though the idea can appear to be straightforward, there are different levels of interaction and meaning attributed to symbol allocation. One of the pivotal works on symbolism dates to the 19th century from C.S. Peirce, who differentiates between Icons (a sign that is directly indicative, such as in naturalistic representations of animals), Indexes (a sign that contains some trait that could be suggestive of something else, such as a bird referring to the sky), and Symbols (signs with an arbitrary relationship to their referent) (Hopkinson 2013219, adapted from Peirce 1974). By these standards, the numerous paintings of animals throughout the cave sites of the Upper Palaeolithic are Icons and perhaps Indexes at best. Even though numerous ethnographic contexts that contain images depicted in rock art contexts around the world, such as in Australia (Clarke and Frederick 2006; Morphy 2012; Mulvaney 2013; Ouzman 2001) or Africa (Lewis-Williams and Pearce 2015; Loubser 2011; McGranaghan and Challis 2016) often operate simultaneously as Icons, Indexes, and Symbols, these can vary highly depending on the time, place, and person interpreting them (Lewis-Williams 1990). Furthermore, immediately allocating ancient images and materials as symbols or symbolic forms detracts from the range of interpretations that often accompany such contexts in modern-day arenas.

From an archaeological standpoint, the definition of what exactly a symbol is centres around their physical representation and how these can be recognised in material culture. According to Henshilwood and Marean (2003635), symbols are:

> *"…representative of social conventions, tacit agreements, or explicit codes that link one thing to another and are mediated by some formal or merely agreed-upon link irrespective of any physical characteristics of either sign or object."*

This definition would invite the concept that material and physical objects are used as a medium to convey a conceptual idea or message, much in a way that skull and crossbones suggest "poison" or that a green traffic light means "go". The ability to store external information through material culture would represent a critical moment in hominin cognitive evolution, "…allowing material culture to intervene directly in social behaviour," and thus allow actual material items to act as an intangible symbolic medium (Henshilwood and Marean 2003635). However, the issue therein lies with how to identify these objects imbued with symbolic messages in archaeological contexts. Lyn Wadley (2001, in Henshilwood and Marean 2003) builds upon this initial phase and suggests that artwork, personal ornamentation, lithic and artefact style, and the social use of space are evidence for storing abstract and symbolic information on material objects that modern-day researchers can recognise. The presence of such physical evidence for external symbolic storing would, therefore, imply advanced cognition, complex language and cultural innovativeness, all central traits comprising the behavioural modernity complex.

The recognition, creation, and use of red pigment on material objects is sometimes interpreted as direct evidence of symbolic behaviours. Thus, the presence of anthropogenically modified ochre pieces confirms the use of symbols and the encompassing cognitive and behavioural traits at the respective archaeological site (d'Errico et al. 2003; Watts 2009; Watts et al. 2016). This scenario presents several issues. First, if we establish the presence of archaeological pigments (whether bearing physical evidence of anthropogenic use or not, such as stated by Watts, et al. 2016) as direct indicators of symbolic behaviour, we would, therefore, be obligated to include archaic hominins and Neanderthals in our definition of behaviourally modern. Second, we immediately subscribe symbolic meaning to the use of red pigments and disregard the possibility and applicability of the material for functional or practical purposes (or at least imply that these uses are secondary). Third, we detract the recognition of other traits relating to behavioural modernity and suggest that red pigments encompass not only symbolic denotation, advanced cognition, language, and cultural innovativeness, but also represent planning depth and innovative technology. Lastly, we reduce the importance of the association of other forms of material culture to modern behaviours. In this scenario, the presence of ochre is often perceived as a "package" piece of evidence for symbolic behaviours, and that its presence at archaeological sites is an immediate indicator of modern behaviours. Accepting the presence of one archaeological material at a site, even if it boasts evidence of anthropogenic modification (also often a topic of debate between specialists), is a generalist and perhaps over-ambitious approach to defining the features of modernity. Instead of campaigning for red ochre as an exclusive indicator for modern behaviours, exploring the precise nature of its use and application might reveal better results and build our inferences on what we can observe archaeologically. Marshack (1981) also warns against using too much inference when studying ochre and the use of symbols, he states:

> *"…early symbolic modes, whether they involved the use of colour or engraving and carving, cannot be subsumed under any prior theoretical concept as to their meaning. Our concern should rather be for the range of such usage…the intentional carving of symbolic artefact and its intentional colouring represent different modes of symbolic usage…it would be hazardous to state that the ochre represented blood, life, or status." (1981:189)*

Associating the presence of ochre materials with symbolic behaviours would additionally declare ancient groups of Neanderthals as cognitively and culturally equal to anatomically modern humans, though the long-lasting Mousterian techno-complex (200-40 kya) and comparatively sparse and sporadic record of "symbolic behaviour" suggests otherwise (see Mithen 2014). In Europe, it is predominantly during the later Neanderthal assemblages, such as the Châtelperronian (60-40 kya), that pigments at archaeological sites occur more with more frequency (Dayet et al. 2014). Châtelperronian assemblages are problematic, as the contextual assignment of the Châtelperronian (and other regional techno-complexes, such as the Uluzzian in southern Europe) exclusively to Neanderthals is debated and is often argued to be a result of cultural mixing or lack of stratigraphic integrity (Mellars 2010). However, these arguments and the lack of strong archaeological evidence do not necessarily negate the possibility that Neanderthals were capable of symbolic behaviour. Indeed, d'Errico (2008) proposes that Neanderthals did contain the necessary cognitive capacity for external symbolic storage, which thus allowed them to create and interact with symbolic materials. He states:

> *"The systematic use of pigments by Neanderthals shows that this is not species-specific behaviour and supports the view that the cognitive prerequisites of modern human behaviour were in place*

prior to the emergence of both biologically 'archaic' and 'modern' populations." (2008:173)

Nevertheless, much of the evidence for Neanderthal use of pigments is from these proposed transitional cultural complexes, such as the Uluzzian and the Châtelperronian. If Neanderthals were creators of symbolic material culture, then it lacks preservation archaeologically in comparison with archaic humans in Africa and modern humans in Europe. If Neanderthals were using symbolic communication in the same ways and with the same materials as humans, this evidence would arguably have maintained a greater presence than has so far been discovered (Mithen 2014). Lastly, it is also entirely possible that Neanderthals communicated with symbols in ways completely unknown and unidentifiable to us today.

The topic of the capacity for symbolic behaviours in Neanderthals was one of the initial causes for the definition of modern behaviour through the way of symbolic artefacts. Previous debates on symbolic capacities were rooted in a "human vs non-human" dualistic mindset (Chase 2003), where behavioural modernity was seen as a uniquely human trait that separated *H. sapiens sapiens* from other hominin species. In the context of the Western Intellectual tradition which was heavily influenced by linear views of human evolution, White stated that "Human behaviour is symbolic behaviour, if it is not symbolic, it is not human" (White 194934-35). This emphasis on symbolic behaviour as a defining feature for *H. sapiens* is problematic; indeed, much of the argument in support of the cognitive capabilities of Neanderthals and archaic humans rests on identifying (and disputing) their capacities for symbolic communication (Dayet et al. 2014; Hoffmann et al. 2018; Salomon et al. 2012a; Soressi and d'Errico 2007; Zilhão 2007; 2011; Zilhão et al. 2010). It, therefore, becomes an argument as to the "humanness" of Neanderthals, while simultaneously disavowing them of their types of behavioural and cultural complexities which may be unrecognisable (or not archaeologically sustainable) to us in their remaining material culture. This emphasis on symbolism as the keystone for behavioural modernity has led to the avoidance of conceptual developments and theoretical conversations discussing the problems associated with using the umbrella term of "symbolism" to define all behaviours not linked to functional actions (Hopkinson 2013). These terms then operate as a categorical "other", an interpretive limbo where artefacts are thrown into that are not seen to serve any obvious functional or practical purpose. This emphasis on symbolic behaviours further separates the roles of “functional” and “symbolic” uses of various archaeological materials; however, this division is likely not so black and white.

3.3. The dichotomy perspective

Traces of ochre use by ancient populations can often be more discrete in archaeological contexts than other forms of material culture, and thus can prove difficult for interpretation. Ochre behaviours and uses are thus frequently divided into two categories: functional and symbolic. Functionality implies lack of symbolic, religious, or mythical connotations. Uses are technical or practical applications that operate as a tool or utensil. Though there are differences in ochre use geographically, and some authors report preferences for different geological varieties based on the physical traits of certain ochre materials (d’Errico, et al. 2012; Dayet, et al. 2015; Hodgskiss 2012, 2013; Watts 2002; Velliky, et al. 2018; Zipkin 2015), these possible preferences do not construct boundaries of identifiable social markers or cultural traits. This, therefore, reduces the interpretation of ochre in archaeological contexts to an interpretation by association (i.e., ochre found on lithics classified as a loading adhesive). This is perhaps where the strong correlation of ochre and symbolism first arose, such as with the brilliantly painted caves (Chauvet et al. 1996; Clottes 2008; Cuenca-Solana et al. 2016; d'Errico et al. 2016; González-Sainz et al. 2013; Hoffmann et al. 2018; Iriarte et al. 2009) or burials in Upper Palaeolithic Europe (Dobrovolskaya et al. 2012; Pettitt et al. 2003; Román et al. 2015; Román et al. 2019), or finds such as the Blombos ochre piece in South Africa that displays a pattern of lines intentionally carved by ancient humans (Henshilwood et al. 2011; Henshilwood et al. 2009; Henshilwood et al. 2001).

There are numerous sites in southern Africa with ochreous materials and earth pigments (for review, see Dapschauskas 2015; Wolf et al. 2018), and the amount of ochre found at these sites indicates that red ochre was routinely collected and used throughout the MSA (Barham 2002; Bernatchez 2008; 2012; Dayet et al. 2013; Hodgskiss 2013; Hodgskiss and Wadley 2017; Mackay and Welz 2008; Wadley 2005a; Watts 2009; 2010; Watts et al. 2016). This, together with the nature of ochre finds (e.g., engraved ochre pieces, ochre powder processing kits), has prompted hypotheses into the mechanisms surrounding ochre behaviours during the MSA. Previously, most of these contexts were assumed to represent symbolic behaviours, including body painting or artefact decoration (d'Errico et al. 2005; Henshilwood 2009; Henshilwood and Dubreuil 2009; Watts 2002; 2009; Watts et al. 2016). Wadley (2001, 2005) questions this symbolic emphasis and instead opts to work towards investigating and exemplifying the utilitarian nature of ochre that might account for the large amounts found at sites. These explorations are not meant to exclude the symbolic and ritual aspects of ochre artefacts; rather, they aim to build upon the knowledge within the archaeological record and enhance the scope of this form of material culture. Instead of separating ochre use into opposing categories and debating the efficacy of symbolic or functional behaviours, we should continue to build upon what has been established and use these observations to explore other scenarios and hypotheses. It is even more likely that these two dichotomies of ochre use were not mutually exclusive, that functional purposes were symbolically laden, and both were part of a symbiotic relationship (Wadley 2005a). The versatility of ochre as a functional material and its archaeological presence in ritual and symbolic contexts support the notion that it was an effective technical medium while containing symbolic aspects unknown to us today.

Several other researchers (e.g., Rifkin 2015; Hodgskiss 2010) also present compelling evidence that the potential uses of ochre are numerous and span both categorical boundaries of functional and symbolic. Indeed, d’Errico (2003:197) states that “There is no traditional society in which the production and use of colourant is merely functional.” When observing ochre use through an ethnographic lens, it is also important to note that “Ethnographically, the symbolic/functional divide would be an alien concept to most contemporary hunter-gatherer societies,” (d’Errico and Stringer 2011:1065). Symbol use and symbolic behaviour can indeed operate in a functional sphere, such as marking group identities or declaring personal identities or ownership, and alternatively, functional processes and actions can be imbued with symbolic dimensions (d’Errico and Stringer 2011; Wadley 2001, 2005).

Red ochre in archaeological contexts represents something more than ephemeral behaviours and was likely perceived and interacted with in a multitude of different scenarios and also evolved and changed over time and space. However, because of its vagueness in sediments and sites, interpretations often rely on identifying specific artefact attributes or sensational findings. Most often an artefact or context with ochre is not "tested" for functional aspects, and instead is immediately classified as symbolic, a grey "in-between" zone, where symbolism is a typology and ochre is a defining feature. It is as Terry Hopkinson states, "Symbolism is the residue when all functional dimensions of an archaeological artefact or pattern have been accounted for" (Hopkinson 2013:219). However, ochre research is not necessarily an "other" category lost in an interpretive limbo, but there exists a lack of a universal framework to explore ochre contexts and their contextual associations that can be applied to different archaeological sites worldwide. Thus, it will be highly beneficial to approach the archaeology of ochre holistically, without the categorical functional or symbolic dichotomy and a symbolism-or-not checklist. Ochre is a versatile material, spreading across vast distances in space and time, and assuming that this material was always perceived and used in the same way throughout human history can devoid this material of the range of its uses and applications, and its presence in a variety of contexts over space and time. Not engaging with the differences in collection strategies, manipulations, meanings and practices associated with ochre can obscure investigations of alternative scenarios and perhaps block new dimensions and investigations, and overall lead to an impoverished and short-sighted understanding of human behavioural complexity.

3.3.1. Applying an incorporative methodology

The research field of ochre has intensified within the past 20 years, mainly due to increased reports of findings (Bouillot et al. 2017; Cavallo et al. 2017a; Hodgskiss and Wadley 2017; MacDonald et al. 2018; Moyo et al. 2016; Román et al. 2019; Rosso et al. 2017; Scadding et al. 2015; Smith and Fankhauser 2018; Zipkin et al. 2017), geographic and temporal range (Aubert et al. 2014; Aubert et al. 2018; Bodu et al. 2014; Brooks et al. 2016; Brooks et al. 2018; Hoffmann et al. 2018) and increased recognition of ochre as a distinct artefact class (Bouillot et al. 2017; Hodgskiss 2012; Rifkin 2012a; Stafford et al. 2003). Numerous hypotheses have explored the role of ochre in the development of advanced cognition (d'Errico and Henshilwood 2011a; Hodgskiss 2014a; Mithen 2014; Wadley 2010; Wadley et al. 2009), language development (d'Errico et al. 2003; d'Errico and Henshilwood 2011a; Watts 2009;

Zilhão 2011), symbolism (d'Errico et al. 2003; d'Errico and Henshilwood 2011a; Henshilwood 2009; Hovers et al. 2003b; Zilhão et al. 2010; Zipkin 2015), and in general the emergence of modern human behaviours (Bernatchez 2012; Henshilwood 2004; Rifkin 2012a; Rosso et al. 2016; Wadley 2003). Additionally, there has been an increase in the testing of functional hypotheses and the expansion of our knowledge on the range of total possible uses for ochre (Hodgskiss 2006; Rifkin 2011; 2015a; Rifkin et al. 2015; Wadley 2005b).

There has furthermore been a resurgence in the terminology of "symbolism" and what this implies (Gamble 2012; Hopkinson 2014), more critiques on how we define and address behavioural modernity (Ames et al. 2013; Nowell 2010; Porr 2011; Porr and Matthews 2017; Roberts 2015; Shea 2011), as well as more discussions on the role of ochre in behavioural modernity and to what degree the presence of this material item at archaeological sites implies complex behaviours and cognition (d'Errico 2008; d'Errico et al. 2012; Hodgskiss 2014a; 2014b; Hodgskiss and Wadley 2017; Rosso et al. 2016; Wadley 2010; 2011; Wadley et al. 2009). Perhaps the problem does not rest with the idea of relying on ochre's presence as a direct indication of certain behavioural traits, but with the way we are analysing this material and incorporating it into the larger discussion. Documenting ochre materials and contexts at a site is a central part of the analytical process, but the following stages after this initial recording phase are less clear. Other materials with more "direct" evidence, such as worked lithics and faunal elements, receive a thorough round of documentation and analyses, but it is often the case that the presence of ochre artefacts are merely documented. There are, of course, studies where ochre artefacts are described and contextualised in detail (see Rosso, et al. 2016, 2017; Hodgskiss 2014; Rifkin 2012). However, the majority of these research projects are in African contexts. Perhaps with the inclusion of more thorough analyses of ochre assemblages across all temporal and geographic contexts, a more detailed picture of the nature and evolution of ochre behaviours over time will come to light. This suggestion is not a criticism, but rather, an observation as to how archaeologists can work towards investigating the full scope of certain material types and how they interact with each other at archaeological sites throughout time.

My research aims to not only conduct a holistic approach to investigate ochre materials at the site of Hohle Fels, but also to acknowledge and explore the notion that symbolism does not occur in geographic isolation and instead is created and used in different ways, means, and contexts globally. Since the region of the Swabian Jura which hosts Hohle Fels cave boasts some of the earliest Aurignacian contexts in Western Europe (Conard 2011; Conard and Bolus 2006; Conard and Bolus 2008), studying ochre behaviours here provides a window into the origin and evolution of when, how, and why anatomically modern humans used this material after migrating into the European continent. Therefore, I will explore the range of ochre related behaviours that were present at Hohle Fels from its earliest occupational sequences and whether there is diachronic change or continuity. This exploration includes researching individual ochre artefacts, artefacts associated in context, artefacts containing traces of ochre residues, and investigating the selection, acquisition, and transport of these materials from ochre source locations to the cave. These objectives will not only shed light on how cave inhabitants interacted with this material but also the movement of ochre in the region surrounding the cave. The research potential is not only limited to Hohle Fels but also extends to the surrounding landscape and how it was perceived and utilised throughout the Upper Palaeolithic. Such behaviours and the landscape use are not isolated, and I will emphasise how these behaviours, within site and around, shift, change or are stable throughout time. This will include both artefact specific and assemblage overview approaches, with an emphasis on the *chaîne opératoire* method. My focus will not be on assigning general typologies or quantifications, as these overlook the process of human agency as well as other behavioural aspects. Instead, I will emphasise the processes leading up to their deposition at the site. The purpose of using the *chaîne opératoire* approach in this area is to incorporate different stages of the life-cycle of ochre and why each of these stages in and of themselves are significant. I will investigate how the ochre assemblage at Hohle Fels represents different stages in the selection, acquisition, and interaction processes, without focusing primarily on distinguishing between functional and symbolic uses as these are the end process of the behavioural process building them.

The wide range of research approaches to ochre attests to its status as a versatile and complex material. The range of its applications and variety in uses presents an issue archaeologically; due to the frequent ambiguity of archaeological contexts, researchers often cannot pinpoint the exact nature of its use at these given places when looking exclusively at ochre artefacts. Instead, micro-approaches are preferred to macro-approaches, where hypotheses explore specific contexts and occurrences as opposed to general over-arching thematic interpretations (Dayet et al. 2013; de la Peña et al. 2018; Pradeau et al. 2014; Roman et al. 2015; 2019). Incorporating both of these approaches in order to form a holistic methodology to investigate ochre at an archaeological site is essential; otherwise, we run the risk of overlooking certain aspects or traces. My approach here will draw collected information from ochre artefacts, contexts, associated artefacts, regional trends and landscape orientations in order to investigate diachronic changes and continuity in ochre use at Hohle Fels Cave. Since Hohle Fels contains a deep stratigraphic sequence and over 100,000 single-find artefacts alone, interpreting ochre as an independent item would overlook the complexity and intensity of behaviours in general at the site. By employing an integrative approach, I will not only explore the occurrence and features of ochre artefacts at the site but also how ancient humans at the cave interacted with ochre across a multitude of scales (personal, site, regional) and how ochre impacted their lives and behaviours throughout the Upper Palaeolithic.

Other doctoral research projects incorporated similar multi-staged, multi-perspective approaches, such as by Zipkin (2015) in northeastern Africa who focused primarily on source differentiation and the acquisition stage, as well as Rifkin (2012a) whose emphasis was on the potential uses of ochre at Blombos Cave and how these uses are identifiable archaeologically. Since investigating the total range of behaviours surrounding ochre use at archaeological sites can be quite vast, this could account for the current lack of such detailed approaches in peer-reviewed articles. Instead, the total scope of the relationships between humans and ochre at specific sites should first be explored, allowing for more detailed investigations to then take place. This type of approach is precisely the aim of this project on the entanglements between humans and ochre at Hohle Fels. My first goal is to diachronically explore the behaviours and uses of ochre at the Hohle Fels cave site, which will frame future studies extending into the broader region of the Swabian Jura and potentially Central Europe. This study will also be the groundwork for future materials containing ochre residues as Hohle Fels is still actively excavated as of 2020. Previous research on other material types, such as lithics (Burkert and Floss 1999; Hahn 1977; 1987) and mammoth remains (Barth et al. 2009; Münzel 2001a; Scheer 2001), as well as behaviours such as bead and figurine production (Dutkiewicz et al. 2018; Wolf 2015a; 2015b) and hunting (Münzel 2001b; Münzel and Conard 2004a; Niven 2003), have painted an intricate picture of the relationships and interactions between people in the region of the southwestern Swabian Jura. Investigating the ochre will not only build on these already established relationships but might bring new information to light about the behaviours and beliefs of these people during the Upper Palaeolithic of southwestern Germany.

Chapter 4. Materials and Methods

> *In the case of ochre, the conceptualisation is composed of more interrelated parts. It demands the recognition and selection of the appropriate minerals, their heating or firing, abrasion or pulverisation, the collection of the powder on or in a receptacle, the addition of liquid, mixing to the desired viscosity, and application.*
>
> *Ernst Wreschner, 1976:717*

Studying mineral pigments in archaeological contexts can be complex because of the multiplicity of pigment types utilised by hominins. Pigments, and specifically ochre pieces, can be any solid or powdered rock, clay, or sediment with colouring properties. Often these are iron-oxides mixed with other minerals. The varied nature of ochre pigments has generated a number of different methodologies. Depending on the proposed hypotheses and/or the characteristics of the assemblage, these approaches are either qualitative or quantitative. To apply a non-biased methodology (as discussed in section 3.4), I aim to combine these two approaches to conduct a holistic examination and assessment of the ochre assemblage and to work towards highlighting all stages of the ochre *chaîne opératoire*.

While many of the methods, procedures and specific protocols I employed during this research are outlined in each of the three papers submitted as part of this thesis (Chapters 5-7), they do not discuss the underlying analytical framework and concepts in detail. Given the specific publication formats and requirements of each of these journals (limiting space for content, figures, tables and supporting data), my method descriptions are necessarily brief. In this chapter, I describe the contextual setting of Hohle Fels and the excavation protocol at this site. I describe how the artefacts are catalogued and processed in order to establish the handling and identification of ochre artefacts during all stages of the excavation process and how this impacted their selection as part of this research project. This is followed by a description of the methods used for this research and the specifics of their application, scope and the projected outcomes. These methods include the identification, categorisation and documentation of materials (qualitative) and the methodological justification and descriptions of analyses that were applied (quantitative).

4.1. Materials

Artefact collection, description, and cataloguing form the basis of the subsequent analyses conducted for this thesis. This first process of recognising ochre artefacts, assessing their qualities and identifying their spatial and temporal context allowed for further analysis on their individual physical and chemical structures. It is therefore essential to first gain an understanding of the orientation of Hohle Fels cave, the structure of the stratigraphy, the association of temporal boundaries and the designation of artefact categories. The excavation and laboratory protocol of the Hohle Fels excavation is described, including general artefact cataloguing terms and post-excavation procedures. While the ochre artefacts are described at length in Paper 1, in this section, I provide additional background on the sorting and selection procedures for locating the ochre artefacts, as numerous pieces were previously misidentified or mislabelled.

4.1.1. Hohle Fels excavation protocol

Joachim Hahn first implemented the current structure of operations at Hohle Fels in the 1970s (Hahn 1977) based on the French system of plotting artefacts in 3 dimensions allowing for the documentation of their *in-situ* spatial orientation. The excavation area is organised into 71 1x1 m squares ranging from quadrant 10 to 138. These are set up into a grid system with the 0,0 point in the SW corner of the square. Each square is excavated in 50 x 50 cm quadrants labelled *a-d*, with *a* beginning in the southwest corner, *b* in the southeast, *c* in the northwest and *d* in the northeast. Though this organisation is counter-intuitive, it follows the original system first implemented by Hahn and is thus used to maintain consistency with the older excavations and datasets. Each quadrant is excavated in approximately 3 cm *Abträge* or spits which are vertically confined to specific geological horizons (GH's) which are meant to distinguish larger cultural periodic events and are separated by numbers (e.g. 3, 4). Geological horizons are further sub-divided into more specific archaeological horizons or stratigraphically recognisable archaeological layers designated by Roman numerals (e.g. III, IV). Both can be subdivided by the addition of a letter (e.g. 6/IIIa, 6/IIIb). Archaeological layers are also differentiated when they are adjacent to a wall and labelled as "wall facies" or

Table 4.1: List of research objectives (Section 1.2) and corresponding methods used for their investigation.

Research Objective	Method of Investigation
1) To catalogue and describe the ochre assemblage from the cultural periods of Hohle Fels cave, including their physical (qualitative) and geochemical (quantitative) characteristics.	• Qualitative and quantitative assessment of assemblage: numbers of artefacts, size, weight, macroscopic assessment of visual and textural characteristics. • SEM and XRD of selected samples to examine their micro-fabric and mineralogical components. • NAA of ochre artefacts to document their elemental constituents and identify potential compositional groups.
2) To locate and sample potential sources where ancient populations may have collected ochre materials, and to document their geological and chemical components.	• Survey for ochre sources in the Swabian Jura and the Black Forest. • NAA analysis of the source materials to identify their geochemical components.
3) To compare the modern-day source samples and the archaeological materials for a provenance analysis of the ochre artefacts from the Swabian Jura caves.	• Comparison of NAA results from ochre sources and ochre artefacts, statistical assessment to associate compositional groups to sources based their geochemistry.
4) Based on the three points above, to conduct a holistic analysis of the ochre materials from Hohle Fels in order to interpret the operational chain of ochre behaviours at the site and understand the relationship with ochre, humans, and their cultural practices during the Upper Palaeolithic of the Swabian Jura.	• Document diachronic trends in ochre source collection and types of ochre collected per period. • Compare ochre collection strategies to other material collection strategies to identify any (in)consistencies in acquisition and movement networks. • Observe these trends and behaviours within a landscape and climatic perspective. • Clarify the *chaîne opératoire* of ochre at Hohle Fels based on the data. • Describe how the nature of ochre collection as use at Hohle Fels fits into the regional and widespread pattern of behavioural complexity regarding pigment use.

wf (e.g., IIbwf, IVwf) and excavated separately as wall erosion can alter the visual and textural characteristics of these layers. Each *Abtrag* is excavated into a bucket with corresponding coarse-fraction (*Sammelfunde*) and fine-fraction (*Eimerfunde*) bags with their exact location recorded with a Leica total station (these are two readings on the same spot as both the bucket and coarse fraction come from the same quadrant and layer). The bucket is then water-screened in both coarse and fine-fraction screens. These sediments are left to dry back at the lab house in Blaubeuren, Germany, and sorted by lab team members.

During excavation, several find categories are recorded *in-situ* as single finds, or *Einzelfunde*. Their artefact abbreviations follow the Tübingen system and include identifiable stone tools and cores (*Werkzeuge,* WZ, *Kerne,* KE), unmodified lithic flakes larger than 1 cm or *Grundformen* (GF), general lithic debitage (*Trümmer*, TR), fragments of mammoth ivory and modified mammoth ivory (*Elfenbein,* EB, *Bearbeitetes Elfenbein,* BE), fragments of antler and modified antler (*Geweih*, GW, *Bearbeitetes Geweih*, BW), identifiable faunal elements or those larger than 3 cm as well as modified bones (*Knochen*, KN, *Bearbeitete Knochen*, BK), burnt faunal elements larger than 1 cm (*Knochenkohle*, KK), large intact teeth (*Zähne,* ZN), charcoal pieces larger than 3 mm (*Holzkohle,* HK), pieces of stone with traces of pigment residue (*Farbspuren*, FS), smoothed limestone altered by cave bears (*Bärenschliff*, BS), and red ochre and hematite (*Rötel,* RO, *Hämatit,* HA). In the past, excavators collected numerous pieces of yellow ochre (*Ocker,* OK); however, today this continues at a much smaller scale as many of these are actually weathered limestone derived from inside the cave. These oxidised limestones are known as micritic calcite, a type of *éboulis*, which are pedogenically stained yellow by iron (Miller 2015) and are found throughout the sequence but most commonly in the Middle Palaeolithic layers. Lastly, any stone larger than 10 cm is measured by the long axis and by its circumference in order to create a 3D map of its orientation. Artefacts with a long axis ratio of 1.8 are measured with three points in order to record orientation; these are most often lithics and long bones.

During excavation, if recovered artefacts are not optimal for *in-situ* recording, they are placed in a *Sammelfunde* (coarse fraction) bag and are washed and processed separately back at the lab. These are commonly larger unidentifiable bone fragments and sometimes burnt limestones (*Gebrantenekalk,* GK) or yellow weathered limestone fragments (OK). After each completed *Abtrag* in a total square, elevations and layer borders are recorded using the total station, and the excavator records the sediment including texture, grain size, inclusions, clasts, and Munsell colours. Since 2015, photogrammetric models are used to reconstruct the site using several photos of each *Abtrag*. At the end of each season, the main profiles (Figure 4.1) and the stratigraphy are either confirmed or re-discussed. Several AHs have been re-labelled throughout the years due to the complex stratigraphy in the cave, such as discontinuous layers, stacked hearth features and the influence of wall facies, as well as the designation of older stratigraphic layers to new ones (e.g. I to IIb). Furthermore, the presence of features within AHs that also renders classification difficult at times; this is particularly the case for the Magdalenian layers.

The lab work coincides with the excavation and includes the washing and drying of single and coarse fraction finds drying of the water-screened bucket sediments and the processing and cataloguing of finds. Several workers sort through excavated sediments under a combination of natural and artificial light. During sorting, in addition to the single-find artefact categories which if found during sorting are “upgraded” to get specific find numbers (BE, BK, BG, WZ, KE, TR, GF), small (5-10mm) and micro-*débitage* (<5 mm) (*Klein- and Mikro-debitage*, KD and MD) and bones that are larger than 3 cm or are identifiable are also “upgraded”. Teeth (ZN) found during sorting are not given find numbers, and neither are small pieces of mammoth ivory (EB), burnt bones (KK), or charcoal fragments (HK). Find categories other than previously listed that are collected during sorting and organized by find category include fish bones (FI), microfauna (MF), molluscs (MO), rounded pebbles (*Gerölle*, GR), fossils (FO), unidentifiable materials (*Unbekanntesmaterial*, UM), coprolites (KO), small compacted iron ores (*Bohnerze*, BO), and other (*Sonstiges*, SO). All artefacts with individual find numbers are labelled, single finds are stored separate from bucket finds (*Eimerfunde*), or the coarse fraction finds (*Sammelfunde*). All finds coming from one bucket are organised by find category then placed inside a large bag in the order of bucket finds or *Eimerfundfolge*, and then stored inside a box according to the bucket information (square, bucket find number, GH, AH). All of the bucket-find bags are collectively organised by square and stored accordingly by square and excavation year, as are coarse fraction finds.

4.1.2. Identifying ochre artefacts

In order to acquire the total assemblage of excavated ochre artefacts, I located all recorded single finds with the categorical designations of RO, HA, OK, and UM. In addition to the single finds, I, with the help of a technician employed by Tübingen, Lennard Schnoor, sorted through the fine and coarse fraction bags from all excavation seasons housed at Tübingen to find the documented artefacts. During this process, it became apparent that numerous ochre artefacts had been misidentified and mislabelled, the most common mislabels being GK and UM. Therefore, we also sorted through numerous boxes containing only GK artefacts as in previous years artefact categories were stored separately. We found at least 86 mislabelled ochre artefacts. The sorting of the bucket and coarse fraction bags, though time-consuming, also allowed for the identification of artefacts containing ochre residues that were previously unreported or unnoticed. This does not, however, include pieces of stone with traces of pigment residue (FS), as these are treated as a separate find category and in most cases stored separately.

Most of the faunal artefacts containing ochre residues had been previously noted and recorded by Dr Susanne Münzel, an archaeozoologist at the University of Tübingen who has worked closely with the Hohle Fels faunal assemblage for many years (Münzel 2001a, b; Münzel and Conard 2004; Münzel et al. 2001). The Hohle Fels ochre assemblage is curated at the University of Tübingen, in both the Institute for Archaeological Sciences (INA) and the Department of Early Prehistory and Quaternary Ecology in Schloss Hohentübingen.

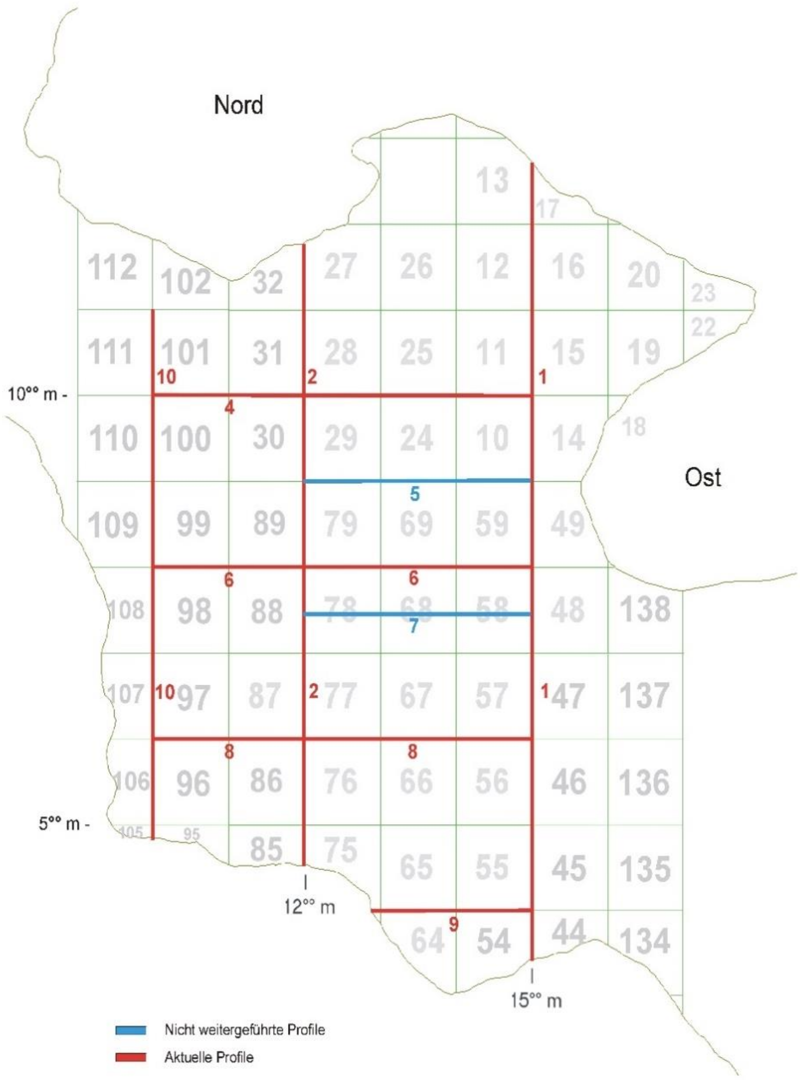

Figure 4.1: Overview of Hohle Fels cave interior with square units and main profiles labelled (main profiles in red).

4.2. Methods

The first method I employed for studying the Hohle Fels ochre assemblage is the descriptive/qualitative approach, focusing on the numbers of specimens and their visual qualities and characteristics. The goal of this method is to create a catalogue of individual artefacts and their ascribed traits in order to study these traits over time and space. This sort of approach is common for African, and more specifically South African, ochre assemblages as they tend to be large in number (>1,000) and exhibit a range of different visual qualities (de la Peña et al. 2018; Hodgskiss 2012; 2013; 2014b; Hodgskiss and Wadley 2017; Rosso et al. 2017; Watts 1998b; 2002; 2009; 2010). Commonly measured characteristics include external colour, streak colour, size, hardness, grain size, texture, rock type, brilliance (mica inclusions), and presence, location, and type of anthropogenic modifications or "use-traces" (Hodgskiss 2013). Observed models or trends can be correlated to other materials in the archaeological assemblage to observe patterns in occupational intensity and resource acquisition patterns (de la Peña et al. 2018; Douze et al. 2018; Rosso et al. 2014; Rosso et al. 2017). These models can also be compared to climatic and environmental data to study natural fluctuations and how these may have impacted or altered ochre behaviours in the past (Hodgskiss et al. 2017). Previous studies that used this approach converge on a similar observation – over time, ochre preferences generally shift to darker, more saturated blood-red hues with a clayey or wet texture (de la Peña et al. 2018; Hodgskiss 2012; Watts 2009; 2010).

Other methods increasingly used over the past ten years focus on applying analytical techniques to study the mineralogical, physical, and elemental structure of ochre pigments. Here, I collectively refer to these methods as "quantitative methods" as they generally incorporate measurements and statistical data to investigate research questions. These methods have not replaced qualitative classification of ochre assemblages but instead offer a new type of characterisation to observe the chemical and mineral varieties of ochre pigments present at sites. Not only are visual qualities documented, but information on the micro-texture, the specific Fe-oxide and hydroxide mineral phases present and the geological formation of ochres are available through certain analytical techniques. For example, Scanning Electron Microscopy equipped with Energy Dispersive Spectroscopy (SEM-EDS) can observe the micro-fabric of ochres that can help to classify ochres into groups that may come from a similar deposit (Dayet et al. 2016; Dayet et al. 2013; Pradeau et al. 2014; Salomon 2009). Fourier-transform Infrared Spectroscopy (FTIR) provides petrographic insight on ochre pigments which can offer insight into the geological formation of certain ochre types (Bikiaris et al. 2000; Genestar and Pons 2005; Moyo et al. 2016). Mineralogical techniques, such as X-ray Diffraction (XRD) and Raman spectroscopy are used to identify unique and common minerals in ochre materials and to classify the type of Fe-oxide phase, such as hematite or goethite (Dayet et al. 2016; Moyo et al. 2016; Sajó et al. 2015a; Trąbska and Gaweł 2008). These techniques are also particularly useful for analysing Fe-oxide-based rock art pigments (Bikiaris et al. 2000; Edwards et al. 1998; Froment et al. 2008; Lahlil et al. 2012; Smith et al. 1999; Tournié et al. 2011) and ochre residues on artefacts (Bouillot et al. 2017; Dayet et al. 2017; Wojcieszak and Wadley 2018). Elemental techniques that quantify major, minor, and trace elements in ochre pigments include X-ray Fluorescence (XRF), Neutron Activation Analysis (NAA), Particle Induced X-ray Emission (PIXE), Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS), and Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), to name a few. These methods have been used to investigate ochre artefact provenance (Cavallo et al. 2017b; Dayet et al. 2016; MacDonald et al. 2018; Román et al. 2015; Román et al. 2019; Sajó et al. 2015a) and the elemental mapping of ochre sources in a given region (Eiselt et al. 2011; Kingery-Schwartz et al. 2013; MacDonald et al. 2013; Popelka-Filcoff et al. 2007; Sajó et al. 2015a; Zipkin et al. 2017; Zipkin et al. 2015), in order to build a database for future artefact comparisons.

It is becoming increasingly common to implement a range of analytical techniques in order to investigate ochre artefacts (Beck et al. 2014; Cavallo et al. 2017b; Dayet et al. 2016; Moyo et al. 2016; Pradeau et al. 2014; Román et al. 2015; Román et al. 2019; Salomon 2009). These studies offer the groundwork for building a robust framework to study these materials across different regions and different ochre types. Furthermore, the incorporation of a detailed qualitative assessment of ochre artefacts can serve to supplement analytical information and shed light on different aspects of ochre formation, collection and use that were previously overlooked or unknown. A holistic approach using both qualitative and quantitative methods serves to identify and describe all stages of the *chaîne opératoire* of ochre artefacts. Describing their physical appearance and textures accommodates the selection phase of choosing certain materials to use for specific reasons, such as certain textures that are easier to work with, or that a particular colour is preferred. Geochemical methods can offer insight into the acquisition and collection stages. Lastly, investigating ochre-related artefacts, or artefacts bearing ochre residues or processing tools (such as grindstones) satisfies the last stages of altering material and using it for the desired outcome.

I conducted a detailed qualitative report of the ochre assemblage from Hohle Fels (described in section 4.2.1), as well as a series of analytical investigations using a combination of NAA, XRD, and SEM-EDS (section 4.2.2). My aim in implementing a series of techniques was to build a comprehensive framework to investigate ochre materials at archaeological sites, expanding on previously published PhD theses using similar approaches (Bernatchez 2012; Zipkin 2015). My approach also exemplifies the benefits of conducting both qualitative and quantitative assessments of assemblages in order to explore the life-cycle of these materials and their relationship with past human practices in greater detail.

4.2.1. Hohle Fels qualitative protocol

For the qualitative assessment, I first created a database of each piece classified by its visual qualities. The general ochre characteristics described for each piece, including non-modified and modified pieces, are shown in Table 4.2. Descriptions of the modification terms and specifications are in Table 4.3. Additional terms were adapted and defined as needed and include rounding and faceting. Qualitative characteristics were also described based on a similar system used by Hodgskiss 2013; however, these traits are common descriptive variables used for more qualitative ochre analyses elsewhere (Bernatchez 2012; Brooks et al. 2016; d'Errico et al. 2012; Dayet et al. 2013; Henshilwood et al. 2009; Pradeau et al. 2014; Rifkin 2012a; Rosso et al. 2017; Salomon 2009; Watts 2009; 2010). I use these terms to maintain consistency within the research field and to allow for future cross-comparisons between sites and ochre assemblages. Moreover, the structure of the database stems from Hodgskiss' original database for the Sibudu assemblage (Hodgskiss 2014b). Though several alterations have been made to account for differences in assemblage and ochre types, I used this database format with her permission (Hodgskiss, personal comm., 2016).

The processes of recording and categorising the physical ochre artefacts included creating a database of the pieces classified by archaeological information such as square, find number, GH, AH, date, bucket information (if available), artefact classification (RO, HA, UM, OK, GK), date of excavation, time period, and x-y-z coordinates. Descriptive variables included their size (length, width, and depth in millimetres, weight in grams), type of mineral (hematite, iron oxide, clay, red sediment, sandstone, limonite/goethite, shale, siltstone, specularite, and degraded limestone), mineral features (specular, porosity, oolitic), primary colour and secondary colour (based on visual description under natural light), texture (sand, silt, clay, mixtures of these), possible modifications, and definite modifications. One common variable not incorporated in this analysis is hardness. This omission is intentional because, in order to test hardness, a piece must be scratched upon a comparative material, and many of the Hohle Fels ochre artefacts were too small for such an analysis. The dataset showing the measured variables is in Appendix A.

The qualitative analysis also included materials containing traces of what appear to be red ochre residues, called ochre-related artefacts. This category includes pieces of limestone (FS), lithics (GF), faunal elements (KN, ZN), freshwater and marine shells (SH, MO), and pieces of ivory (EB). Observing the types of materials with ochre residues and the contexts in which they occur can offer an opportunity to see the conditions of its appearance and preservation, whether anthropogenic or natural, and whether or not there are any consistencies or patterns in other material types throughout the site. The measured characteristics for these materials are listed in Table 4.2.

Table 4.2: Categories of characteristics used for ochre and ochre-related artefacts at Hohle Fels.

Category - Ochres	**Variables**
Size	L x W x D (mm), weight (g)
Rock type	Hematite, sandstone, iron oxide, clay, red sediment, siltstone, specularite, degraded limestone
Ochre group	
Characteristics	Specular, oolitic (yes or no)
Porosity	High, medium, light, none
Texture	Clay, silt, sand (mixtures), medium sand, fine sand, very fine sand
Colour	Purple (dark/light), red (dark/light), pink, brick red, rust, orange, yellow, brown, black,
Other colour/feature	Purple (dark/light), red (dark/light), pink, orange, yellow, brown, black, grey, quartz inclusions, mica inclusions
Modified	See Table 4.3 for characteristics.

Category - Residues	**Variables**
Size	L x W x D (mm), weight (g)
Material	Stone, mammoth ivory, limestone, bone, tooth, shell, fossil
Colours	Artefact colour, residue colour, # of colours
Residue	Applicator, grinding stone, personal ornament, painting, mixture, container
Residue origin	Direct application, indirect staining, natural

Table 4.3: Description of the terminology used for ochre description and modification descriptions, adapted from Hodgskiss 2013:49, with some modifications.

Term	Definition
Groove	A narrow linear furrow caused by a secondary object abrading the ochre.
Striations	Multiple, parallel grooves, most often caused by hard-surface grinding.
Micro-striations	Microscopically visible parallel striations can also be located within grooves or independently, the latter associated with rubbing.
Polish	Lustre that can result from rubbing or general use
Incisions	Narrow, linear furrow with a higher depth than a groove, caused by scoring.
Grinding	Hard-surface rubbing of an ochre piece, leaves a use-wear pattern of multiple parallel striations. Different profile shapes arise from different grinding stone materials (Rosso et al. 2017).
Scoring	Deep incisions caused by a tool such as a lithic or bone, if the scoring forms a pattern then can be described as an engraving.
Rubbing	Also referred to as “soft-surface grinding”. Generally leaves micro-striations and polish, though it can also cause smoothing.
Facet	A flattened surface resulting from use-wear, usually grinding.
Rounding	Artificial rounding of the edges of the ochre piece (Hodgskiss 2010:4)
Smoothing	Removal of natural and artificial surface features, rendering a homogeneous appearance. Also a form of modification that can leave micro-striations.
Residues	Traces of foreign substances found on an artefact. Throughout this thesis, most commonly used in reference to ochre residues on other artefacts.
Modern traces	Including scratches and scuff marks (Hodgskiss 2010:4). Usually identifiable by irregular patterns and depths, non-uniformity, the presence of “fresh” powder.

4.2.2. Ochre surveys in the Swabian Jura

One aspect of ochre research is to identify the possible source location of archaeological ochres, also referred to as provenance analysis (Weigand et al. 1977; Zipkin et al. 2017). This type of analysis has previously been applied to ochre assemblages with success (Dayet et al. 2016; Eiselt et al. 2011; Kingery-Schwartz et al. 2013; MacDonald et al. 2018; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Zipkin et al. 2017). In order to accommodate a provenance-based assessment, I organised and conducted two surveys to locate and sample Fe-oxide deposits which may be related to sources where people collected ochre during the Upper Palaeolithic.

The first survey region was the Swabian Jura, as sources in this area would have been the most easily accessed by inhabitants of Hohle Fels cave. The survey was co-organized with Alvise Barbieri, a geomorphologist at Tübingen who specialises in landscape fluctuations of the Ach and Lone valleys during the late Pleistocene (Barbieri 2019; Barbieri et al. 2018). Assistance and insight from Volker Sach, a geologist specialising in the Swabian Jura, was pivotal in structuring our survey strategy (Sach, personal comm., 2017). Contained in the karstic landscape of the Swabian Jura are Tertiary deposits which accumulated in fissures and dry valleys. Of these features, dense Fe-oxide (generally goethite and hematite) nodules called *Bohnerz* accumulate after following iron precipitation (Borger et al. 2001). These small nodules are thought to have once formed an expansive formation across the Swabian Jura, but now occur in isolated deposits under the topsoil (Borger et al. 2001; Ufrecht 2008).

Geological maps and data from the *Landesamt für Geologie, Rohstoffe und Bergbau (LGRB) im Regierungspräsidium* Freiburg allowed us to locate 10 *Bohnerz* deposits within ca. 20 km of Hohle Fels cave, nine of which were sampled. Often occurring with the *Bohnerz* nodules is *Bohnerzlehm*, iron-rich kaolinite forming in sheets in the deeper deposits of the Swabian Jura. Several samples of these clay deposits were provided by Rudolf Walter, as well as found nearby the vicinity of Allmendingen (map of sampled source areas shown in Paper 2, Chapter 6). All sampled Fe-oxide sources were recorded using a GPS tracker and photographed in the field. At least 100 g were taken from each sampled sub-outcrop and placed in individual sample bags.

After discussions with Udo Neumann (Petrologie und Mineralische Rohstoffe, University of Tübingen), I conducted another survey in the Black Forest region ca. 80-100 km west of the Ach Valley cave sites. This survey began as a result of Neumann stating that some of the Hohle Fels ochres were visually similar to hematite from the Black Forest region. The visual differences in the Swabian Jura ochres with a large amount of the archaeological assemblage further supported this survey. The survey strategy focused on previously identified hematite deposits by geologists and hobbyists in the central-eastern portion of the Black Forest. Ochre sample locations were recorded with GPS coordinates and photographed; all samples taken were > 100 g. Lastly, donations from a geological hobbyist, M. Pipelow, of four ochre nodules from two different areas in Germany were also analysed. The ochres came from the Harz Mountains range in Thuringia (*Thüringen*) and from an iron ore mine near Geyer-Erzgebirge in Saxony (*Sachsen*). More detailed descriptions of the geological background for all of the regions sampled can be found in Paper 2 (Chapter 6) and Appendix E.

4.2.3. Analytical techniques

Ochre source specimens and some of the archaeological ochres were characterised for their elemental fingerprint (NAA), their mineral phases (XRD), and their mirco-fabric (SEM-EDS). Ochre as a useable pigment is geochemically heterogeneous as it can be any rock, sediment, or clay containing varying amounts of iron oxide or hydroxide (Cornell and Schwertmann 2003; MacDonald et al. 2018; Singh et al. 1978). As a result, characterising these materials is difficult without paying particular attention to the diagnostic major, minor and trace elemental data. These concentrations and trends must then be explored and compared using basic and multivariate statistics, such as bivariate plotting, principal components analysis (PCA) and canonical discriminant function analysis (CDA). Here, I provide some of the theoretical details of NAA, XRD, and SEM-EDS as well as the statistical treatment of the data in the following sections (note that Papers 2 and 3 offer some specifics on the lab protocol and procedures).

Neutron Activation Analysis (NAA)

All NAA characterisation of materials was conducted at the Archaeometry Laboratory at the University of Missouri Research Reactor (MURR) in Columbia, Missouri, USA, from October 2017 to February 2018. NAA has proven to be an ideal technique for analysing iron oxides as it can measure diagnostic elements, such as transition metal and rare earth elements, facilitating the differentiation of compositional groups (Eiselt et al. 2011; Kingery-Schwartz et al. 2013; MacDonald et al. 2013; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007). On an atomic level, NAA "…involves the irradiation of a sample by neutrons to make the sample radioactive. After irradiation, the gamma rays emitted from the radioactive sample are measured to determine the amounts of different elements present in a sample" (Glascock and Neff 20031516). This measures the decay of characteristic elemental half-lives resulting from the nuclei from each element transforming into unstable isotopes following exposure from neutrons. The radioisotopes emit gamma rays which are measured by a high-purity germanium (HPGe) detector-based gamma-ray spectrometer. These are then sorted into channels (measured in keV) and form peaks, representing qualitative and quantitative elemental representations. Aside from the benefits of elemental sensitivities that support provenance research, NAA is nearly free of any matrix interference, offers little opportunity for laboratory contamination, and requires a simple sample preparation process by allocating the correct weight of powder into the appropriate vials (Glascock and Neff 2003).

In total, I selected 183 ochre samples from Hohle Fels for NAA, with 62 out of 164 (ca. 38%) samples from Magdalenian deposits, 61/278 (ca. 22%) from the Gravettian, 13/35 (ca. 37%) from the Aurignacian/Gravettian transition and 60/371 (ca. 16%) from the Aurignacian. An equal sampling strategy would have been ideal for achieving an even diachronic spread; however, the final selection was limited by artefact size and weight. For instance, 221 pieces (ca. 60%) of the Aurignacian ochre artefacts were <100 mg and therefore not suitable for analysis with a required absolute minimum mass of 100 mg. In addition to the Hohle Fels ochres, nine ochres from the nearby cave sites of Geißenklösterle and 18 from Vogelherd, located in the neighbouring valley (Figure 2.1) were analysed using the same protocol in order to compare ochre materials between the caves.

No anthropogenically modified ochre artefacts were analysed. Before sample preparation, I personally weighed each ochre piece to determine the amount taken for sample preparation and to preserve as much of the ochre piece as possible. In order to prepare the artefacts for NAA, individual pieces were superficially ground with a Dremel in order to expose a clean surface free of debris. The cleaned pieces were then pulverised in an agate mortar and pestle syphoned into a glass vial, then covered and dried in a low-temperature oven at 110ºC for 24 hr to remove all water. These samples were then weighed at roughly 75 mg for short-irradiation procedure into high-purity polyethene vials, and at 100 mg in high purity quartz vials for long irradiation, constituting two analytical specimens per archaeological sample. Individual weights were recorded to the nearest 0.01 mg and vials were sealed before irradiation. In addition to the analytical samples, geological reference materials were also characterised as per standard procedure (Eiselt et al. 2011; Glascock et al. 2004; MacDonald et al. 2018; Neff 2000; Popelka-Filcoff et al. 2008) and include National Institute of Standards and Technology (NIST) certified reference materials: SRM-1633b (coal fly ash), SRM-688 (basalt rock), as well as quality control samples SRM-278 (obsidian rock) and New Ohio Red Clay (a standard used in MURR for in-house applications).

X-ray Diffraction (XRD)

X-ray diffraction is an analytical technique used for mineral phase identification of crystalline material. It can thus be used to determine which iron oxide phases are present in a material and can assist in investigating the differences between ochre specimens. XRD operates by generating X-rays in a cathode ray tube that is filtered to produce monochromatic radiation. This tube is directed towards a sample and then bombards the sample with electrons. This interaction causes the inner shell electrons to dislodge and thus create a diffracted ray producing characteristic spectra that can be measured. It is particularly useful for the identification and characterisation of unknown crystalline materials in solids and offers a simple sample preparation and relatively straightforward data interpretation (matching spectral peaks to widely published XRD units).

Powdered ochre samples were already available from some surplus unused NAA specimens and were also prepared at the MURR Archaeometry Laboratory in

Columbia, Missouri. The XRD patterns were collected using a Scintag X2 powder diffractometer equipped with a Peltier cooled energy sensitive detector operating at 40kV and 50 mA, using Cu-Kα radiation (1.54060 Å). A monochromatic X-ray beam was oriented at each target sample and scanned from 5° to 80° 2Ө at a scanning step size of 0.02°, and a dwell time of 2.0 s each. The peak patterns were identified and matched with crystallography reference libraries of diffraction patterns using FullProf and Match software, and comparison to Crystallography Open Database (Gražulis et al. 2009; Gražulis et al. 2011) and RRUFF database.

Scanning Electron Microscopy equipped with Energy Dispersive Spectrometry (SEM-EDS)

Scanning electron microscopy offers a visual way to investigate the varieties of geological micro-fabric on selected archaeological ochre samples. During the initial phase of artefact categorisation, ochre pieces were classified into nine distinct "ochre type" groups based on their various colours and textures (shown and described in Appendix A). This categorisation is similar to previous analyses on ochre assemblages (Pradeau et al. 2014) and assisted the results of the NAA ochre characterisation by offering another way to observe variations in ochre types. I observed each piece in several different places in order to investigate homogeneity and potential mineral inclusions. In total, I investigated 16 ochre pieces with SEM-EDS, and the results of nine of these are shown and discussed in Paper 3.

The SEM instrument is a Phenom XL desktop SEM from Thermo Fisher Scientific with a field emission gun (FEG) source and built-in user interface. The EDS contains a thermoelectrically cooled Silicon Drift Detector (SDD) with a 25 mm^2 active detector area and Silicon Nitride (Si_3N_4) window. The Phenom XL uses built-in elemental identification software for peak analysis and can identify elements ranging from Boron (5) to Americium (95). All SEM analyses were conducted using the instrument at the Senckenberg Centre for Human Evolution and Palaeoenvironment (HEP) Tübingen, with the technical assistance of Tatiana Miranda.

Statistical techniques

I employed several different statistical methods for the investigation of the archaeological and ochre source materials. Before any statistical analyses, two transformations were applied to the data: Fe-normalization and log^{10} (Eiselt et al. 2011;

Kingery-Schwartz et al. 2013; MacDonald et al. 2018; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007). Fe-normalization is particularly relevant for ochre provenance research as it allows the Fe-concentration of samples to become relative instead of absolute, permitting diagnostic elements to stand out without being affected by high Fe concentrations (Popelka-Filcoff et al. 2007). This is useful as the Fe-content of individual ochre samples can vary significantly depending on their primary bedrock and formation (Cornell and Schwertmann 2003). Log^{10} transformations were then applied to these ratios in order to account for non-normal distributions of the elements and to include all major, minor, and trace elements in the analysis.

In the first round of data exploration, I used bivariate plots to explore and observe any geochemical relationships or trends in the ochre data. This type of visual analysis is often the first employed as it can be highly informative for the identification of elemental correlations and outliers present in the dataset. Bivariate plots, also referred to as scatterplots, scatter diagrams, or scattergrams, visualise the relationship between two nominal scale variables (Shennan 1997). They offer information about the direction, form, fit, strength, and dependence of the two variables measured. In addition to bivariate plotting, I used multi-elemental techniques principal components analysis (PCA) and canonical discriminant function analysis (CDA) for further pattern recognition and interpretation of compositional groups. For PCA, in some cases, the measured elements in archaeological and geological data sets were large in number, which can result in difficulties in the handling of the data and interpreting patterns. PCA is useful for large data sets with similar variables (redundancy), as it shrinks the observed variables into a smaller number of linear combinations of the original variables, or principal components (PCs). These PCs account for most of the variation in the dataset and allow for observation on the data from a multitude of dimensions, instead of only the numerical value of specific elements (Eiselt et al. 2011; Popelka-Filcoff et al. 2008). PCA is particularly useful for investigative motives, such as identifying sub-groups in an undifferentiated dataset, for data evaluation, or to determine the coherence of already existing groups based on other criteria. PCA is scale dependent and is dominated by elements with high concentration values (Mardia et al. 1979), which is another reason why the log^{10} transformation of the data can be necessary.

Canonical discriminant function analysis (CDA) is another multi-elemental evaluative technique. Similar to PCA, CDA is useful for reducing the dimensions of the data as it transforms multiple independent variables into corresponding linear combinations. These combinations are the canonical discriminant functions (CDs), which are percentage representations of the magnitude of separation between the compositional groups. The produced CDs are typically shown in bivariate plots showing group separation. CDA differs from PCA in that CDA maximises the variances between known groups rather than amplifying the variance in the total dataset (MacDonald et al. 2013; MacDonald et al. 2011; Shennan 1997; Zipkin et al. 2017). It is therefore advantageous to use CDA when compositional groups are already known or identified, as is often the case with mineral sources sampled for provenance studies.

Chapter 5. Paper 1

Ochre and pigment use at Hohle Fels cave: Results of the first systematic review of ochre and ochre-related artefacts from the Upper Palaeolithic in Germany

Authors: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard

In this chapter and the following two chapters, I present the analysis and results which have already been published (Chapter 5), have been accepted for publication (Chapter 6), or are submission ready (Chapter 7). Though each of the papers contains information on the background of site, study, and methods, the most significant contributions lie in the results and discussions that, when taken together, construct the narrative of this thesis. It should be noted that published manuscripts are kept in their published format, including separate figure and tabling numbering and referencing styles. Different English spellings (British vs. American English) are used for each of the papers in order to adhere to specific journal regulations. That being said, these do not interfere with the content and contribution of each of the papers.

This chapter presents the results of an artefact-based qualitative assessment of the entire Hohle Fels ochre and ochre-related assemblage, published in PLOS ONE in 2018. The protocols used for the analysis of the collection and the results thereof are described, including numbers per each time period, visual and textural characteristics, the modified ochre assemblage, and ochre-related artefacts. The site stratigraphic integrity is discussed, as well as environmental and climatic impacts and possible ochre-use scenarios. The results show that people not only collected a variety of ochre types during different time periods in the Upper Palaeolithic, but they also used them in different ways. The ochre record at Hohle Fels, however, may only represent a fraction of the original total amount. This is likely due to several scenarios operating simultaneously, such as the impacts of erosion, seasonal migration patterns as well as people making every piece of ochre count. This paper sets the stage for the other two thesis papers as it documents the ochre assemblage, the variety in ochre textures, colours, and types, and the behavioural inferences related to ochre use at the site. The article was originally published with Supplementary Information, which is shown in Appendix D, pg. 311.

PLOS ONE

RESEARCH ARTICLE

Ochre and pigment use at Hohle Fels cave: Results of the first systematic review of ochre and ochre-related artefacts from the Upper Palaeolithic in Germany

Elizabeth C. Velliky[1,2]*, **Martin Porr**[2,3], **Nicholas J. Conard**[4]

1 Institut für Naturwissenschaftliche Archäologie, Mathematisch-Naturwissenschaftlichen Fakultät, Tübingen, Germany, **2** Archaeology/Centre for Rock-Art Research and Management, M257, Faculty of Arts, Business, Law and Education, School of Social Sciences, The University of Western Australia, Crawley WA, Australia, **3** Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, ROCEEH—The Role of Culture in Early Expansions of Humans, Tübingen, Germany, **4** Department of Early Prehistory and Quaternary Ecology & Senckenberg Centre for Human Evolution and Quaternary Ecology, University of Tübingen, Schloss Hohentübingen, Tübingen, Germany

* elizabeth.velliky@research.uwa.edu.au

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Abstract

Though many European Upper Palaeolithic sites document early examples of symbolic material expressions (e.g., cave art, personal ornaments, figurines), there exist few reports on the use of earth pigments outside of cave art–and occasionally Neanderthal–contexts. Here, we present the first in-depth study of the diachronic changes in ochre use throughout an entire Upper Palaeolithic sequence at Hohle Fels cave, Germany, spanning from ca. 44,000–14,500 cal. yr. BP. A reassessment of the assemblage has yielded 869 individual ochre artefacts, of which 27 show traces of anthropogenic modification. The ochre artefacts are from all Upper Palaeolithic layers, stemming from the earliest Aurignacian horizons to the Holocene. This wide temporal spread demonstrates the long-term presence and continuity of ochre use in a part of Europe where it has not been systematically reported before. The anthropogenic modifications present on the ochre artefacts from the Gravettian and Magdalenian are consistent with pigment powder production, whereas the only modified piece from the Aurignacian displays a possible engraved motif. The non-modified artefacts show that more hematite-rich specular ochres as well as fine-grained deep red iron oxide clays were preferred during the Gravettian and Magdalenian, while the Aurignacian layers contain a broader array of colours and textures. Furthermore, numerous other artefacts such as faunal elements, personal ornaments, shells, and an ochre grindstone further strengthen the conclusion that ochre behaviours were well established during the onset of the Aurignacian and subsequently flourished throughout the Upper Palaeolithic at Hohle Fels cave.

Introduction

Hohle Fels (HF) cave has contributed significantly to our current understanding of the earliest culture associated with the first anatomically modern humans (AMHs) in Europe known as the Aurignacian (ca. 44,000–34,0000 cal. BP) [1]. The Aurignacian assemblage at HF includes the earliest known musical instruments in the form of flutes, personal ornaments, figurines, and the earliest female statuette dating to ca. 38,000 years BP [2–5] most of which are made from mammoth ivory. Less known in the HF assemblage is the presence of numerous ochre artefacts stemming from all Upper Palaeolithic (UP) periods. In this paper, we present the first systematic study of an ochre assemblage at HF cave and, more broadly, the first detailed analysis of an ochre assemblage from a Central European UP site through different time periods. HF in southwestern Germany presents a unique opportunity to observe diachronic change throughout the UP due to its well-established chronology and stratigraphy. Our recent reassessment of the HF excavated material yielded 869 individual ochre artefacts, 27 (3.1%) of which show traces of anthropogenic modification. The artefacts stem from all UP periods present at HF and were found over the course of excavations at the site from 1975–2018. Here, we report the qualitative characteristics of the HF ochre assemblage that hitherto have not been reported. These aspects include the variety of ochre types present, differences in visual characteristics such as colour and texture, and the types and range of modifications. We then discuss how ochre use changes throughout the UP and the behavioural implications of these use patterns on a local and regional scale.

Overview of European and African research history

Ochre is a colloquial term frequently used by archaeologists in reference to any sediment, clay, or rock containing varying amounts of iron oxide or oxyhydroxide (generally, $2Fe_2O_3$ and FeO) minerals [6]. It appears in sedimentary, metamorphic, and igneous contexts as most rock types contain varying amounts of Fe that are oxidised at variable rates in different geological settings [7]. Because of the different amounts of iron content in the material, the colours expressed vary from yellow and red to purple and brown. Various types of ochre can be heat-treated in order to alter their original colours directly, yet archaeological support of this behaviour is at this point limited (however, see [8, 9, 10]). Experimental studies show that the characteristics between heat treated and non-heat-treated ochre are subtle and can be difficult to differentiate [11].

The habitual exploitation of ochre in Pleistocene contexts is often cited to be related to cognitive complexity, syntactical language, and symbolically mediated behaviour [12–23]. Due to the antiquity of ochre in African sites, with the earliest examples stemming from contexts dating to ca. 300,000 years BP [24–27], a heavy emphasis is placed on researching ochre materials in these areas in relation to the emergence of behavioural modernity. The discussion of this topic is vast, with some authors supporting a primarily symbolic interpretation of ochre due to the sheer abundance at specific sites [25, 28], others cautioning against assuming such interpretations without proper investigation [29, 30], and others exploring the range of functional applications and geological varieties of ochre materials [31–37]. This latter functional perspective has shown ochre to be a useful material for tanning hides [38, 39], as an insect repellent and UVA/UVB shield [40, 41], and as an adhesive for weapon manufacture [36, 42–44]. Indeed, archaeological contexts from Sibudu Cave in South Africa provide support for ochre as a residue on lithics [43, 45] as well as in a mixture with a milk-based protein that could have been applied to skin or other surfaces [46]. In Europe, comprehensive reports of ochre assemblages have decreased within the last 20 years (however, see [47, 48, 49]). Though several reports from older excavations exist [50–53], their contextual and stratigraphic integrity is often not secured and becomes blurry over time and with multiple handlings of collections. Furthermore, often larger pieces or associated finds, such as ochre grindstones or artefacts "painted" with ochre [52, 54–57] are the primary focus while overlooking other artefacts and not providing comprehensive overviews. Comparatively, another earth pigment, manganese oxide, has been the subject of more intensive recent investigations due to its prevalence in Middle Palaeolithic contexts [58] and association with questions surrounding Neanderthal behavioural complexities [59–61]. Some ochre contexts are present in Middle Palaeolithic and Châtelperronian horizons [62–67]; however, modified manganese oxide nodules appear more frequently and were apparently the preferred pigment-producing material for our hominin cousins. Additionally, one may argue that compared to African ochre studies, relatively few European UP ochre assemblages are systematically studied to the same extent (see [68, 69]). There is also a comparative lack of experimental studies within the last 20 years of investigations of the range of ochre applications specific to European contexts (however, for example see [38, 70, 71]), though more recent work is published on the applications of manganese oxides [58, 59]. However, this focus on other pigments in the place of ochre is not due to a lack of ochre and other pigment producing artefacts in European UP archaeological sites [8, 48, 66, 69, 72, 73]. Here, we present a systematic overview of ochre and pigments from a Central European cave site, and discuss how this record fits into the network of cultural traits in the late Pleistocene.

Hohle Fels cave and the Swabian Jura

Swabian Jura geological and archaeological context. The Swabian Jura (German: *Schwäbische Alb*) is a mountain range bordering the Danube River, located in the southern part of Baden-Württemberg (BW), Germany. This part of the BW region falls within the larger geological complex of the Jura Mountain range in Europe [74, 75]. The Swabian Jura consists of Jurassic limestones and is characterised by karstic landscape features such as caves, dry valleys, underground watercourses, and sinkholes [74, 76–78]. The landscape and geological formation of the Swabian Jura, and more specifically the region near HF is the result of extensive erosional processes and weathering since the Cretaceous period due to severe climatic fluctuations [79–81].

The Swabian Jura is regarded as a critical area for understanding the early development of cultural and symbolic behaviours in human populations and contains numerous Middle Palaeolithic (MP) and UP sites [1, 82–84]. Most of the known MP and UP sites are located in two tributary valleys of the Danube (German: *Donau*), the Ach and Lone (German: *Achtal* and *Lonetal*) and include: Sirgenstein, Brillenhöhle, Hohle Fels and Geißenklösterle in the Ach Valley, and Vogelherd, Bockstein (Bockstein-höhle and Bockstein-Törle), and Hohlenstein (Stadel and Bärenhöhle) in the Lone Valley (Fig 1).

The assemblages from the Swabian Jura sites are among the earliest occurrences of the Aurignacian technocomplex in Europe, dated up to ca. 43,751 ± 654 cal. BP [3]. They are referred to by some as the *Swabian Aurignacian* due to their distinct artefact and tool composition [1, 85, 86]. Specifically, the *Swabian Aurignacian* is unique in Europe for its specimens of figurative art, musical instruments, blade and bladelet production as well as an organic tool industry [2, 3, 82, 87]. There is widespread agreement that the Swabian technocomplex is associated with AMHs who migrated into a favourable and apparently uninhabited region by way of the so-called Danube-Corridor around 45,000 years BP [82, 88].

In addition to the Aurignacian cultural sequence, the Gravettian (ca. 34,000–30,500 cal. yr. BP) and Magdalenian (ca. 16,500–14,500 cal. yr. BP) layers have also yielded a rich assortment of artefacts. The Gravettian boasts a large lithic assemblage including burins, Gravette points,

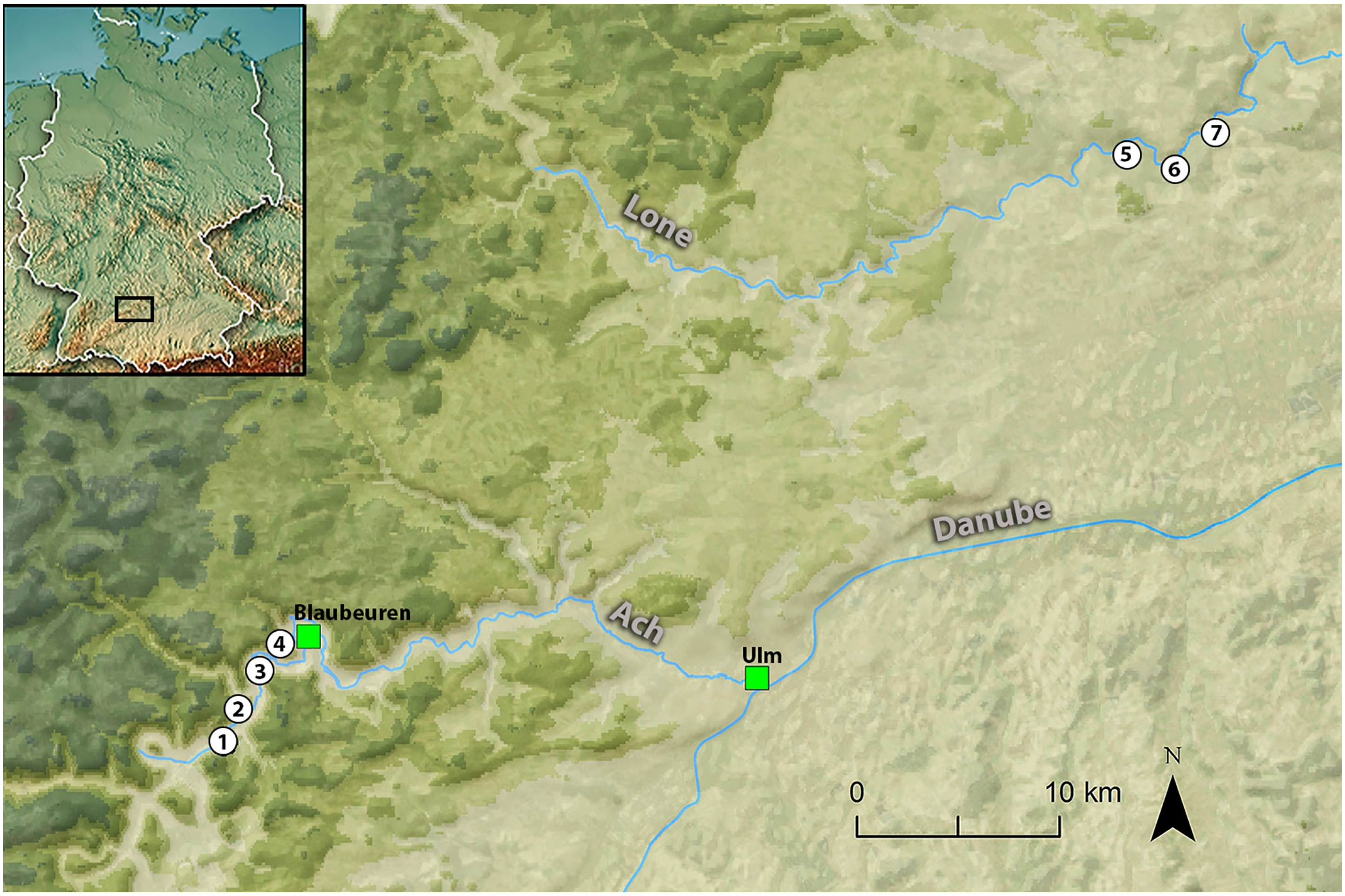

Fig 1. Map of southwestern Germany with the principal Upper Palaeolithic cave sites. Ach Valley: 1) Hohle Fels, 2) Sirgenstein, 3) Geißenklösterle, 4) Brillenhöhle; Lone Valley: 5) Bocksteinhöhle and Bockstein-Törle, 6) Hohlenstein-Stadel and Hohlenstein-Bärenhöhle, 7) Vogelherd.

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and backed knives made from both local and non-local raw materials [89]. Numerous organic tools made from bone, antler, and ivory as well as personal ornaments made from various animal teeth and ivory characterise the assemblage [89, 90]. The Magdalenian lithic assemblage is similar to the Gravettian and also includes blades and bladelets, scrapers, and backed knives and points, to name a few [91] made from both local and non-local materials. Included in the assemblage are perforated animal teeth and freshwater snail shells, osseous tools of needles, harpoons, points, and notched rods, and jet "pendants" [91].

Hohle Fels cave. HF cave is 534 m above sea level, located between the modern-day towns of Blaubeuren and Schelklingen, some 17 km west of Ulm (Fig 1). HF is situated within a large, free-standing rock outcrop (i.e. tor, eng. or *Felsen*, ger.) of Jurassic limestone. The interior of HF is ca. 6000 m^3 and is thus one of the largest caves in the Swabian Jura [77]. HF has an archaeological research history that extends back to the late 19th century, beginning with Oscar Fraas' excavations in 1870/71 with Theodor Hartmann [85, 92–94], though many of the finds went missing in World War II. Joachim Hahn and colleagues resumed research in 1973 with excavations at both Geißenklösterle and HF [93]. Here, Hahn implemented a systematic recording system and established the chrono-stratigraphy which is still the framework for the modern-day understanding of both sites. This work was continued in 1997 by Nicholas Conard in collaboration with Hans-Peter Uerpmann with the University of Tübingen.

The current excavation, which is still ongoing, operates with 71 m^2 spatial units in the northern apse of the cave close to the entrance, and bedrock has not yet been reached (Fig 2). The stratigraphy is organised based on litho- and archaeo-stratigraphic categories, resulting in the documentation of both geological horizons (GH) and archaeological horizons (AH). Although local variation occurs, the HF sediments are mainly composed of calcareous clay and locally phosphatic clay with less frequent inclusions of quartz, phosphatic grains, and organic material. The sediments throughout the sequence contain varying amounts of bone, lithic, and charcoal fragments intermixed throughout [76–78].

The three-metre deep HF stratigraphy is divided into six major archaeological horizons assigned to the Magdalenian (ca. 16,500–14,500 cal. yr. BP), Gravettian (ca. 34,000–30,500 cal. yr. BP), Aurignacian (44,000–34,000 cal. yr. BP), and MP (>44ka BP) layers (see Table 1 for uncalibrated radiocarbon dates). These are further sub-divided into finer excavation units (Fig 2), starting with the uppermost Magdalenian layers AH I and AH IIa, both dated to around 16 ka cal. BP [91]. The Magdalenian layers show some internal mixing (I and IIa) as well as with the overlying Holocene layers [91]. The most recent Gravettian layer AH IIb also contains some Magdalenian artefacts, especially in the northwestern units, and may represent a period of post-depositional mixing [95]. The layers IId and IIe are brief and document a short, if at all existing, occupational hiatus between the Gravettian and Aurignacian (ca. 34,500–32,500 cal. yr. BP) [96, 97]. The Aurignacian complex contains sequences AH IIIa-b, IV, Va, Vaa-ab, and Vb, all of which have yielded many figurative art and symbolic artefacts as well as a rich lithic industry [91, 95, 98].

Previously recorded ochre and ochre related artefacts. In the years 2009 and 2010, five different ochre artefacts were recovered from Magdalenian contexts at the site, all bearing different forms of anthropogenic modification [99, 100]. Four of the five pieces are hematite, a purple to silver iron oxide (Fe_2O_3) that produces deep red streaks and is often found as a red pigment in archaeological contexts [6, 8, 33, 67, 72, 101, 102], the other piece is classified as a "red chalk" (Find # 102.555.1). This find contains scoring incisions on all four of its worked surfaces, forming a "pencil" or "crayon" shape (S1A Fig). A specular hematite artefact (Find # 102.630.1) was ground on two sides forming two faceted surfaces which converge to a point, though the tip is broken off (S1A Fig). The remaining three pieces, referred to as the *Rondelle* artefacts [100], appear to be of the same specular hematite material and were rounded into a circular shape with a perforation in the centre (S1A Fig). Two of these pieces refit together (Find # 110.1104.1 & 110.992), and it is possible that the third piece (Find # 110.434.1) is part of the same or an entirely different artefact. The exact purpose of this worked piece is unknown, though similar forms of disc-shaped artefacts made from shale and jet were found in Switzerland and the Czech Republic as well as HF [91], though they are thought to have had a functional purpose in the construction of habitation structures [103, 104]. Other *Rondelle* made from bone have been found in Magdalenian contexts in Southwest Europe and later on in Central Europe, indicating that this style may have been trans-regional [103, 105].

