Hominin Survival and Lithic Procurement Strategies at a Pleistocene Desert Refugium during Periods of Environmental Stress: A Case Study from Shishan Marsh 1 in the Azraq Basin, Jordan

by

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M.A., University of Manitoba, 2014

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Abstract

A century of intermittent archaeological research in the Azraq Basin of the eastern desert of Jordan has demonstrated that a long period of hominin occupation exists in this environmentally inhospitable region during the Pleistocene. Recent excavations at the site of Shishan Marsh 1 in the Azraq Basin have uncovered several artifact-bearing layers that correspond to the Middle (266 ± 40 kya) and Upper (125 ± 12 kya) Pleistocene. An examination of paleoclimatic data from this period indicates predominantly warm and dry conditions in the region and a gradual reduction of water availability. These factors forced hominins to modify their resource acquisition strategies and exploit the receding spring- and *wadi*-fed Azraq wetlands. This dissertation investigates the nature of lithic procurement strategies practiced by hominins at Shishan Marsh 1, a Middle-Upper Pleistocene site in the former wetlands, during periods of environmental stress. It involves a provenance analysis of sources within the region and a sample of lithic artifacts from Shishan Marsh 1 through laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). The results indicate that the artifacts were procured from local and regional sources and likely through embedded procurement in an effort to provision individuals. They further provide insight into the nature of survival within the Azraq Basin, as hominin groups performed tethered mobility whereby they contracted around the Azraq wetlands. In this case, this stable water source operated as a desert refugium for hominins within the Azraq Basin.

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Lastly, I would like to thank my parents for their support over the years. Of course, the greatest appreciation is bestowed to my wife, Jocelyne, for her patience, encouragement, and understanding.

Dedication

This dissertation is dedicated to my late brother Jordan, who passed away during its undertaking. You are missed.

CHAPTER 1: INTRODUCTION

During the Middle (781-126 kya) and Upper (126-12 kya) Pleistocene, the Levant featured in a critically important event in human evolution—the dispersal of prehistoric hominins, in particular anatomically modern humans (hereafter AMH; *Homo sapiens*), out of Africa and into Eurasia (Bar-Yosef & Belmaker 2011; Bar-Yosef & Belfer-Cohen 2013; Groucutt & Petraglia 2012; Shea 2008a). The Levant encompasses the geographic area along the eastern Mediterranean coast that extends eastward inland to the Syrio-Arabian Desert, north to the Taurus Mountains, and south to the Red Sea (Cordova 2007; Mazar 1990; Suriano 2014). It is an environmentally diverse region connected to Africa by several biogeographic corridors that pass along the coasts and through the interiors of the Sinai and Arabian peninsulas (Breeze et al. 2016; Derricourt 2005; Groucutt & Petraglia 2012; Petraglia & Alsharekh 2003). During periods of environmental stress, survival in parts of these corridors was facilitated by various refugia (Ames et al. 2014a, 2014b; Ames & Cordova 2015; Cordova et al. 2013; Le Tensorer et al. 2007; Petraglia et al. 2019). Hominins, our species and our closely related bipedal ancestors under the tribe Hominini (Figure 1.1), would have contracted around stable sources of water and other subsistence resources in otherwise inhospitable regional environments. Recent archaeological excavations in the Shishan Marsh in the eastern desert of modern Jordan are investigating how this particular wetland may have operated as a desert refugium during the Pleistocene (e.g., Nowell et al. 2016; Pokines et al. 2019). The present study examines the nature of survival and lithic procurement of the Middle and Upper Pleistocene occupants at the site of Shishan Marsh 1 (hereafter SM1).

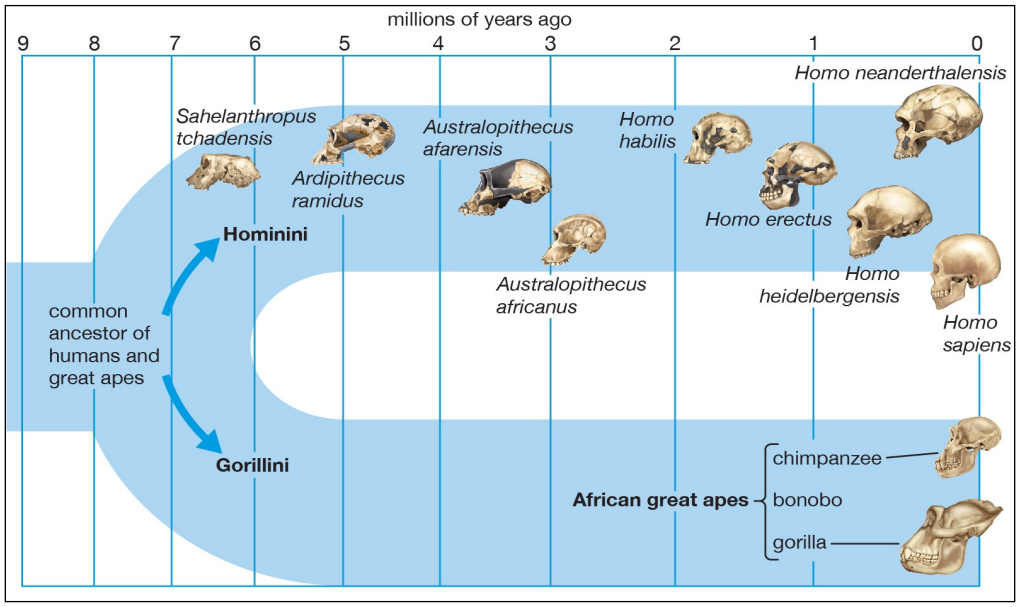


Figure 1.1: Simplified depiction of hominin lineage. Figure from https://www.britannica.com/topic/hominin.

1.1 Desert refugia during dispersals

Broadly stated, the Levant underwent fluctuating cycles of wet and dry conditions during the Middle and Upper Pleistocene (Bar-Matthews et al. 2003; Cordova et al. 2013; Drake et al. 2013; Jones & Richter 2011). The resulting environments caused by wetter conditions likely facilitated group movement, whereas the drier conditions may have hindered dispersal/expansion (Petraglia et al. 2019). Certain *palaeohydrological corridors*, chains of interconnected basins that feed into the Levant from the interior of the Arabian Peninsula, may have served as potential routes along which hominins could move (Breeze et al. 2016; Derricourt 2005; Drake et al. 2013; Groucutt & Petraglia 2012). During several periods of increased humidity, water levels in these basins would rise, creating paleolakes and providing sources of fresh water on which hominins and other fauna could subsist (Breeze et al. 2016; Parker 2009; Rosenberg et al. 2011). The onset of arid conditions resulted in decreasing water levels and receding shorelines. Consequently, regions with reduced water availability and low biodiversity may have created challenges for the survival of hominin groups.

The *Azraq corridor* is a potential dispersal route that connects the Levant to Arabia through the Wadi Sirhan depression (Ames & Cordova 2015; Breeze et al. 2016). The Azraq Basin is

located at the northwestern end of this corridor in eastern Jordan and contains the Greater Azraq Oasis Area (hereafter GAOA; Figure 1.2) at its center. The spring-fed wetlands that characterize the GAOA operated as a desert refugium during regionally dry periods of the Middle and Upper Pleistocene (Ames & Cordova 2015; Cordova et al. 2013; Nowell et al. 2016). This refugium could offer a stable source of water and other concentrated resources around which hominin groups and other animals congregated (Nowell et al. 2016; Pokines et al. 2019; Stewart & Stringer 2012).

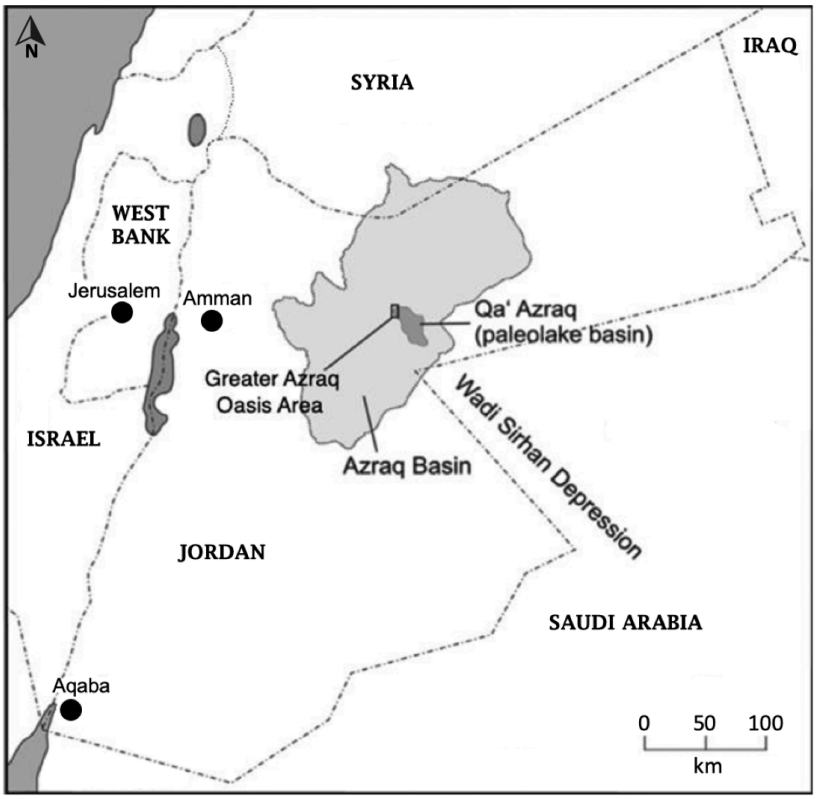


***Figure 1.2*: Location of the Greater Azraq Oasis Area, Jordan. Figure modified from Ames et al. (2014a: 61).**

1.2 Shishan Marsh 1

Previous research organized through the Azraq Marshes Archaeological and Paleoecological Project (hereafter AMAPP) has studied how the GAOA may have operated as a desert refugium during periods of environmental stress throughout the Pleistocene. Archaeological excavations from 2013-2015 at the site of SM1 and associated geological soundings (SM2 through

SM13) have exposed stratified deposits and cultural remains reaching back to the Middle and Upper Pleistocene (Figure 1.3) (Nowell et al. 2014, 2016; Pokines et al. 2019). The artifact-bearing layers, which are indicative of hominin occupation in the Azraq Basin, are dated to 266 +/- 40 kya (Layer 8), 125 +/- 12 kya (Layers 7b), and 119 +/- 40 kya (Layer 7a) by optically stimulated luminescence dating (Nowell et al. 2016). The sediments of Layers 8-7 indicate a transitional environment from a receding lake to marshy ponds located at the edge of a fan delta. Drying of the GAOA gradually increased throughout hominin occupation, as overall warm and arid conditions persisted in the region (Abed et al. 2008; Ames & Cordova 2015; Ames et al. 2014a; Macumber 2001; Nowell et al. 2016). However, as the spring-fed wetlands were maintained by a local aquifer, the GAOA remained an isolated locale of refuge for various flora and fauna.

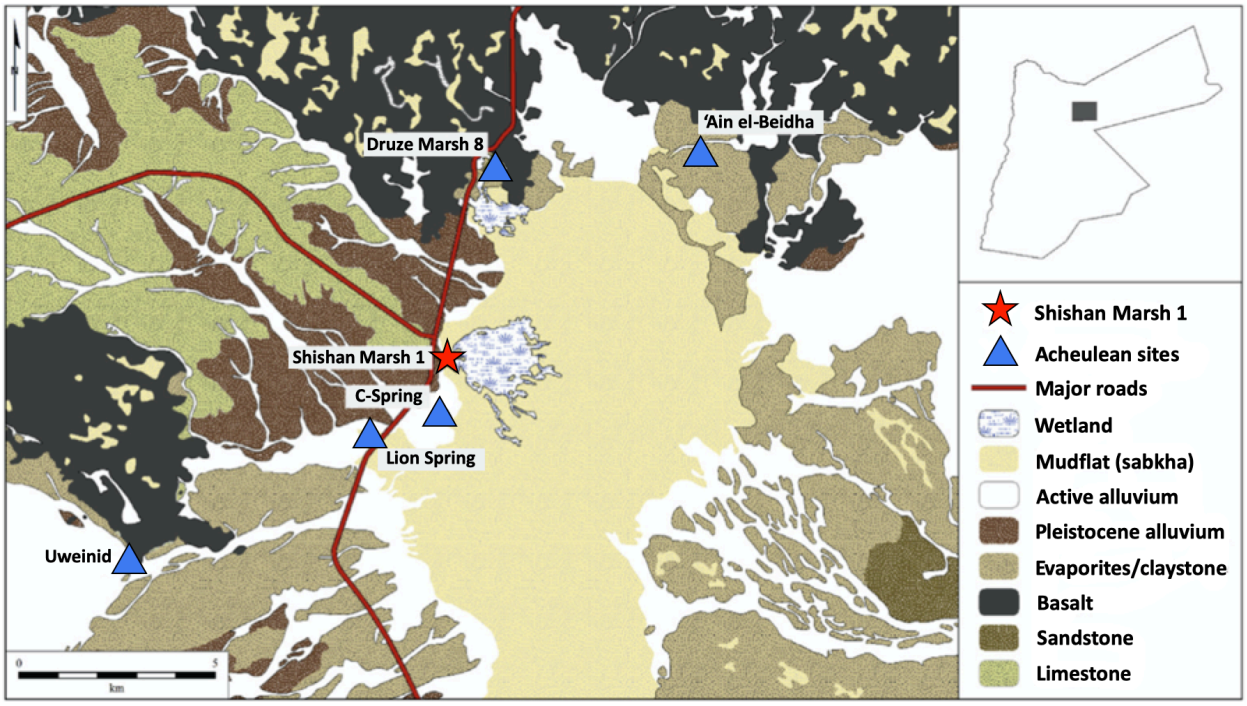


Figure 1.3: Location of Shishan Marsh 1 and various Acheulean sites within the Azraq Basin. Figure modified from Nowell et al. (2016: 37).

1.3 Importance of procurement

Stone tools are a major component of hunter-gatherer sites during the Pleistocene and often the means by which they are identified. These implements enabled hominins to cope with their

environments for the past 3.3 million years (Harmand et al. 2015; Lewis & Harmand 2015). For archaeologists, stone tools offer insight into many facets of daily life and provide high-resolution evidence of behavioral change throughout human evolution (Adams & Blades 2009; Montet-White & Holen 1991; Potts 1991; Shea 2013, 2017; Stout et al. 2015; Torrence 1989).

For hominins congregating around desert refugia, the development of effective foraging and lithic procurement strategies was essential to their survival, particularly in the dry season when the surrounding landscape was most inhospitable. In a broad sense, *procurement* encompasses the suite of decisions and activities involved in the acquisition of raw material (Andrefsky 2009; Delage 2007a; Odell 2000; Wilson 2007a). The initial selection of raw material during lithic procurement is an important step in the *chaîne opératoire* of stone tool production, as the decisions involved in procurement have implications for the subsequent reduction, transport, utility, and longevity of the tools (McAnany 1988; Newman 1994; Shott 1996). Indeed, Andrefsky (2009: 76) stressed that "…the information gained from lithic raw materials regarding sources location, shape, size, durability, and abundance has increased our understanding of stone tool technological organization in the past decade".

Unfortunately, little systematic investigation has been conducted on lithic procurement strategies in the Levant during Middle-Upper Pleistocene. Many reports on Levantine sites simply assume local procurement was the prevailing strategy, due to the relative abundance of chert in the Levant. However, the integration of provenance analyses into procurement studies indicate that lithic procurement was more complex than previously assumed (e.g., Ekshtain et al. 2014, 2016; Finkel et al. 2016, 2019; Verri et al. 2004, 2005). This realization has renewed implications for the understanding the paleoeconomy and mobility of prehistoric foragers in the Levant.

1.4 Aim of study

The overarching aim of this study is to reveal how hominins coped with environmental stress and survived in inhospitable regions of the globe. It does this through an investigation of the nature of lithic procurement strategies at a desert refugium in the Levant during the Middle and Upper Pleistocene. The Paleolithic site of SM1 is an appropriate research locale for this purpose. Excavations of SM1 have recovered a wide range of chert artifacts, such as bifaces, cores, utilized

flakes, and debitage. However, suitable raw material for the manufacture of larger tools, specifically bifaces (e.g., handaxes, cleavers), is not fully available within the vicinity of SM1. Clasts moved into the Shishan Marsh by seasonal streams are not appropriate sizes to serve as blanks (Dan Stueber pers. comm. 2015; Gary Rollefson pers. comm. 2017). The excavators of ‘Ain Soda, a nearby contemporaneous site to SM1, have also noted that some sources for their bifaces have not been located (Rollefson et al. 2006). An off-site origin for the bifaces is supported by the lack of substantial debitage connected to biface manufacture in the SM1 lithic assemblage (Stueber pers. comm. 2015). Therefore, it is likely that the raw material for these important multi-purpose tools was procured outside the Shishan Marsh and their manufacture occurred elsewhere.

This study involves a provenance analysis of 32 sources and 38 artifacts (36 bifaces and two biface cores) to establish the location of their origin and nature of their movement throughout the region. In accordance with the overarching aim, this study seeks to answer the following questions related to hominin occupation at SM1.

1) From which sources did the hominins procure raw material for the manufacture of lithic artifacts?
2) What are the long-term procurement strategies practiced by the hominins and how do these change over time (e.g., from the Middle to Upper Pleistocene)?
3) How do the collective foraging strategies inform our perspective of hominin familiarity and interaction with the landscape?
4) What is the response of the hominins of SM1 to increased aridity and water reduction in the region and how does it compare to that of contemporaneous hominin groups within the GAOA and Levant, as well as to those of modern hunter-gatherer (*Homo sapiens*) groups in similar environmental circumstances?

1.5 Significance of study

The results of the provenance analysis demonstrate that the chert bifaces originate from several geological sources within the Azraq Basin. Most artifacts are connected to sources within a local range (<10 km) of SM1, but others to more distant sources, approximately 15-21.5 km northeast of the site. A reconstruction of their procurement strategies indicates the bifaces were

likely procured through a primarily embedded strategy as their foraging concentrated on the GAOA overt time. This study contributes to several important fields of knowledge. It is the first geochemical characterization of chert sources within the central Azraq Basin and is the first systematic investigation of artifacts to originate from a site within the GAOA during the Lower-Middle Paleolithic. Furthermore, when combined with additional data from SM1, the procurement results contribute to understanding the GAOA as a desert refugium. In this case, survival was enabled by tethered mobility and the execution of various risk-mitigation strategies.

1.6 Outline of research

The study addresses aspects of provenance, procurement, and mobility within the specific context of a desert refugium. Each chapter presents information that builds upon content in the previous chapters. Chapters 2-4 review three major areas of scholarship that provide the background information for this study. Chapter 2 explores the concept of provenance in archaeology and how it relates to lithic materials. In specific, this discussion focuses on chert, particularly its petrogenesis and geochemistry as a geological material, and reviews the methods and strategies through which the provenance of chert artifacts has been conducted in previous studies. Chapter 3 discusses the nature of procurement strategies within the organization of lithic technology and mobility, namely how they are investigated and interpreted. It draws on studies of modern hunter-gatherer groups and makes specific reference to foragers of the Paleolithic. Chapter 4 provides contextual information on the study region, the GAOA, in order to establish the paleoanthropological, geological, and archaeological setting in which the research occurs. Chapter 5 describes the research aims, methods, and materials involved in the reconstruction of procurement strategies. These include components of the provenance analysis, such as the geoarchaeological survey, lithic sample, and analytical instrument. Chapter 6 presents detailed descriptions of the sources and evaluates the geochemical profiles of the chert sources and artifacts, as well as the results of the provenance analysis. The results are interpreted in Chapter 7, which further discusses how they fit into the larger patterns of lithic procurement within the Levant. The broader implications of foraging and risk-mitigating behavior around a desert oasis complex in an otherwise inhospitable desert environment are also explored. Lastly, Chapter 8 is a conclusion of

the study; it stresses the contributions that it makes to current scholarship and posits future directions of inquiry.

CHAPTER 2: PROVENANCE OF LITHIC ARTIFACTS

The reconstruction of procurement strategies often begins with an identification of the source(s) of origin of the artifactual material, commonly known as its *provenance*. Provenance analyses involve the comparison of data between sources and artifacts in order to establish the most likely fit. In order to perform a successful provenance analysis of chert artifacts, it is first necessary to obtain an understanding of chert petrogenesis and how its resulting composition has been examined for provenance in the past. This chapter describes the nature of provenance studies with a specific focus on chert.

2.1 Provenance analyses

The common-sense relationship between an artifact and its parent source is best described as the *provenance postulate*. It was first explicitly stated by Weigand et al. (1977) and maintains that efforts to link artifacts to sources rely on the existence of identifiable compositional differences between separate raw material sources whereby any compositional variations will be larger between two sources than within one source. This definition has been simplified by Glascock & Neff (2003: 1521) to note that the determination of the parent source is possible "as long as between-source chemical differences exceed within-source differences". If true, it then follows that an artifact should maintain less compositional variation with the parent source than with non-parent sources. Although initially provided for geochemical evaluations, the provenance postulate remains applicable to other forms of analysis (e.g., individual attributes, petrography).

Secure provenance is based on the degree of consistency between artifact and source data (Glascock & Neff 2003). This means archaeological materials cannot be truly "sourced", because, as noted by Shackley (2008: 196), the extent of what archaeologists can do is limited to providing a "characterization and a probable fit to known source data". This reality does not suggest such inquiry should be foregone, but rather to ensure that scientifically rigorous measures are implemented to support the interpretation. Luedtke (1992: 117) stressed that a "good source analysis is usually complex and expensive, and should not be initiated merely as a fishing expedition in the vague hope that you might find some-thing interesting". Consequently, most provenance analyses follow one of two approaches (Glascock & Neff 2003), depending on the

distribution and abundance of potential sources. In regions where raw material sources are unknown or widespread, it is impractical to sample and characterize every potential source. Instead, artifacts are first characterized in order to create reference groups, then any source samples can be compared to the range of variation between reference groups (Glascock & Neff 2003). This approach is most commonly applied to ceramic provenance, as clay is so ubiquitous across the landscape. A second approach begins with the collection and generation of source data (Figure 2.1). The initial examination of source data allows the identification of certain variables that enable a discrimination of the sources from each another and their inclusion in a regional database (Earle & Ericson 1977; Glascock & Neff 2003). If the sources can be successfully segregated, then the artifacts can be integrated for comparison through the same strategy (Fowler et al. 2019; Neff 2000; Shackley 2005, 2008). This approach is commonly applied to lithics and in regions with known or localized sources.

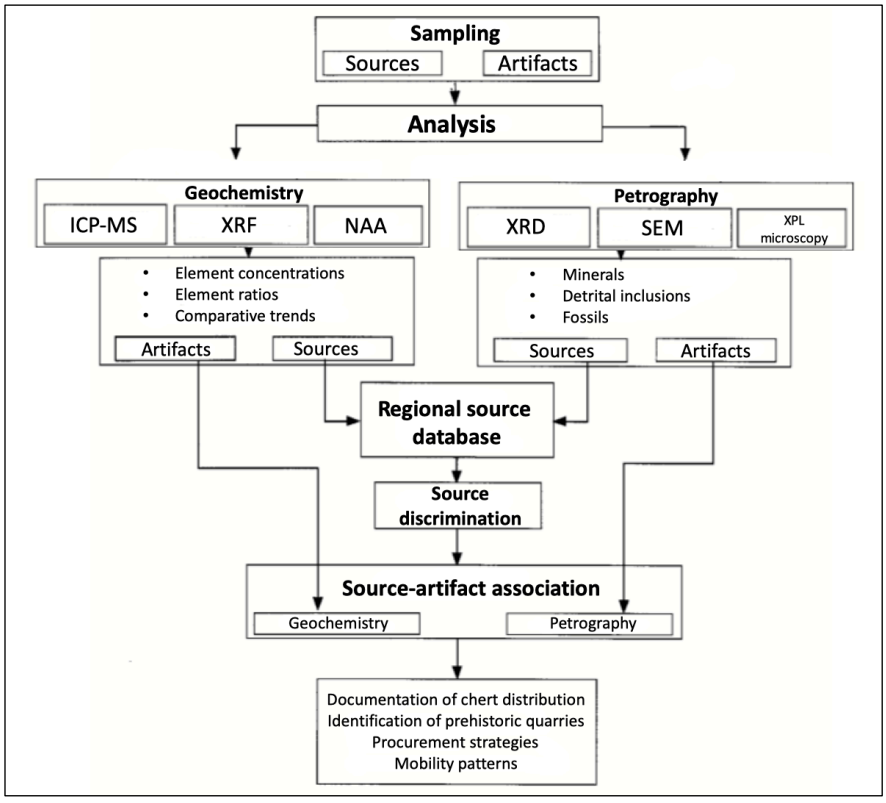


Figure 2.1: Flowchart of provenance analysis using geochemical or petrographic data. Figure modified from Malyk-Selivanova et al. (1988: 678).

Two types of sources can be included in provenance analyses: primary and secondary. Analytical preference is usually given to the former. *Primary sources* refer to the *in situ* location where the outcrop is exposed or the bed is situated in its order of stratigraphic formation. Secure provenance associations are complicated by the existence of secondary sources. *Secondary sources* are collections of clasts of various sizes that have become free from a primary source and are deposited at varying distances away from it. Typically, natural weathering will free the clasts, transporting them to locations of lower potential energy, such as downhill and/or downstream, where they are often sorted based on size (Biró 2009; Boggs 1992). The locations of both primary and related secondary sources can vary, as they can be close to one another or kilometers apart. The identification of the sources of origin does not imply that the whole reduction locale has been discovered.

2.2 Generation of provenance data

In archaeology, provenance has been investigated through three forms of data: individual attributes, petrography, and geochemistry. An overview of their utilization is discussed in the sections below.

2.2.1 Individual attributes

A visual examination of the individual attributes of lithic artifacts and sources performed by the archaeologist can provide inferences of provenance. This analysis involves a documentation of various observable geological properties, such as color, grain size, texture, and structure (Luedtke 1992; Milne et al. 2009). However, some qualities may not be present on every type of artifact or source; others may be altered by natural or anthropogenic means. For example, the heat treatment of some lithic materials can alter their color (Schmidt & Mackay 2016). Individual attributes can certainly serve as an effective and appropriate discrimination of one rock type from another (e.g., dolostone from schist; basalt from rhyolite). However, skepticism of the results and harsher critiques continue to be applied to studies that rely upon attributes for discriminating among the same rock type (Bustillo et al. 2009; Crackler et al. 2000; Odell 2004). Much of this aversion is because the association between artifact and source is dependent upon the subjectivity

of the analyst. Many rock types (e.g., chert, sandstone) are highly variable in appearance, often causing archaeologists to segregate artifacts by minute variations, creating more potential sources within an artifact assemblage than there are actual sources in a region. This "splitting" overestimates the number of sources, since many overlapping attributes could be present in the same source. Consequently, individual attributes, especially color, are becoming recognized as an unreliable basis upon which to confidently reconstruct provenance (Crackler et al. 2000; Milne et al. 2009; Shackley 2008).

2.2.2 Petrography

The petrographic characterization of lithic material is based upon composition, proportion, and distribution of minerals and/or fossils. Each rock type contains certain minerals that aggregate together during rock formation or undergo alteration by heat and pressure. Organisms may contribute a significant or trace amount to the composition of bioclastic and chemical sedimentary rocks. Therefore, a limestone artifact with distinct inclusions of calcareous tests should only be linked to sources with the same inclusions. In archaeology, thin-section analysis and X-ray diffraction (XRD) are the most utilized petrographic techniques, although XRD has mainly been applied to ceramics (e.g., Fowler et al. 2011; Neff 2012a; Rice 2005).

2.2.3 Geochemistry

The rise of the New Archaeology during the 1960s brought a motivation to utilize new methods and models for conducting archaeological research (Trigger 2006). For procurement studies, this shift involved a greater reliance on scientific methods in order to generate and evaluate sets of quantitative data that could establish geochemical consistencies between sources and artifacts (Earle & Ericson 1977; Glascock et al. 1998; Shackley 2008). This scientific foundation was particularly attractive during the 1960-70s and became a rapidly adopted avenue of research (e.g., Aspinall & Feather 1972; Renfrew et al. 1966, 1968). As affordability and availability of geochemical techniques increased, academic pressure mounted to incorporate geochemical data into provenance research. Geochemical techniques have been applied in provenance studies of a variety of lithic materials, but most commonly to obsidian (e.g., Dixon 1976; Shackley 1988;

Weigand et al. 1977) and chert (e.g., Aspinall & Feather 1972; Glover & Lee 1984; Luedtke 1979), both of which are ideal for the manufacture of chipped stone tools (Andrefsky 2005; Clark 1980). Initially, atomic absorption spectroscopy (AAS) and neutron activation analysis (NAA) were relied upon for generating such data (e.g., Renfrew et al. 1966, 1968). Improvements in instrument technology and detection limits led to their gradual replacement by X-ray fluorescence (XRF) (e.g., Newman & Nielsen 1985; Shackley 1988) and more recently by several modes of inductively coupled plasma-mass spectrometry (ICP-MS) (e.g., Nathan et al. 1999; Evans et al. 2007). Since their introduction into archaeological research, geochemical techniques have undergone more routine application, but the accuracy of establishing provenance is considered best maximized by a combination of techniques (Brandl 2016; Navazo et al. 2008).

2.3 Petrogenesis of chert

Chert is the term for sedimentary rocks predominantly comprised of the micro- to crypto-crystalline quartz (SiO_2). The individual quartz grains are nearly equidimensional and cannot be perceived by eye or under light optical microscopes (Folk 1974; Knauth 1994). Cherts make up a minor fraction of all sedimentary rocks and typically range in age from the Archean Eon to Tertiary Period. However, the focus of this present study pertains to cherts formed after the Precambrian, as these were produced by significantly different processes.

Chert predominantly occurs in marine sedimentary rocks (Hein and Parrish 1987). Here, free silica (SiO_2) must appear in sufficient abundance for chert to form in the deep ocean (Murray & Buchholtz ten Brink 1992). Free silica is largely produced by the weathering of continental rocks, but is transported to the oceans by stream systems as H_4SiO_4. It is also generated by the reaction of seawater and hot volcanic rocks along midocean ridges and through halmyrolysis, the low-temperature alteration of oceanic basalts and detrital silicate particles (Boggs 2006). To balance these inputs, SiO_2, in the form of opal-A (a polymorph of quartz), is (and was) constantly removed by diatoms, sponges, radiolaria, and other silica-secreting organisms to construct their opaline tests (skeletal structures) (Calvert 1983; Treguer & de la Rocha 2013). After the death of such organisms, dissolution of their test begins. However, not all tests fully dissolve, and some reach the ocean floor relatively intact (Figure 2.2). The solubility of SiO_2 increases with rising pH

(bases), temperature, and pressure (Dove & Rimstidt 1994; Rimstidt 1997). Therefore, the lower these values, the more likely it is to precipitate, fully coalesce to form a siliceous ooze, and eventually crystalize into quartz. As the ooze gets buried and compacted, it undergoes additional dissolution to the point where the silica cannot escape and clogs the pore spaces (Hein et al. 1990). Fluid flow is eventually inhibited and the pore water, often as structural OH molecules, becomes enriched in silica, ultimately permitting the precipitation of chert (Knauth 1994).

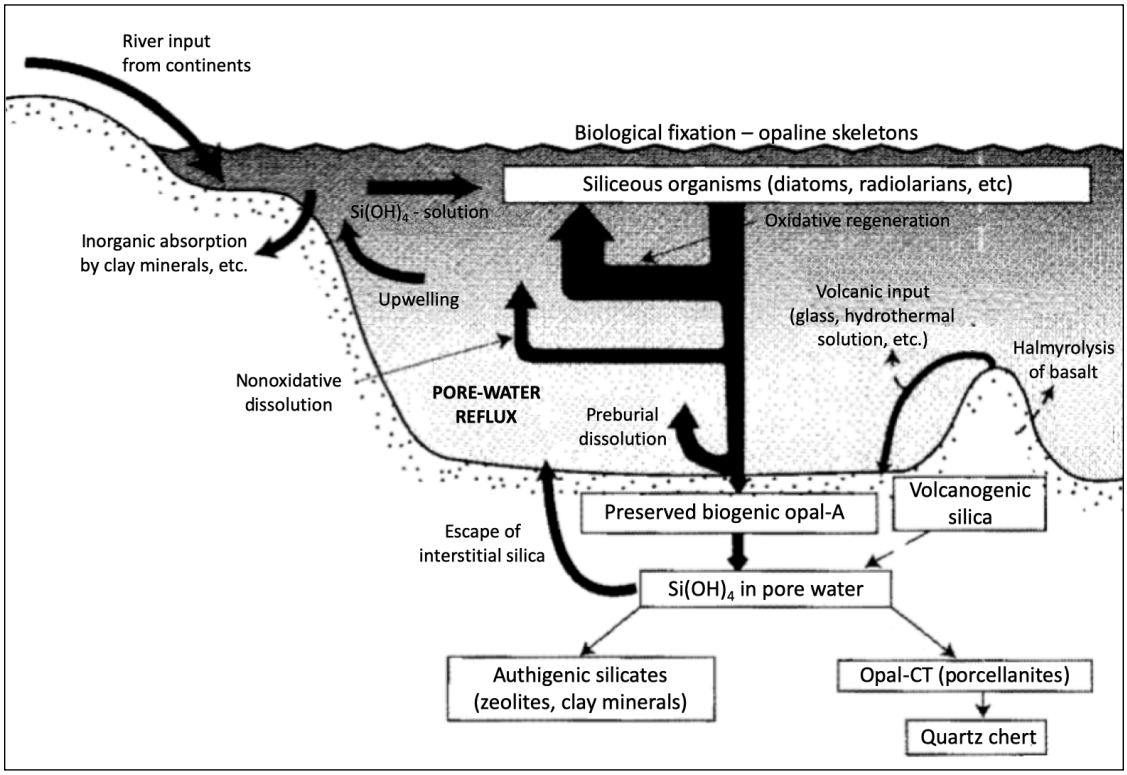


Figure 2.2: Sources of dissolved silica in sea water. Figure modified from Boggs (2006: 211).

The precipitation process involving the transformation of biogenic silica from opal-A to microcrystalline quartz often goes through an intermediate metastable phase of opal-CT (Figure 2.3). Both transformations are solution-reprecipitation processes: opal-A dissolves to generate silica-rich pore water from which opal-CT precipitates, and then opal-CT dissolves and precipitates as microcrystalline quartz (Boggs 2006; Knauth 1994). These transformations are controlled by various physiochemical factors, including temperature and pressure (Bohrmann et

al. 1994; Kastner 1981; Siever 1992), though the later transformation of microcrystalline quartz to megaquartz does not involve solution-reprecipitation.

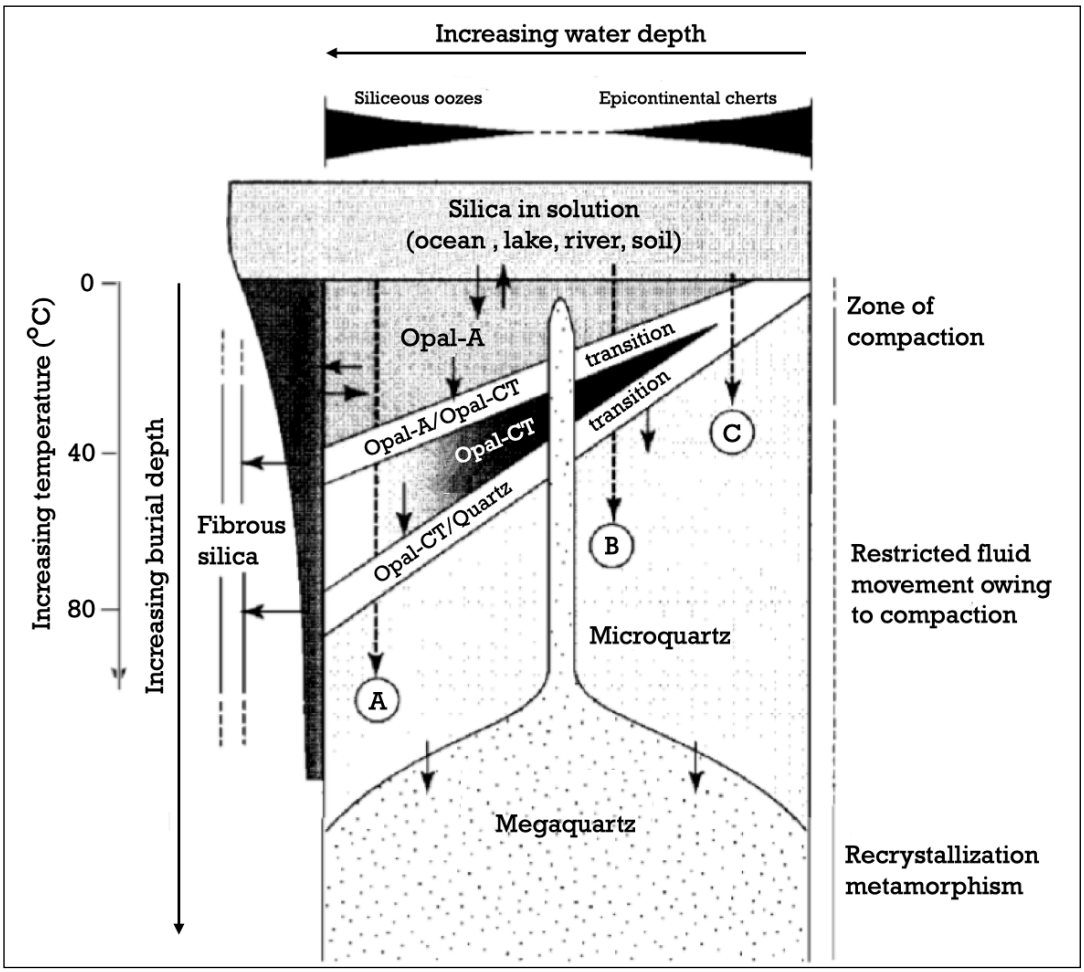


Figure 2.3: Schematic diagram of major silica phases and their diagenetic transformations. Figure modified from Boggs (2006: 214).

Unlike $CaCO_3$, the mineral component of chalk and limestone, there is no equivalent to the carbon compensation depth for SiO_2, allowing it to precipitate at most depths in the deep ocean and at great distances from areas of initial clastic deposition. The residence time for dissolved silica has been calculated to be 200-300 years for biological utilization in the ocean and an additional 11,000-16,000 years for initial incorporation into the geological record (Heath 1974). This estimation is very short on a geological time scale, but the transformation of siliceous

sediment to chert may take up to tens of millions of years under modern deep-sea sediment conditions, particularly due to the low reaction rate of the opal-A to quartz diagenetic pathway (Bohrmann et al. 1994).

Cherts appear in largely two forms of gross morphology: nodules and beds. Most nodular cherts originate through diagenetic replacement, particularly of carbonate material with SiO_2 on a "volume to volume" basis (Knauth 1994). Although the exact mechanism is not fully established, the occurrence is indicated by the presence of partially silicified remains of calcareous ooids or fossils. These appear as oblate subspheroidal masses or lenses in larger shelf-type carbonate rocks (e.g., chalk, limestone) and even some shales and sandstones. The nodules reside with their long axis lying in the bedding plane of the host carbonate and rarely exceed over a meter in size (Knauth 1979). By contrast, bedded (or ribbon) chert is formed of layers of nearly pure microcrystalline quartz that is often interbedded with smaller laminae, but can lack significant internal sedimentary structures (Boggs 2006). The individual beds can be up to several centimeters thick, though they rarely exceed 25 cm. Bedded cherts can be further divided based on the types of siliceous organisms (e.g., diatoms, radiolaria) that are present within them. Over time, tectonic forces uplift and expose these beds on continents.

In geology, much of the evaluation of geochemical data is to reconstruct the depositional environment in which the chert formed. The results provide information about plate tectonics, paleogeography, and paleooceanographic circulation patterns (e.g., Boggs 2006; Hein & Parish 1987; Lu et al. 2019; van den Boorn et al. 2007). Chert is essentially monomineralic, as the predominant component is micro-cryptocrystalline quartz (SiO_2) that appears in extremely high concentrations (up to 99.99%). As noted previously, the source of SiO_2 is largely from the tests of radiolaria or diatoms, which may occasionally survive fairly intact to be seen under a powerful microscope. Due to its overwhelming abundance, Si is often excluded from further consideration, since any variations in SiO_2 are likely to be insignificant. Instead, most studies tend to focus on minor and trace elements, which also contribute to the composition of chert, albeit in lower concentrations. Minor elements are found in 1-0.01% concentration, while trace elements are those that appear in less than 100 parts per million (ppm) (McNaught & Wilkinson 1997). Together, minor and trace elements serve as good indicators of the depositional environment due to their

more variable nature. They are typically incorporated into chert as terrigenous clasts, volcanic detritus, and submarine hydrothermal precipitates (Kato & Nakamura 2003).

Microscopic terrigenous clasts, typically in the form of siliciclastic material, which are moved into the deep depositional basin can become incorporated into chert (Boggs 2006; Keene & Kastner 1974; Murray 1994). This is most evident with light suspended particles of clay minerals that are pushed farthest from shore and gradually settle on the basin floor. These inclusions can lead to the detection of certain elements that predominate in them (e.g., Li, Al, K Na, Mg). It is also possible that some larger cations (e.g., Al^{3+}, Fe^{3+}, Mg^{2+}) precipitated from seawater or porewater and substitute for Si^{4+} with the overall charge being balanced by the inclusion of smaller cations (e.g., Li^{+}, Na^{+}, K^{+}, Cu^{+}) in interstitial positions (Brandl et al. 2014; Goetze et al. 2001). Other elements, Ca and C, are due to carbonate mineral inclusions (Luedtke 1992).

A good example of how certain elements can provide information on the formation of chert is by distinguishing between biogenic (and related terrigenous) and hydrothermal sources of silica. Elements Al and Ti are considered a largely terrigenous input and Fe and Mn are considered to be generated by hydrothermal fluid. Therefore, chert rich in Fe and Mn has formed under significant hydrothermal influence. The ratio of Al/(Al+Fe+Mn) provides a calculation of this influence, where the ratio increases with the distance from the center or expansion (Bostrom & Peterson 1969). In this case, values below 0.4 indicate a greater influence of hydrothermal fluid and values above 0.4 relate to greater terrigenous input (Bostrom et al. 1973). Others (Adachi et al. 1986; Yamamoto 1987) report the ratio of 0.6 as further indicative of primarily siliceous organisms and 0.01 as dominated by hydrothermal fluid.

Rare earth elements (hereafter REEs: La-Lu) are largely immobile in cherts and little influenced by diagenesis, thus their concentrations offer significant indications of the original depositional environment. For instance, the overall sum (Σ) of REEs can indicate over all purity of chert, where lower values reflect a more homogenous lithology (Eker et al. 2012). Dissolved REEs can be entrained in sediment due to the adsorption from sea water, as the rate of sediment supply can limit sea water exposure (Murray et al. 1990; Ruhlin & Owen 1986). REEs also function as proxies to determine whether cherts are marine (biogenic) or hydrothermal in origin. For example, the Ce anomaly (Ce/Ce*) is directly correlated with the influence of terrigenous

material (Murray et al. 1991a), where the latter will increase the value of the former. These values are correlated with the location of formation, where 0.29 (average) is associated with mid-oceanic ridges, 0.6 (average) with open oceans, and 1.11 (average) with continental margins (Murray 1994; Murray et al. 1991a). By contrast, positive Eu anomalies (Eu/Eu*) are direct indications of high-temperature hydrothermal solutions (Bau & Alexander 2009). Furthermore, the values of light REE-enrichment (La_n/Yb_n) increase from the mid-oceanic ridge to the open ocean to the continental margin (Eker et al. 2012; Murray et al. 1991b), indicating their connection to terrigenous input. These vary inversely with those of La_n/Ce_n, which decrease in the same direction.

2.4 Provenance studies of chert in archaeology

In 1992, Barbara Luedtke published a comprehensive guide to understanding chert from an archaeological perspective. This book and related articles (e.g., Luedtke 1978, 1979) have served as a foundation for all manner of studies addressing chert, including its provenance. The provenance of chert has been mainly investigated through individual attributes and geochemistry.

2.4.1 Individual attributes

In geology, qualitative and quantitative attributes are useful for the classification of minerals and rocks. Similar attributes are used by archaeologists for describing chert, although it should be stressed that, despite the use of the same terms, most attributes are not synonymous between the disciplines. Furthermore, since most attributes are subjectively evaluated by the analyst, most archaeologists do not describe the rubric used and simply present the results. The following is a list and description of the most common individual attributes analyzed by archaeologists:

- Color: Color is related to the chemical and physical structure of the material. For example, the inclusion of chromophore elements (Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn) can greatly influence the color of a mineral. Quartz (SiO_2), the main mineral constituent of chert, is normally colorless. It is the impurities (e.g., other minerals) within chert that provide its color.

Chert presents in a variety of colors, though grays and blacks tend to be most commonly reported. Color is often described by three aspects: hue, value, and chroma. Hue describes the part of the color spectrum this is reflected. Value refers to the luminous intensity of the color in relation to the extremes of white and black. Lastly, chroma describes the degree of saturation of the dominant color with lower chroma being less pure or "washed out". The most common reference for identifying colors is the Munsell soil color charts. Although not perfect, it is a standard utilized by many academic disciplines and industries, including archaeology.

- Translucency: Translucency (or diaphaneity) refers to the degree that light can passes through a material. It is often reported on a spectrum from transparent to opaque. Materials that are transparent allow almost all light to pass through, such as glass. Materials are described as opaque if light cannot pass through them and is entirely absorbed or reflected. Like most material, chert varies in translucency, though purer cherts will be more translucent. It should be noted that translucency is also affected by the thickness of the material. There is no systematic technique to measure translucency and it is often a subjective classification determined by the analyst (Luedtke 1992). However, holding samples of a similar thickness up to a light for comparison is typically performed (Ahler 1983).

- Texture: Texture is a common descriptor of rock, particularly siliciclastic sedimentary rocks, that describes maturity and fabric of the compositional grains (Folk & Weaver 1952). However, in regard to chert, archaeologists refer to texture as the feel or appearance of the fracture surface. The nature and path of fracturing may be influenced by several causes, including grain size, grain clusters, and porosity (Luedtke 1992). Archaeologists describe the fracture surface of chert on a scale of fine- to coarse-grained. It should be stressed that this classification of "grain size" is not synonymous with the geological grain size of the individual minerals or clasts, as in other rocks (Udden-Wentworth scale), and has been pervasive in descriptions despite being a misnomer. The greater the fracturing, the more coarse-grained the surface will appear. There is no suitable technique to quantify the "grain size" and archaeologists typically described it on a subjective spectrum from fine- to coarse-grained.

- Luster: Luster refers to the appearance of light reflected from the surface of a material. The type of luster is influenced by other attributes, such as color and grain size. Luster is a common property in mineralogy, which uses terms such has metallic, vitreous, resinous, and waxy. Quartz is a non-metallic mineral with a vitreous (glass-like) luster. However, chert comprises innumerable grains of quartz that collectively form a microscopically uneven surface. Furthermore, the surface of chert can be anthropogenically modified by heating or polishing. There is no sufficient manner to quantify luster for chert and archaeologists tend to classify it on a subjective spectrum from shiny to dull.

- Quality: The quality of raw material has implications for the utility and longevity of the tools. In archaeology, quality refers to the reliability and predictability with which raw materials can be knapped. Experimental knapping has determined that brittle, homogenous, isotropic rocks are most suitable for the manufacture of chipped stone tools (Andrefsky 2005). These rock types, such as obsidian and chert, tend to contain a high composition of SiO_2. The abundance of chipped stone tools made from these rocks in the archaeological record attest to an early recognition by hominin knappers that these raw materials were most suitable. Quality is influenced by certain aspects, namely the homogeneity of the matrix, abundance of inclusions, and cracks or flaws (Luedtke 1992). Higher quality materials with be homogenous with fewer inclusions and flaws (Goldman-Neuman & Hovers 2009). Archaeologists classify quality subjectively through a low to high scale.

Source-artifact associations based on individual attributes is common for studies of chert provenance. Although color appears as the most frequent discriminator, a combination of attributes provides more secures results. For example, Eixea et al. (2016) found color, texture, and quality to be most sufficient at discriminating among chert sources exploited during the Middle Paleolithic by occupants of several sites within the Iberian Peninsula. Each chert source exhibited at least one attribute that was noticeably different from the others.

A different approach (the first described in Section 2.1) was applied to artifacts the Lower Paleolithic site of Gesher Benot Ya'aqov in the Levant. Delage (2007b) first divided the lithic assemblage into different reference types based on shared attributes in order to determine the minimum number of sources from which they originate. This resulted in the description of 17 different chert "types", which could then be identified on the landscape.

Other studies have utilized individual attribute analysis as a first step in provenance—to reduce the number of potential sources tested by geochemistry. For example, Milne et al. (2009, 2011) examined the individual attributes of several sources of chert and a collection of artifacts from a Paleo-Eskimo site in the Canadian Arctic. Quality and texture were similar among the sources and not suitable discriminants. Color was more variable and sufficiently narrowed the number of potential sources, although geochemistry was ultimately relied upon for provenance. Similarly, Newlander & Lin (2017) documented multiple attributes for sources within the Great Basin of North America. Again, color was found to be a prime discriminant in reducing the number of potential sources for artifacts found at Paleo-Indian sites.

A recent pilot study by Sánchez de la Torre et al. (2019) characterized several chert sources of three formations in the southwestern Azraq Basin through a combination of geochemistry, petrography, and individual attributes, in order to identify what sources were available to Epipaleolithic occupants of Kharanah IV. The results indicated that many attributes (e.g., texture, translucency) were highly variable within each formation (Sánchez de la Torre et al. 2019). Others (e.g., color, quality) served as more secure discriminants (Sánchez de la Torre et al. 2019). No artifacts were included as a provenance component.

2.4.2 Geochemistry

A foundational understanding of chert geochemistry has been well developed by geologists (e.g., Bohrmann et al. 1994; Keene & Kaster 1974; Knauth 1979; Murray 1994; Murray et al. 1990; van den Boorn et al. 2007). A consideration of geochemical data allows geologists to reconstruct the depositional environments of cherts. However, geologists pursue different research questions than archaeologists, who focus on the exploitation and utilization of chert as raw material

for stone tools. When available, archaeologists can use the same generated data to identify which elements might serve to differentiate one chert source from another.

Although there are many studies, provenance analyses of chert through geochemistry have not yet become the standard within archaeology. Part of this issue is that a uniform strategy by which geochemical data of chert can be discriminated has not been (or cannot be) established. For many other rock types, geochemical provenance is a straightforward exercise that follows a rubric put forth by geologists. For example, extrusive igneous rocks (e.g., andesite, basalt, rhyolite) are geologically classified based on their ratio of total alkali ($Na_2O + K_2O$) to silica (SiO_2) content (Le Bas et al. 1986; Le Maitre 1984; Le Maitre et al. 1989; Zanettin 1984). This specific contrast of major elements has been effectively utilized by archaeologists in provenance analyses involving artifacts of such materials (e.g., Gluhak & Rosenberg 2013; Gluhak et al. 2016). By contrast, there are no "one size fits all" discrimination strategies for the geochemical provenance of cherts. This has led archaeologists to experiment with and apply various forms of data evaluation, namely bivariate scatterplots and ternary graphs, REE trends and anomalies, or a combination of these.

The contrast of concentrations or proportions of select elements through bivariate scatterplots and ternary graphs is the most common form of discrimination. Often, the identification of which elements function to discriminate among sources is obtained through extensive trial and error. These can be individual elements, the ratios of elements, or even the sum of a group of related elements. Commonly used elements include those of a terrigenous origin (e.g., Li, Na, Mg, Al, K, Ti), as they are often present in relatively high concentrations and exhibit suitable variation between sources (e.g., Brandl et al. 2018; Sánchez de la Torre et al. 2019; Gurova et al. 2016). For example, the discrimination of Al vs. K, Na, and Mg was used to identify the sources of origin for chert artifacts in Bulgaria (Andreeva et al 2014). A similar discrimination, Al vs. Mg and Ti, was useful for chert in Belgium (Moreau et al. 2016). Still other archaeologists, such as Glover & Lee (1984), have utilized the ratios of certain elements (e.g., Ca/Mg vs. Na/K) in the discrimination of chert sources and artifacts in Australia. In addition, other elements, such as those that originate from iron minerals (Mn, Fe, Co, Ni, Cu, Zn), are used as well. Several of these elements proved effective in contributing to the discrimination among chert sources in northern Israel (Ekshtain et al. 2016). Other archaeologists have identified seemingly unrelated

elements that provide a useful discrimination, such as in the Canadian Arctic where the contrast of Al vs. Ga/Zr was used (Milne et al. 2009, 2011). In essence, the discrimination of chert is obtained by identifying which elements or element ratios can effectively segregate the sources on a plot.

Another form of discrimination is the examination of REE (La-Lu) trends and associated anomalies of each source. REEs are present as trace elements in extremely low concentrations, some of which may not be suitably detected. The values of the REEs are first normalized to a pre-established standard (e.g., North American Shale Composite – Gromet et al. 1984, Upper Continental Crust – McLennan 2001, or Chondrite – Piper & Bau 2013) in order to transform all variables to a specific range. The resulting trends can then be compared to each other through the positions of rise-and-fall patterns among the elements. Occasionally, the rise-and-fall patterns are pronounced where large troughs (depletions) and peaks (enrichments) represent negative and positive anomalies respectively. Among cherts, the nature of Ce and Eu anomalies are indicative of the influence of terrigenous material and high-temperature hydrothermal solutions (e.g., Lu et al. 2019; Murray et al. 1994). The use of REE trends in provenance is well exemplified by several studies of chert sources in Israel (e.g., Finkel et al. 2019; Nathan et al. 1999; Segal et al. 2005), where both negative Ce and positive Eu anomalies assisted in connecting artifacts to sources.

2.5 Conclusion

A good starting point for procurement studies is a provenance analysis, the identification of the source of origin of the artifacts. The provenance of lithic materials, such as chert, is rooted in a characterization of geological properties and composition. The petrogenesis of chert is a complex process that involves the input of different materials, which are influenced by and reflective of the depositional environment. The variable composition of chert can create challenges for the provenance of its artifacts. Provenance analyses of chert artifacts have been conducted through individual attributes and geochemistry. The identification of the source of origin permits insight into the nature of raw material procurement and forager mobility by material proxy (artifacts), as will be explored in the next chapter.

CHAPTER 3: LITHIC PROCUREMENT IN ARCHAEOLOGY

A consideration of how modern humans obtain their resources, such as groceries, clothes, and medication, reveals that significant decision-making is invested into determining the schedule, location, order, and route of acquisition (Arnold & Reynolds 2003; Cochrane 1975; Miller 1998; Saad 2007; Tauber 1972). This decision-making is not novel to complex or recent societies, but can be identified in the archaeological record associated with prehistoric foragers. The survival of hominins was intricately linked to the procurement of raw material for the manufacture of stone tools, as these were used for various activities, including tool making, protection, hunting, butchering, and potentially establishing social networks through exchange. Procurement is part of their lithic technological organization, which refers to how foragers organize their activities and lives within the larger paleoeconomy (Andrefsky 2009; Binford 1973, 1977; Kelly 1988; Shea 2017; Shott 1986; Torrence 1989). This chapter explores how archaeologists investigate and interpret procurement strategies, associated with lithic materials in prehistoric hunter-gatherer societies, specifically those of the Levant.

3.1 Paleoeconomy of procurement

The organization of lithic technology, and procurement by extension, is bound by decisions and constraints within the larger paleoeconomy of groups and societies (Odell 2000; Torrence 1989). These decisions and constraints ultimately affect the life-history of stone tools and their variability in the assemblage. The paleoeconomic features of procurement are greatly intertwined and cannot be completely covered, nor do all factor into each scenario of raw material extraction. Some of the main features are discussed below.

3.1.1 Transport

The extraction of raw materials and the subsequent manufacture and transport of finished implements requires a level of manual dexterity, cognition, and locomotion that has only been observed in humans (Shea 2017). Non-human primates do not quarry and manufacture lithic materials, nor do they transport them over distances further than a kilometer (Carvalho et al. 2012; Toth & Schick 2009). By contrast, ethnoarchaeological accounts document humans transporting

lithics and other materials over tens of kilometers (Binford 1978, 1979; Hayden 1987; Fowler et al. 2011). Indeed, a benefit of bipedalism is that the hands are free to utilize and carry objects, particularly in ways that non-human primates cannot. Carrying may be performed with rudimentary sacks made from hides or plant fibers (and later ceramic vessels), which are placed on the head, grasped with the hands, suspended from the waist, or slung across the shoulder (Hayden 1987; Shea 2017). The carrying capacity of hominins permits them to engage in extended movement across the landscape. Transport and carrying costs can be mitigated by combinations of decisions regarding which source to exploit and the type of tools that can be effectively produced by its quality.

3.1.2 Provisioning and personal gear

Procurement is performed for provisioning. Provisioning has been described in two forms: provisioning of the individual and provisioning of a place. The provisioning of an individual describes how foragers will outfit themselves with personal gear (Kuhn 1992, 1995), a specific toolkit that can be carried on their person for anticipated tasks. This behavior can be identified at sites, as it is largely based on the abundance of knapping material (e.g., debitage, failed cores) and/or the proximity to a source. Such sites are consistent with knapping locales, where finished tools are manufactured then removed from the site for later use.

Provisioning of a place describes how foragers transport and stockpile tools and blanks for later reduction and anticipated use, often at strategic points on the landscape or at their camp (Kuhn 1992, 1995). It is an effort to create more available sources of raw materials within the extent of their territory and decreases the necessity of later mobility (Kuhn 1995; Potts 1991). The identification of this pattern relies on the high frequencies of primary stage reduction lithics (e.g., cores, blanks) and finished tools an assemblage, a low frequency of debitage, and on the distance that these lithics have been moved. What constitutes a "high frequency" (e.g., by % of assemblage) is not defined even in the most extensive descriptions (e.g., Henry 2003; Hovers 2009; Kuhn 1995), nor is there a stipulated minimum number of lithics that need to be recovered before making such inferences. Whether short or long term, provisioning requires a degree of planning, as the materials are stocked and tools are manufactured for future activities.

Provisioning may also vary depending on the types of tools intended for manufacture, not necessarily the quality or availability of raw material. In this case, a visit to a source may lead to the manufacture of finished implements of one type of tool, yet cores may also be brought home to make other types. Such patterns were noticed among the *Alyawara* of Australia (also see Section 3.2.5), where members manufactured special "men's knives" at the source and also collected cores to make more expedient tools at the camp (Binford & O'Connell 1984). Raw material quality and availability were not the factors influencing the decisions to employ different provisioning strategies, but rather because "different perceived costs were associated with different demands for different tools within the system" (Binford & O'Connell 1984: 428). Perhaps it should be expected that different types of tools in an assemblage were obtained through different procurement and provisioning strategies (e.g., burins vs. handaxes vs. scrapers).

3.1.3 Formality

Investigations into the formality of tools have offered insight into the relationship between raw material abundance and quality (Andrefsky 1994). Formality refers to tool types and their associated effort expended in manufacture (Andrefsky 1994; Graf & Goebel 2009). Formal tools are those that are specialized, often hafted, that are designed to be rejuvenated and can perform various functions (e.g., bifaces, retouched flakes) (Goodyear 1979). Informal tools are more general, crude, less standardized, and with little design afforded to them (Graf & Goebel 2009). However, early discussions of curation and expediency conflated these concepts with the formality of tool types, as *curated* tools were often equated with those of a formal nature, while expedient tools were informal. Shott's (1996) exegesis on curation more appropriately defined it as a reflection of actual utility of a tool relative to its maximum potential utility, rather than a tool type. Utility is the work that can be performed, the time that a tool can be used, or the ratio of return to effort in use of the tool (Shott 1996; Shott & Seeman 2015). Curation is measured on a low-high scale by the archaeologist through the intensity or degree of rejuvenation (retouch), the intentional modification of a tool or flake blank edge (the objective piece) by detached pieces (Andrefsky 2009).

Whether formal or informal tools are produced is considered dependent upon the abundance and, to a lesser extent, quality of sources that foragers exploit. In general, foragers typically prefer local higher quality material, but such sources are not always available. Among specific case studies (e.g., Andrefsky 1994; Graf & Goebel 2009), several patterns are apparent and are summarized as the following: 1) in the presence of high quality and abundant stone, both types of tools are made as there is no need to conserve material and there are no restrictions; 2) in the presence of low quality but highly abundant stone, informal tools are dominant, as they are unlikely to last long and sources can readily be accessed for new ones; 3) in the presence of high quality and low abundance material, formal tools are likely to be made, although this correlation did not occur in the study; and 4) in the presence of low raw material quality and low abundance, informal tools tend to be manufactured. In this final situation, foragers recognize the inability of the raw material to produce formal tools without fracturing and often access regional or more distant sources for higher quality formal tools. In addition, mobile groups tend to produce more informal tools in comparison to sedentary populations, due to their knowledge of the landscape and location of sources, affording them more casual procurement (Andrefsky 1994).

Is it possible that these observations of procurement and manufacture apply to all foragers? Not necessarily. Brantingham et al. (2000: 257) found that "regardless of quantity, poor quality rocks usually lead to informal technologies" is not always the case. Here, sophisticated (formal) prepared core technology was discovered at the Paleolithic site of Tsagaan Agui, China, where lithic quality is low and abundance is high, suggesting that tool technology is not always constrained by raw material quality (Brantingham et al. 2000).

3.1.4 Recycling

One of the most common forms of procurement that is rarely identified or described is that of opportunistic collection and recycling. The lack of discussion is likely due to the mundane and almost incidental pattern of behavior, as well as the difficulty in discerning its occurrence in the archaeological record. To archaeologists, recycling appears to have two characteristics: 1) a functional change of the artifact, and 2) the modification of previously discarded artifacts (Barkai et al. 2015). The first definition is closely linked to curation, difficult to identify in reductive

technologies, and can be confused with the versatility of multi-functional tools. The second definition aligns with standard definitions of recycling – waste utilization. Although these two conceptions of recycling are not mutually exclusive, additional emphasis is placed on the latter.

Opportunity is often equated with fortune, the encounter with or "stumbling upon" of older, forgotten, previously used tools and the modification of them (Shott & Seeman 2015). In order for an artifact to be re-utilized, it must first become waste and undergo a period of discard. However, such a period cannot always be established and its actual existence becomes blurred in the archaeological record. In more fortunate studies (e.g., Belfer-Cohen & Bar-Yosef 2015), a sufficient gap is identified, not only in time, but in technology as well. Recycling provides the opportunity to procure raw material from an anthropogenic secondary source with minimal effort expended. The difficulty is distinguishing between recycling and routine maintenance. As such, there needs to be greater clarification between the concepts of curation and recycling or they need to be merged and then divided into multiple subcategories dependent upon variations in behavior.

3.1.5 Optimization models

Optimization models are an underutilized approach to examining the decisions applied in raw material procurement. These models follow from optimal foraging theory, a subset of human behavioral ecology, which places an emphasis on the utilization of models and quantitative data to predict and evaluate optimal behavior (Bettinger 2009; McAndrews et al. 1997; Stephens & Krebs 1986). In procurement, these models are similar to gravity models applied in economics to understand the decisions made by consumers when acquiring their commodities and to help identify ideal locations at which to erect businesses (Butzer 1982). Once again, the procurement of lithic material can be paralleled to "shopping" and evaluated in a similar manner.

The application of optimization models offers quantitative predictions and a baseline for optimal behavior (Bird & Bleige 1997; Emlen 1966; Pulliam 1974). These models are designed through simulated and predictive operations that center on a hypothetical actor that operates within a fixed set of constraints and options (Bettinger 2009; Shennan 2002). The constraints consist of a series of ranked variables or documented qualitative and quantitative attributes of the sources. For lithic sources, these include quality, abundance, areal extent, ease of access, and terrain difficulty

(Browne & Wilson 2011; Wilson 2007a). These attributes can be used to develop a raw material attractiveness index for each source (Wilson 2007a). The resulting indices of each source are then ranked relative to each other, thereby identifying which sources should be exploited for optimal gain. It is the overall "attractiveness" of the source that would guide the selection by hominins (Broughton 1994; Wilson 2007a). The model relies on the assumption that foragers will exhibit behavior that maximizes a "gain" variable, which is identified by the researcher. In an optimal sense, foragers will exploit a source upon encounter if its post-encounter return rate is higher than the overall foraging return rate of continuing to search for and exploiting any higher ranked source (Kelly 2013). The foragers are presented with decisions based on the cost/benefits of exploiting particular sources (Smith 1983; Wilson 2007a). For example, will there be a greater benefit (e.g., energy conserved, time expended, raw material quality) of exploiting source 'A' relative to source 'B'? Consequently, optimization models can provide insight into the nature of paleoeconomics and the resource acquisition decisions made by foragers (Wilson 2007a-c).

Any actual behavior that aligns with the optimal model is readily explainable by the nature of the cost/benefits involved in foraging. However, adherence to an optimal model of behavior in reality is rarely, if ever, the case (Bettinger 1991). Instead the actual (or reconstructed) behavior frequently deviates from what would be most appropriate for its evolutionary fitness, thereby appearing suboptimal (Lupo 2007). It is the deviations from the model, which represent alternative decisions made by foragers, which archaeologists then seek to explain (Sheehan 2004). For instance, when low ranked sources are exploited in high frequencies, it may be that they have ritual significance or occur in clusters, or are simply rooted in the "geography of opportunities" that the archaeologist cannot (yet?) access (Raven 1992: 7; Browne & Wilson 2013).

3.3 Insights from ethnoarchaeology

During the 1970-80s, the application of ethnoarchaeology within field contexts offered a means by which hypotheses could be actively tested and eventually led to the development of several interpretive patterns of behavior (David & Kramer 2001). These patterns could be associated with certain characteristics of the lithic assemblage and procurement of such material.

The nature of these associations and the debates over the confidence of the interpretive patterns are explored in the sections that follow.

3.2.1 Hunter-gatherers as analogues

Approximately 99% of the human evolution has been spent as hunter-gatherers. In short, hunter-gatherers are largely defined by their mode of subsistence, as they acquire non-domestic resources and do not conduct any deliberate manipulation of the reproduction of flora and faunal species (Smith et al. 2010; Winterhalder 2001). They rely largely on the hunting and fishing of wild game, the scavenging of carcasses, and the gathering of wild vegetation. While there is satisfactory utility in this working definition (Panter-Brick et al. 2001), it is apparent that there are some exceptions among recent hunter-gatherer groups. Some may also engage in the cultivation of a small range of crops, the herding of a staple species, or even the occasional exchange with sedentary societies. Despite these exceptions, it is estimated that rarely will such groups exceed 5% of their dietary needs from these practices (Hunn & Williams 1982). Consequently, in regards to subsistence activities, there are some useful distinctions between hunter-gatherers and agriculturalists that can be drawn.

Hunter-gatherers have long held the attention of scholars, as they appear to be the most ancient form of society known, preserving the most archaic way of life (Testart 1988). Early depictions ranged from overtly degrading and inferior (Hobbes 1651) to uncharacteristically environmental, such as “the noble savage” (Dryden 1670). However, academic anthropology sought to document and understand existing hunter-gatherer societies before their lifeway dwindled and became transformed by external contact. Ethnographic and ethnoarchaeological work has demonstrated that there is extreme variability among almost all aspects of hunter-gatherer lifeways (Barnard 1983; Kelly 2013; Lee & Daly 1999; Panter-Brick et al. 2001). This variability complicates the fitting of all hunter-gatherer societies into a neat “one-size-fits-all” anthropological category (Kelly 2013). Much of this variability is assumed to be due to the environmental conditions and distribution of resources across the landscape (Kuper 1988; Marlowe 2005; Smith & Winterhalder 1992). Given the great range of environments that hunter-

gatherers occupied over time, it is likely that the diversity and variability was even greater in prehistory (Kelly 2013).

Archaeologists often turn to hunter-gatherer societies of the 19-20th centuries for foundational insights into the origins of human behaviors. More specifically, the residues of modern hunter-gather behavior are used as interpretive analogues for archaeological patterns of the distant past (Ascher 1961; Roux 2007; Wylie 1985; Yellen & Harpending 1972). These analogies take several forms, ranging from the formal to relational (Cummings 2013; Johnson 2010). The former allows precise parallels to be drawn between societies. Cross-cultural generalizations are then constructed, as similar environments are tentatively expected to generate similar behavioral responses from their occupants (Binford 2001). Meanwhile, relational analogies identify different expressions of the same structuring principle within societies, including ritual and symbolism. Other archaeologists describe analogies with similar conceptions, but by different terms (e.g., Yellen 1977).