Excavations in 1998 uncovered a painted fragment of the same Jurassic limestone of the interior of the cave. This piece might have originally been attached to the cave wall [106]. In total, seven painted rocks, including limestone and dolomite materials, have been found in the Magdalenian layers [99, 100, 106–110]. All of these pieces contain traces of red ochre arranged in a series of painted rows of dots. The rows occur in pairs and range from one to three pairs on each stone (S1B Fig). Two of the limestone fragments are rounded and do not refit with any of the other pieces or the cave wall. Their material and lack of refit suggest that instead of sourcing from the interior of the cave, it is possible that they are river cobbles from the Ach

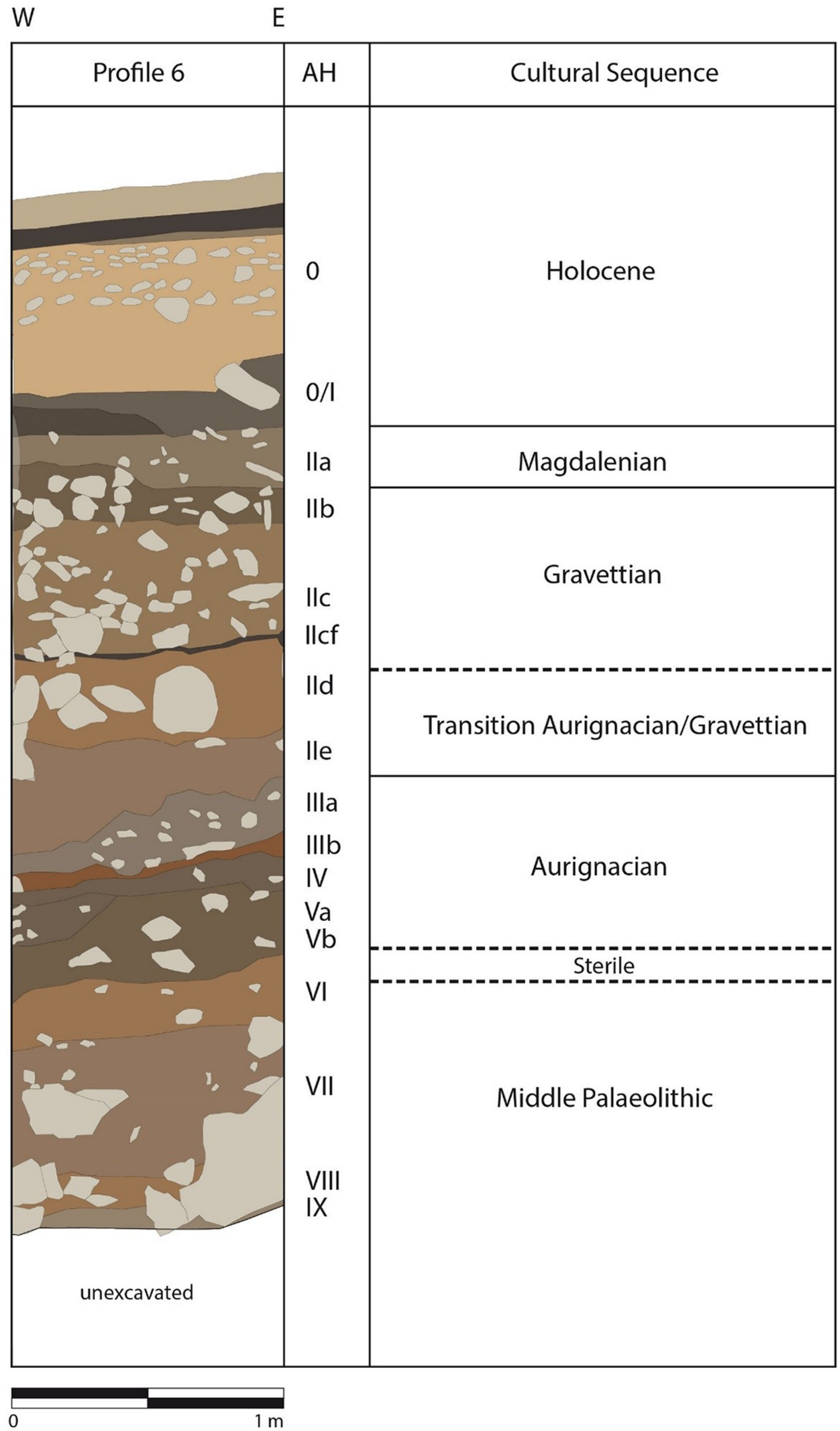
W
E
Profile 6
AH
Cultural Sequence
0
Holocene
0/I
IIa
Magdalenian
IIb
Gravettian
IIc
IIcf
IId
Transition Aurignacian/Gravettian
IIe
IIIa
IIIb
Aurignacian
IV
Va
Vb
Sterile
VI
VII
Middle Palaeolithic
VIII
IX
unexcavated
0
1 m

Fig 2. Cultural stratigraphy from Hohle Fels main profile. Schematic of main profile six at HF with archaeological horizons (AHs) in roman numerals and corresponding time period.

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(located directly outside of the cave) or the Danube rivers. The stones come from layers AH I and IIad and contain some of the better-preserved series of rows of dots on the painted stone assemblage. It is likely that the original paintings were more substantial and may have contained numerous designs, whether they were stylistically similar or not [69]. The lack of preservation of painted artefacts, whether it be parietal or portable art, may be due to the deterioration of the cave walls in this Karstic region which are subject to expansion and retraction during climatic warming and cooling phases, as well as erosional processes [111].

In addition to the painted stones, faunal elements with traces of ochre from the Magdalenian and Aurignacian levels of HF also constitute part of the assemblage (S1C Fig) [107]. One long bone (Find # 14.69) displays two large oblong smudges of red ochre. A fragment of a reindeer cranium (Find # 89.48) contains traces of red ochre powder on the interior. One temporal fragment of a cave bear (Find # 29.1484.13) with traces of red ochre residue on the interior comes from the Gravettian layers [69]. In summation, the previously recognized modified ochre artefacts, as well as the artefacts exhibiting visible traces of anthropogenically applied red residues, suggest that ochre behaviours were well in place at the site by the late Pleistocene.

Materials and methods

The term *ochre* is used quite liberally in the archaeological community in reference to any earth-derived colouring material, often showing red, orange, yellow, purple, brown, or black hues, which can be manipulated into a pigment [23, 28, 35, 112–116]. The designation of ochre also implies the intentional recognition, acquisition, and transportation of the material [117]. Thus, in the archaeological sense, the term *ochre* does not only refer to minerals in the landscape that are red but also minerals that were interacted with and collected by hominin species. We use the term *ochre artefact* or *ochre piece* in order to specify that these items are archaeological materials recorded and collected from excavations at HF, whether they be unmodified iron oxide nodules or patches of red iron-rich sediment. Other terms used throughout this paper include *anthropogenically modified* or simply *modified ochre* which refers to ochre artefacts that were further altered by hominins and contain visible traces from these physical interactions. We emphasise the ochre data and results from the Aurignacian,

Table 1. Dates for the Hohle Fels Upper Palaeolithic. Uncalibrated radiocarbon dates for corresponding archaeological horizons at HF. Period abbreviations are: M = Magdalenian, G = Gravettian, A/G = Aurignacian/Gravettian transition, A = Aurignacian.

AH	Period	Uncal. date	References
I	M	13,240 ± 110–12,506 ± 32	Hahn, 1995; Taller, 2014
IIa	M	13,350 ± 140–12,520 ± 130	Housley et al., 1997
IIb	G	28,350 ± 220–28,170 ± 180	Hofreiter et al., 2007
IIc	G	29,500 ± 650–26,000 ± 360	Hahn, 1995; Housley et al., 1997
IIcf	G	27,970 ± 140–27,030 ± 240	Conard, 2003
IId/IIe	A/G	30,640 ± 190–28,060 ± 170	Conard and Bolus, 2003; Conard and Moreau, 2004
IIIa/b	A	29,990 ± 330–29,710 ± 210	Conard and Bolus, 2003; 2008
IV	A	33,090 ± 250–30,110 ± 210	Conard and Bolus, 2003; 2008
Va	A	35,710 ± 340–31,750 ± 260	Conard and Bolus, 2003; 2008
Vb	A	40,000 ± 500–31,290 ± 180	Conard, 2009

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Aurignacian/Gravettian transition (A/G Trans), Gravettian, Magdalenian, and, to a lesser extent, Holocene ochre artefacts. All artefacts catalogued as RO (*Rötel* or red ochre) or HA (*Hämatit* or hematite) recorded as single plotted finds found *in-situ* during excavation, bucket sediment finds, and coarse fraction finds were included in this in-depth analysis. The entire HF assemblage, including the ochre materials, is housed and curated at the University of Tübingen in the *Institut für Naturwissenschaftliche Archäologie* (INA) and the Department of Early Prehistory and Quaternary Ecology in the *Schloss Hohentübingen*, and therefore no special permissions were required for analysing the artefacts. The archaeological assemblage was reinvestigated by the primary author (EV) between the years 2015–2018, and this revealed hundreds of previously unidentified and non-categorized ochre pieces. The ochre artefacts were catalogued under a unique system (specimen numbers HF Ochre 1–955) in order to avoid duplicates for rediscovered ochre artefacts and are correlated to the general HF archaeological database. No permits were required for the described study, which complied with all relevant regulations.

One category frequently collected at HF is OK (*Ocker* or yellow ochre). Even though yellow ochre artefacts outnumber red ochre artefacts (n = 1,007 for plotted single finds alone), the vast majority of these yellow ochre pieces are likely weathered limestone naturally occurring in the cave. Therefore, we did not include the yellow ochre artefacts as there was no way to distinguish between naturally occurring and anthropogenically transported yellow ochre at the site without using chemical or mineralogical techniques. The exclusion is not meant to suggest that yellow ochre was not collected and brought to the site or perhaps even heat treated to alter the colour as seen in other archaeological sites [9–11, 72]. This extensive work of chemically and mineralogically comparing the yellow ochre artefacts to the naturally occurring weathered limestone fragments is therefore left for future analysis but does not form part of the current research project.

In our revised ochre artefact database from HF, each piece was given a unique identifying code and was classified by a series of qualitative characteristics (Table 2). Each of the artefacts in this database was macro- and microscopically examined for traces of modification using a Euromex binocular microscope with 10–30 x magnification. Macroscopic variables were determined using a combination of natural and artificial light. If pieces were determined to bear traces similar to anthropogenic modifications, they were further examined in more detail using a Zeiss Discovery V8 Stereomicroscope. Photographs were taken with either the Zeiss or

Table 2. Ochre characteristics for Hohle Fels artefacts. Descriptive variables for ochre and ochre-related artefacts.

Category—Ochres	**Variables**
Size	L x W x D (mm), weight (g)
Rock types	Hematite, sandstone, iron oxide, clay, red sediment, siltstone, specularite
Characteristics	Micaceous, oolitic, porosity
Texture	Clay, silt, sand (mixtures)
Colour, second colour	Purple, red, orange, yellow, brown (dark/light)
Modified	Striations, micro-striations, score marks
Category—Residues	**Variables**
Size	L x W x D (mm), weight (g)
Material	Stone, mammoth ivory, limestone, bone, tooth, shell, fossil
Colours	Artefact colour, residue colour, # of colours
Residue	Applicator, grinding stone, personal ornament, painting, mixture, container
Residue origin	Direct application, indirect staining, natural

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a Keyence VHX500 digital microscope. CIELAB colour measurements were conducted on digital images taken with the Keyence VHX500 using the same fixed light setting and then measured in Adobe Photoshop. Similar protocols for measuring colour using CIELAB values have also been incorporated into previous qualitative studies of ochre and pigments [31, 32, 118]. While the resulting colour values refer to the true calibrated surface colour of the ochre piece, it is our opinion that the internally consistent CIELAB values we produced are indeed representative of the original surface colour.

Our classification of ochre modifications builds on protocols established in previous ochre studies in order to maintain consistency within the research field and to allow for future cross-comparisons between sites and ochre assemblages [23, 31, 119–121]. Qualitative characteristics such as texture, colour, rock type, and size of the ochre artefacts are described based on a system created by Hodgskiss (119); however, these traits are common descriptive variables used for more qualitative ochre analyses elsewhere [27, 31–33, 120, 122–124]. Our HF protocol (for details see Table 2) allows us to characterise grinding, rubbing, scoring or more specifically incisions or engraving striations, micro-striations, rounding and faceting.

Physical characteristics

Our examination and description of the HF ochre assemblage are inspired by and adapted from methodologies employed by researchers investigating Middle Stone Age (MSA) ochre from South Africa [31, 113, 120, 123], with some alterations made by the primary author. Since the HF ochre artefacts vary considerably from MSA assemblages, several categorical descriptions were altered to accommodate local characteristics of the HF assemblage. These descriptions are not meant to apply to all European assemblages. They do, however, provide a starting point for further discussion on how to apply commonly used terms and techniques in ochre research to a geographical region where research on pigments in the UP is comparatively less emphasised. The characteristics, based on Hodgskiss and Wadley [123], are as follows:

1. *Rock type*. Each artefact classifies to one of seven rock types (hematite, sandstone, specularite, clay, red sediment, siltstone, iron oxide) based on visual examination. These rock type categories are purposefully broad, as the artefacts show a high degree of heterogeneity, preventing a precise mineralogical classification. *Hematite* is classified by a visually purple colour with a fine-grained texture, a red to dark red streak and often containing mica inclusions. *Specularite* is generally extremely dark purple to black and contains a high amount of mica inclusions. *Sandstone* is characterised by a redder colour and sand-sized granular texture, *siltstone* and *clay* are differentiated based on grain size. *Red sediment* was any ochre material recovered not in a solid form. *Iron oxide* was treated as an "other" category when could not be classified into one of the aforementioned categories. Quartz and mica inclusions are noted, as well as the presence of porous and oolitic textures.

2. *Grain Size*. Individual pieces were given approximate texture classifications: clayey (diameter <2 μm), silty (diameter $<50–2$ μm) and sandy (diameter $<2000–50$ μm) [125]. In most cases pieces contained a combination of grain sizes, so a descriptive combination of different textures was employed based on the primary and secondary textures (e.g. clayey/silty, silty/sandy).

3. *Colour*. Artefacts were assigned a subjective category based on their external colour including purple, red, pink, orange, yellow, and variations of these including dark or light. We also recorded streak colour as it is likely that pigment colour played a more significant role than the exterior surface colour of the physical piece. Streak tests were conducted on an

unpolished white ceramic plate and were subsequently photographed; Adobe Photoshop CS6 was used to measure the average CIELAB colour values in an 11 x 11-pixel area.

In general, ochre found at archaeological sites tends to exhibit hardness levels between three and five [28, 35, 113, 119, 120, 123]. Given the small size (<10 mm) of many of the HF ochre artefacts (n = 512), it was not possible to systematically measure hardness. Colour streak tests were conducted on the ochre artefacts in order to identify the colour of the produced powder. The most obvious example is pure hematite pieces, which commonly exhibit a silvery or greyish shimmer on their exterior, and produce a dark red streak or powder. This form of analysis is semi-destructive but provides essential information on the pigment colour of the artefact, which likely played a larger role in ochre selection than exterior colour. Each of the ochre pieces large enough to hold (≥ 5 mm) underwent a streak test on an unpolished ceramic plate. The streaks were grouped based on their stratigraphic temporal assignment: Aurignacian, A/G transition, Gravettian, and Magdalenian. All of the ceramic plates were photographed under the same magnification and light conditions using a Keyence VHX500 digital microscope. The images were taken in TIF format and exported to Adobe Photoshop CC 2016. The colour of each streak was measured within a 3-dimensional colour space, CIELAB, or International Commission on Illumination (CIE) $L^*a^*b^*$ colour space using an 11x11 pixel average method. This method for measuring colour has been applied to other archaeological ochres with the intention of studying behavioural patterns relating to colour selection and preference [31, 32], and allows for a more quantitative assessment of the range and distribution of colours that ochre artefacts can produce.

Anthropogenic modifications

According to previously conducted ochre studies [47, 113, 120, 124], an evaluation of the frequency and nature of surface modification can allow inference on the nature of anthropogenic modifications. After visual examination, the HF ochre artefacts were classified into three categories of modification: *modified*, *possibly modified*, or *non-modified*. The presence of modifications was established based on the occurrence of certain traits including striations, micro-striations, faceting, polish, and scoring. These definitions are based on Hodgskiss' [112] initial experimental work on ochre use-wear patterns and are as follows:

1. *Grinding*. Defined by the presence of multiple groups of parallel striations or grooves. Micro-striations may also be present, and extensively ground pieces may become faceted. This type of modification is caused by rubbing an ochre piece on a hard surface and was likely done to create a concentrated patch of pigment powder. Profile shapes of grooves can vary based on the surface morphology of both the ochre piece and the grindstone.
2. *Rubbing*. Defined by the presence of micro-striations, polish, and the removal or smoothing of surface morphological features. Rubbing is also defined as soft-surface grinding and indicates a direct application of an ochre piece to a soft surface such as human or animal skin. Rubbing can also coincide with grinding ochre pieces, as post-ground surfaces can contain much powder and could have been directly applied to soft surfaces to create a streak of colour. Traces of rubbing can also be created post-depositionally and are differentiated in this research based on other post-depositional characteristics (e.g., scuff or scratch marks), or with the presence of other forms of anthropogenic modification. If no definitive assertion could be reached, then the piece was categorised as *possibly modified*.
3. *Scoring*. Refers to a deep incision of cut as applied by a tool or device, likely a lithic or bone fragment. Profile shapes of score marks vary greatly depending on depth and precision of

the incision, often contain micro-striations within the incision, can show varying depths in the incisions, and can contain frayed ends due to multiple-stokes in an incision. Several score marks can form an *engraving* which shows an intentional shape or form designation.

4. *Faceting*. A result of intensive grinding which changes the shape of an artefact so substantially that the ground surface is entirely flat. The surface often contains striations or micro-striations, however rubbing or post-depositional processes can erase these.
5. *Rounding*. A general shaping of an artefact so that the outer edge shows a circular profile. Striations or micro-striations are often present on the rounded surface. Rounding can refer to both convex and concave edges.

Ochre artefacts can also exhibit evidence for more than one form of anthropogenic modification. Rounding is a form of grinding, faceted surfaces are often the result of grinding, and scoring can occur on faceted surfaces. Rubbing or smoothing can decrease the severity of profile shapes or striations, and also alter edge shapes on the artefacts. For each category, profile shapes of striations, orientations, surface morphology, the presence of polish, and presence of modern modifications (scuff marks, scratches) were noted.

Ochre-related artefacts (ochre residues)

In addition to the identification and cataloguing of individual ochre pieces, artefacts with traces of what appeared to be red ochre residues were collected and categorised in order to investigate broader patterns of ochre use. Many of these artefacts, such as faunal elements, perforated ivory beads, and freshwater snail shells, were visually identified and separated during the reassessment of the HF ochre assemblage. Dr. Susanne Münzel of the University of Tübingen previously identified other artefacts during various analyses of the faunal assemblage. We categorised these by similar variables used for the ochre artefacts such as artefact type, size, period, and type of material, the colour of residue, the presence of residue, possible use, and final decision or designation of the cause of the residues. These are defined below. However, a breakdown of the other qualitative variables is described in Table 2.

1. *Direct application*. This category describes artefacts that based on all visual evidence were likely intentionally and directly coloured with red ochre. Examples include the previously discovered painted limestone pieces [69, 99, 100, 110].
2. *Indirect colouring*. This category contains artefacts that are covered with ochre, potentially during ochre powder processing, or by indirectly colouring as a result of other anthropogenic processes like rubbing against hides or other surfaces. It is also possible that the colouring of artefacts in this category is a result of sediments rich in anthropogenically derived ochre powder. Examples include freshwater snail shells or faunal elements with a visible layer of ochre powder.
3. *Natural*. The colouring and staining of the object is likely the result of natural cave processes, staining from geogenic cave sediments, non-anthropogenically derived iron oxide or other post-depositional processes. *Natural* colouring differs from *indirect colouring* by considering the sedimentary micro-context of the artefact, i.e. staining was considered natural when the colouring agent was part of the sedimentary matrix. Examples include limestone pieces with red surfaces that likely result from oxidisation, and faunal elements where the colouration is part of the material matrix and not an external application of ochre powder.

Results

Our reassessment of the HF ochre assemblage yielded a total of 869 individual ochre pieces, including artefacts from the Holocene, with a total weight of 925.768 g (average 1.07 g). A breakdown of the total number of ochre artefacts and modified pieces in all time periods from HF is summarised in Table 3. 27 artefacts show definite signs of anthropogenic modification (3.1% of the assemblage) and another 21 show possible traces of anthropogenic modification (2.4% of the assemblage). The Aurignacian layers yielded the most ochre artefacts with 371 (Fig 3), yet it contains only one anthropogenically modified artefact and two possibly modified pieces. The Gravettian layers contain 278 individually recorded ochre artefacts (Fig 4), of which seven show traces of anthropogenic modification and two of which are possibly modified. The Magdalenian layers yielded fewer ochre artefacts (n = 164) (Fig 5), yet this period has the most modified (n = 17) and possibly modified (n = 14) artefacts.

Below, we will focus further on the in-depth analyses of UP cultural periods: the Aurignacian, the A/G transition, the Gravettian, and the Magdalenian. Though the Holocene layers are likely mixed with Magdalenian layers and perhaps contain numerous Magdalenian ochre artefacts, their stratigraphic integrity cannot be assured.

Rock types

Table 4 displays a detailed breakdown of the qualitative ochre characteristics per cultural period in the UP at HF. In the entire HF assemblage (modified, possibly and non-modified) from all periods, hematite is the dominant rock type (48.4%), followed by sandstone (27.8%) and iron oxide (17.8%). A period comparison shows that this pattern is mainly present in the Magdalenian and the Gravettian non-modified ochre assemblages, however, in the Gravettian iron oxide is the second most abundant (16.8%) followed by sandstone (13.9%). This pattern changes slightly for the Aurignacian non-modified ochres, where the dominant rock type is sandstone at 45.3%, followed by hematite (25.7%) and iron oxide (18.2%). When looking at only the modified ochre, hematite is also the favoured rock type (74%) followed by iron oxide (11%).

Textures

The textures of the ochre artefacts from HF correlate well with their rock types. For example, hematite pieces are often of a silty texture with varying sandy or clayey mixtures. This textural affiliation is present in the A/G transition, Gravettian and Magdalenian, all of which contain about 30% silty-textured ochres for modified, possibly, and non-modified ochres (see Table 4). The texture preference changes for the Aurignacian, as the majority of the ochre artefacts are sandstones with a fine-grained sand texture constituting 50.6% of the assemblage. All of the time periods contained varying amounts of sandstone and iron oxides, which contributed to the most frequent texture type of all time periods and modification types combined being fine-grained sand (31.2%).

Table 3. Hohle Fels ochre artefact totals. Final number of ochre pieces, modified ochre artefacts, and possibly modified ochre artefacts from HF.

	Holocene	Magdalenian	Gravettian	A/G Trans	Aurignacian	Total
Total	**21**	**164**	**278**	**35**	**371**	**869**
Unmodified	17	133	269	34	368	821
Modified	1	17	7	1	1	27
Possibly Modified	3	14	2	0	2	21

https://doi.org/10.1371/journal.pone.0209874.t003

Fig 3. Hohle Fels Aurignacian and A/G transition ochres. Selection of unmodified ochre artefacts from the Aurignacian and A/G transition at HF. Numbers correspond to Table A in S1 Table.

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Fig 4. Hohle Fels Gravettian ochres. Selection of unmodified ochre artefacts from the Gravettian layers at HF. Numbers correspond to Table B in S1 Table.

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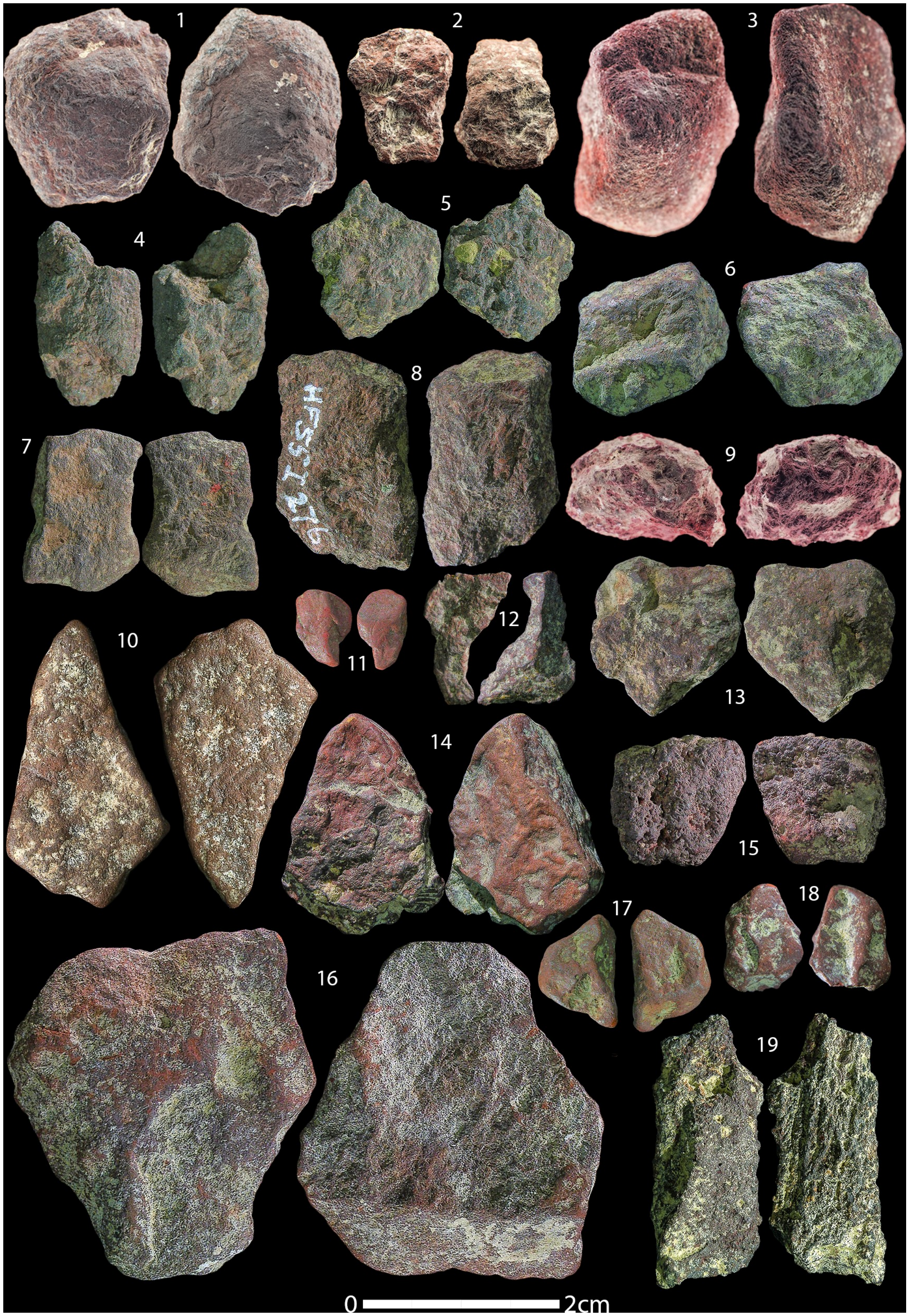

Fig 5. Hohle Fels Magdalenian ochres. Selection of unmodified ochre artefacts from the Magdalenian layers at HF. Numbers correspond to Table C in S1 Table.

https://doi.org/10.1371/journal.pone.0209874.g005

Table 4. Numbers and percentages of measured qualitative characteristics on the Hohle Fels ochre assemblage. Highest values are indicated by green and lowest values indicated by red.

Ochre qualitative characteristics by period		Aurignacian		A/G transition		Gravettian		Magdalenian		Total	
		n = 371	%n	n = 35	%n	n = 278	%n	n = 164	%n	n = 848	%n
Rock type	Hematite	93	25.7%	9	31.0%	185	67.5%	112	70.0%	399	48.4%
	Iron oxide	66	18.2%	16	55.2%	46	16.8%	19	11.9%	147	17.8%
	Sandstone	164	45.3%	7	24.1%	38	13.9%	20	12.5%	229	27.8%
	Clay	5	1.4%	1	3.4%	3	1.1%	7	4.4%	16	1.9%
	Siltstone	4	1.1%			1	0.4%	4	2.5%	9	1.1%
	Deg. Limestone	2	0.6%	1	3.4%					3	0.4%
	Specularite	3	0.8%							3	0.4%
	Red sediment	34	9.4%	1	3.4%	5	1.8%	2	1.3%	42	5.1%
Grain Size	Clayey	37	10.2%	3	10.3%	31	11.3%	23	14.4%	94	11.4%
	Clayey/Silty	19	5.2%	1	3.4%	75	27.4%	25	15.6%	120	14.5%
	Silty	45	12.4%	10	34.5%	23	8.4%	25	15.6%	103	12.5%
	Silty/Sandy	31	8.6%	8	27.6%	75	27.4%	50	31.3%	164	19.9%
	Very fine sand	34	9.4%	4	13.8%	24	8.8%	17	10.6%	79	9.6%
	Fine sand	183	50.6%	8	27.6%	45	16.4%	21	13.1%	257	31.2%
	Medium sand	22	6.1%	1	3.4%	5	1.8%	3	1.9%	31	3.8%
Colour	Pink	5	1.4%			7	2.6%	3	1.9%	15	1.8%
	Light red	61	16.9%	3	10.3%	28	10.2%	11	6.9%	103	12.5%
	Red	91	25.1%	4	13.8%	26	9.5%	22	13.8%	143	17.3%
	Dark red	48	13.3%	5	17.2%	9	3.3%	14	8.8%	76	9.2%
	Brick red	40	11.0%	1	3.4%	7	2.6%			48	5.8%
	Rust	6	1.7%	5	17.2%	6	2.2%	1	0.6%	18	2.2%
	Light purple	1	0.3%	1	3.4%	6	2.2%	5	3.1%	13	1.6%
	Purple	18	5.0%	5	17.2%	124	45.3%	48	30.0%	195	23.6%
	Dark purple	86	23.8%	7	24.1%	61	22.3%	58	36.3%	212	25.7%
	Yellow	2	0.6%	1	3.4%					3	0.4%
	Orange	1	0.3%	3	10.3%	2	0.7%	1	0.6%	7	0.8%
	Brown	8	2.2%			1	0.4%	1	0.6%	10	1.2%
	Black	4	1.1%			1	0.4%			5	0.6%
Mica	Present	41	11%	5	14.2%	128	46%	47	28.6%	221	26%
Oolitic	Present	44	12.2%			7	2.6%	2	1.3%	53	6.4%

https://doi.org/10.1371/journal.pone.0209874.t004

Colours

The surface colour of the ochre artefacts also corresponds to the frequency of certain rock types. Dark purple is the most common colour designation for the total assemblage at 25.7%, followed by purple at 23.6%, which both correspond to the most frequent rock type for the total assemblage, hematite. The most common colour designation for the Aurignacian is red (25.1%), with dark purple as the second most frequent colour in the Aurignacian at 23.8%. The colour preferences shift to dark purple beginning with the A/G transition (24.1%) and continuing throughout the Magdalenian (36.3%), with the Gravettian containing a majority of purple ochre artefacts at 45.3%.

For the streak colour tests, we tested 694 individual ochre artefacts. Each of the corresponding CIELAB values was statistically analysed using principal components analysis on correlations (PCA) in order to observe the total amount of variance within the assemblage (Fig 6). The first two principal components account for 95.5% of the total variation in the dataset

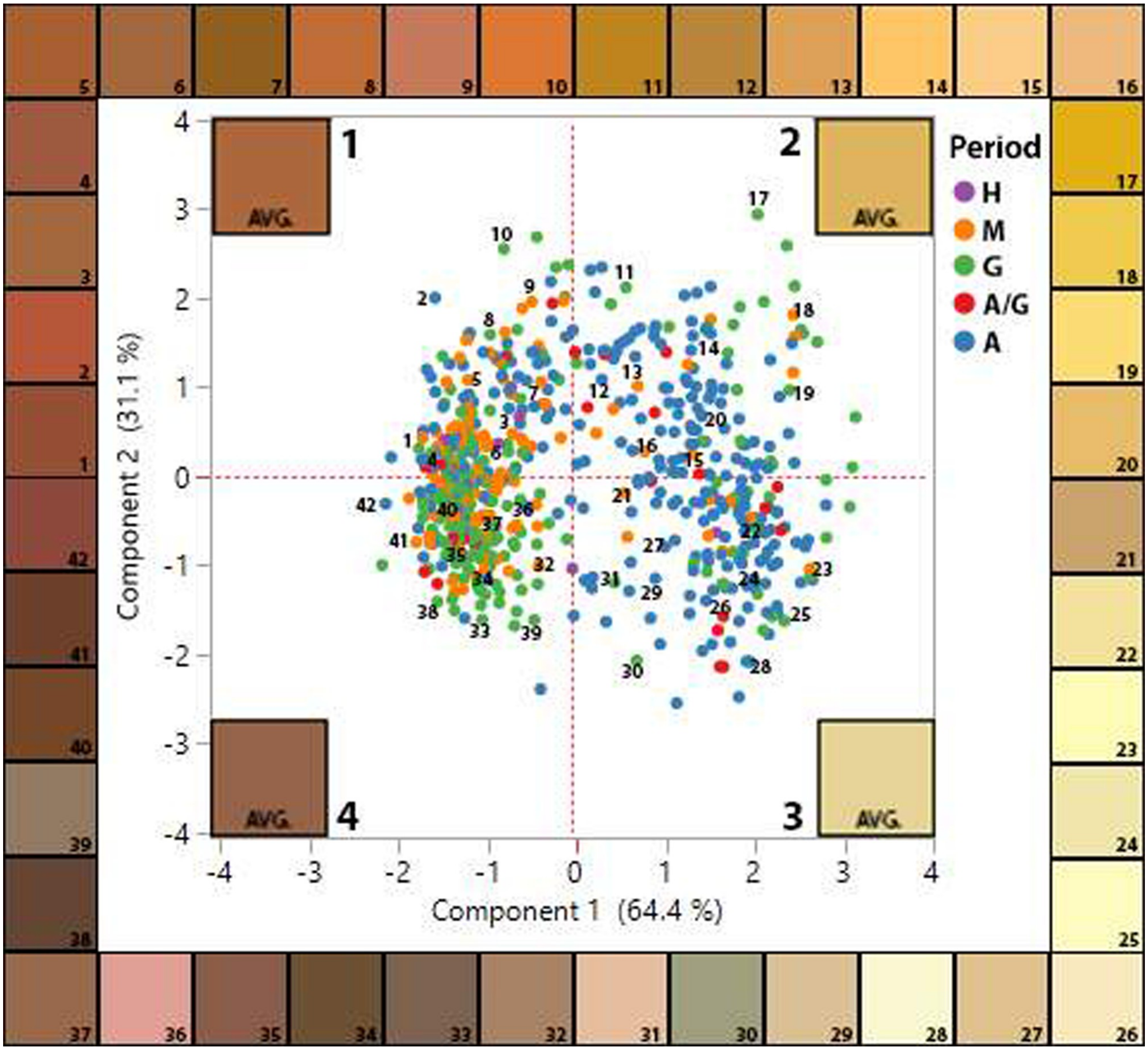

Fig 6. PCA plot showing first two components of CIELAB colour values on ochre streak tests from Hohle Fels ochres. Average CIELAB colour of the quadrant shown in corner of the quadrant. Specific point colours shown around the border of the plot with numbers in the PCA chart indicate corresponding data points. Data points are organized by period as shown on legend: H = Holocene, M = Magdalenian, G = Gravettian, A/G = Aurignacian/Gravettian transition, A = Aurignacian.

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(eigenvalue: 1.9328). Several notable observations can be made. The data generate two clusters separated along the *y*-axis, which account for differences in lightness (L*) and green-red components (a*) of the ochre pieces. The blue-yellow component (b*) also accounted for some variation, especially in quadrant two. The separation of groups along the *y*-axis also show some distinction in the temporal spread of the ochre streaks. Group 1 (quadrants one and four) contains 70% of the Magdalenian ochres tested and 76% of the Gravettian ochres tested, while Group 2 (quadrants two and three) contains 56% of the Aurignacian ochres, indicating visible differences in the lightness and green-red values of the colour streaks between the earlier and later time periods. This is further indicated by comparing the average LAB colour for each

Period	Total	Group 1 (n)	%	Group 2 (n)	%	Avg. L	Avg. a	Avg. b	Colour
Holocene	13	5	38%	8	62%	53	19	30	
Magdalenian	120	84	70%	36	30%	53	19	32	
Gravettian	217	165	76%	52	24%	56	16	30	
A/G Trans	25	14	56%	11	44%	63	12	33	
Aurignacian	286	125	44%	161	56%	71	11	37	

Fig 7. Hohle Fels ochre streak data per time period. Total number of streaks analysed as well as totals for corresponding cultural periods. The average values for $L^*a^*b^*$ per period are also displayed, as well as the corresponding colour for the averaged values.

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period (Fig 7), showing a darker colour and lower L^* (lightness) value for the later time periods and high L^* values displaying lighter colours in the earlier time periods.

The measurement of colour using CIELAB can account for nuances that even the human eye cannot notice, and as a result, there is redundancy in the colour values of the ochre streaks as some of the variations in streak colour are so subtle. Even so, there are noticeable differences in the colour streaks that the ochre pieces from HF produce. Streak colours in Quadrant 1 (mean LAB value = 51, 25, 36) are visibly darker and redder. Quadrant 2 (mean LAB value = 76, 9, 49) are lighter and appear orange or dark yellow. Quadrant 3 (mean LAB value = 85, 0, 32) are light yellow and beige, while Quadrant 4 (mean LAB value = 47, 18, 23) contain the darkest colour streaks and appear dark brown or dark purple-brown. Quadrant 1 and 4 contain the highest percentage of colour streaks (combined 57%), indicating that darker, redder and more purple hues are more common amongst the streaks produced by HF non-modified ochre artefacts.

Anthropogenically modified ochres

Of the total HF ochre assemblage (n = 869), 3.1% (n = 27) bear traces of anthropogenic modification (images of selected modified pieces are shown in Figs 8 and 9). Due to the small assemblage size, our analysis of these artefacts is more qualitative as large-scale and long-term trends cannot be inferred. However, of the modified pieces, there is a preference towards hematite ochres (n = 20, 74%) with silty (n = 14, 52%) or clayey (n = 10, 37%) textures. Dark purple (n = 13, 48%) and dark red (n = 8, 30%) are the most frequent colour categories, and only 25% of the assemblage is specular in appearance (n = 7). Table 5 outlines the presence of different modification types present on the modified ochre artefacts, including grinding, rubbing, scoring, polish, and shaping (faceting and rounding). These traits often occur together, such as grinding leading to shaping and rubbing leading to polish. The combination categories included: *Shaped and rubbed*, *scored*, *rubbed and scored*, *rubbed*, *rounded*, *ground and rounded*,

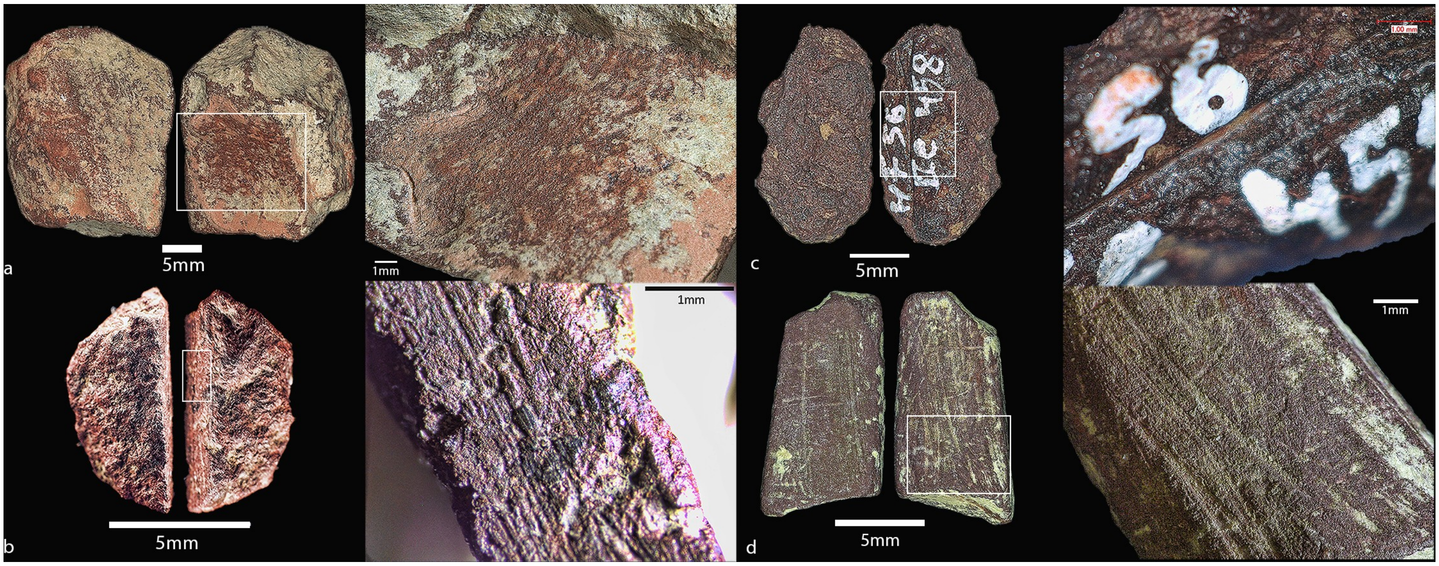

Fig 8. a-d. Anthropogenically modified ochre pieces from Hohle Fels. Artefact numbers and details are as follows: a) 59.IIa.629, ground out cavity, Magdalenian; b) 100. IIb.263, ground surface with striations, Gravettian; c) 56.IIb.458, scoring marks, Gravettian; d) 68.IIa.124, ground surfaces with resulting "crayon" shape, Magdalenian.

https://doi.org/10.1371/journal.pone.0209874.g008

ground, and *faceted*. Overall, *ground and rubbed* and *rounded* are the most common modifications with five artefacts each, followed by *ground* then *rubbed and scored*. Of the artefacts with evidence of scoring (whether it was rubbed beforehand or not), only one seems to have incisions that possibly form an engraving or a design. This ochre artefact (Fig 10) is the only modified ochre from the Aurignacian (AH IIIa) and also the only piece of yellow ochre collected and included in this analysis due to the presence of the modifications. It shows two deep scored incisions on a prepared flattened surface. The incisions are deeper on the right side where they are closer together, then taper off both in width and in depth. The transitioning depths suggest a sort of "sweeping" motion with the incisions, which were likely made with a stone tool or sharpened bone artefact.

Ochre-related artefacts (residues)

The ochre-related artefact category contains a variety of material types including lithics, limestone, bone, tooth, shell, mammoth ivory, and fossil (Fig 11). In total, 256 individual artefacts with traces of red residues were found and collected from the HF collection. A detailed overview of the artefact types with traces of red residues is shown in Table 6.

Of the artefact types with coloured residues, the most frequent is limestone with 104 (41%) artefacts. The previously published seven limestone pieces with patterns of red dots [99, 100, 106, 110, 126, 127] are included in this total. Bone artefacts are the second most frequent category with 33 (13%) specimens, followed by mammoth ivory (n = 24, 9.4%) and shell (n = 23, 9%).

The nature of the residues on the artefacts was also classified if the residues were considered anthropogenic, whether intentional or secondary, in origin. These categories include *applicator*, *grindstone*, *personal ornament*, *painting*, *ochre mixture*, and *container*. The most frequent residue types are personal ornaments with red colouring on 39 (15.8%) (Fig 11.4–11.8) artefacts. Personal ornaments are counted as a residue type because mammoth ivory beads and tooth beads, specifically reindeer tooth, were found containing red residues. It is yet unestablished whether the origin of these residues was due to direct action or the result of indirect

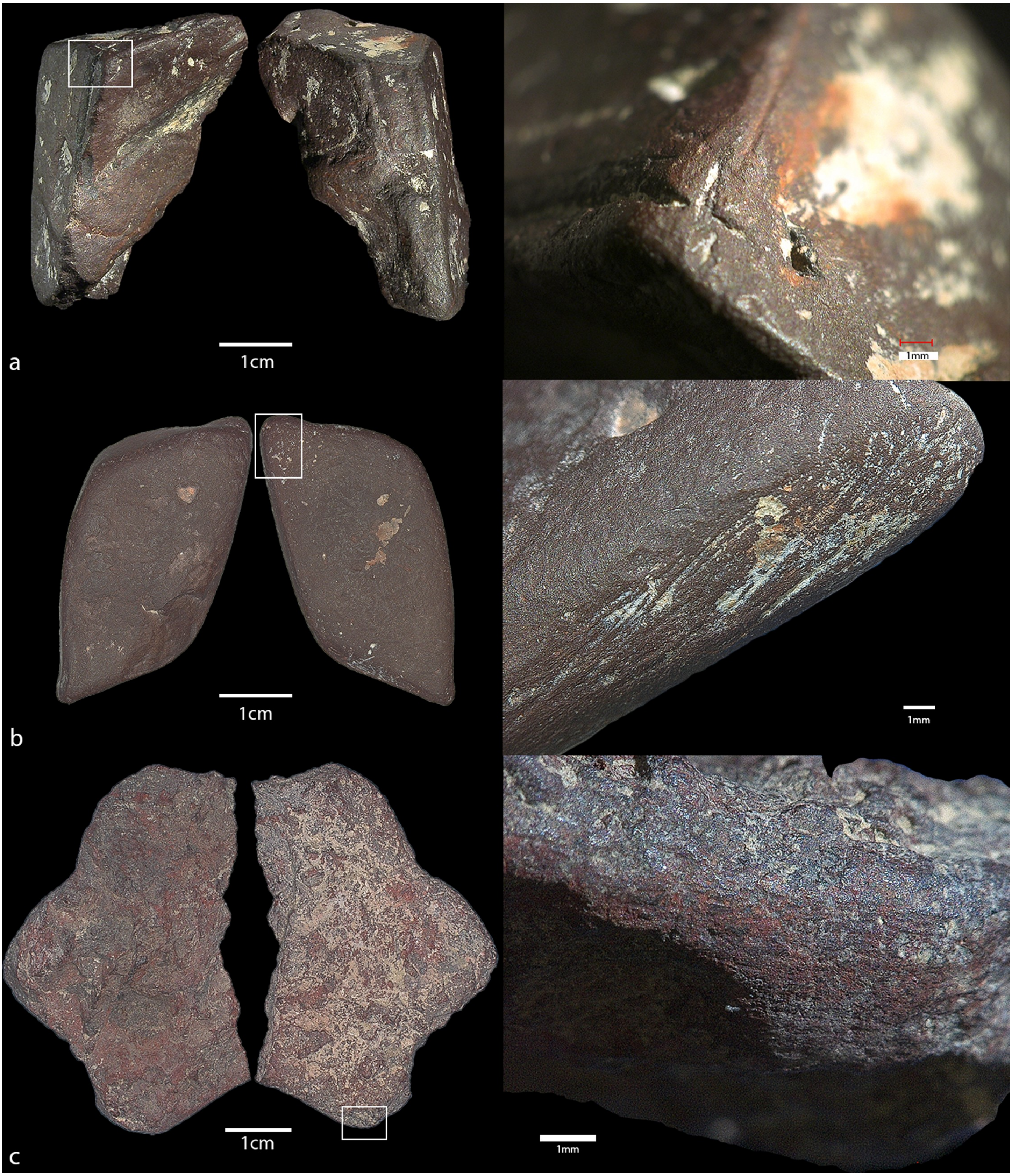
a
1cm
1mm
b
1cm
1mm
c
1cm
1mm

Fig 9. a-c: Anthropogenically modified ochre pieces from Hohle Fels. Artefact numbers and details are as follows: a) 102.Ib.420, scoring and grinding marks, Magdalenian; b) 102.Ia.399, ground and smoothed surfaces, Magdalenian; c) 49.IIa.218, ground surface with striations, Magdalenian.

https://doi.org/10.1371/journal.pone.0209874.g009

processes, such as the rubbing off of ochre onto the beads. The category *painting* includes the painted limestone pieces as well as artefacts with residues forming what appear to be a defined shape or outline, and total 11 artefacts (4%). A mollusc fossil from the Magdalenian with a red circle on one side is included in this category and is shown in Fig 11.21. *Ochre mixture* is the third most frequent (n = 7, 2.7%) and designates residues containing a thick visual application of ochre with small fragments of quartz and charcoal mixed in (such as the reindeer rib fragment shown in Fig 11.1).

One of the least common categories, *grindstone*, is one of the most important regarding ochre use at the site. One of the grindstones from HF, artefact #112.1157 (Conard and Malina, 2019, in prep) was found in 2018 and comes from the Gravettian layer IIb. It is a rounded fine-grained oolitic dolomite cobble with one faceted surface containing abrasive striations filled with red powder (Fig 12). It measures 7.8 x 7.1 x 4.1 cm and weighs 316 g. Red residues are also visible on a side surface of the artefact, which is also rounded and contains striations. Several notches and percussion marks on this side surface suggest the artefact's use as a hammerstone in addition to a grindstone.

For the *residue origin* category, the majority of the artefacts contain red residues likely as a result of non-anthropogenic post-depositional processes, or *natural* processes (n = 140, 56.7%). This is followed by *indirect colouring* (n = 67, 27.1%), and lastly as a *direct application* or as a result of anthropogenic intent (n = 40, 16.2%). We note that the proposed residue types and final decisions are based solely on visual inspection. We also considered find context and sediment description in determining whether residues could have a natural or anthropogenic origin.

Discussion

In the following section, we will first discuss the temporal changes in qualitative ochre characteristics throughout the sequence and how this is related to behavioural or environmental changes at HF during the late Pleistocene. We will further elaborate on the modified ochres as well as the ochre-related artefacts and how these reflect behavioural processes and what we can infer about symbolic processes surrounding the use of ochre pigments at the site. Following this, we will discuss the stratigraphic integrity of the site and the geogenic vs anthropogenic transportation of ochre materials to the site, as well as the role that post-depositional and anthropogenic processes likely played in the current physical condition of the ochre artefacts at HF. Lastly, we discuss the evidence of ochre artefacts and how these reflect the nature of ochre use at the site and in Europe during the UP.

Table 5. Modifications types on Hohle Fels ochre. Anthropogenic modification categories for ochre artefacts from all time periods.

Period	Grinding	Rubbing	Scoring	Polish	Shaping
Holocene	1		1	1	1
Magdalenian	9	14		11	8
Gravettian	3	2	2	3	2
A/G trans		1		1	
Aurignacian		1	1		
Total	13	18	4	15	11

https://doi.org/10.1371/journal.pone.0209874.t005

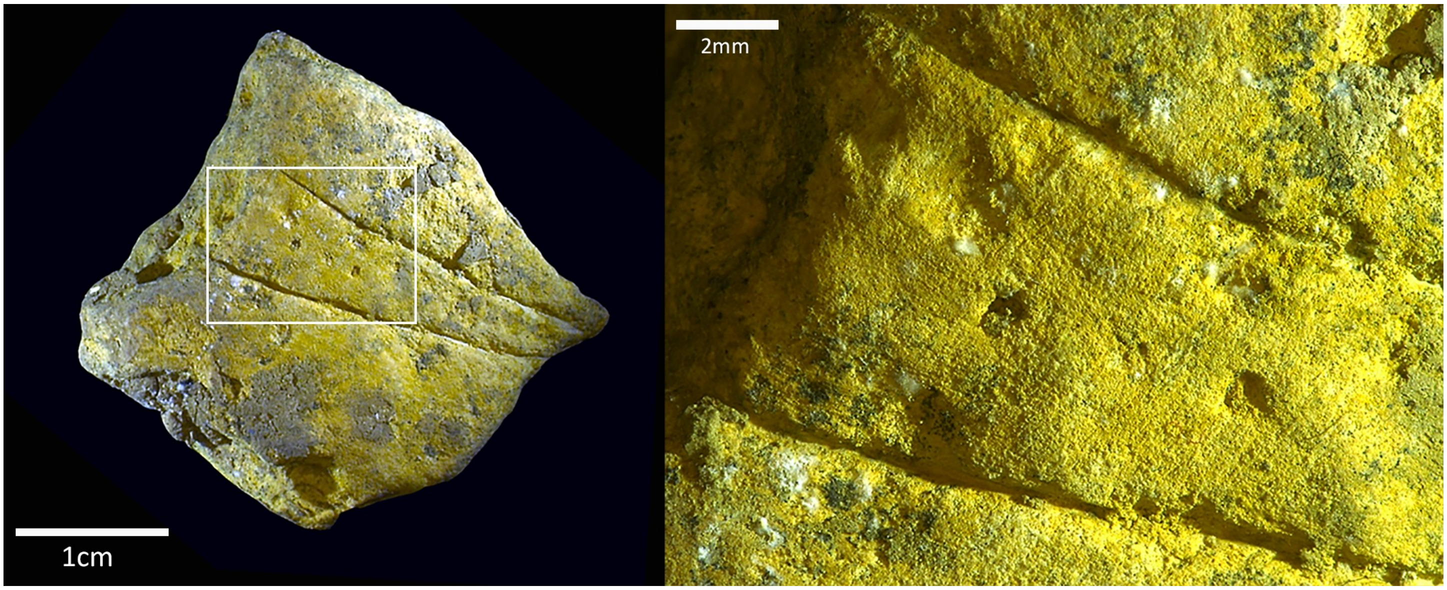

Fig 10. Modified ochre from the Hohle Fels Aurignacian. Artefact 87.1271, from the Aurignacian layer IIIa, showing two incisions with dots in the middle on a prepared surface.

https://doi.org/10.1371/journal.pone.0209874.g010

Ochre qualities and characteristics at Hohle Fels

The HF ochre assemblage totals 869 artefacts, and the observed diachronic changes show clear trends in the types of ochre that were collected and deposited at the site. For example, there is a marked difference in textural and colour preference in the Aurignacian compared to the later periods. CIELAB results of the streak tests show a higher degree of lighter hues during the Aurignacian (71 avg. lightness), with darker hues becoming more frequent during the Gravettian (56 avg. lightness) and Magdalenian (53 avg. lightness). The significance of the differences of each time period were assessed using a post-hoc multiple comparisons test for the L^* value mean between each pair. The null hypothesis was rejected in every comparison with the Aurignacian except for the A/G transition (Table G in S1 Table), showing that the lightness values for the Aurignacian are statistically significantly different ($p < 0.05$) when compared to most of the other time periods. This observed change in streak colour records either a shift in resource availability or a shift in preferences for deeper redder and purple hues in the later time periods. Furthermore, whereas the majority of the Aurignacian ochre assemblage consists of fine-grained sandy ochres with a red colour, this changes during the A/G transition layers where more silty textures are present in the assemblage. This latter pattern of silty texture preference also continues into the Gravettian and Magdalenian at HF. The relative amount of micaceous hematite also increases towards the end of the Pleistocene, first occurring with relatively low frequency in the Aurignacian (n = 41, 11%), peaking in the Gravettian (n = 128, 46%), and then again slightly decreasing in the Magdalenian (n = 47, 29%). The preference for hematite-rich ochre (n = 20, 74%) with silty and clayey textures is reflected in the anthropogenically modified ochre assemblage as well, though micaceous hematite is not as frequently anthropogenically modified (n = 7, 35%).

There is more variability in ochre texture and rock types in the Aurignacian than in the later periods at HF, as evidenced by the representation of all eight rock type categories and no types occurring more frequently than 46% (the Gravettian has 67.5% hematite with six categories represented, Magdalenian has 70% and also six categories).This narrowing of textural and

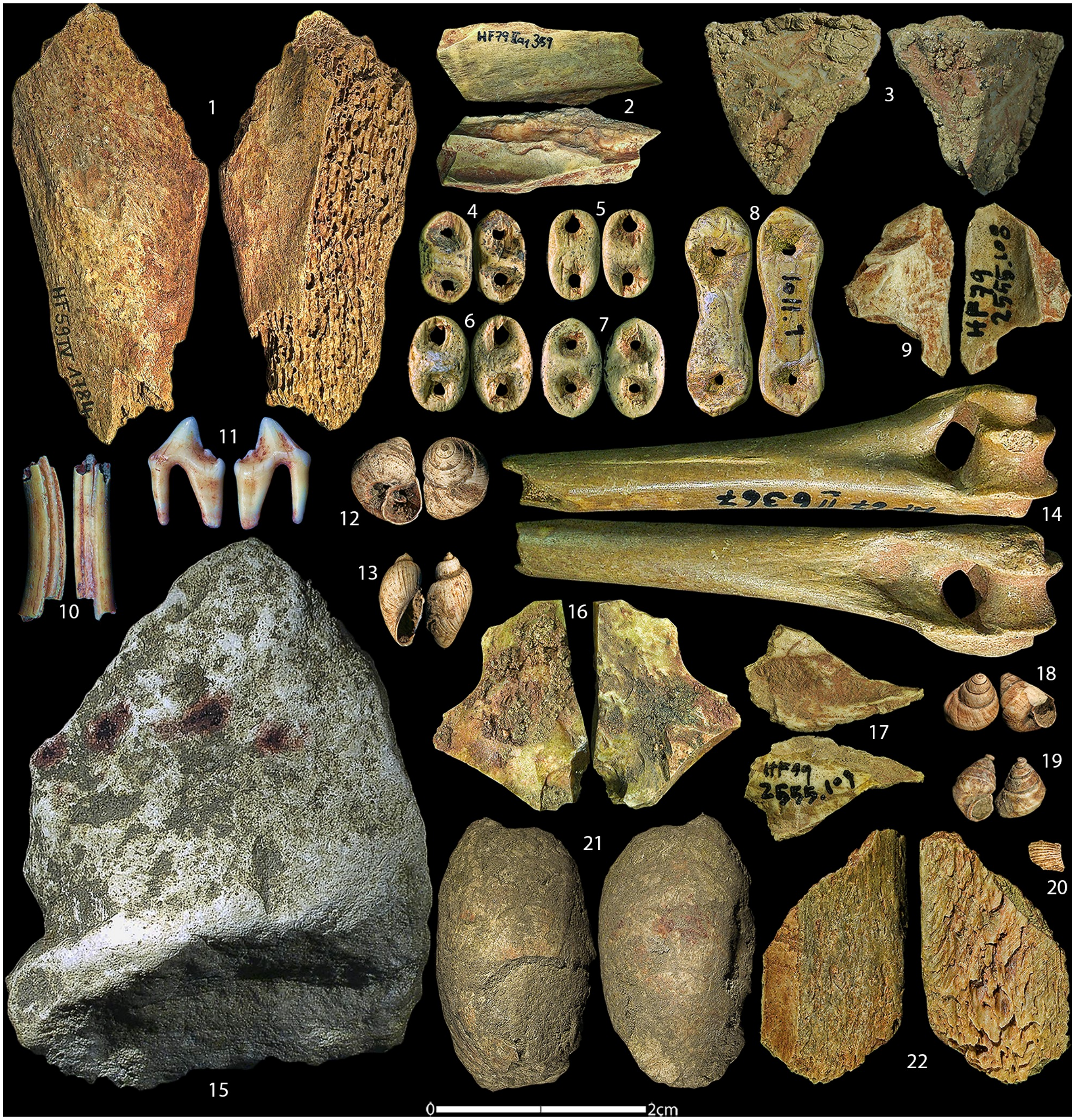

Fig 11. Ochre related artefacts from Hohle Fels. Assorted artefacts containing red ochre residues from all time periods at HF. Artefacts include faunal elements, teeth, mammoth ivory beads, freshwater snail shells, a fossilized mollusc, and lithics. Numbers correspond to Table D in S1 Table.

https://doi.org/10.1371/journal.pone.0209874.g011

material types throughout time suggest that ochre preferences were being continuously refined at the site. Though preferences and changes in behavioural patterns could account for the shifts in ochre types brought to the site, a fluctuating landscape and palaeoenvironment may have played a role as well. During the Aurignacian, the Swabian Jura maintained a relatively stable warm and wet climate with minor cold fluctuations, which gradually changed to a much colder climate during the Gravettian and Magdalenian [77, 79, 128]. These shifts impacted the

Table 6. Ochre related artefact types per time period from Hohle Fels. Distribution of material types per time period of artefacts with red colour residues, as well as type of residue and final decision as to the nature of the residue application. Abbreviations are as follows: A = Aurignacian, A/G = A/G transition, G = Gravettian, M = Magdalenian, H = Holocene.

		A n = 110	A/G n = 14	G n = 56	M n = 57	H n = 10	Total n = 247
Material type	Bone	7	4	3	18	1	**33**
	Limestone	79	10	29	12	5	**135**
	Fossil			1	5		**6**
	Ivory	20		4			**24**
	Shell			12	11	2	**25**
	Other stone	4		1	2		**7**
	Tooth			6	9	2	**17**
Residue type	Applicator	1		2			**3**
	Grindstone			1	1		**2**
	Per. ornament	19		11	7	2	**39**
	Painting				10	1	**11**
	Ochre mixture	5		1	1		**7**
	Container	2					**2**
	Total	27		15	19	3	**64**
Final decision	Direct application	19		9	10	2	**40**
	Indirect colouring	10	4	16	33	4	**67**
	Natural	81	10	31	14	4	**140**
	Total	110	14	56	57	10	**247**

https://doi.org/10.1371/journal.pone.0209874.t006

physical landscape surrounding the cave and the river valleys by decreasing terrestrial forest and allowing for major erosional phases inside and outside the cave during the Gravettian and Magdalenian [79]. These dramatic landscape changes may also have shifted or impacted the accessibility of particular ochre sources, or allowed the identification and exploitation of new ones.

The shift in resource gathering strategies is also present in the modes of lithic raw material acquisition. During the Aurignacian, local lithic resource areas were preferred as evidenced by the abundance of the local *Jurahornstein*, a type of chert, at HF [129, 130]. The Gravettian and Magdalenian lithic assemblages contain both local and non-local lithic raw materials, indicating changes in resource acquisition later in the Pleistocene [90, 129, 131]. This change in behavioural patterns reflected in lithic acquisition patterns, and material culture more generally, has also been suggested to be closely linked to processes related to the construction of social and individual identity [132]. Porr [133] has, for example, noted a shift in symbolic material culture forms, from a smaller and more varied ivory figurine tradition in the Aurignacian to a higher standardisation of figurative forms during the Gravettian. Porr [133] has suggested that the variability in artefact categories during the Aurignacian is higher than in other periods because Aurignacian social groups were comparatively smaller, more flexible and more conducive to individualised expressions of identity in material objects. The greater standardisation in Gravettian objects, which is visible all-over Central Europe [134], is indicative of larger, socially more cohesive and regionally inter-linked groups [135, 136].

In the HF ochre assemblage, there are differences in the Aurignacian ochre materials versus the Gravettian and Magdalenian. The differences in ochre types, ochre textures, and streak colours (signifying powder colour) may also reflect changes in behaviours, with more individual-based experiential collecting during the Aurignacian followed by a shift to "standardised" mass-collecting at specific source areas for certain ochre types in later periods. Though the

Fig 12. Ochre grindstone from the Hohle Fels Gravettian. Dolomitic limestone cobble which was likely used as a grindstone (#112.1157). Inserts show presence of ochre powder as well as striated surfaces.

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specifics of ochre acquisition strategies and source locations are still unknown, the existing assemblage suggests that there were several different ochre types available to the cave inhabitants and that these were accessed throughout the UP with different behavioural intensities.

Discussion of the modified ochre assemblage

Though the modified ochre assemblage is comparatively small (n = 27), 18 of these contain apparent striations, and half of the total assemblage (n = 14) bears evidence of grinding. Soft-surface grinding or rubbing is even more frequent (n = 17) while scoring or incising is the least common modification type with only four known examples. The majority of the modified ochres have silty or clayey textures, and the general trend of darker purple and red hues is consistent with other ochre studies which report a preference for fine-grained ochre with deeper red and purple hues in later time periods [23, 119, 121, 123, 137].

The types of modification present on the ochre artefacts suggest that the production of pigment in the form of ground powder was the primary objective for the inhabitants of the cave. Grinding and pulverising are the most effective ways of creating pigment powder from solid ochre pieces [112]. It is also possible that the pieces were first prepared by grinding and after that used for direct application onto a soft material such as skin, or the pieces were used as "crayons" on hard surfaces. The yellow ochre artefact from the Aurignacian (Fig 9) represents the only modified artefact with evidence for engraving or the application of a design. The two lines form a V shape and contain two dots between them. Aside from interpreting the design as figurative, possible scenarios could include "testing", such as for lithic or bone artefacts for sharpness, or for the pigment or textural potential of the yellow ochre artefact. It is unlikely that this engraving was meant for pigment extraction as engraving or incising produces little to no pigment powder.

Discussion of ochre-related artefacts

The ochre-related artefacts offer further insights into the way ochre was processed and used at HF. In cases where the anthropogenic application is certain (e.g. the painted limestone pieces), ochre was collected, processed, and lastly applied to these artefacts before deposition. They represent a direct link between physical artefact, intermediate state (powder) and intentional behaviour (rock painting). The presence of two ochre grindstones in the Gravettian and Magdalenian contexts at the site indicate that ochre was processed at least at a minimal level during these time periods. These provide a link between the operational chain of ochre use at HF, considering the presence of modified and unmodified ochre artefacts, a grindstone as an object to pulverise ochre into a usable pigment powder, and painted artefacts indicating its use as a pigment. Furthermore, the textural varieties of these grindstones could suggest a technological awareness of which grain sizes are more useful for grinding ochre artefacts into finer powders [120]. This entire sequence of ochre processing attests to the entrenchment of ochre into behavioural patterns of the cave inhabitants during the UP.

The personal ornaments with red residues also offer insight into the nature of ochre use at the site. During the Aurignacian, mammoth ivory was the preferred medium for creating personal ornaments as evidenced by the frequency of ivory beads during this period [5, 138, 139]. This changes during the Gravettian to an increase in faunal elements, such as teeth from cave bears, foxes and wolves [140, 141]. Regardless of the reasons for this change in material preferences, red residues are found on personal ornaments during all time periods and on ivory and other faunal ornaments.

There are several possible scenarios why red ochre may have been applied to ivory and faunal beads. In the case of ivory, White [142] suggests that red ochre, specifically in the form of hematite, assisted in the creation of the ivory beads by facilitating the smoothing and polishing of the ivory surfaces, as well as helping grind the perforations in the beads [143]. This interpretation would also explain the predominance of residues appearing only in the perforations of the ivory beads, as is the case with all 24 ivory bead artefacts. Another scenario that explains the presence of red residues in the perforations is that the string or other fabric that the beads were worn on was painted with red ochre. Further analyses on use-wear traces as well as residue analyses might allow for more detailed insights into these scenarios. The personal faunal ornaments with traces of red residues are all reindeer teeth incisors. Similar reindeer teeth artefacts are found at other archaeological sites from the Magdalenian [103, 105, 144, 145], though HF also contains six from the Gravettian. It is believed that the lower jaw of a reindeer was broken and the lower incisors were sawn off while remaining in the gums and were worn like a pendant [103]. The presence of red ochre on these teeth suggests a use as a decomposition deterrent (in order to preserve the gums for longer), for aesthetic purposes, or that red ochre was worn as body paint and rubbed off onto the pendants. These scenarios are not mutually exclusive, and red ochre may have been applied both to slow putrefaction as well as to make the pendants red. Considering the types of personal ornaments and other artefacts collectively, red ochre was not used exclusively on one material or artefact type. Instead, the evidence suggests that no single explanation can account for all occurrences of ochre in the UP record of HF. Red ochre seemingly had significance on a multitude of levels and was perceived and interacted with accordingly (see also [23, 113, 120, 121, 123]).

Stratigraphic integrity and human transportation of ochre materials

Throughout the UP, there have been several periods of soil formation, cave sediment erosion and river fluctuation in the Swabian Jura and more specifically in the Ach valley [79]. Climatic transitions during the Würm interstadials and stadials resulted in a lack of stabilising vegetation which led to water erosion in the surrounding area and of cave sediments. These shifts in climate also contributed to major erosional phases within the cave after ca. 26 ka BP, resulting in truncated Gravettian and Magdalenian deposits [79, 82, 146]. Soil surface instability, as well as possible resource scarcity [147], appeared to have resulted in abandonment phases in HF around 27–26 ka BP. Magdalenian groups migrated back into the area around 16.5–15.5 ka BP [91, 148] during a cool interstadial period, though these sediments were also eroded on a smaller scale. Erosion ceased ca. 12.5 ka BP and the remaining Magdalenian deposits were capped by a *Bergkies* accumulation [79].

The beginning of the Aurignacian at HF is characterised by an initially mild, dry phase followed by a warm wet phase, with the environment being largely tundra-based with boreal elements indicated by the presence of several characteristic pine species represented in the palynological record [149]. Micromorphological investigations show that there was little erosion of sediments into or out of the cave during this time period [77]. Furthermore, the presence of ochre artefacts in layers that are dense with lithic artefacts and bone debitage (AH Va) strongly correlate with periods of human occupation. We argue that this lack of erosion shows that the ochre materials of the Aurignacian were intentionally collected and brought to the site, rather than being deposited by landscape erosional processes.

However, the Gravettian and Magdalenian periods differ from the Aurignacian layers. The Gravettian began within a cold and wet climatic phase, which shifted towards increasingly cooler and drier conditions and was largely dominated by a tundra environment [149]. These fluctuations caused a decrease in arboreal and woody plant coverage leading to a higher rate of soil erosion due to increased water transportation in the landscape [77, 79, 149]. A higher rate of sediment movement, combined with more frequent periods of freezing and thawing, likely affected ochre materials within the cave. The non-eroded Gravettian deposits remaining in the cave yielded 278 ochre artefacts or approximately 32% of the entire assemblage. Comparatively, the Aurignacian contains ca. 43% of the entire assemblage, and the majority of these layers are considered as intact sediments. Though the Gravettian occupation at HF was not only short but also heavily eroded, the high amount of ochre artefacts indicate that the collection and use of ochre was a well-established by at least 29 ka BP.

Furthermore, the decrease in ochre rock type variability and the focus on mica-rich fine-grained hematite pieces producing darker and redder streaks suggest that specific source zones were known, sought, and continually accessed during the Gravettian and Magdalenian. This type of activity requires intimate knowledge of the landscape and the available outcrops, and may thus indicate the development of more pronounced social and cultural preference for ochre textures, colours, and appearances. It may also suggest adaptability in a changing landscape (one ochre source eroded away, another one sought after and accessed), an increased movement range in order to access specific sources, or increased communication and trade with other social groups.

On the nature and size of the assemblage

The size of the HF ochre assemblage (n = 869), and the highly fragmentary condition of the ochre artefacts themselves (average weight: 1.07 g) begs the question: why are there so few ochre pieces and why are they so small? Does the nature and condition of the HF ochre assemblage suggest that the people occupying HF during the UP only exhibited a limited range of ochre behaviours that were mainly opportunistic? In order to investigate this hypothesis and the range of geogenic processes occurring at the cave in the late Pleistocene, we propose four scenarios that may account for the assemblage size as well as the conditions of the artefacts:

1. *Ochre-use efficiency*. Experimental studies on ochre powder production show one of the most effective ways to produce fine-grained pigment is by pulverising the ochre using a mortar and pestle method [37, 123]. This technique is employed by modern-day indigenous groups in Africa, e.g. the Ovahimba in Namibia [41, 150], and it results in a solid piece of ochre being transformed entirely into powder. This type of ochre processing would thus leave little or no archaeological footprint, as experiments show that this form of processing leaves a barely discernible "splash pattern" of ochre at the processing site. Consequently, the prehistoric inhabitants of HF may have been very efficient in processing raw ochre nodules into a useable powder suitable for pigments, leaving only a few macroscopic (ca. 5 mm) ochre pieces.

2. *Post-depositional deterioration*. The extent and intensity of certain geogenic processes at HF, specifically erosion, freezing and thawing, contributed to the fragmentation and complete relocation of ochre artefacts contained within the cave [77, 79]. Thus, it is conceivable that the recovered HF ochre assemblage is only a partial representation of the ochres that were originally used and deposited, and that these were likely eroded out of the cave during the Gravettian and Magdalenian. This has further been evidenced by the recovery of a reworked bone fragment from a core sample at a depth of 8.2 m in front of HF, dated to the Gravettian (28,000 ^{14}C BP), indicating that it was likely eroded out from HF [79]. The ochre artefacts remaining in the cave were situated in a moist and mobile environment with typical taphonomic processes taking place, such as the phosphatisation of sediments, cryoturbation, and trampling from animals or other cave visitors, to name a few. These processes are detrimental to ochres, especially for the fragile clay-based iron oxides that are abundant in the region, and may most certainly have contributed to the degradation of the ochre artefacts within the cave. Furthermore, the processing of sediments and artefacts post-excavation, such as water-screening, likely contributing to the eradication of certain modification traces as evidenced by experiments on the secondary processing of ochres by other researchers [35].

3. *Limited ochre use*. Lastly, we consider the possibility that ochre use was simply not as prevalent at HF as at other sites during the late Pleistocene. One may also argue that relatively few artefacts with definite traces of direct anthropogenic ochre pigment application, namely the painted limestone pieces (n = 7), is further evidence that UP occupants at HF did not regularly interact with ochre. This scenario is also potentially impacted by the availability of ochre in the landscape. Though sources of ochre are present in the modern-day Swabian Jura landscape (see [69]), it is possible that these were not known or accessible during the

UP. Restricted access to sources would in turn limit the availability and subsequent use of ochre at HF.

4. *Landscape mobility/seasonal migration*. Archaeological evidence shows that HF was likely an occupation site during certain seasons, but it is probable that there were several temporary open-air sites corresponding to seasonal hunting and foraging cycles. These landscape mobility patterns, also seen with indigenous groups in Africa [151, 152], could potentially split up certain types of behaviour, such as ochre use, amongst the different camps and temporary habitation sites. Lithic raw material studies show that the total area covered by Aurignacian populations was ca. 7,000 km^2, and the Gravettian may have been up to ca. 9,000 km^2 [153]. Based on these possible landscape movements and migrations, ochre may have been collected and processed elsewhere, and the deposited assemblage at HF may only represent a fraction of the total amount of utilized ochre.

The average size (9.78 mm) of the individual ochre artefacts and the condition of the ochre assemblage is likely due to a combination of the first two scenarios, and may have been further compounded by seasonal migrations represented by the last scenario. Given the post-depositional influences outlined in the second scenario, it is likely that these had at the very least a minor effect on the assemblage size and artefact size. This is further supported by modern-day experiments, which show that artefact cleaning and processing can almost wholly destroy a soft clay-based ochre artefact even after it is excavated [35]. It is plausible that the existing assemblage is a minimum estimate of the total size, and the original assemblage was most likely much more substantial. Furthermore, few informative open-air sites in the Swabian Jura have been identified [1, 154]. This is due in part to the intensity of landscape and environmental changes which had impacted these sites on a greater scale than the cave sites, where entire occupational horizons have been eroded. Nevertheless, the interpretation of characteristic faunal species identified key periods of cave occupation during cold phases, indicating some seasonal flucutation of cave inhabitants in the Swabian Jura [155, 156].

Regarding the size of the total HF ochre assemblage, the number 869 can at first appear small, especially when compared to ochre assemblages from Africa that can total in the thousands [23, 33, 113, 120, 123]. However, we argue that this comparison is unwarranted, considering both the geographical and temporal spread of the ochre assemblages. For European contexts, the majority of ochre assemblages that have been reported in detail date to the Châtelperronian [49, 63, 66, 157] or the Acheulian [47]. At *Grotte du Renne* in France, which is perhaps the most extensively reported ochre assemblage in Europe, albeit 40 years after the end of the excavations, over 2,000 artefacts are reported from the Châtelperronian layers and include red, yellow and black colourants, weighing in total around 18 kg [49]. As for the UP, currently the only available comparison comes from an open-air Aurignacian site, *Régismont-le-Haut*, where 1,001 artefacts are reported, including both red and yellow ochre, weighing in total 730 g (compared to HF with 925.768 g) and 98% of the assemblage containing artefacts smaller than 2 cm [48]. Because the availability of published systematic overviews of ochre assemblages is limited in Europe for UP sequences, we cannot claim that the 869 HF ochre artefacts are or are not indicative of a limited ochre use scenario. Furthermore, our focus rested on red ochre artefacts, which do not occur naturally inside of the cave, and did not include yellow or black colourants which would have resulted in a dramatically different number (see Materials and Methods regarding yellow ochre at HF). The assemblage does, however, represent regular and long-term ochre use at an UP cave site in Central Europe, and can serve as a benchmark for comparisons of other ochre assemblages from European UP sites in the future. Further analyses, surveys for local and non-local ochre sources and future excavations may shed more light on ochre behaviours at the site.

Lastly, we consider the artefacts with traces of red residues as indicators of ochre use at the site. The appearance of residues on several artefacts types, including bone, ivory, stone, and shell, while similar artefacts from similar contexts have no colourants, suggests that ochre was processed in the cave in specific areas at different points in time. Furthermore, the presence of two grindstones suggests that ochre was processed at the site during the Gravettian and Magdalenian. If the colouring was the result of post-depositional processes, the appearance would likely be more random and would cover artefacts from similar and possibly neighbouring contexts. If the colouring was caused by staining from the overlying sediment, we would also expect this to be visible on associated artefacts, especially artefacts with porous textures such as bone or ivory, and this is not the case. It is possible that these residues were not intentionally applied and the artefacts were merely "innocent bystanders" during different ochre processing phases; however, this is still indicative of ochre behaviours at the site. It is our future goal to conduct more intensive analytical investigations on artefacts with colour residues in order to identify the elemental constituents of these residues, and perhaps extend and enhance our knowledge on the range of ochre behaviours at HF.

Ochre behaviour and ochre use at Hohle Fels cave during the Upper Palaeolithic

Ochre use was already well entrenched in the behavioural repertoire of AMHs by at least 80 ka BP [23, 32, 33, 113, 114, 122, 158] in Africa and the Levant. Though there is a sizeable contextual separation in both time and space between African and European Pleistocene populations, many of the behaviours observed at these sites are shared, such as the creation of stone tools, personal ornaments, and ochre and pigment use. Furthermore, the body of evidence showing pigment and ochre use by European Neanderthals is continuously growing [58, 59, 62, 64, 66, 67], which further supports the hypothesis that ochre use was well in place in Europe even before the onset of the UP. Whether these behaviours migrated with hominin populations as they traversed into regions outside of Africa, or whether they were independently developed, is still uncertain. However, working towards understanding the extent and range of ochre behaviours in Europe and comparing these assemblages globally will enhance our knowledge of ochre materials and how related behaviours evolved over time and across space.

At HF, red ochre artefacts occur in all stratigraphic contexts at the site. Red ochre is highly present during the UP time periods and is found alongside an assortment of other artefacts that contain red residues, as well as artefacts that were directly painted with ochre pigments. The different lines of evidence show that ochre was recognised in the landscape, collected, transported, and brought to the site and subsequently processed in order to create pigment powder. This pigment powder was then mixed with a suitable binder and used to create painted dots on a series of limestone fragments, and was likely directly or indirectly applied to other items such as ivory and tooth beads. This series of actions, recognition, collection, transportation, modification, application, and deposition represent part of the operational chain or *chaîne opértoire* of ochre use at HF. Among other aspects, these actions and cognitive processes and foci are connected to the perception of need [159], a procedural knowledge [160], a preference for specific textures of colours, and a desire to utilise and thus "create". The presence of ochre throughout the UP suggests that the recognition of ochre as an item worth collecting was already well represented in the behavioural repertoire of populations living in the Swabian Jura during the earliest phases of modern human occupation in Europe. Whether or not this behaviour was transported from other regions, such as Africa or the Levant, is as of yet uncertain. The total range of behaviours surrounding ochre use is also unknown. Several theories propose the use of ochre for aesthetic purposes or in order to alter or enhance physical appearances [161], as a form of sham-menstruation by females in order to secure resources during vulnerable times [20, 25, 28], or for a variety of other more utilitarian purposes such as a hafting adhesive or sunscreen [35, 39–41].

We believe the most likely scenario is that both functional and ritual uses were occurring simultaneously and perhaps intertwined together, as is often the case in ethnographic examples regarding ochre use [14, 150, 162]. Our goal is instead to explore and expand the current knowledge base of ochre use during the earliest modern human cultural phases in Europe. The ochre assemblage of 869 individual artefacts, as well as the artefacts with traces of red residues, suggest that these behavioural traits were well in place by the arrival of AMHs in Europe and were intricately woven into the complex cultural-symbolic framework already shown in other forms of material culture, such as personal ornaments and figurines. Our analysis has also demonstrated that pigment selection, acquisition and use show significant patterns of change and stability over time. These processes can be linked to changes in the environment and respective social behaviours and the related dynamics of identity and group formation. Thus, the use of pigment and ochre artefacts at Palaeolithic cave sites is considered to be a further thread in the fabric of behaviours of the earliest modern human populations in southern Germany and Europe more generally.