The applicability of hunter-gatherer analogies has been met with warranted critique for potential inconsistency and equifinality (Hodder 1992; Hodder & Orton 1976; Skibo 2009; Wobst 1978) or even the extent back in time (Foley 1988). However, the utilization is difficult to avoid (Sheehan 2004; Winterhalder 2001). Much of this research has focused on food acquisition (e.g., Keeley 1992; O'Connell et al. 1988) and social organization, including aspects of hierarchy, kin selection, and inter-group exchange (e.g., Wiessner 1977, 2002). Less attention has been afforded to the procurement and manufacture of lithic material by hunter-gatherers (McCall 2012). There are very few ethnoarchaeological stone tool studies and, therefore, very few models of lithic procurement (Odell 2000). This dearth of knowledge is largely due to the adoption of metal or plastic technology by some modern hunter-gatherer groups for their tools and gear. This further indicates contact and exchange with industrialized societies, which ultimately influences procurement and mobility patterns. As a result, there is regrettably limited information on this critical aspect of hunter-gatherer life.

3.2.2 Forager mobility

In ethnoarchaeology, mobility refers to the movement of camps throughout the year (a max of 365—1 per day) and movement of individuals as they forage. The relationship between camp relocation and the foraging range from camp is largely elucidated by Binford's (1980) discussion of mobility patterns, where these exist on a spectrum, from residential to logistical mobility (Figure 3.1).

Residential mobility describes how hunter-gatherers will move and relocate the entire camp frequently throughout the year. These moves are typically made once local resources are low. The camp is packed up and relocated to a new area with abundant resources (Figure 3.1). Ethnoarchaeological studies have documented that foragers often establish their camp next to vital resources (e.g., water, edible vegetation) and seek out stationary resources, such as lithic raw material (Gould & Saggers 1985). The groups operating within this system are conceptualized as *foragers* and exhibit high residential mobility (Binford 1980).

In contrast, *logistical mobility* describes how camp moves are relatively rare and camps are often static throughout the season or year, while individual foraging trips are extensive and prolonged. Individuals will travel from the main camp, where most members will remain, to temporary sites across the landscape for task-oriented purposes. These foraging trips involve the acquisition of various resources (e.g., lithics, meat) before a return to the main camp with them (Figure 3.1). The groups operating within this system exhibit high individual mobility and are described as *collectors* (Binford 1980). Although most hunter-gatherer societies will find themselves at some point along the spectrum, it appears that there is an inverse relationship between the movement of groups (camp) and that of individuals. In this respect, as foragers decrease their movement as individuals, they increase their movement as groups and vice-versa. Therefore, residential mobility moves people to resources, while logistical mobility moves resources to people (Kelly 2013).

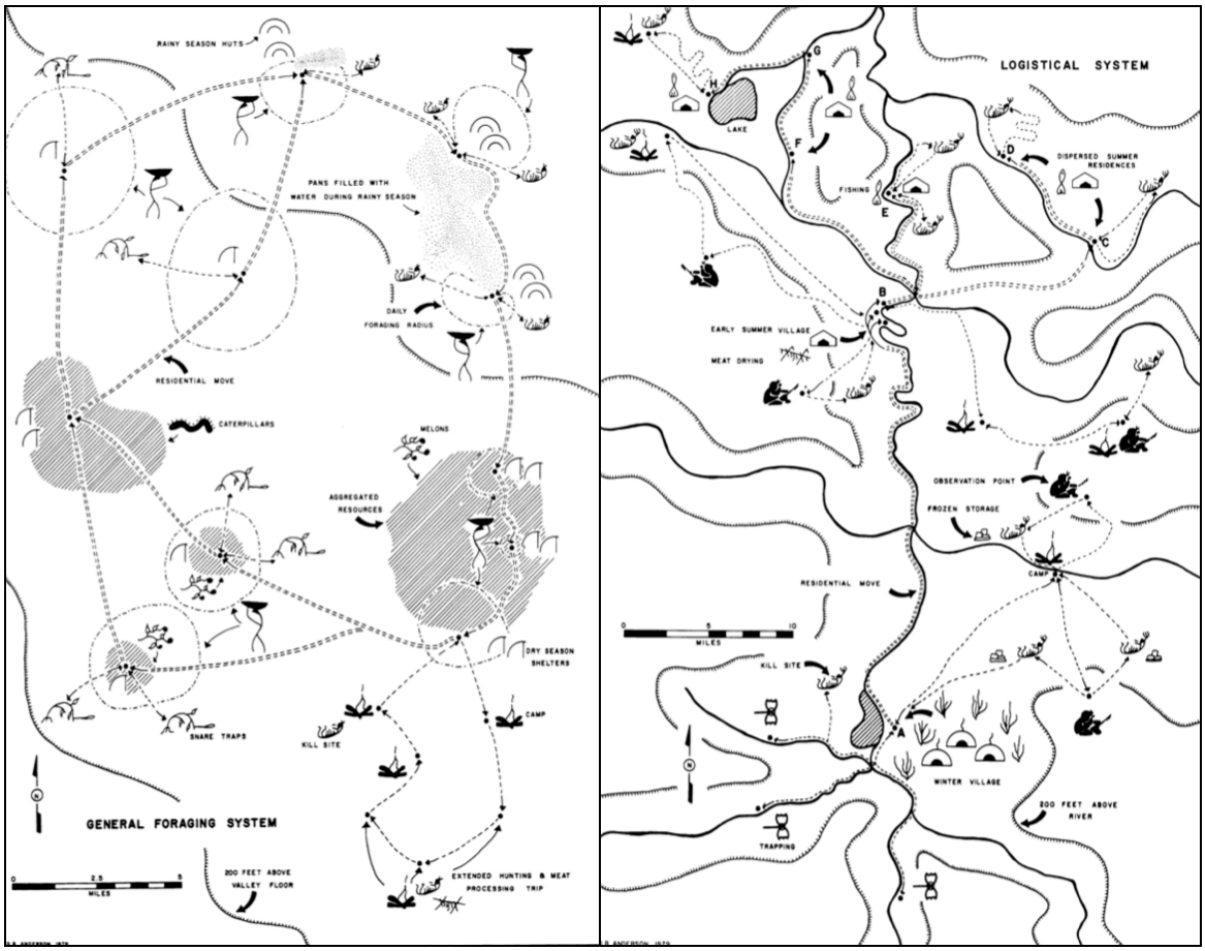


Figure 3.1: Schematic of residential mobility depicting a foraging system (left) and logistical mobility depicting a collector system (right). Figure modified from Binford (1980: 6 and 11).

Shortages of resources often force hunter-gatherers to confront decisions regarding the nature of their mobility. A common strategy is to increase their mobility if shortages persist (Kelly 1983; Kuhn & Stiner 2001), since certain resources are more vital than others. Water presents some complications for hunter-gatherers—they need it daily and it is difficult to collect and transport. The *Jo/'hoansi* of Namibia and Botswana will use nearly intact ostrich egg shells as portable canteens, but even these retain a limited volume of water during transport (Lee 1979). These innovations enable foragers to venture greater distances from water resources. It is not surprising that water-stressed environments (e.g., deserts, some grasslands) create a unique dependence on the most vital resource. For most hunter-gatherer societies in such regions (e.g.,

Hadza of Tanzania, *Pume* of Venezuela, *Mikea* of Madagascar), the distribution of water, even more than food, is the determining factor for where they establish camp and is a well-documented constraint on their mobility (Greaves 2006; Marlowe 2010). Therefore, the mobility of most hunter-gatherers in desert environments, namely the movement of camp or home base, is greatly influenced by the need to reduce the energetic cost of water acquisition. They will often tether themselves to a water hole despite decreasing foraging return rates of other resources, often until the water hole dries up or they ascertain the status of another one. Hunter-gatherers in such situations are described as exhibiting *tethered mobility* (Kelly 2013; Taylor 1964); in this case they are tethered to a water resource. For example, northern portions of the Kalahari Desert, which the *Jo/'hoansi* inhabit, contain extensive pans that retain water during the dry season (May-September). During these periods of low water availability, the *Jo/'hoansi* are less mobile residentially and perform long stays next to these water sources (Yellen 1976). They prefer to make long logistical trips (~10 km) outward from the camp sites to collect other resources. Similarly, groups of Aboriginal Australians are hesitant to abandon their water resources and instead expand their foraging range up to 15 km (Cane 1987; Gould 1969). Water-tethered foragers tend to retain some aspects of both residential and logistical mobility, as they are found on Binford's (1980) spectrum: they move camp to be near a resource, but undertake great individual foraging excursions. Since they are temporarily restricted to a specific location, they must forage outward from camp and extend their foraging radius. It should be noted that in contrast, the *G/wi* of the central Kalahari Desert in Botswana where there are no pans, exhibit greater residential mobility during their dry season, moving camp fairly often (Silberbauer 1981a). They depend largely on *tsama* melons and rumens of game animals for primary sustenance and only forage up to 5 km per day (Silberbauer 1972, 1981b; Tanaka 1980). The *Jo/'hoansi* and *G/wi* demonstrate that there are several mobility strategies that can be adopted to survive in water-stressed environments.

3.2.3 Procurement ranges

Once the provenance of an artifact is established, the distance that the artifact has moved from source to site can be calculated (Andrefsky 2009). However, this distance is typically related

in a linear or an "as the crow flies" manner, rather than the actual route traversed. This measure does not necessarily reflect the full scale that it may have been moved across the landscape (Kuhn 1992, 1995; Potts 1991). Despite this obvious pitfall, archaeologists continue to describe procurement in terms of such distances (or ranges), namely making a distinction between local and non-local (Odell 2000), with the latter being further characterized by regional, long, and extreme distances (e.g., Biró 2009; Graf & Goebel 2009). The specific rubric used to equate these distances with a range of procurement is rarely specified and often intuitively assumed.

Local procurement is the most commonly identified range of procurement and its distance essentially corresponds to that of the general foraging radius in central place foraging models. These models describe how humans (and other animals) forage outward from a camp or home base (or den, nest, etc.) to provision themselves before returning (Binford 1980; Orians & Pearson 1979). In his study of the *Nunamiut* of Alaska, Binford (1978, 1982) noticed that the majority of foraging was conducted within a certain distance of the camp, which he termed the *foraging radius*. This distance corresponded to approximately 9 km (6 miles) and was described as the area searched and exploited by foragers who can depart and return within a single day. Others (e.g., Ekshtain et al. 2014, 2016) have described this area as the daily exploitation territory (DET). Herein lies a large issue for archaeologists—not all the sites that contain tools are camps or home bases, nor is it often known where the camp is located. Instead, many sites represent butchering, ritual, or other task-specific locales. A distance from source to these locations of deposition may still be established, but how does this movement of material fit within the idea of a foraging radius? This dilemma is still unresolved.

Depending on the terrain and resource distribution, travel could extend to a much further distance, though additional ethnoarchaeological studies suggest that the upper time limit for daily pedestrian one-way foraging from a site is approximately two hours or 5-10 km for groups targeting vegetation and slightly higher for hunting parties (Hill & Hawkes 1983; Hitchcock 1982; Lee 1979; Vickers 1989). In fact, most predictive models also indicate that, based on caloric return rates, the effective foraging radius (for food resources) is approximately 5-7 km (Kelly 2013). For example, *Nukak* adults make roundtrips that average 8.4 km (Politis 2006) and *Pume* travel 11.4 km when hunting and 1.6 km when gathering (Greaves 2006). *Hadza* women walk an average of

5.5 km and *Hadza* men 8.3 km while foraging (Marlowe 2010). Similarly, GPS-assisted studies of 1431 documented hunting trips by *Hadza* foragers indicated that 98% were <10km (Raichlen et al. 2014).

Based on these observations, distances between 5-12 km from camp to source are typically regarded as local. While these data on modern human groups may provide an initial rubric, Kuhn (1992) cautions against assuming that Paleolithic hominins were subject to the exact constraints on mobility; they may have ranged farther or nearer. The variation in time and distance is also important to consider, as travel is not always undertaken in a direct route or across uniform terrain (Wilson 2007b). For instance, 10 km through undulating terrain or snow requires more time to traverse than the same distance through level grasslands. The discovery of local procurement is often dismissed as unimportant under the assumption that 5-10 km is not a substantial distance. However, such artifacts were carried on the individual and most likely not on a direct route to where they were finally deposited, ultimately increasing their distance moved. Similarly, the distance of a source from the camp is only one of two legs of travel. Therefore, artifacts that originate from a source 7 km away from the camp mean the foragers travelled (at minimum) 14 km.

Non-local procurement is less categorized than local, as the terms *regional*, *supra-regional*, *long*, and *extreme* are often used and subsequently conflated or used synonymously (Dobosi 2009; Kandel et al. 2016). The only agreed parameter seems to be that *non-local* procurement occurs outside the local range. There is also no clear duration over which categories of non-local procurement might occur (Cole 2009). For example, Binford (1982) describes an area beyond the foraging radius as the *logistical radius* (related to logical mobility), which is exploited by task groups who remain away from the camp at least 1 night before returning with provisions. Perhaps the logistical radius may correspond to a *regional* range, but there is no distance provided. A notable rubric is provided by Kandel et al. (2016) which describes local (0-5 km), regional (6-20 km), and supra-regional (21-100 km) procurement ranges for hominins of the Middle Stone Age of southern Africa. These ranges may also be culture- or species-specific (Dobosi 2009), as what may be long distance for *Homo habilis* (e.g., >10 km) may still fall under local for *Homo sapiens*. The fact that it is often unknown which species manufactured the lithic assemblages under

investigation further complicates this matter. Furthermore, it is not always clear whether the acquisition of raw material or finished artifacts outside the foraging radius (or DET) occurs through direct or indirect procurement (see below). There is no specified distance for how far foragers will intentionally venture for raw materials through direct procurement. In regions that contain abundant local lithic raw material, a significant quantity of lithics obtained from outside the foraging radius (e.g., >10 km away) would not be expected in the assemblage. Non-local mobility may then be limited if resources (lithic and otherwise) are sufficient within that area. In summation, the discussion of non-local procurement is hindered by the inconsistent terminology for ranges of procurement used in the literature. While the distances (km) themselves will offer comparisons, other factors (e.g., terrain, availability, species) suggest that more work is required to elucidate the relationship between them and range terminology.

3.2.4 Embedded procurement

Interest in the paleoeconomy of hunter-gatherers and the manner in which they partition energy to various activities led to the observation of embedded procurement strategies (Binford 1978, 1979). These were initially documented among the *Nunamiut* of Alaska by Binford (1979: 259), who noted that lithic raw materials were procured "incidentally to the execution of basic subsistence tasks". Procurement was not conducted through pre-planned trips solely to obtain lithic material, but was flexible and scheduled around the execution of other activities and outings, such as fishing and hunting (Binford 1978, 1979). These activities may be deemed more essential for subsistence, but when unsuccessful, lithics could still be procured at a cost that was not referable to the distance between source and site, as this distance was already travelled for the other task(s). However, there is cost in the extra time to manufacture tools (at the source) and the additional weight to transport. Lithic sources are stationary and visits to them are simpler to organize in comparison to mobile resources, such as prey or even seasonal vegetative patches, which are less predictable (Goodyear 1979; Hovers 2009). Procuring mobile resources requires constant modification in mobility and scheduling on the part of foragers in order to be successful (Andrefsky 2009). Mobile resources are often a higher priority for modern hunter-gatherers than stationary resources and lithic procurement, a technological endeavor, becomes *embedded* in the

acquisition of the former (Binford 1982; Lee 1979; Meltzer 1984, 1989; O'Connell & Hawkes 1981). It is important to note that embedded procurement may also be encounter-based or opportunistic, rather than deliberate and is not without significant effort (Bamforth 1990). Embedded procurement is arguably most convenient (and plausible) when there is a high availability of raw material, thereby allowing a surplus to be obtained or provisioning to be maintained in the anticipation of future needs (Binford 1979; Blades 2001).

3.2.5 Direct procurement

Direct procurement occurs through an organized excursion with the express purpose of outfitting foragers with raw material from dedicated extraction forays (Blades 2001). These sources are typically within the larger territory that the foragers control or frequently explore. Foragers will repeatedly visit a known quarrying site, as is often indicated by a high volume of debitage and manufacture implements at the site (Barkai et al. 2006). Such expeditions are often assumed to follow minimal cost strategies, where the reduction will occur at the source and finished implements will be transported back to the site, thereby eliminating excess weight during travel.

For the *Nunamiut* of Alaska who routinely engaged in embedded procurement, Binford (1979: 259) stressed that "…only when things have gone wrong, does one go out into the environment for the express and exclusive purpose of obtaining raw material for tools". However, this observation does not hold for all societies, as further ethnoarchaeological work led to the documentation of direct procurement among Aboriginal Australians. For example, Binford & O'Connell (1984) accompanied several *Alyawara* men on an expedition to procure raw material. Although the trip was requested by the aforementioned authors, it did represent an outing with a specific aim in mind: the manufacture of stone tools through intentional raw material procurement. Further supporting evidence for direct procurement comes from Gould and Saggers (1985), who observed that the movement of Aboriginal Australians of the Western Desert is often strictly from the camp to quarry and back. In this scenario, lithic sources assume a secondary or tertiary priority, as the camps are situated near other important resources, such as water or edible vegetation.

3.2.6 Indirect procurement

Indirect procurement, or exchange, is the transfer of lithic raw materials or finished tools from one group to another. These transfers also involve the movement of lithics from sources in the territory of one group into the territory of another group, typically over long distances. Therefore, indirect procurement is often inferred by the presence of raw materials in the lithic assemblage that are deemed "non-local" or "exotic" (Blades 2001; Glascock 2002; Gould & Saggers 1985). This *exotic stone hypothesis* was largely promoted by Gould (1978) and colleagues (e.g., Gould & Saggers 1985), who noticed that a significant portion of the adze assemblage at Puntutjarpa Rockshelter, Australia, was manufactured from inferior chert located over 40 km away. Since better quality material was available at closer distances, it was interpreted that the Indigenous Australians had obtained these tools through long-distance exchange networks with other groups (Gould & Saggers 1985). Indirect procurement is largely identified by complete tools in the assemblage that have been moved over long distances, with "long" being subjective. The quality of material does not necessarily play a role in the identification of indirect procurement, as high- and low-quality materials can be exchanged.

Indirect procurement holds significant implications for survival, as social networks can operate to mitigate environmental stress (Apicella et al. 2012; Draper 1978). Groups of hunter-gatherers engage in mutually supportive exchange networks in order to acquire resources during times of local scarcity. For mobile hunter-gatherer groups, food storage is largely untenable, so the "stored surplus" is found as resources controlled by distant groups in the bush. For example, the *Hadza* maintain an on-going complex exchange system based on honey, a significant and valued source of nutrition (Marlowe 2010). Here the scale of cooperation between groups is based on several proximities, including kinship and geographic distance (Marlowe 2010). Exchange is also identified among other groups, such as the *Jo/'hoansi* where a unique system, termed *hxaro* exchange, involves a delayed reciprocity for resources (Lee 1979; Wiessner 1977, 2002). In this case, the *Jo/'hoansi* have developed a system for sharing and recirculating commodities, at staggered times, as a form of "insurance" against local scarcity and environmental variability (Draper 1978; Wiessner 1977). This collective pooling of risk among groups is especially important over long distances, as more distant groups are less likely than neighboring groups to

encounter the same stress (Kuhn & Stiner 2001; Kelly 2013; Wiessner 1982). Systems of boundary defense can certainly be established during periods of stress, as access for affected groups is granted via permission on the basis of such networks, even among non-kin relations (Cashdan 1983, 1985; Heinz 1972; Peterson 1975). These exchange networks provide more than food resources, as they allow the exchange of tools, ideas, and mate partners, ultimately reinforcing an obligation for mutual support when necessary (Wiessner 1982).

Artifacts that have been transported over great distances (e.g., >25 km for Neanderthals and *Homo sapiens*) are often regarded as more valuable than those of local origin, due to the effort expended in their retention (Binford 1979; Valde-Nowak 2009). Value has also been associated with the aesthetic nature of the raw material (Assaf 2018). Archaeologists tend to apply (projected?) value to aesthetic materials as well, such as the pink quartzite handaxe, nicknamed "Excalibur", found at Sima de los Huesos (~600 kya), Spain among numerous *Homo heidelbergensis* fossils, which may be the first grave good (Arsuaga et al. 2007; Carbonell et al. 2003). Value can assume several forms besides function, including symbolism, prestige, or ritual. However, similar to direct procurement, the ranges that would classify raw materials as exotic or non-local are not clear. While great distances may be assumed as indicators of exchange (Glascock 2002), it is possible to conflate this movement of artifacts with greater hunter-gatherer mobility within a large foraging territory. This observation was made by Binford (1979) who emphasized that Gould (1978) may have underestimated the scale of mobility of the Aboriginal Australians. Binford (1979) maintained that if greater routine foraging territories are assumed, then embedded procurement at greater distances requires no extra effort expended, ultimately diminishing the perceived value of the artifact. In this case, it can be emphasized that increasing mobility during periods of resource shortages is a common risk-mitigating strategy among hunter-gatherers (Kuhn & Stiner 2001).

3.3 Lithic procurement in the Levant during the Lower-Middle Paleolithic

The lithic procurement strategies in the Levant during the Lower-Middle Paleolithic exhibit considerable variety. Their reconstruction has been partly stymied by the dismissal of their significance and the presumed difficulty in establishing provenance, both due to the perceived

abundance of chert in the Levant. As a result, the procurement strategies for many lithic assemblages from previously surveyed and excavated Paleolithic sites remain unexplored or poorly discussed due to the assumption that they simply occur within a local range. However, recent research has indicated that lithic procurement strategies take many forms in the Levant and are more complex than previously assumed (e.g., Ahmad & Shea 2009; Barkai et al. 2006; Ekshtain et al. 2014, 2016; Finkel et al. 2016, 2019; Wilson et al. 2016; Verri et al. 2004, 2005). The following sections provide a brief discussion of selected studies to demonstrate the variety of lithic procurement strategies that occur in this specific part of the globe.

3.3.1 Geology of the Levant

A reconstruction of lithic procurement begins with a consideration of the geology of the Levant. The most prominent geological feature of the Levant is the Harrat Ash-Shaam, an extensive intra-continental basalt plateau, which covers a large (~45,000 km^2) extent of Lebanon, Syria, and Jordan (Al-Malabeh 1994; Cordova 2007; Ilani et al. 2001). Despite the periodic production of igneous rock by the Dead Sea Rift Valley and associated volcanoes, a large portion of the exposed geology of the Levant is sedimentary rock. These sedimentary formations are beds of chalk, limestone, and occasionally chert, though chert also occurs in nodular and brecciated form as well (Flexer 1971; Kolodny 1969; Kolodny et al. 2005; Lewy 2010). The distribution of chert is not uniform across the Levant, as nodular chert and secondary sources dominate in the northern regions of Israel (Ekshtain et al. 2016; Flexer 1971; Finkel et al. 2019). There is considerably more exposure of beds in the *Shephelah* (Hebrew – rolling hills) and Negev regions of Israel and the Central Plateau of Jordan (Momani 2005; Steinitz 1970, 1977), though this exposure wanes among the sandstone beds in the southern desert of Jordan. Chert and, to a considerably lesser extent, basalt appear to be the only materials from which stone tools are made during the Paleolithic, as other suitable materials, such as obsidian or silcrete, are not found within the Levant (Bar-Yosef 1991). Collectively, these cherts are considered to be the raw material sources for groups and societies from multiple successive periods, spanning the Paleolithic to Iron Age (Delage 2007a, 2007b; Rosen 1996, 1997; Shea 2013).

3.3.2 Quarrying activity and landscape familiarity

Many hillsides in the chert-rich region of Galilee contains extensive outcrop exposures. These (e.g., Nahal Dishon, Sede Ilan, Sasa) served as long-term raw material sources during the Lower-Middle Paleolithic (Barkai & Gopher 2009; Barkai et al. 2006; Gopher & Barkai 2006, 2011, 2014; Finkel et al. 2016), leading to their reference as extraction and reduction or "E&R" complexes (Finkel et al. 2019. An abundance of bifaces, characteristic of the Acheulean industry, and others tools belonging to the Mousterian industry were discovered among the manufacture debitage and the detritus of the tailing piles at these locales. The high number of tailing piles and the large-scale extraction at quarries attest to repeated exploitation and an industrial nature of these sites (Barkai & Gopher 2009; Barkai et al. 2002, 2006; Gopher & Barkai 2014). Barkai and Gopher (2009; Gopher & Barkai 2014) describe a systematic organization to these sites, as backfill piles were arranged in between outcrops and outcrops were kept relatively clear of waste. Because of this anthropogenic modification to the natural landscape, it was tentatively posited that this was performed as a form of resource management or to mitigate an ecological imprint (Barkai & Gopher 2009; Barkai et al. 2006; Gopher & Barkai 2011, 2014).

It is not known which group(s) exploited these E&R complexes. The provenance record is too incomplete to determine whether certain groups of Levantine hominins controlled their own quarries or if territorial boundaries were established between groups. A trek towards the chert outcrops on the hillsides in the Galilee region brings Mt. Tabor into view as an imposing silhouette in the distant background. Due to the imposing nature of Mt. Tabor on the landscape, Barkai & Gopher (2009) propose that hominins may have used this natural protrusion as a topographic beacon or territorial marker by which to locate these sources. A utilization of various landmarks for guidance and the large-scale quarry maintenance suggest hominins possessed a high degree of familiarity with the regional landscape (Barkai & Gopher 2009; Barkai et al. 2002, 2006).

3.3.3 Deep mining

Several unique studies on the Acheulo-Yabrudian lithic assemblages of Qesem and Tabun caves revealed that a significant number of tools were procured at depths of up to 2 m (Boaretto et al. 2009; Verri et al. 2004, 2005). This investigation was performed through a geochemical

analysis that measured the content of ^{10}Be isotopes in the sampled stone tools. The amount of ^{10}Be isotopes in lithic material varies with the amount of exposure to cosmic rays (sunlight) – there is a direct correlation between the amount of ^{10}Be isotopes and exposure (Verri et al. 2004, 2005). Stone tools that were obtained through deep mining were expected to have significantly lower concentrations of ^{10}Be isotopes in their composition due to less exposure to cosmic rays.

At Tabun Cave, the results indicate that the sampled lithics from Lower Bed XIV and Layer G (Acheulean) were extracted/collected on the surface and those from Layer E (Acheulo-Yabrudian) were mined (Verri et al. 2004, 2005). Throughout the sequence at Qesem Cave, both surface extraction/collection and deep mining were practiced, but mining was a smaller component of procurement (Boaretto et al. 2009; Verri et al. 2004, 2005). The quality of chert from Qesem Cave is considered to be higher than from Tabun Cave (Verri et al. 2005), possibly alleviating the demand to expend a great effort mining for the occupants of Qesem Cave.

Although the sample sizes were very small, deep mining, the extraction of material from depths greater than 2 m, was practiced as early as the late Lower Paleolithic. Deep mining during the Paleolithic is not limited to the Levant and has been identified in other regions, such as Egypt (Vermeersch et al. 1990, 1995) and India (Blackwell et al. 2001). This activity may indicate a preference for certain materials and a well-planned organization of lithic manufacture, despite the additional difficulties associated with mining.

3.3.4 Foraging ranges and strategies

The provenance of stone tools provides a measure of foraging range and distance the material has moved. Most Paleolithic sites have been discovered in the Galilee-Mt. Carmel regions where primary and secondary chert sources of the Araqan, Bina, and Maresha formations are exposed (Ekshtain et al. 2014; Finkel et al. 2016). A dominant factor in determining distance is raw material quality, as there is often a distinct preference for high quality material (Gopher et al. 2005; Shimelmitz et al. 2011). There is an abundance of both high- and low-quality chert in the Levant, but very few tools are manufactured from inferior materials.

There is a predominant exploitation of sources within 5-10 km (classic foraging radius or DET) of many sites within the Levant (e.g., Qesem, Tabun), which may be regarded as local. The

same sites often have a low frequency of material procured from regional distances (10-25 km). The availability of high-quality chert within a local range often leads archaeologists to assume embedded procurement was a default strategy. This assumption can be supported by provenance investigations. For example, the occurrence of embedded procurement was suggested at Amud Cave, based on the results of a provenance study by Ekshtain et al. (2016). A sample of stone tools was found to be geochemically consistent with Eocene sources of varying distances within the DET of the site (Ekshtain et al. 2016), although these sources exhibit a similar profile.

The rockshelter site of Tor Faraj is a notable exception to the prevailing pattern of local procurement, as it is situated among predominantly sandstone formations with a paucity of knappable chert (Henry 2003). The occupants procured the majority of raw material from a distinct chert source (22 km) on the Ma'an plateau (Henry 1995a, 1995b, 2003). The high proportion of cortical material on tools and primary reduction elements at Tor Faraj indicates that material was also brought to the site as nodules (Henry 2003). While this distance would usually fall under the classification of regional by most rubrics, Ekshtain et al. (2016) described this procurement as local, given that the dominant chert source exploited is also the most available.

The E&R complexes in the Nahal Dishon basin were initially connected to nearby local Acheulean sites situated next to seasonal sources of water, such as Yiron and Baram (Finkel et al. 2016). This hypothesis was confirmed through a provenance study conducted by Finkel et al. (2019) that examined the attributes and geochemistry of several outcrops and lithics from the two sites. Artifacts from a more distant (~20 km) Paleolithic site, Ma'ayan Barukh/Hamara, were also included in the study. These also maintained similar profiles with the sources in the Nahal Dishon basin, indicating movement over regional distances (Finkel et al. 2019). The scale of quarrying activity and manufacture around the E&R complexes of Nahal Dishon led to the proposal of long-term exploitation and direct procurement by the occupants of the three sites (Finkel et al. 2019).

Other E&R complexes (e.g., Mt. Pua, Sede Ilan, Sasa) have not been connected to specific residence sites in the Levant. As a result, there is no clear indication how far their lithics were eventually moved. Similarly, Ar-Rasfa and WZM-2 are smaller scale reduction locales located next to chert sources, but it is not known to which site(s) the lithics were taken or from which

site(s) the hominins came (Ahmad & Shea 2009; Bisson et al. 2007, 2014). A greater exploration of provenance may enable connections between the home bases, activity sites, and sources.

It should be noted that there is no significant movement of material that can be categorized as long-distance, at least based on a common rubric (see Section 3.2.3). This observation lies in contrast to hominin groups of the Middle Paleolithic of Europe where studies report routine movement from 50-100 km (e.g., Féblot-Augustins 2009; Turq et al. 2013). This lack of detected movement of lithics at long-distances has stymied the identification of indirect procurement. Future results from Amud Cave could overturn this pattern, where some procurement is suspected at 50-60 km, although its investigators are skeptical this would correspond to exchange (Ekshtain et al. 2016). Perhaps the means by which exchange is typically identified is not suitable or applicable in the Levant.

3.3.5 Provisioning

As noted previously, procurement is performed for provisioning. In the Levant, provisioning is performed for both the individual and the place. For example, the Middle Paleolithic open-air sites of Ar-Rasfa and WZM-2 are regarded as knapping locales where the individual was provisioned with mobile toolkits (Ahmad and Shea 2009; Bisson et al. 2014; Shea and Crawford 2003). This strategy is interpreted from the high number of reduced cores and debitage relative to finished tools; the latter were likely removed. These sites are located near chert outcrops and create a suitable manufacture locale for new gear. The provisioning of the individual with finished tools allowed them to engage their technology on demand.

Provisioning of place is largely associated with home bases, most notably cave (e.g., Tabun, Qafzeh, Qesem) and rockshelter (e.g., Tor Faraj) sites in the Levant, where long-term residence occurred (Druck 2004; Gisis and Ronen 2006; Gopher et al. 2005; Henry 2003; Hovers 2009). Extensive evidence of anticipated manufacture (e.g., blanks, cores) and an abundance of finished tools, ready for use, have been discovered. Open-air sites within the Levant are also of interest, as their lithic assemblages often contain an abundance of finished tools. This abundance is typically viewed as more than what is necessary to accomplish the associated tasks which characterize the site function, namely butchering or foraging pit-stops. For example, ‘Ein Qashish

is notable for blending both provisioning strategies. Individuals provisioned with Levallois points from local-regional sources visited the site, while blanks and cores provisioned the site with local material (Ekshtain et al. 2014).

3.4 Conclusion

The reconstruction of procurement strategies entails investigation into the decisions associated with scheduling, preferences, locations, order, and routes. While provenance can establish the occurrence of raw material exploitation and the distance of artifact movement, paleoeconomic features and ethnoarchaeological models can provide insight into the nature of these activities. It is likely that the tools in a single lithic assemblage represent several forms of procurement (Blades 2001; Ekshtain et al. 2014), such as both direct and indirect strategies. The reconstruction of lithic procurement strategies offers insight into how hominin groups lived in various environments, including the Levant. Such investigation is applicable to Shishan Marsh 1, Jordan.

CHAPTER 4: CONTEXT OF RESEARCH

Situated at the intersection of three continents, the Levant provides variable biogeographical environments in which hominins could dwell. These range from coastal plains on the edge of the Mediterranean Sea to rocky highlands and interior deserts. Archaeological research in the Azraq Basin and GAOA has revealed a rich record of hominin occupation during the Paleolithic. The archaeological site of Shishan Marsh 1 is situated within the GAOA and provides the material remains that are the focus of this study. The following sections discuss the paleoanthropological chronology of the Levant and the geohydrological and archaeological setting of the GAOA, as well as SM1.

4.1 Hominin occupation of the Levant

The fossil record of the Levant is patchy and does not always provide secure evidence of occupation by species during the late Middle and early Upper Pleistocene (Table 4.1). Several articulated individuals and isolated remains cast some light on which species were present at certain times. The majority of fossils originate from cave sites where better preservation is more likely to occur. In addition, there are multiple open-air sites that are primarily characterized by lithic assemblages, some of which also contain incomplete specimens with uncertain taxonomic assignments. The following sections reflect on the evidence for hominin occupation of the Levant during the Middle-Upper Pleistocene through a review of the fossil record and associations with lithic industries.

Table 4.1: Chronological list of important sites within the Levant and beyond that contain hominin remains.

Age	Site	Country	Hominin remains	Species attribution	Associated lithic industry	Key references
~1.8 mya	Dmanisi	Georgia	Several crania	*Homo erectus*	Oldowan	Gabunia & Vekua 1995; Gabunia et al. 2000
1.5-1.4 mya	'Ubeidiya	Israel	Cranial fragments and teeth	*Homo erectus*	Oldowan; Lower Acheulean	Bar-Yosef & Goren-Inbar 1993; Belmaker et al. 2002; Tchernov 1988; Tobias 1966
~780 kya	Gesher Benot Ya'aqov	Israel	Femora	*Homo erectus*	Lower-Middle Acheulean	Geraads & Tchernov 1983; Goren-Inbar & Saragusti 1996; Goren-Inbar et al. 2000; Saragusti & Goren-Inbar 2001; Stekelis 1960
~500 kya	Nadaouiyeh	Syria	Parietal fragment	*Homo erectus*	Upper Acheulean	Jagher 2016; Jagher et al. 1997; Schmid 2015
~500 kya	Kocabas	Turkey	Cranium	*Homo erectus*		Kappelman et al. 2008
400-200 kya	Qesem Cave	Israel	Teeth	"Pre-Neanderthal"	Acheulo-Yabrudian	Hershkovitz et al. 2011a, 2011b
~315 kya	Jebel Irhoud	Morocco	Several crania	*Homo sapiens*	Mousterian	Hublin et al. 2017; Richter et al. 2017
250-150 kya	Mugharat el-Zuttiyeh	Israel	Cranio-facial fragment	"Pre-Neanderthal"	Acheulo-Yabrudian	Bar-Yosef & Vandermeersch 1993; Keith 1927; Schwarcz 1980; Zeitoun 2001
~210 kya	Apidima Cave	Greece	Cranium	*Homo sapiens*		Harvati et al. 2019; Tourloukis & Harvati 2018
~195 kya	Omo River	Ethiopia	Cranium	*Homo sapiens*		McDougall et al. 2005, 2008
~180 kya	Misliya Cave	Israel	Mandible	*Homo sapiens*		Hershkovitz et al. 2018
120-80 kya	Skhul Cave	Israel	Crania and post-cranial fragments	*Homo sapiens*	Mousterian	Grun et al. 2005; McCown & Keith 1939; McDermott et al. 1993; Stringer et al. 1989

120-80 kya	Qafzeh Cave	Israel	Crania and post-cranial fragments	*Homo sapiens*	Mousterian	Boutié 1989; Schwarcz et al. 1988; Valladas et al. 1988; Vandermeersch 1981
100-50 kya	Tabun Cave	Israel	Almost complete skeleton (C1) Mandible (C2)	Neanderthal	Mousterian	Bar-Yosef & Callendar 1999; Grun & Stringer 2000; McCown & Keith 1939; McDermott et al. 1993; Mercier & Valladas 2003; Stefan & Trinkaus 1998
70-60 kya	Kebara Cave	Israel	Two nearly complete individuals	Neanderthal	Later Levantine Mousterian	Bar-Yosef, O., & Vandermeersch, B. 1991; Valladas et al. 1987
70-60 kya	‘Ein Qashish	Israel	Various fragments	Neanderthal	Mousterian	Ekshtain et al. 2019; Malinksy-Buller et al. 2014
70-50 kya	Dederiyeh Cave	Syria	Multiple individuals	Neanderthal	Later Levantine Mousterian	Akazawa & Muhesen 2003; Akazawa et al. 1999
70-40 kya	Shanidar Cave	Iraq	Multiple individuals	Neanderthal	Mousterian	Solecki 1963; Stewart 1961, 1963; Trinkaus 1983
60-50 kya	Amud Cave	Israel	Multiple individuals	Neanderthal	Later Levantine Mousterian	Hovers et al. 1995; Rak et al. 1994

4.1.1 Homo erectus

The earliest fossil evidence of hominins outside of Africa comes from Dmanisi Cave, Georgia (Gabunia et al. 2000). This site produced five crania of *Homo erectus* (or *Homo ergaster*, *Homo georgicus*) that were discovered among Oldowan tools dating to ~1.8 mya (Gabunia & Vekua 1995; de Lumley et al. 2005; Rightmire 2017; Vekua et al. 2002). Although dispersals passed through the Near East, a *Homo erectus* presence in the Levant is not demonstrated by fossils until ~1.4 mya at 'Ubeidiya, Israel where several cranial fragments and teeth were discovered (Belmaker et al. 2002; Tchernov 1988; Tobias 1966). However, it should be noted that their classification as *Homo erectus* has been approached with skepticism, as they exhibit some affinities with *Homo ergaster* (Belmaker et al. 2002). These remains were discovered among a mixture of both Oldowan and Acheulean tools, with the former dominating the assemblage (Bar-Yosef & Goren-Inbar 1993; Ronen 2006).

By 1 mya, remnants of the Oldowan industry give way to large caches of Acheulean tools over the next few hundred millennia of the Lower Paleolithic (Bar-Yosef 2006; Shea 2013). Acheulean material culture is most recognized by the bifacially worked stone tools and/or elongated core tools, most notably large cutting tools (LCTs), such as handaxes, knives, and cleavers (Goren-Inbar & Sharon 2006a, 2006b; Isaac 1977; Shea 2013). The handaxe is considered a defining and aesthetic tool of the Acheulean, often appearing in the distinctive "tear-drop" form, though some regional and diachronic variations are evident (Debénath & Dibble 1994; Norton et al. 2006)

Acheulean tools continue to appear at both open-air and cave sites during the Middle Pleistocene, some of which are associated with *Homo erectus* specimens. A foremost example is Gesher Benot Ya'aqov, Israel at ~780 kya, where fragmented remains of femora were uncovered (Geraads & Tchernov 1983; Goren-Inbar & Saragusti 1996; Goren-Inbar et al. 2000; Saragusti & Goren-Inbar 2001; Stekelis 1960). The most recent date for a secure *Homo erectus* presence in the Levant is approximately 500 kya at Nadaouiyeh, Syria (Jagher 2016; Schmid 2015). Here a large fragment of a parietal bone was discovered among a cache of Acheulean tools (Jagher et al. 1997; Jagher 2016; Schmid 2015). Similarly, the most recent fossil evidence for *Homo erectus* in the

Near East also dates to ~500 kya, where a cranium originates from Kocabas, Turkey (Kappelman et al. 2008; Ozkul et al. 2004).

Homo erectus is not associated with Mousterian technology (Shea & Brooks 2000), as this species did not develop or adopt it or were out-competed or enveloped by species associated with this more complex technology. Even in southeast Asia, where *Homo erectus* survived the most recently, the Mousterian industry does not appear in association with them. The latest dates of their existence have long been controversial and technique dependent, ranging from 500-35 kya within the Solo basin, Indonesia (Barstra 1987; Indriati et al. 2011; Swisher et al. 1996; Yokoyama et al. 2008). The implication of these dates is that *Homo erectus* was a contemporary species to anatomically modern humans (AMH), in some regions, perhaps as groups of the latter species migrated into Australia (Baab 2015; Swisher et al. 1996). Furthermore, it could also suggest that groups of *Homo erectus* might have survived longer in other regions, possibly even the Levant.

4.1.2 "Pre-Neanderthals"

Around 400 kya, the Acheulo-Yabrudian techno-complex developed as a Levantine variation of the Acheulean industry (Garrod 1956; Rust 1950; Rink et al. 2004). It consists largely of bifaces, Quina scrapers, laminar blades, and blade tools (Copeland 2000; Malinksy-Buller 2016). Where they occur at the same site, the Acheulo-Yabrudian is found beneath Mousterian layers with transitions as recent as 200 kya (Barkai et al. 2003; Bar-Yosef 1994; Gopher et al. 2010). Archaeologists are divided over whether the Acheulo-Yabrudian techno-complex is best related to the initial phase of the Middle Paleolithic rather than the final phase of the Lower Paleolithic, due to its prolonged utilization well into the early Middle Paleolithic (Bar-Yosef 1994; Malinsky-Buller 2016). Further complications arise from the presence of mixed assemblages, comprised of Mousterian and Acheulean industries, throughout the Levant (Barkai et al. 2006; Barkai & Gopher 2009; Gopher & Barkai 2011).

The manufacturers of the Acheulo-Yabrudian techno-complex and, by extension, the occupants of the Levant from 400-200 kya are not clear. There are very few contemporary fossils associated with this regional industry. These are several teeth from Qesem Cave, Israel (Hershkovitz et al. 2011a; Hershkovitz et al. 2011b) and a cranio-facial fragment from Mugharat

el-Zuttiyeh, Israel (Bar-Yosef & Vandermeersch 1993; Keith 1927; Schwarcz 1980; Zeitoun 2001). Both the Qesem and Zuttiyeh remains have been subject to extensive comparisons of geometric morphology with other hominin species (e.g., Fornai et al. 2016; Freidline et al. 2012: Zeitoun 2001), but with inconclusive results as to their appropriate classification. Close affinities are drawn to *Homo erectus*, *Homo heidelbergensis*, Neanderthals, and AMH. Although the provisional classification as "early" or "pre-" Neanderthals is emphasized, the tentative dating, poor preservation, and incompleteness of the remains have ultimately left their taxonomic classification unresolved.

4.1.3 Neanderthals and AMH

Within the Levant, the Middle Paleolithic is considered to commence around 250-220 kya with the first secure indications of Mousterian technology, an industry associated only with Neanderthals and AMH (Alvarez-Alonso 2014; Lindly 2005; Shea 2003a, 2003b). The chronology is constructed primarily from the long Middle Paleolithic stratigraphic sequence at Tabun Cave (Mercier & Valladas 2003; Porat et al. 2002; Schwarcz & Rink 1998). Despite the tentative support from neighboring sites, such as Hayonim and Qesem caves (Gopher et al. 2005, 2010; Mercier et al. 2007), the chronology remains somewhat muddled due to inconsistent results from multiple techniques.

The Mousterian industry is named after Le Moustier (~45 kya), France, the site at which it was first recognized, and serves as the type-site for this industry (Chase and Dibble 1987; Peyrony 1930). The Mousterian industry features the use of prepared-core technology, the Levallois technique, and discoidal flaking reduction (Debenath and Dibble 1994; Shea & Brooks 2000). More sophisticated tools, such as points and side scrapers, that are slender, but "heavy duty", appear (Shea 2013). Points were likely hafted to spears. Originally, Bordes (1961) identified over 60 types of tools and over 10 types of scrapers that he attributed to Neanderthal "ethnicities". However, a more meaningful interpretation by Dibble (1987) suggests the types are actually variations of the same tool type, which exhibit different degrees of curation (reduction intensity). In addition, handaxes, similar to those of the Acheulean industry, continue to be produced. However, handaxes found in Mousterian assemblages of the Levant are described as thinner, more

symmetrical, and with straighter borders (Hovers & Belfer-Cohen 2013). Since both Neanderthals and AMH have been discovered associated with Mousterian lithics, the attribution of either species to an isolated assemblage is difficult, if not impossible (Shea & Brooks 2000).

Although Neanderthals were well established in Europe around 400 kya, it is AMH that appears first in the Levantine fossil record. The chronological distribution of the two species represents an alternating pattern of occupation in the region (Shea 2003a, 2008). The oldest fossil evidence of AMH in the Levant comes from Misliya Cave, Israel at ~180 kya (Hershkovitz et al. 2018). At Skhul and Qafzeh caves in Israel, troves of AMH fossils were found among Mousterian lithics and date to 120-80 kya (Boutié 1989; McCown & Keith 1939; McDermott et al. 1993; Schwarcz et al. 1988; Stringer et al. 1989; Valladas et al. 1988; Vandermeersch 1981).

A Neanderthal presence in the Levant and wider Near East is first attested by a mandible (C2) and Neanderthal adult (C1) at Tabun Cave (Bar-Yosef & Callendar 1999; McCown & Keith 1939; Stefan & Trinkaus 1998). The dating of these remains has been obfuscated by their ambiguous stratigraphic position. These appear in Layer C (160-100 kya), but are likely an intrusive burial from Layer B above, which dates to approximately <100 kya (Grun & Stringer 2000; Mercier & Valladas 2003; McDermott et al 1993). More definitive evidence of Neanderthal occupation occurs shortly after the initial AMH occupation. For example, clear stratigraphic associations between Neanderthal remains and Mousterian artifacts are found at several sites in Israel, notably Kebara and Amud caves and ‘Ein Qashish, from 70-50 kya (Bar-Yosef & Vandermeersch 1991; Ekshtain et al. 2019; Malinksy-Buller et al. 2014; Valladas et al. 1987). In Syria, the nearly complete skeletons of two Neanderthal children and the partial remains of several other individuals were discovered at Dederiyeh Cave. The specimens are associated with Mousterian lithics and also date to 70-50 kya (Akazawa et al. 1999; Akazawa & Muhesen 2003). Lastly, the famous site of Shanidar Cave, Iraq yielded multiple Neanderthals individuals dating between 70-40 kya and more continue to be recovered (Solecki 1963; Stewart 1961, 1963; Trinkaus 1983). By approximately 50 kya, Neanderthals are absent from the Levant, which coincides with the movement of AMH into Europe.

4.2 Out-of-Africa dispersals

Recently discovered fossil evidence indicates not only did AMH appear much earlier than previously thought, but that several pulses of their migration reached Eurasia before ~55 kya (Groucutt et al. 2015; Petraglia et al. 2010; Stringer 2011). Currently, the earliest presence of AMH occurs in Africa. Fossil crania from Morocco indicate their appearance by ~315 kya (Hublin et al. 2017; Richter et al. 2017) and in East Africa along the Omo River, Ethiopia by ~195 kya (McDougall et al. 2005, 2008). A *Homo sapiens* cranium (Apidima 1) from Apidima Cave, Greece dates to ~210 kya and represents the oldest instance of our species outside of Africa (Harvati et al. 2019; Tourloukis & Harvati 2018). Additional fossil evidence from the Levant further indicates the occurrence of AMH at ~180 kya (Hershkovitz et al. 2018; also Section 4.1.3). A probable *Homo sapiens* fossil from Tongtianyan Cave, China and assorted stone tools at Madjedbebe rockshelter in northern Australia demonstrate the movement of AMH into east Asia and beyond by 65-60 kya years ago (Clarkson et al. 2015, 2017; Shen et al. 2002). Consequently, it is plausible that several AMH dispersals occurred between 300-50 kya, some which likely passed through the Levant.

4.2.1 Paleoclimatic cycles in the Near East

Dispersals out of Africa and into Eurasia are thought to have been facilitated by periods of favorable climate and environment, most notably humid conditions (Breeze et al. 2016; Frumkin et al. 2011; Jennings et al. 2011; Petraglia & Rose 2009). The general global trend of marine isotope stages (hereafter MIS) is that glacial episodes are cold and dry (arid), whereas interglacial episodes present warm and wet (humid) conditions (Figure 4.1). In general, the monsoons and Westerlies that operate in the Near East are linked to oscillations in global climate (glacial-interglacials), which, in turn, are driven by the orbital parameters of Milankovitch cycles.

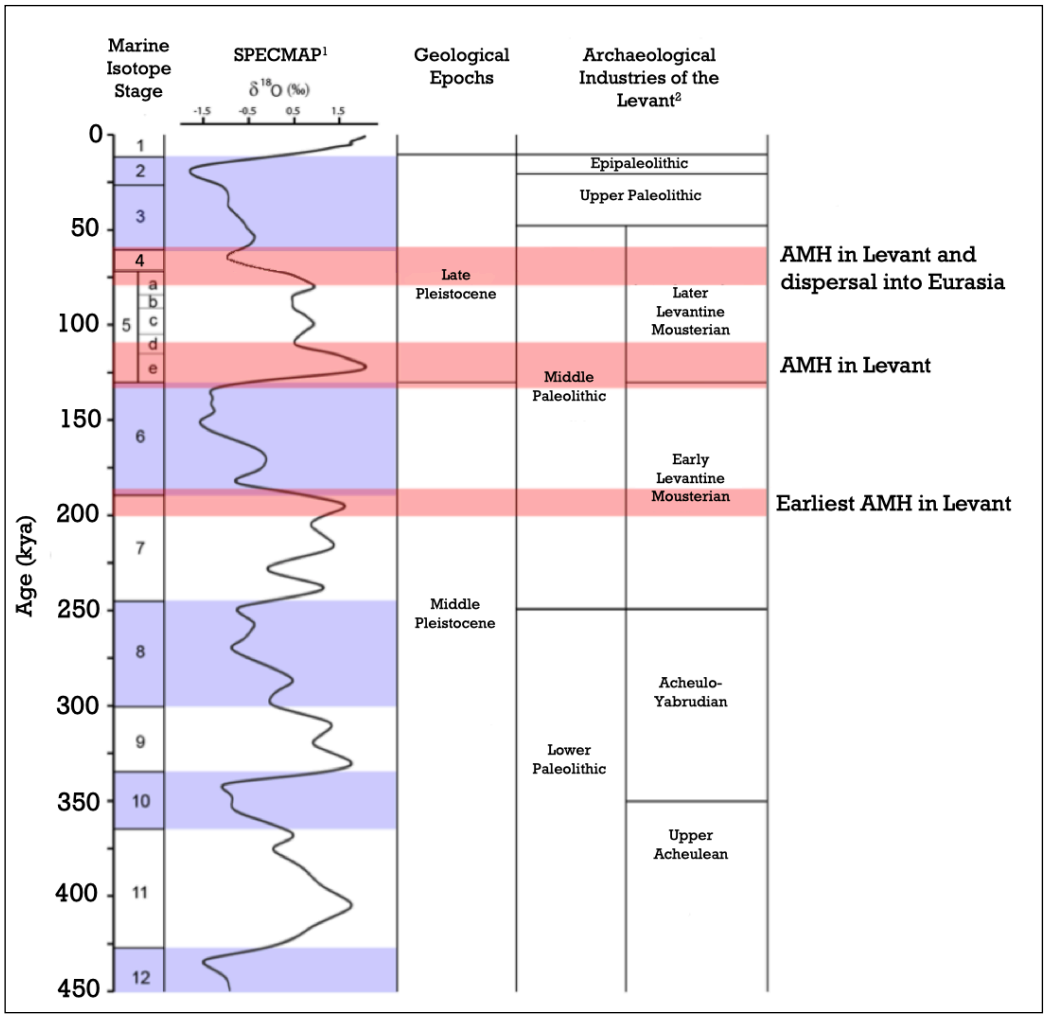


Figure 4.1: Marine isotope stages and associated archaeological events. Figure modified from Ames (2013: 21). Data from 1) Imbrie & McIntyre (2006) and 2) Shea (2008b) combined by Ames (2013).

In Arabia, the humidity and associated precipitation that causes the deserts to contract is controlled by the Southwest Indian Ocean Monsoon system and, to a lesser extent, the African summer monsoon (Kutzbach 1981; Kutzbach & Liu 1997; Trauth et al. 2003, 2009). The paleoclimatic records of southern Arabia largely correlate with the overall MIS trends. For much of Arabia, increased humidity from the incursions of monsoons is most evident during interglacial episodes, particularly MIS 9, 7, and 5e. During these periods, precipitation would cause paleolake levels to rise (Petraglia et al. 2011; Rosenberg et al. 2011, 2013; Matter et al. 2015), speleothem

growth (Burns et al. 1998; Fleitmann et al. 2003), and fluvial activity in the highlands (Blechschmidt et al., 2009; Parton et al., 2013, 2015). Glacial episodes, such as MIS 8 and 6, would see an increase in aridity and a reduction of precipitation, as the intensity and inland reach of monsoons decreased (Anton 1984; Parker 2009).

The paleoclimatic records of the Levant exhibit notable deviations from the overall MIS trends observed in Arabia. Their reconstruction is arguably more complex, as the Levant is located at the intersection of several inputs. Precipitation in the central and northern Levant is largely driven by mid-latitude processes, most notably the North Atlantic and Mediterranean Westerlies (Cooke et al. 1993; Gat & Magaritz 1980). Evidence from speleothem deposition and lake-stand levels indicate that glacial episodes, most notably MIS 6, were fairly wet (Frumkin et al. 2011; Torfstein et al. 2009). This trend is likely due to the southward migration of high-latitude climatic belts by high pressure systems over the continental glaciers of Eurasia (Frumkin et al. 2011; Horowitz 1987). Meanwhile, interglacials remained fairly dry, particularly MIS 7 and 5e, with very little speleothem deposition, particularly in the semi-arid and arid zones of the Negev (Enzel et al. 2008; Frumkin et al. 2011). This precipitation rarely fully penetrates into the Negev Desert in the south or over the central mountains along the Dead Sea Transform, leaving the rain shadow deserts of the eastern Levant without significant rainfall (Frumkin et al. 2011; Jennings et al. 2015). As a result, the Azraq Basin (see below), a region of the eastern Levant, is often left uninfluenced (directly) by the climatic forces of the Mediterranean and Arabia and retains a distinct regional climatic record.

4.2.2 Paleohydrological corridors of the Arabian Peninsula

A growing body of literature from the past two decades indicates that hominins likely moved through the Arabian Peninsula when a "mosaic of ecosystems and plentiful rivers, wetlands and lakes were present" (Petraglia et al. 2019: 675). The distribution of surface freshwater was likely a significant control upon the degree of movement of hominins, as the high temperatures of deserts compounds water loss and heat stress (Breeze et al. 2016; Finlayson 2013; Groucutt and Blinkhorn 2013). Dispersals had to follow routes containing available freshwater. These include the Red Sea coast (Stringer 2000), the Nile River to the Mediterranean Sea then through the Sinai

Peninsula (Van Peer 1998), and the Arabian Peninsula (Bailey et al. 2015; Breeze et al. 2016; Petraglia 2011; Petraglia & Alsharekh 2003; Petraglia & Rose 2009). Access into the Arabian Peninsula from Africa can be obtained at the Horn of Africa, across the Bab al-Mandab strait between modern Djibouti and Yemen (Petraglia 2003; Rose 2004). Currently, the strait is 32 km wide and interrupted by Perim Island (Derricourt 2005), though low sea levels during glacial episodes may have caused the width to shrink to 5 km (Flemming et al. 2003). Movement through the Arabian Peninsula can be further divided into the Red Sea coastal margin (Blue Arabia) and the inland paleolakes (Green Arabia). Blue and Green Arabia have taken the forefront of dispersal investigations within the last two decades, though the focus has largely been limited to the past 250,000 years (time frame of AMH). Several isolated sites have been identified and recovered along Blue Arabia, which demonstrate its utilization, but lacks clear indication of coastally-oriented groups (Bailey et al. 2015; Petraglia et al. 2019). Along Green Arabia, recent research has identified a series of ancient lake basins, typically denoted by large topographic depressions and paleoshorelines, that may have operated as palaeohydrological corridors (Breeze et al. 2016; Derricourt 2005). In this scenario, increased precipitation during wetter periods, typically interglacials, would cause the water levels in the basins to rise. The movement of hominins could occur along the security of the lake margins.

4.2.3 The Azraq corridor

The Azraq corridor is a potential paleohydrological corridor that connects the Arabian Peninsula to the Levant. This corridor comprises a sequence of (now dry) subcatchments that stretch from the Nefud Desert in northwest Arabia, through the Wadi Sirhan depression, and into the Azraq Basin in eastern Jordan (Figure 4.2). The subcatchments (SE-NW) include Al Qutb, Qa' Hazawa, Qurrayat, and finally the Azraq Basin. Increased precipitation during humid periods could cause the basins to fill and maintain paleolakes. The drainage in these basins is primarily orthogonal to the larger Wadi-Sirhan depression, requiring them (or most) to be synchronously active to facilitate movement (Breeze et al. 2016).

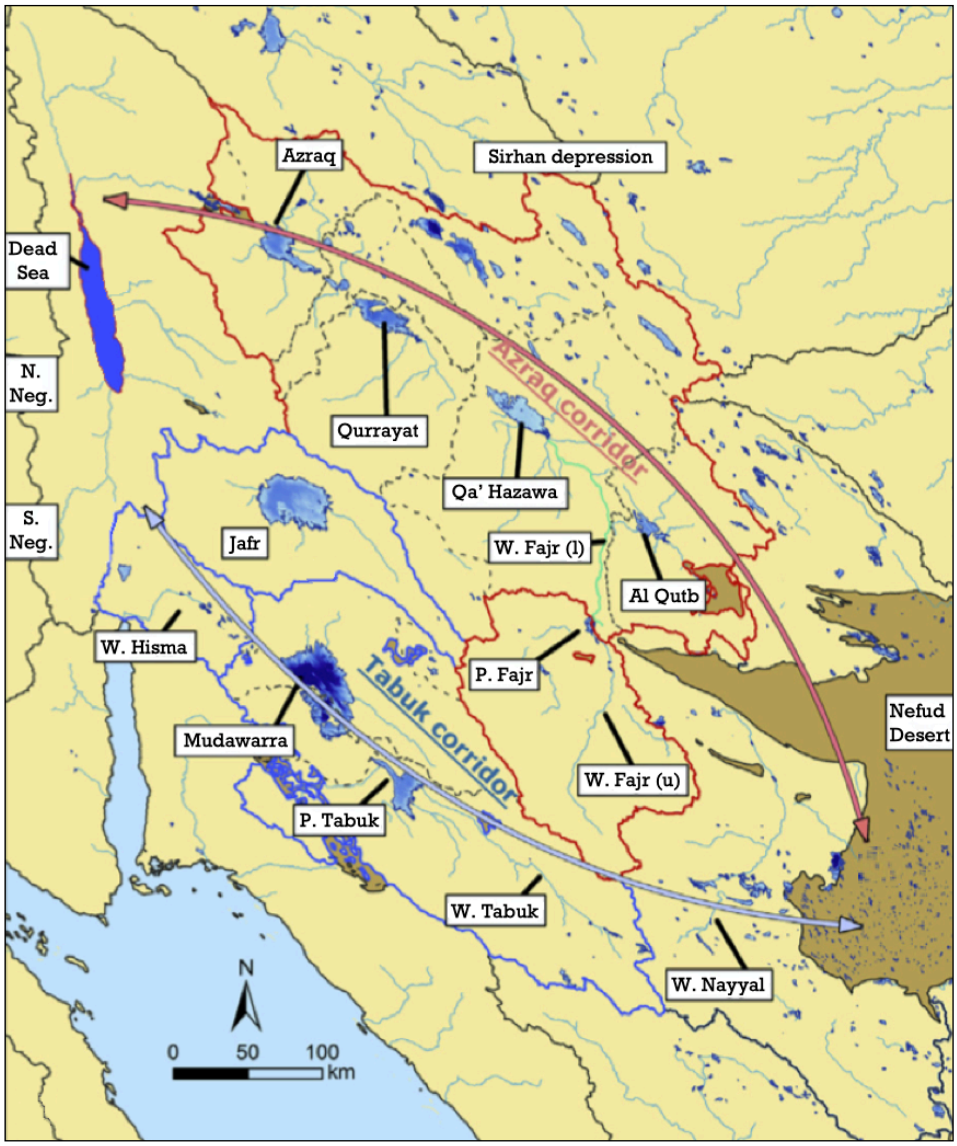


Figure 4.2: Location of Azraq and Tabuk paleohydrological corridors in northwestern Arabia and Jordan. Figure modified from Breeze et al. (2016: 166).

The Azraq corridor transects a large extent of an arid inland region adjacent to the Levant, known as the *northern Arabian Desert barrier*, that is largely devoid of springs and receives very little precipitation, as it is isolated from the reaches of both the monsoons and Westerlies (Breeze et al. 2016; Jennings et al. 2015). The Westerlies and monsoons need to converge for optimal conditions to migrate through Arabia. This convergence was likely to occur in the early stages of interglacial periods with a cool Earth and high insolation (Drake et al. 2013). During these more

humid phases, the retreat of glaciers affected the Indian Ocean insolation patterns and the resulting monsoons migrated northward into the Arabian interior, reaching the eastern portions of the Azraq corridor (Parker 2009). However, the influence of the Westerlies is unclear, as the highlands along the Dead Sea Transform create a barrier (Jennings et al. 2015). Furthermore, the paleoclimatic records of the Levant and Arabia indicate that there was little or no overlap between the Westerlies and the monsoon systems (Enzel et al. 2008; Vaks et al. 2007, 2013).

Recent investigations in the Azraq Basin provide important information on the environmental conditions at the heart of this region. For example, the fossil (*Cardium* horizon) and sedimentological records at several locales indicate a high lake stand during MIS 9, which suggests increased precipitation in the region (Abed et al. 2008; Ames & Cordova 2015; Ames et al. 2014a). This was likely due to intense Mediterranean cyclones, though some high latitude monsoonal rains may have assisted (Abed et al. 2008; Parker 2009). Northwestern Arabia experienced humidity during MIS 9 and 7 and again during a short phase in MIS 6 (178-152 kya) (Parker 2009). North of Azraq, speleothem growth in basalt caves of the Harrat Ash-Shaam indicate increased moisture during MIS 7 and (Frumkin et al. 2008). Consequently, early passage for AMH through the Azraq corridor may have been possible during the interglacial episode of MIS 9 and possibly MIS 7, although the exact nature of the hydrology during these periods is not firmly established. However, a drying trend during MIS 8-6 is evident in the Azraq Basin, as the lake receded into marshy ponds (Ames & Cordova 2015; Ames et al. 2014a; Cordova et al. 2013). These regional conditions of MIS 7-6 in the Azraq Basin may have temporally stymied movement within it. MIS 5 also saw the onset of substantial humidity in the Azraq Basin and the surrounding regions, particularly in MIS 5e (128-123 kya), 5c (96-87 kya), and 5a (82-71 kya) (Ames & Cordova 2015; Breeze et al. 2016; Frumkin et al. 2008). This may have presented another window for hominins to move along the Azraq corridor.

4.3 Geology of the Azraq Basin

The modern Hashemite Kingdom of Jordan can be divided into six broad physiographic units (Figure 4.3). These include the low-lying Dead Sea Rift Valley and the adjacent Western Highlands along the western border of the country. In the south, extensive, yet heavily weathered,

sandstone beds constitute the Sandstone Mountains and Valleys. The northeastern arm of Jordan is divided based on the rock types that cover the regions, namely the Northern Basalt Plateau (Harrat Ash-Shaam) and the Northeastern Limestone Plateau. The Central Plateau is the largest physiogeographic unit in Jordan and extends from the highlands in the west to the eastern border with Saudi Arabia. Two large topographic basins are contained within the Central Plateau: the Al-Jafr basin and the extensive Azraq-Wadi Sirhan basin. The latter is of importance for this present study.

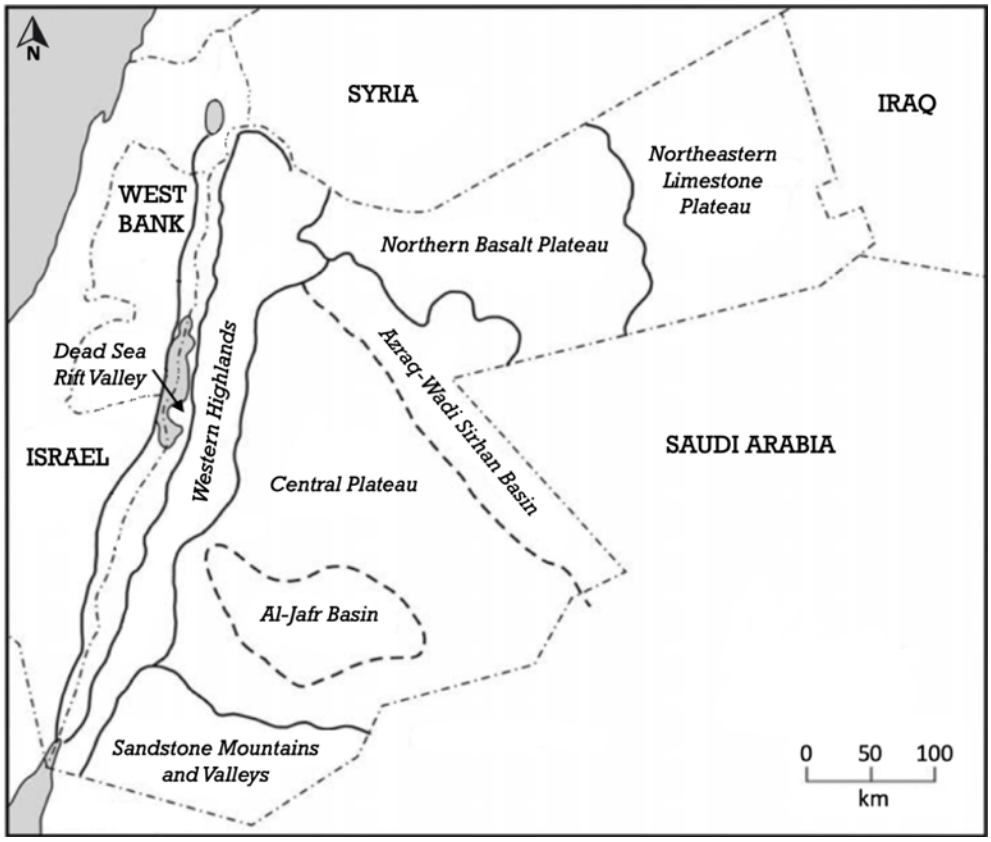


Figure 4.3: Physiogeographic units of Jordan. Figure modified from Cordova & Ames (2017: 532).

A considerable portion of the early research on the geology of Jordan was synthesized by Bender (1974). Many studies have focused on the rifting along the Dead Sea Transform (Barberi et al. 1980; Duffield et al. 1988), documenting the interior igneous flows (Al-Malabeh 1994; El-Hasam & Al-Malabeh 2008; Ilani et al. 2001; Saffarini et al. 1985), and establishing the

depositional history and environments associated with the sandstone and limestone beds of the southern desert (Abed 1982; Amireh 1992; Powell et al. 2014). Less attention has been afforded to the petrographic and geochemical characterization of sedimentary rocks within the Central Plateau. However, several geological maps and bulletins composed by the Geology Mapping Division of the Ministry of Energy and Mineral Resources of Jordan provide relevant information.

The Azraq Basin, as part of the Azraq-Wadi Sirhan basin, is situated within the northern portion of Central Plateau and extends into the Northern Basalt Plateau (Harrat Ash-Shaam) (Figure 4.3). Its immediate geology is a mosaic of igneous and sedimentary rocks, which are covered by alluvium and topsoil (Bender 1974; Worzyk & Huester 1987). The Azraq Formation contains the most recent deposits, which are dominated by sandstones and other clastic sediments of Quaternary age (Ibrahim 1996; Turner & Makhlouf 2005). The underlying geology of the Azraq Basin consists largely of Quaternary-Paleogene igneous flows and Paleogene-Upper Cretaceous sedimentary sequences (Alsharhan & Nairn 2003; Bender 1974). In the northern portion of the Azraq Basin, these sedimentary sequences are overlain by a large exposure (c. 11,000 km^2) of the greater Harrat Ash-Shaam, the intra-continental basalt plateau, formed from six main lava flows of the Oligocene-Pleistocene (Al-Malabeh 1994; Cordova 2007; Ilani et al. 2001). The dating of the most recent flow is unclear, but estimated at 3.5-0.5 mya (Moffat 1988).