Conclusion

In this paper, we have presented the first systematic assessment of the HF ochre assemblage dating to the UP, and the first analysis of a diachronic sequence of ochre artefacts from the UP in Central Europe. Through qualitative analysis of the nearly 900 ochre pieces, we have demonstrated that UP populations occupying the cave collected, transported, and used ochre regularly throughout the Aurignacian, Gravettian, and Magdalenian periods. They ground ochre to produce pigment powder, and they used these pigments to paint geometric motifs on rock slabs and possibly to colour other artefacts, such as personal ornaments and faunal remains. Consequently, we suggest that ochre played a significant role in practical and symbolic aspects of the behavioural repertoire of UP groups at HF and that these behaviours were transferred and shared throughout the millennia. We believe the qualities presented here and their evolution over time do coincide with those observed in other MSA sequences. In Europe, the few existing reports on ochre studies in UP contexts do not allow us to make robust regional comparisons; though with combining the existing research, we can ascertain that ochre behaviours were already in place by at least the Aurignacian in Europe [48, 49, 63]. While only a few ochre pieces (n = 27) show evident traces of anthropogenic modification, we relate the fragmentary state of the assemblage primarily to local preservation conditions and to the nature of ochre powder production (grinding and pulverising). The original ochre assemblage deposited at HF may thus have been considerably more substantial, and the documented ochre assemblage should be regarded as a minimum representation.

This study demonstrates that despite poor preservation conditions and a fragmentary record, important observations and inferences are still attainable. Thus, we hope that this study may serve as a starting point for future research, from which regional European comparisons can more robustly be made. That may ultimately expand our understanding of ochre use during the UP and how our human ancestors interacted with and were influenced by this fascinating material.

Supporting information

S1 Fig. A-C. Previously reported ochre and ochre-related finds from Hohle Fels cave.
Fig A: Modified ochre pieces from Hohle Fels. Previously found Hohle Fels ochre artefacts:

a) Specular hematite piece with two facets, #102.630.1; b) Red chalk "crayon" piece with four striated surfaces, #102.555.1 (from [1]) (photos by E. Velliky); c) Rounded Rondelle-shaped fragment, #110.434.1; d) Two refitted Rondelle artefacts from hematite, #110.1104.1 & #110.992 (from [2]) (photos by M. Malina, 2009).
Fig B: Painted limestone fragments from the Magdalenian of Hohle Fels. Find numbers: a) limestone, #44.92 (from [3]) (photo by M. Malina); b) limestone, #110.985, c) limestone, #135.197 (from [2]) (photos by M. Malina); d), limestone, #55.253 (from [4]) (photo by H. Jensen); e) dolomitic limestone, #102.487, f) dolomitic limestone, #102.495 (from [1]) (photos by M. Malina); g) dolomite, 67.?? (from [5]) (photo by H. Jensen).
Fig C: Previously found faunal elements with traces of red residues from Hohle Fels. Descriptions and find numbers: a) broken long bone shaft, #14.69, Magdalenian (photo by H. Jensen), b) reindeer cranial fragment, #89.48, Magdalenian, c) cave bear temporal fragment, #29.1484.14, Aurignacian (photos by A. Blanco-Lapaz).
(PDF)

S1 Table. A-J. Artefact numbers, contextual details, and statistical tests for corresponding figures.
Table A: Fig 3 (Hohle Fels Aurignacian) artefact descriptions.
Table B: Fig 4 (Hohle Fels Gravettian) artefact descriptions.
Table C: Fig 5 (Hohle Fels Magdalenian) artefact descriptions.
Table D: Fig 10 (Hohle Fels artefacts with residues) artefact descriptions.
Table E: Means and standard deviations for $L^*A^*B^*$ values per time period.
Table F: One-way ANOVA results for measured L^* values for each time period.
Table G: Tukey-Kramer post-hoc test data for L^* (lightness) colour values on Hohle Fels colour streaks per time period.
Table H: Hohle Fels ochre rock type sorted by archaeological horizon (AH) and time period. Abbreviations are as follows: H = Holocene, M = Magdalenian, G = Gravettian, A/G = A/G transition, A = Aurignacian. For the rock types: RS = Red sediment, DL = Degraded Limestone.
Table I: Hohle Fels ochre textures sorted by archaeological horizon (AH) and time period. Abbreviations are as follows: H = Holocene, M = Magdalenian, G = Gravettian, A/G = A/G transition, A = Aurignacian. For the textures: Med. Sand = Medium grained sand.
Table J: Hohle Fels ochre colours sorted by archaeological horizon (AH) and time period. Abbreviations are as follows: H = Holocene, M = Magdalenian, G = Gravettian, A/G = A/G transition, A = Aurignacian. For the colours: BR = Brick Red, DP = Dark Purple, DR = Dark Red, LP = Light Purple, LR = Light Red.
(PDF)

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Author Contributions

Conceptualization: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

Data curation: Elizabeth C. Velliky.

Formal analysis: Elizabeth C. Velliky.

Funding acquisition: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

Investigation: Elizabeth C. Velliky.

Methodology: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

Project administration: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

Resources: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

Supervision: Martin Porr, Nicholas J. Conard.

Validation: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

Visualization: Elizabeth C. Velliky.

Writing – original draft: Elizabeth C. Velliky.

Writing – review & editing: Elizabeth C. Velliky, Martin Porr, Nicholas J. Conard.

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Chapter 6. Paper 2

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

Authors: Elizabeth C. Velliky, Alvise Barbieri, Martin Porr, Nicholas J. Conard, Brandi Lee MacDonald

The results of the previous chapter show that there are several ochre rock types present in the Hohle Fels assemblage, and that different sources of ochre were likely visited in order to collect these ochre materials. This chapter details the surveys undertaken in the Swabian Jura and other regions in order to identify and sample potential source locations. This chapter presents my second thesis paper, which was published on October 1st, 2019, in the Journal of Archaeological Science: Reports. The publication includes Supplementary Information, which is shown in this thesis in Appendix E, pg. 323.

Following an intensive investigation on the geological setting of the region as well as discussions with geological specialists, we were able to identify several Fe-oxide sources. Following a discussion with a geologist at the University of Tübingen, I also conducted surveys in the Black Forest region of Germany to sample other Fe-oxide sources. I, alongside Dr Brandi MacDonald, analysed these as well some samples donated by geological hobbyists at the MURR Archaeometry laboratory at using NAA. The purpose of this study was to establish whether the ochre sources in Germany were geochemically unique enough to satisfy the *provenance postulate*, i.e. that inter-source variability is greater than intra-source variability (Weigand et al. 1977). If this postulate was satisfied, then it would thus be possible to compare archaeological ochres to their source counterparts, and work towards exploring where people collected ochre during the Upper Palaeolithic. The research indicates that the ochre sources in Germany are unique enough to be separated by region and by specific sources, thus showing promise for an artefact-based comparison.

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

Elizabeth C. Velliky[a,b,d,*], Alvise Barbieri[a,e,g], Martin Porr[b,c], Nicholas J. Conard[a,d,e], Brandi Lee MacDonald[f]

[a] Institute for Archaeological Sciences, University of Tübingen, Tübingen, Germany
[b] Archaeology/Centre for Rock-Art Research and Management, M257, Faculty of Arts, Business, Law and Education, School of Social Sciences, The University of Western Australia, Crawley, WA, Australia
[c] Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, ROCEEH—The Role of Culture in Early Expansions of Humans, University of Tübingen, Tübingen, Germany
[d] Department of Early Prehistory and Quaternary Ecology, University of Tübingen, Tübingen, Germany
[e] Senckenberg Centre for Human Evolution and Quaternary Ecology, University of Tübingen, Tübingen, Germany
[f] Archaeometry Laboratory, University of Missouri Research Reactor, Columbia, MO, 65211, USA
[g] Interdisciplinary Center for Archaeology and Evolution of Human Behaviour (ICArEHB), FCHS, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

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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. We aimed to determine whether specific 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.

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

* Corresponding author at: Abteilung Ältere Urgeschichte und Quartärökologie, Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Eberhard-Karls Universität Tübingen, Burgsteige 11, Schloss Hohentübingen, D-72070 Tübingen, Germany.
E-mail address: elizabeth.velliky@research.uwa.edu.au (E.C. Velliky).

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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. Collectively observing qualitative and quantitative data allows for a holistic approach to investigating the entire process behind mineral pigment behaviors of ancient populations.

In European contexts, much research emphasis focuses 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 has 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.

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 regarding 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 6000 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 (*Niedersachsen*), 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. Erosional processes removed much of the overlying layers, 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 ironstones 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 more extensive formation extending into Bohemia and was formed by the Variscan Orogeny during the late Paleozoic. The geological basement consists of medium to high-grade mica schists and gneisses (Seifert and Sandmann, 2006; Daly, 2018). The region is well-known for its large silver and tin deposits which were mined extensively in the 13th century but was 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 known 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 mostly treeless tundra-based environment (Ivy-Ochs et al., 2008).

3. Materials and methods

3.1. Sample selection and description

We conducted surveys in the Swabian Jura and the 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, we conducted no physical surveys in these regions. Fig. 1 displays a map with the source locations.

To clarify terminology, we use *ochre source* and *Fe-oxide source*

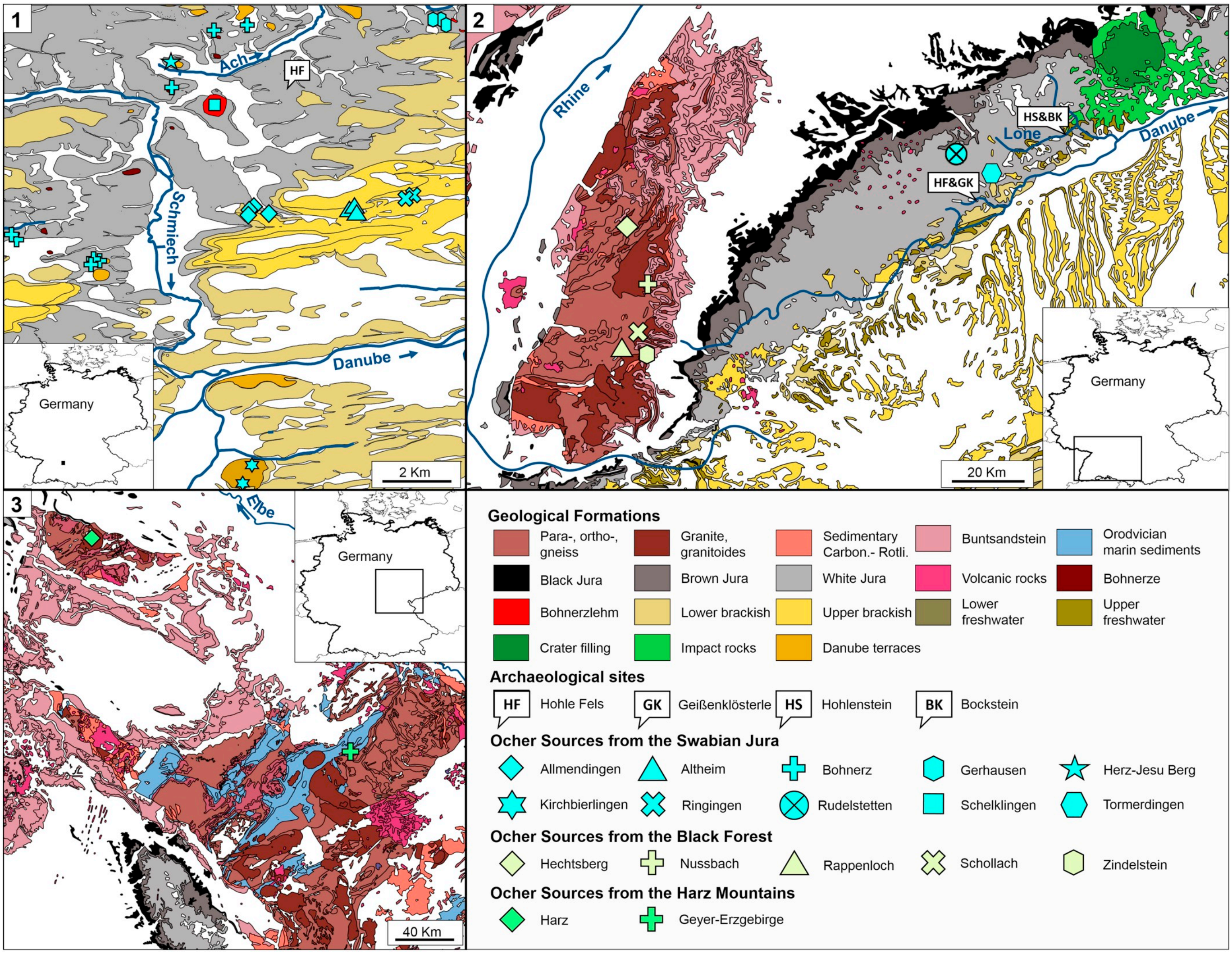

Fig. 1. Geological maps of southern and eastern Germany, showing all ochre source areas analyzed in this study. Sub-figures are as follows: A) Swabian Jura (local) sources, B) Black Forest (regional) ochre sources, as well as two sources (Rudelstetten and Tormerdingen) included in the Swabian Jura sources, 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.

interchangeably to refer to specific locations where these materials were collected. *Source regions* refer to the large-scale areas where several mapped outcrops, such as the Black Forest or the Swabian Jura, and *sub-sources* or *outcrops* refer to specific, confined points where we collected individual ochre samples. We refer to the materials that we collected and analyzed in this study 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. 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 outcrop 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 Mountains, 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).

We photographed and described all sampled outcrops 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 also described cohesion (USDA-NRCS, 2012) and color (Munsell Soil Color Book 2009) of iron nodules and concretions. When possible, we also described stratigraphy and bedding of the sources.

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

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)	

from the Black Forest, and ten 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 8×10^{13} n cm^{-2} s^{-1}. Samples were each allowed to decay for 25 min, 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 6×10^{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 the comparator method. These analyses generated elemental concentration values for 33 elements in most of the samples analyzed.

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 grain 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 gray 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, we 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 every 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 the surface during mining activities, and appears to be part of a more significant *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 gray 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 more extensive 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 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.

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 × 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 with 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 × 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 map certain exposures properly, 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 we cannot describe the exact stratigraphical context, 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

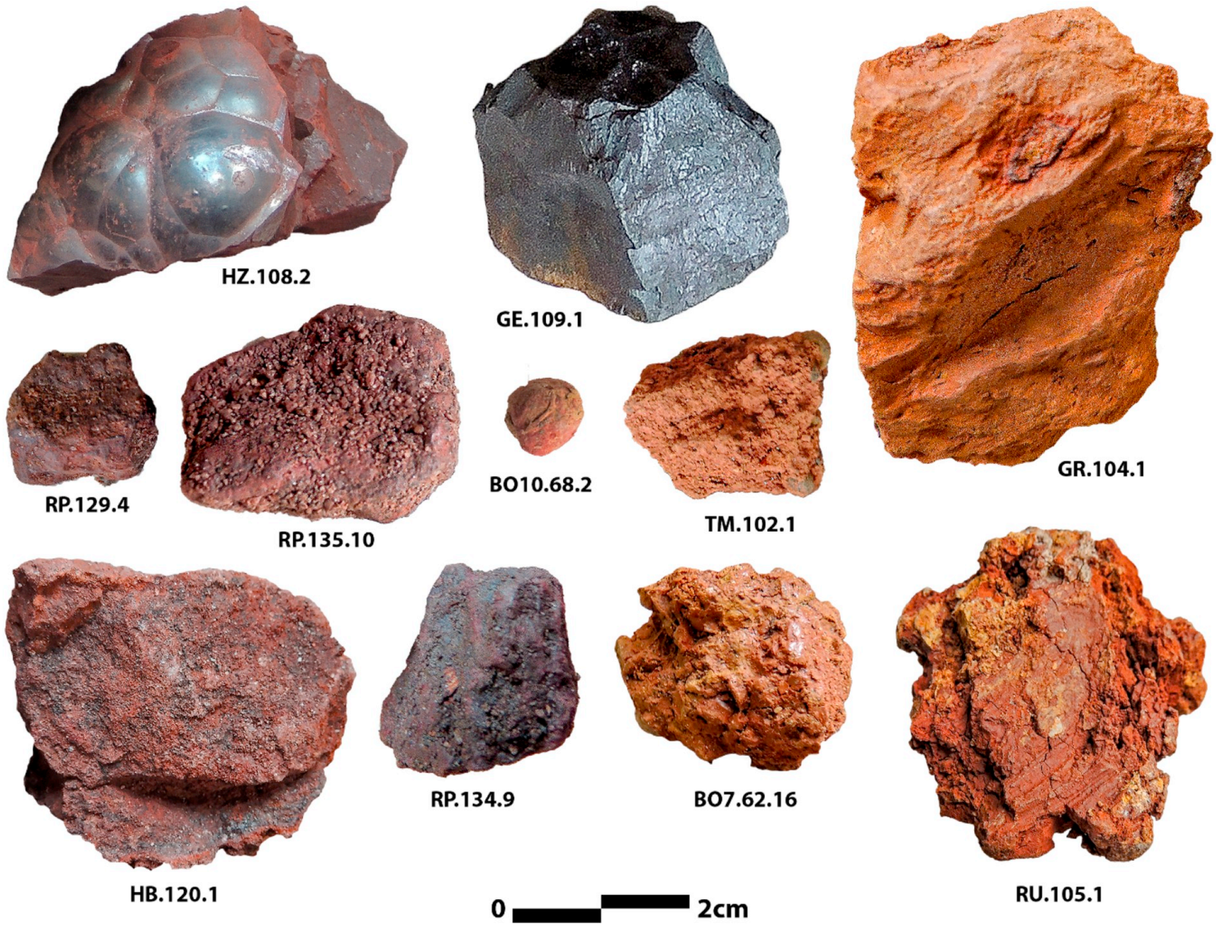

Fig. 2. Ochre samples from each of the regions analyzed. Selected analyzed samples from all investigated regions. Sample ID's correspond to SI Table C. HZ and GE labels are Harz Mountain samples, RP and HB are Black Forest specimens, and GR, BO, TM, and RU are Swabian Jura samples.

elements (REEs) to iron readily permits their substitution into Fe-oxide structures (Cornell and Schwertmann, 2003). Therefore, the data were transformed before statistical testing with Fe-normalization and $\log_{10}$. 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, such data transformations need to be assessed for their efficacy before considering those values as statistically representative. In our statistical exploration, including iterative bivariate plotting (element concentrations, $\log_{10}$ 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 $\log_{10}$ 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 individual samples, likely due to their varying Ba content. Based on this, we decided 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 the 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, the Black Forest and Harz Mountain sources could be reasonably differentiated; however, the Swabian Jura samples exhibited consistent overlap (see Fig. 3). When the 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.

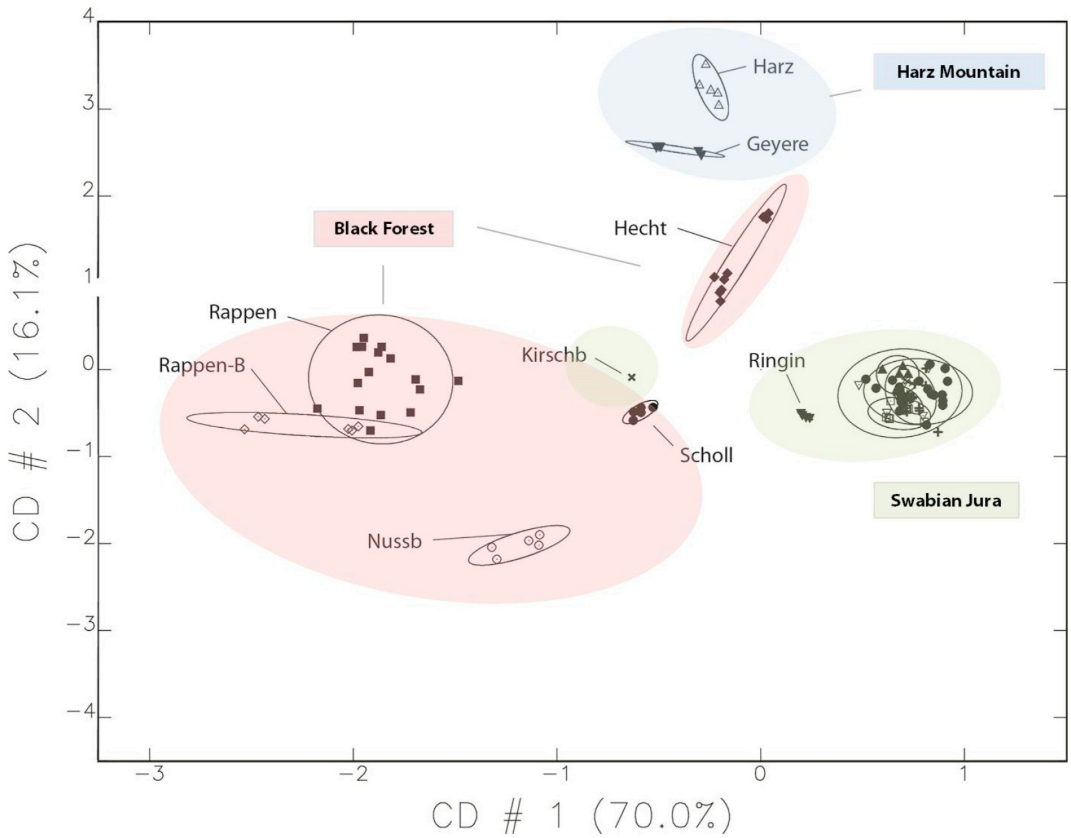

Fig. 3. Bivariate plot of CD#1 versus CD#2 for all sources, highlighted by region. Note how most Swabian Jura groups overlap. Harz Mountain sources are significantly different, while Black Forest sources exhibit the widest distribution at both source and sub-source levels. Ellipses are drawn at 90% confidence.

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

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 are 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), which is likely because these sources formed in the same region and likely in a 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 because 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 from *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

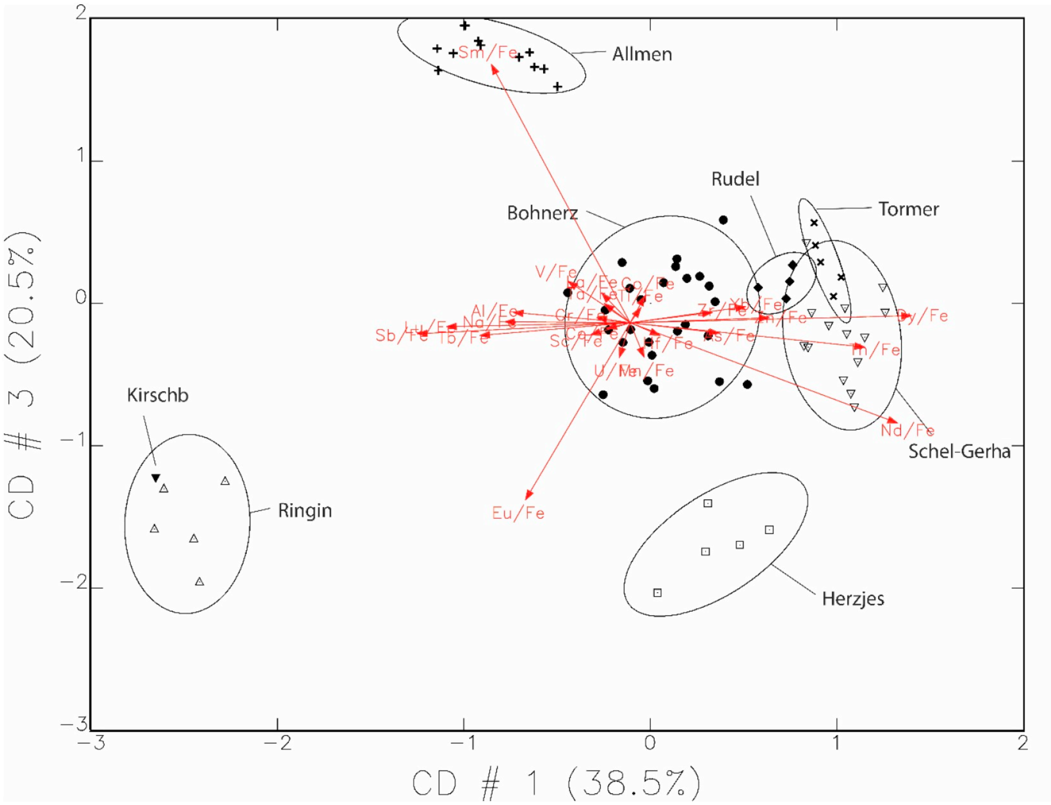

Fig. 4. Bivariate plot of CD#1 versus CD#3 for eight Swabian Jura sources. Note that while the single Kirchbierlingen (Kirschb) sample falls within the ellipse of Ringingen source in this projection, it separates in other CDA projections. Also, note the similarity of the Bohnerz source group when projected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

granites located in the Alps and molasse deposits located in the Swabian Jura (Geyer and Villinger, 2001; Szenkler et al., 2003).

The Harz Mountain sources (both Harz and Geyer-Erzgebirge) exhibit high Fe and Sb values and separate from all the Black Forest and the 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. These elemental concentrations may be due to the volcanic rock basin 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 subsources (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

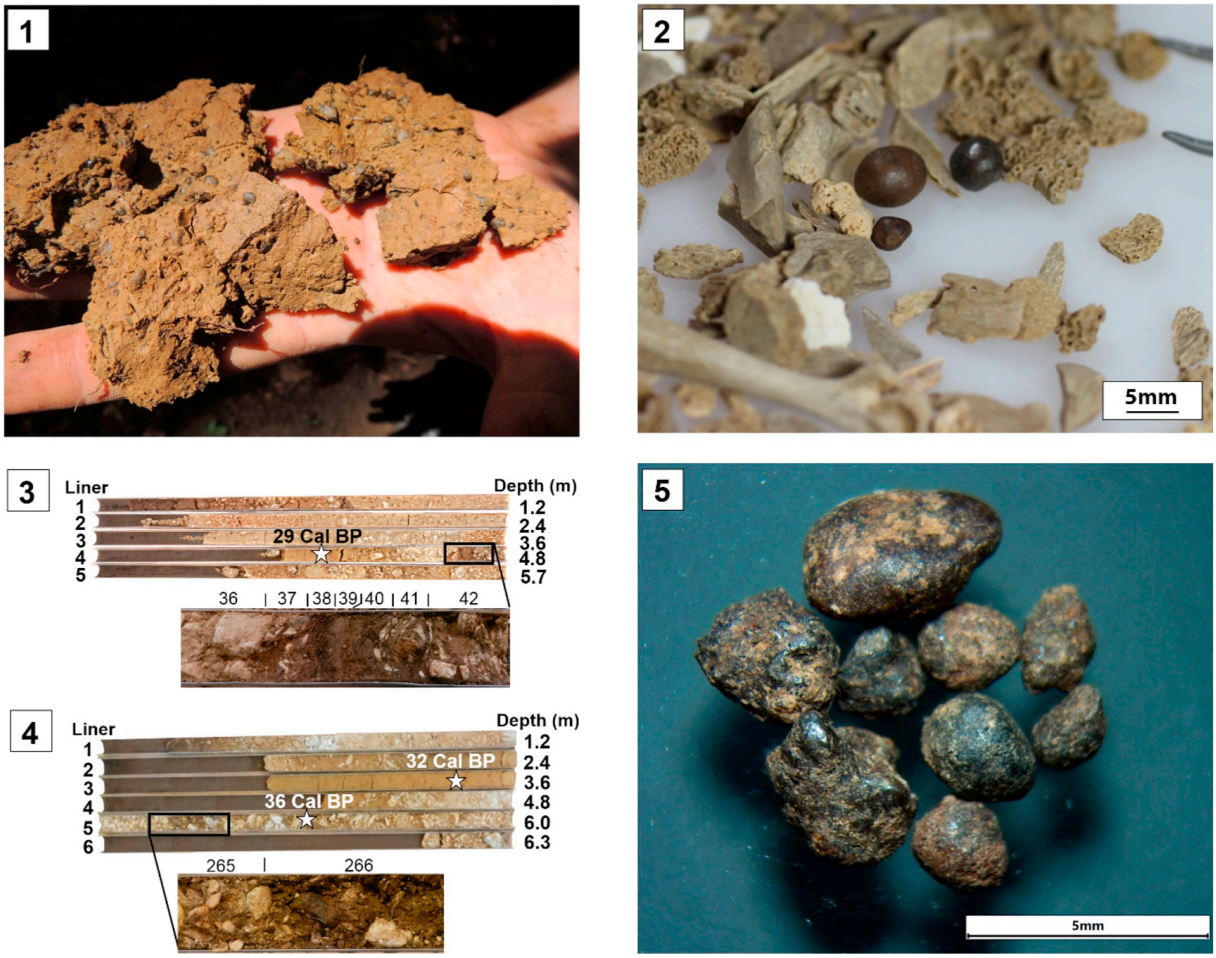

Fig. 5. Bohnerz from the Swabian Jura. 1) Sediment aggregates containing Bohnerz fragments, photo taken during Swabian Jura survey; 2) Larger Bohnerz fragments identified during sorting of archaeological material excavated at Hohle Fels (photo: Maria Malina); 3) Core 12 drilled in the Lone Valley opposite 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 shows 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.

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.

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 artifacts 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.,

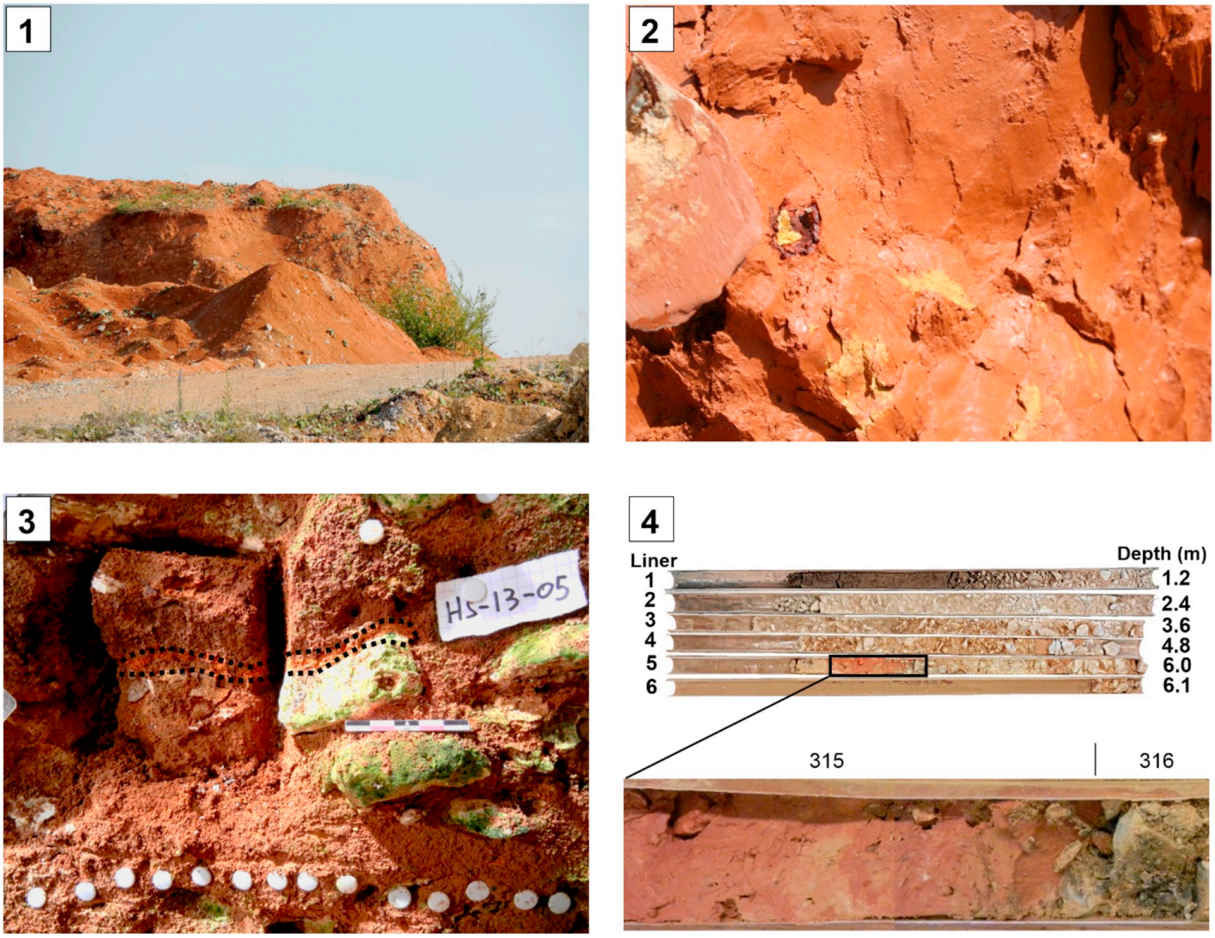

Fig. 6. Clays impregnated with Fe-oxide from the Swabian Jura. 1) Red clay and sand outcropping at Schelklingen, photographed during Swabian Jura survey; 2) Detail of a clay aggregate from Gerhausen (picture width is ca. 10 cm) (photo: Rudolf Water); 3) Aggregate composed of clay, silt and sand within 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). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2019.101977.

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Chapter 7. Paper 3

Evidence for long-term symbolic behavioural continuity through pigment use from three Upper Palaeolithic cave sites in the Swabian Jura

Authors: Elizabeth C. Velliky, Brandi Lee MacDonald, Martin Porr, Nicholas J. Conard

Since the ochre assemblage at Hohle Fels is relatively small compared to other assemblages, e.g. South Africa), observing subtleties in behavioural complexity is more difficult to access. The modified assemblage of only 27 individual artefacts restricts observations on the nature and types of ochre utilisation throughout time. Because of these factors, I have implemented a different approach to the ochre assemblage to explore and answer my original research questions. An opportunity arose at the University of Missouri Research Reactor (MURR) Archaeometry laboratory to incorporate a provenance-based approach to the Hohle Fels ochres using NAA.

Here, I present the NAA results of a selection of ochres from the assemblage at Hohle Fels, as well as smaller ochre collections from the neighbouring site of Geißenklölsterle and from Vogelherd, located in the adjacent valley. The results are included in Paper 3 as the culmination of both the assessment of the archaeological ochre assemblage and the analysis of the ochre source materials. The NAA data show that nine distinct compositional groups can be differentiated amongst the archaeological assemblage, indicating that ancient groups collected ochre from nine discrete ochre source outcrops. Some of these sources were accessed in isolated time periods, and some were visited throughout the entire duration of the Upper Palaeolithic (ca. 30,000 years). Other sources were visited by inhabitants of all three cave sites, and others were only accessed by people from one cave site. The archaeological NAA results were then compared to the source materials in order to see if any of the archaeological ochres could be attributed to their geological source origins. The results are then discussed within the context of environmental and climatic fluctuations and other raw material acquisition strategies. Lastly, the complexities, trends and nuances of ochre behaviours in the Swabian Jura during the Upper Palaeolithic are discussed in light of symbolic and functional practices more generally.

Overall, the three papers present my thesis work in three sequential phases. First, the artefacts are identified and described. Their relevance in the stratigraphy and their deposition at the site are outlined and discussed. These results led to the question of where these materials could have been collected in the landscape. When Fe-oxide sources were identified, it was then possible to work towards locating the origin of the artefacts and point of collection. For most of the samples, I was able to identify a potential source location, which facilitated inferences on collection strategies over time, behavioural adaptations in light of a changing environment and climate, possible social interactions with other cave inhabitants and also people over long-distances, and lastly, the social memory of people in the Swabian Jura over tens of thousands of years.

Note for Chapter 7: *This manuscript is formatted in the PNAS style, which is formatted as a short and concise text with additional relevant information included in the Supplementary Information. Therefore, the Supplementary Information (SI) for this paper was kept in the main thesis text, which is different from the previous thesis papers (Chapters 5 and 6), where the SI was formatted as Appendices to the main text. The reference style and figure captions have been changed to maintain consistency with the formatting of this thesis document.*

7.1. Abstract

The use of red and yellow earth pigments, or ochre, is a key component of early symbolic behaviours for anatomically modern humans and possibly Neanderthals. Though red ochre artefacts are often reported in European Upper Palaeolithic contexts, little is understood about the complexity of behaviours surrounding the relationships of hominins and these materials in Europe. Here, we present results on the first ochre provenance study in Central Europe showing long-term ochre acquisition and selection strategies by inhabitants of Hohle Fels cave in southwestern Germany, spanning the entire Upper Palaeolithic sequence (44-14.5 kcal BP). Using a combination of neutron activation analysis (NAA), X-ray diffraction (XRD) and scanning electron microscopy (SEM), our results show distinct compositional groups which indicate that known ochre source areas were continuously accessed for ca. 29,500 years. These data, combined with ochre assemblages from the Aurignacian layers (44-30.5 kcal BP) of nearby sites of Geißenklösterle and Vogelherd caves, show both shared and unique ochre behaviours through time and space. The data were compared to modern-day ochre source materials and showed that some local areas were visited throughout the entire Upper Palaeolithic, and an unidentified non-local source was exploited during the Gravettian and Magdalenian. Furthermore, a distant ochre source (ca. >300 km) was identified from the Aurignacian, suggesting a larger scale of landscape mobility than previously thought for this time period. Our results here reveal long-term, complex temporal and spatial interrelationships of a range of symbolic behaviours at a crucial time of human history.

Mineral pigments / Palaeolithic archaeology / Symbolic behaviours / Human evolution

Significance statement

We present results of a provenance study of archaeological ochres from the Upper Palaeolithic layers of three caves and ochre sources throughout Germany. Our results show that ochre was gathered from local areas throughout the Upper Palaeolithic (44-14.5 kcal BP) by inhabitants of all three caves, with some of these sources being unique to certain cave sites. Evidence for distant (>300 km) ochre acquisition is revealed for the Aurignacian of Hohle Fels, and an unidentified semi-local source was collected on a large scale during the later time periods. These findings describe a vast and intricate knowledge of the landscape that was shared amongst cultural groups throughout almost thirty millennia and expand our knowledge on the entanglements between humans and pigment materials.

7.2. Introduction

The early use of mineral pigments by hominins is generally accepted as an important element in the early material expressions of complex cognitive thought, syntactical language, and mediation of symbolic communication (d'Errico 2003; 2007; d'Errico et al. 2003; Henshilwood 2009; Henshilwood et al. 2002; Henshilwood and Marean 2003; Knight et al. 1995; Nowell 2010; Watts 1999; 2009). One of the most common mineral pigments used by hominins is colloquially referred to as ochre. Ochre is varied and encompasses a range of materials containing mineral phases of Fe-oxides/oxyhydroxides, and can be used to create colourful pigments. The habitual use of ochre is thought to emerge as far back as 500-300 kya (kya = thousands of years ago) in southern Africa (Brooks et al. 2018; Watts et al. 2016), 90 kya in the Levant (Hovers et al. 2003; Salomon et al. 2012), and 200-60 kya in Europe. In the latter case, the utilization of ochre is related to occupations by Neanderthals (Hoffmann et al. 2018; Roebroeks et al. 2012). Though these reports present compelling evidence for the collection and manipulation of ochre pigments, the conceptualization of these processes and the identification of unambiguously symbolic items in the archaeological record remains a highly contested field (d'Errico and Henshilwood 2011; Hopkinson 2013; Mithen 2014; Wadley 2003; Zilhão 2011). Much debate exists around the discussion of whether ochre was used primarily in symbolic or functional contexts, as several recent experiments have shown ochre to be a useful hafting mastic (Hodgskiss 2006; Lombard 2006; Wadley 2005; Wadley et al. 2004; Zipkin et al. 2014), insect repellent (Rifkin 2015a), sunscreen (Rifkin et al. 2015), and in hide tanning (Audouin and Plisson 1982; Rifkin 2011), amongst other things (Villa et al. 2015). With the onset of the Upper Palaeolithic in Europe and the migration of anatomically modern humans (AMHs) into the continent, several forms of material culture, including painted and engraved cave art (Clottes 2008; d'Errico et al. 2016; González-Sainz et al. 2013; White et al. 2017), personal ornaments (Heckel 2018; Vanhaeren and d'Errico 2006; Wolf 2015a), musical instruments (Conard and Malina 2008; Conard et al. 2009), and sculpted figurines (Conard 2003; 2009; Dutkiewicz et al. 2018) suggest forms of complex and well-established symbolically mediated behaviours. The use of ochre and pigments is included in this palimpsest, yet, little work exists emphasizing the diachronic development and social and environmental interplay between AMHs and this material item that seems to be so closely intertwined with material reflections of symbolic behaviours. Even though ochre may have been perceived and interacted with in a multitude of forms, both functional and symbolic, our aim here is to contribute to knowledge regarding the role of ochre materials in human evolution and history beyond a functional and symbolic dichotomy.

The Swabian Jura region in southwestern Germany is of crucial importance for an understanding of early modern behaviours in Europe. Some of the cave sites here (Figure 7.7) offer the earliest examples of human occupation in Europe, dating to ca. 44 kcal BP (Conard 2003; Conard and Bolus 2006; Conard and Bolus 2008), and document the Middle to Upper Palaeolithic transition in Europe (Conard 2011; Conard and Bolus 2008; Higham et al. 2012; Richter et al. 2000). Two tributary valleys of the Danube, the Ach and Lone Valleys, contain several of these cave sites which have offered detailed temporal sequences and a wealth of material culture. In specific, the cave site of Hohle Fels in the Ach Valley presents a deep and intact stratigraphy which allows for a detailed analysis of ochre materials and their associated behaviours throughout the entire Upper Palaeolithic (44-14.5 kcal BP). This cave site is well-known for its elaborate assortment of early figurative art (Conard 2009), personal ornamentation (Wolf 2015a; 2015b), musical instruments (Conard et al. 2009), and lithic technology (Conard and Bolus 2006; Hardy et al. 2008). The neighbouring cave sites of Geißenklösterle and Vogelherd also yielded ochre artefacts, in addition to their assemblages of figurative art and personal ornaments (Conard 2003; Dutkiewicz et al. 2018; Hahn 1988; Wolf 2015b). The assemblages of ochre from these three cave sites offer an opportunity for a diachronic assessment of ochre behaviours during the Upper Palaeolithic in this region and for a comparison to previously established behavioural patterns for lithic (Burkert and Floss 1999; Floss and Kieselbach 2004; Hahn 1987; Scheer 2000) and osseous (Barth et al. 2009; Münzel 2001a; Scheer 2001; Wolf 2015a) resources. Furthermore, it allows for a detailed investigation of some of the earliest symbolic behaviours associated with AMHs in Europe. In addition to the cave sites, several Fe-oxide sources lie near the cave and in nearby and distant regions which would have also existed during the Late Pleistocene. A survey in the summer of 2017 yielded numerous Fe-oxide samples of various forms in the Swabian Jura as well as other regions and, following geochemical analyses, showed promise for a potential provenance study with the nearby archaeological ochre artefacts (Paper 2, Chapter 6). The analyses of the ochre sources satisfied the *provenance postulate* (Weigand et al. 1977)for differentiating intra- and inter-source samples, and therefore offered a valid platform upon which to conduct a provenance-based geochemical study of the ochre materials, which until now had not been conducted on any of the artefacts from this region.

Here, we present the first provenance study on ochre assemblages in Central Europe. Our aim is to explore the geochemical variability of ochre materials at the three sites to determine how many ochre sources are represented in the assemblage, how their use changed over time, if ochre from specific areas is present at all three caves, and how these materials compare to modern-day ochre sources from local (Swabian Jura, <80 km), semi-local (Black Forest, 80-300 km), and distant (Thuringia and Saxony, >300 km) areas. We used a combination of qualitative data (Velliky et al. 2018b), scanning electron microscopy (SEM), neutron activation analysis (NAA) and X-ray Diffraction (XRD) in order to investigate the physical and elemental characteristics of the archaeological assemblages and compare these to previously collected geochemical data from ochre ochres in the region (presented in Paper 2, Chapter 6). With the results of these analyses, we can reasonably infer aspects of landscape knowledge and interaction and how people may have adapted to or were influenced by changing environmental conditions. Lastly, from the material-acquisition strategies, we can make further inferences about the symbolic material culture and if the perceptions of and interactions with ochre changed or remained constant through time.

7.3. Results

Examples of ochres illustrating their visual characteristics from all three cave sites are shown in Figure 7.1. Characterization by NAA produced elemental concentration values for 33 elements in most of the analysed samples and yielded data for 183 ochre artefacts from Hohle Fels (ca. 21% of the total assemblage), 18 (ca. 14%) from Vogelherd (VH), and 9 (ca. 3%) from Geißenklösterle (GK). Statistical analysis revealed nine compositional groups and sub-groups representing the geological diversity of ochre materials present within the assemblage. Figure 7.2 is a scatterplot of log^{10} Sc/Fe versus log^{10}Sm/Fe, showing the distribution of the compositional groups. Table 7.1 shows group totals separated by time periods and sites. The groupings of the ochre artefacts consist of three major compositional groups that compromise the majority of the samples (ca. 84%) with five minor compositional groups accounting for the remainder of the samples (ca. 16%) (Figure 7.3). Mineralogical analysis by XRD was conducted on eight sub-samples, representing all groups except Group 1 and Group 3. Groups 1 was highly distinct based on elemental data and Group 3 was too small in number. For Group 7a, we opted to analyse two samples to assess any potential within-group variation. All samples showed strong peak pattern matches for one or more forms of iron oxide, primarily hematite (Fe_2O_3), proto-hematite, goethite (FeO[OH]), and iron-phosphate (spectral data can be found in Section 7.8 Table 7.4 and Figure 7.12).

The ochre samples from HF represent a diachronic spread as well as a lateral spread with 40 of the total 71 excavated quadrants represented (Figures 7.16-19, Section 7.8). Therefore, similar geochemistry based on post-depositional processes can be ruled out by basis of proximity. The identified compositional groups suggest certain preferences in specific time periods with both changes and continuity over time. Ochres from Group 2 ochre were highest represented during the Aurignacian, containing ca. 36% of the total sampled Aurignacian assemblage and constituting ca. 47% of the total population of Group 2. As represented by the distribution in the compositional groups, Aurignacian-period ochre artefacts are present in every group except from Groups 1 and 3. Samples from Groups 5 and 6b are exclusively from the Aurignacian period, and Group 6a is similarly dominated by Aurignacian (ca. 76%). During the Gravettian (34-30.5 ka cal. BP), almost all of the major and minor compositional groups are represented (except for Groups 5 and 6b), but the highest represented group of the Gravettian is Group 1 (ca. 55%). Group 1 was likely discovered during the A/G transition (34.5–32.5 kcal BP) and was then accessed throughout the remainder of the Upper Palaeolithic.

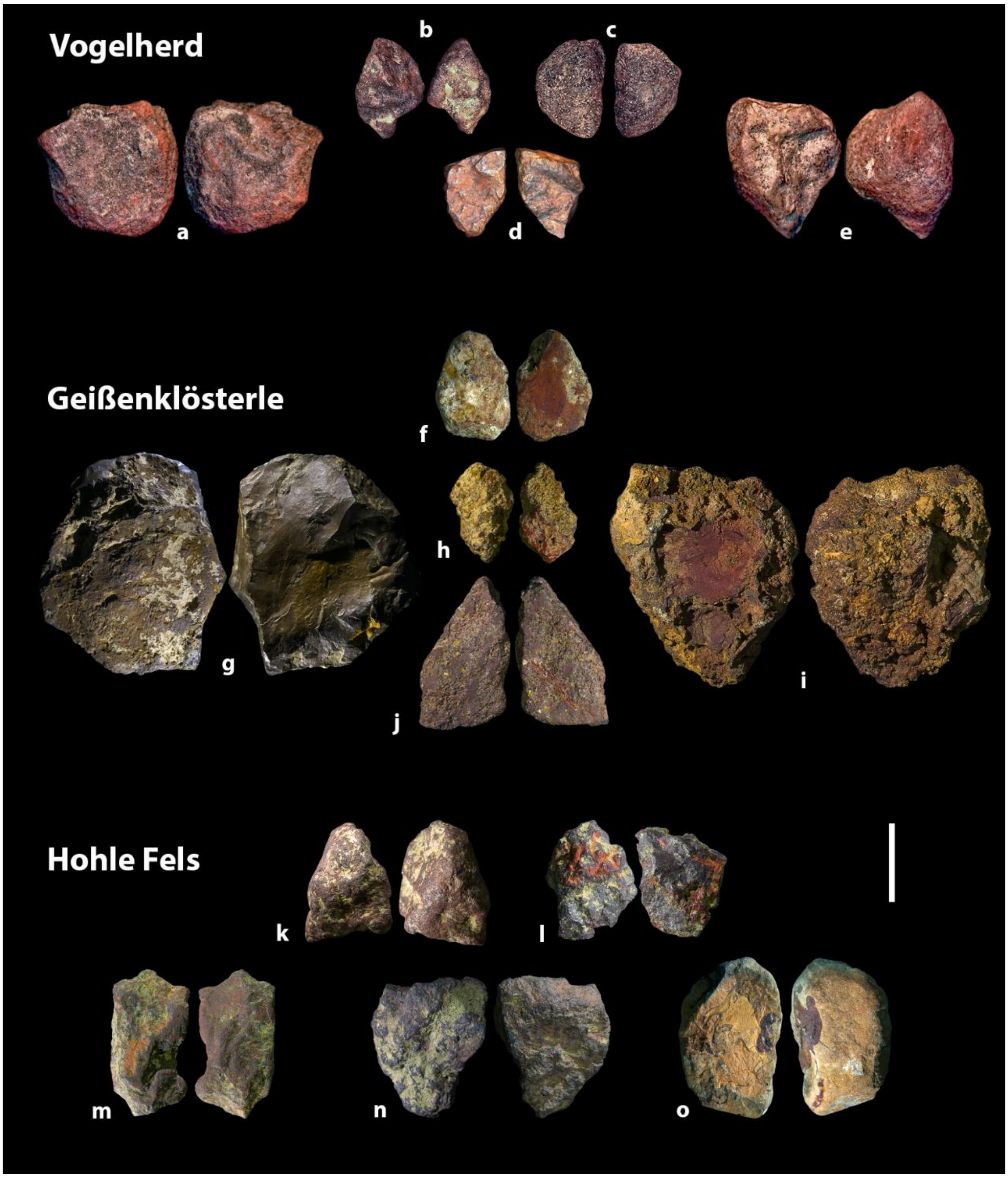

Figure 7.1: Selected ochre artefacts from Vogelherd, Geißenklösterle, and Hohle Fels, showing the visual and textural variety in ochre types and sizes. Scale = 1cm.

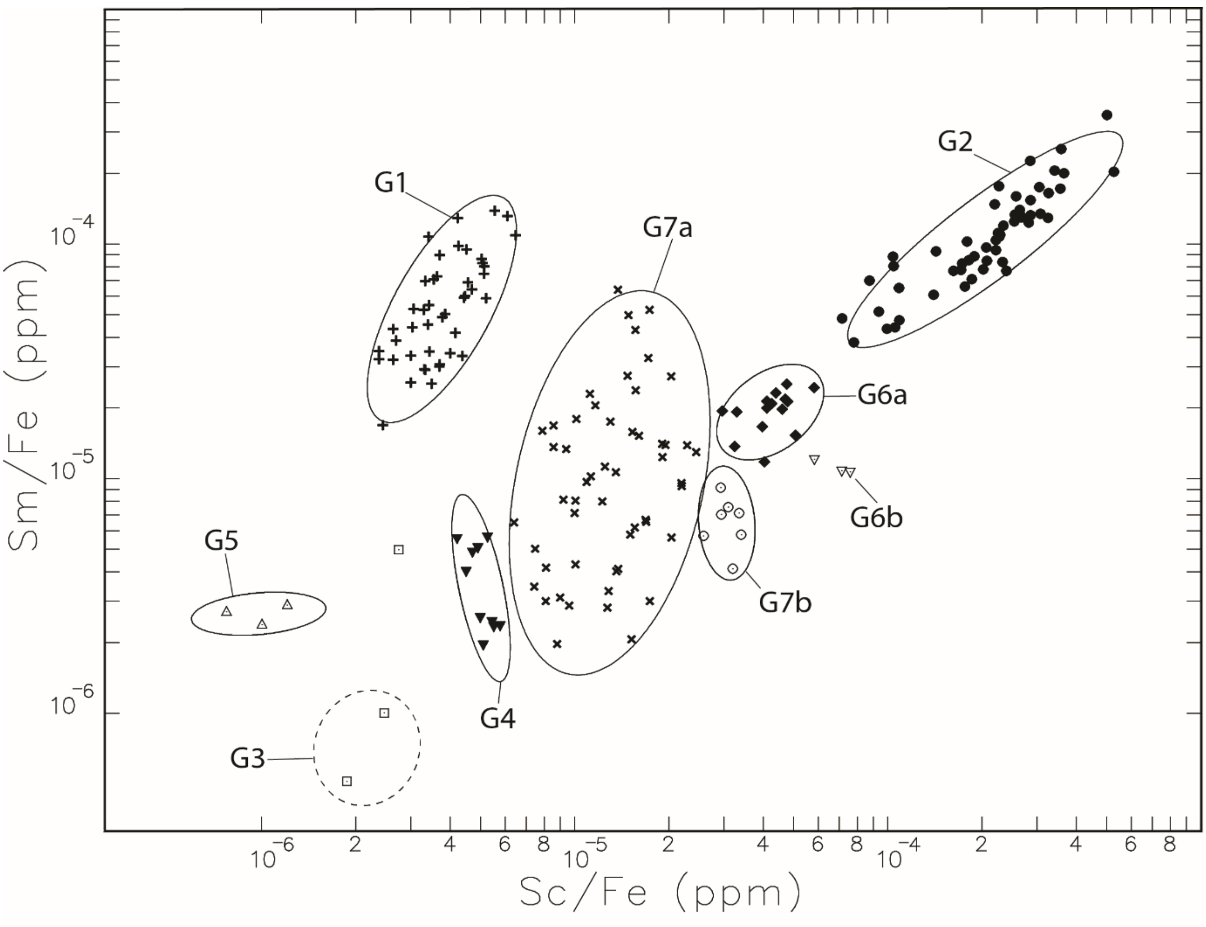

Figure 7.2: Scatterplot of $\log^{10}$ Sc/Fe versus $\log^{10}$Sm/Fe for all ochre artefact samples, showing the distribution of compositional groups. Ellipses are drawn at 90% confidence interval, with the exception of G3.

Since NAA only requires 150 mg of a powder sample for analysis, in many cases, fragments of the original ochre artefact were intact. A representative artefact from each compositional group (n = 9) was selected for analysis by SEM to examine its micro-fabric. The results showed different fabrics (Section 7.8, Figure 7.13) amongst the ochre artefacts, indicating different ochre textures and geological settings. Several specimens contained platy micaceous particles, rendering a “glittery” or “brilliant” appearance in visible light. The differences in fabric and texture indicate different qualitative characteristics in the compositional groups that may have played a role in their having been selected.

Table 7.1: Archaeological group totals and sub-totals for time periods per site. Abbreviations are as follows: GK = Geißenklösterle, HF = Hohle Fels, VH = Vogelherd, G = Group.

		Sites			
Groups	**GK**	**HF**	**VH**	**%**	**Total**
G1		**44**		**23%**	**44**
Magdalenian		20		45.5%	20
Gravettian		20		45.5%	20
A/G trans		4		9%	4
G2		**53**		**27.8%**	**53**
Magdalenian		11		21%	11
Gravettian		11		21%	11
A/G trans		5		9%	5
Aurignacian		26		49%	26
G3		**3**		**1.6%**	**3**
Magdalenian		1		33%	1
Gravettian		2		67%	2
G4		**5**	**5**	**5.2%**	**10**
Magdalenian		2		20%	2
Gravettian		3		30%	3
Aurignacian			5	50%	5
G5		**3**		**1.6%**	**3**
Aurignacian		3		100%	3
G6a	**2**	**11**	**2**	**7.8%**	**15**
Magdalenian		1		7%	1
Gravettian		1		7%	1
Aurignacian	2	9	2	86%	13
G6b	**3**			**1.6%**	**3**
Aurignacian	3			100%	3
G7a	**3**	**45**	**5**	**27.7%**	**53**
Magdalenian		26		49%	26
Gravettian	1	12		24.5%	13
A/G trans		2		3.8%	2
Aurignacian	2	5	5	22.6%	12
G7b	**1**	**5**	**1**	**3.7%**	**7**
Gravettian		1		1.4%	1
A/G trans		2		2.9%	2
Aurignacian	1	2	1	5.7%	4
Grand Total	**9**	**169**	**13**		**191**

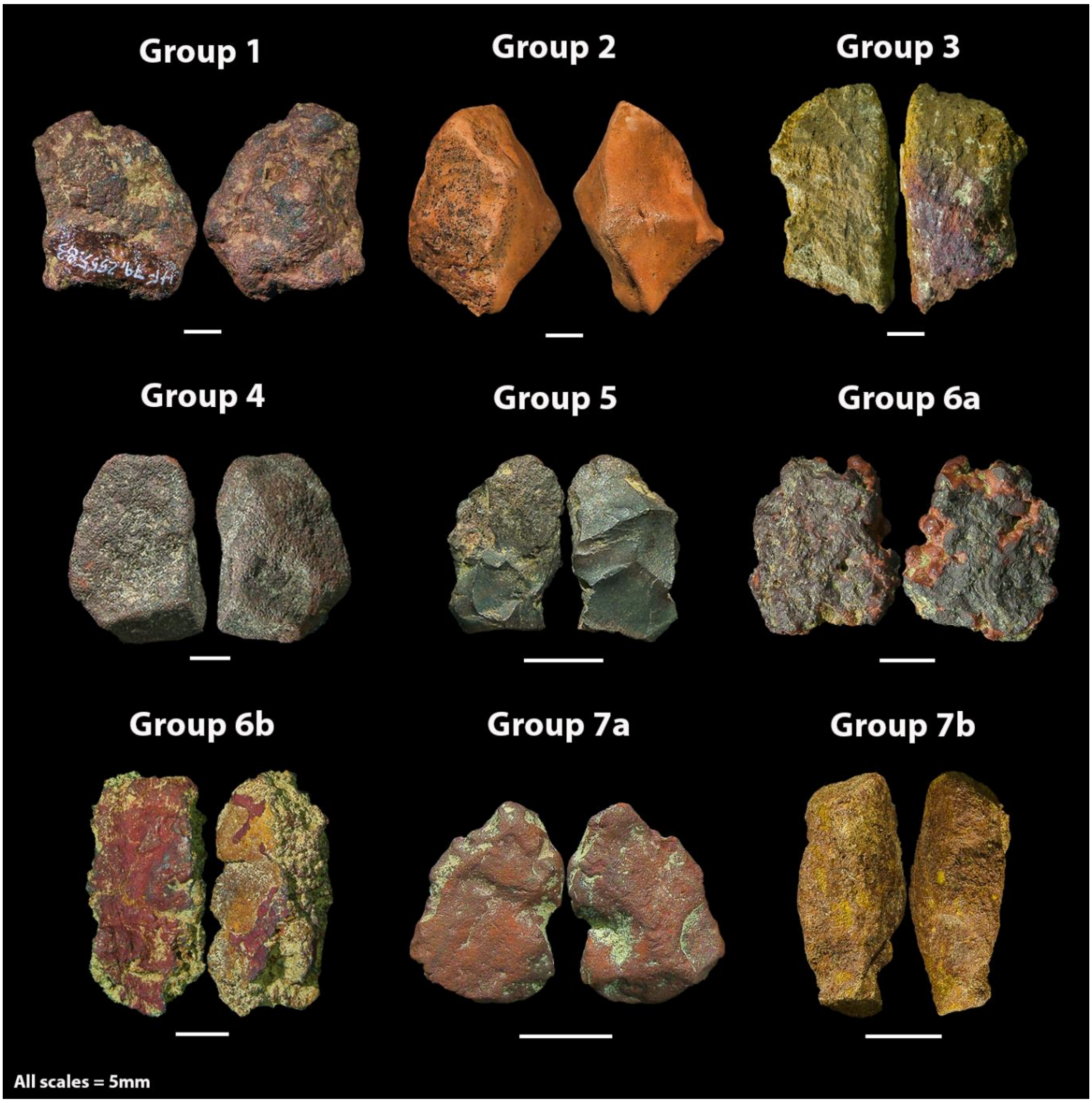

Figure 7.3: Representative examples of the visual characteristics of ochre from each of the compositional groups. Scales are at 5mm.

7.3.1. Artefact and source comparison

The final research question in this study sought to determine if the ochre artefacts from HF, GK, and VH could be associated with ochre samples from specific sources previously analysed in Chapter 6, Section 6.5. Because CDA showed the greatest clarity in statistically differentiating sources and regions, we applied this approach to the combined data set of all artefacts (organized by the compositional groups) and sources. Figure 7.4 is a bivariate plot of CD#1 versus CD#2, showing the distribution of all samples. Ellipses indicate the projection of the sources, while sample icons indicate the samples within each compositional group.

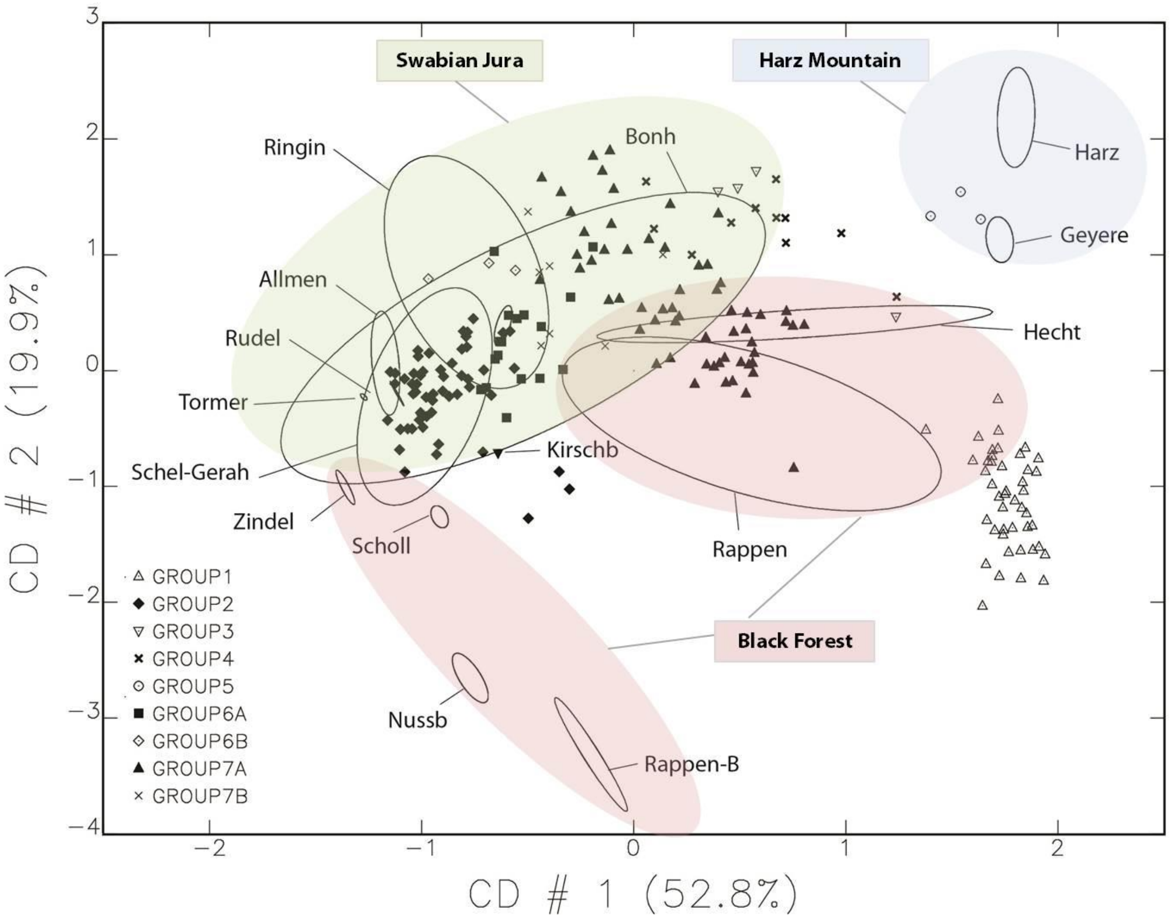

Figure 7.4: Bivariate plot of CD#1 versus CD#2, including all sources and all artefact samples sorted by group. Ellipses indicate the projection of sources, while icons indicate the individual samples in each compositional group. Ellipses encircling the source groups are at 90% confidence.

Samples in compositional Group 1 are unique from the core cluster and appear to trend similarly to some Black Forest source ellipses. However, this is not consistent with other projections of other discriminant functions (e.g. CD#3, CD#4). Compositional Group 5 trends similarly to Harz Mountain sources and this is consistent in other CDA projections. The majority of artefact samples in the remaining compositional groups plot within the same clusters representing the Swabian Jura region sources. This local cluster was investigated further (Figures 7.14-15 in Section 7.8), and display a strong association of Group 2 to Fe-oxide sources within 10 km of the cave sites of HF and GK.

7.4. Discussion

7.4.1. Evaluation of geochemical comparison of artefacts and sources

The comparison of the ochre artefacts and sources revealed some insights into the nature of ochre collection behaviours at the three cave sites in the Swabian Jura. First, compositional Group 1 does not appear to be local to the Swabian Jura, though there is the minor potential for an unidentified source. However, this is unlikely, as its characteristics are significantly different (i.e. enriched in rare earth elements and actinides) from other Swabian Jura sources. Another observation is the Ca-enrichment (ca. 38.3%) of Group 2. Of all of the compositional groups identified here, Group 2 is the most likely of all groups to be sourced from a locality near HF and GK due to the Jurassic limestone geological bedrock. This is further evidenced by XRD results summarized in Table 7.4, indicating $CaCO_3$ and relatively low Fe content. Since GK is located only about 5 km from HF, it is surprising that no GK ochres are associated with the Group 2 geochemistry. However, this could be due to the sample size of ochres from GK (n = 9), and future sampling of this cave site may offer more insight into the local ochre-acquisition strategies in the Ach Valley cave sites. Lastly, and perhaps the most significant finding, is the association of Group 5 to the distant ochre sources from the Harz Mountains, located ca. 300 km from the site of HF.

Of the other cave sites, ochre artefacts from GK in the Ach Valley are distributed through Groups 6a, 6b, 7a, and 7b, with 6b being an entirely GK group of goethite and hematite Fe-oxide phases (Table 7.4, Figure 7.12 in Section 7.8) The CDA projections of these groups and sources suggest that inhabitants at GK were using Swabian Jura sources, though not the same source as Group 2. Samples from VH in the Lone Valley are distributed between Groups 4, 6a, 7a, and 7b, which show consistent separation from the cluster of Group 2 and some of the Swabian Jura sources (Tormer, Rudel, Schel-Gerha, Allmen, Kirschb, Bohn-B) (Figures 7.14 and 7.15 in Section 7.8), also suggesting the use of sources in an area different from Group 2, but are likely still local to the region.

In summation, the results of the artefact provenance analysis show four noteworthy observations: 1) Ochres from Group 1 were not acquired from the local area of the Swabian Jura; 2) Group 2 is, however, likely from the area in the immediate vicinity (ca. 20 km) of the cave sites of HF and GK; 3) The other compositional Groups (3, 4, 6a, 6b, 7a, 7b) could be from local (<80 km) sources, but not the same outcrop as Group 2, and; 4) Group 5 is from a distant (>300 km) ochre source, likely in the north-eastern region of Central Germany.

7.4.2. Behavioural implications of diachronic and synchronic ochre use in the Swabian Jura

Within compositional group data, glimpses into the different ochre collection events can be seen. The major compositional groups, Groups 1, 2, and 7a, are suggestive of long-term and large-scale collection strategies by the inhabitants of the Swabian Jura cave sites. Though Groups 1 and 2 are unique to HF, they show a shift in collection strategies following the last glacial maximum (LGM), ca. 28 kya. Group 1 contains mostly Gravettian (34-30.5 kcal BP) ochres (n = 24, ca. 55%) followed by the Magdalenian (16.5-14.5 kcal BP) (n = 16, ca. 36%) and the A/G transition (34-32.5 kcal BP) (n = 4, ca. 9%), with no ochres from the Aurignacian. Group 1 is also the most chemically, physically, and visually homogeneous: almost all of the ochres are purple to dark purple with micaceous inclusions and produce a dark-red streak. The source that this group represents, though as of yet unidentified, was well-known and extensively accessed by HF inhabitants after its discovery. This source was also increasingly accessed following the A/G transition, coinciding with the narrowing of ochre selections at HF to silty and purple ochres producing dark-red streaks (Velliky et al. 2018b). When the spatial organization of the source groups are observed within the cave site of Hohle Fels (Figures 7.16-19 in Section 7.8), the ochre samples from Group 1 are almost entirely found within four excavation units located in the south-eastern portion of the cave (Figure 7.19). The Gravettian samples of Group 1 all stratigraphically source from AH IIb, the first Gravettian horizon, which exhibits some possible mixing with the overlying Magdalenian layer AH IIa (Miller 2015b; Taller 2014; Taller and Conard 2016; Taller et al. 2019). The spatial organization of this group within the cave either represents random deposition events from internal transportation processes in the cave during both time periods; or, the mixing of layers IIa/IIb in this location, meaning that this group was either mostly Gravettian or Magdalenian. This observation can offer insight into taphonomic processes within

Hohle Fels and may provide further assistance in identifying internal nuances in these transportation and mixing events within HF.

Group 7a is the largest and most varied of the compositional groups – it includes ochres from all three caves and from all time periods. It includes two Aurignacian ochres from GK, six Aurignacian ochres from VH, and five from HF (Table 7.1). Of the other time periods, two samples are from the A/G transition at HF, 11 are from the HF Gravettian, and 27 from the HF Magdalenian. The high chemical variation, as well as the temporal and spatial distribution of this group, suggest that not only was it widely distributed with multiple accessible outcrops, but also perhaps the closest as evidenced by its association to the Swabian Jura source samples (Figure 7.4, Figures 7.14 and 7.15). Moreover, Group 7b is chemically similar to Group 7a and may represent a sub-group of that source deposit. This association supports the hypothesis that 7a was a larger Fe-oxide source as intra-source variability amongst ochres can still be high, especially in an open and exposed environment (MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007).

Throughout the minor compositional groups (Groups 3, 4, 5, 6a, 6b, 7b), certain temporal and geographic restrictions or perhaps special events are discernible. Group 3 contains only three specimens, two from the Gravettian and one from the Magdalenian, and all three samples are from different stratigraphic layers at HF. Though one of the Gravettian samples is from layer IIb (and possibly mixed with the Magdalenian), the other sample is from layer IIcf, a possible “dumping” layer (Goldberg et al. 2003; Schiegl et al. 2003) which has confidently been ascribed to the Gravettian. This may represent opportunistic collection events, or a source with availability restricted by quantity, access, or human behavioural choices. Group 4 shows a similar pattern to Group 3, containing three Gravettian and two Magdalenian ochres from HF, but additionally, four samples are from VH. Though the possible collection scenarios from Group 3 also apply to Group 4, the addition of ochres from a cave in the neighbouring valley indicate that either two chance encounters with an ochre source occurred, or that the location of the source was shared and communicated between groups at the two caves over several generations. These scenarios resonate with ochres within Group 6a, which is comprised of Aurignacian ochres from all three cave sites, as well as one sample each from the HF Gravettian and Magdalenian. A similar temporal distribution is also seen in Group 7b, containing a single ochre piece from the GK Aurignacian and Gravettian each, as well as two from the HF Aurignacian, two from the HF A/G transition, and one specimen from the HF Gravettian. All of these compositional groups represent some level of cohesion in the ochre collection strategies by inhabitants of all three caves or the sharing of resources between them.

Simpler scenarios can be inferred from Groups 5 and 6b, yet they offer valuable insights into the interactions between the cave inhabitants though their sample sizes are small. Group 5 contains three Aurignacian samples from HF. The arrangement of Group 6b mirrors that of Group 5, except this source location was exclusively accessed by the inhabitants of GK. As the sample selection is relatively large for HF compared to the other caves (HF: 183, GK: 9, VH: 18), the opposite scenario (ochre groups exclusive to HF) is to be expected and is realized in Groups 1, 2, 3 and 5. Even with a small overall sample size, the GK ochres display both shared and restricted ochre collection strategies during the Aurignacian in Group 6b, indicating that not all traditions and practices were inter-group and, rather, some were also only intra-group and restricted for reasons that are so far unknown. The provenance of Group 5 to distant (>300 km) ochre sources counters many of the previously held notions about landscape mobility and the transportation of resources during the Aurignacian in Southern Germany. Previous studies on lithic raw materials have shown a greater range of resource acquisition areas during the later time periods than with the Aurignacian (Burkert and Floss 1999; Floss and Kieselbach 2004; Hahn 1987; 2000; Scheer 2000). Furthermore, most of the proposed migration routes for the Swabian Jura sites are oriented along an east-west axis and follow major waterways like the Danube (Burkert and Floss 1999; Floss et al. 2016; Hahn 1987). The association of Group 5 to a distant source originating northeast of the Swabian Jura counters these former hypotheses, indicating a wider area of movement through open landscapes during the Aurignacian of Central Europe.

The distribution of samples suggests that ochre collection strategies during the Aurignacian are different from later time periods and that either opportunistic acquisition strategies, individualistic collection preferences, or a genuine difference in cultural and behavioural cohesion and expression during the Aurignacian existed. We also cannot rule out the possibility that certain landscape or environmental features that may have influenced accessibility to certain areas and therefore had an effect on the material archaeological record (Chapter 6). This is furthermore reflected by the change in the types of ochre present in the later time periods, since significant climatic and landscape fluctuations impacted the physical environment of this region during and after the LGM, causing a drop in the water table and increased hillside erosion in the Ach and Lone valleys (Barbieri 2019; Barbieri et al. 2018).

During the Gravettian and Magdalenian, the predominant collection strategies involve gathering ochre from specific sources more frequently, with more people, or in larger amounts. Aside from landscape changes influencing collection possibilities, another hypothesis is that specific qualities in ochre artefacts were sought after in the later time periods (Velliky et al. 2018b), and sources that yielded ochre with these attributes were identified and then mined preferentially and extensively. These qualities need not be limited to physical attributes, though this is seen with the increase of purple, micaceous ochres with silty and clayey textures in the Gravettian and Magdalenian (Velliky et al. 2018b). Desirable qualities can also rest in physical places and the association of certain areas or landscape features to symbolic or ritual aspects. In some ethnographic examples, specific raw materials are sought after not because they are of superior quality (however, see Rifkin 2015b), but because they are from a symbolically charged place (Boivin 2004; Bradley 2013; Reimer 2012; Taçon 2004), even if those places are located at a great distance. This scenario is more probable in the context of the symbolic associations of ochre throughout widespread temporal and geographic contexts (Cârciumaru et al. 2015; d'Errico et al. 2012; Dayet et al. 2016; Eiselt et al. 2011; Erlandson et al. 1999; Henshilwood et al. 2009; Hodgskiss 2012; Hovers et al. 2003; Kukkonen et al. 1997; MacDonald et al. 2011; O'Connor and Fankhauser 2001; Roebroeks et al. 2012; Roper 1992; Salomon 2009; Wadley 2006; Watts 2002; 2009; Wreschner 1983; Zipkin 2015). Aside from the presence of ochre nodules, the Gravettian and Magdalenian samples at HF contain several pieces with traces of anthropogenic modification, an assortment of artefacts containing traces of red residues including an ochre grindstone (Velliky et al. 2018b), and several limestone fragments with painted dot designs in red ochre (Conard and Malina 2010; 2011; 2012; 2014). However, behaviours for these later periods can only be inferred for HF, as only one Gravettian sample was analysed from GK and there are no ochres from later time periods at VH.

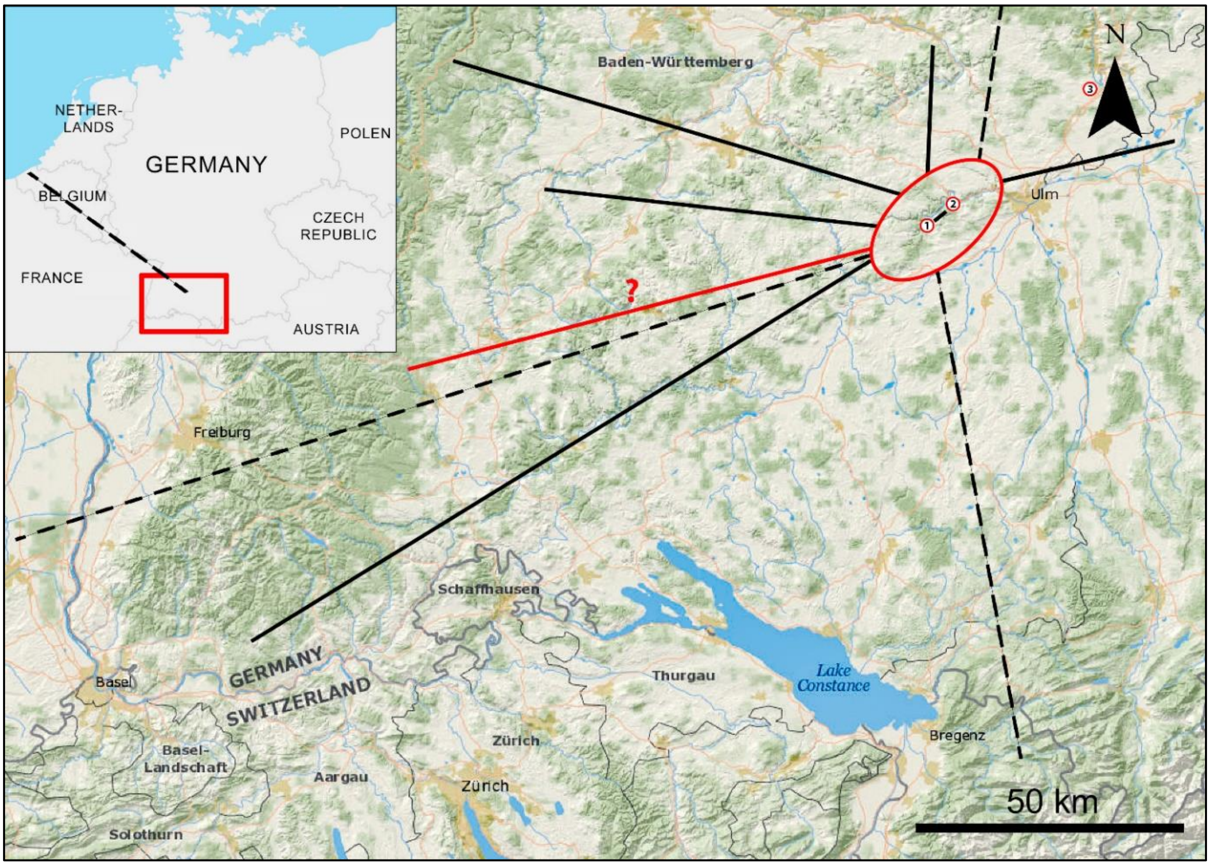

Figure 7.5: Proposed transportation pathways for the Gravettian and Magdalenian. The cave sites in this study are labelled with the corresponding numbers: 1) Hohle Fels, 2) Geißenklösterle, and 3) Vogelherd. Red lines and circles in the main map are proposed movement networks based on ochre data. Solid black lines refer to lithic transportation movements as proposed by Scheer (Scheer 2000). Dashed lines correspond to movement networks based on shell pendants, as proposed by Rähle (Rähle 1994). Note the long-distance shell transportation in the upper left inset.