Three sedimentary rock formations, all part of the Belqa Group and the focus of this study, are found within the Azraq Basin: the Muwaqqar Chalk-Marl, Umm Rijam Chert-Limestone, and Wadi Shallala Chalk formations (Figures 4.4-4.5). Their formation was influenced by eustatic fluctuations of the Arabian-Nubian Shield and the later configuration of the Tethys Sea in the northwest during the Upper Cretaceous-Eocene (Momani 2005; Sonnenfield 1978). More specifically, the formations accumulated on the mid- and outer-shelf during periodic marine transgressions (roughly southeastward movement) of the Tethys Sea. This rise of sea level promoted deep water pelagic sedimentation and high silica productivity, conducive to the formation of chert (Al-Hunjul 2001; Powell 1989). In the late Eocene, the interior eastern Mediterranean underwent a process of upflift, which forced the Tethys Sea to migrate northwest and caused Jordan to remain terrestrial since (Bender 1974; Powell 1989). The depression of the Azraq Basin gradually emerged through this event. These sedimentary deposits provide bedded

and nodular chert as raw material for stone tool manufacture throughout the region (Ames et al. 2014a; Copeland 1991; Sánchez de la Torre et al. 2019; Rollefson 1980). Very little petrographic and geochemical characterization has been performed on these formations. Most information is gathered from boreholes, which reached several hundred meters in depth, though a recent study in the southwestern area of the Azraq Basin by Sánchez de la Torre et al. (2019) provides some relevant information. The three formations are described in the following sections in descending order of age.

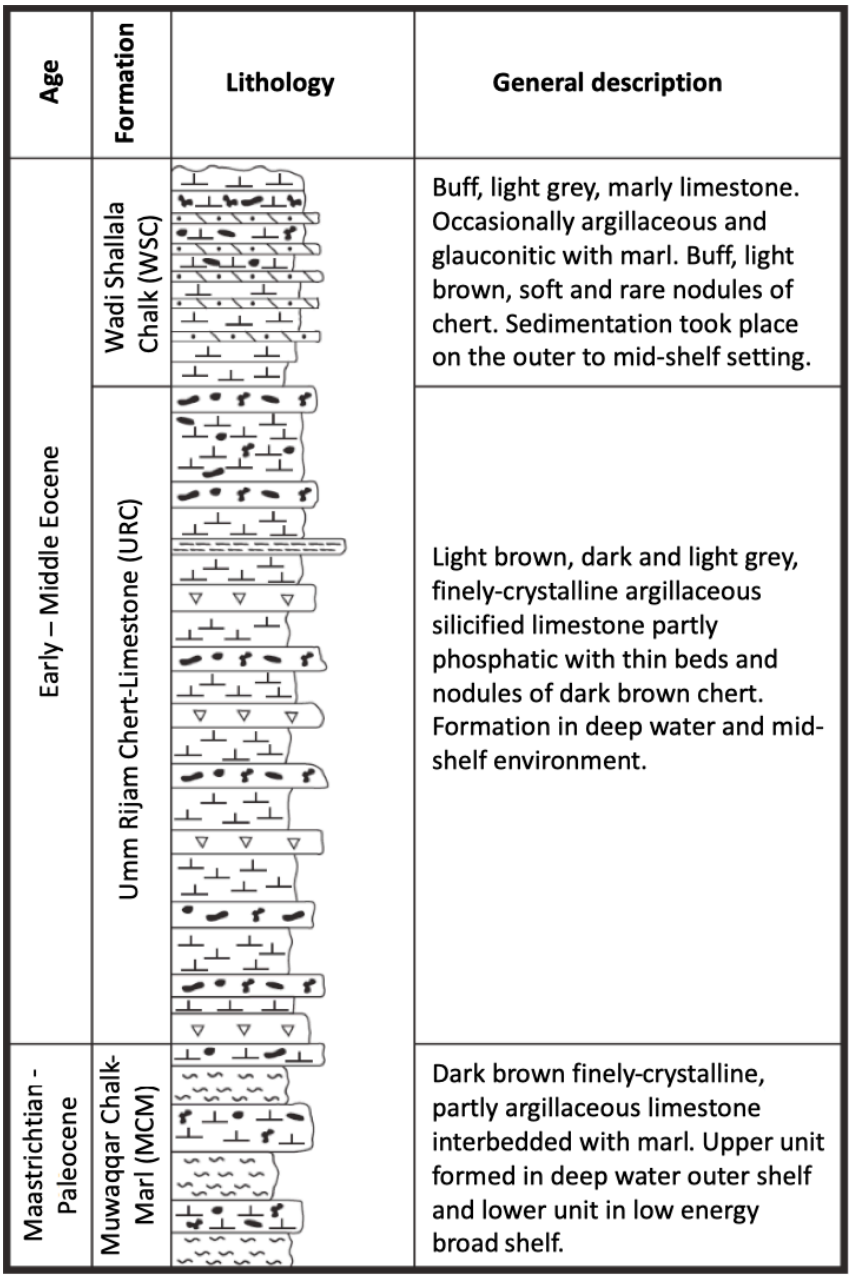


Figure 4.4: Strip log showing lithostratigraphy of marine formations in the Azraq Basin, Jordan. Figure modified from Sánchez de la Torre et al. (2019: supplementary material) with descriptions from Alsharhan & Nairn (2003: 432).

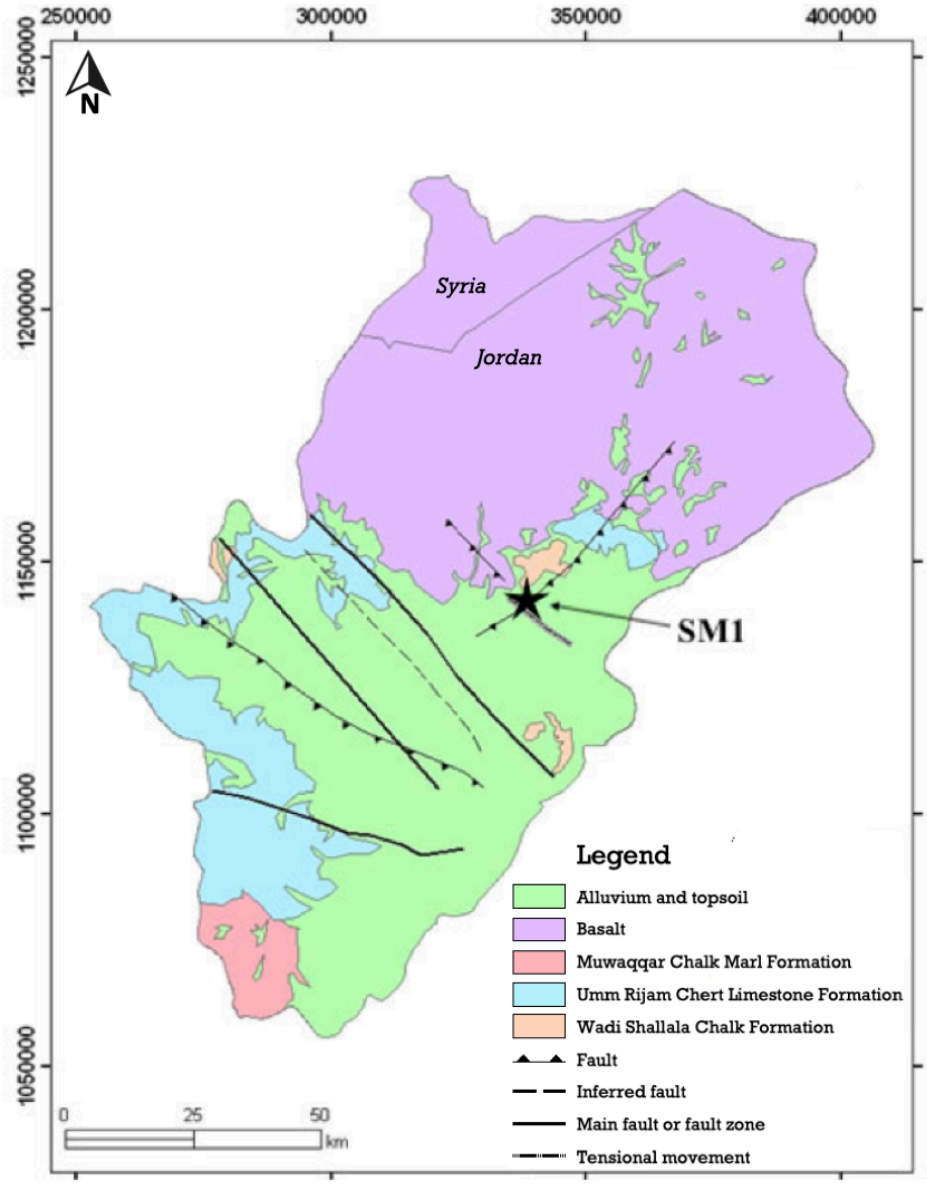


Figure 4.5: Geology of the Azraq Basin. Figure modified from Ta'any (2013: 198).

4.3.1 Wadi Shallala Chalk Formation

The Wadi Shallala Chalk (WSC) Formation is the youngest of the three formations, dating to the Middle-Late Eocene, based on its fossil record. The rock sequence largely consists of chalk and dolomitic limestone sequences (Andrews 1992; Fadda 1998), which yield chert nodules of ~5 cm and 5-15 cm respectively (Sánchez de la Torre et al. 2019). Various buried marl beds that are locally bituminous have also been documented and thin layers of glauconitic sandstone and

siltstone are occasionally present (Andrews 199; Fadda 1998). The WSC Formation was likely deposited in a mid- to outer-shelf, pelagic environment (Alsharhan & Nairn 2003). Today, it is primarily exposed along the Yarmouk River in northwest Jordan and sparsely exposed in the Azraq Basin, being primarily reported in in the southern portion of Azraq Basin (Fadda 1994, 1996; Sánchez de la Torre et al. 2019). It is less extensive than the other two formations, as it has received considerable post-Eocene weathering and much of it is covered by later unconsolidated sediments (Fadda 1998).

4.3.2 Umm Rijam Chert-Limestone Formation

The Umm Rijam Chert-Limestone (URC) Formation is situated between the WSC and Muwaqqar Chalk-Marl formations where it comfortably overlies the latter. It dates to the Early-Middle Eocene and, in some locations, reaches over 100 m in thickness and extends across much of central Jordan, including the Azraq and Wadi Sirhan basins (Alsharhan & Nairn 2003; Fadda 1998). Overall, there is a rhythmic sequence of chalk, chert of various colors, and hard limestone layers (Fadda 1998; Ibrahim 1996; Qudaira 1997, 2000). Although there is a similar sequence of beds throughout, the formation can be parsed into three divisions (upper, middle, lower). The upper member contains an abundance of limestone beds interdigitated with an occasional chert bed. The middle member comprises limestone and chert beds with an occasional porcellanite bed. Lastly, the lower member contains massive limestone and chalk beds interdigitated with thin beds of chert. There is a low ratio (1:10) of chert to limestone in the URC Formation (Abed 2000), particularly in comparison to other formations within the Levant (e.g., Amman ~1:1). The predominance of calcareous nannoplankton and benthic and planktonic foraminifera, as well as the absence of benthic macrofaunal, collectively indicate that the URC Formation was deposited in a deep-water, pelagic environment (Alsharhan & Nairn 2003).

4.3.3 Muwaqqar Chalk-Marl Formation

The Muwaqqar Chalk-Marl (MCM) Formation is the oldest of the three chert-bearing formations, dating to the Maastrichtian (Upper Cretaceous), and is less understood due to its limited exposure. It consists of two informal yet related units (upper and lower). The upper unit

comprises repeated sequences of partly fossiliferous and chalky limestone with marls of various shades (Ibrahim 1996; Al-Hunjul 2001). The depositional environment of the upper unit is interpreted as a relatively deep-water, outer shelf environment (Andrews 1992). The lower unit consists of argillaceous and fossiliferous limestone beds, which often contain flat lenses and nodules of chert (Andrews 1992; Bender 1974). In slight contrast to the upper unit, these beds were gradually deposited in a low energy, broad shelf environment (Alsharhan & Nairn 2003). Sánchez de la Torre et al. (2019) observed that chert nodules were more common than bedded chert and there was a decrease in silicifications at surveyed outcrops moving south to north.

4.4 The Greater Azraq Oasis Area

The Azraq Basin is a large (~13,000 km^2) endorheic basin, a closed body of water with no outflow, located in northeast Jordan. The basin also encompasses a small portion of the Harrat Ash-Shaam in southern Syria, as well as a very small portion of northwest Saudi Arabia. At the center of the Azraq Basin is a salty mudflat, or *qa'* in Arabic (Qa' Azraq), roughly 75 km^2 in size (Ames & Cordova 2015). It is a dry, yet seasonally flooded flat surface and contains the lowest elevation in the basin (Cordova et al 2013). The Qa' Azraq provides a large catchment for a series of springs and input from several large seasonal streams—known locally as *wadis*—namely the Butm, Rattama, Rajil, and Usaykhim channels (Cordova 2007). These watercourses create a radial network that feed into the central sink (Figure 4.6). The northern and western parts of the Azraq Basin receive more precipitation than the southern and eastern. As a result, the *wadi* sectors in the former areas have an extended duration of seasonal flow, as water percolates through fissures in the basalt plateau and keeps the water table elevated (Copeland 1988). During winter, the rainwater causes Qa' Azraq to fill, though most (or even all at times) of this water is evaporated during the summer (Abed 2002).

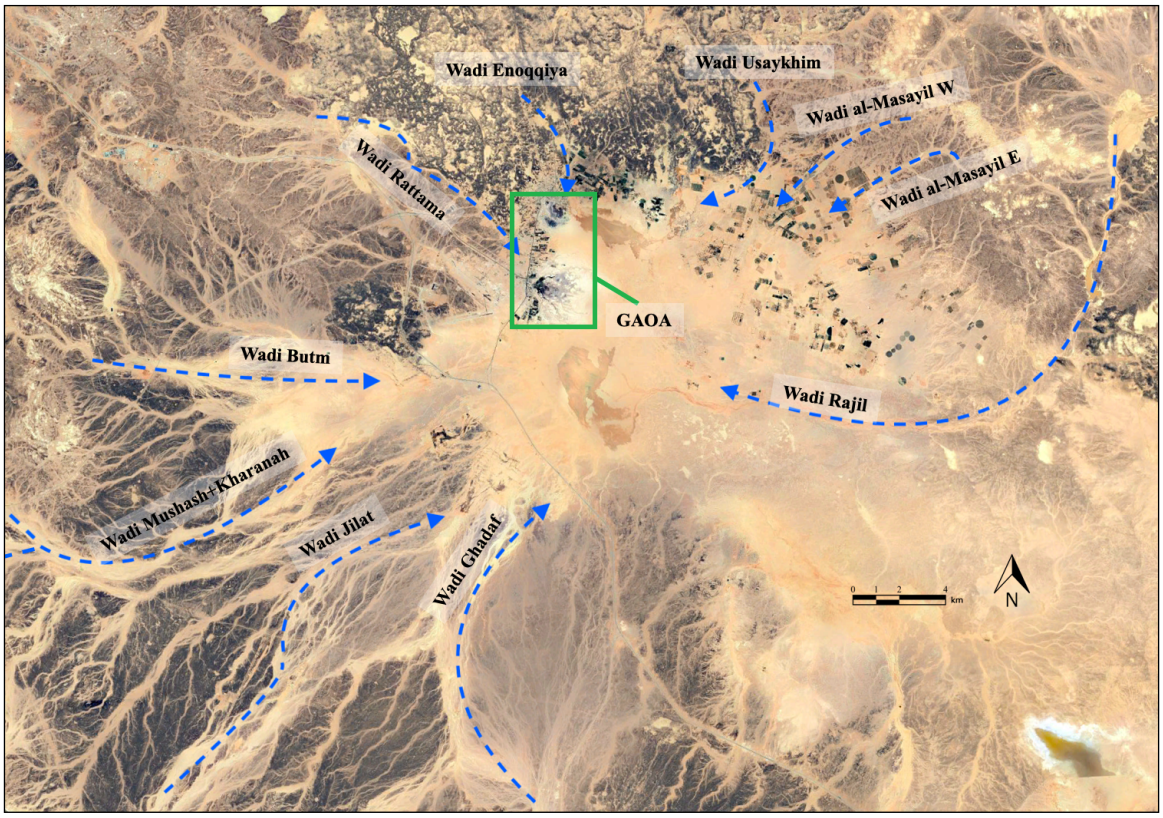


Figure 4.6: Important wadi sectors of the Azraq Basin. Figure created from Google Earth®.

Situated along the northwest portion of the central mudflat in the basin are the historic Druze Marsh and the rehabilitated Shishan Marsh. This wetland complex is considered to be a single geographic unit and is described as the Greater Azraq Oasis Area (Figure 1.3) (Cordova et al. 2013; El-Naqqa 2010). The GAOA is maintained by springs fed by an aquifer system contained in the Tertiary limestones and basalt (Dottridge 1998). In the wet season, the overflow of Qa' Azraq can spill into the GAOA, changing the salinity of the latter (Figure 4.7). The water of the GAOA turns fresher in the dry season, as the water of the *qa'* recedes and evaporates. Therefore, the extent of the wetlands is subject not only to the conditions of the long-term regional climate, but also those of the seasons.

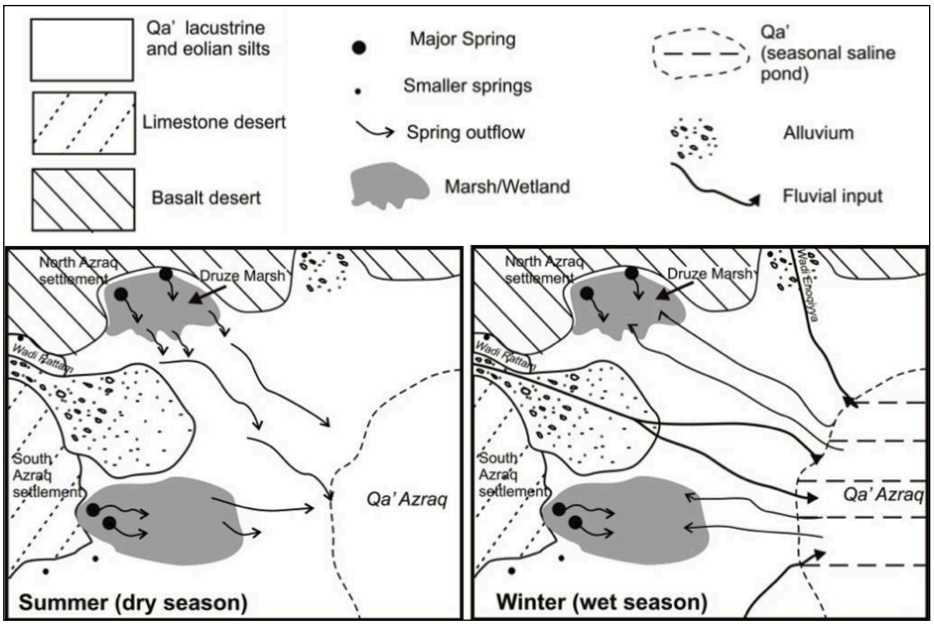


Figure 4.7: Seasonal hydrology of the Azraq wetlands. Figure modified from Cordova et al. (2013: 99).

The aquifer system of the Azraq Basin is among the most important sources of surface and ground water for modern populations in Jordan (Kennedy & Riley 1990). Unfortunately, the onset of pumping water from the aquifer in the early 1980s has led to a substantial drop in the water table and the rapid draining of the two marshes, to the point where they were completely dry in the early 1990s (Al-Kharabsheh 2000; Cordova et al. 2013). The Druze Marsh has not recovered, but a restoration effort led by the Royal Society for the Conservation of Nature has restored a small portion (<10%) of the Shishan Marsh (Fariz & Hatough-Bouran 1998; France 2010). A visit to the modern Azraq Wetland Reserve reveals that it operates as a small desert oasis for migratory birds and a watering hole for various wild animals, some which have been recently re-introduced (Figure 4.8).



Figure 4.8: A section of the revived modern Azraq Wetlands Reserve. Photograph by James Pokines (used with permission).

4.5 Paleolithic occupation in the Azraq Basin

Archaeological research has been intermittently conducted in the Azraq Basin over the past 70 years. Evidence for Paleolithic occupation around the GAOA was first discovered after the turn of the 20th century and again in the 1950s (Field 1960; Rees 1929; Zeuner et al. 1957). However, systematic surveys and excavations did not commence until the 1970s (Garrard et al. 1977, 1988; Turnbull 1989). A small concentration of sites yielded material that collectively span almost every period from the later stages of the Lower Paleolithic to modern times (al-Nahar & Clark 2009; Copeland 1988, Copeland & Hours 1989a). Although much of the evidence for Lower and Middle Paleolithic occupation in the Azraq Basin comes from surface scatters, several excavations have

uncovered *in situ* remains (Table 4.2). It is evident from these discoveries that the Azraq Basin and GAOA, in particular, likely contain a plethora of unexcavated Paleolithic sites.

Table 4.2: Lower and Middle Paleolithic occupation in the Azraq Basin.

Sector/site		Recovery	Relevant archaeological periods	Key references
‘Ain el-Beidha (White Spring)	137	Survey	Lower Paleolithic, Middle Paleolithic	Copeland 1989d
	201A	Survey	Lower Paleolithic, Middle Paleolithic	Copeland 1989d
	201B	Survey	Middle Paleolithic	Copeland 1989d
	209	Survey	Lower Paleolithic, Middle Paleolithic	Copeland 1989d
‘Ain Qasiyya		Survey and excavation	Middle Paleolithic	Rollefson et al. 1997b
‘Ain Soda		Survey and excavation	Lower Paleolithic, Middle Paleolithic	Dirks 1998; Lister et al. 2013; Rollefson et al. 1997a, 1997b, 2006
Basalt plateau		Survey	Lower Paleolithic, Middle Paleolithic	Betts 1988
Butm		Survey	Lower Paleolithic, Middle Paleolithic	Copeland & Hours 1989b; Garrard et al. 1988
C-Spring		Excavation	Lower Paleolithic	Clutton-Brock 1970, 1989; Copeland 1991; Copeland 1989c; Garrard et al. 1987, 1988; Hunt & Garrard 1989
Druze Marsh	DM8	Excavation	Lower Paleolithic, Middle Paleolithic	Ames et al. 2014a; Ames & Cordova 2015; Cordova et al. 2013
Enoqiyya		Survey	Lower Paleolithic, Middle Paleolithic	Hours 1989
Janab-Kharanah-Mushash		Survey	Lower Paleolithic	Copeland & Hours 1989b; Garrard et al 1977
Jilat		Survey	Middle Paleolithic	Garrard et al. 1988
Lion Spring (‘Ain el-Assad)		Excavation	Lower Paleolithic	Copeland 1989a, 1989b; Harding 1967; Rollefson 1980
Rajil	231	Survey	Lower Paleolithic	Copeland 1989d
	251	Survey	Lower Paleolithic	Copeland 1989d
Rattama		Survey	Lower Paleolithic, Middle Paleolithic	Copeland & Hours 1989b
Uweinid		Survey	Lower Paleolithic	Garrard et al 1977; Rollefson 1984

4.5.1 Lower Paleolithic

In an extensive project conducted by the Centre National de la Recherche Scientifique (hereafter CNRS) at the Université Lumière in Lyon, surveys and probes were performed along specific sectors of four of the major *wadi* channels that flow into Qa' Azraq (Figure 4.6): Butm, Rattama, Mushash-Janab, and Enoqiyya (Copeland & Hours 1989b). Both Lower and Middle Paleolithic remains were recovered from each of the sectors (Copeland & Hours 1989b). Except for Wadi Enoqiyya (described later), the Lower Paleolithic remains consisted of medium-large handaxes and few cleavers, thick blades, and proto-Levallois cores. Due to the typological and technological consistencies of the assemblages, they were collectively termed the "Desert Wadi Acheulean" (DWA) (Copeland 1988, 1998; Copeland & Hours 1988b). An extensive surface scatter of Lower Paleolithic artifacts was discovered within Wadi Uweinid, a small tributary of Wadi Butm (Figure 1.3). This scatter primarily includes bifaces, but also flakes and cores, which are collectively described as typical of the Middle Acheulean (Rollefson 1984). Further east, where Wadi Rajil enters Qa' Azraq, two battered bifaces and rolled flakes were discovered that suggest a Lower Paleolithic presence along this sector (Copeland 1989d).

The recovery of lithic artifacts during an irrigation project at the site of Lion Spring ('Ain el-Assad) was among the first systematic examinations of Paleolithic material culture in the region (Figure 1.3). This assemblage was retrieved from the back-dirt piles, which contained hundreds of handaxes and cleavers that were indicative of a Lower Paleolithic occupation (Copeland 1989a, 1989b; Harding 1967; Rollefson 1980, 1982, 1983). Upon realizing the potential of the site, formal excavations were conducted at Lion Spring for two seasons in an effort to reach the Lower Paleolithic layers, but were ultimately unsuccessful (Rollefson 1980, 1982, 1983). Approximately 2.5 km northeast of Lion Spring, the site of C-Spring was also identified by the Baker and Harza engineering firm during an irrigation project in 1956 (Figure 1.3). However, it was not until 1985 that a 3 x 1.5 m sounding revealed a Lower Paleolithic deposit containing a "river of flint" (Garrard et al. 1987, 1988; Hunt & Garrard 1989). This lithic assemblage comprised over 4000 artifacts, most of which were handaxes, unutilized flakes, cores, and debitage (Copeland 1989c). Special note was made of the good condition and lack of use of many artifacts, which are described as "mint-fresh" and "razor-sharp" (Copeland 1991: 3-4). Many cores had either been aborted and

discarded or worked down to a disc, possibly to form bifaces. This observation, combined with the high proportion of preparation and finishing flakes, led to the interpretation of the site as a potential knapping locale (Copeland 1991). The assemblages from these two sites contain a unique suite of artifacts, including of medium-small handaxes, high quantities of cleavers, some Quina racloirs, and Levallois-like flakes, and very few blades. Since this collective toolkit retains elements of the Acheulean industry and indicates a progression toward the Levallois technique, it was termed the "Late Acheulean of Azraq" (LAA) facies (Copeland 1988, 1989c).

The Lower Paleolithic remains discovered during the survey of Wadi Enoqiyya included several small bifaces, a cleaver, a Quina racloir, and flakes. They are also consistent with the LAA facies. Additional surveys and geomorphological investigations focused on the ʻAin el-Beidha (White Spring) area just east of the Wadi Enoqiyya sector (Figure 1.3). Several sites (137, 201A, 201B, and 209), all within a kilometer-and-a-half stretch, contained evidence of further Lower and Middle Paleolithic occupation. The collective assemblage from the ʻAin el-Beidha sites contains several large-small bifaces and flake tools of the Lower Paleolithic (Copeland 1989d). However, the diagnostic tools are considered too few to establish secure consistencies with the DWA or LAA facies (Copeland 1989d).

The over-pumping of the Azraq aquifer during the 1980-90s and the subsequent drop of the water table led to the complete drying of the Shishan and Druze marshes and access to their deposits. Surface surveys and subsequent excavations were conducted in the ʻAin Soda and ʻAin Qasiyya sections of the Shishan Marsh during the late 1990s. An assortment of lithic artifacts was recovered at ʻAin Soda, including flake tools, handaxes, and cleavers (Rollefson et al. 1997a, 1997b, 2006). These remains demonstrate a Lower Paleolithic presence within the GAOA. However, only one biface was found at ʻAin Qassiya, suggesting this section was likely submersed (Rollefson et al. 1997b). The assemblages are described as part of the "Late and Final Acheulean" (Rollefson et al. 1997b), with tools that exhibit striking similarities to the LAA facies, but were not formally described in this manner. Cleavers occur in significantly higher (10-15x) frequencies at ʻAin Soda, C-Spring, and Lion Spring than other sites within the Levant (Gilead 1973; Rollefson 1980; Rollefson et al. 1997b). These tools exhibit deliberately dulled lateral edges, at least one tranchet scar across the distal end, and often a bifacially worked base. The latter modifications

created two functions on one tool: a chopping/hacking (base) and slicing (distal). These typo-technological characteristics led to this potentially distinct tradition being termed the "Azraq cleaver" (Rollefson et al. 1997b).

Recent archaeological excavations led by Dr. April Nowell of the University of Victoria and organized through the Druze Marsh Archaeological and Paleoecological Project (DMAPP) unearthed several Paleolithic layers within the Druze Marsh (Figures 1.3). The exposed stratigraphy offered a detailed record of the nature of changing hydrology and environment and its relationship to hominin occupation (Ames 2013; Ames et al. 2014a; Ames & Cordova 2015; Cordova et al. 2013). For example, excavations at the site of Druze Marsh 8 (DM8) recovered Acheulean handaxes and a cleaver associated with a deep marsh transitioning to dryer conditions in Layer 1b-c (Ames et al. 2014a; Ames & Cordova 2015). While no absolute dates have been obtained, occupation in Unit 1b-c is thought to be contemporaneous (estimated >250 kya) with other Late Acheulean sites around and within the GAOA (Ames et al. 2014a; Ames & Cordova 2015).

Very few faunal remains have been recovered at Lower Paleolithic sites in the Azraq Basin. This is likely due to the open-air nature of sites and heavy salt composition in the sediments, which are not conducive to bone preservation (Rollefson et al. 2006). The only remains comes from two sites, C-Spring and 'Ain Soda, where most remains are represented by teeth; elements that are most resistant to degradation. The taxa of the two sites are similar and include rhinoceros, camel, wild cattle, and various indeterminate equid (Clutton-Brock 1970, 1989; Lister et al. 2013; Rollefson et al. 2006). C-Spring also contains hartebeest and several elephant teeth were found at 'Ain Soda (Clutton-Brock 1989; Lister et al. 2013).

The pattern of hominin occupation in the Azraq Basin during the Lower Paleolithic can be reconstructed based on the typo-technological differences between the DWA and LAA facies and the areas in which they are discovered. The DWA is described as part of the Middle Acheulean and is characterized by medium-large handaxes, thick blades, and proto-Levallois material (Copeland 1988; Copeland & Hours 1988b; Rollefson 1984). The LAA facies is described as part of the Late/Final Acheulean and is characterized by medium-small handaxes, cleavers, and Levallois-like flakes (Copeland 1988, 1989c). Gilead (1977) noted a positive correlation between

increased biface length and increased age among Acheulean assemblages in the Levant. An application of this correlation in the Azraq Basin indicates that the DWA (large-medium bifaces) is older than the LAA facies (medium-small bifaces) (Copeland 1988, 1998). This conclusion is supported by the presence of elements of later industries in the LAA facies. Consequently, hominin occupation was predominantly along the *wadi* sectors during the Middle Acheulean (DWA) and around the GAOA during the Late/Final Acheulean (LAA facies).

4.5.2 Middle Paleolithic

Middle Paleolithic occupation in the Azraq Basin is not as well represented as the Lower Paleolithic. Several of the aforementioned projects identified surface remains along the various *wadi* sectors and buried contexts within the GAOA. For example, the surveys conducted by the CNRS along the Butm, Rattama, and Mushash-Janab sectors recovered relatively few stone tools, largely of heavy and elongated Mousterian types (Copeland 1988; Copeland & Hours 1989b). Similarly, surveys in the 1970s recovered relatively few stone tools indicative of Middle Paleolithic along the Uweinid, Jilat, and Kharanah sectors (Garrard et al. 1977, 1988).

Greater evidence of a Middle Paleolithic presence is found in Wadi Enoqiyya, where over 6000 lithics were collected (Copeland & Hours 1989b; Hours 1989). These include Levallois points and flakes, racloirs, various smaller tools, and debitage, which belong to the classic Levantine Mousterian industry (Hours 1989). The estimated age for this (assumed) collective assemblage is 60-45 kya, based on analogies with other Levantine sites (Copeland 1988). The four sites (137, 201A, 201B, and 209) of ‘Ain el-Beidha yielded similar Middle Paleolithic remains to those along Wadi Enoqiyya (Copeland 1989d). Their collective assemblage contains various cores, racloirs, and flakes, as well as multiple Levallois elements, including points and blades (Copeland 1989d).

Two phases of Middle Paleolithic occupation were identified at DM8 in the Druze Marsh: Units 2a and 3b-c. The lithic assemblage of Unit 2a contains elements reminiscent of the Early Levantine Mousterian, including a Mousterian point, a Levallois core and point, and the prevalence of laminar Levallois technique (Ames et al. 2014a; Ames & Cordova 2015). The typological consistency with similar assemblages in the Near East provides an estimated date of 250-130 kya

(Ames et al. 2014a; Ames & Cordova 2015). Unit 2a is characterized by the transition from a playa to marsh with some eolian accumulation (Ames et al. 2014a; Ames & Cordova 2015). Above it, Unit 3b-c is associated with marsh or shallow lake conditions (Ames et al. 2014a; Ames & Cordova 2015). The lithic assemblage of Unit 3b-c contains few diagnostic pieces, but is dominated by blades and blade fragments, as well as several Levallois elements and a Mousterian point (Ames et al. 2014a; Ames & Cordova 2015). Its age is estimated to be >40 kya, but could represent a palimpsest with later Upper Paleolithic occupation (Ames et al. 2014a; Ames & Cordova 2015).

Middle Paleolithic remains are also found in the Shishan Marsh to the south. Most notably, a small assortment of Levallois flakes, blades, and points were recovered at ʻAin Qasiyya and to a lesser extent at ʻAin Soda (Rollefson et al. 1997a, 1997b). The presence of Middle Paleolithic artifacts at ʻAin Qasiyya suggests that this section was now dry, unlike during the time of Lower Paleolithic occupation at nearby ʻAin Soda (Rollefson et al. 1997b). The few faunal remains from ʻAin Soda include elements of wild cattle and indeterminate equid (Lister et al. 2013).

4.6 Shishan Marsh 1

The excessive draining of the Druze and Shishan marshes contributed to the dry and barren landscape where the name *Azraq*, Arabic for blue, no longer applies. Similar to the Druze Marsh, the lowering of the water table in the Shishan Marsh has exposed deeply stratified deposits that reach back into the Middle and Upper Pleistocene. It is within these deposits that the archaeological site of Shishan Marsh 1 (SM1) is situated (coordinates: 31°49.93’ N, 36°49.13’ E). To date, no hominin fossils have been recovered at SM1, so the species that produced its material culture is/are unknown.

4.6.1 Excavation

Excavations of SM1 and nearby geological soundings (SM2 through SM13) were conducted from 2013-2015 by the Azraq Marshes Archaeological and Paleoecological Project (Figure 4.9-4.10). The project was directed by Dr. April Nowell of the University of Victoria and involved an international team of professors and graduate students representing several

universities. A representative from the Department of Antiquities of Jordan was present throughout the duration of the excavation.



Figure 4.9: Shishan Marsh 1 during excavation in 2013. Photograph by James Pokines (used with permission).



Figure 4.10: Shishan Marsh 1 after a completed excavation in 2015. Photograph by James Pokines (used with permission).

The excavation uncovered an area of approximately 21.5 m^2, but the site is much larger and continues further into the unexcavated baulks. The excavation strategy involved demarcating a series of 1 m x 1 m units. These units were divided into 50 cm x 50 cm quadrants (NE, NW, SE, SW) to define smaller areas of analysis with discrete artificial boundaries. Excavation proceeded downward in 5 cm spits and followed the natural stratigraphy in order to demarcate the boundaries of each layer. A description of the sediment that composed each layer was documented before proceeding into a subsequent layer.

Additionally, the sediment from each NE quadrant was collected in order to reconstruct the depositional environment of SM1. The sediment was sorted by nested geological sieves to identify the natural clast composition and condition, and to compare these patterns to the cultural material. Any marked differences in size and proportions would indicate that the cultural material was

directly deposited by hominins in association with use, rather than having been moved from elsewhere by fluvial action and redeposit at SM1. Preliminary results suggest that fluvial transport did not play a significant role in the formation of the site and that the faunal and lithic remains are in their primary context (Ames et al. 2014b; Christopher Ames pers. comm. 2015).

Altogether, 10 sedimentary units were identified (Figure 4.11). Layers 1 and 2 are mixed Holocene deposits near the surface and contain limited cultural material, including Lower Paleolithic lithics, historical ceramics, and modern trash. Layers 3-7a, 9, and 10 were archaeologically sterile. Layers 7b-c and 8 produced abundant Paleolithic cultural remains indicative of hominin activity and are thus the focus of this study. Optically stimulated luminescence (OSL) dating results of these layers place the SM1 occupations around 266 +/- 40 kya (Layer 8), 125 +/- 12 kya (Layers 7b), and 119 +/- 40 kya (Layer 7a) (Nowell et al. 2016).

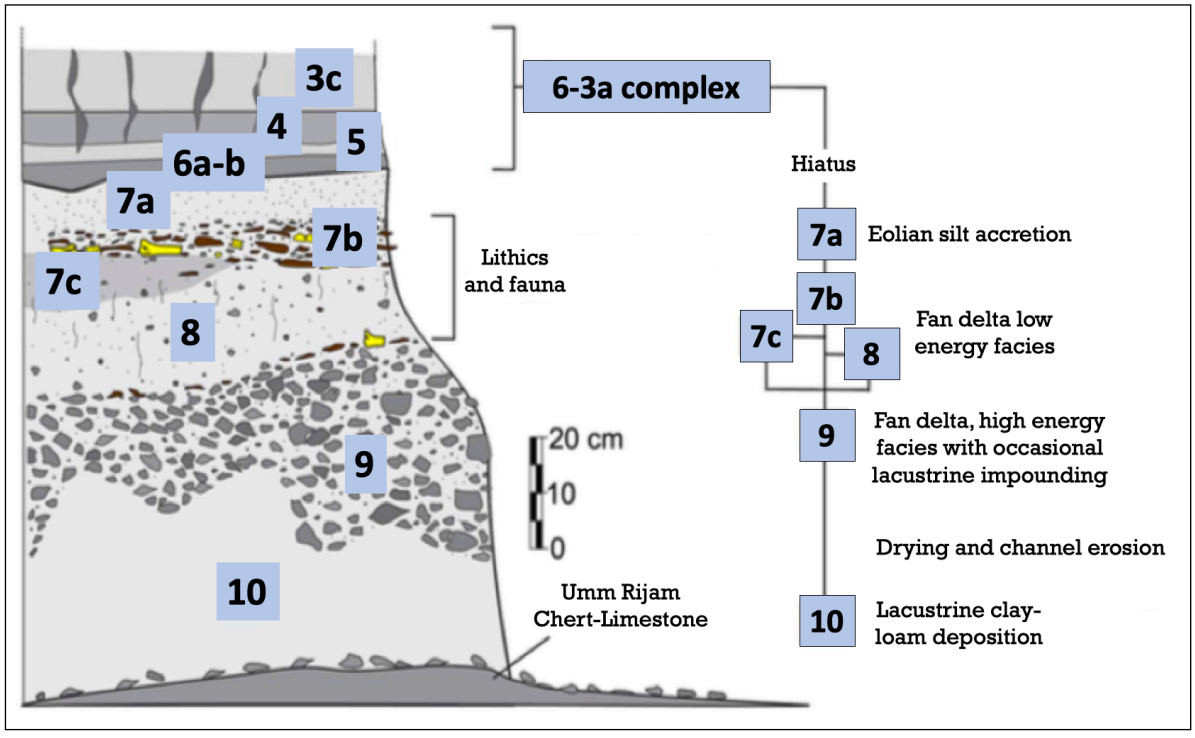


Figure 4.11: Stratigraphic sequence at Shishan Marsh 1. Figure modified from Pokines et al. (2019: 770).

4.6.2 Lithic remains

The typology and technology of the lithic assemblage of SM1 were analyzed by Dr. April Nowell and Mr. Dan Stueber (Archaeological Investigations Northwest) following the Bordean typology (Bordes 1961, 1968; Debénath and Dibble 1994). Approximately 10,000 lithic artifacts, both debitage (n=8000) and identifiable tools (n= ~2000) were recovered from two of the eight layers (Layers 8 and 7b-c) at SM1 of which a large portion (n=1308) of the tools have been analyzed. Each artifact >5 cm was piece-plotted using a Leica total station, where the basal elevations of the specimens were recorded at the lowest point of the cavity. Orientation was also recorded on specimens that exhibited an elongated axis, typically where the length was 1.5 times greater than the width. Each spit was sieved through 0.5 cm sieves to collect debitage. In addition, every NE quadrant was wet sieved to recover any small debitage and other flaking debris.

The lithic assemblage comprises an assortment of bifaces (n=80), cores (n=61), and small tools (Table 4.3). The bifaces include handaxes (n=76) and cleavers (n=4). Handaxes are large bifacial cores with fairly straight edges that converge at the distal end to create a sharp symmetrical point, while cleavers are more elongated with a broad edge (transverse to the long axis) at the distal end (Kelly 1988; Shea 2013). The broad edge is often made through a single or double tranchet strike (McPherron 2003; Rollefson 1997b). The small tools are largely represented by various utilized flakes (n=845), scrapers (n=104), blades (n=61), and borers (n=36). There are two main differences in the composition of lithics between the two layers. The first is that Layer 7 is dominated by both modified and unmodified Levallois flakes and very few biface thinning flakes (Pokines et al. 2019). The second is that Layer 8 contains more bifaces and biface reduction flakes (Dan Stueber pers. comm. 2019; Pokines et al. 2019). The analysis of the lithic assemblage is still ongoing, but typologically, the lithic remains are consistent with the LAA facies (Nowell et al. 2016; Pokines et al. 2019).

Table 4.3: Typology of currently analyzed lithic remains from SM1. Table provided by Christopher Ames.

Type	Number of specimens	Type	Number of specimens
Backed knife, natural	1	Flake, early core reduction	224
Biface (handaxe)	76	Flake, late biface thinning	37
Biface (cleaver)	4	Flake, late core reduction	136
Blade	22	Flake, Levallois	82
Blade, Levallois	39	Flake, tranchet	7
Borer	36	Notch	10
Burin	11	Point	3
Burin spall	11	Point, Levallois	31
Chopper	1	Scraper, bifacial	1
Cleaver	1	Scraper, convergent	15
Core	61	Scraper, déjeté	3
Core tool	15	Scraper, double	21
Denticulate	16	Scraper, end	27
Flake	281	Scraper, single	37
Flake, bipolar	1	Tested material	6
Flake, early biface thinning	77	Unknown	15
Total		1308	

The microdebitage is indicative of opportunistic on-site production of small expedient tools (Pokines et al. 2019). By contrast, there is little evidence for the production of bifaces and Levallois tools save for a few cores and flakes. Most likely these were manufactured to completion off-site.

The burins, borers, and endscrapers are typically present in Middle Stone Age (Africa) and Upper Paleolithic (Eurasia) assemblages, although some are known from Lower Paleolithic assemblages (cf. Chazan 2013; Zaidner 2013). However, those of later assemblages are typically more standardized in shape and considerably thinner (Burdukiewicz and Ronen 2003).

A use-wear study on a subsample of the handaxes demonstrated that they were used as multi-purpose tools (Murray 2017). A high degree of micro-flaking and rounding on the handaxe edges was indicative of their use on medium-hard materials (e.g., bone, hide, wood). The tips of the handaxes also received considerable use, reflecting the versatility of these tools.

4.6.3 Faunal remains

In addition to stone tools, a small collection of poorly preserved faunal remains was recovered from the same layers (Layers 8-7b). The poor preservation was likely due to the open-air nature of the site and low pH of the sediments, conditions that are especially detrimental to the survival of elements from smaller animals (Pokines et al. 2019). There is a preservation bias present whereby most taxa present (by NISP) are large herbivores, such as camel, extinct elephant, equids, and rhinoceros (Table 4.4) (Pokines et al. 2019). As noted previously, similar taxa were discovered at the (assumed) contemporaneous Acheulean sites of C-Spring and ‘Ain Soda (Clutton-Brock 1970, 1989; Dirks 1988; Lister et al. 2013), collectively indicating that herds were present in several pockets within the region. Wild cattle, gazelle, probable lion, and unidentified carnivores (probable hyena or leopard) are also present, but in considerably lower frequencies.

The analysis of protein residue recovered from several stone tools identified the blood from several different taxa (Nowell et al. 2016). These included many large herbivores (e.g., bovine, camel, elephant, horse, rhinoceros), which are also represented by teeth (Figure 4.12), small elements (e.g., calcanei, phalanges), or fragments of long bones (Pokines et al. 2019). In addition, the residue analysis provided positive results for the identification of waterfowl (Family Anatidae), a group that is not represented in the faunal assemblage (Nowell et al. 2016). These analyses further demonstrated that a portion of the stone tools were used for butchering activities. This activity could not be determined from cut marks, as the faunal remains were too poorly preserved.

Table 4.4: List of taxa present in Layers 7b-c and 8 of SM1. Table provided by James Pokines.

Taxon	Layer							
	7b		7c		8		Disturbed deposits	
	NISP	MNI	NISP	MNI	NISP	MNI	NISP	MNI
Bovid	61	N/A			39	N/A		
Gazella sp.					1	1		
Bos primigenius	2	1			1	1		
Camelus sp.	10	1	1	1	21	1		
Carnivore - large	1	1						
cf. *Panthera leo*					1	1		
Elephas cf. *hysudricus*							1	1
Elephantid indeterminate							Multiple	N/A
Palaeoloxodon cf. *recki*	23	1			27	1		
Equus	4	N/A			8	N/A		
Equus caballus	1	1			3	1		
Equus cf. *hemionus/hydruntinus*	1	1	1	1	1	1		
cf. *Stephanorhinus hemitoechus*	11	1			7	1		
Ungulate	394	N/A	13	N/A	265	N/A		
Mammal	1030	N/A	177	N/A	1452	N/A		



Figure 4.12: Remains of several (straight-tusked?) elephant teeth during 2014 excavation season. Photograph by James Pokines (used with permission).

4.6.4 Paleoenvironment

The deposits at SM1 have produced not only lithic and faunal remains, but also well-preserved sediments that record the changing hydrology and depositional environment. A detailed description is provided in Nowell et al. (2016), but a summary of relevant observations follows (Figure 4.11). Layer 10 is a clay-rich sediment resting on top of the limestone bedrock, and is indicative of lacustrine conditions. Layer 9 is similar to layer 10, but the matrix supports a large portion of angular gravels, suggesting alluvial influx and characteristic of a high-energy facies of a fan delta. A high lake stand in the Azraq Basin is documented at 346-316 kya (Abed et al. 2008), likely correlating with the time frame of Layer 10-9. Layers 8, 7c, and 7b comprise a series of alluvial sediment influx with gradual decreasing energy within the wetlands. The drying trend continues with an overlying unit of eolian sandy silt in Layer 7a. The layers of hominin occupation (8 and 7b-c) are associated with a transitional environment from a lake (Layer 9) to a series of marshy ponds formed at the edge of a fan-delta, which are capped by an eolian dune (Layer 7a) (Nowell et al. 2016).

The paleobotanical and mammalian faunal data also provide information on the environmental nature of the GAOA and surrounding region. Both pollen and phytoliths were discovered in the archaeological layers. A variety of aquatic vegetation is present, such as sedges (*Cyperaceae*), rushes (*Juncaceae*), and cattails (*Typha* spp.). The desert plants appear in the form of sand dune vegetation (*Calligonum comosum*) and dry-adapted and salt-tolerant chenopod scrub (*Chenopodiaceae*). Collectively, these remains indicate a predominance of aquatic vegetation surrounded by scrub typical of modern deserts in the Near East (Nowell et al. 2016). The aforementioned faunal remains contain large and medium-sized herbivores, namely camels, rhinos, and elephants, which exhibit grazer and browser patterns (Pokines et al. 2019). These species are primarily associated with open grassland/shrub habitats and savanna ecosystems (Pokines et al. 2019). The surrounding landscape would have looked much different than today, as human modification (e.g., over pumping, tree-cutting) and over-grazing by livestock have greatly contributed to the lack of vegetation (Copeland 1998).

Together, the sediments and biodiversity indicate a general trend towards a decrease in water availability during the later stages of the Middle Pleistocene and early stages of the Upper Pleistocene. The series of marshy ponds associated with hominin occupation is the result of long-term warming conditions within this region of the Levant. The increasing aridity in the Azraq Basin likely pushed the herds and hominins towards the GAOA.

4.7 Conclusion

The systematic documentation of Paleolithic remains within the Azraq Basin since the 1970s demonstrates that this region was repeatedly occupied during the Middle-Upper Pleistocene. The geohydrological conditions facilitated long-term occupation within the region, particularly around the GAOA. SM1 is part of this occupation and recent excavations offer the opportunity to delve deeper into the nature of survival by reconstructing the procurement strategies associated with its lithic assemblage. This investigation will be guided by the hypotheses and objectives that are outlined in the next chapter.

CHAPTER 5: RESEARCH AIMS, METHODS, AND MATERIALS

Many questions within archaeology require structured investigation, traditionally known as the scientific method (Franklin 2009; Popper 1959, 1963), in order to generate robust datasets and provide more grounded interpretations of human behavior. This study is not an exception. As noted in Chapter 1, the overarching aim is to reconstruct the lithic procurement strategies practiced by the hominin occupants of SM1 during the Middle-Late Pleistocene, particularly within the environmental context of the Azraq Basin. This study involves a provenance analysis of stone tools from SM1 and a suite of chert sources from within the Azraq Basin through geochemical data. In this chapter, the research aims are more thoroughly explored and the methods, techniques, and materials used to accomplish them are outlined.

5.1 Hypotheses

The questions posed in Chapter 1 will be investigated through the following hypotheses, which directly pertain to the cultural material discovered at SM1. These are not necessarily mutually exclusive of one another and some are more specific than others. Their acceptance or rejection are dependent upon the data obtained through the methods and techniques discussed in this chapter. Furthermore, they involve treating the lithics from Layers 8 and 7b-c as separate assemblages, thereby offering a comparison of behavior from two periods.

5.1.1 Effect of the environment

The regional climate, environment, and distribution of resources is known to play an influential role in the foraging strategies of hunter-gatherers, particularly those dwelling in desert conditions (Apicella et al. 2012; Hutchet 1991; Kelly 1992). In the GAOA, there is an observed increase in aridity and warming conditions from Layer 8 to Layer 7b-c at SM1 and from Unit 1b to 1c at DM8 (Ames & Cordova 2015; Ames et al. 2014a; Nowell et al. 2016; Pokines et al. 2019). These shifting conditions resulted in a gradual reduction of water and other resources within the Azraq Basin and their concentration within the GAOA. It is possible that these changes affected the procurement strategies exhibited by hominin groups of the two occupational periods at SM1.

- H1) There is a relationship between the environment and procurement. If this is true, it is expected that the following conditions will be observed between the two layers:
  i) Lithics are procured from different sources.
  ii) Lithics are procured from the same sources, but in significantly different frequencies.

- $H1_{null}$) If there is no discernible relationship between the environment and procurement, then no differences are expected between layers.

5.1.2 Logistics of procurement

Procurement strategies appear in several forms, ranging from embedded to direct procurement. Embedded procurement describes the acquisition of lithic material during the execution of other activities (Binford 1978, 1982), such as hunting or fishing. In contrast, direct procurement describes dedicated extraction forays that are conducted to procure raw material from specific sources (Binford & O'Connell 1984). It is possible that the bifaces from SM1 exhibit characteristics of these patterns.

- H2a) The lithics were obtained through entirely embedded procurement. If this is true, it is expected that the following conditions will be observed:
  i) All lithics are procured from sources within the assumed foraging radius or DET (e.g., 5-10 km).
  ii) Lithics are procured from a very high number of sources (>5).
  iii) Lithics appear in a range of quality.

- H2b) The lithics were obtained through mostly embedded procurement. If this is true, it is expected that the following conditions will be observed:
  i) Most lithics are procured from sources within the assumed foraging radius or DET (e.g., 5-10 km).
  ii) Lithics are procured from a high number of sources (>5).
  iii) Lithics may appear in a range of quality.

- H2c) The lithics were obtained through mostly direct procurement. If this is true, it is expected that the following conditions will be observed:
  i) Lithics are predominantly procured from outside the foraging radius or DET.
  ii) Lithics are procured from a low number of sources (<5).
  iii) Most lithics are of high-quality material.

- H2d) The lithics were obtained through entirely direct procurement. If this is true, it is expected that the following conditions will be observed:
  i) All lithics are procured from outside the foraging radius or DET.
  ii) Lithics are procured from a very low number of sources (<5).
  iii) All lithics are of high-quality material.

- $H2_{null}$) If there is no discernible strategy of procurement, then it is expected that lithics are procured from a range of sources at various distances of all qualities.

5.1.3 Forager mobility

The efforts of hunter-gatherers to ensure their survival in the face of fluctuating conditions have been well documented and often include alterations in their mobility (Binford 1980; Greaves 2006; Marlowe 2010; Taylor 1964; Yellen 1976). For the hominins of the Azraq Basin, the diachronic modification to their foraging mobility may have ranged from a close contraction around the GAOA to an expansion well beyond it.

- H3a) Over time, the concentration of foraging shifted toward the GAOA. If this is true, it is expected that the following conditions will be observed:
  i) There is a greater frequency of lithics procured from sources within the GAOA in Layer 7 than in Layer 8.
  ii) There is a greater frequency of lithics procured from sources closer to the GAOA in Layer 7 than in Layer 8.

- H3b) Over time, the concentration of foraging shifted away from the GAOA. If this is true, it is expected that the following conditions will be observed:
  i) There is a greater frequency of lithics procured from sources outside the GAOA in Layer 7 than in Layer 8.
  ii) There is a greater frequency of lithics procured from sources more distant to the GAOA in Layer 7 than in Layer 8.

- $H3_{null}$) If there is no discernible change in foraging range over time, then no differences are expected between layers.

5.2 Provenance analysis

As noted in Chapter 2, provenance analyses characterize the raw materials of artifacts and potential sources in an effort to determine the most probable association between them. This study involves a provenance analysis of a sample of stone tools in order to reconstruct the strategies of lithic procurement at SM1. It follows the approach outlined in Figure 5.1, as it occurs in a region with a known distribution of lithic raw material (Earle & Ericson 1977; Glascock & Neff 2003).

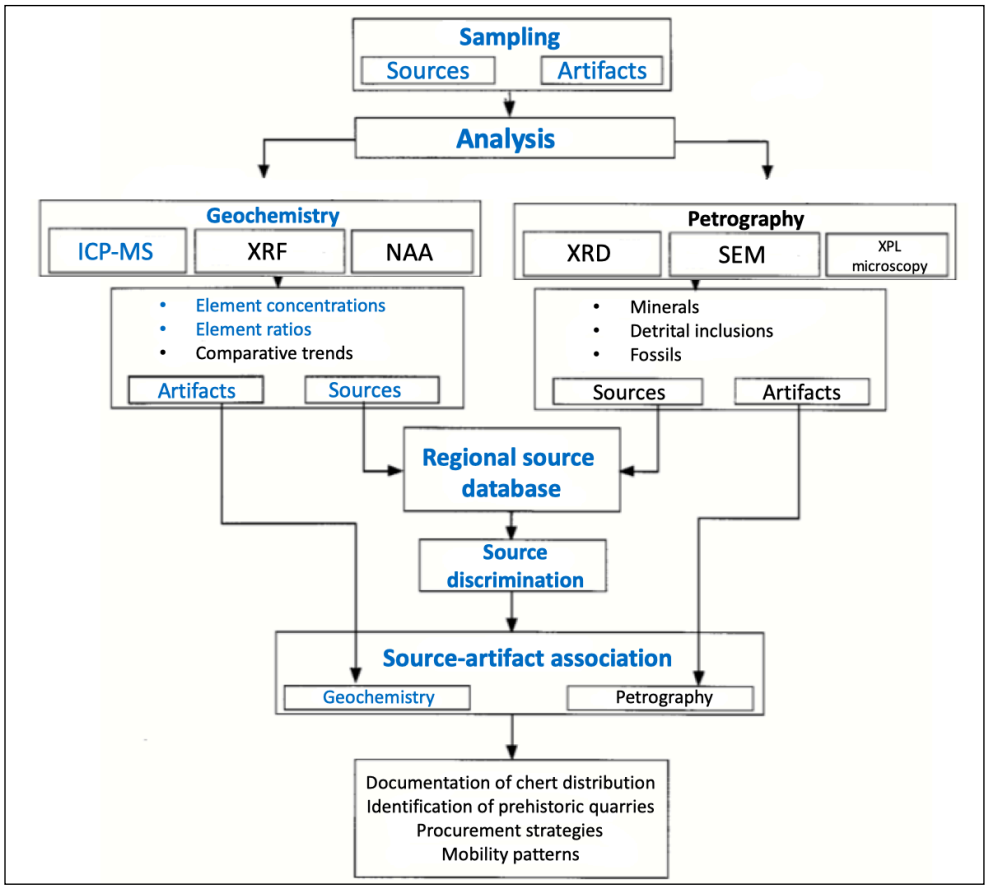


Figure 5.1: Approach (blue text) of provenance analysis involved in present study. Figure modified from Malyk-Selivanova et al. (1988: 678).

The complexities in conducting provenance analyses, specifically chert, have long been recognized (Aspinall & Feather 1972; Dixon 1976; Shackley 1988). A reliance on individual attributes is often applied in regions where chert is found in abundance, such as the Levant (Bar-Yosef 1991; Delage 2007a), as an evaluation of multiple geochemical profiles may seem daunting. Extensive field and laboratory components are incorporated into this study to ensure the most secure results. The objectives outlined below serve to guide the research. They involve individual yet related steps toward achieving the overarching aim that are executed through the methods, techniques, and materials discussed in later sections.

1) Survey for and identify the locations of geological (chert) sources in the Azraq Basin, most notably those within and surrounding the GAOA, through a combined pedestrian and vehicle effort.
2) Document qualitative and quantitative attributes of each source and extract several fist-sized samples using a geological hammer.
3) Generate the geochemical profiles of the artifact and source samples at the University of Victoria through LA-ICP-MS.
4) Evaluate the geochemical data through bivariate scatterplots of trace elements in order to identify geochemical consistencies between artifacts and sources.
5) Interpret the results within the broader context of archaeological patterns and geohydrological conditions in the Azraq Basin.

5.3 Geoarchaeological survey

A geoarchaeological survey is the first step to the provenance analysis. It requires an understanding of the expected geology to be encountered in the survey area—the Azraq Basin in this study. The survey of the GAOA and surrounding Azraq Basin was conducted to document sources (primary and secondary) of chert and collect representative geological samples. Ideally, the survey would obtain sufficient samples to generate a baseline of attributes and geochemical profiles for each formation. These contribute to a reference database of potential raw material sources that may have been accessed and exploited by the hominins of SM1 for the manufacture of bifaces.

The survey was developed through the analysis of geological maps and bulletins (Section 4.3), knowledge of the boarder landscape from the AMAPP project geographer (Dr. Carlos Cordova), knowledge of local exposures and *wadis* from the local residents and Mr. Ashraf Kraysha—a representative from the Department of Antiquities of Jordan, toponymic information, and input from Dr. Dante Canil. While the sedimentary landscape of the Azraq Basin is considered to be chert-rich (Andrews 1992; Bender 1974; Rollefson 1980), it is not necessarily apparent where chert beds are distributed and exposed. Dunes extends for kilometers across the basin and cover a considerable portion of the underlying rock.

Originally, the survey planned to encompass a regional range with a radius of 20 km and to sample sources in all cardinal and intercardinal directions (n=8) every 5 km from SM1. Global positioning system (GPS) coordinates for the ideal locations (or within their vicinity) to sample were obtained from Google Earth®. An initial combined pedestrian and vehicle survey was conducted in Spring 2015. During the afternoons of one week of the 2015 excavation season, surveys in the GAOA and local area were undertaken. Dr. Cordova and the author drove off-road until the terrain required a walk to where exposures were potentially located. Fairly often, an exposure could not be located and they returned empty-handed. In fact, sources could not be found at most desired cardinal and intercardinal on the landscape.

In Summer 2018, another survey was conducted over the course of two weeks by the author and Mr. Kraysha. The skewed distribution of chert within the region prompted any future survey to extend the radius to 35 km in order to (hopefully) include sources in areas that had low elevations or relatively few sources (e.g., Wadi Ghadaf, Wadi Rajil). In addition, greater attention was afforded to the *wadi* sectors that feed into Qa' Azraq, as these likely cut through chert beds, but also served as secondary sources. The innumerable clasts that travel down the *wadis* compose a collective secondary. However, the rigorous sorting and gradual decrease in fluvial energy as the *wadis* approach Qa' Azraq means only small cobbles and under (Udden-Wentworth scale) are deposited into the *qa'*. These clasts are considerably smaller than the required blank size (20-25 cm) of the bifaces found at SM1 (Dan Stueber pers. comm. 2015; Gary Rollefson pers. comm. 2017). Clast sizes were tracked up the various *wadis*, by vehicle and foot, until suitable blank sizes were discovered. It should be noted that ancient water movement during severe flooding could bring clasts closer to the *qa'*, though what additional distance cannot be established. Secondary sources seemed to predominate, though where primary sources occurred there were often multiple beds exposed.

Moving throughout parts of the region were met with difficulty. Quite frequently, Mr. Kraysha would hail a local resident or Bedouin herder and inquire where a *wadi* outlined on the map could be accessed or if the individual knew of any chert exposures. *In situ* chert beds (primary sources) were infrequently exposed along *wadi* sectors, isolated escarpments, modern quarries, and road cuts. In terms of direction, most available sources in the region are located to the west

and southwest of SM1 and materials from these areas compose most of the represented sources included in this study. The landscape within a radius of 15 km from SM1 was almost surveyed in its entirety. Several areas within this range that could not be accessed included the Al-Azraq Air Base, Shawmari Wildlife Reserve, residential plots, and certain agricultural fields.

There were several areas in the 15-30 km range in which chert sources, neither primary nor secondary, could be identified. For example, no sources were discovered within Qa' Azraq, likely due to its low elevation and sediment cover. The extensive cover of the Harrat Ash-Shaam basalt plateau also limited the exposure of chert beds in the northern Azraq Basin. This area was surveyed to the northwest of the GAOA using highway 40 and various trails to which it gave access, as well as walking upstream Wadi Enoqiyya to approximately 12 km from SM1. The *wadi* runs roughly northwest to southeast from the heights of the plateau until reaching the northern boundary of Qa' Azraq (Figure 4.6). It operates as a secondary source, but this sector contained very few clasts of chert and was largely comprised of basalt cobbles and pebbles. While no chert clasts were collected as samples, multiple chert flakes and tools indicative of a Lower-Middle Paleolithic presence were observed. These were not removed from the *wadi* sector and were left in the location of their discovery for future archaeological investigation. Survey was abandoned in this area in order to visit other locations. It is still possible that certain chert exposures are present within the basalt plateau. Upstream Wadi Rattama in the west, there were several other exposed chert beds through which the *wadi* meanders. These were left unsampled as samples were extracted downstream.

A foremost issue with the survey was the inability to cover such a large region, both by foot and vehicle, as several areas and the sources within them were inaccessible. Access to the Umari area in the southeast was prohibited for security reasons, though this was not made entirely clear. It is possible that some exposures (e.g., modern quarries) are present in this area, despite its low elevation. Many sources were located at long distances from emergency services and outside the range of cellular phone service. There were very few "roads" and travel had to occur over dune fields littered with sharp chert detritus. These circumstances caused several problems. For example, the vehicle received two flat tires and a shattered window in the span of an hour in the distant reaches of Wadi Jilat, south of SM1. The entire day was lost, as the vehicle was slowly driven ~10 km on its barrels to a main highway, where the author and Mr. Kraysha hitchhiked to

a mechanic. The survey in this portion of the sector had to be abandoned and no samples were retrieved and included in the study. Another flat tire was also received in Wadi al-Masayil (east), though this sector was revisited at a later date.

A total of 32 sources were sampled at 18 localities. When encountered, specific quantitative and qualitative details regarding each source were documented:

- GPS coordinates: The GPS coordinates allow for the establishment of the distance (straight line in km) from SM1. The coordinates present in latitude and longitude and are based on the WGS84 system. These were taken in the field with a Garmin inReach SE+ handheld GPS at the site of sample extraction.

- Photographs: Images of the sources provide visual information on the scale of outcrops and *wadis*. It further allows the reader to conceptualize how the sources are situated in the broader landscape. The photographs were taken with a Canon PowerShot Sd780 IS Digital ELPH and iPhone 7 as well. They often include a person, stadia rod, rock hammer, or vehicle for scale.

- Parent formation: Identification of the geological formation to which the outcrops belong allows the documentation of their horizontal distribution, location of exposure, and degree of availability within the region. The identifications are determined through the consultation of geological maps and bulletins, as well as the comparison of strip log stratigraphy with that found at the source (Section 4.3). For secondary sources, the *wadis* were tracked upstream to identify the formations that contribute clasts to them.

- Stratigraphic sequence: This involves the identification of the host rock(s) in which the chert is situated. In the formations of the Azraq Basin, chert typically appears in chalk, marl, dolostone, and limestone. These rocks were identified by their distinctive material properties, including effervescence from HCl acid. The sequences of rocks have

implications for understanding the depositional environments and current weathering patterns of cherts.

- Number of chert beds: This involves a straightforward count of the exposed chert beds. It provides a description of the abundance of chert present at the outcrop.

- Source type: Sources are either primary or secondary. Descriptions of primary sources include their degree of exposure, where bed dimensions are recorded with a measuring tape (length x height). For secondary sources, clast sizes, based on the Wentworth (1922) scale, were tracked up the *wadis* until suitable clast sizes for blanks were reached.

- Individual attributes: This collective analysis is relied upon for a subjective description of each source. The sources samples were fractured open to reveal the fresh and untethered interiors for a more accurate description. The attributes were evaluated by eye and a hand lens (40x, 25 mm) under natural light. The relevant attributes are discussed in Section 2.4.1 and are also listed below.
    - Color: The color of each chert sample was evaluated according the codes and terminology used in the Munsell soil color charts (Munsell 2000). Each sample was held against the book under natural light in order to identify the most suitable color. The full range of colors in the samples was noted, as were variations in a single color.
    - Translucency: The translucency of each chert sample was evaluated by viewing pieces of a similar thickness (~0.5 cm) against natural light. Translucency is described on a transparent to opaque scale.
    - Texture: The texture of each chert sample was evaluated by running the thumb over a newly fractured surface and viewing it under natural light. Texture is described on a spectrum from fine- to coarse-grained.

- Luster: The luster of each chert sample was evaluated by viewing and rotating the exposed surfaces under natural light. Luster is described on a spectrum from shiny to dull.
- Quality: The quality of each chert source, specifically primary sources, was evaluated through experimental knapping with a basalt hammer stone and rock hammer, as well as a consideration of its matrix, inclusions, and structural flaws. Additional input on some sources was provided by Mr. Stueber. Quality is described on a spectrum from very low to very high.

5.4 Artifact sample

The near ubiquity of stone tools at hunter-gatherer sites makes them an excellent material through which insight into hominin behavior can be obtained. They are geologically durable and do not weather or degrade at the rates of organic material. Stone tools have long served as tested material for provenance studies.

As noted in Section 4.6.2, the lithic assemblage from SM1 is most consistent with the LAA facies (Nowell et al. 2016). It includes 80 bifaces, which can be further divided into handaxes (n=76) and cleavers (n=4). Two cores related to biface reduction were discovered for a total of 82 artifacts related to biface procurement. Of these 82, 42 artifacts originate from Layer 7 and 40 artifacts from Layer 8. The 42 artifacts from Layer 7 can be further apportioned to four from Layer 7c, 32 from Layer 7b, and six from Layer 7a-b. Contextual information and qualitative and quantitative data on each biface and related cores are included in Appendix 1. An initial evaluation of their raw material identified them as chert. All were manufactured through soft hammer percussion with the use of a billet (e.g., antler, bone) or soft hammerstone (e.g., dolostone, limestone) (Dan Stueber pers. comm. 2019).

The *wadi* sectors that flow into the GAOA deposit clasts that are smaller than the necessary size of blanks for the manufacture of bifaces (Dan Stueber pers. comm. 2015; Gary Rollefson pers. comm. 2017). This observation led to the supposition that the bifaces were manufactured off-site, possibly from distant sources outside the GAOA, and brought into SM1. At the nearby site of ‘Ain Soda, Rollefson et al. (2006: 65) also observed that some sources for the bifaces “had not been

located and may have come from some distances away". The clasts brought into the Shishan Marsh are small and suitable for the manufacture of smaller pebble tools, which dominate the SM1 lithic assemblage. These tools were likely made on-site from material within the immediate vicinity of the site, while the larger bifaces likely originate from more distant sources. This latter supposition was supported by the low amount of debitage related to the manufacture of bifaces in the assemblage (Dan Stueber pers. comm. 2015). In order to investigate their source of origin, a sample of bifaces (n=36) and biface cores (n=2) was selected for the provenance analysis (Table 5.1; Appendix 2). The two cores are biface-like with no functional edges and no evidence of use wear. This total sample size (n=38) is almost half the biface assemblage and is likely to be representative of all 80 artifacts. Since intact bifaces are aesthetically valuable to museums, their destruction, however minimal, is not always possible. This was the case for many of the bifaces from SM1 and limited the sample size.