7.4.3. In light of other raw materials

The UP shows changes throughout time in regards to other forms of material culture. At HF, the lithic assemblage is largely based on local resources during the Aurignacian (Hahn 1987), with 96% of the assemblage having been made from a local (within <10 km) Jurassic chert called *Jurahornstein* (Scheer 2000). This changes in the Gravettian, where only 56% of the lithic material is made from *Jurahornstein*, with an increase in extra-local (10-20 km) and non-local (> 50 km) lithic materials (Burkert and Floss 1999; Conard and Moreau 2004; Floss and Kieselbach 2004; Scheer 2000). This shift in lithic resources from the Aurignacian to the Gravettian was described by Hahn (2000) to have been due to either overexploitation or environmental/geomorphological changes in the landscape. Though the former is possible, the latter is more likely due to the documented significant alterations in the landscapes of the Ach and Lone

Valleys, which resulted in abbreviated Gravettian and Magdalenian deposits in many caves in the region (Barbieri et al. 2018).

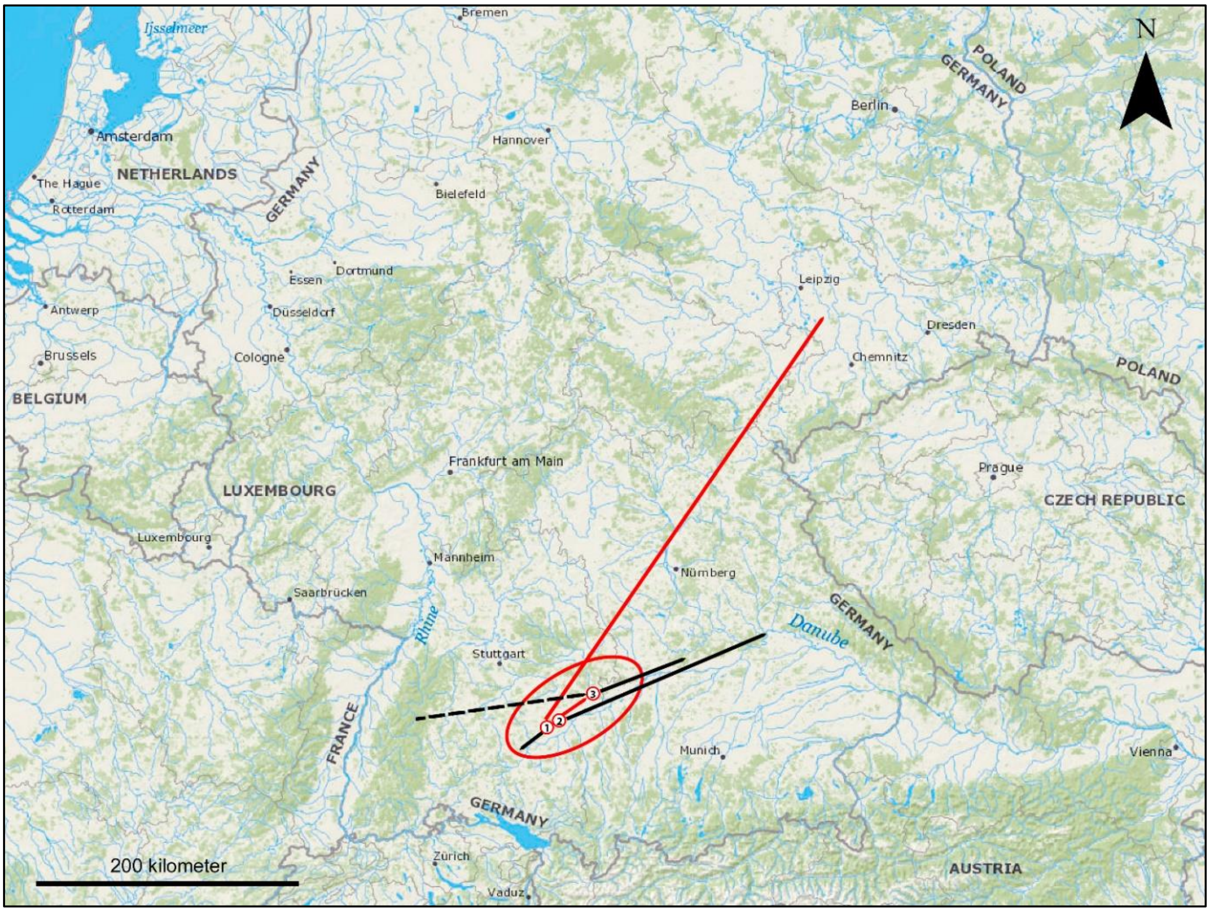

Figure 7.6: Proposed transportation pathways for the Aurignacian. The cave sites in this study are labelled with the corresponding numbers: 1) Hohle Fels, 2) Geißenklösterle, and 3) Vogelherd. Red lines and circles in the main map are proposed movement networks based on ochre data. Solid black lines refer to lithic transportation movements as proposed by Hahn (Hahn 1987). Dashed lines correspond to movement networks based on a notched shell fossil, as noted by Hahn (Hahn 1987).

Though Gravettian and Magdalenian ochres are present in all major and some minor compositional groups, the Aurignacian is the only time period with temporally exclusive groups, suggesting that ochre was collected from unique geographic locations and sometimes at great distances. During the Gravettian and Magdalenian, ochre collection strategies narrow to certain purplish ochres with silty textures (Velliky et al. 2018b) from either local or regional areas. This is shown in the compositional groups by the higher numbers of Gravettian and Magdalenian artefacts in fewer groups (Groups 1, 2, 7a) with some smaller (<2) artefact numbers in the minor compositional groups (Groups 3, 4, 6a, 7b). This contrasts with the lithic assemblage, which is dominated by a homogeneous set of local materials in the Aurignacian with a subsequent increase in non-local and more varied materials in the later time periods. These inverse patterns suggest that may well have developed varying collection strategies for different types of materials, suggesting that behavioural complexities were already established at the onset of the Aurignacian in Central Europe. From a wider regional perspective, the Gravettian period saw an expansion in resource acquisition and/or trade patterns over Western Eurasia as well as in the Swabian Jura (Scheer 1993; 2000; Taller et al. 2019), with the establishment of social networks over greater distances and in more open environments (Hahn 1987; 2000). More importantly, material culture styles and forms become more standardized and ubiquitous in the Gravettian compared to the Aurignacian (Porr 2010a; Soffer et al. 2000). Though the presence of numerous Mediterranean and Atlantic mollusc shells in the Gravettian of HF and GK suggest a broader resource collection area during the Gravettian and Magdalenian periods (Hahn 1988; Scheer 2000), evidence of distant ochre during the Aurignacian suggests that extensive trade and movement networks were possibly already in place before the onset of the LGM. Though this was previously suspected based on the presence of an ammonite fossil from the Black Forest found at Vogelherd (Hahn 1987), our new results further corroborate the presence of long-distance contacts in the Aurignacian. This agrees with recent studies showing that early Aurignacian populations were more widespread over Europe than was previously suspected (Cortés-Sánchez et al. 2019).

The contemporaneity of the ochre artefacts between the cave sites corroborates other lines of evidence that communication and cohesion existed between groups in the Ach Valley. Previous studies on the lithic raw materials show the refitting of some stone artefacts between Hohle Fels, Geißenklösterle, Sirgenstein and Brillenhöhle in the Ach Valley, as well as other corresponding characteristics between raw nodules and reduction stages in the Gravettian (Scheer 2000; Taller et al. 2019). Some perceive the presence of lithic technological stages to suggest that Hohle Fels and Brillenhöhle operated as base-camps with Geißenklösterle and Sirgenstein functioning as temporary satellite occupational areas (Moreau 2010; Taller et al. 2019). Though we cannot refute this hypothesis based on the ochre evidence at this point as we have only sampled two of the cave sites in the Ach Valley, we believe our results are more in line with an alternative scenario that smaller groups inhabited specific caves at alternative or similar points in time (Scheer 1990). It is also likely that the cave sites were primarily occupied during the winter months, as suggested through faunal evidence (Münzel and Conard 2004a), with migrations to smaller seasonal camps during warmer periods. However, this hypothesis is not yet validated as very few intact open-air sites have been found in this region.

Communication and social exchange between caves in the Ach and Lone Valleys can also be inferred from the Aurignacian evidence. Figurines and personal ornaments made from mammoth ivory are found at HF, GK, and VH, as well as at the other cave sites in the Ach and Lone valleys. Some researchers have proposed that while there are subtle differences in the aesthetic arrangement of patterns and production techniques, the similarities are overarching and suggest a generally unified cultural group with specific qualities expressed by individuals at each cave site (Dutkiewicz et al. 2018; Porr 2002; Wolf 2015a; 2015b). These converging lines of evidence offer insight into the demographic of the Swabian Jura, where small, likely kin-based groups were seasonally mobile throughout the region. They likely met during certain periods of the year, exchanged ideas, innovations, stories, and experiences, which are now represented in the material culture of this region. Though some thoughts and beliefs were kept unique to certain groups, overall, they shared together more than what they kept private. This indicates a level of cultural memory or a culmination of individual and collective memories intertwined that signify an on-going process of reproduced social interactions, the sharing of origins, myths, and material memory items situated in time and space (Porr 2010b). The endurance of cultural memory is realized by the connection of memories to material objects, in this case, ochre, which influences both collective (social) and individual behaviours.

7.4.4. The legacy of ochre behaviours

Though much work has been conducted on the material culture from the cave sites in the Swabian Jura (Barth et al. 2009; Bataille and Conard 2018; Bolus 2015; Burkert and Floss 1999; Camarós et al. 2016; Conard 2009; Conard and Floss 2001; Dutkiewicz et al. 2018; Floss et al. 2016; Floss and Kieselbach 2004; Hahn 1986; 1987; Kitagawa et al. 2012; Porr 2010a; Taller 2014; Taller and Conard 2016; Wolf 2015a; Wolf et al. 2018), no chemical-based provenance assessment of any of the artefacts, including lithics, has been conducted up until now. Our results support the hypothesis that inhabitants of these cave sites were not operating in isolation, and in fact may have had on-going contact with each other throughout generations. While some general cultural traditions were shared, as seen in the ivory ornaments and figurines, some behaviours were likely special to specific groups. We can infer from the archaeological evidence that the same cultural groups were revisiting their designated homes repeatedly throughout the Upper Palaeolithic. The patterns of local and regional ochre collection suggest that the movement of people in the landscape varied and groups kept to certain areas and the resources contained within them, as evidenced by the presence of ochre sources exclusive to HF and GK. There was, however, either some regional overlap or perhaps an acknowledgement of shared use of resources in the landscape. We can also not rule out trading between groups, even over extended (ca. 15,000 years) periods of time. Based on the evidence from other forms of material culture as well as the ochre assemblage and the sources represented, it is unlikely that each group knew of the ochre sources independently and accessed these in isolation.

The existence of long-distance ochre transport during the Aurignacian reshapes our previous notions about the mobility of the earliest modern human settlers in Central Europe. Procurement patterns are more random and less focused during this time period, which could be due to a range of factors including environment, climate, the availability of resources, and behavioural, cultural, or ritual reasons. Instead of groups being restricted to moving along rivers or corridors (Floss, et al. 2016; Hahn 1987), we now have a glimpse into a world where either groups or individuals were traversing vast distances and carrying certain items with them. Whether these items held particular ritual, personal, or symbolic importance is unknown; however, at some point ochre from a distant place arrived at Hohle Fels cave, whether by trade or traveller and was left there, whether intentionally or by chance.

Regarding behavioural modernity, the presence of modified ochre is often used as a strong marker for identifying complex behaviours in past populations as the manipulation and use of pigments suggests symbolic mediation, social organization, and culturally complex use of the material environment (d'Errico 2003; Henshilwood and Marean 2003; McBrearty and Brooks 2000; Wadley 2006). This is often debated by those who argue in favour of the range in applications of ochre, including functional uses as a hafting mastic, sunscreen, insect repellent, and hide tanning agent (Gibson et al. 2004; Rifkin 2011; 2015a; Rifkin et al. 2015; Wadley 1987; 2005; 2010; Wadley et al. 2009; Wadley et al. 2004; Wojcieszak and Wadley 2018). However, this debate often overemphasizes a problematic dichotomy, which can overshadow other scenarios where these two are not mutually exclusive, and rather form a cohesive behavioural and cultural construct.

Furthermore, the presence of modern behaviours at UP sites in Europe belonging to AMHs does not need further validation from pigment use as many other forms of symbolic material culture already offer compelling evidence (Conard 2003; 2009; Conard et al. 2009). Our intention here is not to argue in favour of either scenario and rather to shed light on the behavioural processes surrounding the interaction with ochre and the landscape through time. The results regarding ochre use at HF present three aspects: 1) Local (<80 km) ochre outcrops were visited and exploited throughout the Upper Palaeolithic, and distant (≥300km) sources were accessed earlier than previously suspected; 2) The presence of a shared intimate knowledge of the landscape surrounding the cave as evidenced by raw material acquisition strategies and the longevity of ochre acquisition patterns; and, 3) A cultural way of life that was differentially participated in, evidenced by the presence of ochre artefacts from specific sources accessed by inhabitants from different caves throughout the entire Upper Palaeolithic.

7.5. Conclusions

Our ultimate goal is not only to search for behavioural traits preserved in the Upper Palaeolithic record of the three cave sites, but also to elucidate how ochre use was intertwined with the cultural fabric of our earliest ancestors in Europe during a pivotal period of symbolic, cognitive, and cultural evolution. Though the physical evidence for ochre and pigment use in the Swabian Jura is not as abundant compared to other sites in Europe (Pradeau et al. 2014; Salomon et al. 2008) and Africa (Hodgskiss 2013; Hodgskiss and Wadley 2017; Rosso et al. 2017; Watts 2009), and though ochre use is already known in Europe at 200 kya by Neanderthals (Bodu et al. 2014; Roebroeks et al. 2012), less is known about the nuances of ochre behaviours and selection strategies of AMHs as they migrated into the continent. It is likely AMHs already had well-established symbolic behaviours once they arrived in Central Europe and included in this sociocultural set of practices is the recognition of ochre as an important facet of individual and cultural expression. This recognition would not only have been intertwined with the cultural and ritual structures in their societies but would also have permeated into the everyday lives of people living in the Swabian Jura during the late Pleistocene. Our results show that ochre had varied pathways of source locations and patterns of selection, reaching distances up to 300 km, which were maintained throughout millennia in Central Europe. We propose that ochre, as a material, was an integral part of cultural practices in the Swabian Jura over time such that it facilitated cultural memory. These practices suggest that there could have been certain "loyalties" to specific sources. These procurement activities were maintained and sustained over thousands of years despite group mobility and a variety of landscape and environmental changes. The similar patterns of ochre use between and among cave sites in this region evoke the possibility of trading or shared communication concerning ochre sources. Even so, some specific source locations were kept unique to certain individuals or groups who used the ochre.

This can be seen in the exclusivity of some compositional groups to both HF and GK. Whether these locations were kept secret, were part of established territories, or had specific ownership maintained through socio-political means is currently undeterminable. What we can discern through holistically investigating the material evidence is that the diachronic trends shown here indicate that ochre resources were a major and important part in the lives of the Upper Palaeolithic populations of the Swabian Jura.

7.6. Materials and Methods

Ochre artefacts were collected from the excavated assemblages from all three cave sites housed at the University of Tübingen. All ochre artefacts were macroscopically examined, photographed and catalogued. A detailed summary of the HF ochre assemblage is presented and discussed in (Velliky et al. 2018b). Descriptive variables for GK and VH are consistent with those used for the HF ochres and are available in Section 7.9, Table 7.7. Individual pieces were chosen based on size and general visual representation of the assemblage, and also in order to maintain an even sampling distribution between the UP cultural periods. In total, 183 pieces were selected from

HF, 18 from VH, and nine from GK. Recent systematic assessments have at this point not been conducted for the GK and VH ochre assemblages; therefore, sampling from these caves was limited compared to HF where a systematic study has previously been conducted (Velliky et al. 2018b).

The Fe-oxide source samples utilized in this study originate from a previous study on German ochres from the Swabian Jura, Black Forest, and other samples from Central-Eastern Germany. These total to 139 individual samples from 20 outcrops. Details of this report, including geological background, source and sample descriptions, can be found in Chapter 6. All samples were characterized with NAA following identical laboratory protocol and are therefore comparable.

Neutron activation analysis of archaeological materials was conducted at the Archaeometry Laboratory at the University of Missouri Research Reactor (MURR) using standard protocols previously reported elsewhere (Eiselt et al. 2011; MacDonald et al. 2018; Popelka-Filcoff et al. 2008). Duplicate aliquots of prepared ochre powders were submitted for XRD at the Department of Chemistry, University of Missouri. Scanning electron microscopy (SEM) was employed to investigate the mineral fabric on selected samples using instrumentation at the Senckenberg Centre for Human Evolution and Palaeoenvironment (HEP) Tübingen.

7.7. Acknowledgements

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7.8. Supporting Information

Archaeological Background

Hohle Fels cave (HF) is an Upper Jurassic limestone cave situated in the eastern extension of the Swabian Jura, located in the Ach Valley, a tributary of the Danube. This region of the Swabian Jura is known for its caves housing an abundance of Middle and Upper Palaeolithic archaeology, e.g. Vogelherd, Geißenklösterle, and Hohlenstein-Stadel (Figure 7.7). The site has been an area of interest since the late 19th century (Fraas 1872) and has yielded one of the deepest and intact archaeological stratigraphic sequences in the region, spanning from the Middle Palaeolithic (>44 kcal BP) to the Magdalenian (16.5-14.5 kcal. BP) (Conard 2011; Conard and Bolus 2003). The stratigraphy is organized based on litho- and archaeo-stratigraphic layers, labelled in geological horizons (GH) and archaeological horizons (AH). Though there are highly complex differences in the sediment fabric between each GH, generally the sediments are composed of calcareous clay and locally phosphatic clay with less frequent inclusions of quartz, phosphatic grains, and organic material. Varying amount of bone, lithic, and charcoal fragments are also found intermixed in the sediments throughout the sequence (Goldberg et al. 2003).

In 2008, a Venus figurine made of mammoth ivory was uncovered from Aurignacian layers (44-34 kcal BP) (Conard 2009) at HF bearing a loophole in place of a head, indicating its possible use as a pendant. Several other ivory figurines and bead ornaments, as well as the first known evidence for musical behaviours, flutes, have been found from HF and other cave sites in the Ach and Lone Valleys (Conard 2003; Conard et al. 2009), most of which date to the Aurignacian. In addition to the symbolic and artistic artefacts, HF boasts a deep stratigraphic sequence with lithics and faunal elements dating from the entire span of occupation at the cave, including the Middle Palaeolithic (Conard and Bolus 2008). The archaeology here clearly shows the continuous and intensive occupation of the cave during parts of the Upper Palaeolithic, interspersed with cave bear occupation at the site (Münzel and Conard 2004a; 2004b).

Red and yellow ochre artefacts have been documented from HF since its resurgent excavations during the 1970s by Joachim Hahn (Blumentritt and Hahn 1978; 1991; Hahn 1977). These artefacts are reported in almost every stratigraphic layer, including the very early Middle Palaeolithic (MP) horizons. The MP ochre artefacts are quite fragmented and are in total far fewer than UP artefacts (64 vs 869). Numerous other artefacts containing red residues are also reported, ranging from marine and freshwater shells and faunal elements with discreet traces of ochre to limestones bearing distinct geometric patterns of red pigment (Conard and Malina 2010; 2011; 2014). Several ochre artefacts with traces of anthropogenic modification (e.g., grinding striations, engravings), as well as ochre grinding stones, also attest to the present and continued use of ochre for various purposes at the site (Velliky et al. 2018b). A recent re-evaluation of the HF ochre assemblage has uncovered a total of 869 individual ochre artefacts, including 27 anthropogenically modified pieces and 21 possibly modified pieces. A breakdown of the artefact numbers per cultural period can be found in Table 7.2.

Ochre artefacts are also reported from both Geißenklösterle (GK) and Vogelherd (VH), though no systematic studies have been conducted on the assemblages except for a short report on GK ochre by Helmut Gollnisch from 1988 (Gollnisch 1988). From this report, he described 94 pieces of hematite, 20 of limonite or yellow ochre, and ten pieces that appeared to be a mixture of the two. He reports a total weight of 77 g from the Aurignacian ochres and 138.45 g from the Gravettian. The archaeological database of more recent excavations from GK (up until 2012) reports 281 ochre artefacts recorded in coarse and fine fraction as well as *single in-situ* finds. In addition, a so-called “ochre layer” was reported in the Aurignacian horizon IIIa (Hahn 1988). Hahn originally suspected that this layer could represent a decomposed animal skin covered in ochre due to the oily texture of the sediment. Later studies found that this layer might be due to *in-situ* iron precipitation, though this conclusion was based on collected sediment samples and not *in-situ* micromorphological block samples (Dippon 2003). The recent excavations of Vogelherd cave are of the back-dirt from the original excavations in the 1930s; therefore, the stratigraphic integrity is not assured. Even so, 129 individual ochre artefacts are recorded from the site, which most likely corresponds to Aurignacian and Magdalenian deposits based on the original chrono-stratigraphy (Riek 1934) as well as artefact typology (Conard and Bolus 2006). At this point, it is not possible to differentiate individual ochre artefacts to a specific temporal period and therefore, all ochre artefacts from VH are treated as Aurignacian due to the predominance of Aurignacian artefacts at the site. Furthermore, Hahn (Hahn 1986; 1988) suggested that some of the figurines recovered from VH and GK appeared to have traces of red residues on them many years after excavation.

Materials and Methods

NAA. Previous research has demonstrated the potential for ochre provenance by bulk elemental analysis using Neutron Activation Analysis (NAA) (Dayet et al. 2016; Eiselt et al. 2011; Huntley et al. 2015; Kingery-Schwartz et al. 2013; MacDonald et al. 2018; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Pradeau et al. 2015; Zipkin et al. 2017). Neutron activation analysis of archaeological materials was conducted at the University of Missouri Research Reactor (MURR) and consisted of two irradiations and a total of three gamma counts in order 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 m. 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 the comparator method.

Statistical treatment of ochre data. The main goal of our data analysis was to identify distinct homogeneous groups within the ochre sample set from the three cave sites. Based on the provenance postulate of Weigand, Harbottle and Sayre (Weigand et al. 1977), different chemical or compositional groups may be assumed to represent geographically restricted sources. Groups are characterized by the locations of their centroids and the unique relationships (i.e., correlations) between the elements.

Decisions about whether to assign a specimen to a particular compositional group are based on the overall probability that the measured concentrations for the specimen could have been obtained from that group. Some of the pattern recognition techniques that have been used to investigate archaeological data sets are cluster analysis (CA), principal component analysis (PCA), and canonical discriminant analysis (CDA). Bivariate plots are typically the first method that is used to examine data sets to explore geochemical trends and compositional groups, and this initial data review can be informative for visual identification of geochemical trends (i.e. element correlations), and for identifying outliers.

In ochre provenance studies, it is a common step to apply multiple transformations to elemental concentration data prior to statistical testing, including Fe-normalization and log^{10} (Dayet et al. 2016; MacDonald et al. 2018; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007). Log^{10} transformation is used to compensate for the variation in magnitude between major, minor, and trace elements, and is necessary for scale-dependent, multivariate discriminant statistics (e.g. PCA). Moreover, 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). This enhances the ability to identify group clustering and smooths the overall visual variation within chemical groups. The atomic structural similarity of some transition metals and rare earth elements to iron readily permits their substitution into Fe-oxide structures (Cornell and Schwertmann 2003). However, it is important for such data transformations to be assessed for their efficacy before considering those values as statistically representative. In our multi-element statistical exploration, including iterative bivariate plotting (element concentrations, Log^{10} Fe-normalized ratios) and PCA, we consistently found that using data transformed to ratios to Fe content, and subsequently transformed to log^{10} values generated the clearest separation of compositional groups.

X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). In addition to NAA, certain samples underwent a mineralogical assessment using powder X-ray diffraction in order to identify specific iron phases in the materials. This data is complementary to the NAA data and provides a further proxy to observe similarities and differences in any identified compositional groups. Since two analytical samples were already prepared for NAA, small quantities of the reserved powder were submitted for XRD at the Department of Chemistry, University of Missouri. The XRD patterns were collected using a Scintag X2 powder diffractometer equipped with a Peltier-cooled energy sensitive detector operating at 40 kV and 50 mA, using Cu-Kα radiation (1.54060 Å). A monochromatic X-ray beam was oriented at each target sample and scanned from 5° to 80° 2ϴ at a scanning step size of 0.02°, and a dwell time of 2.0 s each. The peak patterns were identified and matched with crystallography reference libraries of diffraction patterns using FullProf and Match software, and comparison to Crystallography Open Database (Gražulis et al. 2009; Gražulis et al. 2011) and RRUFF database.

Scanning electron microscopy (SEM) was used to investigate the micro-fabric on selected samples representing compositional groups. The microscopic observations were performed on recent fractures on the selected samples or on a clean, unaffected surface when possible. The SEM instrument is a Phenom Pharos desktop SEM from Thermo Fisher Scientific with a field emission gun (FEG) source and built-in user interface. Samples were investigated in a low-vacuum mode (pressure: 60pa) setting using 15KeV. All SEM analyses were conducted using the instrument at the Senckenberg Centre for Human Evolution and Palaeoenvironment (HEP) Tübingen.

Results

Statistical analyses

Ochre can exhibit intra- and inter-source geochemical variation, and in some cases, some compositional groups or sources can yield concentration values below the limit of detection for a number of elements routinely measured by NAA. In this data set, a high degree of variation was observed for a number of elements, including Sr, Zn, Ni, Hf, Zr, and others. Appendices B (archaeological ochres) and C (survey samples) show the concentration data (ppm) for all samples, including the limits of detection for zero measurements (denoted in red font). Concentration values for Ni were below the limit of detection for the majority of the samples and were excluded from all subsequent multivariate statistical tests.

Bivariate plots are typically the first method that is used to examine data sets to explore geochemical trends and compositional groups. In this case study, bivariate plots were reviewed for all element pairs on Fe-normalized log^{10} transformed data. This initial data review can be informative for visual identification of geochemical trends (i.e. element correlations), and for identifying outliers. We observed that the scatterplots that typically showed the best group separation included log_{10} Sc/Fe on the x-axis and log_{10} Fe-normalized rare earth element concentrations (i.e. Sm/Fe, Eu/Fe) on the y-axis. The results indicate that there are seven distinct compositional groups, some with sub-groups, and a small number of outliers. Figure 7.8 shown here is a bivariate plot of log_{10} Sc/Fe versus log_{10}Eu/Fe, showing the distribution of the same compositional groups. Note the absence of G5 as samples in that group were below the limit of detection for europium (Eu LOD average = 0.0941 ppm). It is worth noting that samples in G5 are also depleted in other rare earth elements, including La, Ce, Nd, Tb, Dy, Yb, and Lu.

Defining compositional groups within a sample set that shows low variability often requires iterative bivariate plotting to "tease apart" close groups and sub-groups. Figures 7.2 and 7.8 illustrate strong separation of Groups 1-5. To further illustrate group separation Figure 7.9 is a bivariate plot of the same element pairs, but with Groups 2-5 removed. This further illustrates the separation of Groups 6a, 6b, 7a, and 7b.

On outliers. It is important to identify and exclude outlier samples as they can significantly skew multivariate statistical analyses (i.e. PCA, CDA). Outlier samples are typical of every provenance study, and it is not uncommon for up to 5% of a total data set in obsidian studies to be identified as outliers or "unassigned", up to 10% in fine ware ceramics, and even upwards of 20% in comparatively more chemically heterogeneous materials such as coarse ware ceramics, cherts, and ochre. A total of 19 samples were identified as outliers, constituting 8.15% of the total artefact assemblage set. Figure 7.10 is the same projection as Figure 7.2 in the main text, showing the distribution of outliers among the defined groups in compositional hyperspace. Some of the samples were considered major outliers or erroneous samples (e.g. HFC014, HFC071, HFC133, HFC136, HFC124, HFC018, and others) while others were denoted as minor outliers (i.e. VHC005, VHC009, VHC010, HFC132, and others). The minor outliers were individual samples that showed similar chemical characteristics as some of the well-defined compositional groups, however, would not consistently plot within 90% confidence in bivariate plots of critical elements. Here, we take a conservative approach to assigning individual samples to group membership, while acknowledging the difference between major and minor outliers. It is our opinion that the ca. 8% unassignment rate should not be viewed as a negative result, as they unassigned ochre samples represent indicators of compositional groups that up to this point are not substantially represented.

PCA. Principal Component Analysis was performed on the Fe-normalized $\log^{10}$ transformed data set, including artefact samples and all possible elements: Na/Fe, V/Fe, Co/Fe, Zr/Fe, La/Fe, Dy/Fe, Al/Fe, Cr/Fe, Zn/Fe, Sb/Fe, Ce/Fe, Th/Fe, Ca/Fe, Mn/Fe, As/Fe, Cs/Fe, Sm/Fe, U/Fe, and Sc/Fe (excluding K/Fe, Ti/Fe, Ni/Fe, Rb/Fe, Sr/Fe, Ba/Fe, Nd/Fe, Eu/Fe, Tb/Fe, Yb/Fe, Lu/Fe, Hf/Fe, and Ta/Fe due to excessive zero values). Table 7.3 shows the variation (%) and cumulative variation (%) for each of the 27 principal components. The first eight principal components accounted for 95.55% of the variance. The scoring coefficients for each element are representative of that variable's contribution to each principal component. PC1, which accounts for 62.83% of the variance, is driven primarily by elements Ca (0.440), Th (0.284), Al (0.262) and Sc (0.253), while elements driving PC2 (13.9% variance) are U (-0.436), and Sm (-0.296). PC3 (6.54% of variance) is driven by elements Ca (0.467) and Cs (-0.312). Figure 7.11 is an RQ-mode biplot of PC1 versus PC2 showing the separation of compositional groups, and plotting of element vectors. Overall, the PCA confirmed that calcium is a major driver of variance within the sample set (specifically, pulling G2 apart from the remaining clusters), as well as the significance of scandium, cerium, thorium, uranium, and rare earth elements for differentiating groups.

XRD. A number of the spectra appear to be 'noisy', which is suggestive of additional poorly-ordered phases. Other commonly occurring Fe-oxide phases, including magnetite (Fe_3O_4) and ferrihydrite, were not identified in any sample. Quartz is a co-occurring mineral commonly identified with Fe-oxides and is present in Group 4 and in both Group 7a samples. Group 2 and Group 6b had calcite ($CaCO_3$) as a major phase, which is consistent with their mid to high calcium concentration values. A summary of the XRD data is shown in Table 7.4, and Figure 7.12 contains spectral data for the analysed samples.

SEM. A representative sample from each of the compositional groups was examined using SEM-EDX at the University of Tübingen. The results show several different types of micro-fabrics present in the ochre samples, further offering evidence that the identified compositional groups vary in their elemental constituents and geological fabrics. Though EDX was not the primary purpose for these investigations, iron was present in all of the samples analysed. Figure 7.13 shows a visual spread of the samples analysed and the corresponding description of their micro-fabric.

Observations on the chemical characteristics of the groups

The means and standard deviations for each of the compositional groups are shown in Table 7.5, while a detailed breakdown of the elemental variations in each of the compositional groups is shown in Table 7.6. Here, we describe the observed qualitative traits of the geochemical data exhibited in each of the identified groups.

Of the major compositional groups:

- **Group 1** is the most homogeneous in visual and elemental characteristics and contains artefacts from the A/G transition layers and later. It is enriched in concentrations of most rare earth elements (e.g. Nd, Sm, U, and Th) and has high Ca content (up to 10%). It is unique to HF and is characterized by purple to dark purple micaceous ochres with a deep red streak.
- **Group 2** exhibits some of the greatest internal variation based on elemental concentrations, yet in Fe-normalized scatterplots shows fairly distinctive chemistry. The majority of samples in this group are calcium-enriched (20-30%) with relatively low Fe (most <5%). The XRD patterns showed strong matches for calcite ($CaCO_3$), and stoichiometrically complex iron phosphate, though no clear patterns for other crystalline Fe-oxides. Group 2 displays an acquisition peak during the Aurignacian with almost half of the group being Aurignacian ochres. It is unique to HF and in general contains fine-grained, iron-enriched calcitic sandstones that are light red to dark red with red streaks.

- **Group 7a** is the main core cluster for the entire sample set and contains the greatest number of specimens (n = 53, ca. 25% of sampled assemblage). Using the principal criterion of abundance (39), this may be interpreted as the localized ochre signature in the immediate vicinity of HF cave. The XRD patterns for the two samples showed strong patterns for hematite and quartz. This group is one of two groups that contain ochre from all three cave sites and tends to exhibit silty/clayey textures with varying shades of dark red and purple.

Of the minor composition groups:

- **Group 3** exhibits a high degree of internal consistency, though it should be noted that it is a small group (n = 4). This group is unique to HF and later time periods (Gravettian and Magdalenian). The ochres are fine-grained and sandy, with varying shades of red and purple.
- **Group 4** shows consistency with elements Sm, Sc, and Al, and are highly variable K, Mn, and Na. It showed clear pattern matches for hematite and quartz in the XRD spectra. It contains ochres from HF and VH (this is the group with the most ochres from VH, n = 5) and from all time periods, and is generally silty/sandy, dark red and purple ochres with varying proportions of micaceous inclusions.
- **Group 5** is a small group showing high internal consistency. The XRD patterns were strong matches for hematite, though many other minor peaks could not be confidently attributed to any other patterns. This group contains ochres from only the HF Aurignacian period and is visually homogeneous with silty-textured dark purple ochre with a dark red streak.
- **Group 6a** shows internal consistency with elements Sm, Eu, Fe, and Sc. Group 6a contains ochres from all three cave sites and is almost exclusively Aurignacian with some Gravettian and Middle Palaeolithic samples. XRD showed patterns for both hematite and proto-hematite. Proto-hematite has a unique phase structure that may be suggestive of deliberate thermal treatment (40). Visually, it is silty purple-red ochre, sometimes with micaceous inclusions.
- **Group 6b** exhibits similar geochemical trends as Group 6a. However, in multiple iterative bivariate plots, it tended to separate out from 6a. It showed

evidence for both goethite and hematite Fe-oxide phases, plus calcite. It contains GK Aurignacian ochres exclusively and is visually dark red/purple with silty textures.

- **Group 7b** appears to be similar to 7a and is potentially a sub-group or sub-signature of that source deposit. XRD showed strong matches for goethite. Group 7b contains ochres from HF and GK, ranging from the Aurignacian to the Gravettian, and are generally brown to orange with sandy textures.

Ochre artefact provenance assessment

Previous ochre provenance studies have found that transition metals (Sc) and rare earth elements (Sm) served well as diagnostic elements in identifying compositional groups and associating these with source materials (Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007). This may in part be due to the substitution of these elements in the Fe-III oxide lattice (Cornell and Schwertmann 2003), which allows for better differentiation of characteristic ochre signatures despite weathering and the mobilization of elements (Popelka-Filcoff et al. 2008). High variation in the concentrations of an individual element within what is defined as a compositional group is often suggestive of element mobility. This can occur via one or more factors, including formation and deposition processes, leaching, pH, ferrolysis, variable oxidation rates at surface exposure, or other diagenetic effects. In ochre samples, it has been observed that element mobility can vary depending on the type of geologic deposit the Fe-oxide is derived from and its depositional history (MacDonald et al. 2018). In a review of the data set, we observed moderate to high intra-group variability in some elements, including Zn, Zr, Sr, Co, and others. Alternatively, certain elements also consistently showed low variation in the compositional groups, such as Sc and Sm. Scandium is an element that resists alteration during weathering (Dias and Prudêncio 2008; Grave et al. 2014), and in pottery provenance studies is a commonly cited diagnostic element to differentiate high SiO_2 (i.e. sand tempered) ceramic fabrics (Karacic et al. 2018). We also observed Sc as a diagnostic element, which we attribute to high proportions of quartz minerals co-occurring in the iron oxide matrix.

One of our primary research goals was to investigate whether the artefacts from the three cave sites in the Swabian Jura could be reliably compared and associated with modern-day Fe-oxide deposits. Following surveys that took place in 2017, sources were sampled in the region immediately surrounding the cave sites of HF and

GK (Swabian Jura sources) and in the Black Forest region. Furthermore, ochre samples were donated from older collections from sources in Thuringia, Germany, and Sachsen, Germany. A detailed assessment of the geological background, sampling strategy, and NAA results can be found in Paper 2, Chapter 6. The results of this study showed that these sources could be reliably differentiated based on their trace element composition, which offers promise for future provenance-based assessments with archaeological materials. We, therefore, used the data from these analyses and compared them with the archaeological data presented in this article. We present these data through canonical discriminant function analysis (CDA) as this showed the best results during the analysis of the Fe-oxide source materials (Paper 2, Chapter 6).

The first projection of the sources and artefacts is shown in Figure 7.4 and described in the main text. In an effort to further identify affiliation between artefact groups and sources specific to the Swabian Jura region, the second round of CDA was performed on Swabian Jura sources and relevant artefact compositional groups (G2, G3, G4, G6a, G6b, G7a, G7b). In our initial projections, it was observed that the Bohnerz source group showed strong separation into two separate sub-groups, heretofore referred to as Bohnerz and Bohnerz-B. Figure 7.14 is a bivariate plot of CD#1 versus CD#2 showing the distribution of sources and artefacts. Artefacts in Group 6a fall in the Bohn source ellipse, while Group 6b consistently plots in the ellipse of Herzjes source. The majority of artefacts in Groups 7a and 7b fall outside of the ellipse for the Bohn source; however, they consistently fall along the same trend line in other CDA projections. Artefacts in Groups 3 and 4 do not fall near any source ellipses, but to follow a similar trend line as seen in the Bohn and compositional Groups 7a and 7b. The majority of samples in Group 2 project into the clusters of Bohn-B, Schel-Gerha, and other Swabian Jura sources.

In a final effort to identify source affiliation, another CDA iteration was performed, this time excluding Ringingen source. This succeeded in pulling apart some of the sources and artefact compositional groups more clearly, further accentuating their differences. Figure 7.15 is a bivariate plot of CDA#1 versus CDA#2, showing further separation between Bohn-B, Tormer, Rudel, Schel-Gerha, Allmen, and compositional Group 2 from the remaining compositional groups and sources Bohn and Herzjes. No further iterations of CDA in any configurations could demonstrate affiliation of Group

2 to any specific known source, suggesting that it may not be possible to differentiate any sub-regional source signatures further.

Evaluating site contexts and potential ochre sources

Sedimentological analyses have been conducted at both HF and GK (Goldberg et al. 2003; Miller 2015a; Miller 2015b; Schiegl et al. 2003). Vogelherd cave was originally excavated in the 1930s and provided basic stratigraphic observations (Riek 1934). Recent excavations were conducted on the back-dirt, but no original stratigraphy could be established, and thus no micro-morphological studies could be conducted on the cave sediments. Both HF and GK record post-depositional alteration induced by climatic fluctuations, bioturbation, and other taphonomic processes (Miller 2015b). Even though much of the sediment was transported into the caves due to erosion events, the association of the ochre artefacts in anthropogenic layers rules out a natural origin for the ochres analysed here. Based on the environmental and climatic history of the Ach and Lone Valleys, it is more likely that the recovered ochre assemblage (and indeed most of the other artefacts recorded at the sites) are a small representation of what was originally deposited or discarded by inhabitants of the cave (for a more in-depth discussion, see (Velliky et al. 2018b)). Gravettian layers are largely absent in the Lone Valley due to mass erosional processes taking place after the Last Glacial Maximum (LGM) (Barbieri et al. 2018; Miller 2015b). Furthermore, the Magdalenian is entirely absent at GK though the wealth of archaeological evidence at other sites suggests that both valleys were indeed inhabited, though for only a short period (ca. 13,500 -12,500 ^{14}C BP) during the Magdalenian (Bolus 2010; Conard and Moreau 2004; Floss and Kieselbach 2004; Hahn 1987; Scheer 2000; 2001; Taller 2014; Taller and Conard 2016).

The Swabian Jura boasts a complex geological history beginning during the Triassic (Geyer and Gwinner 1991; Ufrecht 2008). One characteristic feature of this region is the well-studied *Bohnerze*, or “bean ores” formations. These are rounded and highly compacted nodules of goethite, limonite, and hematite which formed during the Late Cretaceous and Early Tertiary as iron precipitated into karstic fissures, and once covering a large area of the Swabian Jura (Borger et al. 2001). Associated with the *Bohnerze* is *Bohnerzlehm*, an iron-rich, kaolinitic clay which was also widespread across the Lone and Ach Valleys (Barbieri et al. 2018). The *Bohnerz*-related features offer a possibility of local, Ca-enriched ochre sources in the nearby vicinity of the caves. Other potential iron oxide sources have been reported from nearby regions of the Franconian Alps (dark red ore formations known as *Schwarten-Erz*) (Reinert 1956), the Black Forest (occurring as hydrothermal vein systems in Palaeozoic and Mesozoic sedimentary rocks)(Goldenberg et al. 2003; Wernicke and Lippolt 1993), the upper Rhine Valley (Pleistocene Fe-based ground moraine materials) (Gollnisch 1988), as well as the northern extension of the Swabian Jura near Aalen-Wasseralfingen (middle Jurassic oolitic Fe-ore formations known as *Glaskopf-Eisenerz*) (Deuss 1925; Gollnisch 1988; Reinert 1956), to name a few. It is also possible that numerous so far undiscovered ochre deposits exist in the vicinity. The abundance of iron oxide deposits in the surrounding landscape, as well as the presence of ochre artefacts at the cave sites, suggest that the ancient populations of the Ach and Lone Valleys had an intimate knowledge of the landscape and available ochre sources. Considering the antiquity of the iron oxide formations, past populations would have had access to several varieties of locations and types of ochre, and this assortment of ochre resources could be exploited throughout the UP.

Discussion and Conclusion

All of the analyses presented here further accentuate the geochemical differences in each of the identified compositional groups. It could be that preferences in colour, texture, and location all play a role in determining which sources were accessed for ochre collection. The presence of forms of hematite establish that ochres were collected and brought to the caves, and the presence of Goethite shows that a variety of ochres from different locations were accessed and collected throughout time.

Though the ochre artefacts here were contained within a non-exposed cave environment, the translocation of certain elements has been identified in both HF and GK clay-based sediments (specifically Fe, Mn, and Ca) (Miller 2015b), and many of the artefacts at both of these sites contain Mn staining, such as with the ivory ornaments (Wolf 2015b). We, therefore, emphasize that the results of this study were based on a range of diagnostic elements for the assignment of compositional groups, which offer further support that the ochre artefacts themselves, though likely impacted by various chemical and taphonomic processes, maintained unique chemistry of their source origins.

SI Tables and figures

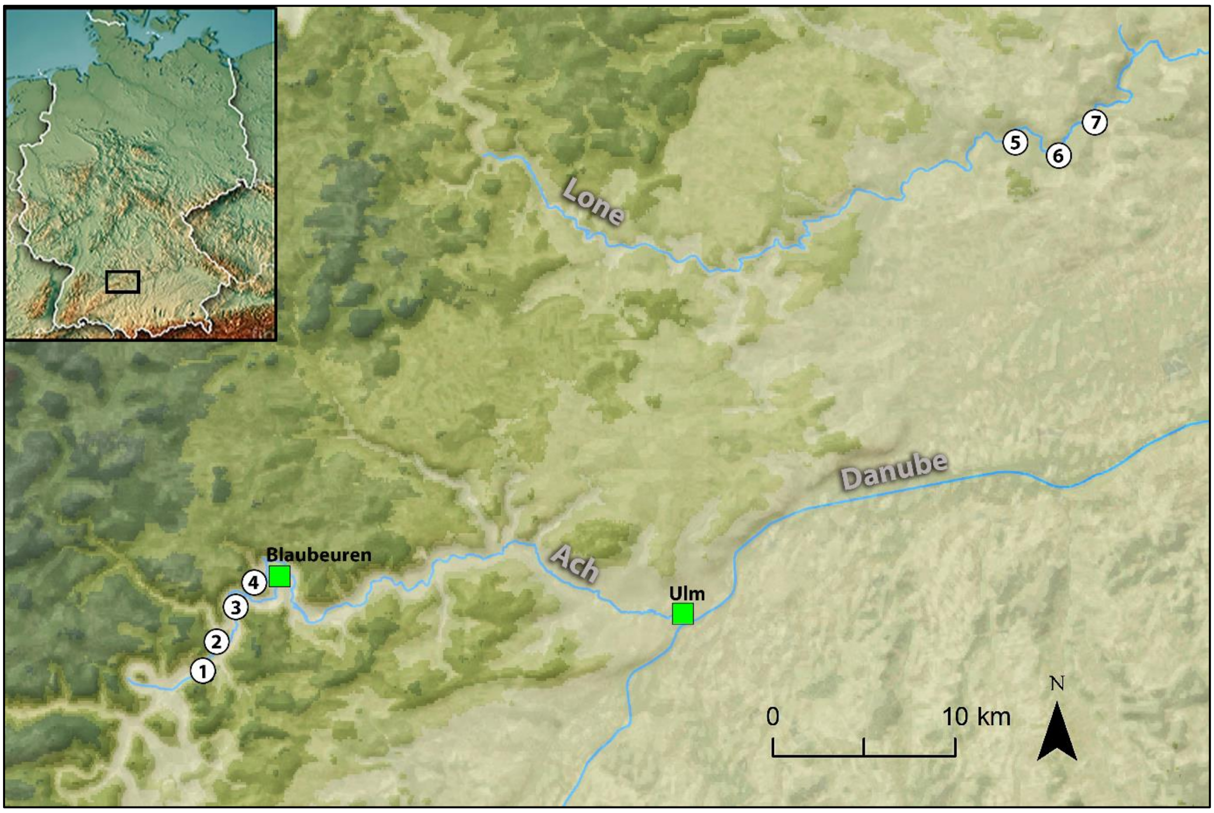


Figure 7.7: Map of noteworthy Swabian Jura cave sites. Sites numbers are as follows: Ach Valley: 1) Hohle Fels, 2) Sirgenstein, 3) Geißenklösterle, 4) Brillenhöhle; Lone Valley: 5) Bocksteinhöhle and Bockstein-Törle, 6) Hohlenstein-Stadel and Hohlenstein-Bärenhöhle, 7) Vogelherd.

Table 7.2: Temporal distribution of ochre artefacts at Hohle Fels, Geißenklösterle, and Vogelherd. Note that comprehensive analyses have not yet been conducted on the ochre assemblages from GK and VH, therefore numbers come from existing excavation databases.

Time period / Site	**Hohle Fels (HF)**		**Geißenklösterle (GK)**		**Vogelherd (VH)**	
	Total	NAA	Total	NAA	Total	NAA
Holocene	21					
Magdalenian	164	67				
Gravettian	278	57	31	1		
A/G transition	35	12				
Aurignacian	373	47	104	8	25	18
Total	**871**	**183**	**135**	**9**	**25**	**18**

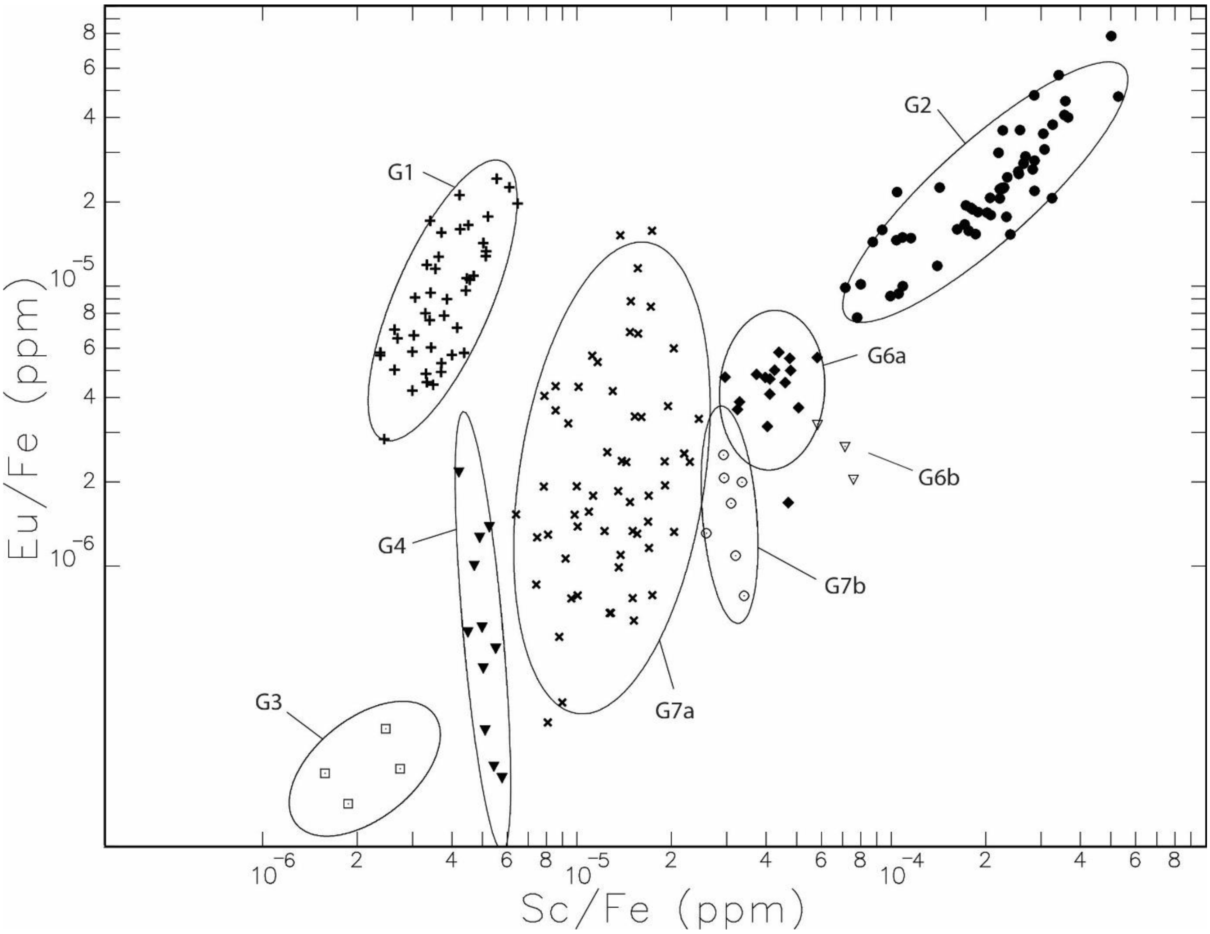


Figure 7.8: Scatterplot of log10 Sc/Fe versus log10 Eu/Fe for all ochre artefact samples, showing the distribution of compositional groups. Ellipses around the clusters represent 90% confidence levels for membership in those groups. Note the omission of G5 as that chemical group did not show levels of Eu above the limit of detection.

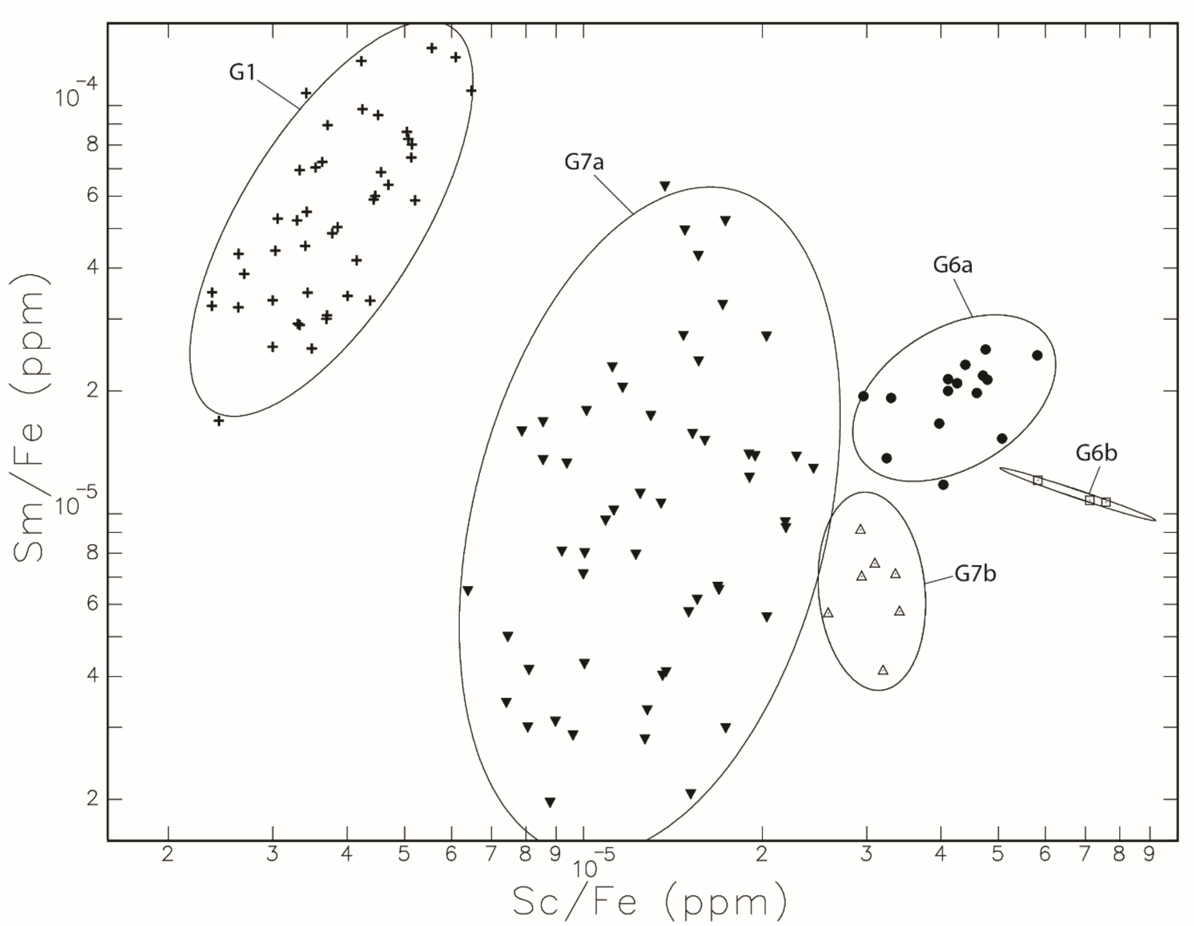


Figure 7.9: Scatterplot of log[10] Sc/Fe versus log[10] Sm/Fe for ochre artefact Groups 1, 6a, 6b, 7a, and 7b, showing the distribution of groups. Ellipses around the clusters represent 90% confidence levels for group membership. This plot further illustrates the separation of Groups 6a, 6b, 7a, and 7b.

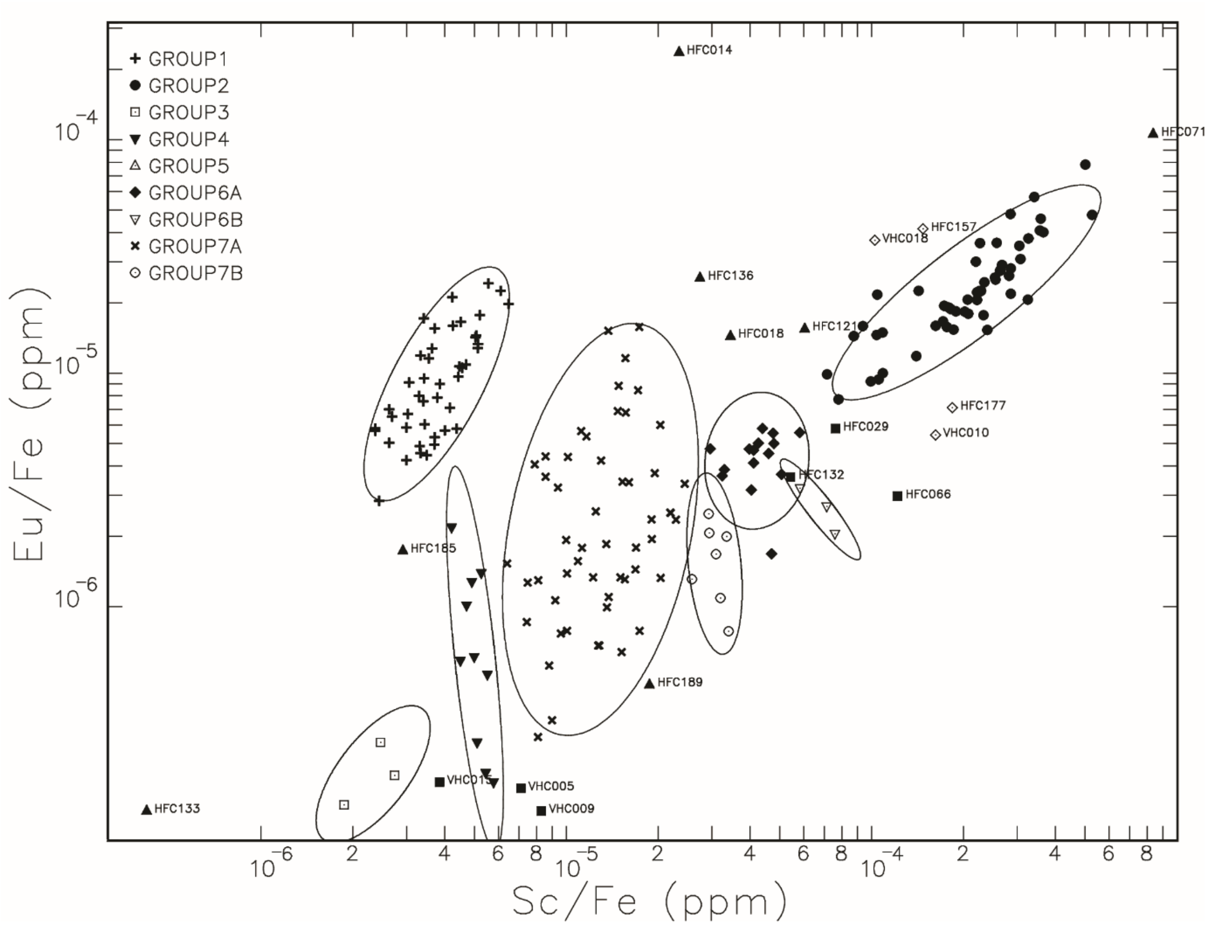


Figure 7.10: Scatterplot of log10 Sc/Fe versus log10 Eu/Fe for all ochre artefact samples, showing the distribution of compositional groups and the placement of outliers in compositional hyperspace. Ellipses around the clusters represent 90% confidence levels for membership in those groups. Note the omission of G5 as that chemical group did not show levels of Eu above the limit of detection.

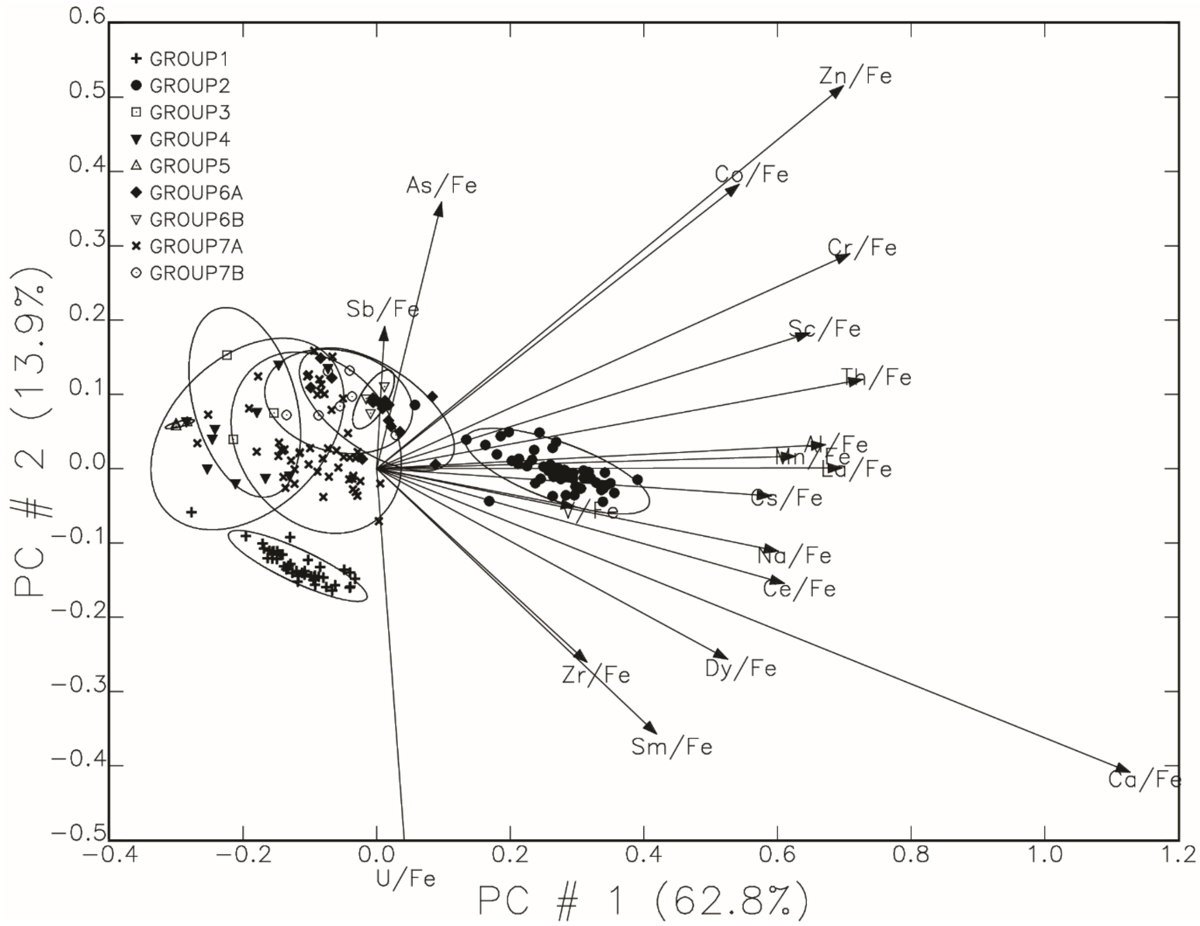


Figure 7.11: Biplot from RQ-mode PCA showing PC1 versus PC2. Compositional groups surrounded by 90% confidence ellipses. Principal Component Analysis was performed on the Fe-normalized log10 transformed data set, including artefact samples and all possible elements: Na/Fe, V/Fe, Co/Fe, Zr/Fe, La/Fe, Dy/Fe, Al/Fe, Cr/Fe, Zn/Fe, Sb/Fe, Ce/Fe, Th/Fe, Ca/Fe, Mn/Fe, As/Fe, Cs/Fe, Sm/Fe, U/Fe, and Sc/Fe (excluding K/Fe, Ti/Fe, Ni/Fe, Rb/Fe, Sr/Fe, Ba/Fe, Nd/Fe, Eu/Fe, Tb/Fe, Yb/Fe, Lu/Fe, Hf/Fe, and Ta/Fe due to excessive zero values).

Table 7.3: Percentage variation and cumulative percentage variation for each principal component.

PC	% var.	% cum.	PC	% var.	% cum.
1	62.83	62.83	11	0.71	98.00
2	13.91	76.75	12	0.49	98.49
3	6.55	83.30	13	0.39	98.88
4	4.64	87.93	14	0.32	99.20
5	2.49	90.42	15	0.29	99.49
6	2.34	92.76	16	0.20	99.70
7	1.47	94.23	17	0.15	99.84
8	1.33	95.55	18	0.11	99.95
9	0.98	96.53	19	0.05	100.0
10	0.77	97.30			

Table 7.4: Summary of samples, chemical groups, and major phases present.

Sample	Chemical Group	Major Component Composition (reported in %)								Phases Present (XRD)	
		Fe	Zn	Al	Ca	K	Mn	Na	Ti	Iron Oxides	Other
GCK006	G6b	29.95	0.10	1.13	0.76	0.08	0.07	0.02	0	Goethite, Hematite	Calcite
HFC031	G4	46.00	0	1.00	0.08	0.03	0.01	0.01	0	Hematite	Quartz
HFC037	G7a	49.77	0.01	2.78	0.28	0.92	0.02	0.10	0.14	Hematite	Quartz
HFC044	G2	2.08	0.02	1.59	**38.37**	0	0.01	0.01	0.05	Iron phosphate?	Calcite
HFC050	G7b	46.82	0.14	4.40	0.89	0.11	0.02	0.01	0.16	Goethite	
HFC053	G6a	41.50	0.09	7.54	0.27	0	0.02	0.01	0.47	Proto-Hematite, Hematite	
HFC076	G5	64.59	0.01	0.64	0	0	0.03	0.01	0	Hematite	
HFC120	G7a	48.39	0.01	3.33	0.78	1.74	0.15	0.10	0.16	Hematite	Quartz

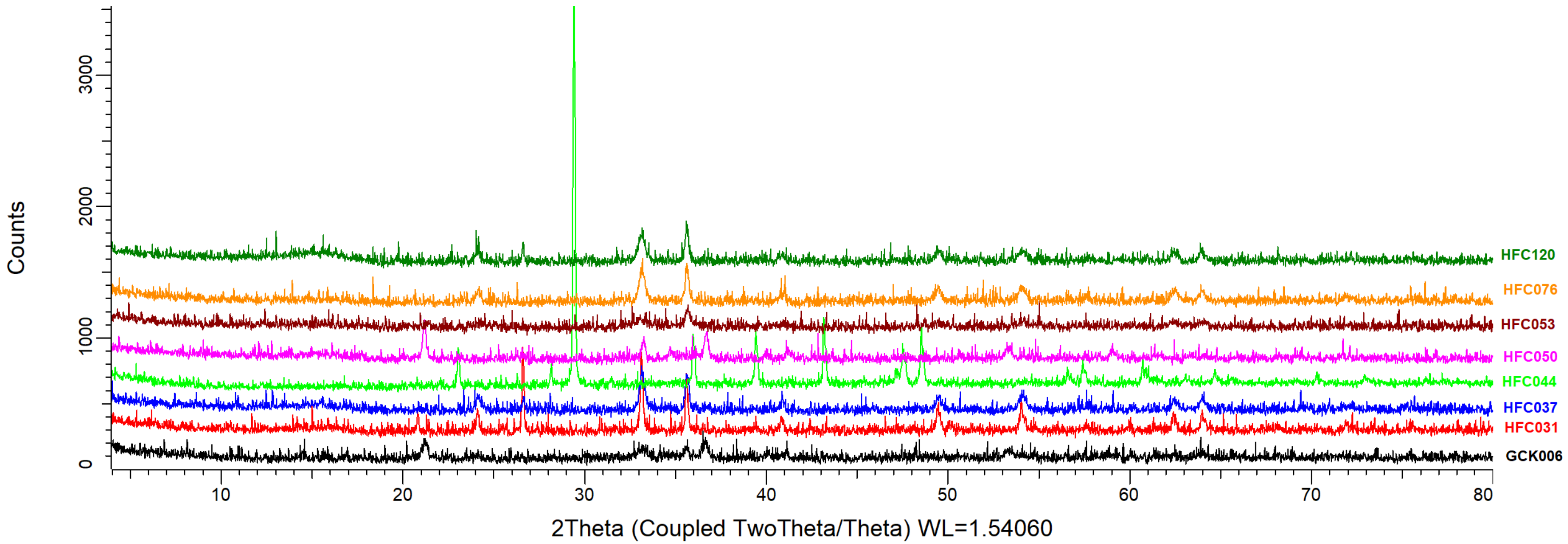


Figure 7.12: XRD analyses of selected samples from the identified compositional groups showing identified and corresponding XRD peaks. Samples are as follows: a) HFC120, HF88.24.IIad.628, Magdalenian, Group 7a; b) HFC076, HF05.98.IV6.1702, Aurignacian, Group 5; c) HFC053, HF13.54.IIIa.363, Aurignacian, Group 6a; d) HFC050, HF96.59.IIe.1652, A/G transition, Group 7b; e) HFC044, HF07.30.IIdb.754, A/G transition, Group 2; f) HFC037, HF08.32.Isa.132, Magdalenian, Group 7a; g) HFC031, HF79.49.Ia.58, Magdalenian, Group 4; h); GKC006, GK82.59.IIIb.350, Aurignacian, Group 6b.

Table 7.5: Means and standard deviations for raw elemental values on ochre artefact samples. All values are represented in ppm unless otherwise stated.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6a	Group 6b	Group 7a	Group 7b
Al (%)	1.53 ± 0.43	2.84 ± 2.18	1.30 ± 0.79	1.49 ± 0.7	0.53 ± 0.12	1.77 ± 0.56	1.77 ± 0.56	2.97 ± 1.84	2.79 ± 1.82
Ca (%)	0.00 ± 2.67	24.82 ± 14.55	8.84 ± 17.19	0.64 ± 0.46	0.03 ± 0.05	0.64 ± 0.17	0.64 ± 0.17	2.15 ± 5.27	5.97 ± 13.13
Fe (%)	52.84 ± 5.31	3.36 ± 5.49	54.34 ± 13.67	59.18 ± 7.83	65.57 ± 0.85	37.65 ± 8.47	37.65 ± 8.47	48.32 ± 13.29	50.06 ± 11.39
Na (%)	0.03 ± 0.02	0.1 ± 0.34	0.01 ± 0.01	0.05 ± 0.08	0.01 ± 0	0.02 ± 0	0.02 ± 0	0.08 ± 0.11	0.01 ± 0.01
Ti	20.98 ± 61.11	1224.91 ± 1191.48	314.94 ± 449.43	365.18 ± 441.24	0	581.14 ± 577.67	581.14 ± 577.67	1160.89 ± 1550.02	1333.92 ± 1541.81
V	394.29 ± 58.15	97.3 ± 165.73	218.91 ± 143.27	382.08 ± 627.57	114 ± 35.57	601.84 ± 167.57	601.84 ± 167.57	392.34 ± 305.08	432.6 ± 435
Mn	222.78 ± 79.79	356.55 ± 544.85	216.94 ± 171.05	367.86 ± 492.93	334.27 ± 178.18	650.19 ± 38.51	650.19 ± 38.51	772.95 ± 5	731.06 ± 1140.21
K	4010.83 ± 1838.88	5040.28 ± 9899.9	156.26 ± 312.51	2510.06 ± 4696.46	0	642.65 ± 593.06	642.65 ± 593.06	6828.6 ± 7116.27	334.58 ± 574.43
Cr	7.49 ± 1.51	47.04 ± 79.49	104.5 ± 96.24	26.92 ± 26.65	3.13 ± 0.55	596.91 ± 120.52	596.91 ± 120.52	41.67 ± 46.09	96.46 ± 119.96
Sc	2 ± 0.4	5.55 ± 5.21	1.13 ± 0.25	3 ± 0.58	0.65 ± 0.14	26.08 ± 8.01	26.08 ± 8.01	6.34 ± 2.32	15.46 ± 4.3
Co	2.29 ± 0.32	5.35 ± 5.86	32.39 ± 35.13	219.49 ± 0	4.63 ± 0.33	16.87 ± 11.49	16.87 ± 11.49	36.73 ± 100.91	36.11 ± 18.47
Ni	10.56 ± 34.44	10.43 ± 28.19	170.82 ± 127.86	331.34 ± 871.98	0	70.34 ± 121.84	70.34 ± 121.84	80.44 ± 168.22	199.68 ± 132.52
Zn	13.36 ± 11.95	153.23 ± 116.15	293.1 ± 214.43	389.35 ± 645.71	104.76 ± 18.82	470.62 ± 468.43	470.62 ± 468.43	384.63 ± 583.83	944.79 ± 484.43
Zr	760.89 ± 313.17	48.5 ± 70.69	17.29 ± 34.58	8.78 ± 29.11	75.53 ± 66.51	132.53 ± 120.13	132.53 ± 120.13	99.79 ± 109.05	40.05 ± 68.43
Rb	61.2 ± 21.47	42.02 ± 81.67	0	6.49 ± 11.99	6.18 ± 10.71	0	0	48.53 ± 47.37	5.71 ± 9.85
Sr	0	30.94 ± 3	0	0	0	0	0	8.22 ± 51.22	0
As	32.98 ± 7.61	21.73 ± 64.98	1039.3 ± 571.25	262.57 ± 351.14	282.36 ± 85.24	163.16 ± 57.43	163.16 ± 57.43	356.61 ± 958.38	1441.56 ± 2399.78
Sb	4.07 ± 0.75	1.94 ± 6.25	45.92 ± 82.63	34.27 ± 67.41	325.09 ± 42.58	5.99 ± 1.05	5.99 ± 1.05	53.6 ± 214.08	322.45 ± 790.43
Ba	555.44 ± 9	32.78 ± 83.75	44.26 ± 88.52	16.2 ± 53.74	0	0	0	76.25 ± 101.1	118.33 ± 313.06
Cs	2.96 ± 1.34	5.45 ± 16.51	0.69 ± 1.38	0.69 ± 0.63	1.95 ± 0.3	0.78 ± 0.69	0.78 ± 0.69	5.87 ± 12.15	3.68 ± 2.15
Hf	0.1 ± 0.14	2.13 ± 2.47	0.12 ± 0.16	0.51 ± 0.53	0	5.47 ± 4.83	5.47 ± 4.83	1.53 ± 1.22	1.03 ± 0.36
Ta	0.01 ± 0.05	0.48 ± 0.64	0	0.03 ± 0.1	0	0.85 ± 0.55	0.85 ± 0.55	0.27 ± 0.35	0.21 ± 0.21
La	10.1 ± 3.58	15.33 ± 15.26	1.29 ± 0.66	5.34 ± 6.76	1.65 ± 0.18	18.16 ± 12.66	18.16 ± 12.66	13.01 ± 9.65	11.82 ± 5.97
Ce	45.04 ± 16.24	28.43 ± 26.16	3.31 ± 1.62	7.85 ± 6.88	6.14 ± 1.81	23.76 ± 14.27	23.76 ± 14.27	27.28 ± 20.64	21.28 ± 8.29
Nd	40.6 ± 16.22	13.79 ± 17.16	1.92 ± 3.85	5.12 ± 4.59	0	13.31 ± 4.05	13.31 ± 4.05	14.64 ± 13.18	11.3 ± 7.7
Sm	29.84 ± 12.22	3.12 ± 4.03	0.79 ± 0.62	2.04 ± 0.92	1.75 ± 0.15	4.18 ± 0.76	4.18 ± 0.76	5.95 ± 5.99	3.31 ± 1.1

Eu	5.13 ± 2.26	0.63 ± 0.83	0.09 ± 0.06	0.43 ± 0.41	0	0.99 ± 0.26	0.99 ± 0.26	1.38 ± 1.47	0.81 ± 0.36
Tb	4.58 ± 2.11	0.49 ± 0.51	0	0.21 ± 0.33	0	0.96 ± 0.5	0.96 ± 0.5	0.84 ± 0.9	0.72 ± 0.41
Dy	17.21 ± 7.66	3.25 ± 3.46	1.3 ± 1.39	1.95 ± 1.31	0.26 ± 0.23	7.85 ± 2.76	7.85 ± 2.76	4.89 ± 3.48	5.32 ± 3.19
Yb	1.86 ± 0.8	1.6 ± 1.38	0.38 ± 0.26	0.81 ± 0.54	0	3.96 ± 2.05	3.96 ± 2.05	1.9 ± 1.22	3.82 ± 2.28
Lu	0.17 ± 0.37	0.22 ± 0.18	0.04 ± 0.04	0.14 ± 0.16	0	0.59 ± 0.26	0.59 ± 0.26	0.34 ± 0.25	0.53 ± 0.31
Th	0.96 ± 0.36	4.39 ± 4.63	0.32 ± 0.27	1.47 ± 1.07	0.09 ± 0.16	17.15 ± 12.3	17.15 ± 12.3	3.64 ± 2.67	5.68 ± 7.59
U	112.17 ± 47.57	1.1 ± 1.53	5.09 ± 8.08	5.36 ± 5.1	21.15 ± 0.92	3.75 ± 1.58	3.75 ± 1.58	9.76 ± 13.19	3.33 ± 7.58

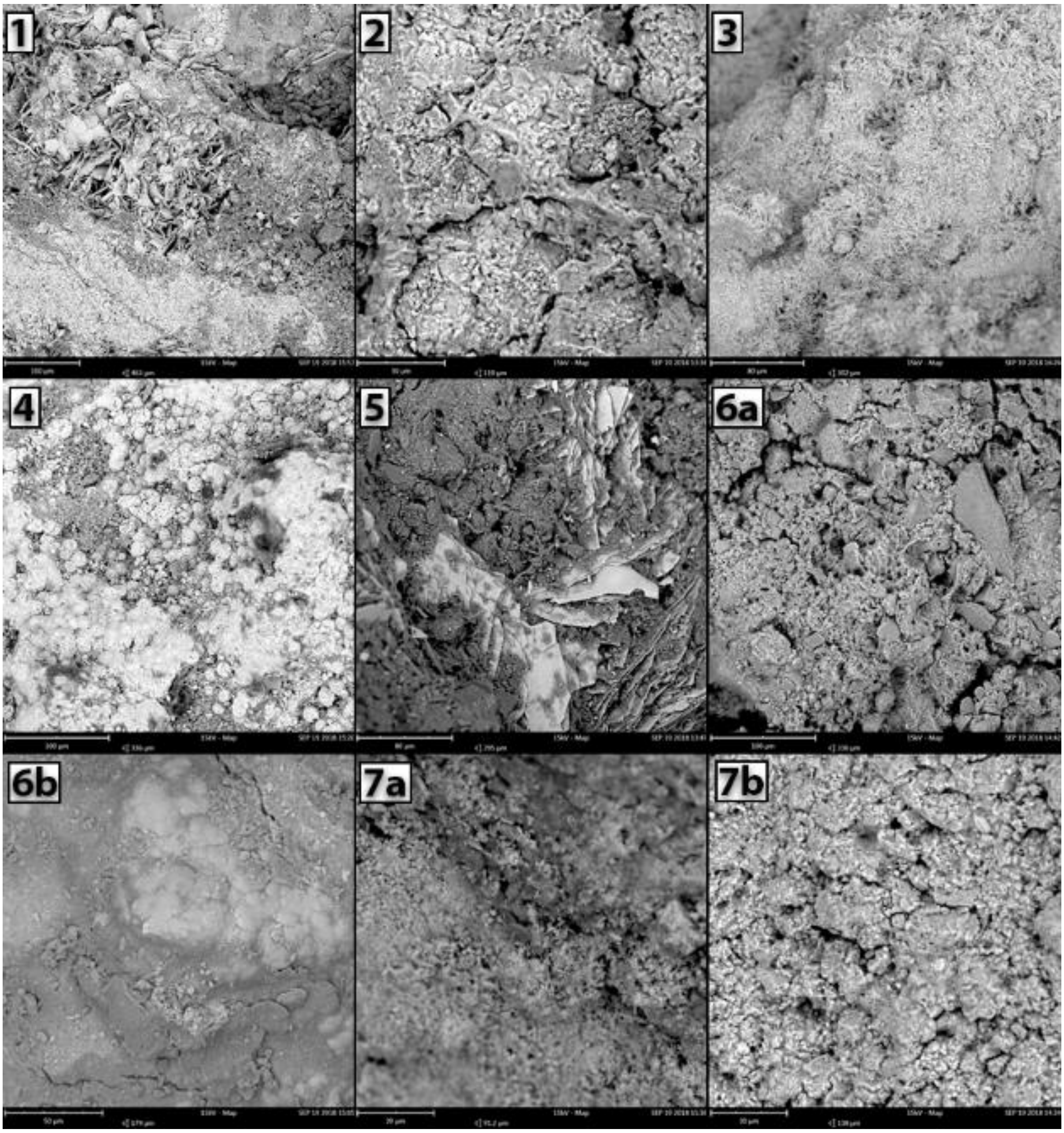


Figure 7.13: SEM BSD images of the surface of some representative examples of the identified compositional groups, identified by numbers in the top left corners. Samples are: 1) HF95.57.IIb.449, laminated texture with platy particles, 2) HF91.78.IIa.201, granular with platy particles, 3) HF10.110.IIb.1166, porous with radiating fibrous iron crystals 4) HF94.67.IIa.208, porous with oolitic iron spheres, 5) VHC004, granular with platy micaceous particles, 6a) HF13.54.IIIa.363, granular with platy particles, 6b) GK01.76.IIIa.1222, massive, botryoidal 7a) VHC001, granular with radiating fibrous iron crystals, 7b) HF99.77.IIc.770, granular with platy particles.