Bifaces are considered versatile and multi-functional tools, similar to the Swiss Army knife of today, making them very valuable gear to the user (Keeley 1980; Keeley and Toth 1981; Posnansky 1959). The long edges and pointed distal ends of handaxes permit their involvement in a number of subsistence activities and possibly defense against predators (Rollefson et al. 2006). Indeed, experimental work has demonstrated their capability for woodworking, butchery, piercing, digging, and other tasks (Keeley 1980; Mitchell 1995; Schick and Toth 1993). Moreover, it is assumed that these generalized tools likely underwent different procurement and manufacture stages than more expedient or even more specialized tools (Ashton & White 2003; Kelly 1988; Shea 2013). In this capacity, bifaces may constitute the personal gear of a mobile forager and could be re-sharpened and modified (curated) for further use (Binford 1979; Hayden 1979; Kelly 1988; Kuhn 1994). Consequently, bifaces are often moved over long-distances and likely for extended periods of time, potentially being indicators of the maximum mobility range.

Table 5.1: Artifact sample selected for LA-ICP-MS.

Artifact ID	Layer	Square	Quadrant	Type	Biface / Core Type	Length (mm)	Width (mm)	Thickness (mm)	Selected for LA-ICP-MS	Material Quality
1200	7	S2	NW	Core	Bidirectional	86.8	60.97	46.63	Yes	Medium
1767	7	R2	SE	Handaxe	Amygdaloid	122.27	80.08	27.7	Yes	High
2557	7	N2	NW	Handaxe	Ovate	92.89	64.17	25.22	Yes	High
2941	7	R3	NW	Handaxe	Ovate	97.45	66.49	25.48	Yes	High
2947	8	Q3	NW	Handaxe	Ovate	105.06	83.25	33.74	Yes	High
3082	8	P3	NE	Handaxe	Ovate	122.68	87.72	20.72	Yes	Very high
3118	7	Q3	NE	Handaxe	Ovate	112.62	94.93	32.61	Yes	Very high
3131	7	Q3	NE	Handaxe	Ovate	89.57	59.84	22.2	Yes	High
3468	7	Q4	NE	Handaxe	Ovate	109.86	82.86	30.94	Yes	Medium
3547	7	R3	SE	Handaxe	Discoid	82.4	72.51	36.44	Yes	High
3591	8	P4	NE	Core	Bidirectional	100.56	63.61	52.37	Yes	Medium
3603	7	Q4	NW	Handaxe	Ovate	92.66	61.47	23.76	Yes	Very high
3711	8	Q5	NW	Handaxe	Ovate	97.74	75.98	30.99	Yes	High
3805	8	Q4	SE	Cleaver	Ovate	121.91	77.76	49.51	Yes	High
3806	8	Q4	SE	Handaxe	Discoid	93.16	85.96	29.46	Yes	Very high
3883	7	P5	NW	Cleaver		88.82	61.27	20.9	Yes	Medium
3912	7	P5	SE	Handaxe	Ovate	79.2	49.83	15.85	Yes	High
4018	7	Q5	NE	Handaxe	Preform	70.12	58.08	26.37	Yes	High
4033	8	P5	NW	Handaxe	Ovate	144.05	95.31	27.31	Yes	High
4038	7	Q5	SW	Handaxe	Ovate	95.56	59.09	29.84	Yes	Very high

4134	7	Q5	NW	Handaxe	Ovate	95.1	63.29	28.71	Yes	High
4192	8	Q5	NW	Handaxe	Ovate	81.78	62.55	28.71	Yes	High
4215	8	O3	SW	Handaxe	Ovate	129.75	92.55	29.73	Yes	Very high
4278	8	P5	SW	Handaxe	Ovate	58.42	49.49	26.09	Yes	High
4396	8	O4	NW	Handaxe	Discoid	126.98	103.16	29.9	Yes	High
4425	8	O5	NE	Handaxe	Ovate	100.23	81.33	30.89	Yes	High
4488	7	O4	SE	Handaxe	Ovate	118.73	75.22	41.2	Yes	High
4495	7	O5	SE	Handaxe	Ovate	98.46	81.14	27.18	Yes	High
4522	8	O5	NE	Handaxe	Ovate	105.9	75.75	31.06	Yes	High
4548	8	O4	SE	Handaxe	Ovate	118.1	66.2	21.05	Yes	Medium
4622	8	O4	SE	Handaxe	Ovate	111.28	98.32	33.11	Yes	High
4651	8	O5	NW	Handaxe	Ovate	118.56	61.28	23.89	Yes	High
4671	8	O5	SW	Handaxe	Ovate	71.9	61.63	22.72	Yes	High
4673	8	O5	SW	Handaxe	Ovate	130.23	77.88	39.91	Yes	High
4675	7	N3	NW	Handaxe	Ovate	84.75	58.7	33.83	Yes	Medium
4751	7	O1	NE	Handaxe	Discoid	130.45	80.59	46.23	Yes	Very high
4752	7	N3	SE	Handaxe	Ovate	107.83	73.18	43.95	Yes	High
4826	8	N3	NE	Handaxe	Ovate	119.1	86.03	26.77	Yes	High

5.5 Laser ablation-inductively coupled plasma-mass spectrometry

The geochemical profiles of both the geological sources and a sample of artifacts are obtained in this study through laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). This technique uses a laser to vaporize a microscopic portion of a material, producing an aerosol that is ejected from the ablation chamber through a stream of argon gas. The aerosol is then coupled into an argon plasma sustained at the ICP-MS torch, which becomes ignited and creates ions by freeing electrons. The ions pass through an interface of cones into the mass spectrometer where they are separated and their concentrations are detected based on their mass-to-charge ratio. Ablating the sample with a laser has provided a viable alternative to other sample digestion methods that involve time-consuming combinations of strong acids and/or heat (Speakman & Neff 2005).

LA-ICP-MS offers several advantages over alternative techniques, such as AAS and NAA. LA-ICP-MS offers rapid analytical time, high sample throughput, minimal damage to the sample, and low detection limits (Neff 2012b; Speakman & Neff 2005). It is sensitive to a wide range of elements (^{6}Li-^{238}U) and provides processing on all elements simultaneously, with multi-element detection limits below parts per million (ppm, 10^{-6}) and even into parts per billion (ppb, 10^{-9}) (Pollard et al. 2007). It has proven to be an effective and reliable technique with the capacity to produce quantitative results with accuracy (Neff 2012b). Previous studies have utilized it for discriminating among potential sources of chert, both primary and secondary, with success (e.g., Andreeva et al. 2014; Finkel et al. 2019; Milne et al. 2009; Moreau et al. 2016; Navazo et al. 2008). Consequently, LA-ICP-MS has become an increasingly preferred technique by archaeologists for provenance investigation (Pollard et al 2007; Dussubieux et al. 2016; Neff 2012b; Speakman & Neff 2005).

LA-ICP-MS analysis of 38 lithic artifacts and 32 sources was conducted at the ICP-MS and Laser Ablation Facility in the School of Earth and Ocean Sciences at the University of Victoria, Canada, under the guidance of Dr. Jody Spence. Several different samples were selected from each source. Source samples were run as two sets under the same instrument conditions, but through slightly different sample preparation procedures. On both occasions, each sample was struck to produce a small flake (or subsample), approximately 1 cm^2 in surface area, from the most

homogenous (or purest) portion. This permitted exposure to the interior in order to avoid ablating the dust covered, weathered, and occasionally patinated or glazed exterior surface. For the first set, subsamples were glued six to a glass slide and placed on the stage for ablation. The subsamples of the second set were crushed into smaller flakes and fitted into the cylindrical chambers of a plastic disc. The chambers were filled with resin to solidify the subsample in place at the bottom of the disc. Once solid, the bottom of the disc was polished with progressively finer-grit sand sheets (800, 2000, 4000) until the flakes of the subsample were exposed and smooth. The disc was then flipped so that the subsamples could be ablated. This preparation allowed for a quicker processing time in the instrument, as 23 subsamples could be run without the interruption and resetting the instrument and computer, rather than six. Both sets of subsamples were ablated 3-10 times. Multiple ablations on the subsamples contribute to establishing a larger potential range of variation for each source. The tested samples of the artifacts were prepared in a similar manner as the first set of source samples. A small flake was carefully struck off each artifact. The flake was further crushed to remove smaller pieces of its fresh ventral side, as these resided at a depth well below the influence of any exterior weathering. These were fixed to glass slides. The artifacts were ablated 3-5 times. For both sources and artifacts, each ablate occurred in a different spot and inclusions were avoided.

The measurements of elements were carried out in a quadrupole Thermo X-series 2 ICP mass spectrometer (Figure 5.2). An internal standard-independent calibration strategy was applied which mirrored Chen et al. (2011). The samples were ablated by a New Wave UP-213 Laser Ablation System with a laser beam diameter of 100 μm and a pulse frequency of 10 Hz. The energy density of ablation was 10 J/cm^2. The first set of source samples were ablated with an immobile laser. The 38 artifacts and second set of source samples were ablated by a 300 μm line raster on the second set of source samples in order to cover a greater surface area and provide a larger bulk composition. NIST Glass 611, 613, and 615 (all SRM) were utilized for external calibration and precision was ensured by repeated analysis of NIST Glass 611 and periodic analysis of NIST Glass 613 and 615. Argon was the carrier gas. The raw data were collected using Thermo Plasmalab v. 2.6.1 software and data reduction was performed offline with Microsoft Excel.

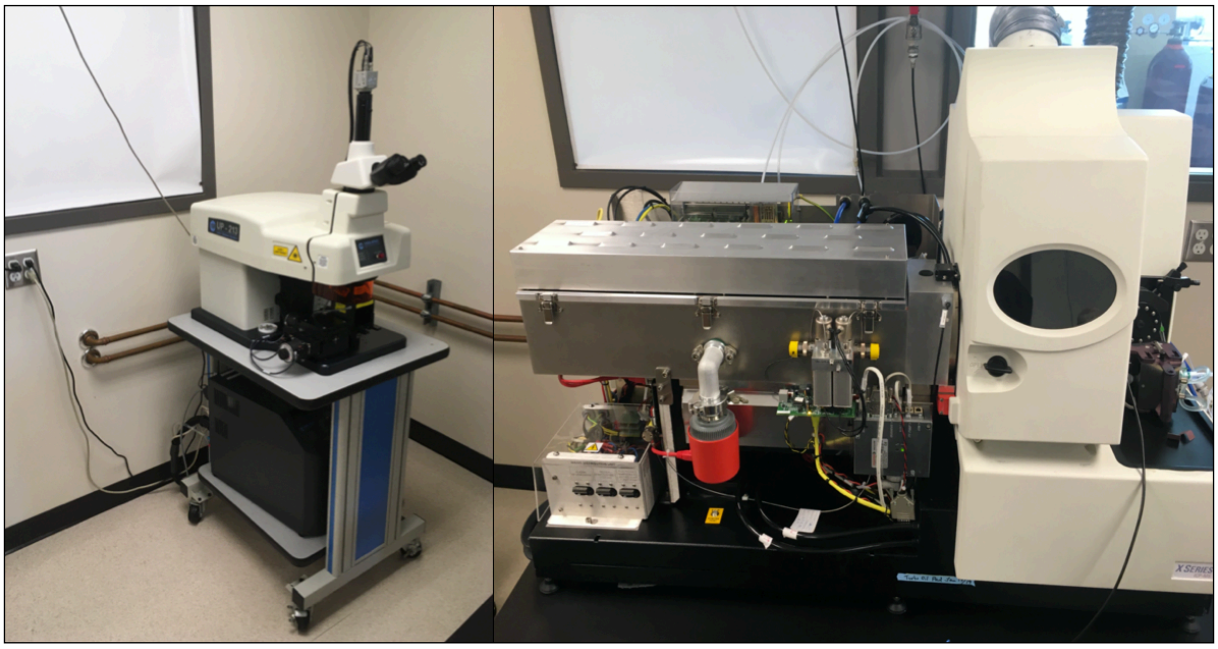


Figure 5.2: LA-ICP-MS instrument at the University of Victoria with laser chamber (left) and mass spectrometer (right). Photographs taken by the author.

5.6 Conclusion

In accordance with the overarching aim, the hypotheses presented in this chapter were designed to permit an effective investigation into the nature of lithic procurement at SM1. These can be tested by first accomplishing the stated objectives, which pertain to the collection and analysis of data. The provenance analysis provides the foundational data upon which interpretations of procurement behavior can be constructed. The results of this analysis are presented in the next chapter.

CHAPTER 6: ANALYSIS AND RESULTS

At the core of this study is a provenance analysis that involves a comparison of the geochemical profiles of chert sources within the Azraq Basin and artifacts from SM1. It was initiated due to the observation that the various *wadi* sectors did not deposit clasts of appropriate blank sizes for the manufacture of bifaces into the vicinity of SM1. As described in Chapter 5, the provenance analysis involved several stages, including the collection of source material within the Azraq Basin, sampling artifacts from SM1, and the generation of geochemical profiles of both through LA-ICP-MS. This chapter presents the results of the provenance analysis.

6.1 Description of sources

The geoarchaeological survey of the GAOA and a large portion of the surrounding region of the Azraq Basin identified and sampled 32 sources (Appendices 3-4; Figures 6.1-6.2; Table 6.1). At several primary sources, more than one chert bed was accessible; each was considered an individual source. Nodules sampled in massive chalk or limestone formations were treated as a single collective primary source. A secondary source sampled at different spots was still considered to be a single extensive source. Each sample selected from a secondary source could indeed represent a different primary source from which it originated. It should be noted that the descriptions of materials from secondary sources do not encompass the full range of attribute variability within secondary sources, as the *wadis* are fed by multiple primary sources. Sampling locations were largely selected for their incremental distances from SM1, ranging from the immediate vicinity (e.g., ‘Ain Soda, ‘Ain Qasiyya) to more distant reaches (e.g., Wadi Ghadaf, Wadi Rajil) from the site. However, the distribution of chert sources in the Azraq Basin is not uniform. There is a predominance of sources outside the GAOA, but within 10 km of SM1, which reflects the availability and exposure of the formations and the distribution of *wadi* sectors in the region. The sources are discussed by the catchment area in which they are located.

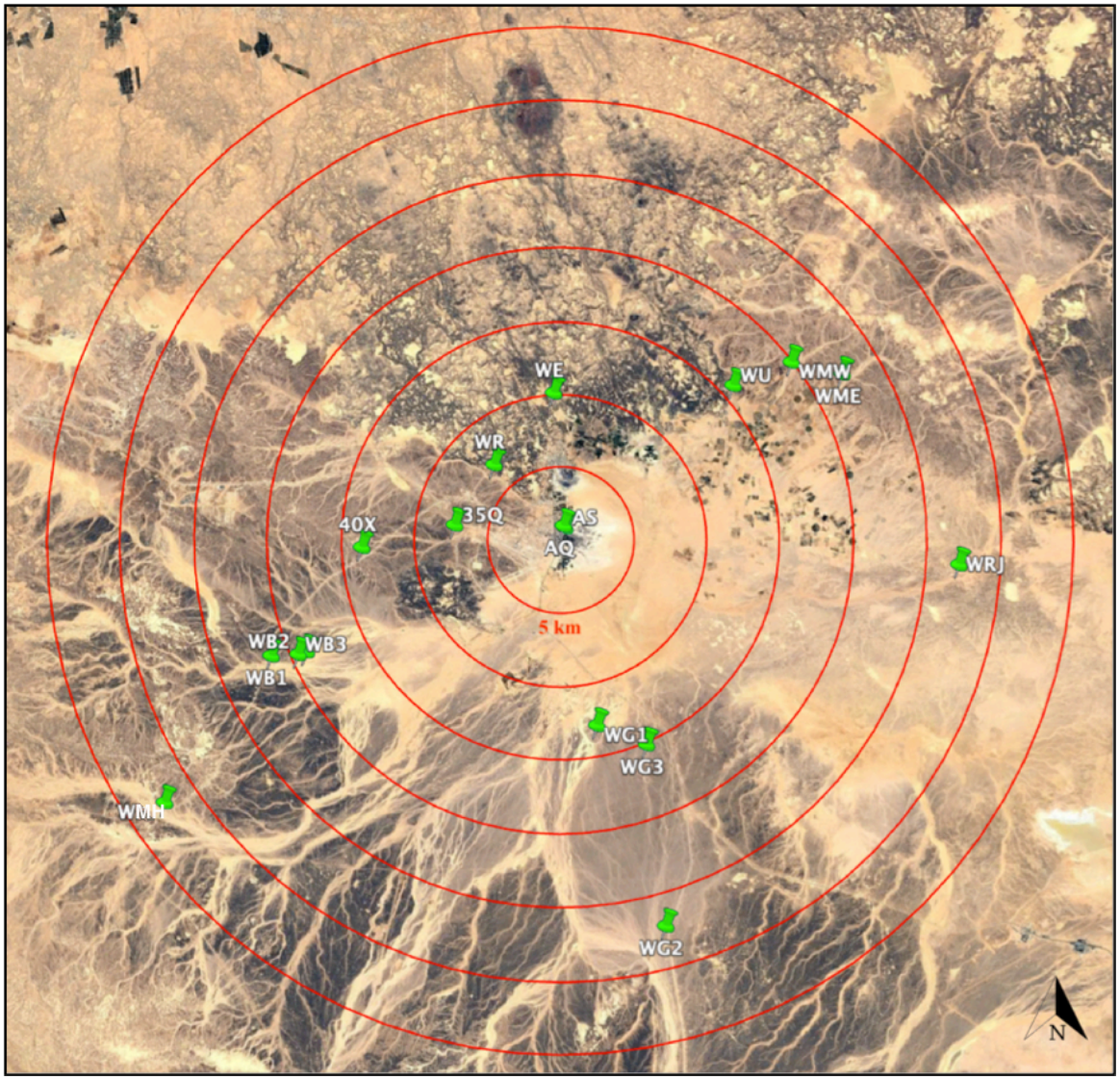


Figure 6.1: Map of the central Azraq Basin with the locations of documented sources included in this study. Each ring is a sequential 5 km. Figure created from Google Earth®.

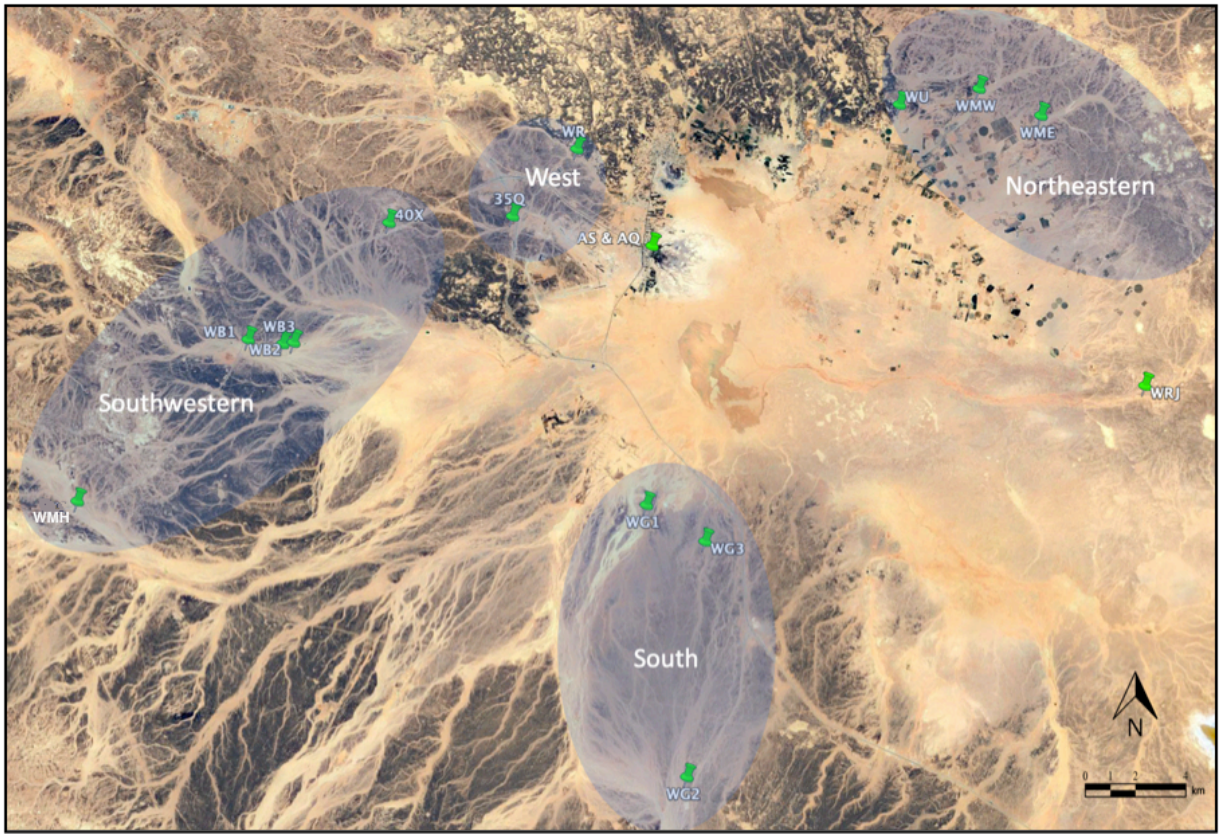


Figure 6.2: Different catchment areas of the Azraq Basin in which sources were sampled. Figure created from Google Earth®.

Table 6.1: Abbreviated description of sampled chert sources in the Azraq Basin. Additional information is provided in Appendix 3.

Formation (Section 4.3)	Source	# of beds or samples	Latitude	Longitude	Distance from SM1	Source type
Harrat Ash-Shaam basalt	Wadi Enoqiyya	N/A	31°54'51.4"	036°50'3.2"	9 km	N/A
Wadi Shallala Chalk	Wadi Mushash 1	1	31°43’38.8”	036°29’26.8”	33 km	Primary
	Wadi Mushash 2	1	31°43’38.8”	036°29’26.8”	33 km	Primary
	Wadi Mushash 3	1	31°43’38.8”	036°29’26.8”	33 km	Primary - disembedded
Umm Rijam Chert-Limestone	35Q	3	31°51’00.8”	036°44’30.6”	7.5 km	Primary
	40X	13	31°51’02.1”	036°40′22.3”	14 km	Primary
	‘Ain Qasiyya	1	31°50’01.2”	036°49’04.5”	200 m	Primary - disembedded
	‘Ain Soda 1	1	31°49’56.4”	036°49’07.3”	50 m	Primary - disembedded
	‘Ain Soda 2	1	31°49’58.5”’	036°49’07.8”	50 m	Primary - disembedded
	‘Ain Soda 3	1	31°49’58.6”’	036°49’07.3”	75 m	Primary - disembedded
	Wadi Rattama	5	31°52’49.1”	036°46’47.8”	6.5 km	Primary
Unclear – secondary sources, most likely WSC	Wadi Ghadaf 1	1	31°42’35.8”	036°48’24.5”	13 km	Secondary
	Wadi Ghadaf 2	2	31°34’49.1”	036°49’12.5”	28 km	Secondary
	Wadi Ghadaf 3	1	31°41’27.8”	036°50’17.5”	16 km	Secondary
Unclear – secondary sources, most likely URC	Wadi al-Masayil (east)	3	31°52’57.8”	037°02’23.6”	21.5 km	Secondary
	Wadi al-Masayil (west)	3	31°53’50.3”	037°00’22.8”	19 km	Secondary
	Wadi Butm 1	1	31°47’57.3”	036°35’26.3”	22 km	Secondary
	Wadi Butm 2	1	31°47’47.9”	036°36’57.0”	19.5 km	Secondary
	Wadi Butm 3	1	31°47’46.3”	036°36’35.0”	20 km	Secondary
	Wadi Rajil	3	31°45’06.8”	037°05’17.9”	27 km	Secondary
	Wadi Usaykhim	3	31°53’31.6”	036°57’41.2”	15 km	Secondary

6.1.1 On-site

This catchment area refers to sources and associated clasts that can be found within the vicinity (<500 m radius) of SM1. These include the disembedded sources of ‘Ain Soda and ‘Ain Qasiyya.

6.1.1.1 ‘Ain Soda (AS)

SM1 is located along the margin of the former ‘Ain Soda pool within the larger Shishan Marsh. Approximately 50 m, 50 m, and 75 m from the excavation are three small exposures of chert beds that currently protrude from the low-lying sediment. These exposures (AS1, AS2, and AS3) are largely disembedded from what is likely a more extensive horizontal portion of the formation, though no underlying lithostratigraphy is currently visible. The ‘Ain Soda outcrops were (re)exposed by heavy equipment excavation during the 1980-90s in an effort to reach the dropping water table. They are situated at approximately the same basal elevation as SM1 and may have been accessible to hominins at the time of occupation.

The interior portions of the samples (AS1, AS2, and AS3), one from each exposure, are fairly homogenous, particularly in terms of color, ranging from gray (5Y 5/1) to dark gray (5Y 4/1). The material is fairly opaque with a fairly dull luster and relatively few calcareous inclusions (<1 mm). It is slightly coarse-grained, but is still suitable for knapping and is described as medium-high quality. Based on their elevation and similar attributes, it is likely that the three sources originate from the same bed, though this cannot be established for certain at present. The various attributes are consistent with observations of the URC and MCM formations (e.g., Sánchez de la Torre et al. 2019). However, given the distribution of the URC Formation in the area, it is most likely that the ‘Ain Soda outcrops belong to it.

6.1.1.2 ‘Ain Qasiyya (AQ)

‘Ain Qasiyya is another former pool within the Shishan Marsh located approximately 200 m north-northwest of SM1. The setting of ‘Ain Qasiyya is similar to the ‘Ain Soda outcrops in that it is currently (re)exposed in a dry section of the Shishan Marsh and protrudes from the surface sediment. The ‘Ain Qasiyya outcrop (AQ1) is largely disembedded from a secure stratum and is

surrounded by a large scatter of free chert boulders and cobbles. Given the distribution of the URC Formation, it is likely that ‘Ain Qasiyya belongs to it. However, it is uncertain whether ‘Ain Qasiyya is part of the same bed as the ‘Ain Soda sources, as it is situated at a slightly higher elevation.

Similar to the ‘Ain Soda sources, AQ1 exhibits a fairly homogenous appearance and ranges in color from gray (5Y 5/1) to dark gray (5Y 4/1). It is fairly opaque with a slightly coarse-grained texture. It exhibits a fairly dull luster, but relatively few inclusions, namely minute calcareous grains (<1mm). This material is of medium-high quality and is suitable for tool manufacture.

6.1.2 Western area

The western catchment area is closest to SM1 and includes *wadi* systems that drain directly into the western portion of the GAOA. It encompasses Wadi Rattama and unnamed *wadi* sectors (35Q) interrupted by the modern Al-Azraq Air Base and industrial development, but can extend north to include Wadi Enoqiyya. Wadi Enoqiyya was surveyed, but no chert beds or clasts were discovered within it (see Section 5.3).

6.1.2.1 Wadi Rattama (WR)

Wadi Rattama flows northwest to southeast into Qa’ Azraq and feeds directly into the GAOA between the Druze and Shishan marshes (Figure 4.6). It cuts through the URC Formation and likely operated as both a primary and secondary source, as boulders, cobbles, and pebbles are freed from the beds along its banks. The fluvial energy of Wadi Rattama decreases so rapidly towards Qa’ Azraq, that only small cobbles and pebbles are found at the entrance to the GAOA. Suitable clast sizes for the manufacture of bifaces were traced to approximately 6.5 km upstream from SM1. Closer to the low elevation of the *qa’*, alluvial and eolian sediments cover the landscape and currently hide all lithostratigraphy of the URC Formation. Six chert beds (WR- 1-6) were exposed at the location of sampling. These are situated among calcareous beds of chalk and limestone, which separate the deposition of chert beds by significant periods of time. Each bed was sampled to establish the vertical variability of the stratigraphic sequence.

Although the beds appear in close vertical proximity to each other, there are some notable differences among their individual attributes. WR-1 presents as reddish gray-brown (2.5YR 5/1) and is overall fairly homogenous with very few inclusions (<1 mm). It is fine-grained, slightly translucent and shiny, and high-quality material. In contrast, WR-2 is of various grays (Gley 2 7-5/5BG-5PB), opaque, dull, and slightly coarse-grained. It is slightly homogenous with numerous minute calcareous inclusions (<1 mm), but medium-high-quality material. WR-3 and WR-5 are similar, appearing as a limited range of grays (Gley 2 6/10BG-10B), opaque, dull and fine-grained. Overall, they are fairly homogenous and high-quality materials. Lastly, WR-4 is very similar to WR-3 and WR-5, but is a different gray (7.5YR 5/1).

6.1.2.2 35Q

The 35Q sources are located 7.5 km west of SM1 and are part of a natural *wadi* sector that has recently been exploited as a modern quarry. Access to the quarry has been enabled through the recent construction of highway 35 that bypasses the main junction within the town of Azraq and detours around the Al-Azraq Air Base. Several chert beds are visible along the *wadi* and clasts of various sizes are strewn along the *wadi* bed. Modern development of the highway has removed most discernible traces of clast movement further downstream (towards Qa' Azraq). Heavy equipment operation of the quarry has cut into a segment of the *wadi* and exposed additional chert beds beneath those in the *wadi*. The beds appear in an almost rhythmic sequence interdigitated with calcareous layers. This pattern is typical of the URC Formation to which they likely belong, given the expansive distribution of the URC Formation in this area. The calcareous layers separate the chert beds by distinct periods of time, indicating that they might exhibit different geochemical profiles. Each bed varies in thickness, from 5-10 cm, across its exposure, allowing disembedded clasts of various sizes to be produced. The three exposed chert beds along the *wadi* were sampled. The quarry contains additional beds that were not sampled, as they were likely buried well below the surface and inaccessible to both hominins and elements of past weathering.

The attributes of the 35Q materials exhibit some variety, although all are high-quality chert. 35Q-1 and 35Q-3 are brown (7.5YR 5/2) and slightly translucent with a fine-grained texture. 35Q-3 exhibits a shinier luster and is more homogenous than 35Q-1. 35Q-3 is grayish brown (10YR

5/2) and slightly shiny and opaque. There are noticeable "patches" of a lighter brown that may represent laminations.

6.1.3 Southwestern area

The southwestern catchment area is fairly extensive, as material from modern road cuts (e.g., 40X) south to Wadi Kharanah becomes incorporated into the various channels, including Wadi Mushash and Wadi Butm. These originate as different sectors, but later converge *en route* to Qa' Azraq.

6.1.3.1 40X

The 40X locality is a road cut through a protruding hill along a portion of highway 40, which runs northeast-southwest across the western half of the Azraq Basin. The cut is through a large section of the URC Formation and is located approximately 14 km from SM1. It exposes 13 chert beds, which are interspersed among rhythmic calcareous beds of chalk and limestone. The presence of these calcareous beds indicates that the intermittent chert beds are separated from each other by significant periods of time. Each chert bed was sampled along the same vertical line.

The attributes within each of the 13 beds (40X- 1-13) are quite variable, but overall the beds are similar to one another. For example, they range in color, from grays to browns, typically gray-brown (7.5YR 5/1-6/3) with a slightly fine- to slightly coarse-grained texture. They exhibit a dull luster and are typically fairly opaque with occasional calcareous inclusions (<1 mm). The attribute providing the greatest variation is structure, as the matrix is fairly heterogenous, with irregular bands or patches of different colors, particularly reddish brown (2.5YR 5/4). The material at this locality ranges from medium- to high-quality and the exposed beds on all sides of the hill and loose clasts within the vicinity provides the opportunity for hominins to select preferable sections.

It is recognized that hominins could not access the specific side that was sampleds, but the sources are included because the beds could be representative of their broader horizontal distribution, as they are heavily eroded on the other three sides of the hill where they are partially

covered in eolian dunes. In addition, they are representative of the vertical variability that can be found at an outcrop with multiple beds.

6.1.3.2 Wadi Butm (WB)

Wadi Butm is an extensive *wadi* sector that flows from the southwest of the Azraq Basin towards Qa' Azraq (Figure 4.6). It is joined downstream by Wadi Janab. This secondary source contains clasts suitable for biface blanks at a distance of 19 km from SM1. At scattered locations, the *wadi* cuts through infrequently exposed chert beds of the WSC and URC formations, releasing clasts of various sizes. Samples were collected at three locations where clusters of clasts aggregated.

The clasts from all three sampling locations (WB1-3) are high-quality material and exhibit strikingly similar attributes and can be described collectively. They appear in two browns (7.5YR 5/2-5/3) with very few calcareous inclusions (<1 mm) and faint indications of laminations. Furthermore, they have a fine-grained texture and are opaque with a slightly shiny luster. The collective attributes of the selected samples are most consistent with those of the URC Formation (Sánchez de la Torre et al. 2019).

6.1.3.3 Wadi Mushash (WMH)

Wadi Mushash is a *wadi* sector that is part of a large braided network. It converges with Wadi Kharanah into the larger Wadi Janab, then later with Wadi Butm and leads through the adjacent alluvial plain toward Qa' Azraq (Figure 4.6). The *wadi* cuts through both the URC and WSC formations and moves their clasts downstream. Appropriate clast sizes for making handaxes do not appear until a significant distance (33 km) from SM1. At this location, a large calcareous outcrop with embedded chert nodules of various sizes was discovered. Based on the images and GPS coordinates, this outcrop is the same as WSC9 surveyed by Sánchez de la Torre et al. (2019). Differential weathering rates caused the carbonate material to erode more rapidly than the chert, gradually exposing the nodules and releasing them into the *wadi*. Two exposed, but embedded nodules were sampled (WMH-1, WMH-2), while a third nodule (WMH-3) was found in a large disembedded chalk boulder next to the outcrop.

The individual attributes of the WMH nodules are largely similar. WMH-1 and WMH-2 are indistinguishable from each other and can be described together. They appear light gray (10YR 7/2), fairly opaque, and slightly shiny. The material has a predominantly fine-grained texture, but is fairly heterogenous with bands, often concentric, of various greys. WMH-3 is brown (10YR 5/3) and shinier and more translucent than the other two samples. It is also fine-grained and fairly heterogenous with similar irregular bands. The quality of chert from WMH is sufficient for biface manufacture, although WMH-3 tends to shatter to a greater extent.

6.1.4 Southern area

This catchment area is fairly distant from SM1, as it deposits material into the southern portion of Qa' Azraq. It includes the multiple braided streams of Wadi Ghadaf and Wadi Jilat, though the latter could not be surveyed (see Section 5.3).