Table 7.6: Elements exhibiting low and high variation within each compositional group.

Group	Low Variation (RSD ~ < 45%)	High Variation (RSD ~ > 45%)
G1	As, La, Nd, Sm, U, Yb, Ce, Co, Cr, Cs, Eu, Fe, Rb, Sb, Sc, Tb, Th, Zr, Al, Ba, Ca, Dy, K, Mn, V	Lu, Hf, Ni, Sr, Ta, Zn, Na, Ti
G2		As, La, Lu, Nd, Sm, U, Yb, Ce, Co, Cr, Cs, Eu, Fe, Hf, Ni, Rb, Sb, Sc, Sr, Ta, Tb, Th, Zn, Zr, Al, Ba, Ca, Dy, K, Mn, Na, Ti, V
G3	Fe, Sc	As, La, Lu, Nd, Sm, U, Yb, Ce, Co, Eu, Hf, Ni, Sb, Th, Zn, Zr, Al, Ba, Ca, Dy, K, Mn, Na, Ti, V
G4	Sm, Fe, Sc, Al	As, La, Lu, Ns, U, Yb, Ce, Co, Cr, Cs, Eu, Hf, Ni, Rb, Sb, Sr, Ta, Tb, Th, Zn, Zr, Ba, Ca, Dy, K, Mn, Na, Ti, V
G5	As, La, Lu, Ns, Sm, U, Yb, Ce, Co, Cr, Cs, Eu, Fe, Hf, Ni, Sb, Sc, Sr, Ta, Tb, Th, Zn, Al, Ba, K, Mn, Na, Ti, V	Rb, Zr, Ca, Dy
G6a	Sm, Eu, Fe, Sc	As, La, Lu, Nd, U, Yb, Ce, Co, Cr, Cs, Hf, Ni, Rb, Sb, Sr, Ta, Tb, Th, Zn, Zr, Al, Ba, Ca, Dy, K, Mn, Na, Ti, V
G6b	As, Lu, Ns, Sm, U, Cr, Eu, Fe, Rb, Sb, Sc, Sr, Al, Ba, Ca, Dy, Mn, Na, V	La, Yb, Ce, Co, Cs, Hf, Ni, Ta, Tb, Th, Zn, Zr, K, Ti
G7a	Fe, Sc	As, La, Lu, Nd, Sm, U, Yb, Ce, Co, Cr, Cs, Eu, Hf, Ni, Rb, Sb, Sc, Sr, Ta, Tb, Th, Zn, Zr, Al, Ba, Ca, Dy, K, Mn, Na, Ti, V
G7b	Sm, Ce, Eu, Fe, Hf, Sc, Na	As, La, Lu, Nd, U, Yb, Ce, Co, Cr, Cs, Ni, Rb, Sb, Sr, Ta, Tb, Th, Zn, Zr, Al, Ba, Ca, Dy, K, Mn, Ti, V

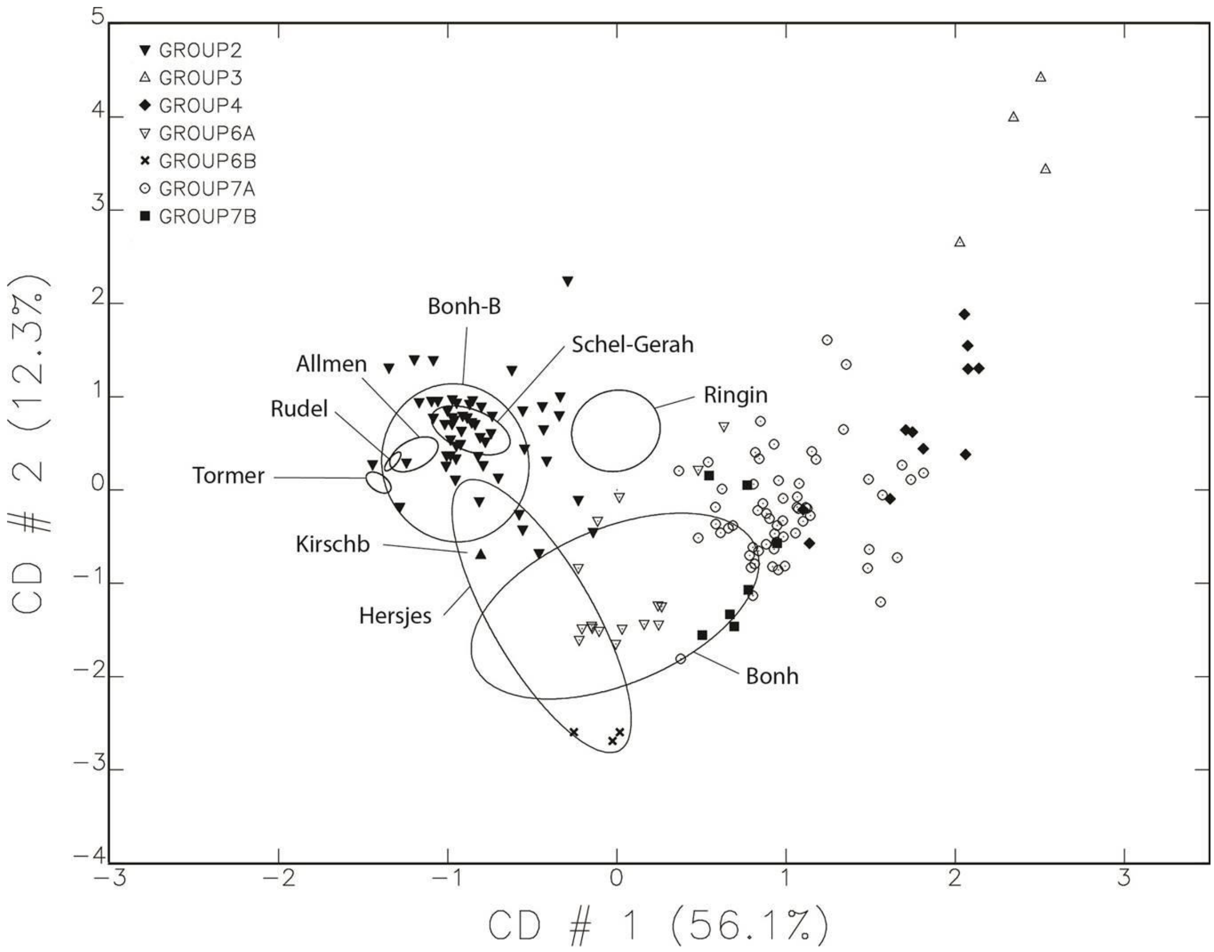


Figure 7.14: Bivariate plot of CD#1 versus CD#2, including only Swabian Jura sources and all artefact samples sorted by group, except for Groups 1 and 5. Ellipses indicate the projection of sources, while icons indicate the individual samples in each compositional group. Ellipses encircling the source groups are at 90% confidence.

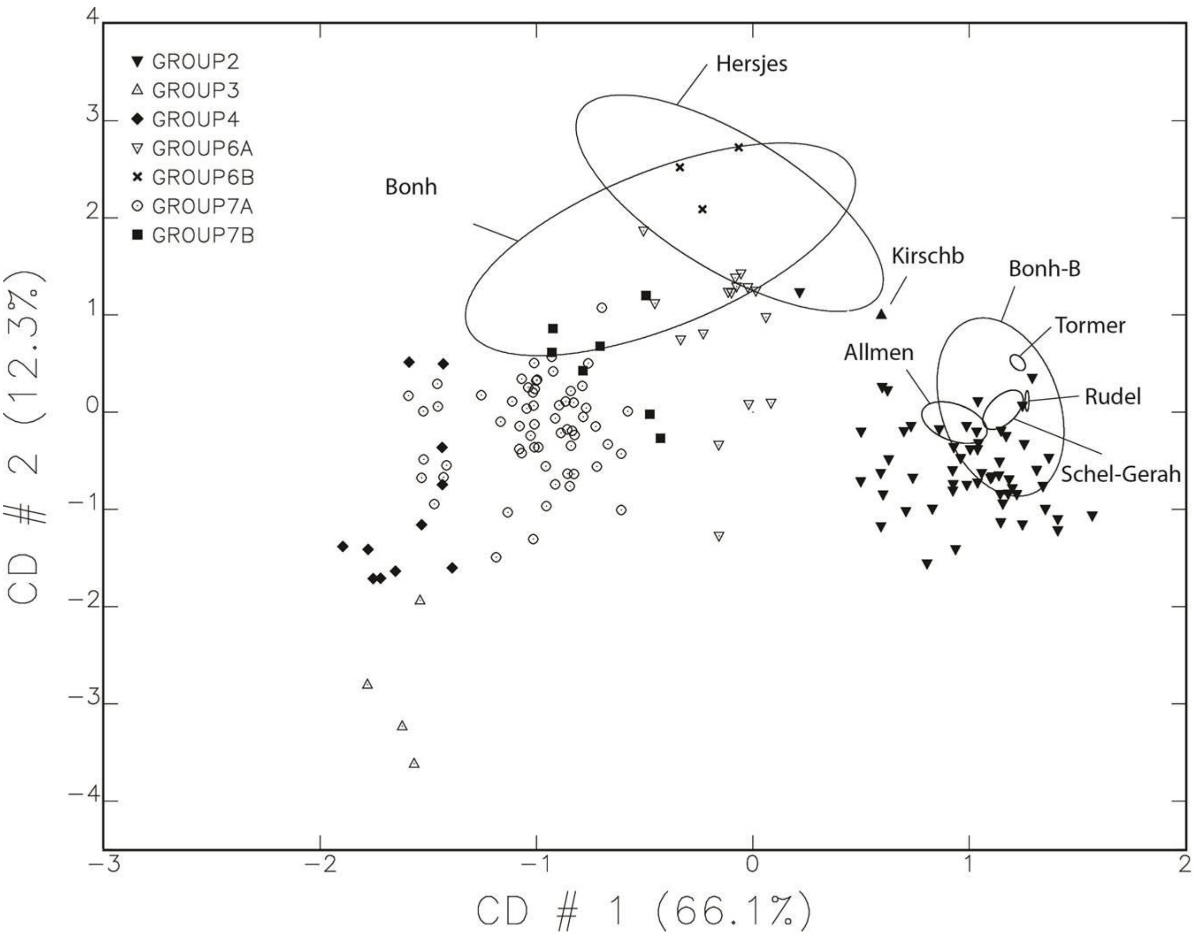


Figure 7.15: Bivariate plot of CD#1 versus CD#2 of selected Swabian Jura sources and compositional groups. Ellipses indicate the projection of sources, while icons indicate the individual samples in each compositional group. Ellipses encircling the source groups are at 90% confidence.

Table 7.7: Descriptive information on Geißenklösterle (GK) and Vogelherd (VH) ochres. Note that since VH was an excavation of the back-dirt and ochre artefacts were not systematically collected, no stratigraphic or spatial information is provided. Data on HF ochres can be found in (17).

ANID	Quad	GH	AH	Find#	Sub#	Best	L (mm)	W (mm)	D (mm)	Grams	Rock_type	Grain_size	Colour	Other_colour	X	Y	Z
GKC004	66	13	IIb	674	0	RO	12.16	10.35	4.80	0.4	Clay	Clayey	Red	Yellow	26.63	28.85	-3.25
GKC005	38	15	III	139	0	RO	20.57	11.33	5.05	1.9	Hematite	Silty/clayey	Dark purple		28.66	25.66	-3.48
GKC006	59	16	IIIb	350	0	HA	14.51	10.16	5.35	0.7	Iron oxide	Silty/clayey	Dark red	White	29.45	27.04	-3.54
GKC007	38	15	III	137	0	RO	23.29	11.38	9.02	1.7	Hematite	Silty	Dark red	Dark purple	28.06	25.71	-3.36
GKC008	58	15a	III	439	0	RO	13.09	8.28	5.28	0.4	Iron oxide	Silty	Dark red	Dark purple	28.75	27.25	-3.44
GKC009	0	5b	Ib	0	0	RO	25.81	21.37	14.23	8.1	Hematite	Silty/clayey	Dark red	Dark purple			
GKC010	48	15	III	231	0	RO	12.91	9.64	7.28	1.1	Iron oxide	Silty	Dark purple	Dark red	28.25	26.75	-3.61
GKC011	77	15	IIIa	1127	2	HA	11.62	8.22	6.42	0.6	Hematite	Silty	Dark purple	Dark red	27.31	29.87	-3.39
GKC012	76	15	IIIa	1222	1	RO	9.51	9.03	8.73	0.5	Iron oxide	Silty	Dark purple	Brown	26.25	29.25	-3.73
VHC001				1	1	HA	16.89	13	10.43	232	Hematite	Silty	Dark red	Mica			
VHC002				2	1	HA	12.3	9.11	6.73	1401	Hematite	Silty clay	Purple	Mica			
VHC003				2	2	HA	12.58	7.74	7.3	1226	Hematite	Silty	Purple	Mica			
VHC004				2	3	HA	10.92	9.41	5.51	1027	Hematite	Silty	Light purple	Mica			
VHC005				2	4	HA	9.37	7.58	5.1	773	Hematite	Silty	Purple	Mica			
VHC006				2	5	HA	10.59	6.75	4.73	553	Hematite	Clayey silt	Purple/red	Mica			
VHC007				2	6	HA	9.47	6.95	4.31	607	Hematite	Clay	Purple/red	Mica			
VHC008				2	7	HA	8.22	7.92	4.35	608	Hematite	Clayey silt	Light purple	Mica			
VHC009				2	8	HA	8.73	5.53	3.37	278	Hematite	Silty	Purple	Mica			
VHC010				3	1	RO	9.49	7.64	7.23	526	Iron Oxide	Silty	Red	Mica			
VHC011				3	2	RO	10.82	6.97	6.07	406	Iron Oxide	Silty	Red	Mica			
VHC012				4	1	RO	12.29	8.68	4.5	760	Iron Oxide	Clay	Dark red	Mica			
VHC013				4	2	RO	11.45	9.16	5.2	448	Iron Oxide	Clay	Red	Mica			
VHC014				4	3	RO	9.96	6.19	4.36	470	Iron Oxide	Clay	Dark red	Dark purple			
VHC015				4	4	RO	10.89	7.28	4.69	403	Iron Oxide	Clay	Dark red	Mica			
VHC016				4	5	RO	8.97	7.17	6.31	568	Iron Oxide	Clay	Red	Mica			
VHC017				4	6	RO	7.15	6.5	4.22	199	Iron Oxide	Clay	Red	Mica			
VHC018				5	1	RO	17.57	17.4	8.68	3008	Iron Oxide	Fine sand	Red	Mica			
VHC019				5	2	RO	18.65	14.1	9.43	2574	Iron Oxide	Fine sand	Red	Mica			

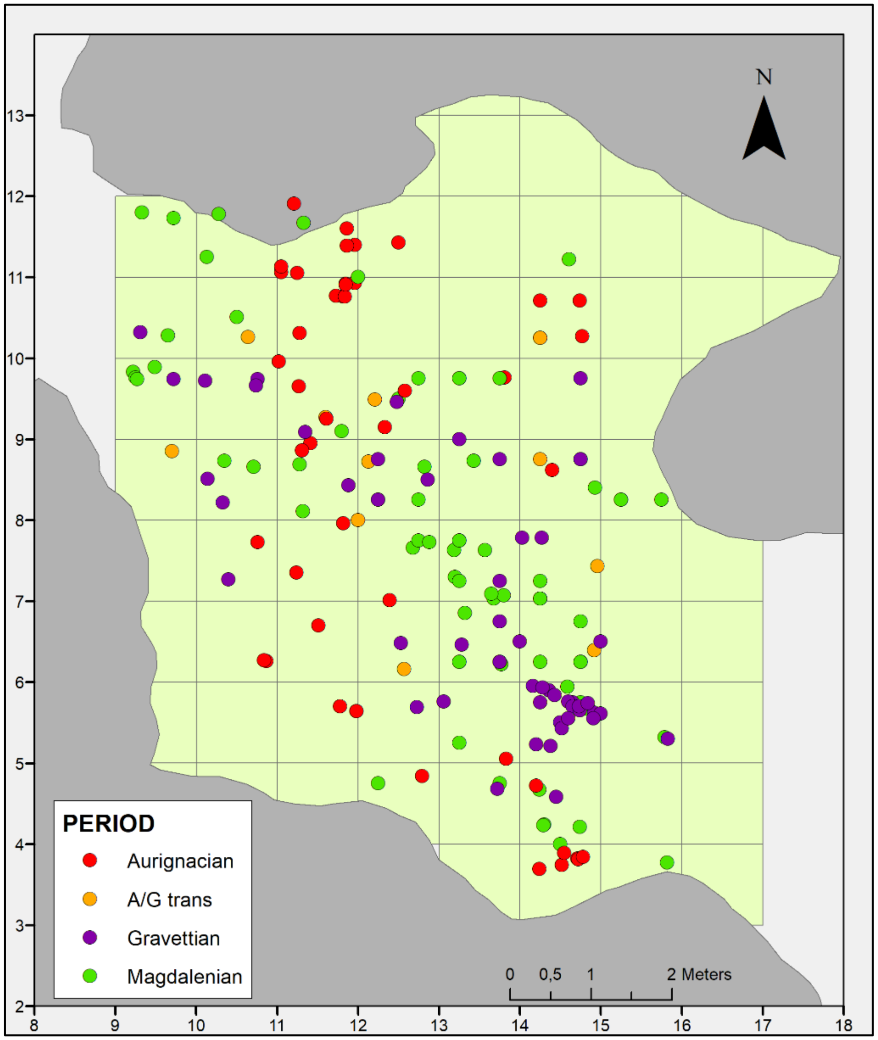


Figure 7.16: Outline of Hohle Fels cave excavation area showing the distribution of ochre artefacts characterized with NAA, labelled by time period. Group 6b is not shown as this group is purely GK ochres.

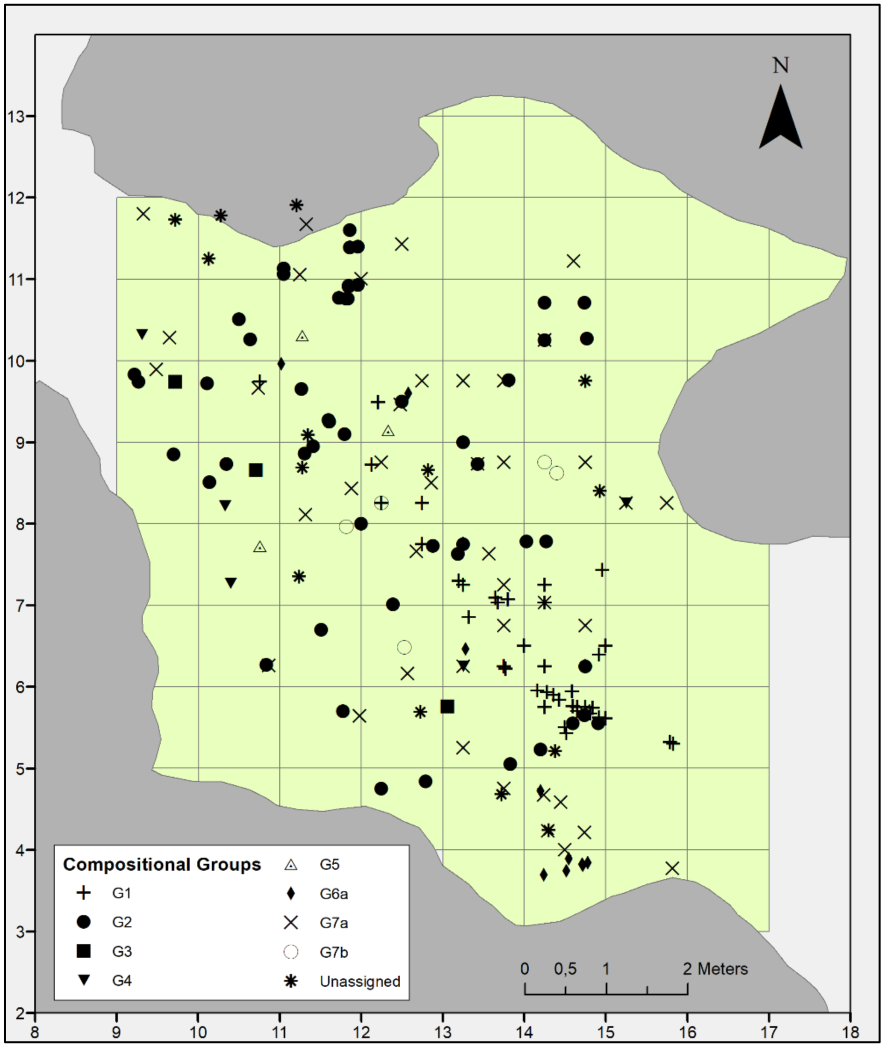


Figure 7.17: Outline of Hohle Fels cave excavation area showing the distribution of ochre artefacts characterized with NAA, labelled by compositional group.

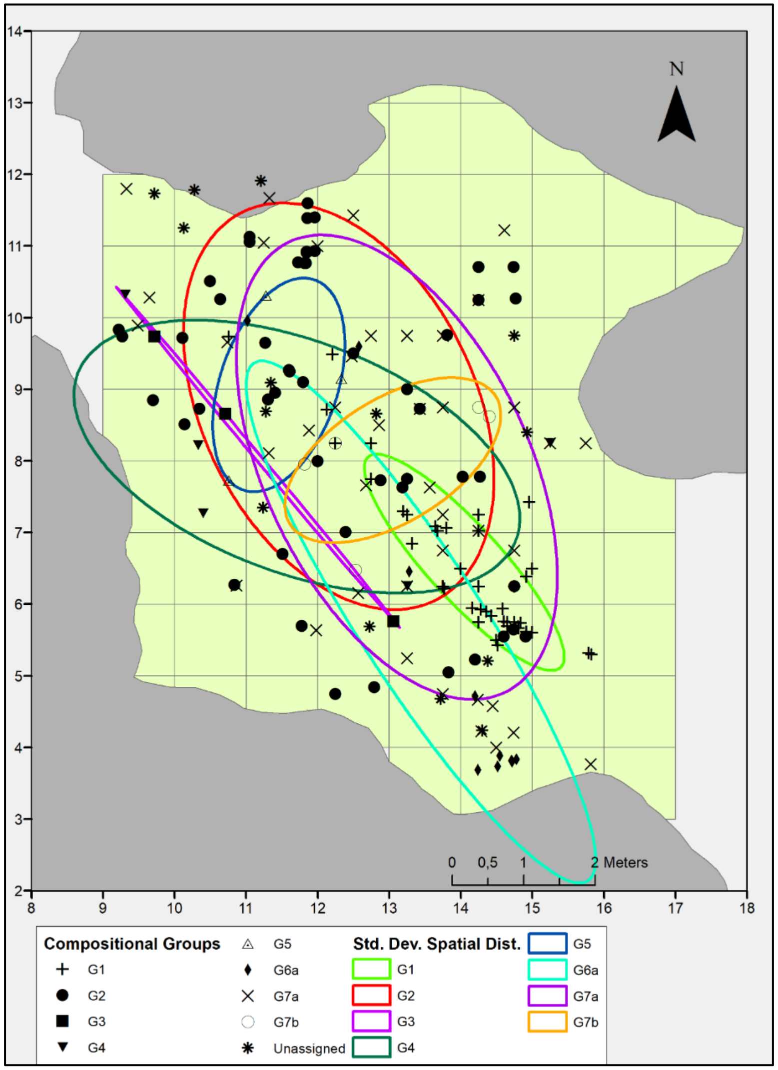


Figure 7.18: Outline of Hohle Fels cave excavation area showing the distribution of ochre artefacts by compositional group. Ellipses show group affiliation and are at 90% confidence.

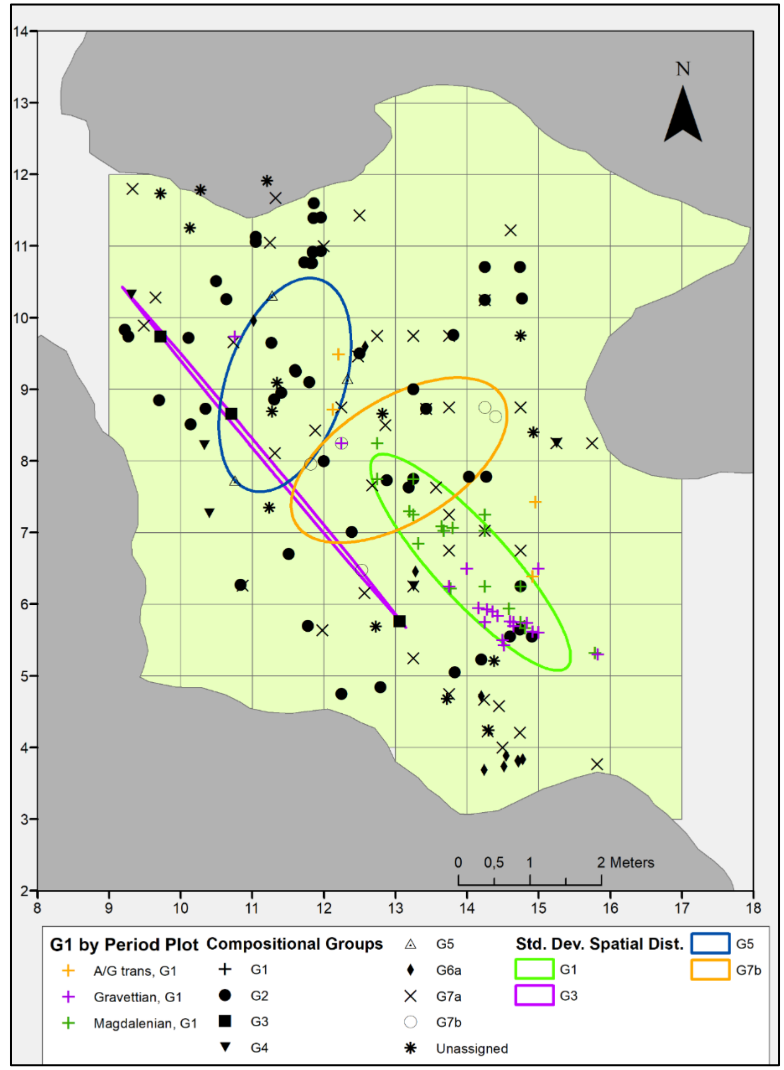


Figure 7.19: Outline of Hohle Fels cave excavation area showing only Groups 1, 3, 5, and 7b. G1 is shown by time period. Ellipses show group affiliation and are at 90% confidence.

Chapter 8. Summary of results and discussion

My research goal was to explore how humans used and interacted with ochre in the Swabian Jura and the interplay of ochre with culture, expression and social structures during the Upper Palaeolithic. At the beginning of this thesis (Section 1.2), and to operationalise my goal, I outlined three research objectives in order to explore these aspects of human-ochre behaviours. These objectives were:

- To investigate the nature and variety of ochre materials at Hohle Fels cave and assess how people used these, and whether these preferences or utilisation patterns changed over time.

- To identify from where in the landscape ochre was collected and whether environmental and climatic shifts impacted acquisition patterns throughout the Upper Palaeolithic.

- To determine if the *provenance postulate* (Weigand et al. 1977) can be satisfied for German ochre sources, and whether or not the ochre artefacts from Hohle Fels can be attributed to specific outcrops or sub-outcrops.

In the following sections, I will first discuss how I achieved each of these research objectives through my three dissertation papers (Chapters 5-7), and then I elaborate on how, when combined, they address my research goal. I conclude with a broader discussion on Palaeolithic ochre use in the Swabian Jura, mobilising the concept of an "*ochre chaîne opératoire"* (see Section 1.2). Specifically, I discuss how a study of life- and use-cycles of ochreous materials in archaeological contexts expands our understanding of the relationships between people, their cultural practices. By linking ochre to other artefact categories at the site level, I demonstrate how ochre use should not be investigated as a single behaviour or an isolated activity, how approaching it with a functional-symbolic dichotomy is disadvantageous, and how it can be contextualised within the broader life-ways of Upper Palaeolithic people in southern Germany. Finally, I identify future research possibilities and opportunities for the expansion of ochre studies in Central Europe.

8.1. Behavioural inferences from the *chaîne opératoire*

Ochre materials and the behaviours associated with them are complex and multi-faceted, which is why interpreting ochre use can problematic. The difficulties begin with the characterisation of hand specimens. Ochre fragments can display a single colour or a mixture of colours; they can have a wide variety of textures, some of which make them particularly suitable for certain applications; and they may have distinct physical characteristics altering their visual appeal. Because of the variety of ochre types, inferring systematic behaviours from visual classifications can be challenging. The original selection criteria used by prehistoric peoples may not be so easily understood, and at other times visual classification alone can lead to open-ended conclusions. This is due to the highly subjective nature of visual categorisation, as viewing pieces at different times with different light settings can alter the colour altogether. Steps can be taken to circumvent this, such as using colourimetry and computer-based CIELAB measurements. Though visual inspections of ochre artefacts may offer valuable insight into qualitative hypotheses, they are less useful when considered alone and often too subjective in questions related to provenance or geological origins. Alternatively, only investigating provenance-based hypotheses can overlook important observations as to why certain ochres were collected in the first place. Using a combination of the two approaches can thus offer robust introspection on different levels of hypotheses related to physical qualities and how these may have impacted or were impacted by, acquisition and collection strategies.

When considering the *ochre chaîne opératoire* – the collection and selection are but two stages of what can be expanded to many more stages. Thus, I propose an operational chain of ochre use with eleven stages that incorporate current research perspectives on ochre and pigment materials (see Table 8.1). Each step contains a description of how we might infer this archaeologically, which analytical method I have used to investigate it and lastly, in which specific paper I address each of the steps. The operational stages in Table 8.1 are modified from Couraud (1988), who outlined a conventional *chaîne opératoire* sequence of pigment procurement, production and use. I also incorporate the work of Hodgskiss (2014a), who applied cognitive thought-and-action phases to her studies of South African prehistoric ochre use. I include only some aspects of the stages outlined by

Hodgskiss (2014a), as I build on her general framework and do not discuss all cognitive processes involved, as researchers have already established this (Hodgskiss 2014a; 2014b; Soriano et al. 2009; Wadley 2010; 2011; Wadley et al. 2009). Rather, I aim to infer behavioural complexity and not cognitive capacity, though these two concepts may not be so far removed and may, in fact, be inter-related.

Table 8.1: The *Operational stages* of ochre use constructed for the Swabian Jura sites. *Materialisation* refers to how each stage can be identified archaeologically and the *Analytical method* column shows which analytical approach was and may be used to investigate them. Finally, in *Addressed in Paper* column, I refer to which of my dissertation papers I investigated and discussed each stage.

Operational stage	Materialisation	Analytical method	Addressed in Paper
1. Desire to utilise ochre	Use-traces on ochre artefacts, modified ochre	Qualitative overview – identification of modifications	1
2. Desire to collect	Ochre manuports, modified and non-modified	Qualitative overview – entire ochre assemblage	1
3. Where to collect?	Possible preferences (textures, colours, etc.)	Qualitative overview – trends/patterns in qualities	1,2
4. Selection	Possible preferences (textures, colours, etc.)	Qualitative overview – trends/patterns in ochre types	1,3
5. Movement/ Transportation	Geological varieties in ochre	Ochre surveys – geological and provenance analysis (SEM, XRD, NAA)	2,3
6. Collection	Ochre mines, geological varieties	Ochre surveys – geological and provenance analysis (SEM, XRD, NAA)	3
7. Preparation station	Grindstones, containers	Qualitative overview – assessment of processing tools	1
8. Processing	Grindstones, containers, *in-situ* powder	Qualitative overview – assessment of processing tools	1
9. Pigment powder	Grindstones, containers, *in-situ* powder	Qualitative overview – assessment of processing tools, modifications	1
10. Application of pigment	Artefacts with ochre residues	Qualitative overview – assessment of ochre-related artefacts	1
11. Deposition	Ochre artefacts/ traces at sites	Qualitative overview – entire ochre assemblage	1, 3

8.1.1. The first stages (1 + 2): desire to use and collect

The first two steps of the operational chain are the desire to utilise ochre and the desire to collect it. Archaeologically, the presence of anthropogenically transported ochre at sites or ochre manuports represents these two stages, as does the presence of use-traces on ochre pieces indicating a direct alteration or interaction by a human agent. The material evidence I use to support the first two stages starts with the qualitative assessment of the Hohle Fels ochre (Paper 1). This assessment shows that there are several ways that the cave inhabitants used ochre pieces once they acquired them, as these different actions left visible traces on the ochre artefacts. Some of these actions, such as grinding, rubbing, scoring, rounding, and faceting, leave characteristic use-wear patterns (Hodgskiss 2010). The modified ochre assemblage at Hohle Fels currently amounts to 27 individual artefacts (Figure 8.1) and offers insight into the nature of the prehistoric ochre use in the Swabian Jura. At Hohle Fels, the most common type of ochre modification is the combination of *grinding* and *rubbing*, followed by *rubbing* (n = 4) and *rounding* (n = 4). A few ochre pieces from the Gravettian show use-traces indicative of *grinding* (n = 3) and *rounding* (n = 1). Only one modified artefact each, which was *rubbed and scored* or only *rubbed,* was found in the Aurignacian and A/G transition.

Even though the sample size is small, these modification types may be used to reconstruct different ochre behaviours at the site. The Magdalenian shows the greatest variety in types of modification, in addition to containing the most numerous modified ochre pieces (n = 16). Previously conducted experiments on ochre show that grinding is one of the most effective ways of creating useable pigment powder (Hodgskiss 2010). The majority of ochre use during the Magdalenian is thus consistent with pigment production and directly applying ochre to a soft surface. Another ochre behaviour found most often during the Magdalenian is rounding, a modification type that may relate to the creation of *rondelles*, a characteristic artefact of the Magdalenian (Álvarez-Fernandez 2009). At Hohle Fels, several fragments of hematite are either definite *rondelles* (Conard and Malina 2011) or possible *rondelles* (Figure 8.2) and are also found in Gravettian-dated layers (IIc). This artefact type is rarely crafted from hematite (Álvarez-Fernandez 2009; Álvarez-Fernández et al. 1999), and thus, the hematite *rondelles* are not only unique in their material type but are also a rare example of a *rondelle* dating to the Gravettian which so far has only been reported from Western Europe (Paris et al. 2017).

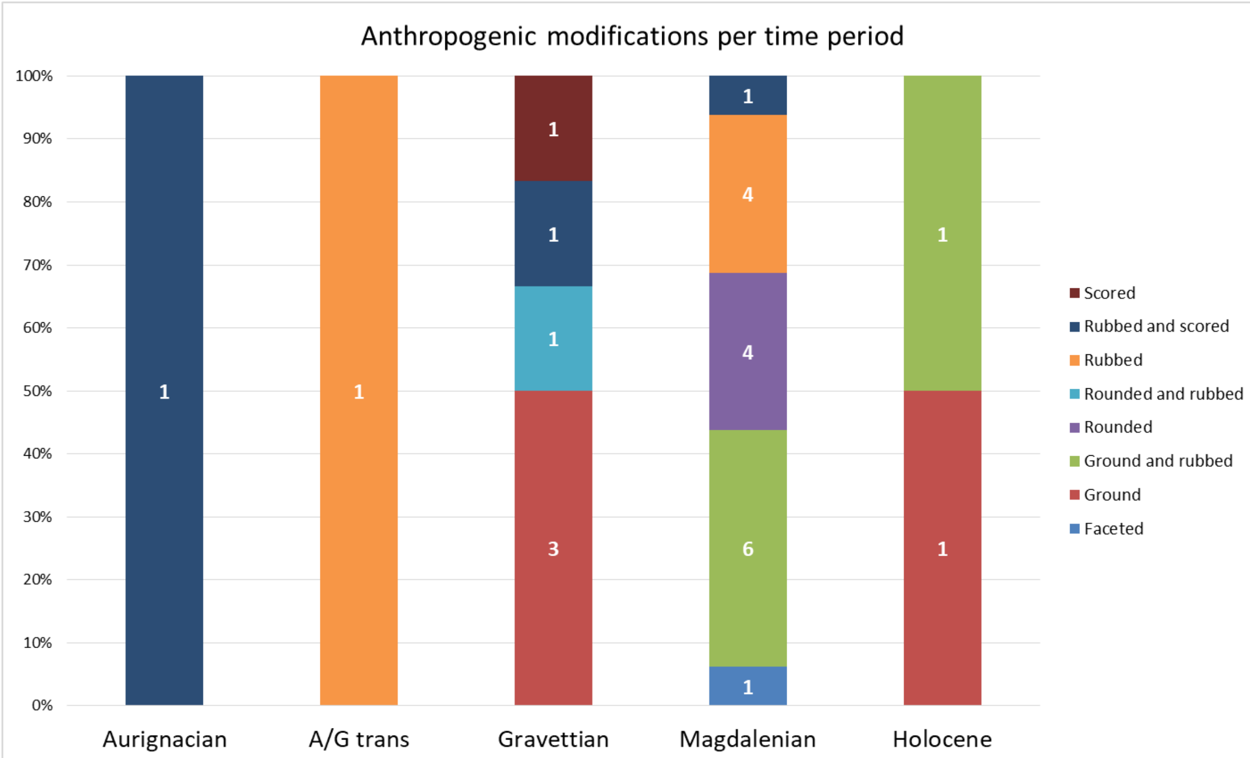


Figure 8.1: Column graph showing the distribution of anthropogenic ochre modifications per time period at Hohle Fels.

The Gravettian modified ochre assemblage (n = 6) also shows evidence of pigment creation (three ground pieces), in addition to rounding (n = 1) and scoring (n = 1). Scoring, or incising, produces very little pigment powder and it is possible that this type of modification could be evidence of raw material testing, e.g. the colour, texture, or hardness of the ochre piece (Hodgskiss 2010; 2013; 2014b). In the case of the single Aurignacian modified ochre artefact, the incisions appear to be in a V-shape, with two small punctures in between the two lines (Paper 1, Chapter 5: Figure 10). This artefact is yellow ochre, yet no yellow pigment occurs as a residue on any other materials. If yellow ochre was not used as a pigment, and given that the act of engraving, scoring and incising produces very little pigment powder, the incised yellow ochre artefact from the Aurignacian was likely created for a different purpose, perhaps as an abstract design or for "testing" lithic sharpness or ochre hardness.

Despite the fact that for the Aurignacian at Hohle Fels, there is only a single (n = 1) modified piece of ochre, these levels yielded the most numerous pieces of unmodified ochre (n = 373) among all periods. Several reasons may account for this seemingly contradictory pattern. One hypothesis proposed in Paper 1 is that though there is less evidence of pigment production from grinding, perhaps the cave inhabitants made their pigment powder in another way during this period. For example, it is possible that they completely pulverised ochre nodules with a mortar-and-pestle, which effectively would leave no traces of modification on ochre pieces. If ochre pulverisation was common during the Aurignacian, that would explain the size and fragmented state of the ochres(245 pieces that are <10 mm, ca. 66% of assemblage), as pulverisation can create secondary ochre “chips” and “flakes” that are offshoots from a larger piece (Rifkin 2012a; 2012b). Yet the assemblage overall contains so few with modification marks, indicating that people used these ochre nodules entirely. Furthermore, Watts (2010) points out that the pigment-producing techniques might vary based on the hardness, texture, and mineral inclusions of the collected ochre. If the availability of different types of ochre changed through time (as discussed in detail in Paper 2), it is thus possible that a change in ochre type also would lead to a change in ochre processing behaviour. During the Magdalenian, there are indeed different modification practices, and it appears that more economical types of pigment powder production, such as grinding and rubbing, occur more frequently. These patterns suggest that during the Aurignacian, the quantity of ochre facilitated intensive pigment creation, while in the later time periods, the practice of creating pigment was more conservative and thus people made every piece count.

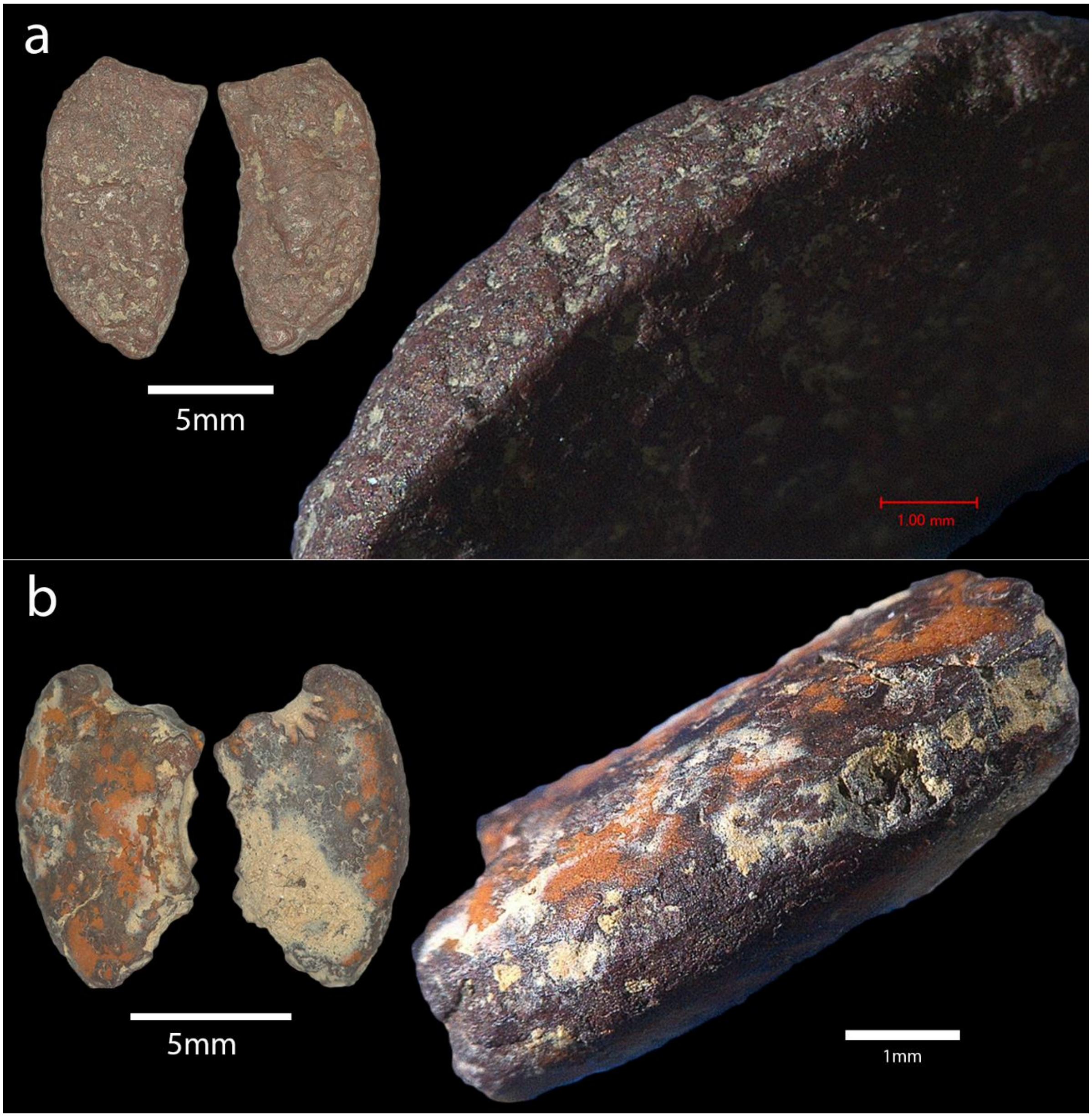


Figure 8.2: Two possible *rondelle* artefact types from Hohle Fels cave. The pieces exhibit rounding on the external surface with visible microstriations. Artefact numbers are as follows: a) HF02.100.IIb.263, Gravettian, b) HF06.100.IIc.731, Gravettian.

8.1.2. Knowing where to go, knowing what to get (stages 3 + 4)

Decisions around the acquisition and use of ochre were likely influenced by a variety of factors. Selection and any preferences for certain material types were likely influenced by personal or cultural convention stemming from social traditions. Additionally, ochre preferences would most likely also have been embedded in a deep knowledge of the landscape and the sources within it. If particular colours, textures or brilliance of ochres were desired, specific source locations that yielded ochre with these types of qualities needed to be known and remembered. The ochre preferences would furthermore be adjusted by the physical ability of the collector and the physical restraints by the terrain; people had to essentially know *how* to access and collect ochre on top of knowing where to go and what to get. Both of these steps in the operational chain– where to go and what to get (i.e. selection), require knowledge of landscape geomorphology and about what was lying beneath the surface in places that were potentially difficult to access.

My results (Paper 2, Chapter 6) show that there are several locations near the vicinity of Hohle Fels where it was possible to collect ochre. The iron-rich and extensive *Bohnerz* and *Bohnerzlehm* deposits (Paper 2, Chapter 6) were likely visible and easy to access in some areas, as they are today. These nearby sources (ca. 5-10 km) represent an abundant and low cost and effort option for the Palaeolithic inhabitants of the Swabian Jura. However, we also know that local ochre was not the only type collected. The provenance results (Paper 3, Chapter 7) show that during the Aurignacian, three ochre artefacts from the layers IV, Va, and Vaa came from a so-far unidentified source, but most likely from an area located ≥300 km to the northeast in modern-day Central Germany. This places them near the large open-air Aurignacian site of Breitenbach (Terberger and Street 2003), though site reports mention no excavated pigment or ochre remains. The results of an XRD analysis (Section 7.8, Figure 7.12) show that the Hohle Fels pieces are hematite, and they exhibit a very fine-grained texture yielding a dark red streak. Given that there are only three small pieces of this ochre type, we cannot at this stage understand the processes that led to their deposition at Hohle Fels. There is no archaeological evidence to suggest direct links between these regions, and no other artefact types at Hohle Fels, such as lithics, suggest that people were moving at these distances during the Aurignacian, let alone moving against major water routes such as the Danube. It is possible that these three small pieces of ochre constitute the only line of evidence for long-distance trade or movement of people in the Aurignacian landscape of Central Europe, but more investigation is needed to confirm this with certainty.

After the Aurignacian (ca. 44-34 kcal BP), the Swabian Jura underwent significant landscape and environmental changes. The climatic conditions became colder and drier (Goldberg et al. 2003; Miller 2015b; Riehl et al. 2015) and tree cover was reduced; the environment was transformed into tundra-like vegetation with increased occurrences of cold-climate animal species (Riehl et al. 2015) and soil erosion (Barbieri 2019; Barbieri et al. 2018). It is during this transformative period, that ochre types from another region were collected and brought to Hohle Fels cave (Group 1). Of the ochres characterised with NAA, 44 of them belong to compositional Group 1; a group of purple, silty, micaceous hematite ochres that are both visually and chemically homogeneous. The results of both Paper 2 (Chapter 6) and Paper 3 (Chapter 7) suggest that people collected these ochres from outside of the Swabian Jura, potentially from a source located in or nearby the Black Forest. It appears that once the inhabitants of Hohle Fels discovered this source during the Aurignacian/Gravettian transition, they did not stop collecting from this source area until the end of the Palaeolithic. Among numerous plausible scenarios, perhaps people at Hohle Fels went there to mine large quantities on fewer trips, maybe they continuously visited it throughout the Gravettian and Magdalenian on numerous occasions while passing through, or perhaps they had consistent contact and trade with another group who accessed this source.

It is also possible that it was not just the physical attributes of ochre materials that kept prehistoric collectors returning to sources outside of the Swabian Jura. Several ochre studies have demonstrated that that certain sources or locations in the landscape can be more symbolically charged than others (Matthews and Khahtsahlano 1955; Smith et al. 1998; Velliky 2013; Watts 1998). Some ethnographic studies report such scenarios with other raw materials, where people regarded certain places in the landscape as more important or ritually significant, and thus materials from that site, though perhaps inferior in quality to materials from elsewhere, were preferred (Bouchard and Kennedy 1986; Gould 1968; Matthews and Khahtsahlano 1955; Reimer 2012). Often sources with symbolic values attached to them can be located at great distances from dwelling places. It is thus conceivable that this type of raw-material acquisition could explain time and energy-intensive long-distance transportation of material items at archaeological sites (i.e., Brooks et al. 2018; Eriksen 2002; Floss and Kieselbach 2004; Rähle 1994). It might also be that the effort and journey to acquire such raw materials was as significant as acquiring the material itself (Bradley 2013; Reimer 2012), and the greater distance certain items travelled, the more their value increased (Bates 1930; Gould 1968).

While none of these scenarios can be supported at this point, the combined evidence shows that ochres from Group 1 were introduced into the site and were repeatedly collected over ca. 20,000 years, starting from the A/G transition (n = 4), through the Gravettian (n = 20) and into the Magdalenian (n = 20). They selected and collected ochre from these spots for specific reasons. These reasons could be related to simple convenience, ochre qualities, general cultural motives, relationships with other groups in the region, or mythological/symbolic ties to the landscape – or combinations of these. The most parsimonious explanation is that the ancient inhabitants of the Swabian Jura possessed an intimate knowledge of the ochre attributes found at each of these locations, and considered these options before undertaking the efforts and methods used to acquire it. Consequently, the intentional selection of specific ochre types and the act of seeking out particular source locations in a shifting landscape represents a largely unknown but intriguing aspect of prehistoric life in the Swabian Jura.

8.1.3. In action: movement (stage 5) and collection (stage 6)

The results of the provenance analysis (Paper 3, Chapter 7) show that the inhabitants of Hohle Fels, Geißenklösterle and Vogelherd were collecting ochre from similar local sources. It has previously been established through the study of other forms of material culture (Dutkiewicz et al. 2018; Taller et al. 2019; Wolf 2015b) that the different groups who inhabited these cave sites shared overarching cultural similarities, while simultaneously maintaining characteristic local cultural traits unique to each group. The ochre assemblages from these caves support this pattern of both a broadly unified – yet unique – material interaction. For example, the presence of compositional Group 6b, which contains ochre from one specific area, was collected only by the inhabitants of Geißenklösterle. Similarly, people at Hohle Fels exclusively collected ochre from source locations represented by compositional groups Group 1, 2, and 5. The current results show that though most cave dwellers knew the nearby (local) ochre sources in the Swabian Jura, knowledge of specific sources further away was not necessarily shared among different groups. However, enhanced sampling and analysis of archaeological ochres from Geißenklösterle and Vogelherd, as well as other nearby cave sites, might reveal a different scenario in ochre collection behaviours in this region.

Following the LGM, the Swabian Jura landscape changed significantly in environment and climate, a drop in the water table, reduced tree coverage and increased hillside erosion in the Ach and Lone valleys(see Paper 2, Chapter 6). These changes not only altered the preservation of cave sediments but likely impacted both the visibility and accessibility of ochre sources in the region. Regardless of these landscape transformations, the inhabitants of Hohle Fels cave continued to acquire and process ochre materials. The presence of local ochres suggests that the cave inhabitants preferred – or at least accepted – ochre from these areas over others. However, the reasons for this local preference may not have remained the same over time. One scenario is that the local sources were originally collected opportunistically during seasonal hunting and foraging routes. If so, these ochre types were an integral part of more general movements and settlement strategies carried out by hunter-gatherers exploiting the local landscape's broader resources. This scenario correlates with the lithic raw material acquisition strategy which focuses heavily on local chert (*Jurahornstein*) during the Aurignacian and before the LGM (see Chapter 7, also Bataille and Conard 2018; Conard and Bolus 2006; Hahn 1987). While there are only three pieces of ochre from more distant sources (compositional Group 5), their origin and transport occurred over much larger distances, regardless of differences in physical characteristics to the local ochre materials.

An alternative collection strategy scenario in the Gravettian and Magdalenian is indicated by the increase in non-local (compositional Group 1) ochres that appear to have been intentionally targeted for collection, as shown by their number (n = 44) and homogeneity. An increase in these ochres relates to broader movement, trade and migration patterns as well as to more recurrent or repetitive cultural practices and selections. However, all of these practices were likely impacted by the changing climate and environment following the LGM (see Chapter 6, also Barbieri 2019; Barbieri et al. 2018). The ochre collection strategies and subsequent changes following climatic shifts correspond to patterns in Human Behavioural Ecological (HBE) frameworks, as outlined by Binford (1980) and Kelly (1983; 1995). Here, they outline that the number and distance of residential moves undertaken by ethnographic hunter-gatherer groups may correspond to general temperature and availability of resources. When effective temperatures and plant and animal resources are high, groups make more frequent, yet shorter-distance trips to secure resources and have relatively random residential moves. This strategy seemingly corresponds to warmer and more stable temperatures during the Aurignacian, where both ochre and lithic resources were, in general, more locally-based. Alternatively, when effective temperatures are lower and resources scarcer, overall hunter-gatherer territory sizes may tend to be larger and could correspond to longer yet more targeted residential moves. The lithic and ochre materials found during the Gravettian and Magdalenian, when temperatures declined and resource availability shifted, could also correspond to this HBE framework and can suggest larger overall resource catchment areas for the Swabian Jura populations as originally proposed by Hahn (1987).

Studies of the faunal (Münzel 2001b; Münzel and Conard 2004a) and lithic (Scheer 1990; Taller et al. 2019) assemblages from Hohle Fels suggest its use as an occupation site during colder seasons with a probable network of open-air campsites or task-specific (e.g. hunting, fishing) locations scattered throughout the region that were occupied intermittently during warmer seasons. This type of settlement pattern is consistent with Binford’s (1980) logistical pattern for semi-nomadic groups living in colder environments, where a centralised residential base form the foci for several task-specific resource “stations”. These types of locations would have resulted in different artefact distribution patterns amongst long-term, short-term and temporary occupation sites. Though the results of the ochre assemblages alone cannot confirm this hypothesis, the occurrence of ochre types from a range of different sources in different periods suggests that seasonal migration patterns may have fluctuated, for example in correlation with the movement of certain game species and the availability of other resources. Such a flexible use of the regional landscape would have facilitated the use of a wide variety of ochre sources, with different hunter-gatherer groups identifying different sources opportunistically and accessing them while being in their vicinity. Similar studies on lithic materials have been previously exemplified through outlining lithic conveyance zones, and the ways in which social and environmental factors impacted the movement of people and their resource acquisition strategies over large distances (Evans et al. 2007; Kelly 1992; Newlander 2018; Smith and Harvey 2018).

When considering other approaches and variables than those specified by the HBE frameworks, it is likely that there were other factors that influenced the selection or desirability of certain ochre types, such as symbolic associations, suitability for certain tasks, certain people being culturally “authorised” to acquire and use the ochre for specific tasks, or to contribute the ochre to other groups or individuals. Some have suggested that ochres, amongst other materials, that were carried over “vast distances” increased its value (Bates 1930; Gould 1968; Smith et al. 1998; Watts 1998). However, while distance and concepts of “exoticness” may increase the value of certain material types, people might not have regarded local materials as less valuable. Indeed, some ethnographic examples suggest that local and easily accessible locations can also be significant place-names or culturally recognised areas (Arsenault and Zawadzka 2014; Bouchard and Kennedy 1986; Bradley 2013; Matthews and Khahtsahlano 1955). Thus, the local ochres that were not brought in from great distances may not have been less symbolically charged than ochre from distant locations, and it is also possible that these ochres appear at other archaeological sites located at great distances. The simple assumption that the continued presence of local ochre at the site is the result of opportunistic or low-cost, low-energy actions fails to acknowledge the cultural complexities or symbolic significance that may have tied into the Palaeolithic cultural landscape. Both local and non-local ochres may have had different levels of symbolic potency attached to them, which would have been interwoven in the cultural fabric of the landscape and people collecting them.

Regarding the ochre from distant locations, we may assume that hunter-gatherers seldom carry unnecessary weight over long distances without just cause, including social and perhaps personal factors. Consequently, the most parsimonious explanation for the occurrence of ochre collected from areas located at a distance of ca. 300 km in the Hohle Fels assemblage is that of intentional transportation, even during favourable climatic conditions that would not necessarily demand such widespread mobility according to the HBE models (Binford 1980; Kelly 1983; 1995). It is also possible that the presence of some of the long-distance ochre materials at Hohle Fels has resulted from contact with other groups or populations nearby or in more distant places, with trade and the sharing of knowledge of source locations being the explanation. It has been reported by several ethnographic and archaeological studies that people from certain groups travelled with ochre and traded it over great distances, with ochre from some sources being preferred over others (Bates 1930; Beaumont 1973; Bleek and Lloyd 1911; Boshier and Beaumont 1969; Dunn 1931; Noetling 1909; Smith et al. 1998; Watts 1998). My current dataset does not refute or support such a specific hypothesis. Broader and more systematic ochre studies at other Palaeolithic contexts will provide more insight into the possibility of long-distance trade networks amongst hunter-gather groups in Central Europe.

8.1.4. Preparing and processing – pigment and people (stages 7-10)

The Palaeolithic inhabitants of Hohle Fels cave processed and used ochre in several ways and for several reasons, including pigment production. The most obvious lines of evidence are the two ochre grindstones that were used to pulverise ochre into a useable pigment powder. One of these, a dolomite grindstone with a secure provenance (the Gravettian layer IIb), was recovered during the 2018 excavation season, (Paper 1, Chapter 5: Figure 12). The other grindstone, which is a coarse-grained brown sandstone, was rediscovered in the legacy Hohle Fels collections and unfortunately did not have a secure provenance. Its elongated shape and clear faceted surface strongly suggest that extensive grinding caused the morphology of the sandstone grindstone. Red residues are visible on all its surfaces beneath a calcium carbonate accretion. When a photo of the artefact is observed using D-stretch (Harman 2005), a colour enhancement program used to help detect and visualise rock art pigments, six red parallel lines are visible on its anterior surface (Figure 8.3b, right). The other surface of this artefact has a facetted area showing a dense accumulation of ochre with no discernible pattern (Figure 8.3b, left). From these observations, it is apparent that the people who used the sandstone grindstone used it for the grinding and processing of ochre. It cannot be determined at this point whether the striped pattern is intentional or accidental (e.g. the stripes look like a handprint; thus, someone with ochre on their hands may have grasped the object), but humans indeed modified the artefact during a process that involved ochre.

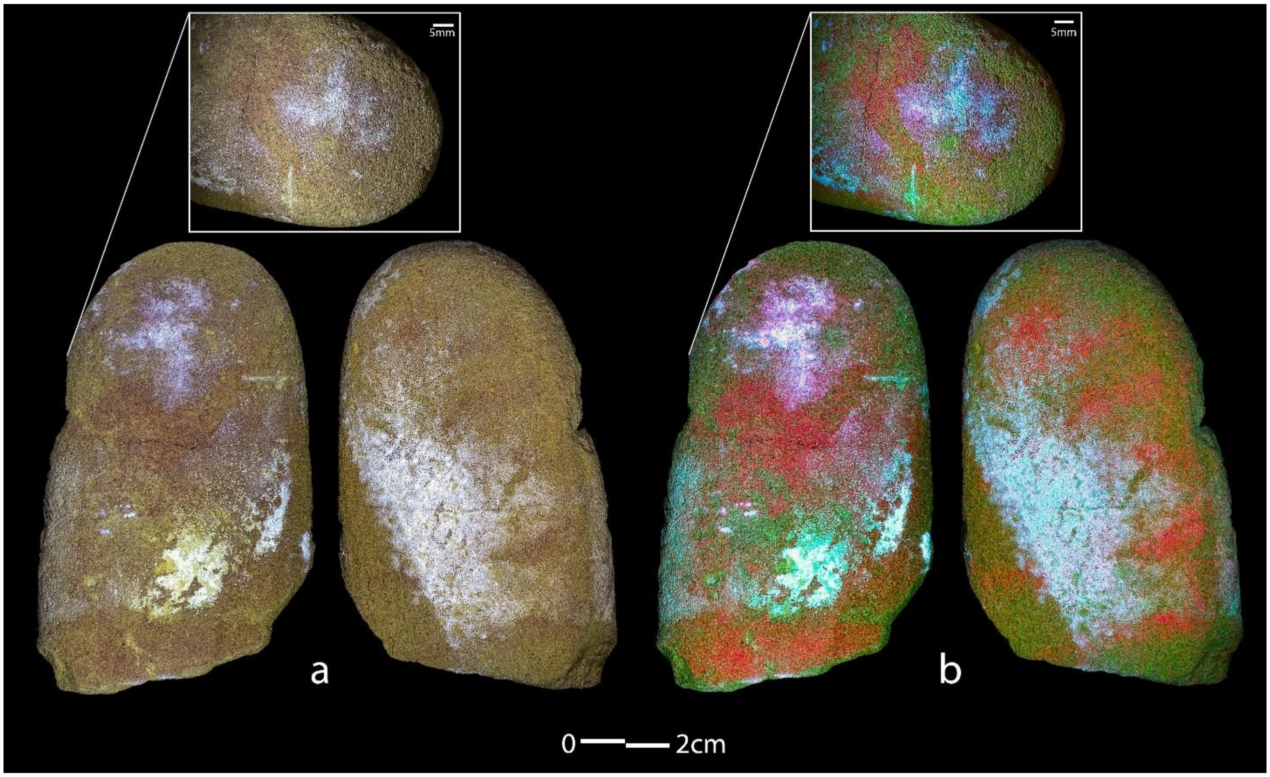


Figure 8.3: Grindstone artefact with unknown provenience from Hohle Fels cave. 8-3a shows the artefact without photo enhancement; 8.3b shows the artefact with D-stretch LAB filter enhancement.

In addition to these two ochre grindstones, 245 non-ochre artefacts from Hohle Fels show traces of red residues on their surfaces. Natural processes most likely stained some of these artefacts, which also seems to be the case for many pieces of limestone that show red colouration (most likely due to some weathering or surface oxidisation processes). However, other ochre-stained artefacts attest to how people deliberately used ochre pigments at the cave site. Bones, shells, fossil molluscs, pieces of ivory, animal teeth, and personal ornaments are all examples of material types that bear red colourants (Paper 1, Chapter 5: Figure 11). This is also true for the six painted limestone pieces (Figure 2.3), where people intentionally painted red ochre onto the stone surfaces in a structured design and pattern. The red residues on these painted limestones represent a style that seems to be unique to southern Germany, and the only other comparable pieces were found at the Klausenhöhle cave sites in Bavaria (Huber and Floss 2014).

Despite having clear evidence for ochre pigment production in Hohle Fels, and despite the occurrence of painted limestones, no painted parietal art dating to the Upper

Palaeolithic occurs in Germany. The lack of painted parietal art could be a condition of circumstance; for example, the interior walls may have been painted only in sections that were affected subsequently by weathering and became detached, as is suspected for some of the painted limestone fragments (Conard and Malina 2010). However, some of these smaller fragments show evidence of never having been attached to the cave wall (Figure 2.3b-c) and should perhaps instead be regarded as portable art (Wolf et al. 2018).

There are three types of personal ornaments in the Hohle Fels assemblage: ivory beads (dating to the Aurignacian and Gravettian), shell beads or pendants; and beads made from other faunal elements, including reindeer teeth beads (both dating to the Gravettian and Magdalenian). All ornament types have examples containing red ochre pigment applied to their exteriors. Several scenarios could have resulted in the presence of red ochre on these objects. First, the red ochre possibly had an aesthetic dimension: it was applied in order to colour the ornaments and make them more visually appealing. This scenario is suggested for ochre stained shell beads found in the South African MSA and Holocene sites (d'Errico et al. 2005; d'Errico et al. 2008; Dayet et al. 2017; Henshilwood et al. 2004). Another hypothesis is that ochre-covered clothing or human skin rubbed off on the beads, resulting in their surface colouration (d'Errico et al. 2005). Lastly, people may have applied the red ochre for practical purposes in the creation and preparation of the beads, and thus the remaining red ochre remnants should be considered a secondary effect. In the case of the Aurignacian ivory double-perforated beads, White (1997) notes that ground hematite is the best material for polishing the beads to give them a shiny lustre. For the reindeer teeth beads, during their manufacture, the front lower incisors were broken and sawed-off from the jaw while still in the gums; Poplin (1972) suggests that they were then worn this way, with the gums still intact. Therefore, it is possible that people applied red ochre to the gums in order to slow the decay process, as red ochre has been found useful for this purpose in tanning animal hides (Audouin and Plisson 1982; Rifkin 2011), or the red ochre was applied for aesthetic purposes. These scenarios are not mutually exclusive, as applying red ochre to personal ornaments may have been perceived as having both functional and aesthetic advantages. The above discussion thus exemplifies a range of benefits of using ochre on different artefacts and attest to the versatility of ochre and how people could have used it during the Upper Palaeolithic.

Above all, the most important observation from the variety and number of artefacts containing ochre residues is that ochre was not simply a manuport brought back to the site. It was processed by different tools and in different ways, including grinding and pulverising. It was applied to almost all artefact types found at the cave site, including discreet micro-contexts observed as *in-situ* ochre-rich sediments during excavation. No other material found at Hohle Fels is applied on so many artefacts and in so many different forms. The presence of ochre on personal ornaments, as well as in painted patterns on limestone fragments, attest to its importance and prevalence in the lives of the Hohle Fels cave inhabitants.

8.1.5. Stratigraphy and deposition: ochre occurrences at Hohle Fels (stage 11)

One of my main research questions was whether there is clear empirical evidence for ochre use, not just its presence, at Hohle Fels cave. Moreover, I wanted to explore if the few previously reported modified pieces (n = 5) and the painted limestones (n = 6) were truly the only representatives of ochre behaviour at the site during the Upper Palaeolithic. One of the major results of this dissertation can answer this question. During my (re)analysis of the ochre assemblage from Hohle Fels, I recovered numerous previously unknown ochre pieces in the assemblage, and thus increased the assemblage number to 930 individual ochre pieces and 247 artefacts with ochre residues from all time periods. Consequently, my reassessment clearly demonstrates that ochre was repeatedly interacted with by humans over a considerable time span. However, if we look beyond the absolute numbers of ochre and ochre related artefacts and compare the nature of these finds with other forms of material culture, we can begin to fully assess the intensity of ochre use in relation to other behaviours at the site.

While questions concerning how much people engaged with different materials and activities in prehistoric contexts are unlikely to be quantified, much less fully known, one possible line of inference might be to compare, in this case, the number of ochre pieces relative to other artefact classes, and to try to calculate relative (and comparative) artefact frequencies per chrono-cultural periods and sediment volume. Table 8.2 shows the artefact totals for the Upper Palaeolithic sequence at Hohle Fels, and Table 8.3 shows corresponding calibrated radiocarbon dates for each of the analysed stratigraphic layers. Based on the values in these tables, several noteworthy patterns emerge. Beginning with the earliest cultural layer at HF, Vb (ca. 44-35 kcal BP), this layer yielded very few ochre artefacts relative to other artefacts. This layer also contains the lowest frequency of ochre relative to the excavated sediment volume. However, if we inspect the values for other artefact types in this period, such as lithics/volume, their numbers also indicate low human activity relative to other layers at Hohle Fels. Layer Vb represents the first human occupation phase at the cave, and these lower artefact frequencies may reflect a period during which the cave was visited infrequently or by smaller groups of people. While this layer has yielded low frequencies of standard artefact types (e.g., lithics and ochre), it nonetheless also yielded some almost unique artefacts, such as the Venus of Hohle Fels figurine made from mammoth ivory (Conard 2009), an almost entirely intact flute made from a griffon vulture wing bone, and a flute fragment made from mammoth ivory (Conard et al. 2009). This layer also yielded the first examples of ivory ornaments (n = 18), though upon visual examination, none contained ochre residues. No modified ochre artefacts date to this archaeological horizon (AH). Regardless, this AH boasts some of the most significant artefacts relating to complex symbolic behaviours during the Aurignacian, and ochre was at least collected and brought back to the site during this time period, or perhaps activities related to ochre were carried out in other seasonal settlements outside of the sporadic occupation of Hohle Fels cave.

The next Aurignacian horizon (Layer Va, ca. 41.5-35.5 kcal BP) is the most artefact-rich layer in the entire cultural sequence, despite being the smallest excavation area (14 m^2) and thinner (ca. 20 cm) than its preceding layer. Though the number of ochres (n = 243) is much lower than the number of lithics (n = 63,689), this layer yielded the highest volume (0.868) of ochres per excavated sediment volume and contained the highest number of both lithic and ochre pieces. There is also the highest ratio of ochre to modified faunal artefacts (0.503). Relative to all other artefact values, layer Va represents a phase of ochre use during a period of more intensive occupation (and artefact deposition). It has also yielded some 75 ivory ornaments (Wolf 2015a; 2015b), two of which contain visible red residues in their perforations, fragments of an ivory flute (Conard et al. 2009), part of a *Lochstab* for making rope (Conard and Malina 2015) and six additional symbolic osseous artefacts (Dutkiewicz et al. 2018). The presence of numerous ochre pieces, as well as evidence of their use on personal ornaments, suggests a possible transition in either the way ochre was used or a change in ochre-related site use (where ochre was processed and used) following AH Vb. This layer also offers evidence for long-distance transportation of ochre materials (as evidenced by two ochres from compositional Group 5 being found in this layer, see Paper 3, Chapter 7).

The Aurignacian layer IV Is similar to AH Va in that it shows relatively high ratios to other artefacts, excavation area and excavated volume, though not as high as Va. This layer is particularly significant for its assortment of ivory figurines, including the waterbird or *Wasservogel*, small lion man (*kleiner Löwenmensch*) and the head of a horse figurine (*Pferdkopf*) (Conard 2003). This layer has also yielded the most ivory beads (n = 87), three of which contain red ochre residues, as well as ten modified symbolic osseous artefacts (Dutkiewicz et al. 2018). Both the layers Va and IV contain evidence for sustained and frequent creation of symbolic artefacts, including the collection and use of ochre pigments, one piece of which was collected from the Group 5 ochre source and suggests long-distance transportation of certain ochres.

Unlike the preceding Aurignacian layers, AH IIIb boasts a relatively low overall artefact count and only three ochre pieces. This period represents a brief cold snap, with the climatic conditions at the cave being cold and unstable (Miller 2015b), and it is possible the low number of ochre and artefacts may be related to fewer and more sporadic occupation events or the changing of site use. Layer IIIa, however, contains the highest ratio of ochre to lithic artefacts for the Aurignacian (0.015), and with moderate ratio-values when compared with excavation area and thickness, as well as to burnt bone and modified fauna. This is also the layer where the micromorphological record shows warmer and wetter climatic conditions (Miller 2015b), and the cave may have been better suited for longer and more intensive visits. There are more ivory beads (n = 20) recovered in this layer than from the preceding layer, and different bead styles, including basket-shape forms (Wolf 2015b). One of these beads contains traces of red ochre residues (Figure 8.4). This layer also shows an increase in ochre pieces (n = 52) from AH IIIb and is the first and only Aurignacian layer to contain a modified ochre artefact, in the form of a yellow ochre piece with two deep incisions (Paper 1, Chapter 5: Figure 10). Following the Aurignacian, the transitional layers IId and IIe show low frequencies of ochre to lithic artefacts, with an increase in the ratio to modified osseous artefacts. These periods mark a slow transition into a cooler yet relatively stable and moist climate (Miller 2015b) and may represent periods of sporadic cave occupation in favour of open-air sites.

The earliest archaeological horizon ascribed to the Gravettian is AH IIcf (ca. 32.5-31.5 kcal BP). This horizon was intensively studied due to its thin, yet widespread presence and the high lithic artefact frequency (Schiegl et al. 2003; Taller and Conard 2016; Taller et al. 2019). Micromorphological studies suggest that it is a redeposited dumping area, in contrast with the original theory that it was a large and extended hearth feature based on a large number of burnt bone within several hearth remains (Schiegl et al. 2003). Due to the lack of trampling features, it has been proposed that ash deposits may have been dumped at the back of the cave and then eroded to the apse area. If correct, this suggests that the main area of occupation was in the front apse near the modern-day cave entrance, and not the large inner cavern (Miller 2015b; Schiegl et al. 2003).

The IIcf layer presents strikingly low ratios of ochre to lithic materials (0.001) as well as a low ratio of ochre to burnt bone (0.001). Thus, it seems that the occupants during this time period either did not use ochre regularly or that ochre was rarely discarded. I have suggested (in Paper 1, Chapter 5) that the low number and fragmented condition of the ochre assemblage may be due to ochre-use efficiency, and that the cave inhabitants were turning entire ochre nodules into pigment powder leaving little to no macroscopic materials behind. The intensive erosional processes that took place in the cave during the Gravettian may also have removed significant actions, which are not mutually exclusive, could readily suggest that ochres were valued, for one reason or another.

Table 8.2: Artefact frequencies related to behavioural intensities at Hohle Fels cave. AH = Archaeological Horizon, Cultural group abbreviations are as follows: M = Magdalenian, G = Gravettian, A/G = Aurignacian/Gravettian transition, A = Aurignacian. Excavation area and thickness values are approximate. Lithics include all tools and flakes larger than 1 cm.

AH	Cultural group	Excav. area (m^2)	Thickness (cm)	Approx. volume	Lithics (n)	Lithics/ Volume (n/m^3)	Burnt bone (g)	Charcoal (n)	Modified fauna (n)	Ochre (n)	Ochre/ Lithics (n/n)	Ochre/ Volume (n/m^3)	Ochre/ Burnt bone (n/g)	Ochre/ Modified fauna (n/n)
I	M	32	40	1280	4903	383	521	43	39	93	0.019	O	0.179	2.385
IIa	M	26	30	780	8680	1113	681	155	52	71	0.008	0.091	0.104	1.365
IIb	G	46	30	1380	11357	636	1975	38	94	227	0.020	0.164	0.115	2.415
IIc	G	42	25	1050	9072	864	3561	55	93	43	0.005	0.041	0.012	0.462
IIcf	G	29	8	232	14548	5010	7957	12	121	8	0.001	0.034	0.001	0.066
IId	A/G	44	40	1760	5491	312	2830	48	151	29	0.005	0.016	0.010	0.192
IIe	A/G	22	15	330	1167	354	315	26	58	6	0.005	0.018	0.019	0.103
IIIa	A	32	20	640	3486	545	690	311	256	52	0.015	0.081	0.075	0.203
IIIb	A	20	5	100	839	839	375	37	129	3	0.004	0.030	0.008	0.023
IV	A	32	20	640	18704	2923	3648	288	715	67	0.004	0.105	0.018	0.094
Va	A	14	20	280	63689	22746	5086	307	483	243	0.004	0.868	0.048	0.503
Vb	A	23	25	575	2068	360	801	35	98	8	0.004	0.014	0.010	0.082

Table 8.3: Calibrated radiocarbon dates for corresponding archaeological horizons (AH) and time periods at Hohle Fels. Time period abbreviations follow those listed in Table 8.2. Dates calibrated using CalPal Hulu.

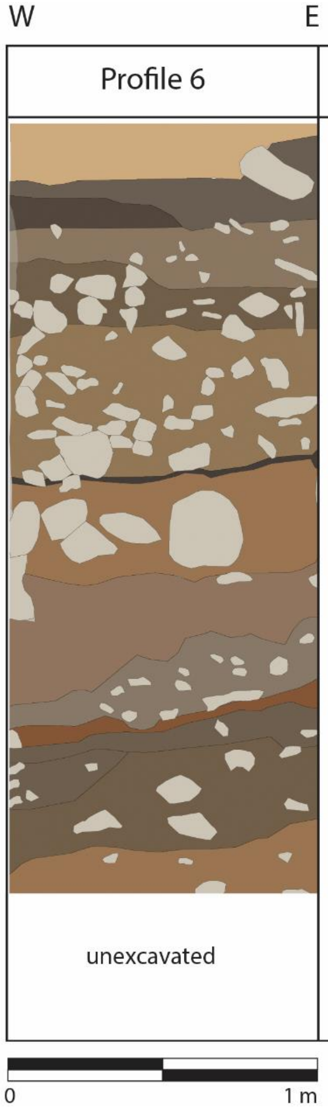
AH	Period	Calibrated date	References
I	M	16,162 ± 348 – 14,918 ± 84	Hahn 1995; Taller 2015
IIa	M	16,305 ± 382 – 14,906 ± 249	Housley, et al. 1997
IIb	G	32,777 ± 305 – 32,612 ± 268	Hofreiter et al. 2007
IIc	G	33,742 ± 568 – 30,897 ± 416	Hahn 1995; Housley, et al. 1997
IIcf	G	32,441 ± 233 – 31,780 ± 151	Conard 2003
IId/IIe	A/G	34,733 ± 240 – 32,520 ± 256	Conard and Bolus 2003; Conard and Moreau 2004
IIIa/b	A	34,248 ± 262 – 34,065 ± 219	Conard and Bolus 2003; 2008
IV	A	37,350 ± 764 – 34,353 ± 183	Conard and Bolus 2003; 2008
Va	A	41,136 ± 343 – 35,594 ± 339	Conard and Bolus 2003; 2008
Vb	A	43,620 ± 543 – 35,218 ± 300	Conard 2009

Figure 8.4: Ivory bead (# 89.IIIa.1211) dating to the Aurignacian showing traces of red ochre residues.

amounts of ochre out of the cave, while soft ochre pieces may have been obliterated during inner cave sediment transportation. This would explain the high number of lithic artefacts, which are more robust than softer ochre clays. However, given the defined internal boundary of layer IIcf in Hohle Fels as well as the morphology of layer IIcf in general, it is more likely that the cave inhabitants simply did not throw away ochre along with the other refuse material that forms this layer. This lack of discarded ochre suggests several possibilities, including a complete usage of collected nodules or that people took their ochres with them upon departure. Both

The remaining Gravettian layers IIc and IIb represent another shift to colder and drier climatic conditions (Miller 2015b) and display an increase in the ratio of ochre to other materials. This observation is particularly true for the layer IIb, which shows the highest frequency of ochre to lithic (0.02) and modified faunal artefacts (2.415). In layer IIb and the subsequent layers, there is a marked increase in modified ochre as well as in artefacts containing definite evidence of pigment production, such as the ochre grindstone which was found in AH IIb. This pattern continues into the Magdalenian layers IIa and I, which contain some of the highest ratios of ochre to lithics, modified fauna, and excavated sediment volume. Furthermore, the Magdalenian layers contain the highest number of artefacts with intentionally or indirectly applied ochre residues (n = 44) as well as the most anthropogenically modified ochre artefacts (n = 17) and the seven ubiquitously painted limestone pieces (Figure 2.3) (Conard and Malina 2010; 2011).

The ratios of ochre to other artefacts, coupled with the presence of more ochre-related artefacts and modified pieces, provide evidence to infer that a shift had taken place in the ways humans were using ochre during the Gravettian-Magdalenian transition. During this timeframe, the cave inhabitants went from the production of personal ornaments and ivory figurines to an increased emphasis on ochre collection, pigment production and use as paint on other objects. A visual representation of ochre behaviours in relation to climate and other types of artefacts is shown in Figure 8.5.



AH	Climate	Ochre behaviours	Other behaviours
0/I		Holocene	
IIa IIb	Cold Very cold	Ochre grinding, pulverising Painted limestones Reindeer teeth beads with ochre Many modified ochres, non-local	Increase in osseous technology Exotic, non-local materials Diversification of tool types Comprehensive settlements
IIc IIcf	Cool	Marked increase in modified ochre *Rondelle* ochre artefacts Increase in non-local ochres Micaceous, glittery ochres, finer textures and purple/red colours Darker and redder streaks	Increase in non-local lithics Increase in exotic shells Decrease in mammoth ivory Increase in faunal and antler tools and ornaments Decreased forest cover
IId IIe	Warm, very wet	New ochre sources identified, loyalty to local ochre sources Low modified ochre	Local raw materials Ivory beads, decrease in figurines Some faunal ornaments Interglacial tundra
IIIa IIIb IV Va Vb	Warm, wetter	Mostly local ochre acquisition Low modified ochre High ochre residues on artefacts	Local raw materials Frequent, local mobility Ivory beads, figurines Large game species Tundra environment with boreal elements
VI		Sterile	
VII VIII IX		Middle Palaeolithic Not studied	

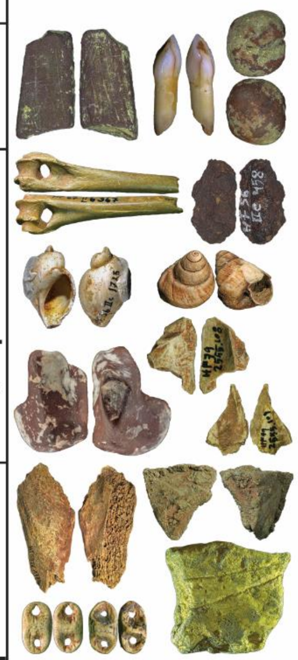


Figure 8.5: Visual representation of the archaeological stratigraphy at Hohle Fels, with corresponding climatic conditions, ochre behaviours, other behaviours of note, and contextually associated artefacts. Note that the Holocene and Middle Palaeolithic are not described. Artefacts are not to scale.

8.1.6. German ochre sources and the provenance postulate

My last objective was to determine if the *provenance postulate* (Weigand et al. 1977) can be satisfied for German ochre sources, and whether or not the ochres from Hohle Fels can be attributed to specific outcrops or sub-outcrops. The *provenance postulate* suggests that for geological sources to be comparable to archaeological materials, then inter-source geochemical variability must be greater than intra-source variability. Simply put, ochre samples collected from different sources should be more different from each other than samples collected from within one source location. This postulate can in certain circumstances be challenging to establish, as ochre is a highly heterogeneous material and some Fe-oxide deposits can cover large areas, with weathering and elemental transportation further altering material compositions (Cornell and Schwertmann 2003; Singh et al. 1978). However, numerous studies on ochre sources have been able successful in showing greater variability between sources rather than within a single source (MacDonald et al. 2018; MacDonald et al. 2013; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007; Zipkin et al. 2015).

In most of the successful ochre provenance studies, specific diagnostic trace elements, such as transition metals and rare earth elements, allowed for the differentiation of ochre samples (Dayet et al. 2016; Eiselt et al. 2011; Kingery-Schwartz et al. 2013; MacDonald et al. 2018; MacDonald et al. 2013; MacDonald et al. 2011; Popelka-Filcoff et al. 2008; Popelka-Filcoff et al. 2007; Zipkin et al. 2015). I, therefore, applied a similar strategy for analysing the ochre samples from German sources (Paper 2; Chapter 6). The results show that ochres from different sources can be separated based on their diagnostic geochemistry, while samples from within an ochre source are more similar to each other. These results thus supported the *provenance postulate* and allowed for the comparison of ochres from Hohle Fels, Geißenklösterle, and Vogelherd to these source materials (presented in Paper 3, Chapter 7). The analyses of the German ochre sources support future research on ochre provenance throughout the European continent as well as ochre comparison studies at sites both in Germany and elsewhere.

8.1.7. Summary

The *ochre chaîne opératoire* at Hohle Fels cave shows a long-term and complex system of intimate landscape knowledge, colour and textural preferences, movement and mobility, processing and ultimately the application of pigments onto artefacts. It should also be noted that even though this is where the inferences we can make from the archaeological material ends, there were likely many expanded and perhaps interrelated uses of ochre that are indiscernible to present-day researchers. The ochre assemblage is not simply a collection of manuports brought back to the cave; it is evidence of a complex social and cultural structure that was already in place amongst the earliest AMH populations in Central Europe. Regional movements, erosional phases, and climate likely affected known sources of collection, routes of transportations, methods of production, and ultimately the nature of ochre and pigment use. The sustained presence of ochre in all archaeological contexts associated with human occupation at the site shows that ochre use was not an ephemeral behaviour for the Upper Palaeolithic populations at Hohle Fels cave. It is difficult to offer an interpretation for the original and perhaps long-term reason(s) of why ochre was applied to certain materials. As seen with the reindeer teeth beads, it could be a combination of aesthetic, symbolic, and functional aspects. The breadth of application and range of associated artefacts shows that ochre was interwoven into their social, symbolic, and technological structures, and was likely something people interacted with frequently throughout their lives on a daily basis.

The provenance analysis of the ochre sources is not only relevant for the materials from the caves studied here, but also for all European Upper Palaeolithic sites, as the results of this reanalysis show that many ochre pieces were previously mislabelled or undocumented. I established (Paper 3, Chapter 7) that people were transporting ochre materials over distances of up to 300 km, and it is furthermore likely that the hunter-gatherers of the Swabian Jura transported these materials over even greater distances; with further sampling and analyses, this hypothesis can be tested. During the Aurignacian people were acquiring ochre from distant locations, and likely in the later time periods, the patterns of ochre procurement changed to focus on the local region of the Swabian Jura, and this was maintained throughout the Upper Palaeolithic. This collection strategy persisted for almost 30,000 years, despite changes in behaviours in other raw material types (such as lithics and personal ornaments) and despite colder climatic fluctuations and large shifts in regional geomorphology. The reason or reasons for these choices held a strong influence in the lives of the Swabian Jura groups and must have impacted the way they structured their movements and acquired their resources. Through these results, we can conclude that while humans were constantly adapting and adjusting to new regions, conditions and environments, they maintained special behaviours and traditions through their perceptions of and interactions with ochre materials at Hohle Fels and in the Swabian Jura.

8.2. Future projections

8.2.1. Ochre residues on non-ochre artefacts

Examination of red residues found on certain materials (Chapter 5, Paper 1: Figure 11) would help to determine if these residues can be attributed to natural or anthropogenic actions. Furthermore, these analyses could prove useful to other researchers studying the presence of apparent residues in other assemblages or contexts. Though iron and iron-coated particles occur in the sediments inside of Hohle Fels and Geißenklösterle (Miller 2015b), most of these are not found in high quantities and mostly contain goethite minerals, not hematite. The identification of hematite would be a strong indication of anthropogenic application. Preliminary SEM-EDS analyses of the reindeer teeth beads from the Gravettian and Magdalenian layers show high amounts of Fe-oxide compared to sediments from the same layers and sedimentary contexts (Velliky et al. 2018a). More in-depth analyses on ochre residues may also provide insight into possible binders mixed with the ochre powder, such as animal fat or other protein-based liquids, as seen with many rock art and similar studies (Chalmin et al. 2003; Clottes 1993; d'Errico et al. 2016; Villa et al. 2015). Such studies could offer valuable information on the later stages of the operational chain of ochre use, provide insight on the range of ochre applications, and can assess whether ochre was processed differently depending on the artefact types containing those residues. In addition to providing valuable information on the ways in which humans created and perhaps used these material objects, ochre residue studies may also inform on site formation processes within the cave that cause red iron-oxide staining. Studying and analysing ochre residues on other artefacts has recently begun to expand in archaeological studies (Bouillot et al. 2017; Dayet et al. 2017; Fiore et al. 2008; Henshilwood et al. 2018; Wojcieszak and Wadley 2018; 2019; Zilhão et al. 2010), and the future for this avenue of inquiry is promising, especially since many residues were previously overlooked in past assemblages.

8.2.2. Expanding the sample size and sampled sites

Of all the archaeological ochre assemblages studied in this dissertation, only Hohle Fels was re-analysed and sampled extensively. Conducting similar in-depth analyses on the assemblages from Geißenklösterle and Vogelherd ought to produce additional ochre pieces and artefacts, likely with additional geological varieties. A reinvestigation of the excavated materials from other cave sites in the Ach and Lone valleys, such as Sirgenstein, Brillenhöhle, Bockstein and Hohlenstein caves may also reveal more ochre materials. A comparison across these sites, both in the Ach and Lone valleys, will expand on what is already known of social or logistical structures, movement patterns and connections and offer further insight into social formations related to ochre collection strategies within the Swabian Jura.

8.2.3. Expansion of landscape surveys and sampling of additional ochre sources

The Fe-oxide deposits that I sampled represent only a small portion of the possible sources of ochre found in Germany and Central Europe more generally. A survey in the neighbouring valley, the Lone, which has been the subject of intensive geomorphological surveys in recent years (Barbieri 2019; Barbieri et al. 2018), could allow for further information on the nature of Fe-oxide deposits in the Swabian Jura. A more systematic study of the erosional and depositional events that may be associated with local ochre deposits in this region is needed. Additional surveys in the Black Forest region would also be beneficial, as the chemistry of compositional Group 1 showed similarity to several Black Forest sources. The relationship was not consistent enough to associate Group 1 to any of specific sampling areas. Sampling Fe-oxide sources near regions where Upper Palaeolithic people acquired other raw materials, such as the Rhine Valley and Bavaria, would also assist in constructing a more detailed picture of regional ochre collection strategies during the Upper Palaeolithic.

Furthermore, surveys need not be restricted to current political boundaries: other raw materials have been found to come from places outside Germany such as Belgium or France (Floss and Kieselbach 2004; Rähle 1994). Ochre was collected and used at other sites in France (Pradeau et al. 2015; Pradeau et al. 2014), Belgium (Germonpré et al. 2014), Spain (Román et al. 2015; Román et al. 2019) and Italy (Cavallo et al. 2017a; Cavallo et al. 2017b; Gialanella et al. 2011), and through some evidence, we can infer that long-distance migration and/or trading existed during the Aurignacian. It is also highly likely that other distant sources have not yet been identified in the Hohle Fels assemblage.

Finally, it would also prove informative to explore the movement of people carrying or trading ochre during the Upper Palaeolithic by mapping the occurrence of ochres types with distinct geochemistry at other archaeological sites in Germany and beyond. Characterising ochres from sources in other regions would help to construct a Central-European ochre database and can serve to support pan-European studies of ochre provenance.

8.2.4. The possibility of Middle Palaeolithic pigments

At the end of the 2018 excavation season, I identified 64 possible ochre pieces from Middle Palaeolithic (IX-VI) levels at Hohle Fels cave. These pieces underwent the same macroscopic assessment as the Upper Palaeolithic ochres but were not included in Paper 1 because the focus of that paper was the Upper Palaeolithic assemblage. Additionally, several ochre pieces have also been recorded from Middle Palaeolithic levels at Geißenklösterle, though no one has of yet examined these in detail and these also were not included in this study.

In addition to iron-rich ochres, a proper assessment of other pigment-producing materials should be conducted on the Middle Palaeolithic assemblage. For instance, at Hohle Fels, numerous black pieces that are often labelled as UM (unknown material) or SO (*Sonstiges*, other) may represent another type of pigment-producing mineral called manganese oxide. These materials are so often found in Middle Palaeolithic contexts that it is suspected that Neanderthals preferred to use black pigments as opposed to red pigments (Bonjean et al. 2015; d'Errico and Soressi 2002; Heyes et al. 2016; Salomon 2009; Soressi and d'Errico 2007; Soressi et al. 2008). The black manganese pigments could also have had a functional purpose, such as facilitating fire (Heyes et al. 2016). Because many of these pieces are not consistently labelled, it is difficult to establish how many of these pieces are in the Hohle Fels assemblage. An in-depth analysis, similar to that conducted on the red ochre assemblage, would offer valuable insight into the total range of pigment behaviours at the site, unrestricted to iron-oxides and anatomically modern humans. Exploring the evidence of pigment use by Neanderthals in the Ach and Lone Valleys might expand what is already known about Neanderthal symbolic capacities and behavioural complexities, and might potentially serve as a comparison in pigment use between different hominin species.

8.2.5. Ochre heat alteration

The presence of yellow materials at Hohle Fels, though likely naturally occurring in most cases, suggest that there was at least the opportunity for the intentional heat treatment of ochre (i.e. turning yellow iron-oxides into red ones through intentional heating). The results of the XRD analysis indicates peak widths matching those of "proto-hematite" for ochres from Group 6a (Paper 3, Section 7.8: Table 7.4). Proto-hematite has a unique mineral phase structure that may suggest thermal alteration (Burgina et al. 2000) and represents an observation that warrants further investigation. Though the transition of some iron phases, like goethite to hematite, is well documented (Cavallo et al. 2018; Salomon et al. 2012; Salomon et al. 2015), the intentional heating of materials is difficult to identify archaeologically, as both indirect heating (e.g. from a superimposed fireplace) and intentional heating may produce the same result. In the case of Hohle Fels, this scenario can be further examined by identifying proximity to hearth features as well as conducting a series of experiments on ochre from sources associated with the artefacts. Exploring the possibility of ochre heat alteration offers another avenue to investigate technological adaptations and human manipulations of this multi-faceted material.

Chapter 9. Conclusion

> *What we call culture is even in its simplest form an infinitely complex whole, composed of numerous factors which for the most part, at least for the present, baffle exact definition.*
>
> *Ernst Grosse, 1987:34*

Building on the findings that ochre was collected and used to create painted rows of dotted lines on pieces of limestone during the Magdalenian period at Hohle Fels cave (Figure 2.3) (Conard and Malina 2010; 2011), this study expanded on that knowledge by examining the ways in which humans during the Upper Palaeolithic period engaged with ochre – that they located various regional sources, selected samples, and carried them to the cave sites where they performed various activities with different uses of the ochre over time. As such, this thesis provides the first comprehensive and systematic assessment of the Hohle Fels ochre assemblage and of an ochre assemblage from a Central European Upper Palaeolithic site in general. In this thesis, I discussed how the ochre materials relate to the large inventory of elaborate artistic artefacts associated with the earliest arrival of AMHs in Central Europe, and I elaborated on how ochre formed an integral part of the lives of Upper Palaeolithic people in the Swabian Jura. The specific research questions I posed in Chapter 1, and which were designed to examine the physical, functional and symbolic aspects of ochre material, were:

- When did ochre first appear in the behavioural repertoire of the site's inhabitants?
- Where did people collect it?
- Was ochre collected from the same places over time or did these places change as people's behaviours changed through time?
- Were collection strategies affected by climatic fluctuations, landscape changes or cultural factors? Did the way people used ochre and the reasons why they used it change over time?

My overall goal was to explore change and continuity in ochre behaviours in the Swabian Jura, and what examining these behaviours reveals about the cultural evolution of the earliest anatomically modern humans in Central Europe. The results presented here show that ochre was collected and used in a variety of ways at Hohle Fels cave during the Upper Palaeolithic. Diachronically, five main ochre patterns can be synthesised:

1. Beginning with the Aurignacian, people used a wide variety of different ochre types, but the later periods saw an increase in the use of fine-textured hematite and a narrowing of the varieties of ochre in general;

2. The presence of use-traces consistent with pigment production, processing tools (grindstones), and several material types with ochre residues shows that ochre was used for a range of applications that may have been both functional and symbolic;

3. Inhabitants of Hohle Fels, Geißenklösterle, and Vogelherd were collecting ochre from the same locations during the Aurignacian;

4. At Hohle Fels, people used ochre from a ≥ 300 km distant source during the Aurignacian, but during the Gravettian, they started collecting massive amounts of silty micaceous hematite from a more proximal (80-300 km) but so far unidentified regional ochre source;

5. In addition to these two collection strategies, for the most part, people at Hohle Fels maintained collection strategies to local ochre sources throughout the entire Upper Palaeolithic (ca. 44-14.5 kcal BP).

Furthermore, this dissertation shows that the Swabian Jura populations collected ochre from at least five local sources as soon as they settled in the region during the Aurignacian ca. 44,000 years ago. In addition to finding ochre in their immediate surroundings, they also accessed ochre from ca. 300 km away during this period, either by trade, through established mobility patterns, or by a wayward traveller who found his or her way to the site. The ochres came in a variety of textures and colours, and the Swabian Jura populations used ochre on ivory ornaments, animal bones, lithics and stones. Though no pieces from the Aurignacian showed traces of pigment production, one yellow piece revealed a stylised V-shape engraved motif. At Geißenklösterle, people went to the same places to collect ochre, but they also used ochre from their own unique Aurignacian-period sources. The processes behind these differences and behaviours are difficult to infer purely form the material culture record. Previous studies on the ivory beads and figurines from Hohle Fels and Vogelherd show that though there are general stylistic trends shared between both caves, unique nuances are seen in production techniques and styles of the personal ornaments and figurines (Dutkiewicz et al. 2018). This suggests a larger social cohesion amongst the Swabian Jura population, with smaller group stylistic manifestations occurring at each of the caves. It is likely that this scenario extends to the ways ochre was collected and used at each of the caves in the Swabian Jura.

Much stayed the same for the next 10,000 years. Then, as the climate became colder and drier changing the surrounding landscape, the behaviours towards resources that were once abundant and close-by changed. Around 30,000 years ago, the people of Hohle Fels found a new source of ochre outside of the Swabian Jura. This source must have been vast, for as soon as people discovered it during the Aurignacian/Gravettian transition, they collected ochre from it extensively. This ochre variant was softer with a fine-grained texture, with its micaceous properties giving it a glittery appearance. People kept revisiting this source or trading with groups outside of their local area, for the next 15,000 years, leading into the Magdalenian. It was ochre like this that was used to make the *rondelle* artefacts. Perhaps it was also used to paint the rows of dots on the limestone pieces, or during the creation of the reindeer teeth pendants. People used this ochre for something different than what they used their local source ochre for, either because it was better quality, or because this source was significant in some other way. During the Gravettian and Magdalenian, the traces left behind on some of the ochre artefacts, as well as stones used to grind them, show that people were beginning to systematically create pigment powder from these ochre pieces. Quantifying certain aspects of geological varieties, observing the changes in colour and texture, and studying the materials with ochre residues reveals how people were using ochres in different ways over time.

Ochre seems to represent a fundamental medium for human expression. It is one of the first materials that humans (and hominins in general) recognised in their environments and realised that it was possible to collect, to change and alter it into something that allowed new creations. They could turn it into a powder, mix it with other materials like animal fat or even water, and used it for tanning animal hides, to haft stone tools to shafts, to eat it for mineral supplements, to paint their bodies and faces to express certain messages, or to protect their skin from insects or the sun, or all of these reasons at once. People could also use ochre to record their thoughts, experiences, memories, and dreams on a range of surfaces, including cave and rock walls. Ochre was so extremely effective at recording human experiences that some of them are preserved to this day, evidenced by the presence of thousands of caves, rock walls, and artefacts that still contain traces of ochre pigments. During the Upper Palaeolithic, it was a complex endeavour to find and locate the means to do this – to find an ochre source, collect it, process it, change it, alter it, then have a limited window upon which to use it, was a multi-faceted and energy-intensive process. People had to have the desire to execute all of these steps. The fact that ochre is useful in so many contexts – symbolic, social, functional and technical, was likely the driving force that encouraged people to acquire it from different places over thousands of years.

Above all, ochre is not necessary: one does not need ochre to survive from a biological or physiological standpoint, nor have hominins ever needed it for survival. Yet it is one of the most abundant, complex and multi-faceted materials, so closely linked to our behavioural evolution that it consistently facilitates new hypotheses and questions as to what exactly it meant for the people in the past who collected it. Using certain lines of evidence, such as qualitative research and geochemical introspection, as with this thesis, we aim to find small glimpses into what, where, and how people were interacting with this material in hopes to unlock *why* they interacted with it. It may be as simple as the concept of "exoticness," that items from afar are rare, and are therefore more highly valued. It may be tied to ideas of place, that items from certain areas are special, and are therefore more meaningful than common or easily accessed items. It may be associated with feelings of identity, that people prefer items from a specific place because of a personal or social connection or reference. It could also be these concepts intertwined together all at once. As shown throughout this thesis, ochre is not a simple material, and whatever perceptions and behaviours that were taking place regarding the collection, activities, attitudes, practices and roles of ochre in these social groups during and throughout the Upper Palaeolithic was complex and varied, and unlikely to be attributed to any single cultural process. Throughout this thesis, I have suggested that is it too simple to think that these processes and activities were only either functional or symbolic. Indeed, there was likely a dynamic interaction in the story of how ochre was integral to their lives, even over many centuries and with changing populations at the cave site.

Furthermore, ochre is not a singular artefact, and rather, occurs as a medium of expression on other artefact types, and likely on humans themselves. Additionally, though ochre acquisition can be related to HBE models of movement in relation to climate and environmental changes, some aspects are counterintuitive to this model, suggesting a different sort of relationship between humans and ochre materials. This is shown in the presence of distant ochre during the Aurignacian; an otherwise “locally” focused time period without much evidence of long-distance movement or other exotic materials. The persistence of some ochre sources throughout time – and the introduction of new and other sources both near and far – show changes and adaptations in the way people used and understood their environment. The change in ochre behaviours at Hohle Fels is also reminiscent of other behavioural changes seen in the Upper Palaeolithic of Central Europe; the Aurignacian being a period of smaller groups, individually-focused expression, and less standardisation of material culture from a broader regional focus. People created ivory beads, ivory figurines, and somehow and in some way, ochre was involved in the creative and technical processes of these people. The Gravettian and Magdalenian show more ubiquitous forms of material culture associated more generally with other sites in Central Europe (Porr 2002; Soffer et al. 2000), and here ochre behaviours become more constrained to somewhat predictable patterns, more focused on certain types of ochre and creating pigment and applying this pigment to objects, whether for functional or symbolic purposes. Mediums of other materials changed, there were fewer mammoth ivory and more faunal ornaments, fewer figurines and a greater variety of artefact types. The climate became colder; people moved more and gathered exotic items from distant places, including ochre. Overall, the behavioural complexities surrounding ochre collection and use exhibited many fluctuations over time; however, one aspect remained constant: collecting ochre from nearby sources in the Swabian Jura. Regardless of climate, environment, subsistence, lithic use, other exotic resources and contact with other groups, Swabian Jura populations remained loyal and stayed true to ochre from their home. This was a consistent pattern of the cultural practices of these groups, passed on to subsequent generations, and consistently taught and practised over almost 30,000 years. No other behavioural tradition has shown to be as long-lasting in the Swabian Jura; ochre was truly a meaningful and powerful material in the lives of the people living there.

Lastly, I hope that this thesis encourages future research into ochre use during the Upper Palaeolithic of Europe. Much work exists on other forms of material culture from this time period and region, such as lithic technology, resource acquisition strategies, personal ornamentation, and symbolic and artistic capabilities. Even with this vast and detailed research history, comprehensive studies on ochre assemblages are comparatively few. Furthermore, the data, results, observations, and conclusions that I discuss throughout this thesis mostly concern only one cave amongst many in this region. If similar studies will focus on neighbouring caves and beyond, there is likely a wealth of insight we might gain through studying this material. In Paper 2, I determined that it is possible to differentiate ochre sources in Germany by observing the nuances in their trace element geochemistry. This offers a door of promise to expand this study to other ochre sources throughout Germany and in other areas and to compare these with collections from other cave sites. By using the methods and approaches I applied in this dissertation to other assemblages, periods and sites, we may achieve a better understanding of the role of ochre and pigments in the cultural evolution of Palaeolithic populations. For now, I believe that my results show that ochre was more than a medium used for symbolic and artistic expression, or for practical and functional applications like polishing ivory beads. It was something ancient humans valued, cherished, shared, and remembered throughout generations. Ochre was a cornerstone in the behaviours and activities of ancient human populations in Southwestern Germany, and with further research, we might begin to grasp what exactly it meant them and for other groups across the continent.

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Appendix A.

Appendix for Hohle Fels ochre artefacts

Contents of Appendix A:

Appendix B.

Appendix for NAA element values for artefacts

NAA raw values for all elements. ANID column corresponds to laboratory sample ID. GKC = Geißenklösterle cave, HFC = Hohle Fels cave and VHC = Vogelherd cave. Table is separated into two sections.

ANID	Group	As	La	Lu	Nd	Sm	U	Yb	Ce	Co	Cr	Cs	Eu	Fe
GKC001	G7a	405.4581	1.4725	(0.0444)	(6.9586)	1.6444	15.8495	0.6358	4.7850	0.5	(1.95)	38.1511	(0.0658)	167420.6
GKC002	G7a	62.7788	12.2037	0.2738	20.0729	5.1100	7.5879	1.2413	32.0136	13.6	34.71	1.4717	1.2104	509632.0
GKC003	G7a	66.1150	19.3699	0.5544	17.4508	4.3198	1.7990	3.0588	23.7499	107.7	19.62	3.7783	1.0237	532422.6
GKC004	G7a	271.0219	4.9218	0.5948	(7.4468)	1.1883	1.1986	4.4303	5.2263	97.8	84.56	3.1193	0.3673	574868.3
GKC005	G7a	247.9847	5.3645	0.3736	12.8661	1.0958	(1.3591)	2.7913	5.9260	84.2	83.51	2.9261	0.3105	556178.4
GKC006	G6b	228.1287	12.2062	0.5612	8.8472	3.6167	1.9710	4.3293	16.2212	14.4	458.79	1.2850	0.9628	299463.4
GKC007	G6a	14.2908	13.9850	0.2693	17.4564	4.9831	(1.0015)	1.7643	32.6962	2.3	153.57	0.4446	1.2160	256951.0
GKC008	G6a	6284.7358	26.4399	0.7313	21.8968	7.7954	(2.4210)	6.0949	36.9112	36.3	136.15	1.0570	2.0655	569793.1
GKC009	G7a	5809.8096	16.5721	0.5306	17.3850	5.0473	1.2219	4.2543	30.0691	35.8	51.46	2.7189	1.3702	543970.2
GKC010	G7b	6628.5688	20.7676	0.5890	25.6855	5.0824	(2.4096)	4.1834	33.6994	36.3	79.17	0.8941	1.3895	555915.6
GKC011	G6b	142.1730	32.6987	0.3518	16.7449	3.8772	4.9768	1.7431	40.2180	6.8	651.26	1.0638	0.7445	362947.0
GKC012	G6b	119.1786	9.5654	0.8599	14.3455	5.0393	4.3066	5.8004	14.8441	29.4	680.68	(0.4729)	1.2542	467183.4
HFC001	G7a	24.2082	12.5530	0.2690	8.4613	3.9829	3.3841	1.4091	26.1471	8.1512	46.7394	3.7396	1.0304	306943
HFC002	G1	32.0801	10.3809	(0.0538)	39.8238	37.0850	136.5399	2.3333	53.9392	2.5151	8.1947	3.8161	6.3573	497607
HFC003	G1	25.3958	3.9133	(0.0448)	17.7141	10.5560	45.3903	0.9142	19.1119	2.1615	5.8642	1.7298	1.7763	625587
HFC004	G1	29.5149	8.9608	(0.0508)	38.4438	30.6559	114.6819	1.7768	45.2779	2.2058	4.6889	2.1061	5.4507	510609
HFC005	G3	1410.5535	0.9199	(0.0678)	7.6950	1.6997	17.1362	(0.4518)	5.5172	1.1799	2.3419	2.7622	(0.0596)	342036
HFC006	G7a	113.1824	11.3836	0.4041	16.4755	7.1389	16.8981	1.5395	28.2495	2.5939	32.5824	2.3902	1.7322	535369
HFC007	G2	9.8305	66.6241	0.6404	56.7408	12.4755	2.1927	5.5082	97.6995	17.6817	136.5463	6.4805	2.6497	55202
HFC008	G2	11.3182	1.3702	0.0772	(2.1397)	0.3062	(0.2473)	0.5735	0.9712	7.3018	19.3438	(0.0602)	0.0947	5962
HFC009	G7a	31.0239	19.0335	0.4874	27.4669	12.2015	8.2719	2.3957	50.7150	5.2205	35.3699	4.6363	3.0521	444851
HFC010	G1	29.8392	6.7231	(0.0488)	24.8005	20.1511	75.8823	1.4518	31.4476	2.2723	6.7110	2.4169	3.4921	579158
HFC011	G7a	43.3660	5.7624	0.2064	4.1052	2.3475	3.9415	0.8797	12.2264	3.5025	29.3698	1.5123	0.5926	467645
HFC012	G1	35.7461	12.5634	(0.0538)	45.1636	35.2440	136.5845	2.1899	54.2252	2.1359	9.4217	2.8723	6.0391	507865
HFC013	G1	26.3454	6.7119	(0.0475)	33.6750	18.6066	66.2116	1.3614	28.0933	2.7558	8.3640	4.6755	3.2253	559288
HFC014	UNASMAJ	6417.9243	6.0413	34.5508	109.4918	379.8899	44.8829	321.1401	59.3789	15.2637	70.1474	15.5702	121.6783	513073
HFC015	G7a	34.8353	18.5701	0.4973	32.0158	14.9045	10.6355	2.5744	54.8771	3.8843	26.9981	3.1671	3.8556	456489
HFC016	G7a	26.2046	10.0463	0.2557	19.7476	9.0839	11.7577	1.2659	29.2537	2.3747	21.8900	1.7828	2.3692	539321
HFC017	G7a	60.8686	7.4039	0.4748	10.0001	2.4483	7.8908	2.1271	15.2226	1.8012	48.7082	1.9267	0.5161	395278
HFC018	UNASMAJ	35.8708	12.4184	0.4130	27.9656	14.5418	4.5520	2.9230	34.8332	4.3584	57.6464	6.8705	4.1307	286005

HFC019	G7a	340.9561	9.4463	0.4872	11.7686	5.5885	29.4464	0.9816	23.7279	2.6082	45.2514	1.8927	0.9758	546636
HFC020	G1	70.2324	10.1623	0.4926	54.9601	34.8586	10.5838	3.4191	49.9539	0.7220	12.0878	(0.3972)	10.5437	595439
HFC021	G7a	93.6478	7.0878	0.4082	6.9298	3.5889	7.2447	1.9521	16.7480	11.0314	51.4904	4.9791	0.9460	375121
HFC022	G7a	23.5662	14.0592	0.3103	15.8005	8.0402	7.0278	1.7389	33.3909	3.6773	27.5092	2.6618	2.1021	392681
HFC023	G7a	354.2320	8.8113	0.5547	8.7708	5.3517	30.6328	1.1722	22.6869	2.5946	36.7431	1.8432	0.8672	553775
HFC024	G1	26.8504	7.9473	(0.0494)	28.8524	22.3126	89.7221	1.4104	35.5071	2.1520	6.7741	2.7512	3.7932	534446
HFC025	G7a	30.2818	8.0139	0.2632	13.3629	7.5914	10.0577	1.2702	23.1046	2.0273	23.7922	1.5472	2.0065	558058
HFC026	G1	25.0170	6.1608	(0.0476)	21.5693	17.2693	68.0504	1.0401	27.9243	2.1102	5.5015	1.9334	2.9963	564306
HFC027	G1	31.4629	7.6613	(0.0501)	33.9917	21.9773	97.2766	1.1726	35.0260	2.2036	7.4582	2.4240	3.7018	568787
HFC028	G1	28.1679	7.3469	(0.0499)	26.5695	19.6751	86.6588	1.2087	31.6954	2.2559	7.8080	1.8670	3.2679	576575
HFC029	UNAS	9.1346	15.2431	0.3694	11.9052	2.8316	0.8188	2.7737	28.0884	15.3932	41.3135	3.4748	0.6624	114529
HFC030	G7a	79.1256	31.3016	0.4082	41.8309	12.1958	7.6293	2.2016	84.5414	5.9690	39.3911	3.5231	2.6788	447104
HFC031	G4	123.0798	1.2603	(0.0556)	7.9298	1.8552	16.5459	0.7080	5.3906	1.8241	4.5646	1.6194	(0.0726)	460022
HFC032	G7a	51.7038	5.5237	0.1706	6.4816	1.8377	5.5262	0.7302	11.0384	2.7352	21.9885	1.1376	0.4560	531120
HFC033	G7a	32.3195	19.5548	0.4707	32.9701	22.0860	6.1825	3.2575	52.6257	4.9741	44.1479	2.5877	6.6523	421973
HFC034	G7a	122.2116	36.7506	0.5384	28.6895	9.6416	20.2238	1.5850	85.8097	21.0174	31.5951	(0.4190)	2.1625	634886
HFC035	G1	37.9381	12.6456	(0.0533)	36.4593	28.5769	112.5845	1.6446	45.6479	2.2597	5.0893	3.0756	4.9207	541074
HFC036	G2	6.0019	52.7560	0.6589	43.6108	9.2510	3.5310	4.7521	105.8928	17.6636	111.3580	7.6004	1.6732	36514
HFC037	G7a	74.3858	11.8157	0.1834	19.0548	5.6013	11.4038	1.0971	30.1235	12.8410	30.1835	1.7091	1.2710	497698
HFC038	G1	25.0893	6.5912	(0.0482)	21.5952	16.7023	70.8727	1.0807	26.5413	2.2308	6.2296	2.0270	2.7463	556715
HFC039	G2	16.1609	33.0414	0.3988	26.7306	5.8873	2.9144	2.9048	68.6043	12.8532	96.8591	12.9545	0.9395	45595
HFC040	G1	29.2622	10.3184	(0.0519)	29.6951	27.0144	92.7578	1.7082	42.0186	2.3040	7.1884	2.7205	4.8223	537165
HFC041	G7b	97.1951	8.8920	0.8915	10.4647	3.6416	(1.4479)	7.1297	18.1281	31.7560	25.6751	3.3170	1.0710	518475
HFC042	G2	2.4652	7.0882	0.0682	4.9439	1.1434	0.4280	0.4691	11.0580	1.4939	16.9372	3.4940	0.2561	8815
HFC043	G1	34.0873	10.1964	(0.0523)	39.4978	24.9794	104.3044	1.4496	40.3382	2.4936	7.3769	3.3971	4.1728	552234
HFC044	G2	5.3108	6.4197	0.1288	5.2396	1.3709	(0.5122)	1.0613	8.3852	3.8752	16.6785	0.9636	0.3284	20848
HFC045	G2	5.1366	14.1260	0.2104	9.8312	2.6422	1.4722	1.6049	29.1007	4.2906	43.5641	2.4311	0.5773	28075
HFC046	G1	36.0713	15.2578	(0.0565)	49.0906	47.5290	129.7890	3.2963	59.5295	2.8782	9.6313	6.8612	8.6354	437483
HFC047	G7a	181.0040	3.3782	0.3317	(7.6260)	1.6380	1.3429	2.5270	6.7569	101.7528	10.0985	0.3095	0.4361	569371
HFC048	G7a	349.7168	9.6565	0.3952	10.6487	2.2176	1.9402	2.9282	15.1359	89.9979	53.0738	4.0142	0.5906	538124
HFC049	G2	7.7111	4.1218	0.4203	5.9281	1.9763	3.8933	3.1343	9.4731	0.6137	1.2239	22.8489	0.3976	11346

HFC050	G7b	56.9942	17.5575	0.3886	9.2536	2.6713	(1.8284)	2.9567	25.5646	54.9385	95.2466	7.4264	0.6142	468202
HFC051	G1	37.7936	12.2217	2.3641	56.9987	42.4573	195.4176	2.3084	68.1010	2.0512	7.7265	2.7049	7.3769	474978
HFC052	G6a	194.4325	62.6769	0.8423	35.1284	8.5597	2.3824	5.3770	81.5871	20.5266	62.2951	3.4352	2.0079	402181
HFC053	G6a	144.9162	60.7137	0.8048	30.0520	8.2030	2.8447	5.4420	77.7334	16.1039	84.1961	3.6871	1.8792	415007
HFC054	G6a	217.2572	55.6040	0.8122	29.6395	8.2401	3.5219	5.5384	72.6755	16.0727	50.2701	3.0050	1.9753	394684
HFC055	G2	7.9259	11.0943	0.2254	12.0840	2.4717	0.7340	1.4878	33.5167	3.6207	51.1398	0.9410	0.5077	51374
HFC057	G7a	237.1249	83.7686	0.8943	42.8340	9.9175	2.9746	6.2609	96.2575	24.7375	49.7680	3.2257	2.2595	406258
HFC058	G6a	192.6927	59.8825	0.9098	34.8106	9.4497	1.6236	6.1777	80.4600	18.5946	66.1299	3.5055	2.3645	407887
HFC059	G6a	3.1585	12.0050	0.2476	11.7730	2.0730	0.6633	1.7514	23.0316	2.1030	27.9617	2.2120	0.4699	13023
HFC060	G2	4.6054	6.9536	0.1576	8.8693	1.5094	0.5476	1.0410	9.2668	3.7091	17.2833	1.0886	0.3550	19384
HFC061	G2	3.7983	9.5370	0.1297	7.9423	1.5299	0.8933	0.9661	16.1525	3.9120	45.6252	1.6401	0.3230	18273
HFC062	G2	6.8132	7.1221	0.2002	7.8649	2.1535	0.5868	1.3334	18.4525	7.2572	21.5216	0.3723	0.5069	26090
HFC063	G2	2.6897	7.4285	0.1649	7.5991	1.8055	(0.4228)	1.0605	8.4578	1.6763	21.4530	1.3402	0.4232	8890
HFC064	G2	2.5636	12.8896	0.1578	9.9377	2.0111	0.3814	1.3210	22.1800	2.2138	34.6922	2.7522	0.4259	15182
HFC065	G2	476.4728	59.3508	0.7557	33.1795	7.7855	2.7054	5.2379	75.2299	17.2051	53.6870	3.1635	1.8170	389583
HFC066	G6a	93.1305	31.7881	0.3833	19.4671	5.0010	4.9460	2.9380	44.4078	12.0549	374.1883	0.4518	1.0886	366677
HFC067	UNAS	327.9927	76.7665	0.7879	53.1313	9.7166	1.5779	5.2751	96.4196	20.0546	55.3841	3.4013	2.1256	385070
HFC068	G6a	20.4233	12.4299	0.4390	11.3364	2.9775	6.0711	3.2827	28.4307	0.2634	1.4861	21.6331	0.4926	33778
HFC069	G2	228.6911	1.6215	(0.0386)	(5.4635)	1.6871	10.9880	0.3913	5.9449	0.7101	1.7626	55.8869	(0.0567)	136846
HFC070	G7a	138.2328	37.4047	0.4640	34.3696	10.2681	23.7097	1.2926	85.7972	14.7716	34.3106	(0.4565)	2.2269	651014
HFC071	G7a	3.6011	10.0499	0.2159	9.9585	2.5128	0.8546	1.5768	12.7116	1.6175	17.0081	1.4721	0.6304	5958
HFC072	UNASMAJ	5.9733	14.9139	0.1687	13.5847	2.4676	0.6142	1.3236	24.1221	4.1976	73.1937	2.7146	0.5443	28957
HFC073	G2	5.3987	14.5102	0.1743	12.0338	2.6065	0.8353	1.1920	26.8920	3.8878	64.7945	2.5356	0.5584	25145
HFC074	G2	29.2130	10.4078	0.5411	8.7943	2.0283	3.0162	3.2953	17.3115	36.1252	74.1273	5.0340	0.5351	490939
HFC075	G7b	27.6435	16.8349	0.1747	18.8199	3.8962	1.0805	0.9564	72.6941	5.1954	67.7169	1.1459	0.7514	182390
HFC076	G6a	355.3906	1.7678	(0.0640)	(8.6731)	1.8678	22.1030	(0.4502)	8.2199	4.3491	3.6099	2.2823	(0.0977)	645881
HFC077	G5	9.4808	23.5135	0.2336	22.1529	3.9389	2.9681	1.7668	38.8441	7.9431	48.8215	4.5792	0.7899	204899
HFC078	G6a	1741.2556	12.1598	0.8926	10.5893	3.8230	(1.6421)	5.9020	22.3452	60.3242	359.0962	2.2357	1.0726	536804
HFC079	G7b	4.5535	11.6047	0.1476	11.1157	2.0194	(0.5525)	1.0974	19.7112	3.4426	42.0387	1.9578	0.4029	26315
HFC080	G2	150.5844	5.5935	0.3014	6.9945	2.6318	15.9502	0.9589	13.2124	6.2342	18.8311	0.6079	0.4801	610619
HFC081	G7a	7.2974	19.3606	0.2883	14.3990	2.7863	1.4352	1.9693	35.3751	10.7961	44.6340	2.8318	0.5896	58998

HFC082	G2	11.3880	18.1613	0.3212	11.7667	2.6403	1.7703	2.1777	34.3980	12.4655	43.8263	2.6540	0.5631	59893
HFC083	G2	8.5988	19.5578	0.3157	17.9339	2.7374	1.5867	2.1166	36.0191	9.9337	46.0097	2.8295	0.5793	62951
HFC084	G2	101.0513	82.8927	1.0684	114.5802	27.5597	3.6161	8.3063	134.4694	33.4586	586.6826	(0.4505)	5.6834	395351
HFC085	G2	302.9912	1.7468	(0.0645)	(8.6713)	1.7919	21.0552	(0.4621)	5.3071	4.9908	2.5300	1.6820	(0.0982)	661599
HFC086	G5	2.5894	4.6572	0.1318	5.5524	1.2160	0.7646	0.8620	11.0373	3.5816	19.2866	0.2764	0.2614	15723
HFC087	G2	1.6153	2.8681	0.0344	3.4766	0.6474	(0.3012)	0.3145	5.3699	1.3125	14.9721	0.1623	0.1207	6333
HFC088	G2	4.1878	9.0463	0.1652	7.9357	1.4990	(0.5203)	1.0992	17.8274	3.9122	32.0119	2.7458	0.3249	21181
HFC089	G2	4.5347	9.2639	0.1561	8.4575	1.5753	0.5644	1.1701	16.7921	3.6531	28.9568	2.5826	0.3341	18607
HFC090	G2	4.9285	21.0976	0.2427	17.8347	3.6314	0.6160	1.6858	39.6948	5.6325	50.3359	3.1991	0.6855	27255
HFC091	G2	188.7005	1.4493	(0.0603)	(8.0569)	1.5773	20.2770	(0.4321)	4.8931	4.5490	3.2609	1.8985	(0.0866)	659539
HFC092	G5	5.7560	26.6500	0.3011	24.8541	5.0795	1.1023	1.8789	56.0908	5.4816	51.4458	3.3191	1.0331	34483
HFC093	G2	32.4160	6.6849	0.3476	(6.6031)	1.6746	4.2262	2.2638	10.2785	335.0986	346.3249	0.7883	0.4393	558209
HFC094	G7a	4.6958	19.8564	0.2287	16.0981	3.3659	0.7880	1.7372	40.0584	6.9485	53.4436	2.8462	0.6798	30294
HFC095	G2	2.4167	15.9186	0.1702	16.0271	2.9643	1.2045	1.0115	38.5378	3.1739	31.8361	2.2805	0.5947	14850
HFC096	G2	4.6177	16.2223	0.2132	15.3124	2.7754	0.9172	1.3501	26.0133	3.6118	37.5002	3.0933	0.5666	23173
HFC097	G2	1.2151	5.1052	0.0642	5.7550	1.3327	0.3525	0.4300	11.5688	1.6094	14.7705	0.1789	0.2722	7567
HFC100	G2	137.7611	10.0044	0.4496	9.7376	2.3911	1.6614	3.0512	19.5285	37.5058	28.2464	5.8443	0.6147	528974
HFC101	G2	18.3836	6.4004	0.7813	7.7154	1.5873	2.0352	4.8990	9.3803	32.8815	24.4479	5.1172	0.4225	550219
HFC102	G2	295.9638	2.2639	0.0620	(7.1948)	0.5365	2.0130	0.5668	3.5008	81.8994	45.5092	(0.4380)	0.1081	594089
HFC103	G7a	94.7091	10.0728	0.5310	16.1642	4.5610	(1.8110)	4.0924	17.9918	64.4096	50.3964	5.9650	1.2795	543788
HFC104	G7a	931.4058	2.5824	0.2923	4.1988	0.8567	0.9067	1.6297	3.9034	76.3663	82.1555	(0.4285)	0.2522	580385
HFC105	G3	18.1464	25.0568	0.4170	15.3398	3.1295	(0.8181)	2.8298	33.2800	58.7856	54.8823	4.0078	0.7525	492571
HFC107	G7a	0.0000	0.0000	0.0517	0.0000	0.0000	0.0000	0.0000	19.7268	7.4	27.84	4.3300	0.5290	221546
HFC108	G4	35.6005	16.2146	0.3906	27.1633	7.4646	0.6019	2.7503	60.8958	9.3347	37.4449	0.5614	1.8083	80367
HFC109	G7a	3.2447	7.2348	0.0776	5.4568	1.2038	0.4986	0.5446	12.0658	1.6161	17.4653	3.5577	0.2482	9677
HFC110	G6a	695.1073	7.7956	0.1289	7.9212	1.4952	0.8970	0.7736	9.0222	5.7536	18.0561	0.7884	0.3541	582853
HFC111	G6a	26.1511	4.8477	0.1388	27.8262	15.1847	61.3437	0.9628	25.9096	2.5212	8.4067	2.1791	2.5096	592867
HFC112	G2	281.2112	8.7771	(0.0390)	10.5309	4.3772	23.8368	0.7950	21.0477	2.7626	42.1918	1.9601	0.7543	543928
HFC113	G2	170.8673	1.4768	0.1783	5.6945	2.3636	21.6991	1.6980	7.6642	0.4957	4.4866	64.3147	(0.0452)	168235
HFC114	G4	4.6842	7.2115	0.0666	5.9322	1.1657	0.3834	0.4675	11.6119	2.6186	18.8576	3.7387	0.2425	15200
HFC115	G1	28.3501	7.7064	0.1744	34.9845	23.9752	102.1048	1.3175	39.4605	1.9775	7.2386	1.9111	3.8718	553551

HFC116	G7a	222.7855	13.3722	0.1573	10.7396	3.9807	20.7414	1.1525	30.2421	2.8666	42.5332	3.3027	0.6659	498667
HFC117	G7a	2.0077	3.0519	0.1719	4.5526	1.0798	(0.2366)	1.2036	3.9197	2.2079	2.3620	0.1803	0.2991	5269
HFC118	G2	58.2545	13.9675	0.2806	21.1561	10.4428	6.2856	1.9567	34.4301	13.7474	40.3475	2.2202	2.9763	439637
HFC119	G1	25.3815	5.5859	0.1787	23.7299	16.8147	66.5384	1.0956	28.8690	2.2335	6.4978	1.6821	2.8005	576250
HFC120	G7a	29.2405	14.1276	0.2831	20.7017	8.6895	10.1042	1.7476	36.9945	3.6096	33.0782	2.8776	2.1136	483940
HFC121	G2	50.4416	33.9360	0.3817	109.5981	27.8972	1.1940	2.8199	149.5533	90.7961	41.9872	0.9912	6.1017	392735
HFC122	G7a	5.0939	9.8518	0.1766	11.4937	2.9057	3.1504	0.7757	26.1358	4.3317	121.2984	0.3883	0.3808	357857
HFC123	G1	285.3090	5.4482	0.0620	7.0096	2.6159	8.3314	0.4926	14.1766	0.8032	3.6789	121.1177	(0.0353)	32549
HFC124	G7a	2.2423	6.1402	0.0693	4.0374	0.9764	0.7011	0.4431	9.2859	1.5978	14.1911	2.9886	0.1920	7008
HFC125	UNASMAJ	1.7915	4.7236	0.0977	3.4128	0.7443	0.4230	0.6521	8.3888	1.4132	12.4641	1.1785	0.1579	6044
HFC126	G7a	63.4492	16.9817	0.2785	31.9470	11.0905	13.1999	2.0187	41.9968	3.4865	35.8052	3.1631	2.7239	483103
HFC127	G2	2238.1765	3.3419	0.2602	(18.5691)	2.6840	12.0213	2.5320	7.6650	3.4627	(4.3024)	7.1504	0.8346	644110
HFC128	G2	2.2332	16.1009	0.3734	27.5924	6.1327	1.5643	2.4420	54.2371	2.1468	100.0117	(0.1804)	0.8725	39908
HFC129	G2	99.7000	14.0105	0.4125	12.7181	3.3455	0.7427	2.5817	18.4058	7.2046	30.5489	4.0082	0.8071	219076
HFC130	G7a	1.4500	4.0146	0.0931	3.7712	1.0802	(0.2540)	0.6297	3.0370	1.3977	3.2601	0.3128	0.2388	3053
HFC131	G7a	299.1597	12.3330	0.1877	12.5093	5.3605	25.9949	1.1288	29.1178	3.5359	38.2559	2.7814	0.9316	503164
HFC132	G2	135.8008	14.2015	0.6359	9.7052	3.2740	(0.8332)	4.4213	8.4550	37.3785	3.5178	(0.3124)	0.9049	252189
HFC133	G6a	4455.6631	1.8827	(0.0584)	(7.9542)	0.3174	1.6162	0.5673	(1.2890)	279.2063	123.1771	(0.4479)	0.0802	600715
HFC134	G2	5.4107	3.6075	0.0491	2.3756	0.5217	0.6949	0.2465	4.2221	1.8037	10.3375	1.1184	0.1058	13713
HFC135	G7a	20.5312	18.0637	0.5894	11.1501	3.0241	2.7349	3.8272	22.4688	67.4963	41.3908	5.5836	0.7005	524759
HFC136	UNAS	18.2012	71.0917	0.8004	169.7289	48.5108	19.4478	6.9933	209.5534	16.4766	31.1247	0.6757	13.3639	521418
HFC137	UNASMAJ	771.1497	3.9527	0.1307	8.0093	1.3150	3.5772	1.2340	4.5502	121.7930	73.9775	1.4932	0.2863	560316
HFC138	G2	28.5780	6.6270	0.1241	26.5614	20.1520	78.5017	1.1278	27.6764	2.0276	6.1906	1.3076	3.3454	578223
HFC139	G7a	25.8590	10.2063	0.2399	47.0171	30.2682	114.4052	1.5461	44.7122	2.2421	7.4015	2.7475	4.9577	514332
HFC141	UNASMAJ	34.8068	6.5154	0.1379	22.2342	18.3743	82.2143	1.0585	28.6558	2.0574	7.7829	1.1595	2.8803	573914
HFC142	G4	35.1449	14.1032	0.3000	45.1806	32.5560	101.8557	2.3404	47.8465	2.8035	6.5764	6.4531	5.5404	509616
HFC143	G1	1.6749	4.8950	0.0665	2.2920	0.7059	0.2465	0.5453	8.2951	1.6883	9.7722	1.1395	0.1510	7311
HFC144	G1	31.8071	9.0261	0.2062	32.4463	24.3980	106.6358	1.3284	38.0760	2.2821	6.3144	2.1889	3.6914	553083
HFC145	G1	25.6337	6.9132	0.1260	25.7398	16.8022	71.0738	1.2006	27.5752	2.0794	6.3321	1.7714	2.6273	579519
HFC146	G1	12.6897	10.3011	0.2223	25.4903	9.9743	4.6078	1.4083	28.5728	1.7360	20.9180	1.5477	2.6850	232011
HFC147	G1	28.8494	6.8129	0.1552	21.7945	18.5176	64.1143	0.9808	29.1895	2.2959	7.2827	1.4407	3.2486	574048

HFC148	G2	38.0929	18.5234	0.4214	77.6576	55.8672	171.3335	3.5093	73.7039	2.5307	9.4802	3.7831	9.5923	425792
HFC149	G1	34.4269	14.7283	0.2872	53.9951	39.1973	139.8928	2.4602	58.1552	2.7024	10.1102	5.2838	6.4682	454822
HFC150	G1	30.9397	12.7917	0.2989	57.0694	40.1636	139.2170	2.2089	54.1529	2.4456	5.3948	4.0452	6.6757	501173
HFC151	G7a	43.8711	17.1756	0.3724	69.1489	49.7993	183.0074	3.2757	70.3836	2.3065	7.3787	4.3487	7.9588	464948
HFC152	G1	32.4634	13.6645	0.3124	58.4318	40.1195	134.5595	2.3843	54.1713	2.2510	6.6007	3.1124	7.0225	484667
HFC153	G1	31.2514	13.2833	0.2272	49.8814	35.7239	154.0654	1.6427	56.0445	2.2835	7.5680	2.3249	5.4824	520811
HFC154	G1	3.2780	7.8470	0.0686	6.5607	1.2853	0.4494	0.4884	12.2126	1.7558	18.1335	3.1972	0.2636	9574
HFC155	G1	36.6941	12.4349	0.3051	45.0379	35.6246	130.8103	2.0877	48.9715	2.4065	6.7290	3.3209	5.8288	505473
HFC156	G1	33.7748	13.0185	(0.0573)	60.1930	44.9604	218.8918	2.2455	77.3788	2.1521	7.9002	3.1840	7.3346	459783
HFC157	G1	0.6630	1.8400	0.0345	1.6394	0.2659	0.7604	0.1454	1.9111	0.3488	1.9688	0.1089	0.0647	1560
HFC158	G1	36.7309	14.8316	(0.0589)	73.0607	57.2845	202.1772	3.3790	78.2167	2.4154	9.5932	4.4887	10.0307	414543
HFC159	G2	4.1353	7.5218	0.0659	6.3775	1.2382	0.5507	0.5982	12.1552	1.9167	18.8970	4.1186	0.2571	13996
HFC160	G1	37.3142	10.2273	(0.0531)	52.0014	36.9897	139.2176	2.3175	54.0673	2.3684	7.4632	3.1117	6.4789	508654
HFC161	G1	33.3681	8.8542	(0.0512)	40.1854	27.6050	140.1170	1.4146	49.1618	2.3893	8.9611	2.9958	4.2186	528150
HFC162	UNASG2	122.6884	10.7982	0.4075	(7.0445)	1.4791	1.7488	2.6774	14.0401	80.0766	30.7321	6.0862	0.3576	525116
HFC163	G1	40.04	13.14	-0.05	55.23	45.28	150.38	3.03	60.38	2.29	8.44	3.99	7.90	478218.22
HFC165	G2	34.51	9.44	-0.05	25.27	19.75	68.95	1.51	34.56	2.28	7.15	2.47	3.46	592554.56
HFC166	G1	25.42	9.13	0.26	20.73	8.85	11.64	1.23	25.68	2.06	21.18	1.44	2.25	554348.50
HFC167	G1	27.04	5.42	-0.05	21.91	15.15	53.63	1.43	24.12	2.43	9.82	2.66	2.66	597078.81
HFC168	G7a	9.63	4.69	0.16	6.20	2.26	4.56	0.57	12.93	3.82	15.93	1.36	0.47	463126.00
HFC169	G1	22.56	21.67	0.35	69.38	30.62	3.18	2.14	77.10	6.50	24.67	2.71	7.30	480935.25
HFC170	G1	33.68	11.26	-0.05	47.08	28.88	117.77	2.13	46.52	2.30	7.73	3.54	4.98	526328.75
HFC171	G1	1458.50	5.80	-0.08	-13.28	2.70	9.58	-0.55	14.05	3.82	44.19	11.33	0.58	405824.28
HFC173	G7a	34.12	16.77	0.39	20.53	8.80	11.93	2.03	41.87	7.35	41.57	4.14	2.13	504173.06
HFC174	G1	1556.53	1.13	0.09	-7.83	0.59	1.20	0.47	2.39	30.64	164.02	-0.43	0.15	590280.56
HFC177	G4	80.09	60.48	1.06	47.39	11.14	6.90	6.40	111.94	36.91	377.32	5.86	2.36	332196.72
HFC178	G7a	286.51	1.70	-0.03	3.52	1.53	9.71	0.32	4.89	0.57	2.28	37.37	-0.05	110249.27
HFC179	G1	85.28	10.54	0.43	14.31	2.12	-0.94	3.30	24.80	29.48	29.86	4.36	0.47	280251.88
HFC180	G7a	5.01	5.61	0.10	6.14	1.31	0.35	0.76	13.94	5.75	23.65	0.27	0.30	20255.15
HFC181	G7a	2.98	9.51	0.20	9.56	2.14	-0.50	1.40	21.73	2.38	29.88	1.85	0.49	15933.43
HFC182	G7a	6.89	27.10	0.21	17.08	3.11	0.96	1.71	38.44	4.57	55.49	1.36	0.64	28439.37

HFC183	G3	32.94	34.91	1.60	50.36	28.53	90.19	3.06	75.38	6.59	65.24	4.17	5.07	574624.69
HFC184	G7a	1274.41	9.50	0.21	15.38	3.59	3.20	1.35	13.75	704.08	26.88	0.48	0.84	551958.00
HFC185	G4	22.65	3.28	0.44	9.82	6.58	31.09	0.60	13.04	2.30	7.34	1.78	1.03	593247.94
HFC186	UNASG2	231.51	18.34	1.25	18.34	5.97	3.09	9.63	39.69	94.75	275.93	5.17	1.70	359105.19
HFC187	G7a	6.71	26.77	0.21	17.63	3.10	1.04	1.52	37.02	4.76	57.93	1.16	0.65	28944.03
HFC188	G7b	6.93	14.40	0.17	8.86	1.96	0.96	1.26	32.70	4.38	48.65	2.70	0.38	32273.81
HFC189	G2	163.16	4.37	0.49	-7.32	0.90	-1.31	3.41	7.01	33.50	51.13	2.28	0.26	556297.19
HFC190	G2	894.14	0.84	-0.05	-7.45	0.33	-1.37	0.48	1.84	15.82	206.12	-0.44	0.09	647205.81
HFC191	G2	6.99	11.42	0.18	8.40	1.93	-0.48	1.43	18.74	2.31	28.70	2.67	0.46	11228.76
HFC192	G7a	8.28	13.22	0.27	11.95	2.41	-0.53	1.95	25.15	2.66	28.89	2.65	0.55	14652.84
HFC193	G7a	-0.09	-0.01	0.00	-0.76	-0.01	-0.07	-0.01	-0.11	-0.01	-0.10	-0.01	-0.01	-6.11
VHC001	G7a	4237.65	13.98	0.33	15.70	3.65	-2.14	2.55	24.96	27.72	58.88	2.89	1.00	558821.88
VHC002	G6a	8209.22	21.60	0.66	24.96	6.23	-2.61	4.87	36.07	38.32	163.81	1.64	1.67	528621.31
VHC003	G7a	133.11	10.68	0.39	12.92	2.46	-1.51	2.93	18.38	33.12	96.56	2.33	0.61	610653.56
VHC004	G4	100.52	1.66	-0.05	-7.29	1.71	-1.55	-0.33	4.69	1.32	6.93	0.98	0.13	692910.56
VHC005	UNAS	107.77	6.82	-0.05	8.01	1.57	2.42	-0.32	9.57	1.47	-2.73	0.68	0.12	692782.69
VHC006	G7a	94.30	42.41	0.64	14.02	3.64	1.16	5.14	16.41	29.78	66.78	-0.48	0.86	648536.31
VHC007	G7b	1452.42	2.41	-0.18	-25.50	3.77	20.32	-1.34	7.12	3.82	12.07	2.48	0.51	653824.94
VHC008	G7a	141.09	5.19	-0.05	-6.91	2.14	-1.29	-0.33	8.00	1.26	2.76	1.27	0.22	688299.50
VHC009	UNAS	114.80	2.57	0.06	-6.22	1.02	5.70	-0.30	12.73	1.99	5.15	1.14	0.08	615630.38
VHC010	UNASG2	137.62	58.98	0.58	30.93	8.33	3.83	3.87	77.01	31.95	481.17	0.72	1.94	357792.00
VHC011	G4	102.13	23.85	0.53	13.32	3.18	5.37	1.34	7.10	2194.94	33.72	-0.82	0.80	624654.75
VHC012	G4	33.30	1.46	-0.04	-5.93	1.23	10.87	0.44	4.46	0.82	18.34	-0.43	0.16	625265.19
VHC013	G7a	21.52	5.41	0.12	6.05	1.70	5.86	0.38	11.75	3.98	30.90	0.63	0.35	512134.25
VHC014	G4	21.30	1.15	0.24	-6.62	3.59	9.55	1.37	4.28	0.72	20.32	-0.44	1.40	644842.75
VHC015	UNAS	31.44	1.38	-0.04	-5.90	1.17	12.97	-0.29	4.04	0.86	10.15	-0.43	0.11	644587.88
VHC016	G6a	607.15	129.11	-0.13	78.58	12.97	8.79	-0.96	189.62	1.99	17.78	1.81	1.00	595408.00
VHC017	G4	7.65	9.41	0.12	8.68	3.28	5.20	0.86	26.76	5.81	17.04	0.63	0.80	579843.19
VHC018	UNASG2	131.42	128.76	0.80	220.87	42.62	2.10	6.59	503.39	14.26	32.10	1.30	9.51	256773.11

Table 1 continued...

ANID	Group	Rb	Sb	Sc	Sr	Ta	Tb	Th	Zn	Zr	Al	Ba	Ca	Dy	K
GKC001	G7a	132.93	185.5400	2.4644	(93.78)	1.0189	0.4339	2.6849	35.19	161.42	18017.1	64.8	2573.1	5.0741	(1533.7)
GKC002	G7a	51.47	3.9738	7.0662	(134.86)	0.2066	0.6876	3.3289	124.32	(86.89)	13943.0	54.8	1937.3	3.6659	(1150.0)
GKC003	G7a	31.03	2.0755	4.1694	(145.67)	(0.1481)	0.9723	2.0140	1906.08	105.51	9834.9	19.2	3329.5	2.4053	(1142.7)
GKC004	G7a	(14.02)	10.3230	8.7172	(154.00)	(0.1531)	0.5012	0.8216	770.13	(98.32)	17394.6	(45.3)	174007.0	6.9314	(1231.5)
GKC005	G7a	(13.48)	11.2799	4.8855	(143.72)	0.1119	0.3487	0.8324	784.70	(92.27)	19044.9	(103.5)	203977.3	5.0612	(3308.7)
GKC006	G6b	(9.82)	7.0276	17.4380	(127.98)	0.2454	1.0994	3.3356	1001.28	(79.11)	11332.5	93.4	7619.6	10.4232	759.1
GKC007	G6a	(8.69)	1.5268	7.6074	192.76	0.2450	1.0427	9.7355	37.21	(64.66)	17448.6	(102.9)	6817.2	6.8785	(2989.7)
GKC008	G6a	(14.02)	93.2439	18.4524	(166.98)	(0.1639)	1.5841	0.7411	552.25	(103.74)	8753.7	25.6	7247.3	6.8086	(2732.9)
GKC009	G7a	(13.57)	97.3885	11.9257	(154.32)	0.2687	1.0373	1.4737	467.34	(96.46)	91912.9	66.4	994.9	3.1212	(1546.4)
GKC010	G7b	(13.85)	94.1982	16.2782	(162.28)	0.2078	1.0955	1.3365	677.21	143.91	61379.1	(63.9)	2873.0	9.2	(2027.3)
GKC011	G6b	(11.03)	4.9350	27.5310	(149.27)	1.0049	0.4016	21.1855	114.60	163.31	19504.1	50.2	4518.5	4.9	1168.8
GKC012	G6b	(13.00)	6.0102	33.2627	(172.19)	1.3118	1.3790	26.9265	295.96	234.27	22118.8	106.5	7073.6	8.2	(2561.5)
HFC001	G7a	82.40	2.1709	7.4846	(96.88)	0.4932	0.6157	6.2355	57.16	115.35	58720.3	199.1	2912.9	3.8179	20828.6
HFC002	G1	77.94	3.0817	2.5514	(119.94)	(0.1430)	5.8471	0.9843	15.53	960.97	28357.4	109.9	72717.1	20.0505	4340.2
HFC003	G1	58.16	5.5998	1.5219	(124.23)	(0.1482)	1.3396	0.5687	(8.40)	317.05	20368.7	9.0	20700.4	5.5022	3221.0
HFC004	G1	40.53	2.8349	2.2762	(118.45)	(0.1422)	4.9812	0.6669	9.28	808.64	20421.2	55.6	66619.9	17.5506	2241.7
HFC005	G3	(10.33)	169.8706	0.9367	(97.69)	(0.1339)	(0.1932)	0.4323	19.81	69.15	14223.8	31.9	1228.8	0.2330	625.0
HFC006	G7a	50.99	8.2405	5.0180	(119.66)	0.3129	0.9072	3.8532	60.17	202.27	25898.8	89.5	3718.7	4.4924	10674.2
HFC007	G2	96.74	0.8987	15.7268	(82.18)	1.2177	1.9990	13.1949	257.76	137.24	86926.8	425.7	124175.8	10.7938	17556.5
HFC008	G2	(2.02)	0.2625	0.5578	(21.70)	(0.0249)	0.0979	0.1377	30.23	(14.98)	13761.1	(45.6)	388814.2	0.6439	(1039.1)
HFC009	G7a	90.58	3.4327	6.5510	(113.36)	0.4522	1.8280	4.1458	104.63	126.10	48263.7	51.2	9843.7	9.2151	16600.9
HFC010	G1	60.65	4.1532	1.9858	(123.23)	(0.1451)	2.9248	0.7856	(8.23)	569.87	15931.4	480.8	40003.3	11.3427	2731.8
HFC011	G7a	58.61	3.4847	3.4879	(107.82)	0.3889	0.2819	3.4519	35.39	(81.89)	32753.8	84.4	2104.2	2.2082	9645.9
HFC012	G1	54.33	4.3670	1.6891	(119.76)	(0.1430)	5.3588	1.0154	11.52	995.04	17855.1	718.6	73624.7	20.5940	2215.2
HFC013	G1	92.95	3.8707	2.4437	(122.17)	(0.1429)	2.9378	0.8931	9.62	407.95	23028.4	267.8	35016.0	11.0572	7260.0
HFC014	UNASMAJ	56.29	39.8062	12.0044	(253.83)	1.1041	193.1033	58.7563	554.70	2280.34	27890.0	301.3	2039.1	1002.08	5205.2
HFC015	G7a	62.01	3.7930	7.8318	(116.31)	0.2672	2.1088	3.1315	109.35	162.97	40687.5	70.0	29414.1	10.3373	12573.8
HFC016	G7a	39.78	6.1184	4.6101	(119.80)	0.1835	1.2103	1.9260	75.06	92.28	29881.8	39.8	7405.1	6.6192	7952.5

HFC017	G7a	56.35	4.2442	6.1412	(104.66)	0.9064	0.4802	7.1905	23.06	138.15	53424.5	204.2	2846.9	3.1493	19228.9
HFC018	UNASMAJ	127.14	3.1243	9.8611	(100.65)	0.7477	2.4970	6.6241	56.51	124.68	67108.0	194.3	11721.3	11.6945	30886.6
HFC019	G7a	66.14	15.6332	6.1485	(122.53)	0.1290	0.5038	4.3944	50.88	264.04	35199.0	59.8	829.8	2.6543	11607.0
HFC020	G1	(14.51)	4.5916	3.0979	(129.56)	(0.1532)	5.8153	0.2851	31.76	216.38	18569.7	(56.8)	31762.3	24.7078	(1350.6)
HFC021	G7a	76.78	5.1460	8.2083	(106.93)	0.5753	0.7443	4.8074	217.73	(79.43)	55801.6	230.2	5169.3	3.6153	24741.7
HFC022	G7a	57.17	2.8997	4.5684	(102.96)	0.2711	1.2452	2.8240	58.81	90.59	33789.4	141.2	84604.5	6.4553	12779.1
HFC023	G7a	52.62	16.6097	6.0348	(124.59)	(0.1438)	0.3365	4.2381	53.87	244.37	29105.4	120.6	4019.1	2.1260	8450.4
HFC024	G1	57.41	3.5515	2.2171	(120.54)	(0.1402)	3.3503	0.7046	15.20	575.23	16893.9	540.0	49963.4	12.6532	3062.0
HFC025	G7a	50.15	6.4435	4.7682	(120.90)	(0.1386)	0.8774	1.9089	60.79	62.49	33175.3	94.6	6344.4	5.1183	7401.2
HFC026	G1	61.35	3.4944	2.0865	(120.32)	(0.1417)	2.7023	0.5164	(7.93)	450.78	19886.5	304.6	41628.9	9.8271	3051.0
HFC027	G1	56.86	4.7255	1.5254	(121.73)	(0.1446)	3.1966	0.9574	(8.00)	659.17	16579.6	473.3	50450.3	11.7054	2696.8
HFC028	G1	51.42	3.8107	2.3081	(123.85)	(0.1435)	2.9476	0.6094	14.02	559.32	16525.4	354.3	42349.4	10.7332	1386.7
HFC029	UNAS	19.46	0.8859	8.7210	(74.21)	0.3069	0.6127	3.5573	431.82	(52.65)	27392.3	18.1	278471.8	3.8491	(1442.5)
HFC030	G7a	64.90	4.5597	9.0873	(117.02)	0.4078	1.4343	4.2929	211.92	154.50	40154.9	143.1	5014.9	7.7299	15335.4
HFC031	G4	17.89	233.7938	2.0703	(117.81)	(0.1583)	0.2035	1.0256	38.72	96.56	10033.2	(48.7)	760.8	0.9556	347.1
HFC032	G7a	68.59	4.0749	3.9393	(116.14)	(0.1346)	0.2511	2.2795	26.28	53.93	31301.8	106.2	1917.5	1.6342	5518.8
HFC033	G7a	90.66	2.7620	7.3126	(114.14)	0.3694	3.7897	3.7620	78.02	193.35	39779.2	131.3	11348.2	17.8450	13246.8
HFC034	G7a	(15.88)	20.0020	10.1681	(140.33)	(0.1561)	0.8791	10.6839	57.89	192.05	19590.7	(209.7)	1881.2	4.9110	(6819.1)
HFC035	G1	41.41	4.5944	1.6524	(122.19)	(0.1415)	4.3079	1.0772	10.31	857.85	16559.5	495.2	61873.7	16.3237	3376.3
HFC036	G2	106.03	0.9808	13.0648	(74.62)	1.5683	1.1888	14.7881	94.67	325.70	71603.7	273.9	7071.0	7.6541	17198.6
HFC037	G7a	44.78	5.3623	6.2040	(117.59)	0.1858	0.6506	2.8847	114.32	149.94	27800.1	81.8	2837.3	3.8377	9217.2
HFC038	G1	69.98	3.4796	2.0534	(119.72)	(0.1384)	2.1911	0.5559	(7.75)	511.83	20321.8	351.7	40859.9	9.1477	4130.9
HFC039	G2	218.51	0.8361	14.8132	39.22	1.5332	0.9243	16.4297	131.33	99.66	99219.1	406.4	6852.6	5.1996	35792.5
HFC040	G1	56.89	3.6635	2.0682	(121.27)	(0.1410)	4.3449	1.0803	11.45	684.70	13491.3	337.9	61786.0	16.4768	3533.1
HFC041	G7b	(14.79)	3.9827	15.2391	(137.84)	(0.1408)	1.1880	1.7422	1595.39	(100.42)	19612.9	16.9	14599.0	9.2381	1273.1
HFC042	G2	30.51	0.1148	2.3572	35.67	0.1373	0.1739	1.6247	71.85	(21.82)	18828.6	32.9	364170.8	1.0345	5716.1
HFC043	G1	52.59	4.2364	1.8763	(121.65)	(0.1414)	3.7220	0.9433	7.71	731.91	14600.5	491.1	55564.9	14.7150	3565.7
HFC044	G2	3.75	0.2827	3.6784	(41.40)	0.0847	0.2255	1.0857	151.26	22.23	15872.2	(46.4)	383710.4	1.9167	(1248.5)
HFC045	G2	20.16	0.4908	6.2205	(53.08)	0.4133	0.3898	3.8161	264.16	81.42	31321.1	(57.9)	335352.4	2.5220	(1619.8)
HFC046	G1	119.41	2.7691	2.8311	(116.33)	(0.1371)	8.2816	1.7336	34.48	905.55	25028.5	649.9	104207.2	31.2717	8168.0
HFC047	G7a	(16.10)	6.2751	5.4638	(133.17)	(0.1523)	0.3339	0.6644	1053.63	(99.11)	9584.6	(41.2)	6778.8	3.3417	(900.0)

HFC048	G7a	16.93	4.9592	7.4086	(130.33)	(0.1506)	0.5279	1.9383	586.15	(97.28)	22999.0	(60.4)	3580.3	3.6719	(1709.2)
HFC049	G2	341.97	2.7903	3.4520	(44.22)	2.2942	0.7547	12.6236	30.74	71.88	69384.8	155.3	1395.6	4.4318	40014.6
HFC050	G7b	(14.75)	5.0107	12.0843	(131.66)	0.5019	0.7156	6.4480	1352.79	(95.67)	44024.4	30.6	8858.6	3.7142	1068.9
HFC051	G1	84.77	3.9191	1.7596	(140.58)	(0.1437)	7.0913	1.1033	(9.80)	1185.49	16040.6	118.9	103744.2	26.1543	4359.3
HFC052	G6a	(12.78)	3.1377	19.2601	(151.07)	1.3293	1.6714	11.4902	953.63	79.14	75124.5	37.4	7855.9	10.5768	(1577.5)
HFC053	G6a	(12.98)	3.4004	19.0680	(152.41)	1.2069	1.3667	12.7109	944.85	148.59	75382.6	47.6	2748.4	10.2847	(1687.6)
HFC054	G6a	(12.60)	3.1463	16.7951	(145.81)	0.9628	1.7120	11.2706	913.40	133.49	71810.9	38.7	23418.3	11.1291	(1694.6)
HFC055	G2	25.68	0.1689	3.6673	(55.99)	0.3534	0.3174	4.6084	116.84	110.92	17420.4	173.3	1807.6	2.4369	4341.6
HFC057	G7a	(13.27)	3.2508	23.5993	(160.38)	1.2722	1.8792	16.0672	1189.17	95.29	80121.1	87.1	10521.8	11.1796	(1563.8)
HFC058	G6a	(12.98)	3.8027	17.9169	(150.33)	1.1021	1.7155	12.6339	940.07	139.24	75297.5	73.1	4317.0	11.8594	1047.2
HFC059	G6a	18.13	0.2893	3.3411	(44.95)	0.3190	0.3912	2.6154	150.61	(25.36)	26876.5	18.8	376883.6	2.8323	(1363.6)
HFC060	G2	6.62	0.3146	3.9095	(49.01)	0.1205	0.3197	1.1951	195.18	(27.69)	15229.4	26.6	381250.3	1.9075	(1318.8)
HFC061	G2	10.33	0.3601	4.2504	(50.51)	0.2353	0.1874	2.2465	144.19	(28.32)	19792.5	(48.9)	363875.5	1.5145	685.5
HFC062	G2	(3.69)	0.4722	4.5123	(53.82)	0.2206	0.4768	1.6369	128.98	52.58	10973.6	(51.0)	241065.0	2.6260	(1343.2)
HFC063	G2	9.18	0.1725	4.6877	(48.66)	0.1425	0.3592	1.0805	127.51	(26.76)	13686.4	(47.0)	373314.5	2.1393	408.4
HFC064	G2	18.10	0.3019	4.3379	(49.10)	0.3140	0.3856	3.0134	85.96	(27.76)	26998.6	(48.9)	350297.3	2.2046	(1525.6)
HFC065	G2	17.63	1.4329	16.0087	(144.43)	1.1746	1.4979	10.5962	956.99	100.61	71581.4	68.3	15111.0	10.0877	(1612.0)
HFC066	G6a	(13.28)	3.0338	44.5788	(182.72)	1.2568	0.5535	14.9308	432.26	160.62	89064.4	59.5	2711.0	5.0419	(3240.7)
HFC067	UNAS	(13.02)	1.7955	18.3128	(149.36)	1.3821	1.5718	12.1285	975.93	(89.07)	79707.0	49.3	7337.8	10.5483	(1701.4)
HFC068	G6a	334.36	6.7531	3.5042	(57.12)	1.8997	0.7992	11.9118	24.50	48.34	64187.2	165.3	1451.9	5.5742	42787.1
HFC069	G2	216.27	125.0849	2.6057	(92.12)	1.4829	0.2523	3.4183	45.14	85.04	33429.8	97.7	3071.7	1.6472	19304.6
HFC070	G7a	(16.73)	24.7592	9.9341	(163.45)	(0.1555)	0.9690	12.4749	41.35	130.90	8337.9	(175.1)	(1388.4)	5.5565	(5979.4)
HFC071	G7a	9.17	0.1748	4.9853	(52.76)	0.1511	0.5417	1.4340	250.41	32.34	14473.1	(63.6)	376429.4	3.2889	(2012.6)
HFC072	UNASMAJ	19.24	0.4926	5.2557	(57.35)	0.4083	0.3742	3.6218	147.05	(32.53)	30972.2	(50.0)	328409.0	2.1854	1544.2
HFC073	G2	16.29	0.4075	5.5623	(56.92)	0.3474	0.4444	3.9335	175.21	44.89	30526.7	14.5	336825.7	2.4203	2364.6
HFC074	G2	22.40	4.2565	15.6829	(158.70)	(0.1392)	0.7817	3.0955	1176.84	(95.31)	20018.7	(55.0)	24154.9	3.8930	(1670.3)
HFC075	G7b	25.18	0.3081	7.4968	(93.86)	0.3670	0.2937	9.3368	317.58	113.69	15185.0	138.4	4265.7	2.5420	4141.6
HFC076	G6a	(17.39)	349.5633	0.7804	(166.40)	(0.1979)	(0.3171)	0.2811	116.61	125.36	6446.0	(65.0)	(735.6)	0.3786	(1552.8)
HFC077	G5	58.55	0.9965	6.7503	(100.91)	0.5448	0.5088	5.0559	554.49	104.43	38527.0	83.7	141865.4	3.2252	5314.5
HFC078	G6a	(16.34)	34.8162	17.9928	(170.48)	0.4095	0.8826	1.1521	893.62	(102.02)	19849.8	127.4	6353.8	7.1251	(6066.2)
HFC079	G7b	12.71	0.2439	6.2961	(59.98)	0.2980	0.2719	2.8850	191.80	(34.14)	20853.6	(48.3)	344541.3	1.7878	(1577.8)

HFC080	G2	(16.33)	14.8799	6.1308	(152.71)	(0.1396)	0.5329	2.2711	63.66	71.77	10841.8	(88.1)	(816.5)	2.0674	959.2
HFC081	G7a	24.22	0.8653	6.4180	(70.29)	0.5295	0.5073	4.3801	266.46	(40.87)	30129.3	(67.6)	301777.4	3.2346	(2204.6)
HFC082	G2	26.71	0.8894	6.3192	(71.28)	0.5378	0.4156	4.3655	372.02	74.91	28635.9	(71.5)	295679.5	3.0088	(2371.1)
HFC083	G2	22.75	0.9373	6.2603	(77.31)	0.5337	0.4417	4.5912	309.65	53.69	32599.2	54.8	299962.1	3.0630	(2157.7)
HFC084	G2	(14.81)	7.9619	34.5620	(179.95)	0.8373	3.2325	22.5147	398.95	273.33	76065.4	(82.2)	1401.7	19.9864	(2620.6)
HFC085	G2	18.55	349.7852	0.5106	(168.48)	(0.1985)	(0.3210)	(0.2639)	114.60	(99.10)	5548.8	35.3	(788.9)	0.4137	(1500.8)
HFC086	G5	(2.98)	0.3318	2.6904	(41.19)	0.2005	0.1876	1.2606	69.80	79.49	7348.6	(42.4)	228357.8	1.4681	(1137.7)
HFC087	G2	(2.04)	0.1836	1.1330	(27.82)	0.1442	0.0914	1.0605	21.19	41.85	4965.6	(64.1)	233494.9	0.5238	(2055.8)
HFC088	G2	21.65	0.4026	3.9248	(50.70)	0.2686	0.2611	2.3044	142.27	(28.61)	24320.0	(47.6)	347771.2	1.8391	2208.4
HFC089	G2	20.91	0.3413	3.8522	(49.46)	0.2354	0.2459	2.2524	140.36	(27.80)	23051.7	55.2	356916.0	1.8463	1706.4
HFC090	G2	18.80	0.4351	6.9441	(63.92)	0.5429	0.4937	4.9739	154.84	69.82	35937.2	(54.5)	315035.6	2.9075	1937.9
HFC091	G2	(18.16)	275.9200	0.6616	(164.43)	(0.1867)	(0.3177)	(0.2574)	83.05	101.24	3986.7	(72.2)	948.3	(0.2933)	(2258.0)
HFC092	G5	26.72	0.5211	7.5756	(68.02)	0.5724	0.6565	5.3590	167.73	66.29	37401.5	16.8	294462.4	3.8138	2617.1
HFC093	G2	(20.13)	3.3434	9.6912	(178.23)	(0.1860)	0.3730	1.1850	657.95	(108.73)	10231.3	(199.7)	3967.2	3.0010	(6826.1)
HFC094	G7a	15.86	0.4302	6.8187	(64.34)	0.5508	0.4172	4.9042	159.28	72.47	35951.4	(53.4)	328484.3	3.0149	943.4
HFC095	G2	16.28	0.2986	5.4197	(54.63)	0.4087	0.3667	3.6689	148.58	60.15	30115.6	59.3	357360.5	2.2339	774.5
HFC096	G2	26.14	0.4646	5.4226	(56.81)	0.4415	0.4731	3.6017	160.13	44.55	27198.3	31.4	357142.4	2.5770	1567.0
HFC097	G2	(2.22)	0.1924	1.7132	(32.30)	0.1126	0.2508	0.9879	36.93	36.03	5597.6	(41.3)	239795.5	1.4214	(1057.6)
HFC100	G2	(16.42)	4.8427	8.9687	(152.41)	(0.1360)	(0.3044)	2.0429	1067.56	(92.66)	17132.4	28.3	4472.5	3.7750	(1057.8)
HFC101	G2	(16.75)	10.2402	8.2613	(154.87)	(0.1388)	0.6971	1.1205	1470.45	(94.14)	20584.8	(40.59)	3579.9	4.4998	744.4
HFC102	G2	(18.69)	3.9442	0.9370	(155.61)	(0.1508)	(0.3220)	0.6261	506.43	(97.36)	12056.7	52.42	4077.0	0.5646	(1399.1)
HFC103	G7a	(17.30)	6.8390	7.8078	(156.88)	0.1358	1.1224	2.0570	1348.31	(95.83)	24301.1	(41.35)	4101.2	8.2180	(833.7)
HFC104	G7a	(12.79)	11.4074	2.9203	(134.54)	(0.1499)	(0.2850)	0.3351	1366.17	(99.92)	10840.0	(45.28)	8700.4	1.9032	(955.7)
HFC105	G3	(11.79)	7.3954	4.8400	(126.15)	0.3943	0.7091	3.3088	1058.93	(92.69)	35992.0	(43.06)	2002.7	4.6504	(1048.0)
HFC107	G7a	0.00	1.6014	4.4048	0.00	0.5549	0.0000	2.6678	1038.90	0.00	30091.5	258.59	111887.1	2.2319	2872.9
HFC108	G4	15.40	0.2532	11.4472	193.73	0.2764	1.2516	4.6415	242.58	89.51	14933.2	190.4815	95473.5	7.0955	(5437.5)
HFC109	G7a	31.75	0.1425	2.4498	45.16	0.1562	0.2244	1.7322	69.27	(22.76)	19284.8	27.74	335364.8	1.1717	5693.5
HFC110	G6a	18.14	9.2769	2.9086	(127.42)	(0.1352)	0.3253	0.9298	83.30	(95.09)	15274.9	82.21	14226.8	1.5688	(1278.6)
HFC111	G6a	66.82	4.6446	1.7751	(130.72)	(0.1458)	2.2901	0.7368	12.57	422.44	14852.8	278.7894	31975.0	7.7143	4035.0
HFC112	G2	57.56	13.1426	5.4629	(126.94)	0.1798	0.2359	4.7738	68.87	242.06	25836.6	180.7517	1770.4	2.0336	11192.0
HFC113	G2	222.51	70.5632	3.1944	(85.31)	1.6937	0.7201	2.9002	39.95	281.63	39353.8	142.0000	2230.8	5.6307	15498.8

HFC114	G4	34.29	0.1801	2.4620	(37.65)	0.1828	0.1202	1.7706	74.77	(24.47)	21121.0	37.2899	344707.2	1.1908	5371.5
HFC115	G1	53.64	4.8005	1.4522	(129.69)	(0.1457)	3.4306	0.8335	12.62	694.16	15545.8	506.7196	53703.4	12.7434	3626.7
HFC116	G7a	71.55	10.5097	6.1063	(123.79)	0.2614	0.5050	5.0610	63.74	185.85	31754.7	170.4852	2201.3	2.3379	16174.3
HFC117	G7a	(1.91)	0.1067	1.7958	(29.33)	(0.0239)	0.2828	0.1919	37.76	(19.17)	5619.9	(26.7227)	392040.5	2.2803	(3012.9)
HFC118	G2	62.42	3.3411	6.8684	(119.73)	0.5176	1.7731	3.9599	59.89	215.55	33066.3	121.35	6371.3	8.8071	12226.9
HFC119	G1	42.06	3.9336	1.9046	(129.42)	(0.1420)	2.0578	0.4932	(9.53)	447.02	11491.4	365.0286	38830.9	9.1682	2379.0
HFC120	G7a	69.10	3.5917	4.8939	(120.00)	0.4027	1.1023	3.7646	91.79	125.42	33297.2	164.3747	7790.7	6.7056	17399.1
HFC121	G2	26.38	2.1242	23.6826	162.47	(0.1480)	3.5592	2.3764	415.11	(104.94)	5943.5	102.0483	(651.9)	0.2278	(526.4)
HFC122	G7a	48.53	1.4016	3.2897	109.90	0.4242	0.1526	13.6542	280.64	137.76	24865.5	104.64	48231.1	1.9280	1513.6
HFC123	G1	364.79	41.0376	3.3954	81.93	3.6855	0.4084	5.8053	77.02	57.89	60103.6	73.1348	1427.0	2.0842	27310.6
HFC124	G7a	24.76	0.1088	1.8470	(31.33)	0.1074	0.1747	1.2045	63.05	(20.25)	17974.4	32.6814	359350.5	0.9582	3641.7
HFC125	UNASMAJ	10.71	0.1045	1.7017	(29.27)	0.1360	0.1295	1.1689	111.98	(19.53)	17500.2	(27.9090)	379969.9	0.9204	874.7
HFC126	G7a	76.71	7.2126	5.4018	(121.94)	0.3513	1.2699	4.4501	73.02	127.97	36104.7	133.6240	4123.9	7.2331	15866.7
HFC127	G2	46.05	1599.2640	5.2133	(220.62)	(0.3662)	0.6337	1.2348	66.72	170.41	9968.9	(65.59)	2326.5	4.1600	1982.5
HFC128	G2	(4.03)	0.4555	11.3925	1107.37	0.0606	0.9031	14.7073	153.06	293.44	13446.6	(78.32)	234578.9	5.1468	(2174.2)
HFC129	G2	40.84	2.2374	11.1058	(98.49)	(0.0905)	0.6160	1.6206	584.29	(69.77)	14087.4	42.67	223329.8	4.1415	3572.6
HFC130	G7a	2.33	(0.0437)	1.5307	(26.99)	0.0160	0.1953	0.4888	106.78	(17.72)	6972.1	(55.61)	386195.6	1.1614	(1190.6)
HFC131	G7a	62.93	13.6630	6.7993	(124.61)	0.2983	0.2902	4.8776	51.93	198.06	31934.2	173.2894	1768.5	2.7181	15643.5
HFC132	G2	(9.24)	10.9810	13.6975	(109.42)	(0.1005)	0.8684	0.1562	672.40	(77.51)	6404.9	(101.67)	243760.7	6.8876	(3517.8)
HFC133	G6a	(15.64)	5.5481	0.2532	(143.71)	(0.1760)	(0.3017)	(0.2027)	192.16	(107.31)	7051.6	(49.78)	5241.5	0.4198	(1127.4)
HFC134	G2	16.24	0.2641	1.0678	116.48	0.0580	0.0975	0.6785	72.40	(19.83)	10524.5	(59.94)	381591.8	0.6125	4326.2
HFC135	G7a	21.97	2.0795	7.8891	(137.15)	0.2822	0.6432	4.6087	1770.56	(99.93)	28662.0	47.48	1844.0	4.5660	1931.3
HFC136	UNAS	(13.56)	3.6153	14.2864	(149.96)	(0.1611)	7.6296	2.2465	82.82	295.56	15311.8	242.9112	48868.4	40.0788	2172.9
HFC137	UNASMAJ	(14.29)	10.2663	3.0920	(135.04)	(0.1510)	(0.2848)	0.4222	990.94	(99.85)	9263.0	81.56	6864.3	1.7310	(1496.0)
HFC138	G2	41.65	5.4772	1.3696	(130.48)	(0.1447)	2.9232	0.4413	(9.42)	594.84	10505.3	359.1244	42705.4	10.2827	3411.3
HFC139	G7a	53.17	3.4152	2.2788	(128.54)	(0.1439)	4.3437	0.8304	15.08	796.47	13247.0	612.4744	71486.7	16.6869	2296.3
HFC141	UNASMAJ	27.10	5.4895	1.5054	(134.94)	(0.1462)	2.2272	0.5709	(9.65)	516.71	10690.8	444.3816	42660.8	10.2561	2329.2
HFC142	G4	100.78	3.8350	2.3909	(127.11)	(0.1422)	5.2322	1.8461	18.80	709.17	19575.8	496.7740	63046.2	19.9842	7877.5
HFC143	G1	9.52	0.1577	1.5089	(28.36)	0.1212	0.1355	1.0194	68.23	(19.04)	11838.9	(27.0851)	386154.3	0.7840	(1404.1)
HFC144	G1	43.60	5.2386	1.6746	(128.30)	0.1252	3.0588	0.7319	(9.25)	747.83	12266.6	504.7661	53693.0	12.9031	4265.6
HFC145	G1	35.83	4.4961	1.9285	(129.75)	(0.1406)	2.3236	0.7002	(9.32)	458.75	11146.7	348.5702	39781.5	9.3541	2277.7

HFC146	G1	29.27	2.7820	3.6205	383.08	0.1703	1.6213	1.4863	44.49	133.21	18261.7	44.64	223863.1	7.8781	7480.7
HFC147	G1	35.73	4.1797	1.3588	(131.07)	(0.1438)	2.9041	0.8287	(9.47)	455.67	9899.4	407.9833	42936.1	10.8903	1109.1
HFC148	G2	88.93	3.1422	2.5937	(125.23)	(0.1431)	8.9646	1.5275	45.45	1326.84	16023.3	982.6389	116002.2	34.3134	6534.0
HFC149	G1	105.80	4.1180	2.2918	(122.73)	(0.1384)	5.8431	1.6979	38.10	989.33	18438.2	685.5400	96624.1	24.4681	8201.0
HFC150	G1	74.43	2.6837	2.5745	(130.04)	0.1249	6.3459	1.0198	12.58	963.07	12855.0	735.1821	83781.5	23.0613	6088.1
HFC151	G7a	59.76	4.6632	1.5852	(126.26)	(0.1432)	7.2480	1.2327	21.55	1288.32	12536.4	936.3586	105130.4	28.1663	3298.4
HFC152	G1	64.14	2.6572	2.4565	(126.95)	(0.1427)	6.4738	0.8838	12.46	909.28	3637.7	610.0971	744.3	0.1092	(293.9)
HFC153	G1	63.09	3.5097	2.3740	(129.55)	(0.1439)	4.9844	0.8960	20.87	989.08	11494.1	812.1379	72455.6	18.4107	2302.8
HFC154	G1	32.26	0.1103	2.5248	28.43	0.1634	0.1855	1.7663	65.07	(23.57)	17619.6	34.07	357099.7	1.0108	6084.3
HFC155	G1	75.96	4.1298	1.7886	(127.68)	(0.1411)	5.4350	1.0037	17.20	953.76	15189.6	741.0439	81110.1	21.3657	5265.5
HFC156	G1	66.13	3.4998	1.9517	(134.64)	(0.1475)	6.5531	1.1900	15.81	1386.98	12658.4	1031.9406	107786.4	23.9196	5363.2
HFC157	G1	(1.34)	0.0418	0.2299	123.43	(0.0188)	0.0525	0.1642	9.64	(8.75)	2880.7	(19.7616)	385471.0	0.3473	(1397.1)
HFC158	G1	71.13	3.0053	2.3017	(133.23)	0.2747	9.7871	1.2258	29.20	1274.45	10703.9	925.7690	124716.8	36.1032	5786.5
HFC159	G2	31.61	0.2098	2.6422	53.96	0.1760	0.1197	1.8318	51.10	(22.87)	18122.1	33.41	353584.5	1.0706	7325.7
HFC160	G1	57.20	4.2016	1.8462	(136.76)	(0.1448)	6.1983	1.1116	19.79	843.31	14172.1	679.7157	78571.0	22.7393	5116.7
HFC161	G1	50.67	4.7791	1.7381	(136.66)	0.1044	3.9169	0.8136	13.02	830.23	13571.5	626.5848	67473.9	12.3253	4639.5
HFC162	UNASG2	31.74	7.1326	6.6623	(143.54)	0.2131	(0.2964)	2.1537	1442.00	(91.03)	21687.5	66.58	6256.8	2.7525	2166.3
HFC163	G1	65.18	3.50	2.16	-135.06	-0.14	7.73	1.56	18.14	963.70	9747.54	657.08	75133.38	21.60	4068.45
HFC165	G2	44.76	5.37	1.77	-140.68	-0.15	3.27	1.15	-9.41	435.31	10026.77	362.90	38636.21	11.75	3985.04
HFC166	G1	40.95	5.96	4.37	-134.60	-0.14	1.45	1.75	63.48	126.72	21151.82	116.04	7476.22	6.34	8265.95
HFC167	G1	65.70	3.63	2.08	-139.51	-0.14	2.35	0.84	13.98	295.55	9165.80	308.22	28688.34	9.06	4346.98
HFC168	G7a	35.38	1.69	2.18	-118.66	-0.12	0.37	2.02	38.94	-78.16	22568.80	178.24	6455.54	1.73	10389.31
HFC169	G1	60.14	3.39	6.59	-133.71	0.29	3.73	2.65	179.99	150.74	27712.52	119.97	20278.26	16.07	-6606.20
HFC170	G1	63.56	4.21	1.80	-135.58	-0.14	4.45	1.04	16.03	691.80	10582.76	524.51	65002.21	18.32	4606.87
HFC171	G1	82.54	468.71	6.83	-148.35	-0.20	-0.27	9.48	214.04	99.34	17311.19	468.00	1956.22	1.38	10702.56
HFC173	G7a	94.06	4.22	6.55	-143.83	0.29	1.19	4.12	111.58	165.54	34676.24	274.56	30530.54	5.79	15373.35
HFC174	G1	-12.49	4.90	1.45	-136.80	-0.13	-0.29	-0.21	233.80	-89.01	3146.89	-46.99	2043.58	1.08	-965.46
HFC177	G4	48.76	2.46	61.13	-194.79	2.86	1.52	23.21	865.69	377.54	23810.29	-64.53	171046.67	3.73	-1729.99
HFC178	G7a	148.06	105.87	2.52	-76.29	1.09	0.19	2.01	38.05	49.86	5206.56	-50.91	233830.48	1.46	565.36
HFC179	G1	17.56	1.51	8.68	-110.49	0.33	0.38	3.58	788.95	-68.96	22116.00	-56.02	360896.75	2.59	-1635.01
HFC180	G7a	-2.69	0.56	2.20	-39.13	0.10	0.21	1.39	95.29	41.44	32930.73	-52.81	325558.06	3.03	-1655.57

HFC181	G7a	11.84	0.34	4.90	-49.50	0.29	0.55	2.66	176.67	27.82	31762.41	-54.22	320733.56	3.04	-1567.58
HFC182	G7a	8.92	0.95	6.49	-58.09	0.49	0.52	4.36	174.17	50.58	9418.93	14.77	17889.19	3.50	207.86
HFC183	G3	70.49	5.36	8.51	-152.47	0.58	4.68	5.19	171.89	618.25	10637.97	413.86	14319.47	3.64	1789.76
HFC184	G7a	-17.71	14.37	3.53	-187.87	-0.23	-0.38	0.54	2912.33	-118.83	77694.88	1336.16	4622.19	12.68	-9840.11
HFC185	G4	50.13	4.51	1.73	-134.67	-0.14	0.91	0.51	-8.90	221.21	33319.04	-54.81	325092.66	2.98	-1595.02
HFC186	UNASG2	47.48	0.68	14.26	-144.91	0.77	1.80	42.95	3240.01	127.44	34538.05	1214.75	312687.78	2.17	1413.22
HFC187	G7a	5.72	0.90	6.56	-58.61	0.48	0.50	4.28	195.59	52.27	11045.75	37.10	2964.56	2.11	-864.96
HFC188	G7b	19.66	0.46	4.52	-52.68	0.43	0.34	4.29	180.04	59.60	4888.71	31.95	6700.35	0.67	-1359.28
HFC189	G2	-12.98	11.41	10.41	-150.60	-0.14	-0.31	1.16	1239.66	-95.59	21729.30	24.96	353858.38	2.30	681.18
HFC190	G2	-13.63	4.98	1.21	-143.01	-0.14	-0.31	0.21	412.39	-93.79	22386.22	-50.69	346179.50	3.32	-1320.24
HFC191	G2	18.15	0.42	3.99	-45.31	0.24	0.33	2.46	110.00	-26.26	11187.20	53.95	55662.46	15.39	5444.77
HFC192	G7a	16.88	0.45	4.78	-48.73	0.23	0.52	2.56	126.36	24.77	26457.17	-44.18	976.06	2.27	10979.64
HFC193	G7a	-0.23	-0.02	0.00	-4.65	-0.01	0.00	-0.01	-0.28	-2.20	29898.79	84.57	1977.10	3.72	9449.27
VHC001	G7a	30.51	125.19	9.45	-152.82	0.23	0.75	1.27	347.36	-95.46	18500.74	87.20	7599.44	3.78	-3047.01
VHC002	G6a	-13.85	73.86	21.33	-166.57	0.45	1.06	2.22	721.41	-103.13	8285.57	-38.51	-617.02	0.47	-946.42
VHC003	G7a	34.24	4.99	8.29	-152.00	-0.15	0.47	2.85	373.04	-97.95	8189.48	-37.66	-676.08	0.35	1462.06
VHC004	G4	-14.97	35.97	3.77	-152.22	-0.15	-0.32	2.09	-9.74	-98.80	6079.02	-36.81	-436.34	0.58	-884.85
VHC005	UNAS	-15.68	36.21	4.91	-146.22	-0.16	-0.31	1.06	-11.10	-100.12	6262.35	-37.08	-456.18	0.62	508.15
VHC006	G7a	-15.61	11.87	13.20	-156.52	-0.16	0.53	1.56	1085.41	-105.12	6989.05	-188.49	3892.71	4.49	-6823.62
VHC007	G7b	-21.56	2113.37	22.26	-268.15	-0.45	-0.42	22.39	128.73	136.45	8265.35	813.88	-802.30	1.45	-2745.89
VHC008	G7a	-15.91	48.29	6.17	-149.53	-0.16	-0.32	2.65	-11.29	-101.71	6242.82	-43.13	-624.76	0.52	-938.30
VHC009	UNAS	-14.87	22.49	5.10	-138.19	-0.14	-0.30	0.29	-10.41	-94.58	6081.15	19.30	1389.55	0.23	1585.43
VHC010	UNASG2	-13.01	4.95	57.91	-180.37	1.32	1.35	23.87	282.54	153.26	99639.30	49.58	2743.01	7.64	-2278.79
VHC011	G4	-32.13	30.67	3.06	-272.04	-0.42	-0.53	2.28	1725.65	-180.50	14982.29	132.84	10393.63	3.09	-3331.32
VHC012	G4	-14.83	4.89	3.19	-133.32	-0.14	-0.29	1.46	18.95	-92.46	15054.19	26.07	1926.72	1.22	2727.84
VHC013	G7a	27.88	3.62	6.56	-126.75	-0.13	-0.27	3.69	103.99	-86.89	34404.64	77.50	5386.98	1.16	4933.53
VHC014	G4	-15.25	3.18	2.71	-136.88	-0.15	1.10	0.91	-10.62	-94.92	10278.79	-37.53	11299.92	5.35	977.66
VHC015	UNAS	25.45	2.94	2.48	-133.48	-0.14	-0.29	0.49	-10.34	-93.11	12337.57	43.67	2122.09	0.26	2142.88
VHC016	G6a	-18.94	1262.07	28.00	-227.79	-0.35	-0.38	18.21	-15.94	-130.25	7170.62	61.82	954.36	0.81	1225.87
VHC017	G4	-15.35	2.74	3.05	-135.82	0.32	0.37	3.98	20.17	-94.59	19293.85	52.45	6672.63	2.14	-2059.18
VHC018	UNASG2	-10.91	0.93	26.31	259.65	0.43	5.59	2.21	599.79	167.77	23114.38	-249.08	163585.28	23.68	-7867.10

Table 1 continued...

ANID	Group	Mn	Na	Ti	V	Ni	Hf
GKC001	G7a	273.09	1068.8700	999.0	137.62	(58.64)	3.1151
GKC002	G7a	142.61	807.5049	371.9	420.56	(100.11)	1.3478
GKC003	G7a	152.03	70.1000	339.8	173.72	211.48	0.8326
GKC004	G7a	98.18	100.4181	829.9	517.77	331.72	0.5643
GKC005	G7a	1278.42	136.5932	1032.2	682.47	348.48	0.3509
GKC006	G6b	694.39	100.5246	(765.4)	724.30	211.03	0.7865
GKC007	G6a	1088.11	416.8477	209.2	429.15	(73.00)	1.2338
GKC008	G6a	918.05	497.0527	(865.5)	1067.03	227.89	0.6497
GKC009	G7a	179.11	598.2466	4115.2	1123.93	216.13	0.7392
GKC010	G7b	376.8	2036.6998	4558.0	1224.2	236.32	0.8249
GKC011	G6b	623.9	315.3552	588.2	410.9	(101.29)	5.2052
GKC012	G6b	632.3	115.0096	1155.3	670.4	(117.76)	10.4323
HFC001	G7a	120.9	4670.8	2196.3	381.3	(92.99)	3.5086
HFC002	G1	228.6	255.8	(505.6)	325.3	(115.97)	(0.1992)
HFC003	G1	96.8	111.7	(381.2)	506.7	(124.98)	0.2314
HFC004	G1	219.2	231.3	(495.7)	299.8	(115.59)	(0.1963)
HFC005	G3	443.3	204.8	(670.4)	408.1	(91.41)	(0.1633)
HFC006	G7a	130.4	782.7	1189.6	237.4	(117.98)	1.2642
HFC007	G2	1304.7	1556.3	3196.6	85.1	(67.81)	6.4601
HFC008	G2	30.4	48.3	(318.3)	20.6	18.94	(0.0358)
HFC009	G7a	1721.8	833.2	1444.8	195.6	(110.31)	1.5026
HFC010	G1	163.0	174.8	(435.5)	383.8	(122.35)	0.2190
HFC011	G7a	68.0	3342.6	1624.6	852.3	(107.47)	2.4744
HFC012	G1	278.8	276.3	(540.1)	433.5	(116.19)	(0.1990)
HFC013	G1	131.6	153.5	(408.9)	379.6	(121.07)	0.2596
HFC014	UNASMAJ	741.1	419.3	584.5	353.3	1403.85	4.1215
HFC015	G7a	1155.8	860.1	606.5	225.6	(112.53)	1.3012
HFC016	G7a	200.6	517.6	392.9	598.7	(118.61)	1.0088
HFC017	G7a	54.0	3642.6	3716.5	154.9	(101.81)	3.4469
HFC018	UNASMAJ	82.7	4264.8	2658.6	141.9	(93.59)	2.8959
HFC019	G7a	113.2	821.7	1211.0	560.3	(120.23)	1.4968
HFC020	G1	132.9	1291.6	(436.0)	401.5	(128.00)	0.2415
HFC021	G7a	104.5	3052.7	2320.5	197.8	(103.31)	2.2294
HFC022	G7a	1818.6	648.3	1065.7	93.1	(100.64)	1.4033
HFC023	G7a	150.4	735.9	916.2	590.7	(121.56)	1.0625
HFC024	G1	196.3	192.8	(458.7)	332.0	(118.63)	(0.2014)
HFC025	G7a	210.1	482.5	337.9	442.4	(119.90)	0.8592
HFC026	G1	157.9	146.0	(420.6)	360.3	(119.71)	(0.2024)
HFC027	G1	207.5	181.0	(476.9)	475.8	(120.50)	(0.2047)
HFC028	G1	167.8	150.0	(425.9)	358.1	(122.32)	(0.2075)
HFC029	UNAS	139.2	89.2	1822.8	67.1	56.03	1.6085
HFC030	G7a	266.6	2576.7	1603.8	516.4	(112.45)	2.2158
HFC031	G4	89.3	87.4	(353.2)	150.6	(109.37)	0.4089
HFC032	G7a	70.6	1696.4	1296.5	515.9	(115.34)	1.5597
HFC033	G7a	92.5	2805.0	1715.2	340.4	(110.12)	3.1834

HFC034	G7a	4828.4	539.6	1087.9	815.1	(136.07)	1.0813
HFC035	G1	241.2	209.8	(473.7)	436.5	(119.61)	0.2653
HFC036	G2	1353.7	6102.5	5042.7	93.6	(60.23)	12.3142
HFC037	G7a	217.7	996.2	1438.5	730.1	(115.27)	1.5956
HFC038	G1	175.7	306.9	(424.0)	330.3	(118.74)	0.1712
HFC039	G2	448.5	1163.2	4471.4	99.1	81.99	4.2117
HFC040	G1	163.1	230.3	(418.8)	332.0	(118.91)	0.2748
HFC041	G7b	77.6	63.2	1068.0	196.2	234.04	0.5513
HFC042	G2	279.9	149.2	486.0	29.5	(25.87)	0.4813
HFC043	G1	205.4	200.1	(452.4)	446.2	(119.16)	(0.2063)
HFC044	G2	84.8	53.6	467.8	31.6	26.39	0.4377
HFC045	G2	191.1	124.6	1908.8	57.3	30.77	2.5037
HFC046	G1	198.8	370.7	126.8	288.5	(110.47)	(0.1983)
HFC047	G7a	80.4	74.0	(302.2)	175.5	465.05	(0.2231)
HFC048	G7a	304.5	71.7	1042.0	144.6	283.67	0.5165
HFC049	G2	79.1	18820.0	(542.4)	(10.2)	(32.96)	2.4423
HFC050	G7b	202.0	120.5	1593.8	129.1	372.17	1.4799
HFC051	G1	278.1	329.2	274.3	367.9	(135.69)	(0.2034)
HFC052	G6a	181.7	130.8	4276.0	109.5	(140.60)	5.5891
HFC053	G6a	234.5	131.4	4674.2	148.7	(141.54)	5.2040
HFC054	G6a	220.5	156.3	4572.5	100.7	(135.81)	5.3003
HFC055	G2	1661.2	232.5	1252.4	48.3	(50.53)	4.4174
HFC057	G7a	149.4	145.0	4296.5	119.1	187.63	5.3345
HFC058	G6a	141.5	129.8	4580.9	78.3	136.52	5.2690
HFC059	G6a	93.6	107.2	1015.2	30.0	(37.16)	0.9486
HFC060	G2	102.8	127.8	398.5	29.4	(41.14)	0.3446
HFC061	G2	84.8	128.4	1251.2	32.5	36.57	1.0140
HFC062	G2	151.3	78.8	768.5	73.5	(45.60)	2.9515
HFC063	G2	83.6	87.6	428.1	25.7	(38.44)	0.3788
HFC064	G2	92.8	121.0	1785.6	38.3	(40.12)	1.0409
HFC065	G2	158.8	119.7	4443.8	87.1	(135.02)	5.2088
HFC066	G6a	927.0	196.5	5030.2	615.4	(159.51)	5.6964
HFC067	UNAS	174.9	118.3	4893.7	103.5	(138.03)	6.3630
HFC068	G6a	79.3	16146.7	(541.3)	8.4	(46.62)	2.1950
HFC069	G2	65.6	697.6	(325.3)	55.2	(74.68)	2.0301
HFC070	G7a	3101.0	586.1	1111.6	1077.3	(160.58)	1.1435
HFC071	G7a	292.2	180.7	623.5	22.6	(40.28)	0.5596
HFC072	UNASMAJ	102.8	98.4	1803.2	57.5	(48.64)	1.2223
HFC073	G2	108.3	126.4	1303.6	58.8	(47.36)	1.2069
HFC074	G2	236.8	158.4	1158.4	215.4	137.97	1.4383
HFC075	G7b	272.5	147.7	1230.8	148.4	(87.35)	5.3957
HFC076	G6a	262.1	55.2	(485.6)	152.0	(155.95)	(0.2465)
HFC077	G5	529.5	1400.0	1526.9	79.2	(93.57)	3.2328
HFC078	G6a	3262.1	149.2	(1652.3)	832.8	329.58	0.7273
HFC079	G7b	119.3	124.1	1018.0	125.3	(50.01)	1.0925
HFC080	G2	773.4	172.4	545.7	1067.4	(150.62)	0.7912
HFC081	G7a	380.2	183.0	2834.9	133.6	72.36	2.0843
HFC082	G2	443.0	169.6	2567.4	138.2	85.81	2.1185

HFC083	G2	341.8	143.6	2373.5	121.8	(68.07)	2.1877
HFC084	G2	599.2	85.0	3414.7	987.0	155.07	6.0458
HFC085	G2	203.5	60.5	(413.5)	108.6	(158.27)	(0.2505)
HFC086	G5	71.1	50.8	769.4	31.9	(34.86)	3.8389
HFC087	G2	393.4	89.1	517.7	29.9	(23.05)	1.6489
HFC088	G2	106.3	128.6	1366.4	44.2	29.43	0.8396
HFC089	G2	130.6	112.6	1145.8	48.9	(41.21)	0.7242
HFC090	G2	172.6	195.5	1933.1	74.5	36.38	2.8054
HFC091	G2	537.2	48.7	(622.0)	81.4	(156.41)	(0.2447)
HFC092	G5	162.6	202.8	2180.7	69.3	(56.81)	3.0642
HFC093	G2	3910.4	172.7	(1799.3)	188.5	201.38	0.5111
HFC094	G7a	176.9	146.9	1783.4	63.6	(53.65)	2.8299
HFC095	G2	157.6	78.9	1939.4	47.4	(44.62)	1.9321
HFC096	G2	146.3	95.8	1942.8	50.7	(46.94)	1.9375
HFC097	G2	73.8	(22.7)	476.1	21.1	(26.56)	0.9236
HFC100	G2	88.8	67.7	593.1	243.9	(147.92)	0.4485
HFC101	G2	47.49	70.6	218.6	105.45	(150.52)	0.4505
HFC102	G2	253.86	(26.9)	306.5	233.85	309.57	0.3332
HFC103	G7a	48.22	75.5	734.8	63.85	291.62	0.4485
HFC104	G7a	91.95	111.1	116.7	270.19	438.77	0.2369
HFC105	G3	90.92	55.3	1997.4	77.52	255.69	1.5678
HFC107	G7a	250.84	517.9	1576.2	106.00	0.00	1.4583
HFC108	G4	3407.43	427.0	(1588.0)	74.45	(70.25)	3.6295
HFC109	G7a	306.24	155.6	788.6	32.71	(29.86)	0.5321
HFC110	G6a	154.17	116.5	267.6	290.21	(135.42)	0.2572
HFC111	G6a	114.98	134.9	(361.8)	391.02	(138.00)	(0.1987)
HFC112	G2	102.87	1074.6	1182.0	329.70	(132.20)	1.3781
HFC113	G2	98.96	467.8	(359.1)	75.36	(76.28)	5.6111
HFC114	G4	330.92	145.7	782.1	29.11	(32.04)	0.5215
HFC115	G1	214.99	191.9	(472.8)	441.04	(135.15)	(0.1972)
HFC116	G7a	81.72	1190.9	1095.5	281.71	(128.08)	1.6092
HFC117	G7a	1161.49	28.4155	(892.6)	(14.11)	(24.72)	0.0891
HFC118	G2	108.31	2852.5	1905.7	471.27	(122.54)	4.2831
HFC119	G1	150.33	157.4	(399.1)	348.87	(136.34)	0.1596
HFC120	G7a	1472.20	1040.4	1638.9	118.39	(125.45)	1.8285
HFC121	G2	27.73	390.5308	(198.6)	(3.17)	132.11	0.8910
HFC122	G7a	90.14	87.4	1587.9	1195.16	(105.69)	6.1624
HFC123	G1	82.13	415.8	(350.0)	11.54	(46.48)	2.4302
HFC124	G7a	235.07	115.0	454.5	22.76	(25.65)	0.3876
HFC125	UNASMAJ	56.85	81.4	537.0	15.50	(25.24)	0.4269
HFC126	G7a	139.41	816.6	1731.0	273.71	(126.60)	1.5704
HFC127	G2	248.75	119.9	(544.2)	133.39	(179.77)	0.8693
HFC128	G2	627.29	108.7	(660.0)	56.75	(60.31)	12.4778
HFC129	G2	164.26	125.7	825.8	128.91	(95.55)	0.4816
HFC130	G7a	107.46	106.3	227.0	8.46	(22.29)	0.0991
HFC131	G7a	117.95	921.1	1457.1	543.56	(128.52)	1.7006
HFC132	G2	1413.92	40.5905	(913.3)	383.56	124.49	0.2367
HFC133	G6a	129.39	53.4	(413.1)	176.74	602.30	(0.2194)

HFC134	G2	388.37	134.5	(518.8)	11.51	(26.43)	0.2584
HFC135	G7a	103.46	84.5	1079.8	237.48	364.18	0.8780
HFC136	UNAS	208.95	1646.5	1158.5	411.55	247.26	1.4941
HFC137	UNASMAJ	242.36	64.7	268.1	534.52	284.05	(0.2071)
HFC138	G2	136.75	167.6	(365.8)	487.29	(136.36)	(0.2016)
HFC139	G7a	252.35	226.4	(453.8)	342.76	(131.90)	(0.1975)
HFC141	UNASMAJ	180.74	173.3	(396.9)	447.66	(141.54)	(0.2083)
HFC142	G4	218.59	272.0	(443.1)	390.56	(130.43)	0.2667
HFC143	G1	123.74	91.7	382.3	17.92	(25.05)	0.3300
HFC144	G1	231.15	177.1	(435.1)	490.75	(132.77)	(0.1985)
HFC145	G1	167.28	162.7	185.6	426.04	(136.03)	0.3190
HFC146	G1	164.44	514.3	455.7	228.39	(88.03)	0.7486
HFC147	G1	183.42	130.3	(398.2)	449.10	(137.16)	(0.2030)
HFC148	G2	281.95	452.9	168.0	349.03	(123.89)	0.3192
HFC149	G1	311.89	393.2	(510.9)	378.74	(124.61)	0.4873
HFC150	G1	270.24	264.8	(478.9)	310.20	(131.98)	(0.2010)
HFC151	G7a	327.93	363.7	(518.0)	417.97	145.49	0.1779
HFC152	G1	1.53	258.4755	(143.5)	3.46	(128.89)	(0.1964)
HFC153	G1	278.40	285.8	(472.1)	378.65	84.40	(0.2008)
HFC154	G1	262.08	145.5	768.9	30.09	(30.48)	0.5084
HFC155	G1	235.94	279.7	147.6	449.39	(131.50)	0.2582
HFC156	G1	489.22	264.4	(598.4)	378.44	(97.12)	(0.2122)
HFC157	G1	136.38	97.2	(360.9)	1.91	(9.32)	0.0420
HFC158	G1	332.81	352.5	(521.3)	302.74	136.10	(0.2104)
HFC159	G2	339.21	154.1	636.6	22.98	(24.42)	0.4817
HFC160	G1	218.36	329.1	(446.1)	428.29	(100.01)	(0.2159)
HFC161	G1	327.49	222.7	(511.0)	449.64	(100.91)	0.2055
HFC162	UNASG2	137.82	106.4	904.3	68.47	266.93	0.6601
HFC163	G1	262.19	275.55	-514.04	334.49	-98.38	-0.21
HFC165	G2	143.07	141.74	-403.80	503.99	-105.86	-0.22
HFC166	G1	186.75	497.10	567.70	465.49	-101.57	0.74
HFC167	G1	104.80	125.31	-368.70	362.83	-105.55	-0.22
HFC168	G7a	1171.54	2883.03	537.71	124.75	-91.20	1.44
HFC169	G1	3644.56	974.08	-1737.05	248.10	-98.76	1.32
HFC170	G1	281.38	237.85	-524.44	410.99	-100.32	-0.21
HFC171	G1	233.10	517.47	-544.25	439.26	-95.56	0.83
HFC173	G7a	2751.38	1001.98	839.62	129.10	-106.80	2.06
HFC174	G1	101.82	44.86	-358.28	165.33	193.88	-0.22
HFC177	G4	302.44	94.30	1194.78	172.04	-125.41	15.34
HFC178	G7a	154.10	46.75	496.13	28.80	-47.36	1.48
HFC179	G1	170.83	248.02	959.30	43.51	87.71	1.25
HFC180	G7a	172.63	86.01	2059.90	69.93	-25.99	1.71
HFC181	G7a	177.13	159.92	2117.97	74.91	-30.50	1.33
HFC182	G7a	135.59	119.28	372.69	498.97	-37.04	1.95
HFC183	G3	80.16	104.99	123.21	408.51	126.72	1.96
HFC184	G7a	7208.58	60.38	752.73	522.21	973.08	0.38
HFC185	G4	166.22	48.72	2319.98	70.50	-102.89	-0.22
HFC186	UNASG2	220.61	209.41	1639.20	72.08	233.22	4.36

HFC187	G7a	63.16	61.50	515.61	565.59	-37.36	1.93
HFC188	G7b	180.73	125.92	-407.30	291.78	-34.06	1.73
HFC189	G2	56.62	165.96	814.11	55.59	235.40	0.76
HFC190	G2	68.82	133.12	953.30	68.32	179.84	0.16
HFC191	G2	173.05	215.60	-431.53	417.22	-27.41	0.72
HFC192	G7a	55.86	200.11	-313.18	56.77	-30.13	0.80
HFC193	G7a	241.90	742.11	1785.41	732.68	-2.23	-0.01
VHC001	G7a	991.41	844.47	1197.75	1035.12	162.86	0.66
VHC002	G6a	74.33	533.18	-286.86	52.35	322.25	1.46
VHC003	G7a	57.68	63.62	391.96	110.96	176.73	1.36
VHC004	G4	58.55	271.43	-283.14	47.87	-115.37	-0.25
VHC005	UNAS	56.63	118.40	107.08	96.93	-109.38	-0.23
VHC006	G7a	4179.69	-112.05	-1793.19	473.93	150.48	1.13
VHC007	G7b	791.28	4124.75	-776.16	387.11	-149.98	0.91
VHC008	G7a	67.84	148.14	-305.39	67.15	-110.48	-0.23
VHC009	UNAS	157.70	135.79	-398.80	127.67	-102.81	-0.22
VHC010	UNASG2	627.23	206.42	4387.71	1028.51	-116.56	6.18
VHC011	G4	1447.44	141.24	-998.96	2226.04	2921.97	0.89
VHC012	G4	97.90	261.55	679.14	182.71	-100.56	0.51
VHC013	G7a	87.97	672.12	739.15	915.69	-93.46	0.81
VHC014	G4	54.81	584.83	757.67	250.65	-103.58	0.42
VHC015	UNAS	42.96	149.15	407.28	133.20	-101.40	0.14
VHC016	G6a	707.45	2998.24	-707.08	272.91	-134.76	0.82
VHC017	G4	576.10	258.27	1390.09	90.31	-102.82	1.45
VHC018	UNASG2	6434.06	916.87	-2259.67	171.92	-90.04	1.58

Appendix C.

Appendix for NAA element values for sources

NAA raw values for all elements. ANID column corresponds to laboratory sample ID. Source locations are identified in a separate column.

ANID	Group	As	La	Lu	Nd	Sm	U	Yb	Ce	Co	Cr	Cs	Eu	Fe	Hf	Ni	Rb	Sb
HFC194	Allmendingen	23.2	45.63	0.378	28.89	5.35	1.77	2.81	79.31	16.69	214.05	17.55	1.06	83585	6.34	0.00	195.00	2.09
HFC195	Allmendingen	29.9	57.41	0.454	34.80	6.64	3.90	2.80	102.15	17.92	169.23	19.64	1.25	97291	5.50	40.99	209.98	1.69
HFC196	Allmendingen	17.5	39.49	0.359	29.48	5.49	2.37	2.40	74.82	13.75	163.28	13.52	1.03	66121	5.64	0.00	155.74	1.70
HFC197	Bohnerz 2	72.0	37.86	0.707	29.92	8.09	7.79	4.97	54.81	29.30	292.91	0.31	1.72	379806	8.14	0.00	0.00	4.14
HFC198	Bohnerz 3	17.6	53.08	0.764	46.92	10.01	3.76	5.52	101.55	20.97	146.05	3.24	1.80	51988	12.61	0.00	58.32	0.85
HFC199	Bohnerz 4	31.7	87.37	1.009	76.58	17.03	1.27	7.16	80.27	15.79	184.91	22.05	3.65	69358	3.87	109.93	165.73	1.14
HFC200	Bohnerz 5	16.9	18.70	1.310	22.99	5.30	1.22	9.17	21.55	10.08	36.64	4.35	1.40	250602	0.43	0.00	17.29	1.05
HFC201	Bohnerz 9	52.0	440.68	1.280	112.11	18.71	6.37	10.32	462.31	48.31	133.54	0.00	3.73	535417	2.10	0.00	0.00	4.80
HFC202	Bohnerz 9	57.4	16.28	0.297	16.28	5.11	2.17	2.33	9.70	13.42	16.98	9.00	1.07	559981	0.30	201.00	15.96	3.79
HFC203	Allmendingen	22.6	41.98	0.339	29.67	5.21	1.67	2.36	79.24	17.60	202.54	14.79	0.99	74408	5.48	0.00	167.96	1.91
HFC204	Bohnerz 7	497.2	36.24	1.172	32.09	10.44	2.09	8.45	126.95	47.76	105.23	6.07	2.62	523539	2.24	107.18	0.00	7.32
HFC205	Bohnerz 7	506.8	15.95	0.618	11.90	3.30	1.46	3.76	18.58	17.94	131.55	2.83	0.73	566822	1.11	182.51	0.00	15.34
HFC206	Bohnerz 7	39.0	36.64	0.402	25.34	5.58	3.44	2.73	73.79	30.49	173.37	42.22	1.15	63335	3.59	104.40	185.71	1.20
HFC207	Bohnerz 1	151.2	33.94	0.354	32.29	8.18	1.19	2.56	41.81	13.45	73.55	5.04	1.76	597227	0.67	0.00	34.90	6.01
HFC208	Bohnerz 7	3964.9	15.66	0.208	14.08	2.46	2.39	1.62	14.59	7.17	65.18	1.61	0.62	580940	0.71	349.60	27.93	26.97
HFC209	Altheim	12.4	40.35	0.526	37.56	7.56	3.94	3.46	82.65	12.71	87.56	7.29	1.31	31818	10.79	0.00	119.68	0.80
HFC210	Altheim	342.9	22.37	0.322	16.62	3.58	5.73	2.08	39.82	60.06	31.55	0.93	0.59	377773	3.77	0.00	24.66	9.29
HFC211	Altheim	955.3	23.13	0.275	17.21	3.30	4.44	1.64	37.42	89.68	23.60	1.15	0.83	468188	0.86	66.49	0.00	8.26
HFC212	Altheim	81.8	15.82	0.169	13.48	3.00	3.10	1.05	35.22	115.66	19.82	3.39	0.67	361678	2.10	94.12	47.65	21.74
HFC213	Ringingen	17.7	10.34	0.221	10.91	1.86	1.43	1.17	16.79	4.95	44.45	2.17	0.39	65464	1.63	0.00	69.27	0.93
HFC214	Herz-Jesu Berg	117.0	34.62	1.293	32.17	9.57	5.98	8.66	76.76	152.58	66.01	0.00	2.25	545004	3.23	0.00	0.00	5.72
HFC215	Herz-Jesu Berg	151.5	40.75	0.575	44.74	9.91	3.95	4.17	104.16	15.57	491.69	0.00	2.08	414321	8.92	0.00	0.00	3.96
HFC216	Gerhausen	23.5	110.18	1.099	75.93	14.90	4.17	7.40	154.51	17.16	167.71	17.35	3.13	107763	8.16	98.33	74.53	1.73
HFC217	Kirchbierlingen	26.0	2.87	0.597	3.40	1.40	11.32	3.96	7.27	2.58	9.94	6.81	0.20	41824	7.02	0.00	159.56	3.65
HFC218	Rudelstetten	28.0	92.88	0.991	70.32	14.04	2.15	6.82	150.22	16.03	275.80	10.67	3.04	89395	11.09	81.00	68.04	2.60
HFC219	Gerhausen	21.7	109.76	1.044	70.11	14.67	5.65	7.65	154.08	17.03	165.09	17.56	3.04	106564	8.28	147.01	73.42	1.71
HFC220	Gerhausen	24.8	110.32	1.006	75.85	14.86	4.14	7.57	156.28	17.00	166.87	17.39	3.11	107635	8.28	126.17	73.27	1.74
HFC221	Gerhausen	23.1	109.16	1.103	72.77	14.73	5.75	7.08	152.58	16.97	166.57	17.53	3.01	106539	8.22	105.28	72.21	1.79
HFC222	Gerhausen	25.2	108.87	1.076	77.68	14.64	5.11	7.51	152.83	16.73	163.36	17.36	3.07	106035	8.26	84.53	82.44	1.82
HFC223	Rudelstetten	28.4	92.79	0.932	68.81	14.06	3.12	6.89	149.93	15.99	275.23	10.71	3.05	89187	10.57	120.60	72.75	2.69

HFC224	Rudelstetten	29.7	93.42	0.943	69.52	14.27	3.63	6.95	151.67	16.46	281.31	10.81	3.11	90785	10.61	82.90	73.71	2.77
HFC225	Rudelstetten	28.7	94.44	0.923	73.85	14.38	2.82	6.77	153.52	16.83	276.07	10.89	3.11	90340	10.48	113.88	65.10	2.68
HFC226	Rudelstetten	28.5	92.84	0.929	72.33	14.20	2.57	6.81	151.47	16.20	277.95	10.79	3.08	90192	10.52	136.71	65.78	2.61
HFC227	Allmendingen	20.7	43.06	0.367	27.22	5.07	2.28	2.40	74.16	15.03	193.54	16.75	0.97	78362	5.99	0.00	186.87	2.00
HFC228	Allmendingen	18.0	43.28	0.377	30.50	5.24	2.00	2.56	74.37	14.62	194.16	16.14	1.00	74358	5.82	76.48	185.54	1.76
HFC229	Allmendingen	16.9	36.60	0.294	26.17	4.92	1.26	2.11	68.62	14.78	149.35	12.91	0.96	62113	5.07	0.00	143.49	1.54
HFC230	Allmendingen	13.3	32.88	0.301	24.44	4.64	1.41	2.03	60.51	13.53	123.40	10.66	0.88	49873	4.40	69.10	120.48	1.12
HFC231	Bohnerz 4	27.7	71.28	0.806	61.99	13.88	2.23	6.46	72.37	14.93	158.50	21.65	3.10	64021	3.10	105.06	175.19	1.19
HFC232	Bohnerz 4	26.1	75.24	0.820	67.24	14.51	1.95	6.00	80.05	15.53	158.81	20.92	3.19	64177	3.38	50.45	164.03	1.22
HFC233	Allmendingen	22.1	41.08	0.376	28.55	5.08	2.45	2.67	76.70	16.12	194.58	14.66	0.95	72299	5.44	0.00	168.02	1.88
HFC234	Allmendingen	21.3	39.00	0.333	25.60	4.76	1.59	2.22	73.91	16.76	175.61	13.62	0.93	67583	5.01	0.00	152.60	1.73
HFC235	Allmendingen	20.0	55.20	0.462	38.06	7.01	2.42	3.11	92.42	13.08	151.34	17.85	1.37	68543	5.21	0.00	199.19	1.18
HFC236	Allmendingen	20.4	54.22	0.431	35.41	6.86	2.74	2.92	92.44	13.46	151.18	17.66	1.38	69314	5.35	0.00	195.82	1.15
HFC237	Bohnerz 9	65.9	26.87	0.377	20.13	4.89	3.84	2.48	19.71	36.67	65.48	3.98	1.13	527070	1.25	0.00	30.30	3.85
HFC238	Bohnerz 1	121.0	49.02	1.393	43.01	12.65	3.31	9.98	59.98	40.48	647.25	1.29	3.33	415669	4.48	120.17	0.00	5.99
HFC239	Bohnerz 7	5354.1	9.50	0.525	7.87	2.11	2.98	3.39	11.73	26.61	361.43	0.67	0.56	580592	0.51	501.64	0.00	13.29
HFC240	Bohnerz 2	69.5	21.64	0.850	26.03	8.11	11.30	5.06	48.19	18.52	311.16	0.00	1.75	423329	7.51	0.00	0.00	4.89
HFC241	Bohnerz 7	39.6	34.96	0.394	26.20	5.43	2.60	2.92	76.21	35.69	158.80	40.48	1.10	61288	3.36	84.26	167.83	1.24
HFC242	Bohnerz 7	40.6	33.64	0.376	25.04	5.24	2.62	2.65	76.27	34.60	157.96	39.89	1.06	62214	3.35	97.76	174.03	1.26
HFC243	Ringingen	9.6	8.19	0.163	6.37	1.47	1.46	0.98	13.97	4.59	36.19	1.84	0.34	57465	1.80	0.00	59.82	0.78
HFC244	Ringingen	8.6	8.68	0.153	7.55	1.57	1.31	0.85	14.63	4.87	37.79	1.94	0.37	61624	2.41	0.00	67.78	0.86
HFC245	Ringingen	10.1	11.25	0.213	9.67	1.89	1.44	1.20	20.05	5.13	43.00	2.08	0.42	62113	1.86	0.00	66.10	0.83
HFC246	Ringingen	9.2	10.70	0.166	8.86	1.81	1.70	0.93	18.50	4.64	42.09	2.03	0.36	58427	1.84	0.00	62.38	1.01
HFC247	Bohnerz 3	127.2	41.66	1.075	45.74	14.46	7.75	7.27	84.40	52.73	224.23	0.00	3.30	392581	5.90	191.41	0.00	3.36
HFC248	Bohnerz 3	123.1	42.68	1.295	49.47	15.49	3.83	9.97	80.38	49.62	407.21	0.00	3.93	421538	4.51	0.00	0.00	3.85
HFC249	Bohnerz 3	126.9	31.96	0.511	32.84	8.01	4.87	3.55	49.47	18.39	322.63	0.00	1.75	363482	7.30	0.00	0.00	3.28
HFC250	Bohnerz 7	137.8	15.30	0.449	14.89	3.53	7.34	2.33	11.94	51.17	56.68	2.40	0.76	541583	0.65	174.00	0.00	7.75
HFC251	Bohnerz 7	462.7	33.83	0.992	32.54	9.48	1.54	7.74	96.89	36.24	116.46	5.27	2.47	518974	2.87	0.00	18.62	7.16
HFC252	Bohnerz 7	55.2	18.50	0.988	22.91	7.74	7.10	6.58	25.85	56.59	45.57	1.59	2.00	550074	0.53	148.01	0.00	1.09
HFC253	Bohnerz 7	1347.3	18.07	0.233	17.32	3.68	1.44	2.04	47.84	25.33	264.59	1.14	0.88	624684	0.72	514.63	0.00	9.96
HFC254	Bohnerz 1	123.1	4.42	0.143	0.00	0.90	0.67	0.41	3.84	45.15	20.36	1.75	0.17	570137	0.29	0.00	0.00	1.22

HFC255	Altheim	19.5	22.09	0.283	19.73	3.78	2.94	1.18	40.81	7.26	43.80	3.79	0.64	170280	3.60	0.00	58.19	1.10
HFC256	Altheim	23.9	2.21	0.125	0.00	0.48	1.68	0.29	3.56	36.84	9.16	4.69	0.10	559386	0.33	0.00	24.21	2.96
HFC257	Altheim	1138.4	4.97	0.122	6.18	1.40	3.77	0.74	9.25	46.32	16.50	0.63	0.28	532403	0.46	58.12	0.00	4.64
HFC258	Altheim	11.6	2.49	0.120	0.00	0.63	2.46	0.53	3.65	64.40	11.04	7.57	0.12	552733	0.41	0.00	0.00	2.89
HFC259	Altheim	790.9	18.60	0.270	11.84	2.62	4.81	1.26	30.22	82.42	22.35	1.39	0.66	455082	0.67	0.00	23.51	7.63
HFC260	Altheim	1648.4	33.79	0.355	28.95	4.74	5.54	2.31	53.10	105.39	36.12	0.95	1.14	474196	2.54	0.00	23.82	13.90
HFC261	Herz-Jesu Berg	290.4	11.35	0.419	11.96	2.94	3.65	2.73	27.13	37.48	633.65	0.00	0.66	552304	4.29	0.00	0.00	10.64
HFC262	Herz-Jesu Berg	171.0	102.06	0.717	124.09	26.73	3.27	5.17	501.47	19.18	625.03	0.00	5.65	459392	11.53	0.00	0.00	8.81
HFC263	Herz-Jesu Berg	129.4	15.48	0.539	12.85	3.81	3.28	4.54	28.66	12.44	636.08	0.00	0.91	457598	9.17	0.00	0.00	7.78
HFC264	Tormerdingen	44.5	87.88	0.970	48.37	9.65	4.69	7.22	163.37	20.30	258.17	5.46	2.03	110440	15.05	61.12	43.67	2.26
HFC265	Tormerdingen	45.4	90.52	0.963	48.25	10.09	5.12	6.96	173.28	21.08	281.84	5.52	2.11	113787	14.43	114.49	34.80	2.21
HFC266	Tormerdingen	46.7	92.59	0.925	50.26	10.11	4.88	7.30	173.44	21.60	255.70	5.87	2.14	112729	15.16	78.01	33.21	2.31
HFC267	Tormerdingen	46.6	88.98	0.892	47.79	9.99	5.13	7.06	161.74	21.92	279.56	5.52	2.03	113628	14.04	79.09	36.45	2.32
HFC268	Tormerdingen	46.4	90.58	0.896	51.23	10.10	4.97	7.16	169.44	20.80	279.79	5.79	2.17	114594	14.43	0.00	43.75	2.31
HFC269	Schelklingen	22.5	111.86	0.938	72.90	15.02	6.09	7.41	157.79	18.22	170.74	18.04	3.13	108179	8.48	98.92	74.59	1.77
HFC270	Schelklingen	22.0	111.13	0.981	72.79	14.76	4.97	6.82	154.08	18.34	172.27	18.03	3.09	108128	8.15	0.00	78.39	1.76
HFC271	Schelklingen	27.2	113.04	0.955	77.42	14.92	7.44	7.20	157.42	19.70	181.49	17.96	3.12	110584	8.50	78.49	80.37	1.90
HFC272	Schelklingen	22.6	111.34	0.999	74.10	14.71	6.23	7.27	156.20	18.51	175.91	17.96	3.07	108495	8.70	73.79	74.53	1.93
HFC273	Schelklingen	23.9	109.64	0.901	72.02	14.51	5.31	7.46	152.03	18.35	168.39	17.43	2.99	106276	8.23	74.66	68.83	1.63
HFC274	Schelklingen	95.1	37.47	0.815	39.41	10.54	3.56	6.27	103.74	47.31	244.57	0.00	2.34	470663	8.26	0.00	0.00	3.98
HFC275	Schelklingen	98.4	95.78	1.193	119.80	30.81	7.77	8.57	812.21	78.87	321.19	0.00	6.76	392017	14.29	154.59	0.00	3.50
HFC276	Schelklingen	158.4	86.80	0.629	41.75	8.60	3.22	4.87	89.95	32.11	575.78	0.72	1.93	404190	7.42	0.00	0.00	5.14
HFC277	Harz	688.1	1.18	0.000	0.00	1.88	4.58	0.00	2.91	0.00	12.99	1.08	1.01	657602	0.00	0.00	0.00	498.74
HFC278	Harz	663.7	1.24	0.000	0.00	1.45	2.53	0.00	2.43	0.00	7.50	1.18	0.87	659793	0.00	0.00	0.00	642.87
HFC279	Harz	674.1	1.25	0.000	0.00	1.50	1.21	0.00	3.28	0.00	4.25	1.33	0.88	671071	0.00	0.00	0.00	652.59
HFC280	Harz	662.7	1.09	0.000	0.00	1.52	3.34	0.00	3.65	0.00	7.77	1.57	0.84	656513	0.00	0.00	0.00	641.57
HFC281	Harz	665.1	1.17	0.000	0.00	1.53	3.73	0.00	4.90	0.00	4.81	1.45	1.01	664074	0.00	0.00	0.00	646.77
HFC282	Geyer	136.6	6.36	0.284	9.45	5.21	15.37	1.63	17.80	1.56	5.89	1.07	1.39	672694	0.00	0.00	0.00	126.33
HFC283	Geyer	129.7	6.14	0.305	12.23	5.17	14.10	1.57	17.80	1.66	7.60	0.92	1.35	664813	0.00	0.00	0.00	123.70
HFC284	Geyer	143.0	7.73	0.392	15.89	6.44	19.23	1.71	23.23	2.24	4.75	1.55	1.61	656952	0.00	0.00	0.00	175.79
HFC285	Geyer	145.1	7.78	0.402	13.63	6.55	19.88	2.08	22.62	1.88	4.93	1.95	1.62	655352	0.00	0.00	0.00	184.98

HFC286	Geyer	151.6	7.66	0.426	14.62	6.45	21.68	1.91	21.93	1.87	5.69	1.59	1.62	654309	0.00	0.00	0.00	184.68
HFC287	Zindelstein	272.0	66.71	0.534	56.64	12.26	6.39	4.09	110.07	19.32	149.62	520.00	2.98	66941	1.94	0.00	486.32	5.58
HFC288	Zindelstein	280.0	66.48	0.571	51.56	12.33	6.23	3.92	113.43	20.55	154.94	515.66	3.01	67662	1.98	0.00	468.46	5.89
HFC289	Zindelstein	260.2	60.71	0.543	46.12	11.51	4.58	4.00	102.99	22.50	148.05	442.29	2.79	62358	2.15	0.00	426.28	5.14
HFC290	Zindelstein	273.9	68.18	0.559	59.63	12.51	4.04	3.80	113.58	21.68	147.46	488.08	3.02	66222	1.93	0.00	454.12	5.51
HFC291	Zindelstein	277.7	67.02	0.574	59.68	12.39	4.49	3.60	114.57	22.15	163.12	492.97	2.99	67281	2.09	0.00	453.39	5.50
HFC292	Schollach	31.3	19.67	0.441	16.97	3.78	5.46	2.62	40.82	2.17	18.75	50.02	0.30	13204	6.10	0.00	322.57	3.25
HFC293	Schollach	31.9	19.80	0.389	17.36	4.03	6.07	2.59	42.11	2.37	21.65	55.00	0.33	13783	5.33	0.00	367.95	3.19
HFC294	Schollach	31.2	19.65	0.444	15.64	3.69	6.29	2.66	41.53	2.33	22.19	55.04	0.29	13363	6.37	0.00	346.31	3.04
HFC295	Schollach	33.6	23.21	0.452	21.54	4.49	5.87	3.16	49.53	3.85	21.93	57.99	0.32	14880	5.97	0.00	371.66	3.18
HFC296	Schollach	29.6	18.32	0.473	18.04	3.85	5.26	3.27	39.54	2.45	22.32	56.31	0.34	14757	6.28	0.00	370.77	3.08
HFC297	Hechtsberg	112.6	3.66	0.000	7.43	2.71	28.94	0.31	14.87	3.24	4.14	11.71	0.44	670823	0.00	0.00	0.00	12.60
HFC298	Hechtsberg	115.5	3.92	0.387	11.58	2.65	28.17	0.31	14.59	3.34	4.27	11.66	0.47	668292	0.00	0.00	30.46	12.36
HFC299	Hechtsberg	113.7	3.81	0.000	9.31	2.65	29.19	0.37	14.42	3.61	4.93	11.13	0.44	646237	0.00	0.00	0.00	12.04
HFC300	Hechtsberg	71.0	5.90	0.000	8.69	2.24	16.11	0.31	16.02	2.55	5.17	9.31	0.40	299996	0.30	0.00	31.53	11.53
HFC301	Hechtsberg	78.0	4.71	0.000	5.61	2.04	16.68	0.22	15.02	2.72	4.88	9.37	0.40	309776	0.22	0.00	23.24	11.91
HFC302	Hechtsberg	71.4	4.67	0.232	9.99	2.12	16.70	0.30	15.32	2.74	5.42	9.81	0.42	306682	0.25	0.00	24.50	12.02
HFC303	Hechtsberg	369.6	5.88	0.371	11.46	2.67	13.22	1.46	15.13	127.88	10.02	10.56	2.20	264235	0.56	0.00	27.75	31.92
HFC304	Hechtsberg	365.6	5.34	0.375	6.75	2.56	13.57	1.33	14.54	126.19	10.32	10.46	2.22	268093	0.59	136.63	30.31	32.15
HFC305	Hechtsberg	370.2	5.49	0.245	9.46	2.58	13.63	1.54	14.39	124.57	9.51	10.56	2.14	265988	0.38	0.00	24.08	32.67
HFC306	NUSSBACH	47.8	23.41	0.621	23.50	6.23	8.55	3.83	54.69	1.18	5.62	52.68	0.16	10075	4.14	0.00	351.58	0.79
HFC307	NUSSBACH	52.2	27.61	0.763	21.69	7.58	9.59	5.39	62.43	1.34	7.58	49.61	0.17	10409	5.35	0.00	360.52	0.76
HFC308	NUSSBACH	47.0	24.64	0.621	21.07	6.83	8.07	5.02	55.83	1.05	3.39	48.62	0.12	9306	3.89	0.00	339.11	0.74
HFC309	NUSSBACH	47.1	22.85	0.842	21.07	6.93	10.01	6.43	53.10	0.93	3.53	47.74	0.13	8950	4.14	0.00	344.64	0.78
HFC310	NUSSBACH	48.3	27.78	0.759	25.80	7.63	9.64	6.04	63.97	0.98	5.70	47.06	0.17	8964	3.94	0.00	349.41	0.74
HFC311	Rappenloch	2966.5	7.92	3.101	51.50	18.96	91.88	23.35	42.36	48.36	0.00	18.27	0.50	23500	0.00	0.00	26.59	130.67
HFC312	Rappenloch	2776.2	7.62	2.856	61.14	18.54	91.40	22.62	39.38	46.88	0.00	17.59	0.41	21262	0.25	0.00	21.89	129.05
HFC313	Rappenloch	2699.7	7.33	2.788	35.59	18.18	90.66	21.90	38.50	46.61	0.00	18.57	0.48	20112	0.00	0.00	29.67	122.88
HFC314	Rappenloch	176.7	8.20	0.505	14.40	3.64	12.95	2.83	20.56	1.95	0.00	26.83	0.11	116842	2.17	0.00	344.91	48.01
HFC315	Rappenloch	192.2	8.39	0.668	14.08	4.28	12.15	4.53	21.24	1.98	1.39	26.77	0.10	115991	2.08	0.00	351.86	47.91
HFC316	Rappenloch	1252.8	13.66	0.000	44.28	8.58	69.09	1.93	36.84	2.98	8.39	10.15	0.26	655855	0.58	0.00	0.00	827.17

HFC317	Rappenloch	1289.8	16.25	0.000	29.29	9.11	67.61	0.00	41.29	2.52	6.80	9.70	0.34	645137	0.29	0.00	0.00	839.96
HFC318	Rappenloch	1300.1	16.32	0.000	31.70	9.12	69.44	0.00	42.48	2.49	6.11	9.67	0.37	650876	0.34	0.00	0.00	840.62
HFC319	Rappenloch	0.0	0.00	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00	0.00
HFC320	Rappenloch	678.7	9.60	0.070	16.19	3.48	15.84	1.57	19.18	11.81	1.29	32.86	0.10	112776	1.68	0.00	235.25	142.01
HFC321	Rappenloch	706.5	10.20	0.196	0.00	3.83	18.82	1.44	21.27	12.69	1.92	31.99	0.16	114030	1.62	0.00	265.97	142.93
HFC322	Rappenloch	1415.7	12.05	0.803	0.00	10.22	65.14	6.60	37.84	40.43	4.42	43.59	0.33	22047	1.27	0.00	297.83	60.01
HFC323	Rappenloch	1387.1	12.11	0.874	24.97	10.06	62.21	6.29	39.46	41.32	3.91	44.66	0.34	22387	1.32	0.00	298.25	58.54
HFC324	Rappenloch	1382.1	12.01	0.923	36.34	10.09	63.15	6.58	37.53	40.70	4.22	42.78	0.32	21824	1.40	0.00	299.79	58.45
HFC325	Rappenloch	1582.9	25.03	0.000	71.45	26.11	337.94	0.00	107.33	0.77	6.08	7.66	0.00	625155	0.00	0.00	28.41	493.05
HFC326	Rappenloch	1625.3	25.44	0.000	115.13	26.66	343.49	0.00	111.14	0.86	5.68	7.53	0.00	623637	0.00	0.00	48.68	502.51
HFC327	Rappenloch	1575.2	25.37	0.000	70.63	26.09	341.25	0.00	108.71	0.69	0.00	7.88	0.00	619771	0.00	0.00	34.14	495.36
HFC328	Rappenloch	271.9	10.36	0.306	15.41	4.46	22.94	1.44	25.56	3.87	13.31	43.00	0.22	72935	2.11	0.00	245.29	64.37
HFC329	Rappenloch	193.2	9.88	0.287	10.22	4.31	21.45	0.88	24.11	1.88	3.41	39.99	0.11	74251	1.26	0.00	215.13	59.70
HFC330	Rappenloch	194.2	7.12	0.320	8.08	3.45	25.41	0.63	19.69	1.41	1.97	33.93	0.09	82934	1.36	0.00	161.49	65.67
HFC331	Rappenloch	932.0	13.07	0.000	0.00	7.36	65.60	0.88	36.72	4.96	5.71	43.61	0.33	178913	1.08	0.00	196.78	418.89
HFC332	Rappenloch	467.6	14.76	0.000	27.59	7.53	67.91	0.37	39.40	3.67	4.29	37.89	0.24	263349	0.94	0.00	97.06	150.68
HFC333	Rappenloch	479.7	15.95	0.606	20.55	8.04	68.64	0.54	42.96	3.74	5.10	38.07	0.23	268062	1.34	0.00	100.45	151.77

Table 1 continued…

ANID	Group	Sc	Sr	Ta	Tb	Th	Zn	Zr	Al	Ba	Ca	Dy	K	Mn	Na	Ti	V
HFC194	Allmendingen	16.77	71.90	1.55	0.79	16.56	112.6	148.3	107768	219	21508	3.94	34065	219	521	6189	345
HFC195	Allmendingen	20.08	136.55	1.56	0.64	15.20	94.2	92.6	114888	161	9617	5.01	31426	255	673	5851	437
HFC196	Allmendingen	14.15	121.52	1.39	0.57	13.05	104.8	149.7	86235	98	87657	4.14	28704	228	454	5303	281
HFC197	Bohnerz 2	36.49	0.00	1.57	1.06	24.65	132.1	198.7	87559	0	2235	8.75	0	962	98	5258	1180
HFC198	Bohnerz 3	12.96	0.00	1.82	1.41	18.13	121.3	248.0	75615	271	2911	8.70	13495	1057	4826	7211	116
HFC199	Bohnerz 4	23.07	0.00	1.16	2.58	13.11	194.9	109.9	129588	288	14458	14.02	16788	920	501	2995	207
HFC200	Bohnerz 5	14.59	0.00	0.00	1.23	1.19	314.5	0.0	10125	0	201682	9.66	0	1602	103	0	322
HFC201	Bohnerz 9	37.84	0.00	0.00	2.49	7.85	334.7	189.7	35259	0	0	15.30	0	871	59	1017	473

HFC202	Bohnerz 9	4.86	0.00	0.00	0.96	1.85	369.6	0.0	8393	0	635	4.81	2747	238	102	427	40
HFC203	Allmendingen	14.73	114.46	1.49	0.61	13.74	94.8	120.3	91222	151	65663	3.56	29371	241	477	5070	333
HFC204	Bohnerz 7	20.00	0.00	0.47	2.11	6.50	286.9	61.3	25820	0	1156	15.50	2586	440	102	1830	651
HFC205	Bohnerz 7	7.97	0.00	0.25	0.44	3.88	511.8	0.0	20356	0	1002	4.34	0	578	88	732	345
HFC206	Bohnerz 7	19.37	0.00	1.13	0.71	14.81	196.4	60.8	129597	213	16196	4.82	24117	728	632	4200	205
HFC207	Bohnerz 1	5.15	0.00	0.22	0.91	2.73	85.4	0.0	11878	0	347	6.64	2665	169	111	435	206
HFC208	Bohnerz 7	2.47	0.00	0.00	0.61	1.50	380.6	0.0	11935	0	2197	3.06	648	45	43	756	331
HFC209	Altheim	11.82	0.00	1.19	1.13	13.63	81.4	276.2	74033	440	13859	6.06	26497	833	5285	4725	82
HFC210	Altheim	5.19	0.00	0.78	0.52	5.71	43.6	85.8	16040	125	3958	4.66	4154	982	587	3769	16
HFC211	Altheim	1.93	0.00	0.00	0.58	1.17	78.4	0.0	9154	0	3107	3.03	2301	1560	509	433	50
HFC212	Altheim	3.25	0.00	0.28	0.36	2.93	109.2	77.6	18700	159	3309	2.41	6321	1591	896	1331	18
HFC213	Ringingen	4.57	0.00	0.40	0.24	3.39	36.2	28.4	39573	222	1877	1.48	16312	208	700	2124	70
HFC214	Herz-Jesu Berg	34.50	0.00	0.36	1.79	8.11	168.0	0.0	28203	0	3025	12.10	0	1133	64	1187	462
HFC215	Herz-Jesu Berg	45.65	0.00	2.52	2.20	36.11	123.5	273.2	78952	0	2390	7.62	0	1151	77	3555	1202
HFC216	Gerhausen	26.66	338.90	2.17	2.10	19.81	459.1	220.0	141878	0	22562	12.87	5847	677	323	7933	248
HFC217	Kirchbierlingen	10.53	0.00	1.25	0.71	5.52	32.0	165.4	65748	153	0	5.13	38647	155	599	737	56
HFC218	Rudelstetten	23.54	0.00	2.71	2.07	19.22	346.4	242.6	120674	104	8712	12.76	5130	448	252	7885	196
HFC219	Gerhausen	26.54	292.69	2.02	2.36	19.87	454.4	210.7	145924	0	23576	12.92	8182	696	327	8063	266
HFC220	Gerhausen	26.58	357.87	2.04	1.89	19.94	440.7	259.9	140984	0	23012	12.67	7533	671	324	7896	267
HFC221	Gerhausen	26.32	344.49	2.00	1.88	19.77	448.9	218.0	140959	0	21293	12.86	9263	669	345	7645	255
HFC222	Gerhausen	26.19	327.65	2.07	2.01	19.69	449.8	252.2	138778	0	23517	12.44	4361	670	332	7203	251
HFC223	Rudelstetten	23.45	0.00	2.60	1.94	19.22	339.9	253.7	118531	98	9629	12.37	6851	443	286	7566	204
HFC224	Rudelstetten	23.76	0.00	2.65	1.86	19.54	351.8	263.2	121505	171	8904	12.83	6952	455	338	8064	205
HFC225	Rudelstetten	23.91	0.00	2.70	2.49	19.36	347.3	236.2	121639	0	9203	12.73	7137	456	317	7953	210
HFC226	Rudelstetten	23.71	0.00	2.66	1.96	19.27	344.0	255.9	124715	0	10138	13.14	8723	462	358	8526	200
HFC227	Allmendingen	15.85	168.89	1.57	0.67	15.15	103.9	136.0	101388	184	19971	3.88	29174	206	499	5349	314
HFC228	Allmendingen	15.51	112.00	1.54	0.52	15.26	101.3	133.9	102137	107	33520	3.98	30149	229	511	5667	313
HFC229	Allmendingen	13.21	158.77	1.29	0.63	12.33	95.0	83.2	82272	0	93146	3.60	26487	228	442	4839	258
HFC230	Allmendingen	11.08	153.82	1.11	0.60	10.09	81.9	109.1	65564	99	155023	3.50	21099	274	351	3630	202
HFC231	Bohnerz 4	21.36	0.00	1.00	2.09	11.85	181.9	100.0	118466	189	11129	12.12	13664	851	524	3462	184
HFC232	Bohnerz 4	21.14	0.00	0.98	1.93	12.05	177.4	101.4	122799	224	13188	12.76	14521	934	560	3747	199

HFC233	Allmendingen	14.34	129.12	1.39	0.53	13.46	96.2	120.8	90226	200	60412	3.67	27579	230	503	5183	345
HFC234	Allmendingen	13.66	121.89	1.36	0.64	12.99	95.2	87.6	88253	157	85442	3.41	27456	232	447	5071	291
HFC235	Allmendingen	18.09	136.02	1.37	0.75	14.76	84.4	121.3	105080	209	21571	4.95	32499	193	625	5647	317
HFC236	Allmendingen	18.20	106.25	1.43	0.87	14.80	99.5	142.7	105269	180	21634	5.18	31184	194	618	5418	332
HFC237	Bohnerz 9	5.00	0.00	0.33	1.01	3.19	149.9	0.0	18306	0	1341	5.46	4755	373	50	1064	388
HFC238	Bohnerz 1	51.35	0.00	0.82	3.16	16.19	302.3	0.0	79228	0	1531	19.75	0	1021	74	3447	799
HFC239	Bohnerz 7	4.30	0.00	0.00	0.67	1.05	439.3	0.0	6177	0	2198	3.97	0	932	26	0	525
HFC240	Bohnerz 2	35.50	0.00	2.01	1.01	23.98	84.0	232.8	74468	0	720	8.69	0	333	52	6422	859
HFC241	Bohnerz 7	17.80	0.00	1.07	0.69	13.70	205.0	112.2	121674	238	30761	4.28	21010	676	548	4074	185
HFC242	Bohnerz 7	17.70	0.00	1.13	0.74	13.77	199.6	79.2	119964	232	29636	4.37	19987	716	582	3723	194
HFC243	Ringingen	3.98	0.00	0.40	0.17	2.63	30.3	42.9	40997	230	1257	2.00	14968	226	682	1281	69
HFC244	Ringingen	4.14	0.00	0.46	0.23	2.91	35.7	62.4	40378	257	1906	1.54	15261	214	650	1819	65
HFC245	Ringingen	4.40	0.00	0.49	0.24	3.10	27.3	53.3	40193	181	1222	1.56	13094	204	655	1454	60
HFC246	Ringingen	4.02	0.00	0.46	0.26	3.41	29.1	62.5	40386	171	1468	1.66	15794	226	706	1628	62
HFC247	Bohnerz 3	43.92	0.00	0.98	2.51	15.00	208.6	216.2	74030	0	0	14.69	0	696	90	4057	945
HFC248	Bohnerz 3	43.61	0.00	0.93	3.05	19.33	202.4	225.9	71641	0	0	18.24	0	527	100	3707	1111
HFC249	Bohnerz 3	43.67	0.00	1.38	1.18	16.99	99.5	143.9	91852	0	0	7.25	0	219	83	5168	869
HFC250	Bohnerz 7	2.57	0.00	0.17	0.38	1.49	729.0	0.0	14937	0	4066	4.39	1764	158	140	718	129
HFC251	Bohnerz 7	14.51	0.00	0.57	2.10	5.54	272.3	142.7	29746	0	1467	14.10	999	331	61	2006	295
HFC252	Bohnerz 7	17.31	0.00	0.00	3.40	1.17	163.5	0.0	11477	0	1198	12.55	0	611	50	344	150
HFC253	Bohnerz 7	3.84	0.00	0.00	0.57	2.96	213.0	0.0	9535	0	1847	3.92	1082	423	123	467	501
HFC254	Bohnerz 1	1.08	0.00	0.00	0.00	0.46	40.4	0.0	6515	0	1491	0.96	0	390	51	0	22
HFC255	Altheim	6.67	0.00	0.65	0.46	5.69	31.7	93.2	54223	242	4243	2.73	14367	266	1058	2815	52
HFC256	Altheim	0.72	0.00	0.00	0.00	0.67	224.9	0.0	5832	0	2343	0.58	0	536	66	549	44
HFC257	Altheim	1.50	0.00	0.00	0.00	0.89	80.3	0.0	6559	0	3631	1.45	1657	162	264	233	37
HFC258	Altheim	0.89	0.00	0.00	0.00	0.53	326.1	0.0	8225	1916	2188	0.88	4100	922	143	903	8
HFC259	Altheim	1.88	0.00	0.00	0.38	1.56	74.7	0.0	12999	238	1841	2.47	5812	1309	474	708	35
HFC260	Altheim	2.79	0.00	0.26	0.60	2.13	85.3	0.0	15382	0	3733	4.58	0	1724	422	1698	68
HFC261	Herz-Jesu Berg	42.44	0.00	0.50	0.39	26.96	102.0	0.0	39214	0	2104	4.55	0	769	120	1858	1185
HFC262	Herz-Jesu Berg	35.35	0.00	1.72	2.67	32.50	124.6	322.1	60044	0	8519	13.44	0	1497	83	6141	1216
HFC263	Herz-Jesu Berg	26.09	0.00	2.02	0.80	27.59	96.5	203.4	52510	0	2942	6.44	0	2817	0	6305	1093

HFC264	Tormerdingen	32.03	0.00	2.73	1.52	25.10	312.1	333.4	148385	0	37194	10.67	1389	639	416	9350	368
HFC265	Tormerdingen	33.00	0.00	2.85	1.70	25.97	320.7	342.7	141998	0	33531	10.81	0	622	392	9427	377
HFC266	Tormerdingen	32.70	0.00	2.85	1.55	25.82	318.7	293.1	140722	0	38353	10.79	2998	711	369	9487	388
HFC267	Tormerdingen	32.46	0.00	2.71	1.57	25.22	338.6	302.5	142135	0	41091	10.42	0	622	423	9367	370
HFC268	Tormerdingen	32.79	0.00	2.65	1.55	25.80	323.7	303.5	141931	0	37665	10.47	2962	640	400	9993	367
HFC269	Schelklingen	27.02	445.50	2.13	2.03	20.40	416.9	253.8	148811	139	22446	13.01	8049	763	304	8342	254
HFC270	Schelklingen	26.96	451.32	2.06	1.97	20.15	415.6	232.9	147839	0	23988	12.94	8940	772	305	7659	247
HFC271	Schelklingen	27.44	379.07	2.09	2.20	20.52	400.3	248.8	162525	0	24107	13.86	6401	815	339	9297	293
HFC272	Schelklingen	26.98	385.41	2.11	1.98	20.08	394.7	239.1	155524	0	22701	13.00	7690	764	343	8085	278
HFC273	Schelklingen	26.17	412.89	2.06	1.84	19.63	396.1	232.7	155207	0	24135	13.50	5824	861	339	8085	271
HFC274	Schelklingen	25.82	0.00	1.18	1.45	12.74	140.7	252.6	75654	0	15357	11.51	0	1435	41	4592	695
HFC275	Schelklingen	44.83	0.00	1.62	3.48	19.25	174.0	378.2	84900	0	32313	21.33	0	1560	66	6451	902
HFC276	Schelklingen	46.70	0.00	1.59	1.42	54.76	182.8	199.9	103782	0	1928	8.59	0	2250	109	6074	2007
HFC277	Harz	0.26	0.00	0.00	0.00	0.00	0.0	0.0	12668	0	0	1.70	0	82	2321	0	20
HFC278	Harz	0.18	0.00	0.00	0.22	0.00	0.0	0.0	14104	0	0	1.55	0	89	2104	0	0
HFC279	Harz	0.16	0.00	0.00	0.00	0.00	0.0	0.0	10349	0	0	1.43	0	89	2154	0	19
HFC280	Harz	0.20	0.00	0.00	0.34	0.00	0.0	0.0	12662	0	0	1.81	0	98	2103	0	15
HFC281	Harz	0.16	0.00	0.00	0.00	0.00	0.0	0.0	11162	0	0	1.67	0	89	2128	0	0
HFC282	Geyer Erzgebirge	0.39	0.00	0.00	1.10	0.00	20.2	114.6	9683	0	0	8.12	0	398	87	0	47
HFC283	Geyer Erzgebirge	0.45	0.00	0.00	1.27	0.46	0.0	0.0	11085	0	448	7.96	0	409	86	0	41
HFC284	Geyer Erzgebirge	0.48	0.00	0.00	1.65	0.00	13.9	208.7	7244	0	700	9.44	0	562	86	175	34
HFC285	Geyer Erzgebirge	0.50	0.00	0.00	1.50	0.00	11.3	208.9	6474	112	0	10.05	0	570	64	345	49
HFC286	Geyer Erzgebirge	0.49	0.00	0.00	1.44	0.00	6.5	112.0	7915	169	0	9.59	0	574	67	0	72
HFC287	Zindelstein	40.45	0.00	0.54	1.39	20.76	171.6	107.2	157592	928	7896	8.13	35123	854	1797	2099	224
HFC288	Zindelstein	40.52	0.00	0.74	1.45	21.07	177.1	68.0	124986	1011	8809	8.00	36236	908	1723	1865	212
HFC289	Zindelstein	37.23	0.00	0.62	1.26	17.81	174.1	113.0	118488	944	7931	7.78	36936	1060	3906	2339	191
HFC290	Zindelstein	40.23	0.00	0.76	2.03	20.54	181.3	181.6	142790	1028	7013	8.66	34518	911	2805	1166	203
HFC291	Zindelstein	40.22	0.00	0.66	1.44	20.11	191.4	93.2	119687	1002	8835	8.21	34480	1003	2152	1976	195
HFC292	Schollach	4.90	63.08	2.48	0.64	12.52	26.2	115.8	69892	268	816	3.88	39597	198	4780	1365	22
HFC293	Schollach	4.81	37.40	2.61	0.66	12.93	29.8	149.7	67073	318	1239	3.51	48823	226	5105	1650	39
HFC294	Schollach	4.72	0.00	2.44	0.54	13.08	28.8	148.7	69777	356	710	4.18	42606	235	5380	1845	22

HFC295	Schollach	5.22	0.00	2.55	0.63	14.92	33.7	121.8	73328	340	505	3.87	49061	359	5118	2022	24
HFC296	Schollach	5.41	0.00	2.77	0.53	12.28	27.4	139.3	72693	386	0	4.11	46891	225	4878	1885	19
HFC297	Hechtsberg	1.12	0.00	0.00	0.00	0.53	0.0	88.7	13781	0	0	0.84	2174	313	138	0	35
HFC298	Hechtsberg	1.07	0.00	0.00	0.00	0.57	0.0	0.0	26010	128	0	0.76	3145	286	162	0	43
HFC299	Hechtsberg	1.13	0.00	0.00	0.00	0.49	0.0	135.2	29632	104	0	0.80	627	280	118	0	43
HFC300	Hechtsberg	2.12	0.00	0.00	0.00	1.68	0.0	91.6	22060	117	0	0.76	2968	152	242	267	30
HFC301	Hechtsberg	2.14	0.00	0.00	0.00	1.28	0.0	79.3	19245	104	724	0.82	2882	149	224	348	34
HFC302	Hechtsberg	2.18	0.00	0.00	0.00	1.25	0.0	96.0	23357	0	0	0.82	3501	154	196	390	30
HFC303	Hechtsberg	3.60	0.00	0.00	0.30	1.11	295.2	105.5	24499	111	106760	1.67	0	4357	298	0	65
HFC304	Hechtsberg	3.60	0.00	0.00	0.32	1.28	299.6	57.4	16682	150	109957	2.15	0	4349	407	0	49
HFC305	Hechtsberg	3.52	0.00	0.15	0.29	1.26	297.5	99.7	18130	111	106209	1.60	703	4345	333	0	74
HFC306	NUSSBACH	5.44	0.00	2.49	0.96	24.47	22.5	93.3	75451	712	696	7.93	46949	276	7196	730	9
HFC307	NUSSBACH	5.90	70.77	2.56	1.40	26.73	26.9	115.8	75602	777	442	6.68	44902	285	6147	363	0
HFC308	NUSSBACH	5.19	0.00	2.47	1.01	27.96	15.5	82.4	76934	908	1663	7.57	43472	265	6205	494	0
HFC309	NUSSBACH	5.03	0.00	2.36	1.31	25.76	15.8	105.1	82769	600	1586	8.44	48739	325	6046	571	0
HFC310	NUSSBACH	5.29	39.71	2.32	1.40	27.58	20.2	83.9	71048	455	1310	6.80	43801	256	5540	754	10
HFC311	Rappenloch	8.51	742.77	0.25	4.42	1.51	373.2	534.3	0	62142	0	0.00	0	0	0	0	0
HFC312	Rappenloch	8.20	723.00	0.31	4.32	1.44	371.7	474.4	0	61241	0	0.00	0	0	0	0	0
HFC313	Rappenloch	7.92	807.23	0.25	4.20	1.37	348.3	487.5	0	62758	0	0.00	0	0	0	0	0
HFC314	Rappenloch	3.57	0.00	2.69	0.79	9.40	16.0	108.6	52617	381	0	4.80	34573	448	966	976	75
HFC315	Rappenloch	3.65	0.00	2.62	1.20	9.72	12.1	66.2	49598	309	0	6.01	37625	435	945	0	87
HFC316	Rappenloch	8.25	0.00	0.00	0.56	4.69	14.1	342.4	14100	1193	0	3.10	2555	303	151	0	310
HFC317	Rappenloch	7.74	0.00	0.00	0.42	4.22	0.0	325.9	14494	898	0	3.32	0	218	173	0	312
HFC318	Rappenloch	7.84	0.00	0.00	0.61	4.30	0.0	323.6	16483	1089	0	3.13	0	645	136	0	348
HFC319	Rappenloch	0.00	0.00	0.00	0.00	0.00	0.0	0.0	34563	0	0	0.00	7898	11298	331	0	134
HFC320	Rappenloch	2.21	0.00	1.88	0.38	6.01	15.1	77.2	20298	2897	0	1.11	20892	11315	444	0	240
HFC321	Rappenloch	2.52	117.26	1.94	0.41	6.13	18.2	91.4	21378	3309	0	1.39	14292	10670	436	0	198
HFC322	Rappenloch	5.66	0.00	1.46	1.57	5.81	59.8	350.6	0	33059	0	0.00	0	7	0	0	0
HFC323	Rappenloch	5.67	0.00	1.40	1.77	5.83	61.3	376.3	0	32734	0	0.00	0	3	0	0	0
HFC324	Rappenloch	5.42	0.00	1.33	1.50	5.65	60.0	301.6	0	32652	0	0.00	0	0	0	0	0
HFC325	Rappenloch	3.00	0.00	0.00	0.00	1.30	0.0	1749.3	10383	1283	0	0.79	2390	358	81	0	310

HFC326	Rappenloch	2.91	0.00	0.00	0.00	0.86	0.0	1795.1	9996	1395	0	0.80	0	386	72	0	320
HFC327	Rappenloch	3.00	0.00	0.00	0.00	1.51	0.0	1661.3	8883	1770	0	0.72	2777	361	107	0	326
HFC328	Rappenloch	4.17	358.07	2.30	0.36	7.90	23.2	120.3	50206	12013	0	2.91	21465	2184	1445	0	81
HFC329	Rappenloch	2.96	98.83	1.86	0.27	6.79	25.8	128.0	46556	3459	532	1.83	21313	1071	700	0	68
HFC330	Rappenloch	2.82	58.75	1.62	0.23	5.68	12.6	121.1	38328	2227	780	1.27	16796	601	467	0	50
HFC331	Rappenloch	3.22	318.38	0.87	0.34	5.40	29.5	323.9	41297	22960	0	2.60	19414	2477	876	0	217
HFC332	Rappenloch	3.24	0.00	0.62	0.26	4.52	8.6	356.0	27367	1412	490	1.69	10222	537	258	0	160
HFC333	Rappenloch	3.29	0.00	0.46	0.15	5.01	10.2	343.9	26250	1517	0	1.41	7668	531	248	0	132

Appendix D.

Appendix for Paper 1 (Chapter 5) Supplementary Information.

NOTE: *SI Figures are not included in this section as they are previously shown in Chapter 2 – Background, Section 2.2.1*

Table 4: Figure 5.3 (Hohle Fels Aurignacian and A/G transition) artefact descriptions.

Aurignacian	Year	Quad	AH	Find #
1	2013	54	IV	557
2	2002	58	IId-IV	2099.2
3	2002	58	IId-IV	2099.1
4	2002	57	IId	3149
5	2016	31	Vaa	2095
6	2013	27	Va	1271
7	2016	32	Vaa	1635
8	2012	29	Vb	1966
9	2014	28	Vab	1856
10	2006	86	IV	1122.1
11	2003	59	V-VII	2365
12	2004	87	IIIa.1	1205
13	2013	54	IIIa	338
14	1996	79	IId	2224
15	2016	32	Vaa	1635.2
16	2007	29	Va	1838
17	2000	79	IIe	2555
18	1995	79	IId	2083
19	2015	31	IIIa	984.2
20	2015	32	IV	215
21	2006	86	IV	1122.2
22	2015	32	Va	1079
23	2015	31	IIIa	984.1
24	2004	75	IV	631
25	2016	32	Vaa	1635.1
26	2005	86	IIIa	975
27	2004	97	IIIa.1	1054
28	2006	99	IId-IV	2087
29	2013	54	IIIa	363.1
30	2005	98	IV.6	1702
31	2004	66	IIIa-V	4347

Table 5: Figure 5.4 (Hohle Fels Gravettian) artefact descriptions.

Gravettian	Year	Quad	AH	Find #
1	1998	56	IIb	404
2	1998	65	IIb-IVb	205.1
3	2017	111	IIb	621
4	1995	58	IIb	571
5	2002	56	IIcf	3502.1
6	1998	65	IIb-IV	205.3
7	1977	12	IIbf	54
8	2004	55	IIc	1256
9	1977	12	IIbf	54.2
10	2011	136	IIb	328
11	1990	79	IIb	887
12	1977	12	IIbf	54.3
13	2012	46	IIb	251
14	2007	30	IIdb	754
15	1995	56	IIb	245
16	1995	56	IIb	245.2
17	1998	56	IIb	358.1
18	1995	57	IIb	444
19	1995	57	IIb	443
20	1995	67	IIb	350.1
21	1998	65	IIb-IV	205.2
22	1990	79	IIb	852
23	1995	56	IIb	278
24	1998	56	IIb	358.2
25	2010	110	IIb	1166
26	1995	58	IIb	572
27	1977	12	IIbf	54.1
28	1988	59	IIb	867
29	1995	67	IIb	350.2
30	1998	56	IIb	454
31	1990	79	IIb	865
32	1998	65	IIb-IV	205.4

Table 6: Figure 5.5 (Hohle Fels Magdalenian) artefact descriptions.

Magdalenian	Year	Quad	AH	Find #
1	2011	111	IIad	357
2	2011	112	IIaf	475
3	2010	112	IIaf	547
4	95	68	I	826
5	1993	67	I	147
6	1991	68	IIa	268
7	2001	89	I	129.1
8	1998	55	I	276
9	2002	99	0I	132
10	1978	24	IIa	380
11	2001	89	I	129
12	2009	102	IIaf	693
13	1992	67	I	52
14	2010	110	IIad	1104
15	2010	110	IIad	971
16	1978	59	Ia	214
17	2001	89	I	179
18	1979	24	Ic	531
19	94	67	IIa	208

Table 7: Figure 5.11 (Hohle Fels artefacts with residues) artefact descriptions.

Residues	Period	Year	Quad	AH	Find #	Material
1	Aurignacian	1996	59	IV	1784	Reindeer rib
2	Magdalenian	1988	79	IIa	3592	
3	Aurignacian	2004	97	IIIa	1083	Jurahornstein
4	Aurignacian	2003	76	IV	1510.1	Ivory bead
5	Aurignacian	2009	25	Vab	1340.2	Ivory bead
6	Aurignacian	2009	25	Vab	1310.2	Ivory bead
7	Aurignacian	2014	25	Vab-VII	1354.2	Ivory bead
8	Aurignacian	2013	27	Va	1011	Ivory bead
9	A/G trans	2000	79	IIe	2555.108	
10	Magdalenian	1988	79	IIa	314.1	Rabbit tooth
11	Magdalenian	1988	79	IIa	314.2	Fox tooth
12	Magdalenian	1988	49	Ib	158	Shell
13	Magdalenian	1977	11	IIa	82	Shell
14	Gravettian	1995	67	IIb	367	
15	Magdalenian	2001	59	0-IIIb	1842	Limestone
16	Aurignacian	2009	99	IV.6	2262	Jurahornstein
17	A/G trans	2000	79	IIe	2555.109	
18	Gravettian	1988	69	IIb	232	Shell
19	Gravettian	2006	100	IIb	598	Shell
20	Gravettian	1994	67	IIb	222	Shell
21	Magdalenian	2015	110	0/I-IId	1314	Mollusc fossil
22	Aurignacian	2005	98	IIIawf	1254	

Table 8: Means and standard deviations for L*A*B* values per time period.

L (lightness)*

Period	n	Mean	SD	SE	Lower 95%	Upper 95%
A/G Trans	25	62.8	20.78	4.16	54.22	71.38
Aurignacian	286	70.52	17.86	1.06	68.44	72.6
Gravettian	217	55.72	16.46	1.12	53.52	57.93
Holocene	13	52.92	12.22	3.39	45.54	60.31
Magdalenian	120	53.03	14.07	1.28	50.48	55.57

A (green-red)*

Period	n	Mean	SD	SE	Lower 95%	Upper 95%
A/G Trans	25	11.56	10.53	2.11	7.21	15.91
Aurignacian	286	11.04	10.89	0.64	9.77	12.30
Gravettian	217	16.38	9.25	0.63	15.14	17.62
Holocene	13	18.92	6.73	1.87	14.86	22.99
Magdalenian	120	19.12	7.53	0.69	17.76	20.48

B (blue-yellow)*

Period	n	Mean	SD	SE	Lower 95%	Upper 95%
A/G Trans	25	32.92	12.65	2.53	27.7	38.14
Aurignacian	286	36.81	10.39	0.62	35.6	38.02
Gravettian	217	30.13	12.29	0.83	28.5	31.78
Holocene	13	30	5.57	1.54	26.64	33.37
Magdalenian	120	32.28	9.16	0.84	30.62	33.93

Table 9: One-way ANOVA results for measured L* values for each time period.

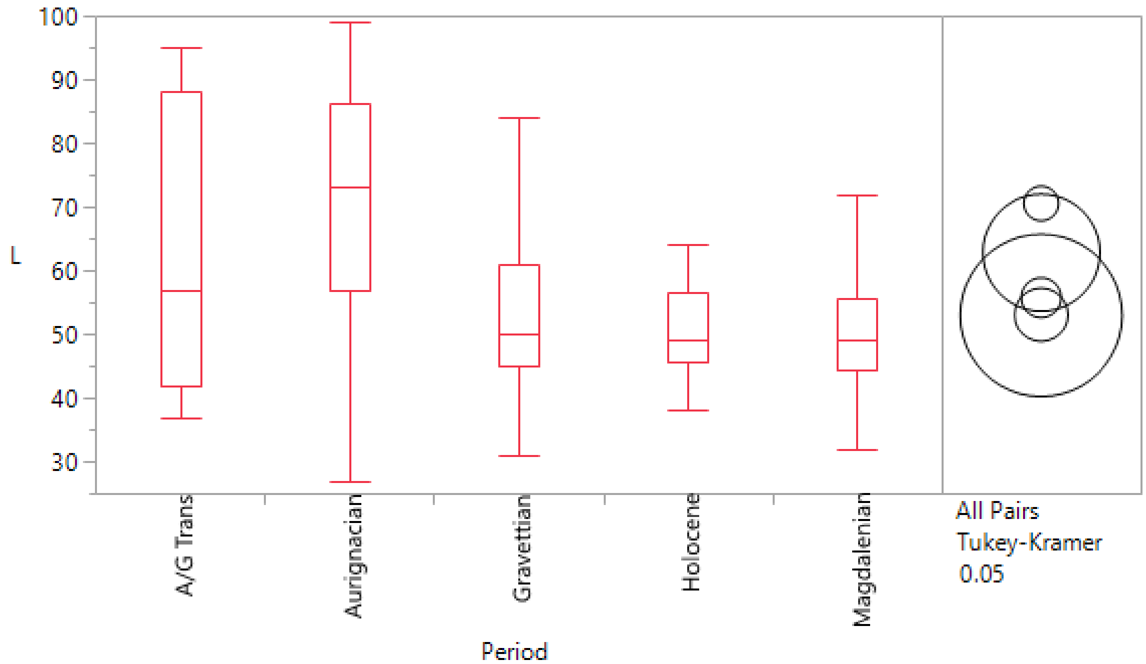
Analysis of Variance

Groups	df	Sum of Squares	Mean Square	F	Prob > F
Between	4	40034.90	10008.7	35.4745	*<.0001**
Within	656	185082.67	282.1		
Total	660	225117.57			

Means for Oneway Anova

Period	n	Mean	SE	Lower 95%	Upper 95%
A/G Trans	25	62.80	3.36	56.20	69.40
Aurignacian	286	70.52	0.99	68.57	72.47
Gravettian	217	55.72	1.14	53.49	57.96
Holocene	13	52.92	4.66	43.78	62.07
Magdalenian	120	53.03	1.53	50.01	56.04

Table 10: Tukey-Kramer post-hoc test data for L* (lightness) colour values on Hohle Fels colour streaks per time period.



Ordered Differences Report from Tukey-Kramer's test on each pair

q = 2.73540, α = 0.05, starred (*) and italicized values are statistically significantly different pairs.

Group comparisons		Difference	SE	Lower CL	Upper CL	p-Value
Aurignacian	Holocene	17.59441	4.763343	4.5647	30.62407	*0.0022**
Aurignacian	Magdalenian	17.49248	1.826923	12.4951	22.48986	*<.0001**
Aurignacian	Gravettian	14.79398	1.512175	10.6576	18.93039	*<.0001**
A/G Trans	Holocene	9.87692	5.743559	-5.8340	25.58788	0.4225
A/G Trans	Magdalenian	9.77500	3.692788	-0.3263	19.87627	0.0633
Aurignacian	A/G Trans	7.71748	3.503145	-1.8650	17.30000	0.1798
A/G Trans	Gravettian	7.07650	3.547634	-2.6277	16.78071	0.2697
Gravettian	Holocene	2.80043	4.796156	-10.3190	15.91985	0.9774
Gravettian	Magdalenian	2.69850	1.910845	-2.5284	7.92543	0.6200
Magdalenian	Holocene	0.10192	4.904497	-13.3139	13.51770	1.0000

Table 11: Hohle Fels ochre rock type sorted by archaeological horizon (AH) and time period. Abbreviations are as follows: H = Holocene, M = Magdalenian, G = Gravettian, A/G = A/G transition, A = Aurignacian. For the rock types: RS = Red sediment, DL = Degraded Limestone.

AH	Period	Total	Volume	Clay	Hematite	Iron Oxide	RS	Sandstone	Siltstone	DL	Specularite
0-0/I	H	21	9814.18	1	14	3		2	1		
I	M	93	65669.22	5	70	6	2	8	2		0
IIa	M	71	112625.5	2	42	13		12	2		
IIb	G	227	208972.9	1	172	31	2	21			
IIc	G	43	29283.49	2	11	15	2	12	1		
IIcf	G	8	14820.5		2		1	5			
IId	A/G	29	111990	1	7	12	1	7		1	
IIe	A/G	6	14644.24		2	4					
IIIa	A	52	256249.6	1	27	5	1	15		2	1
IIIb	A	3	793.61		2	1					
IV	A	67	19292.87	1	11	16	15	22	1		1
Va	A	241	59783.42	3	51	42	17	124	3		1
Vb	A	8	2756.56		2	2	1	3			
Total		**869**	**877412.6**	**17**	**413**	**150**	**42**	**231**	**10**	**3**	**3**

Table 12: Hohle Fels ochre textures sorted by archaeological horizon (AH) and time period. Abbreviations are as follows: H = Holocene, M = Magdalenian, G = Gravettian, A/G = A/G transition, A = Aurignacian. For the textures: Med. Sand = Medium grained sand.

AH	Period	Total	Volume	Clayey	Clayey/Silty	Silty	Silty/Sandy	Very fine sand	Fine sand	Med. sand
0-0/I	H	21	9814.18	2	1	5	7	3	3	
I	M	93	65669.22	13	17	15	31	6	10	1
IIa	M	71	112625.5	10	8	10	19	11	11	2
IIb	G	227	208972.9	26	69	18	69	9	33	3
IIc	G	43	29283.49	5	6	5	6	13	6	2
IIcf	G	8	14820.5					2	6	
IId	A/G	29	111990	3	1	6	6	4	8	1
IIe	A/G	6	14644.24			4	2			
IIIa	A	52	256249.6	1		25	3	5	15	3
IIIb	A	3	793.61			2	1			
IV	A	67	19292.87	4	4	5	8	9	31	6
Va	A	241	59783.42	31	15	12	18	19	134	12
Vb	A	8	2756.56	1		1	1	1	3	1
	Total	**869**	**877412.6**	**96**	**121**	**108**	**171**	**82**	**260**	**31**

Table 13: Hohle Fels ochre colours sorted by archaeological horizon (AH) and time period. Abbreviations are as follows: H = Holocene, M = Magdalenian, G = Gravettian, A/G = A/G transition, A = Aurignacian. For the colours: BR = Brick Red, DP = Dark Purple, DR = Dark Red, LP = Light Purple, LR = Light Red.

AH	Period	Total	Volume	Black	Brown	BR	DP	DR	LP	LR	Orange	Pink	Purple	Red	Rust	Yellow
0-0/I	H	21	9814.18				5	5	1	2		1	7			
I	M	93	65669.22				34	8	4	5	1	1	31	9		
IIa	M	71	112625.5		1		24	6	1	6		2	17	13	1	
IIb	G	227	208972.9			2	52	5	6	14	1	6	117	19	5	
IIc	G	43	29283.49	1	1	5	9	3		9	1	1	5	7	1	
IIcf	G	8	14820.5					1		5			2			
IId	A/G	29	111990			1	4	5		3	3		4	4	5	
IIe	A/G	6	14644.24				3		1				1			1
IIIa	A	52	256249.6	1		10	28	2		2				5	3	1
IIIb	A	3	793.61	1	1		1									
IV	A	67	19292.87		6	2	8	7		12		2	5	25		
Va	A	241	59783.42	2	1	28	47	37	1	47	1	2	13	58	3	1
Vb	A	8	2756.56				2	2				1		3		
Total		**869**	**877412.6**	**5**	**10**	**48**	**217**	**81**	**14**	**105**	**7**	**16**	**202**	**143**	**18**	**3**

Appendix E.

Appendix for Paper 2 (Chapter 6) Supplementary Information.

This document contains:

1. Results

In this section, we provide more in-depth descriptions of the geochemical traits of the Fe-oxide sources sampled in this study. Figure A shows an element-pair bivariate plot of Sc/Fe and U/Fe of all source samples. For the most part, bivariate plotting did not show clear distinction between sub-outcrops. Some Swabian Jura sources, including Allmendingen (Allmen) and Tormerdingen (Tormer), showed high internal homogeneity and low "spread" in compositional space. Sources Gerhausen and Schelklingen showed consistent overlap in chemical trends, and because those two localities (<5 km from each other) are likely from the same extensive Fe-oxide deposit (*Bohnerzlehm*), we combined the two and subsequently treated them as a single source (Schel-Gerha). Figure B shows a bivariate element plot of Sc/Fe and Sb/Fe, with the combination of Schel-Gerha, the separation of Rappen and RappenB, and the separation of the Bohnerz 1-8 outcrops into "Bohnerz" and "Bohn-B". In many element-pair scatterplots, "distant" source areas (Harz, Geyer-Erzgebirge) were highly differentiated from the Swabian Jura and Black Forest sources. However, the general trend observed was significant overlap between Swabian Jura and Black Forest sources, indicating that differentiating those sources on a statistical basis required a multi-element approach. It is worth noting that in our initial exploration of the source data we determined that samples from Altheim to have a highly heterogenous chemical signature (based on chemistry and other quantitative variables), and excluded those samples from further statistical testing (such as shown in Figure C).

Table Notable geochemical trends include:

Swabian Jura sources

-Allmendingen (Allmen): High K, Al, Ti, and Ca, high internal consistency for most elements except for Ba and Ca.

-Altheim: Significant internal element variation within samples in this group, suggesting the potential for a non-representative data set (perhaps another geological deposit).

-**Bohnerz and Bohnerz-B subgroup (Bohnerz/Bohn-B):** Due to the high variation amongst the Bohnerz 1-8 sources, they were combined during analyses to form the collective group “Bohnerz”. This group had the greatest degree of “spread” in bivariate plotting. A sub-group high in K was separated out as Bohnerz-B, and two in-source outliers were identified (HFC202, HFC250) and excluded from further statistics.

-**Gerhausen (Gerhau):** High Al and Ca, and enriched in light rare earth elements (Ce, Nd, Sm). The high amount of Al likely indicates that the ochre source may contain clay minerals.

-**Herz-Jesu Berg (HerzJes):** High Sc, Cr, and V relative to most other sources, very high REE content in sample HFC262.

-Kirchbierlingen (Kirschb): Single sample low in Fe, high in K, Ca.

-Ringingen (Ringin): Moderately high Al, K, and Ti. High internal consistency for most elements.

-Rudelstetten (Rudel): High Al, above average light rare earth element concentrations. High Al may also indicate clay minerals.

-Schelklingen (Schelk): Three samples (HFC274-276) noted as inconsistent with remainder (i.e. high Fe and low Fe group).

-Tormerdingen (Tormer): High Al and Ca, high internal consistency with most element concentrations.

Harz Mountain sources

-**Geyer-Erzgebirge (Geyere):** High Fe-content source, with below detection limit values for some major and trace elements (K, Ta, Hf).

-**Harz:** High-purity Fe-oxide source, with most trace and rare earth elements below the limit of detection. High Sb.

Black Forest sources

-**Hechtsberg (Hecht):** High Fe-content source with characteristic rare earth element distribution. High internal variation in Ca.

-Rappenloch (Rappen): Split into two groups; one sub-group has significantly high Ba (up to 6%), suggesting a barium-sulfide mineral adjunct in Fe-oxide deposit. Due to an unanticipated high Ba content, many of the elemental measurements in the

Rappenloch-B sub-group are quoted as below the limit of detection. High Ba concentrations resulted in significant spectral interferences and a number of elements could not be measured by NAA.

-Schollach (Scholl): Very low Fe, high K, Al. High internal consistency with most element concentrations.

-Zindelstein (Zindel): Above average rare earth element concentrations, high Al and Ti.

1.2 Bivariate Plots and Canonical Discriminant Analysis (CDA)

Canonical discriminant analysis (CDA) is a dimension-reducing method that transforms multiple independent variables into a linear combination of those variables (one fewer than the total number of groups), which describe decreasing amounts of separation between compositional groups. These are referred to as the canonical discriminant function (i.e. CDA#1, CDA#2, etc.), and are expressed as a percentage of the magnitude of separation. Additionally, each independent variable (i.e. element) is calculated a score relative to its influence on the separation of groups. Bivariate plots of discriminant functions are a typical visual output showing group separation. CDA differs from principal components analysis (PCA) in that it extracts a new set of variables that maximize the differences between two or more groups rather than maximizing the variance of the total data set, and is more advantageous in circumstances when known sources can be treated as groups.

The most useful statistical approach for exploring the data set of ochre sources proved to be CDA. It shows the clearest visual output for differentiating regions (i.e. Swabian Jura, Harz Mountain, Black Forest), and for separating sources within each of those regions. It is a more effective approach when a data set is comprised of known sources (i.e. pre-designated “groups”), as it will maximize inter-group variation (as opposed to overall variation as done in PCA). CDA assumes that all samples within the data set belong to a known group. In recent literature, CDA appears to be a most common statistical approach for provenance analysis of ochre (Zipkin et al., 2017).

2. SI Figures

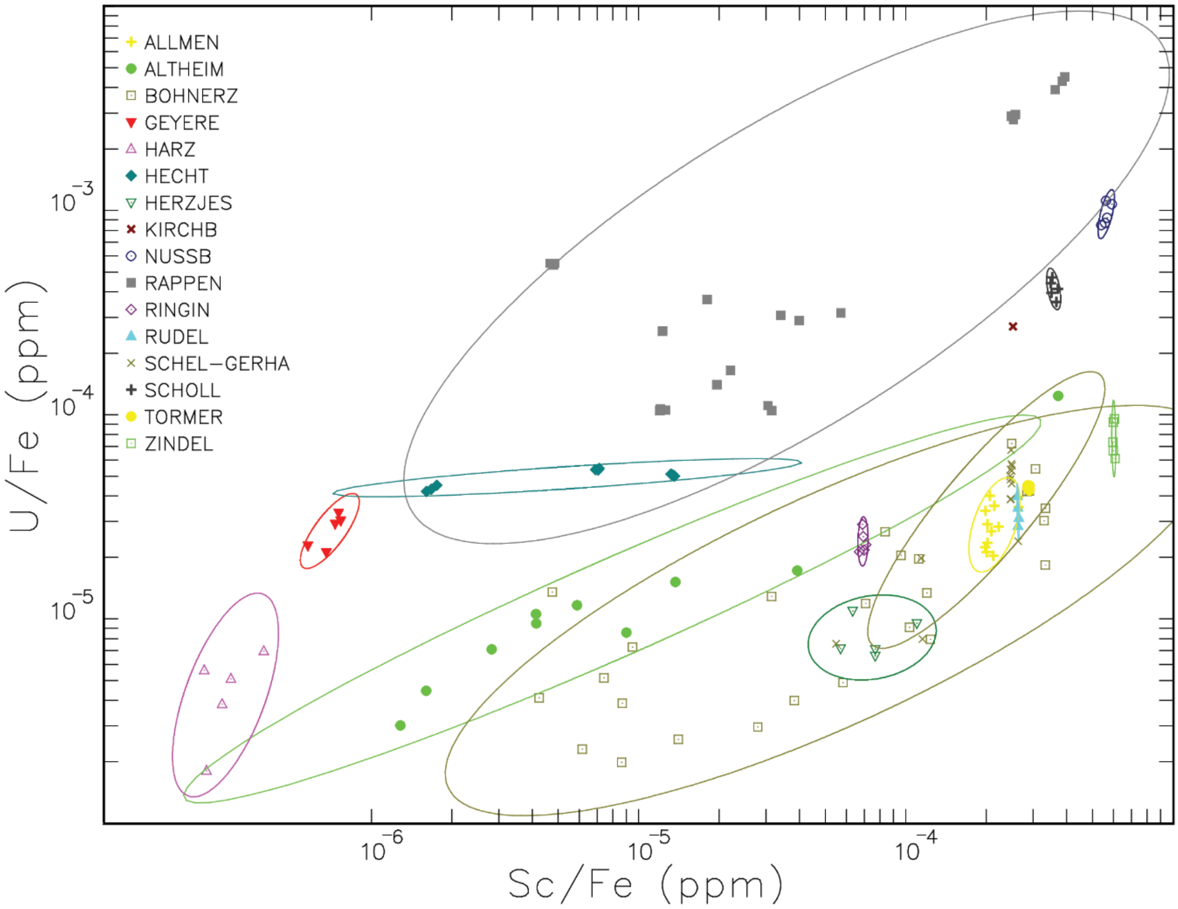


Figure F: Bivariate plot showing Sc/Fe and U/Fe values for all sampled sources showing little distinction outside of general source-areas. Note the combination of Schelkingen and Gerhausen into Schel-Gerha. Ellipses are drawn at 90% confidence.

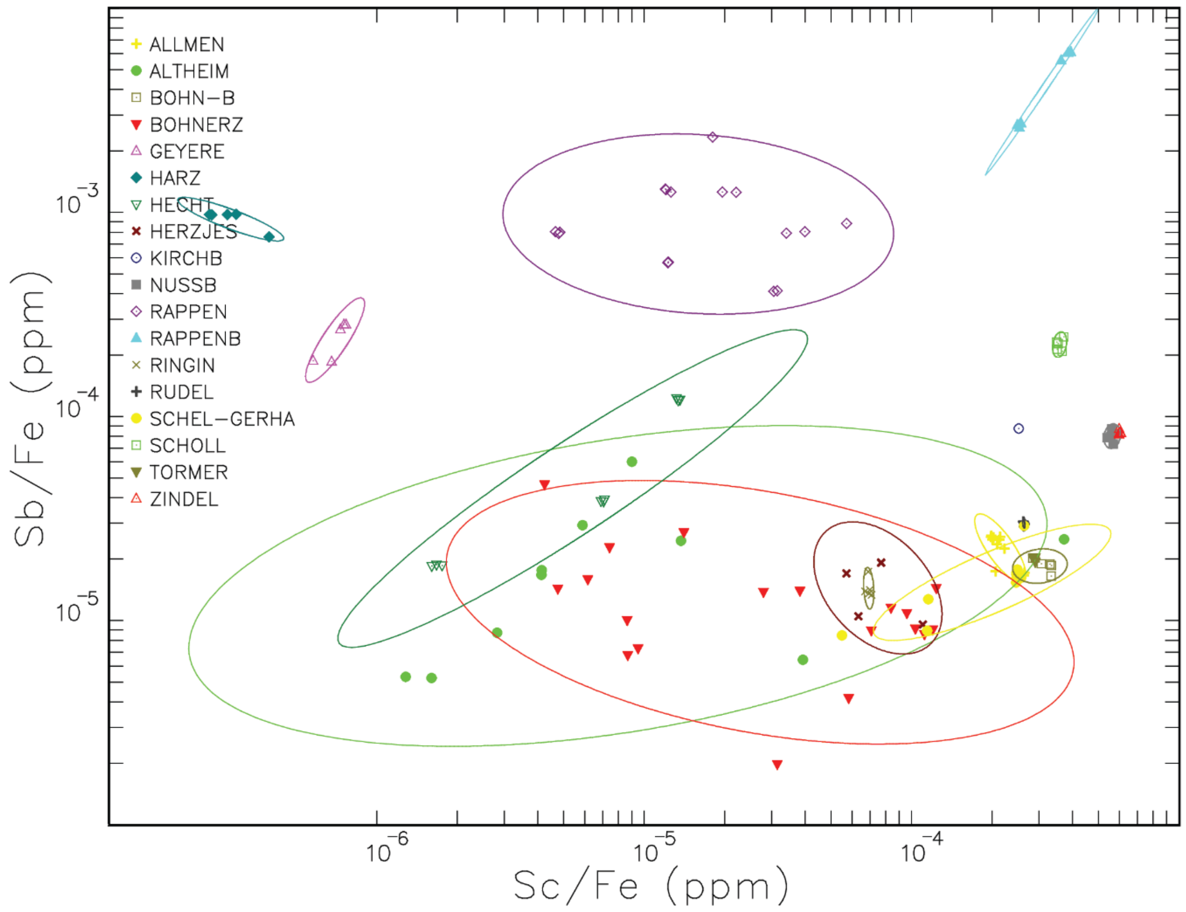


Figure G: Element bivariate plot showing Sc/Fe and Sb/Fe values for sampled ochre sources. Notice the separation of the “Bohn-B” subgroups due to high compositional spread, the separation of Rappenloch samples into Rappen and RappenB, and the combination of Schelkingen and Gerhausen into Schel-Gerha. Ellipses are drawn at 90% confidence.

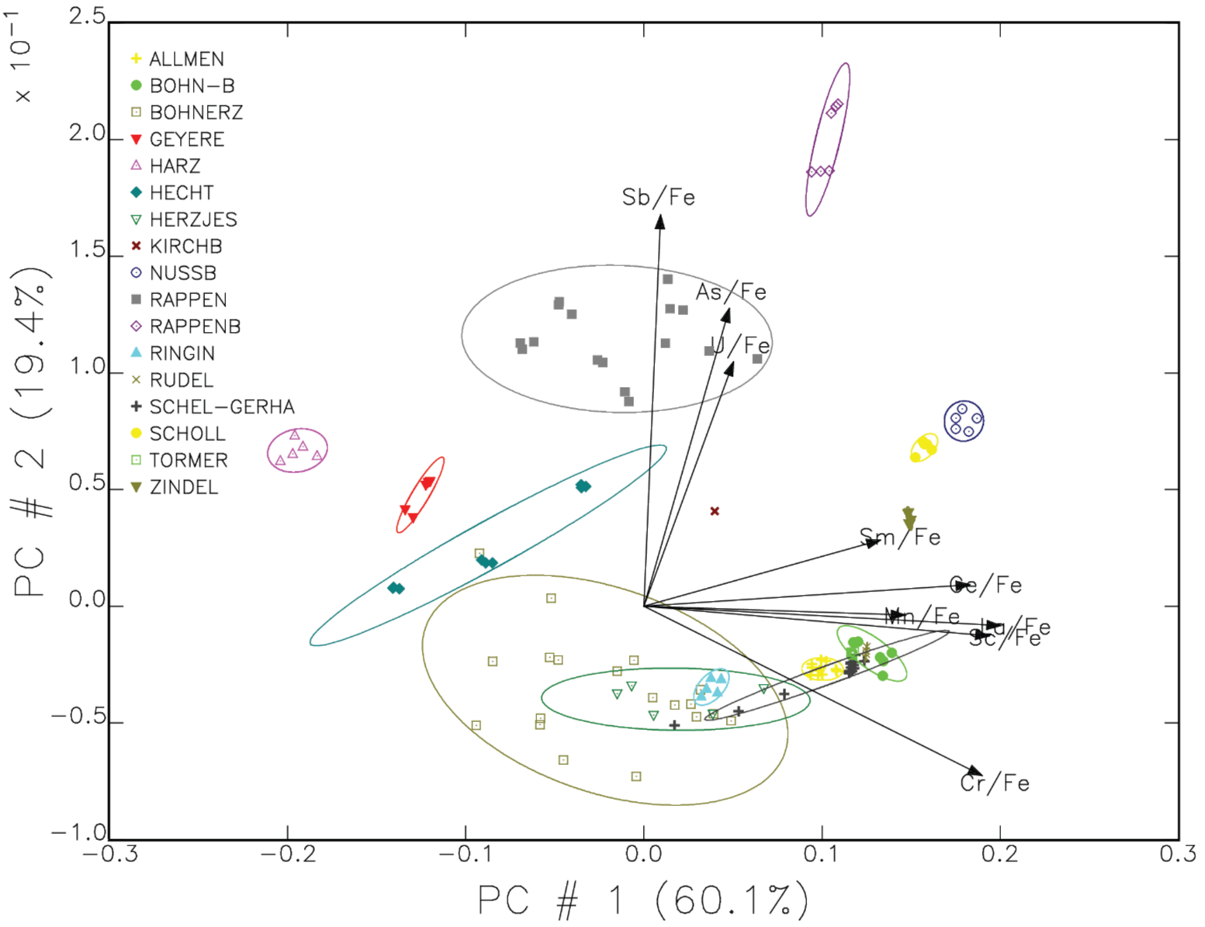


Figure H: Biplot of PC1 versus PC2 including all sampled outcrops. The PCA shows distinctions between the source regions but some clustering within Swabian Jura samples. Note the exclusion of Altheim due to high compositional spread. Element loading vectors are drawn and labelled.

3. SI Tables

Table N: Means and standard deviations for elemental concentrations for Swabian Jura ochre source samples. All values are represented in ppm unless otherwise stated. Kirchbierlingen (Kirschb) is presented only as concentrations due to the small sample size, and two unassigned Bohnerz (Bohn-UNAS) samples HFC202 and HFC250 are not shown.

Raw data	Allmendingen (Allmen) n = 12	Altheim (Altheim) n = 10	Bohnerz (Bohnerz) n = 18	Bohnerz B (Bohn-B) n = 7	Gerhausen (Gerha) n = 5	Schelklingen (Schelk) n = 5	Rudelstetten (Rudel) n = 5	Ringingen (Ringin) n = 5	Tormerdingen (Tormer) n = 5	Herz-Jesu Berg (HerzJesu) n = 5	Kirchbierlingen (Kirchb) n = 1
Al (%)	2.8 ± 1.6	2.2 ± 2.3	3.8 ± 3.2	11.7 ± 1.9	14.2 ± 0.3	12.9 ± 3.5	12.1 ± 0.2	4.03 ± 0.05	14.30± 0.3	5 ± 2	6.6
Ca (%)	0.01 ±0.02	0.4 ± 0.4	1.2 ± 4.7	2 ± 1	2.28 ± 0.09	2.1 ± 0.9	0.9 ± 0.1	0.15 ± 0.03	3.8± 0.3	0.4 ± 0.3	<LOD
Fe (%)	32.6 ± 25.5	39.8 ± 17.3	49.01 ± 10.21	6.2 ± 0.5	10.69 ± 0.08	22.6 ± 16.4	9.00 ± 0.07	6.1 ± 0.3	11.3± 0.2	48.57 ± 6.03	4.2
K (%)	2.9 ± 0.3	0.7 ± 0.8	0.1 ± 0.1	1.8 ± 0.5	0.7 ± 0.2	0.5 ± 0.4	0.7 ± 0.1	1.5 ± 0.1	0.1 ± 0.1	<LOD	3.9
Na (%)	0.05 ± 0.04	0.1 ± 0.2	<LOD	0.1 ± 0.2	0.0330 ± 0.0009	0.02 ± 0.01	0.031 ± 0.004	0.068 ± 0.003	0.040± 0.002	0.007 ± 0.004	0.1
Ti	61 ± 244	1716.3 ± 1545.9	2039.3 ± 2086.2	4201.8 ± 1385.1	7748.1 ± 340.5	7323.1 ± 1511.3	7998.9 ± 348.2	1661.1 ± 326.8	9524.6 ± 267.6	3809.3 ± 2366.9	737.2
V	202 ± 110	40.9 ± 23.4	554.0 ± 337.4	184.3 ± 31.6	257.5 ± 8.7	618.5 ± 612.8	202.9 ± 5.3	65.1 ± 4.4	374 ± 9	1032 ± 322	56.4
Mn	2033.8 ± 3559.3	989 ± 555	584.6 ± 379.1	840.2 ± 139.9	676.8 ± 11.2	1152.6 ± 547.4	452.8 ± 7.4	215.8 ± 10.2	646.5 ± 37.1	1473.4 ± 793.8	155
Cr	4.5 ± 3.5	30.2 ± 22.9	201.4 ± 166.3	162.6 ± 12.6	165.9 ± 1.7	251.3 ± 141.6	277.3 ± 2.5	40.7 ± 3.5	271 ± 13	490.5 ± 244.9	9.9
Sc	4 ± 2	3.7 ± 3.4	21.6 ± 17.6	19.1 ± 3.3	26.5 ± 0.2	31.5 ± 8.8	23.7 ± 0.2	4.2 ± 0.3	32.6 ± 0.4	36.8 ± 7.6	10.5
Co	3.6 ± 3.6	62.1 ±36.9	32.2 ± 15.8	24 ± 9	17.0 ± 0.2	31.4 ± 21.8	16.3 ± 0.4	4.8 ± 0.2	21.1 ± 0.6	47.5 ± 59.6	2.6
Ni	<LOD	21.9 ±36.3	117.5 ± 172.9	78.8 ± 40.2	112.3 ± 24.6	60.1 ± 56.1	107 ± 24	<LOD	67 ± 42	<LOD	<LOD
Zn	11.6 ± 9.7	113.6 ± 91.2	234.5 ± 130.8	182.4 ± 28.6	450.6 ± 6.9	315.2 ± 124.5	345.9 ± 4.4	32 ± 4	322.7 ± 9.8	122.9 ± 28.2	32
Zr	495.9 ± 625.1	53.3 ± 88.2	78.4 ± 97.5	116 ± 61	232.2 ± 22.2	254.7 ± 52.8	250.3 ± 10.8	49.9 ± 14.4	315 ± 22	159.7 ± 151.8	165.4
Rb	145.3 ± 122.7	32.2 ± 36.4	7.2 ± 12.5	155.8 ± 43.6	75.2 ± 4.1	47.1 ± 39.1	69 ± 4	65 ± 4	38 ± 5	<LOD	159.6
Sr	59.5 ± 115.5	<LOD	<LOD	<LOD	332.3 ± 24.7	259.3 ± 216.2	<LOD	<LOD	<LOD	<LOD	<LOD
As	807.4 ± 554.7	502.5 ± 591.7	735.4 ± 1481.4	31.8 ± 8.6	23.7 ± 1.4	58.7 ± 52.1	28.7 ± 0.6	11.1 ± 3.7	46 ± 1	171.9 ± 69.4	26
Sb	330.7 ± 301.8	7.3 ± 6.5	6.9 ± 6.4	1.2 ± 0.1	1.76 ± 0.05	2.7 ± 1.3	2.7 ± 0.1	0.9 ± 0.1	2.28 ± 0.05	7.4 ± 2.6	3.7
Ba	3632.0 ± 5838.7	312 ± 582	<LOD	236.3 ± 33.6	<LOD	17.4 ± 49.2	74.6 ± 73.9	212.2 ± 35.6	<LOD	<LOD	153

Cs	25.5 ± 14.2	3.2 ± 2.6	2 ± 2	27.2 ± 14.3	17.4 ± 0.1	11.3 ± 9.1	10.8 ± 0.1	2.0 ± 0.1	5.6 ± 0.2	<LOD	6.8
Hf	1.1 ± 0.8	2.6 ± 3.2	2.8 ± 2.7	4.8 ± 3.5	8.2 ± 0.1	9.0 ± 2.2	10.7 ± 0.2	1.9 ± 0.3	14.6 ± 0.5	7.4 ± 3.5	7
Ta	1.1 ± 1	0.3 ± 0.4	0.5 ± 0.6	1.2 ± 0.3	2.1 ± 0.1	1.9 ± 0.4	2.67 ± 0.04	0.44 ± 0.04	2.8 ± 0.1	1 ± 1	1.3
La	14.4 ± 6.2	18.6 ± 12.8	49.8 ± 98.3	56 ± 22	109.7 ± 0.6	97.1 ± 25.9	93.3 ± 0.7	9.8 ± 1.3	90.1 ± 1.8	40.9 ± 36.4	2.9
Ce	45 ± 33	33.6 ± 24.3	70.5 ± 103.2	80 ± 10	154.1 ± 1.5	222.9 ± 239.6	151.4 ± 1.4	16.8 ± 2.6	168.3 ± 5.5	147.6 ± 200.5	7.3
Nd	30.6 ± 31.1	15.2 ± 11.9	30.7 ± 24.1	47 ± 22	75 ± 3	71.3 ± 24.8	71 ± 2	8.7 ± 1.8	49.2 ± 1.5	45.2 ± 46.2	3.4
Sm	9.8 ± 8.5	3.1 ± 2.1	8 ± 5	10 ± 5	14.8 ± 0.1	15.5 ± 6.6	14.2 ± 0.1	1.7 ± 0.2	10.0 ± 0.2	10.6 ± 9.6	1.4
Eu	0.2 ± 0.1	0.6 ± 0.4	1.9 ± 1.1	2.2 ± 1.1	3.07 ± 0.05	3.3 ± 1.5	3.08 ± 0.03	0.37 ± 0.03	2.1 ± 0.1	2 ± 2	0.2
Tb	0.4 ± 0.3	0.4 ± 0.4	2 ± 1	1.5 ± 0.8	2.0 ± 0.2	2 ± 1	2.1 ± 0.3	0.23 ± 0.04	1.6 ± 0.1	2 ± 1	0.7
Dy	2.3 ± 1.5	2.9 ± 1.8	9.6 ± 5.6	8.7 ± 4.3	12.8 ± 0.2	13.5 ± 3.6	12.8 ± 0.3	1.6 ± 0.2	10.6 ± 0.2	8.8 ± 3.8	5.1
Yb	1.1 ± 1.2	2 ± 1	5.5 ± 3.2	4.8 ± 1.9	7.4 ± 0.2	7 ± 1	6.8 ± 0.1	1.0 ± 0.2	7.1 ± 0.1	5.1 ± 2.2	4
Lu	0.2 ± 0.2	0.3 ± 0.1	0.8 ± 0.4	0.7 ± 0.3	1.07 ± 0.04	0.9 ± 0.2	0.94 ± 0.03	0.18 ± 0.03	0.93 ± 0.04	0.7 ± 0.3	0.6
Th	5.2 ± 2.6	4 ± 4	8.6 ± 8.4	13.9 ± 2.1	19.8 ± 0.1	23.4 ± 12.9	19.3 ± 0.1	3.1 ± 0.3	25.6 ± 0.4	26.3 ± 10.8	5.5
U	98 ± 123	3.8 ± 1.3	4 ± 3	2.6 ± 0.9	5 ± 1	5.6 ± 1.6	2.9 ± 0.6	1.5 ± 0.1	5.0 ± 0.2	4 ± 1	11.3

Table B: Means and standard deviations for elemental concentrations for Harz Mountain and Black Forest ochre source samples. All values are represented in ppm unless otherwise stated. Harz Mountain samples include Geyer-Erzgebirge and Harz. Black Forest samples include Hechtsberg, Nussbach, Rappenloch, Schollach, and Zindelstein.

Element	Geyer-Erzgebirge (Geyer) n = 5	Harz (Harz) n = 5	Hechtsberg (Hecht) n = 9	Nussbach (Nussb) n = 5	Rappenloch (Rappen) n = 22	Schollach (Scholl) n = 5	Zindelstein (Zindel) n = 5
Al (%)	0.9 ± 0.2	1.2 ± 0.2	2.2 ± 0.5	7.6 ± 0.4	<LOD	7.1 ± 0.3	13.3 ± 1.7
Ca (%)	0.02 ± 0.03	<LOD	3.6 ± 5.4	0.1 ± 0.1	<LOD	0.1 ± 0.1	0.81 ± 0.08
Fe (%)	66.1 ± 0.8	66.2 ± 0.6	41.1 ± 18.9	0.95 ± 0.07	2.2 ± 0.1	1.4 ± 0.1	6.6 ± 0.2
K (%)	<LOD	<LOD	0.2 ± 0.1	4.6 ± 0.2	<LOD	4.5 ± 0.4	3.5 ± 0.1
Na (%)	0.008 ± 0.001	0.22 ± 0.01	0.02 ± 0.01	0.62 ± 0.06	<LOD	0.51 ± 0.02	0.25 ± 0.09
Ti	104.1 ± 154.6	<LOD	111.7 ± 170.5	582.4 ± 163.8	<LOD	1753.7 ± 254.5	1889 ± 441
V	48.6 ± 14.2	11 ± 10	44.8 ± 15.4	3.8 ± 5.2	<LOD	25.5 ± 7.7	205 ± 13
Mn	502.5 ± 90.7	89.4 ± 5.7	1598 ± 2065	281.5 ± 26.9	2 ± 3	248.6 ± 63.1	947 ± 83
Cr	5.8 ± 1.1	7.5 ± 3.5	6.5 ± 2.6	5.2 ± 1.7	2.1 ± 2.3	21.4 ± 1.5	152.6 ± 6.6
Sc	0.46 ± 0.05	0.19 ± 0.04	2.3 ± 1.1	5.4 ± 0.3	6.9 ± 1.5	5.0 ± 0.3	39.7 ± 1.4
Co	1.8 ± 0.3	<LOD	44.1 ± 61.6	1.1 ± 0.2	44 ± 4	2.6 ± 0.7	21.2 ± 1.3
Ni	<LOD	<LOD	15.2 ± 45.5	<LOD	<LOD	<LOD	<LOD
Zn	10.4 ± 7.6	<LOD	99.1 ± 148.7	20.2 ± 4.8	212.4 ± 166.8	29.2 ± 2.9	179.1 ± 7.7
Zr	128.8 ± 86.4	<LOD	83.7 ± 37.6	96.1 ± 14.3	420.8 ± 90.9	135.1 ± 15.5	112.6 ± 42.3
Rb	<LOD	<LOD	21.3 ± 12.5	349 ± 8	162.3 ± 149.3	355.9 ± 21.3	457.7 ± 22.1
Sr	<LOD	<LOD	<LOD	22.1 ± 3.2	378.8 ± 415.9	20 ± 29	<LOD
As	141.2 ± 8.3	670.7 ± 10.7	185.3 ± 138.5	48.5 ± 2.2	2104.6 ± 782.3	31.5 ± 1.4	272.8 ± 7.7
Sb	159.1 ± 31.3	617 ± 66	18.8 ± 10.1	0.76 ± 0.02	93.3 ± 37.6	3.1 ± 0.1	5.5 ± 0.3
Ba	56.2 ± 79.5	<LOD	91.6 ± 53.8	690.4 ± 172.2	47431.1 ± 16018.9	333.7 ± 44.1	982.7 ± 43.7
Cs	1.4 ± 0.4	1.3 ± 0.2	10.5 ± 0.9	49.1 ± 2.2	31 ± 14	55 ± 3	491.8 ± 30.9
Hf	<LOD	<LOD	0.3 ± 0.2	4.3 ± 0.6	0.7 ± 0.7	6.0 ± 0.4	2.0 ± 0.1
Ta	<LOD	<LOD	<LOD	2.4 ± 0.1	0.8 ± 0.6	2.6 ± 0.1	0.7 ± 0.1

La	7.1 ± 0.8	1.2 ± 0.1	4.8 ± 0.9	25.3 ± 2.3	9.8 ± 2.4	20.1 ± 1.8	65.8 ± 2.9
Ce	20.7 ± 2.7	3.4 ± 0.9	14.9 ± 0.5	58 ± 5	39.2 ± 1.7	42.7 ± 3.9	110.9 ± 4.8
Nd	13.2 ± 2.5	<LOD	9 ± 2	22.6 ± 2	34.9 ± 21.4	17.9 ± 2.2	54.7 ± 5.8
Sm	6 ± 1	1.6 ± 0.2	2.5 ± 0.3	7 ± 1	14.3 ± 4.6	4 ± 0.3	12.2 ± 0.4
Eu	1.5 ± 0.1	0.9 ± 0.1	1 ± 1	0.2 ± 0	0.4 ± 0.1	0.3 ± 0	3 ± 0.1
Tb	1.4 ± 0.2	0.1 ± 0.2	0.1 ± 0.2	1.2 ± 0.2	3 ± 2	0.6 ± 0.1	1.5 ± 0.3
Dy	9 ± 1	1.6 ± 0.1	1.1 ± 0.5	7.5 ± 0.7	<LOD	3.9 ± 0.3	8.2 ± 0.3
Yb	1.8 ± 0.2	<LOD	0.7 ± 0.6	5.3 ± 1	14.6 ± 8.8	2.9 ± 0.3	3.9 ± 0.2
Lu	0.4 ± 0.1	<LOD	0.2 ± 0.2	0.7 ± 0.1	1.9 ± 1.1	0.4 ± 0	0.6 ± 0
Th	0.1 ± 0.2	<LOD	1.0 ± 0.4	26.5 ± 1.4	3.6 ± 2.4	13.1 ± 1	20.1 ± 1.3
U	18.1 ± 3.2	3.1 ± 1.3	20 ± 7	9.2 ± 0.8	77.4 ± 15.3	5.8 ± 0.4	5.1 ± 1.1

Table C: Descriptive characteristics for the analyzed sources. Abbreviations are as follows: SJ = Swabian Jura, BF = Black Forest, HM = Harz Mountain, SS = Sediment sample (sand, silt, clay combination), OK = Fe-oxide enriched clay, BO = Bohnerz, HA = Hematite nodule.

ID	Site	Find #	Sub #	Best	Weight (g)	Grain Size	Munsell	Source	Region	Geo. group	Geo. Period	Chem. Group
1	AM	1	8	SS	42	Silty clay	2.5YR 5/6	Allmendingen	SJ	U-MOL	Oligocene to Miocene	Allmen
7	AM	7	6	OK	236	Clayey/sand	5YR 5/6	Allmendingen	SJ	U-MOL	Oligocene to Miocene	Allmen
12	AM	12	5	OK	244.9	Clayey/sand	5YR 4/4	Allmendingen	SJ	U-MOL	Oligocene to Miocene	Allmen
13	AM	13	7	OK	246.1	Clay	2.5YR 3/6	Allmendingen	SJ	U-MOL	Oligocene to Miocene	Allmen
76	AT	76	5	SS	21.5	Silty/Sand	10YR 6/3	Altheim	SJ	O-MOL	Oligocene to Miocene	Altheim
77	AT	77	6	SS	2.9	Sandy	2.5YR 2.5/1	Altheim	SJ	O-MOL	Oligocene to Miocene	Altheim
79	AT	79	8	SS	15.4	Sandy	mixed	Altheim	SJ	O-MOL	Oligocene to Miocene	Altheim
83	AT	83	12	SS	42.1	Sand	mixed	Altheim	SJ	O-MOL	Oligocene to Miocene	Altheim
85	AT	85	14	SS/OK	17.2	Sand	7.5YR 4/6	Altheim	SJ	O-MOL	Oligocene to Miocene	Altheim
68	BO10	68	2	BO	2.5	Silty	7.5R 3/6	Bohnerz 10	SJ	BOHN	Cretaceous	Bohn-B
71	BO10	71	5	BO	13.5	Silty	5YR 2.5/1	Bohnerz 10	SJ	BOHN	Cretaceous	Bohn-B
17	BO2	17	2	BO/SS	93.4	Clayey/silty	mixed	Bohnerz 2	SJ	BOHN	Cretaceous	Bohnerz
18	BO3	18	1	BO	11.5	Clayey/silty	2.5YR 5/8	Bohnerz 3	SJ	BOHN	Cretaceous	Bohnerz
23	BO3	23	6	SS	158.3	Silty/sandy	10YR 6/3	Bohnerz 3	SJ	BOHN	Cretaceous	Bohnerz
30	BO4	30	4	SS/OK	87.3	Clay	5YR 4/6	Bohnerz 4	SJ	BOHN	Cretaceous	Bohn-B
32	BO5	32	1	BO	4.2	Silty	5YR 5/6	Bohnerz 5	SJ	BOHN	Cretaceous	Bohnerz
37	BO7	37	1	BO	28.8	Silty	2.5YR 2.5/2	Bohnerz 7	SJ	BOHN	Cretaceous	Bohnerz
43	BO7	43	7	BO	107.1	Silty	5YR 3/4	Bohnerz 7	SJ	BOHN	Cretaceous	Bohnerz
46	BO7	46	10	BO	87.2	Silty	5R 2.5/1	Bohnerz 7	SJ	BOHN	Cretaceous	Bohnerz
52	BO7	52	16	SS	135.3	Silty/Clay	2.5YR 4/6	Bohnerz 7	SJ	BOHN	Cretaceous	Bohn-B
63	BO9	63	5	BO	132.7	Silty	10YR 3/6	Bohnerz 9	SJ	BOHN	Cretaceous	Bohn-B
64	BO9	64	6	BO	6	Silty	5YR 3/1	Bohnerz 9	SJ	BOHN	Cretaceous	Bohnerz
109	GE	109	1	HA	154	Silty	5R 4/1	Geyer Erzgebirge	HM	M-META	Cambrian	Geyer
104	GR	104	1	OK	193	Clay	2.5YR 5/8	Gerhausen	SJ	BOHN-L	Cretaceous	Schel-Gerha
120	HB	120	1	HA	1306.1	mixed	mixed	Hechtsberg	BF	P-META	Trias-Juras	Hechtb
121	HB	121	2	HA	1046.9	mixed	mixed	Hechtsberg	BF	P-META	Trias-Juras	Hechtb
122	HB	122	3	HA	1040.9	mixed	mixed	Hechtsberg	BF	P-META	Trias-Juras	Hechtb

94	HJB	94	1	BO	60.3	Silty	7.5R 2.5/3	Herz-Jesu Berg	SJ	BOHN	Early Pleistocene	HerzJes
96	HJB	96	3	BO	271.9	Silty	2.5YR 2.5/1	Herz-Jesu Berg	SJ	BOHN	Early Pleistocene	HerzJes
108	HZ	108	2	HA	551.4	Silty	7.5R 3/1	Harz	HM	EISEN	Hercynian	Harz
101	KB	101	2	HA	57.7	Silty	7.5R 3/1	Kirchbierlingen	SJ	RG	Pleistocene	KirchB
138	NS	138	1	OK	127.8	Sandy	7.5R 3/6	Nussbach	BF	P-MAG	Paleozoic	Nussb
93	RG	93	2	SS	13.7	Sandy	10YR 4/6	Ringingen	SJ	U-MOL	Up. Jurassic	Ringin
126	RP	126	1	HA	77.6	Sandy	10R 2.5/1	Rappenloch	BF	OMSAND	Triassic	Rappen-B
129	RP	129	4	OK	109	Sandy	7.5R 3/6	Rappenloch	BF	OMSAND	Triassic	Rappen
131	RP	131	6	HA	116.6	Silty	7.5R 2.5/1	Rappenloch	BF	OMSAND	Triassic	Rappen
132	RP	132	7	HA	192.7	mixed	mixed	Rappenloch	BF	OMSAND	Triassic	Rappen-B
134	RP	134	9	HA	101.1	Silty/Clayey	5R 2.5/1	Rappenloch	BF	OMSAND	Triassic	Rappen
135	RP	135	10	OK/HA	144.7	Sandy/Clayey	5R 3/2	Rappenloch	BF	OMSAND	Triassic	Rappen
137	RP	137	11	OK/HA	166.6	Sandy	5R 2.5/3	Rappenloch	BF	OMSAND	Triassic	Rappen-B
105	RU	105	1	OK	35	Clay	10R 3/4	Radelstetten	SJ	BOHN-L	Cretaceous	Rudel
117	SH	117	1	SS	104.7	Clay	2.5YR 2.5/4	Schollach	BF	P-META	Trias-Juras	Scholl
103	SK	103	1	OK	200	Clay	2.5R 5/8	Schelklingen	SJ	BOHN-L	Cretaceous	Schel-Gerha
106	SK	106	2	BO	153.7	Silty	10R 2.5/2	Schelklingen	SJ	BOHN-L	Cretaceous	Schel-Gerha
102	TM	102	1	OK	217	Clay	2.5YR 4/8	Tormerdingen	SJ	BOHN-L	Cretaceous	Tormer
113	ZS	113	4	SS	46.1	Clay	10R 3/2	Zindelstein	BF	OMSAND	Triassic	Zindel

Table O: Descriptions of geological groups (Geo. Groups) presented in Table C for ochre source samples.

	Swabian Jura
RG	Riß-aged river terraces made from limestone from the Swabian Jura, together with rocks from the Alps and the Black Forest in a sandy matrix.
O-MOL	Upper freshwater and saltwater molasse from Jurassic, Tertiary deposits in the molasse basin
U-MOL	Upper and lower freshwater and saltwater molasses from Jurassic, Tertiary deposits in the molasse basin
BOHN-L	*Bohnerzlehm* deposits, made of red, iron-rich kaolinite. Often associated with *Bohnerz* nodules.
BOHN	*Bohnerz*, accumulated Fe-oxide precipitates mostly consisting of limonite, goethite and hemaitite.
	Black Forest
P-META	Paragneiss (predominantly) – metamorphic rocks
P-MAG	Granite pluton - Paleozoic Magmatite, Lower Cretaceous - Permian
OMSAND	Granitplutone – Paleozoic Magamtite, upper and middle Bundsandstein (left Rhine, (partly with lower Buntsandstein) – Triassic
	Harz Mountains/Geyer-Erzgebirge
M-META	Aquifers, metamorphic, siliceous, metamorphic magmatite, basic (metabasite, diabase, gabbro, monzonite) or acidic (gneiss, mica, granulite, quartzite)
EISEN	Metabasite, Keratophyr (Diasbase, Schalstein, iron ore)

Table P: Canonical discriminant functions and elemental contributions based on all groups. This calculation includes all source groups (n = 15), data are relevant for Figure 3 in text.

Wilk's lambda:	7.13E-07
Approx. F:	18.68028
p-value:	1E-240

		CD1	CD2	CD3	CD4	CD5	CD6	CD7	CD8	CD9	CD10	CD11
Variable	Magnitude	**70.08**	**16.10**	**7.20**	**3.04**	**1.51**	**1.11**	**0.34**	**0.26**	**0.21**	**0.11**	**0.06**
Sm/Fe	3.53	-1.36	-1.10	1.18	0.74	-2.06	-0.59	1.19	-0.83	0.71	0.30	0.41
Eu/Fe	2.59	1.36	1.39	-0.98	-0.42	0.30	0.04	0.25	1.27	-0.15	-0.02	-0.13
La/Fe	2.16	0.39	-0.50	-0.21	0.10	0.66	-0.20	-0.11	1.24	-1.31	-0.67	0.04
Ce/Fe	1.85	0.06	0.35	0.30	-0.18	0.86	0.30	-0.48	-0.98	0.40	0.86	-0.52
Tb/Fe	1.36	-0.14	0.11	-0.85	-0.05	0.48	-0.16	-0.60	-0.54	0.27	-0.27	-0.18
Sb/Fe	1.25	-0.79	0.61	-0.35	0.24	0.40	0.25	-0.19	0.22	0.02	-0.19	-0.16
Sc/Fe	1.08	-0.34	-0.56	-0.18	-0.18	-0.42	0.47	0.07	0.22	0.06	-0.23	-0.40
Cr/Fe	0.99	0.54	0.02	-0.09	0.22	0.12	0.03	-0.16	-0.49	0.21	0.08	0.56
As/Fe	0.96	-0.07	-0.46	-0.15	-0.13	-0.38	-0.13	-0.14	0.65	-0.13	0.18	0.06
Mn/Fe	0.89	-0.16	-0.01	0.56	0.01	-0.02	-0.09	-0.04	0.58	0.32	-0.01	0.07
U/Fe	0.86	-0.28	0.13	-0.01	-0.32	0.48	0.05	0.09	-0.25	-0.17	-0.08	0.44

CD	% var.	% cum.
CD1	**70.1**	**70.10**
CD2	**16.1**	**86.18**
CD3	**7.2**	**93.38**
CD4	3.0	96.42
CD5	1.5	97.93
CD6	1.1	99.04
CD7	0.3	99.38
CD8	0.3	99.64
CD9	0.2	99.85
CD10	0.1	99.96
CD11	0.1	100.0

Table Q: Canonical discriminant functions and elemental contributions based on Swabian Jura sources. This calculation includes Swabian Jura (n = 8) groups: Allmen, Herzjes, Bohn-All, Kirschb, Ringin, Rudel, Schel-Gerha, Tormer. Data are relevant for Figure 4 in text.

Wilk's lambda:	2.21E-06
Approx. F:	9.439425
p-value:	3.55E-60

		CD1	**CD2**	**CD3**	**CD4**	**CD5**	**CD6**	**CD7**
Variable	Magnitude	**38.48**	**28.80**	**20.54**	**7.06**	**2.90**	**1.22**	**1.00**
Sm/Fe	3.195	-0.351	-1.334	1.370	-2.247	-0.965	0.571	0.342
Eu/Fe	2.929	-0.265	1.767	-0.939	0.856	0.633	-0.207	-1.825
Nd/Fe	1.863	0.677	-0.093	-0.531	0.188	0.728	-0.787	1.240
Yb/Fe	1.488	0.292	-0.165	0.086	-0.826	-0.092	0.641	-0.996
Dy/Fe	1.405	0.712	-0.414	0.038	0.579	-0.349	-0.538	0.740
Lu/Fe	1.322	-0.464	0.180	-0.020	0.776	-0.092	-0.473	0.815
Sb/Fe	0.907	-0.538	-0.107	-0.058	-0.174	0.460	-0.511	-0.122
Al/Fe	0.832	-0.295	-0.052	0.056	0.336	-0.468	0.017	0.516
Th/Fe	0.819	0.593	-0.023	-0.129	0.147	0.106	-0.010	0.519
La/Fe	0.741	-0.072	0.177	0.159	0.129	-0.262	0.337	-0.537
Sc/Fe	0.692	-0.100	0.008	-0.064	-0.128	0.352	0.198	-0.534
Hf/Fe	0.674	0.076	0.091	-0.067	0.080	0.109	0.073	-0.642
Ce/Fe	0.593	-0.059	-0.055	-0.030	0.485	-0.052	0.132	0.299
Tb/Fe	0.481	-0.380	-0.184	-0.067	-0.009	0.177	0.019	0.129
Zr/Fe	0.481	0.208	-0.047	0.055	0.349	0.013	0.245	0.025
Cr/Fe	0.459	-0.084	0.054	0.027	-0.239	-0.026	-0.152	-0.345
Na/Fe	0.451	-0.317	0.053	0.006	-0.135	0.048	0.102	-0.262
V/Fe	0.440	-0.158	-0.104	0.221	-0.245	0.016	0.128	0.180
Zn/Fe	0.375	0.351	0.007	0.027	-0.089	-0.011	0.037	-0.084
As/Fe	0.375	0.225	-0.007	-0.053	-0.003	-0.171	0.237	-0.039
Ti/Fe	0.308	0.027	0.034	0.081	0.163	-0.005	0.045	0.241
Co/Fe	0.275	0.037	0.019	0.143	-0.150	0.101	-0.141	0.027

CD	**% var.**	**% cum.**
1.00	**38.48**	**38.48**
2.00	**28.80**	**67.28**
3.00	**20.54**	**87.82**
4.00	**7.06**	**94.88**
5.00	2.90	97.78
6.00	1.22	99.00
7.00	1.00	100.00

Mn/Fe	0.259	0.036	-0.001	-0.182	0.017	0.054	-0.011	0.171
U/Fe	0.250	-0.027	-0.007	-0.183	-0.131	0.013	-0.004	-0.104
Ta/Fe	0.237	-0.065	0.013	0.103	0.005	-0.005	-0.203	0.010

4. Field photos of ochre sources

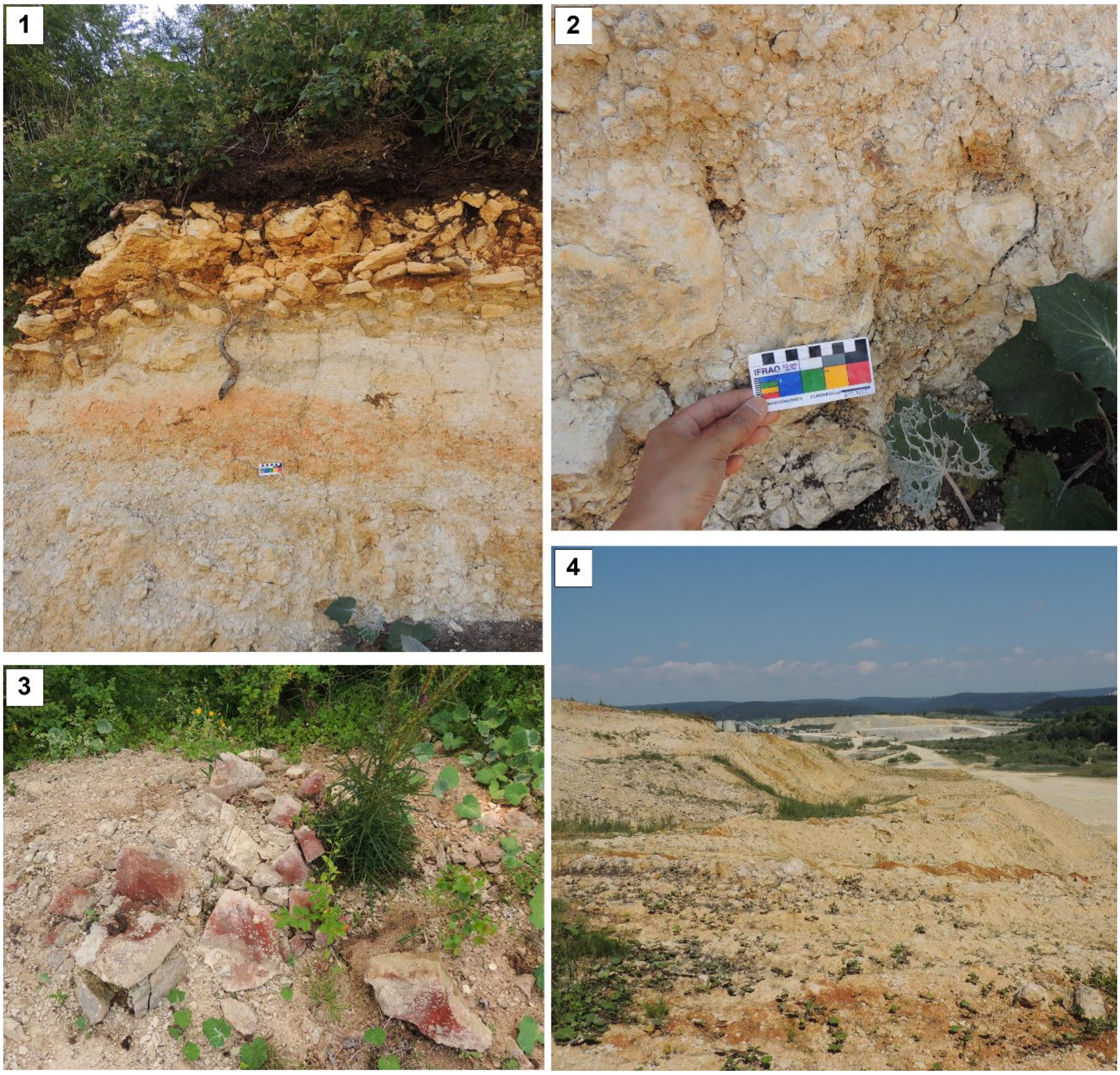


Figure I: Allmendingen. 1) Exposed section; 2) Detail from the exposed section showing likely iron-oxides crusts on the coarse fraction; 3) Other examples of iron-oxides crusts on limestone boulders, photo taken at the feet of the exposed profile; 4) Overview of the quarry showing outcropping reddish brown sediment.

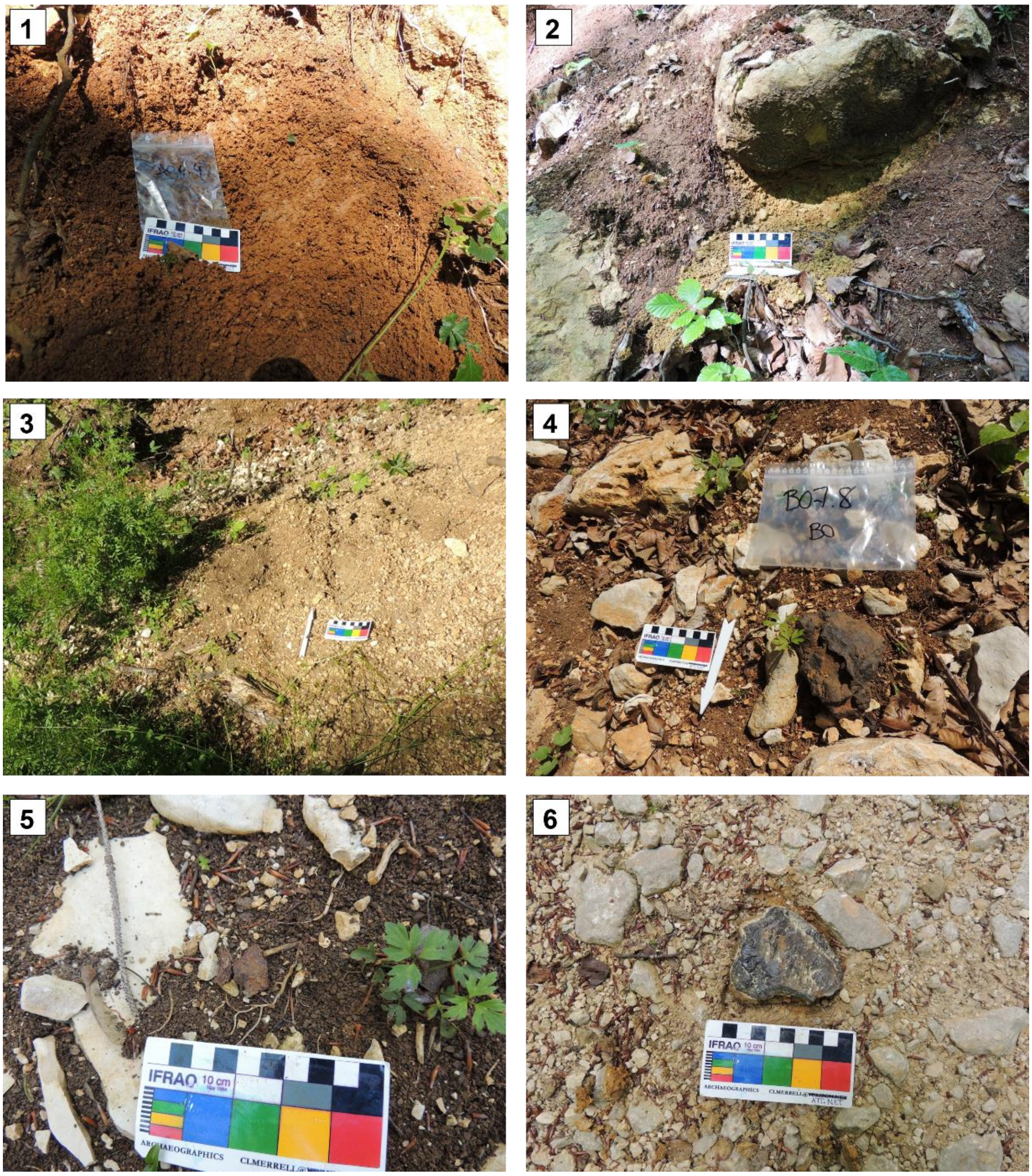


Figure J: Bohnerz outcrops. Details 1 and 2 showing sediment outcrops yielding fine gravel-sized fragments of Bohnerz, from the source Bohnerz 3. Details 3, 4, and 5 exhibiting sediment outcrops and Bohnerz fragments from the source Bohnerz 5. Detail 6, Bohnerz fragment from the source Bohnerz 8.

Figure K: Exposed section at Ringingen. Iron oxides veins visible as dark-orange layers in the exposure.

Figure L: Rappenloch. Details 1 shows extraction point for samples RP. 131.6, while detail 2 shows the level of overgrowth as well as extraction point for RP.126.1. These spots were previously dug out by local rock hunters. Detail 3 shows sample collection points for RP.132.7 and RP.134.9, with an exposed clay matrix with overlying sand due to construction activities.

Figure M: Schollach. Exposure of Schollach ochre outcrop showing a loosely compacted sandy clay texture with varying well-sorted gravel inclusions. Color is relatively homogenous.

1. References

Zipkin, A.M., Ambrose, S.H., Hanchar, J.M., Piccoli, P.M., Brooks, A.S., Anthony, E.Y., 2017. Elemental fingerprinting of Kenya Rift Valley ochre deposits for provenance studies of rock art and archaeological pigments, Quaternary International.