6.1.4.1 Wadi Ghadaf (WG)

Wadi Ghadaf is an extensive *wadi* sector that converges with Wadi Jilat downstream, before feeding into the southern portion of Qa' Azraq (Figure 4.6). It is dominated by recent alluvium and Pleistocene sediments with supposed intermittent outcropping of the WSC Formation. However, outcrops along Wadi Ghadaf are not readily accessible, despite visits to their documented exposed locations on geological maps. Their reduced visibility is likely due to the low elevation, extensive dune coverage, and fairly flat topography. No intact exposed beds could be located, but location WG1 is best described as containing clasts that have not undergone significant weathering and were recently removed from beds partially exposed by industrial activity. WG1 is located approximately 13 km from SM1. Due to the absence of a secure bed to which these fractured angular clasts could be connected, they are considered part of the larger secondary source of Wadi Ghadaf. These clasts are thin and tapered, but several portions were thick enough to be used for biface manufacture. The chert was situated between layers of thin, yet coarse calcareous material. The flat angular clasts from these greatly disembedded clasts ranged from pebble to boulder size, while the rounded surrounding clasts were occasionally of mid-cobble size. Three kilometers further to the southeast, 16 km from SM1, a cluster of clasts were discovered and

sampled as WG3. A divergent tributary of the *wadi* was traced further upstream (28 km from SM1) to a choke point where several samples were collected as WG2.

The cherts of Wadi Ghadaf exhibit a variety of individual attributes. The material from WG1 is light gray (10YR 7/2) and fairly homogenous with infrequent calcareous inclusions (<1 mm). It is fairly opaque and mostly dull with a mostly fine-grained texture. Overall it is high quality material and suitable for knapping. The sample of WG2 is also of high quality. It is mostly opaque and homogenous, ranging from gray (10YR 5/1) to grayish brown (10YR 5/2). It exhibits a fairly shiny luster and a fine-grained texture with a sparse but even distribution of minute calcareous inclusions (<1 mm). In addition, several loose cobbles and pebbles were observed to be a deep reddish brown (2.5YR 5/4), denoted as WG2-R. The material is homogenous with no distinct impurities and a very fine texture. They are mostly translucent and exhibit a slightly shiny luster. It is high quality chert that would be ideal for stone tool manufacture. The material from WG3 is pale brown (10YR 6/3) and mostly homogenous with no perceivable impurities. It is dull, fairly translucent, and fine-grained. It is of medium-high quality. The similarity of the WG1, WG2-R, and WG3 chert to other reports of chert in the WSC Formation may indicate the parent formation of this material (Sánchez de la Torre et al. 2019). However, the WG2 material is more consistent with descriptions of the URC and MCM formations (Sánchez de la Torre et al. 2019), though its connection in southern area cannot be established at present.

6.1.5 Northeastern area

The northeastern catchment area is fairly distant from SM1 and somewhat restricted by the Harrat Ash-Shaam that surrounds it on all sides except the south. Several *wadi* sectors, from Wadi Usaykhim in the west to Wadi Rajil in the east, move material from this area towards Qa' Azraq, though those these channels do not converge.

6.1.5.1 Wadi Usaykhim (WU)

Wadi Usaykhim flows roughly north to south into the small agricultural community of Um Masayil northeast of Qa' Azraq. Upstream, where Wadi Usaykhim originates, it cuts along the border of the basalt fields and through exposed escarpments of the URC Formation where it is fed

by clasts of both igneous and sedimentary rock (Figure 4.6). The *wadi* is fairly well constrained by the descending elevation of the rocky escarpments, but does lose considerable fluvial momentum as it exits them and enters the *qa'*. The numerous chert clasts that are transported down the *wadi* towards into the *qa'* constitute a collective secondary source. The clasts were tracked upstream until they were a suitable size for the manufacture of bifaces, approximately 15 km northeast from the site of SM1. Several clasts (samples WU-1, WU-2, and WU-3) were collected at this location. The rocky escarpments where chert beds are exposed and accessible appear approximately 3 km farther upstream, though this distance cannot be covered in a straight line. These outcrops exhibit repeating beds of limestone, dolostone, chalk, and chert, which are characteristic of the URC Formation. The sedimentary rock in this section of the Azraq Basin does not present as extensive coverage or exposure, as it does in the southern and western sections, as the basalt fields enclose it.

The cherts within Wadi Usaykhim are fairly consistent in their attributes, mainly presenting variations in color. WU-1 and WU-3 appear as reddish gray-brown (5YR 5/2-5/3) and WU-2 is primarily brown (7.5YR 5/2). These materials are fairly opaque and dull in appearance with very few calcareous inclusions (<1 mm). They are fine-grained, mostly homogenous, and of a high-quality, ultimately suitable for the manufacture of bifaces.

6.1.5.2 Wadi al-Masayil (WM)

Aside from Wadi Usaykhim, the small agricultural community of Um Masayil in the northeast of Qa' Azraq is fed by two other *wadis*. Locally named Wadi al-Masayil (east and west), these two *wadis* flow northeast-southwest and the sectors are roughly parallel to one another in orientation (Figure 4.6). Upstream, the *wadis* cut through outcrops of the URC Formation that are exposed in the catchment area of the Azraq Basin as Wadi Usaykhim. Chert clasts from multiple chert beds are transported downstream towards Qa' Azraq. Due to the decreased fluvial energy, clasts suitable for biface blanks are discovered at 19 km (WMW) and 21.5 km (WME) from SM1. At these locations, several clasts were collected.

Wadi al-Masayil east (WME) and west (WMW) are considered separate secondary sources. The samples collected from WME exhibit noticeable variation, although all are high-

quality material. WME-1 is gray (Gley 2 7/5B-10B), dull, and fairly opaque. It exhibits a mostly fine-grained texture with parallel "pin-stripes" across the structure. By contrast, WME-2 is light brownish gray (10YR 6/2), slightly shiny and trransluscent, with infrequent small inclusions (<1 mm). WME-3 is grayish-brown (10YR 5/2), slightly coarse-grained, and with few inclusions as well (<1 mm). It is fairly homogenous, dull and slightly opaque.

The material from WMW also exhibits some variability. WMW-1 appears light brownish-gray (10YR 6/2), slightly opaque, and dull. It contains relatively few calcareous inclusions (<1 mm) and mostly homogenous overall. WMW-2 is gray (Gley 2 6/10BG), opaque, and dull in appearance. It exhibits a speckling of minute calcareous inclusions (<1 mm), but is otherwise fairly homogenous. WMW-3 is noticeably different than the other two samples. It is brown (7.5YR 5/2), slightly translucent, and fairly shiny. The structure is slightly heterogenous, as there are intermittent patches of a lighter brown. Despite the variation, the materials are of high quality and fine-grained texture.

6.1.5.3 Wadi Rajil (WRJ)

Wadi Rajil enters Qa' Azraq from the east and currently cuts across it, almost reaching the GAOA (Figure 4.6). It is among the largest *wadis* draining into Qa' Azraq (Ta'any 2013). This secondary source is comprised of clasts of several geological materials, namely basalt, limestone, and chert. The chert is likely part of the URC Formation, which has several exposures along the northernmost reaches of the stream well beyond the GAOA. Wadi Rajil steadily undergoes a reduction of fluvial energy as it leaves the undulating terrain of the basalt flows and URC Formation and enters the *qa'*. This transition is well demonstrated by the lack of cobbles until 27 km from SM1. At this location, several samples were collected.

There are few commonalities among the sampled chert, except that they are largely of medium quality. WRJ-1 is pinkish gray (7.5YR 6/2), opaque, and slightly dull in appearance. It contains very few inclusions and is slightly coarse-grained, although fairly homogenous overall. In contrast, WRJ-2 is brown (7.5YR 5/2), slightly shiny and translucent and fine-grained. WRJ-3 is also brown, though with some variation (7.5YR 5/2-4/2) due to the sequence of laminations (1-3 mm in thickness). It is slightly coarse-grained, fairly opaque, and slightly shiny.

6.2 Complications of individual attributes

An important observation to be made in regards to the attributes of the bifaces from SM1 is that the majority of these lithics exhibit what can be described as a "glaze" on their exterior surface. This glaze assumes a glossy appearance and gives the artifact a smooth feel, as it rounds the sharper edges. The thin coating of the glaze is most noticeable on fractured artifacts, which reveal their interior in cross-section. In this case, there is a stark contrast between the exterior glaze and interior material, as the former appears darker in color, shinier in luster, and often smoother than the latter. One artifact (4488) "fortunately" fractured upon discovery during excavation and provides an excellent illustration of this disconnect between the fresh and protected interior and glazed exterior (Figure 6.3).



Figure 6.3: Cross-section of artifact 4488, which exhibits a distinct contrast between the attributes of the interior and exterior surfaces. Photograph taken by the author.

This glaze occurred after manufacture (and deposition), as it appears only on the exterior of artifacts. Similarly, the chert sources in the Shishan Marsh (AS and AQ) exhibit the same glaze on the exterior of their disembedded clasts. Their exteriors are also smoother and a darker color than their interiors. The geological samples from all sources were purposely fractured open in order to more effectively reveal their interior attributes, as these are fresh and unweathered (Appendix 3-4). A similar glaze was also discovered on artifacts from the nearby site of Lion Spring, which exhibit a high luster as the result of "stream polish" (Rollefson 1980). An analysis of this glaze identified it as a thin silica coating created by localized dissolution and precipitation of silica at or near the surface of the artifact (Shackley 1989). The occurrence is documented at other sites in the Near East with a common factor being conditions found in sediments associated with artesian springs (Shackley 1989). Here sediments heavily saturated with circulating silica at a near neutral pH and raised temperatures may promote the recrystallization of silica (Fournier 1973; Meeks et al. 1982). The glaze patterns on the SM1 lithics and nearby sources, AS and AQ, are likely due to the same post-depositional conditions in the Shishan Marsh. These chert beds are either situated in some sort of local depression or a down-thrust block, which contribute to the low-lying elevation and are readily covered by water-saturated sediments. Shackley (1989) emphasizes that this particular glaze seems unrelated to friction gloss and water or wind abrasion (Masson 1982; Walwer 1993).

Furthermore, the clasts from the many secondary sources found in the *wadi* sectors also exhibit additional forms of exterior modification. These manifest as combinations of the classic desert varnish, some crazing, and encrustation (Crabtree & Butler 1964; Walwer 1993). A common observation is that their exteriors are a coarser texture (aside from the varnish), often with a chatter marks related to physical damage during fluvial transport. The exterior colors are typically darker shades of the interior, but can also appear as reddish brown. The desert varnish provides a smooth and glossy appearance, though this is often interrupted by the encrustation of calcareous sediments on the exterior.

Provenance associations between sources and artifacts based on the individual attributes of the interior material were not possible, as permission could not be obtained to fracture the pristine bifaces. An initial association based on its exterior attributes of artifact 4488 might readily

associate it with AS1, although its interior is more consistent with WR-2 and WME-2 (Figure 6.4). This contrast exemplifies how the exterior is often not representative of the original raw material. The interior is subject to less physical and geochemical alteration than the exterior. Consequently, an analysis of the exterior attributes is likely an insufficient basis upon which to solely establish provenance for the stone tools of SM1.

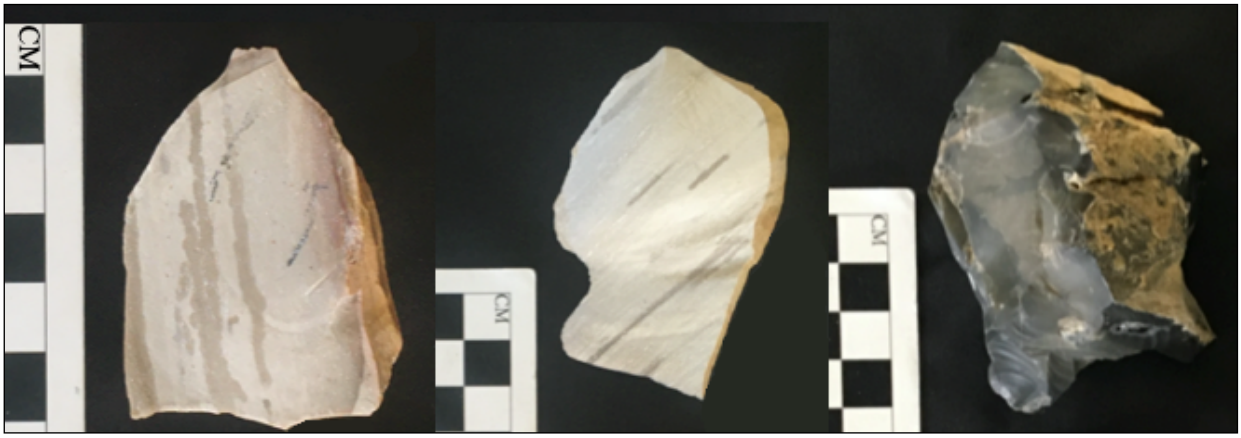


Figure 6.4: Samples from sources WME-2 (left), WR-2 (middle), and AS1 (right). Each sample exhibits different interior attributes. All photographs taken by the author.

6.3 Geochemical evaluation of sources and artifacts

The geochemical profiles of 32 sources and 38 artifacts were generated through LA-ICP-MS (Section 5.5; Appendices 5-6). In total, 53 elements were measured (Li, Be, B, Na, Mg, Al, Si, P, S, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, In, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Yb, Lu, W, Pb, Bi, Th, U). However, in both the sources and artifacts, 10 elements (P, S, As, Mo, Cd, In, Cs, W, Bi, Tb) were often below detection and were excluded from further consideration. Si was also not afforded further consideration due to its direct propensity to form SiO_2 and overwhelm the composition of samples (Murray 1994). The remaining data, a total of 42 elements, were used to evaluate any geochemical differences among the 32 sources. When applicable, data from Sánchez de la Torre et al. (2019) are consulted, although only 30 elements were measured in their study.

An initial focus was placed on the characterization of primary sources, as their parent formation is known. These include the WMH outcrop from the WSC Formation and the AS, AQ,

40X, and WR localities from the URC Formation. It was initiated in an attempt to establish a baseline profile for each formation.

Previous geological investigation has indicated that the WSC and URC formations were formed in pelagic conditions with the former on an outer to mid-shelf environment and the latter on a mid-shelf environment (Figure 4.4) (Al-Hunjul 2001; Alsharhan & Nairn 2003; Fadda 1998). These depositional environments are supported by the calculated ratio of Al/(Al+Fe+Mn), which evaluates the contribution of silica through hydrothermal fluid (proximity to mid-ocean ridges). Most ratios values of the individual ablations fall between 0.5-0.9 with the infrequent ratio below 0.4 (Appendix 5). The averages of the collective ratios from individual ablations are presented in Table 6.2. The ratios indicate that hydrothermal activity had a negligible influence on the formation of these cherts and that silica contributions are predominantly biogenic in origin (Adachi et al. 1986; Bostrom et al. 1973; Yamamoto 1987). Furthermore, since values above 0.4 relate to greater terrigenous input, it is most probable the depositional environments were indeed within a mid-shelf location (Murray 1994).

Several important observations can be made in regards to the overall concentrations of elements. Some consistencies among the geochemistry of the WMH samples and those of WSC 09 (the same outcrop from Sánchez de la Torre et al. (2019)) can be identified. For example, while all samples exhibit elevated concentrations of Ca, sample WMH-3 (3633-4600 ppm) is most similar to those from WSC 09 (2672-3482 ppm). Notable differences include a much higher concentrations of Mg (5324-5755 ppm) and Al (3763-3889) in the WSC 09 samples, than in WMH where both Mg (37-50 ppm) and Al (401-707 ppm) were considerably lower. The elevated Mg and Al concentrations are also present in several other WSC samples from the southwestern Azraq Basin (Sánchez de la Torre et al. 2019). Fe also appears in higher concentrations than most elements, although there is a great disparity between the values of the WMH samples (~500 ppm) and WSC 09 (3925-4633 ppm). WMH-3 exhibits large spikes in Ba and Sr that are uncharacteristic of other samples from this outcrop.

Table 6.2: Average Al/(Al+Mn+Fe) values of primary sources.

Formation	Sample	# of ablations	Average Al/(Al+Mn+Fe)	σ
Wadi Shallala Chalk	WMH-1	3	0.47	0.16
	WMH-2	3	0.75	0.08
	WMH-3	3	0.64	0.29
Umm Rijam Chert-Limestone	35Q-1	5	0.8	0.04
	35Q-2	5	0.59	0.3
	35Q-3	5	0.53	0.12
	40X-1	5	0.64	0.23
	40X-2	3	0.58	0.06
	40X-3	3	0.82	0.06
	40X-4	3	0.66	0.02
	40X-5	3	0.7	0.08
	40X-6	3	0.7	0.1
	40X-7	3	0.59	0.21
	40X-8	3	0.59	0.17
	40X-9	3	0.76	0.12
	40X-10	3	0.71	0.04
	40X-11	3	0.72	0.05
	40X-12	3	0.6	0.12
	40X-13	3	0.65	0.14
	AQ1	6	0.57	0.07
	AS1	5	0.49	0.07
	AS2	7	0.61	0.1
	AS3	10	0.68	0.12
	WR-1	7	0.73	0.1
	WR-2	3	0.65	0.2
	WR-3	3	0.41	0.14
	WR-4	5	0.56	0.25
	WR-5	3	0.6	0.13

The many primary sources of the URC Formation are located multiple kilometers from one another and with beds at different elevations. These differences indicate that the beds were formed

at different times and potentially under different (however slightly) depositional conditions. It is anticipated that they may exhibit different geochemical profiles as well. Overall, the URC samples exhibit several similar patterns. These include high amounts of Ca and, to a lesser extent, Fe. Smaller spikes include Sr, Na, and Al. The latter two are contrasted with comparatively low concentrations of Mg across all samples. Spikes of various sizes are present in Ba (7-7823 ppm), but are especially elevated in AQ1 (3767 ppm average) and AS2 (7823 ppm average). Although these patterns are consistent in all samples, the concentrations vary from sample to sample. The URC samples (URC 03A-B and URC 07A-B) from Sánchez de la Torre et al. (2019) exhibit similar elevated concentrations of Ca and Fe, as well as smaller spikes in Mg, Ba, and Sr. Na was not tested in their study. There are several occurrences of element enrichments or depletions in specific beds that can be identified. For example, AS2 is enriched in Ga and 40X-7 in Zn. AQ1 and 40X-4 have significantly higher Pb concentrations (average 5.7 ppm and 9.1 ppm respectively) compared to all other sources (<2 ppm). High concentrations of Pb in chert are not unusual, but the reason for these comparatively higher concentrations is speculative. Pb may be present in galena (PbS) inclusions, which can make chert darker (Eker et al. 2012). The similarities of the ‘Ain Soda profiles and their elevation suggest they may be part of the same bed, but this cannot be confirmed. Alternatively, it is possible for beds at the same locality to exhibit very similar profiles with each other (e.g., 35Q).

In general, the REEs (La-Lu) from samples in both the URC and WSC formations appear in significantly low amounts. Even the sum (ΣREE) are considerably low and rarely exceed 5 ppm. Some REEs (e.g., Tb) were often under detection in most sources while others were under detection in a few sources (e.g., WR-2, WR-3). Such low values are commonly reported among cherts of the Near East (e.g., Nathan et al. 1999; Segal et al. 2005), but can appear 10-100x higher in cherts elsewhere around the globe (e.g., Lu et al. 2019). Furthermore, these are highly variable within the same sample, as ablations may differ by a factor of 5. Elements anomalies, namely the depletion of Ce and enrichment of Eu, occur regularly. The latter is common in Eocene cherts of the Levant (e.g., Finkel et al. 2019; Nathan et al. 1999; Segal et al. 2005).

The many samples obscure definitive distinctions between the WSC and URC formations. The composition of chert in the latter formation can assume a variable composition, as evident

from the inclusion of numerous samples. The occurrence of relative enrichments or depletions in both trace elements and REEs indicate a general trend, although one that is reminiscent of chert in general.

Overall, the secondary sources exhibited many similar patterns to the primary sources. Most samples could be linked to either the URC or WSC formations by their attributes, albeit with some reservation. The Al/(Al+Mn+Fe) values were consistent with minimal contribution of silica from hydrothermal activity (Table 6.3). Mn values were extremely low and largely insignificant for this determination, although this is not uncommon in chert (Lu et al. 2019). The primary and secondary sources included in this study were formed by contributions of by terrigenous input and siliceous organisms.

The profiles of the samples from Wadi Butm are remarkably similar to each other, as are those of Wadi Rajil. There is expected variation among the samples of secondary sources. Such variation is evident in the material from Wadi Usaykhim, where noticeable ranges appear in Mg, Al, and K. A source that is not fully evaluated against the artifacts is Wadi Ghadaf 2-R. It was eliminated from consideration due to elevations in certain elements (see below) and the unlikelihood of association based on its individual attributes. The WG2-R material is a deep reddish brown, a color that is uncharacteristic of most chert beds in the Azraq Basin. It was discovered in a secondary source and the bed from which it originates could not be located. Its profile exhibits very high concentrations of Fe and Zn, elements which are often contributors to a distinctive red color, in comparison to other sources (Brandl 2016; Luedtke 1978). Fe, in particular, is a primary element in detrital hematite and can potentially substitute in the structure of moganite (SiO_2), a mineral polymorph of quartz and an indicator of vanished evaporites that often contributes to the red color of cherts and chalcedony (Knauth 1994). It should be noted that none of the artifacts are red, nor have a similar geochemical profile to WG2-R, nor are red.

Table 6.3: Average Al/(Al+Mn+Fe) values of secondary sources.

Sector	Sample	# of ablations	Average Al/(Al+Mn+Fe)	σ	Most probable parent formation
Wadi al-Masayil (east)	WME-1	4	0.74	0.12	URC
	WME-2	4	0.66	0.08	URC
	WME-3	4	0.55	0.30	URC
Wadi al-Masayil (west)	WMW-1	5	0.55	0.17	URC
	WMW-2	5	0.59	0.18	URC
	WMW-3	5	0.62	0.14	URC
Wadi Butm	WB1	6	0.68	0.06	URC?
	WB2	8	0.6	0.22	URC?
	WB3	5	0.77	0.04	URC?
Wadi Ghadaf	WG1	6	0.54	0.20	WSC
	WG2	5	0.44	0.26	WSC?
	WG2-R	5	0.53	0.04	WSC
	WG3	5	0.64	0.19	WSC
Wadi Rajil	WRJ-1	5	0.63	0.1	URC
	WRJ-2	5	0.55	0.06	URC
	WRJ-3	5	0.59	0.06	URC
Wadi Usaykhim	WU1	5	0.61	0.23	URC
	WU2	5	0.67	0.11	URC
	WU3	5	0.5	0.05	URC

The profiles of the samples from Wadi Butm are remarkably similar to each other, as are those of Wadi Rajil. There is expected variation among the samples of secondary sources. Such variation is evident in the material from Wadi Usaykhim, where noticeable ranges appear in Mg, Al, and K. A source that is not fully evaluated against the artifacts is Wadi Ghadaf 2-R. It was eliminated from consideration due to elevations in certain elements (see below) and the unlikelihood of association based on its individual attributes. The WG2-R material is a deep reddish brown, a color that is uncharacteristic of most chert beds in the Azraq Basin. It was discovered in a secondary source and the bed from which it originates could not be located. Its profile exhibits very high concentrations of Fe and Zn, elements which are often contributors to a

distinctive red color, in comparison to other sources (Brandl 2016; Luedtke 1978). Fe, in particular, is a primary element in detrital hematite and can potentially substitute in the structure of moganite (SiO_2), a mineral polymorph of quartz and an indicator of vanished evaporites that often contributes to the red color of cherts and chalcedony (Knauth 1994). It should be noted that none of the artifacts are red, nor have a similar geochemical profile to WG2-R, nor are red.

Successful provenance analyses rely upon the identification of variables that can discriminate among the sources. For chert, there is not a "one-size-fits-all" discrimination strategy (Section 2.4) and trial-and-error is often applied. This study is no exception. Several discrimination strategies were attempted before a suitable strategy was discovered. For example, a comparison of normalized REE trends was unsuccessful, due to the spurious nature of their concentrations. Because all sources were from similar depositional environments, a contrast of Al/(Al+Mn+Fe) values with a Fe/Ti clustered most sources and artifacts together with little segregation. Certain elements (Ca, Mg, P, Sr, and Ba) were avoided as they were often subject to considerable post-depositional diagenetic effects (Murray 1994).

To reiterate Shackley (2008), the aim of this provenance analysis was to identify the most probable fit based on geochemical consistencies between sources and artifacts. The identification of these consistencies relied upon the discrimination of several trace elements through bivariate scatterplots, a common strategy in provenance analyses (Baxter 1992; Brandl 2016). More specifically, the contrast of Al (ppm) and the ratio Ni/Co (ppm) proved useful in discriminating among sources and establishing consistencies with the 38 artifacts. Unfortunately, the profiles presented by Sánchez de la Torre et al. (2019) could not be used in this regard, as they did not analyze Ni or Co.

Al was selected for several reasons. It is a metalloid that commonly appears in detrital material, such as clay minerals, that frequently find their way into chert as microscopic grains. Al appears in variable concentrations and is well measured by LA-ICP-MS. Previous studies indicate that Al is among the elements least likely to be influenced by diagenesis and may be immobile in the structurally bound terrigenous phase (Hower et al. 1976; Murray 1994). These factors make Al a common discriminator. Since the chert included in this study is from formations formed with considerable terrigenous input, Al appears in sufficient abundance in the samples.

Ni and Co are among a small group of elements that can indicate the scale of hydrothermal or terrigenous input associated with the formation of chert (Bostrom et al. 1973). Ni and Co form two-thirds of the iron triad; the third element is Fe. These elements are adjacent to each other on the periodic table and share several physical and chemical characteristics. They tend to behave similarly in depositional environments, often occurring together in oxide (laterite) or sulfide ores (Moats & Davenport 2014). Furthermore, Ni and Co can appear in chert through biogenic origins or submarine volcanism as iron minerals (Bostrom et al. 1973). In the present dataset, these elements exhibit sufficient abundance and low variation within a source. The exceptions are 40X-9 and WU2 ablations where Co was under detection.

Considerable variability exists among the Al and Ni/Co values of the sources, which serves to segregate most of them (Figures 6.5-6.6). However, the Al and Ni/Co concentrations of most sources near SM1 (AS1-3) and to the western catchment area (35Q, WR) are relatively low. Several samples from Wadi Usaykhim and Wadi al-Masayil (east) also exhibit low Ni/Co values, but higher Al concentrations. Those from Wadi Mushash and Wadi al-Masayil (west) have relatively low Al, but moderately high Ni/Co. Notable distant sources (WRJ, WB, WG, 40X) exhibit significantly higher values of Ni/Co.

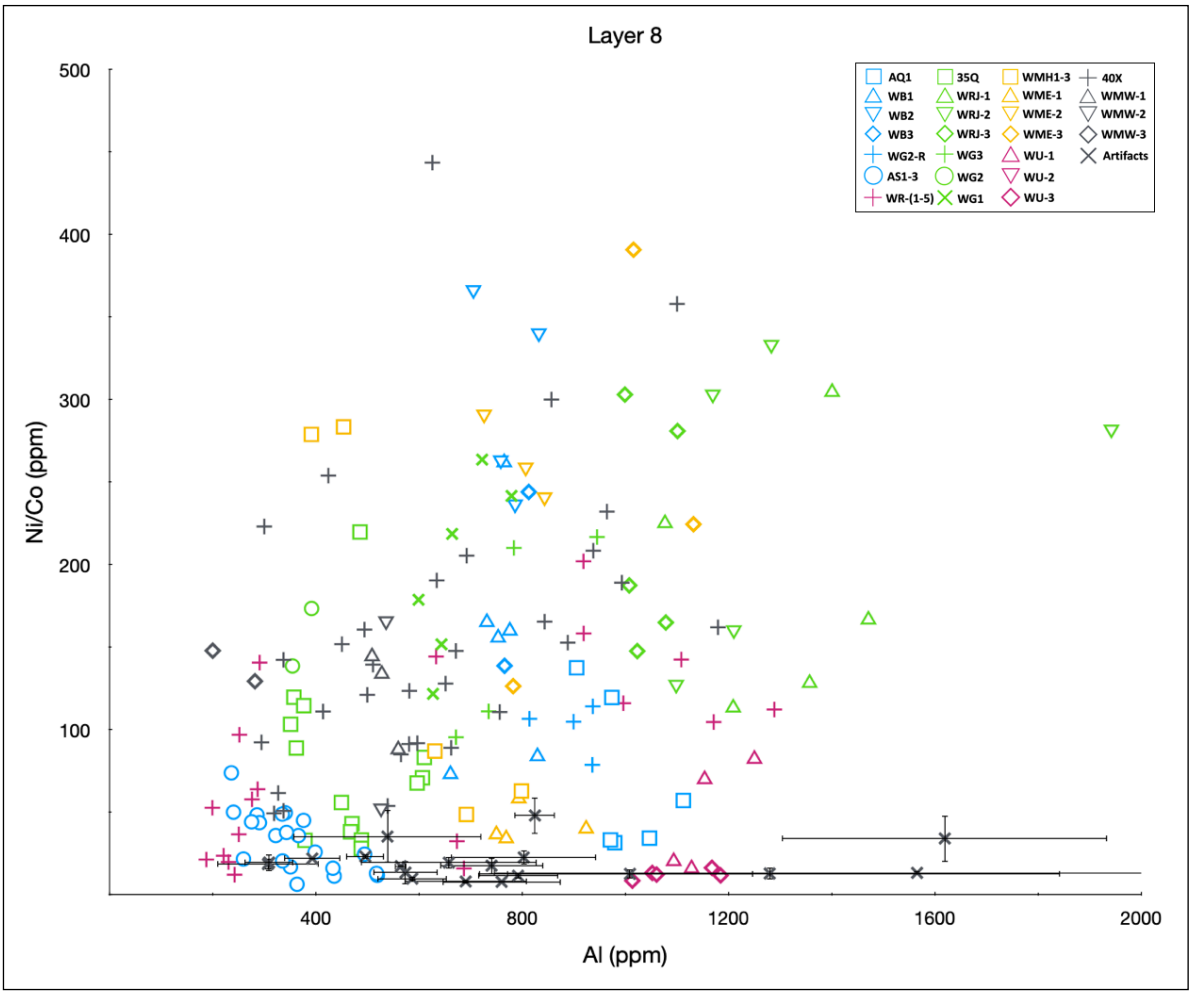


Figure 6.5: Scatterplot of sources (points) and artifacts (averages) from Layer 8. Individual plots of each artifact by its data points are provided in Appendix 7.

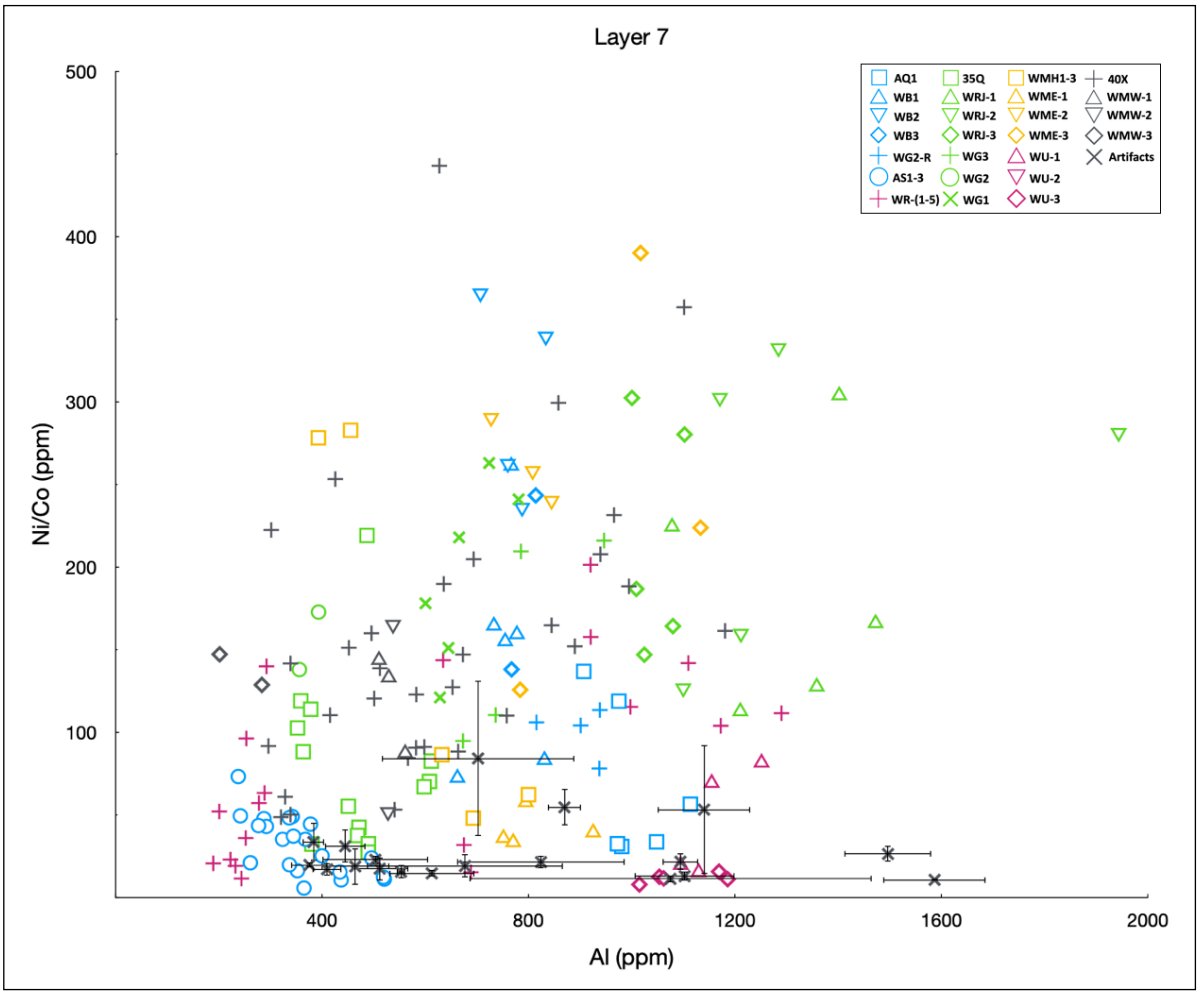


Figure 6.6: Scatterplot of sources (points) and artifacts (averages) from Layer 7. Individual plots of each artifact by its data points are provided in Appendix 8.

The artifacts are concentrated together within the range of several sources that fall under 100 ppm for Ni/Co. The predominance of relatively low values of Ni and Co in the dataset are not unusual, as these trace elements are most likely to be integrated into chert through hydrothermal activity at mid-ocean ridges (Bostrom et al. 1973; Kemkin & Kemkina 2015), whereas the cherts included in this study are formed on a shelf environment. However, Ni and Co can potentially be brought down by calcareous organisms (Bostrom et al. 1973), allowing Ni/Co variation within the cherts of rhythmic calcareous beds to occur. This discrimination is effective in reducing the number of sources for consideration, as those that do not offer initial overlap with the artifacts are eliminated (Figures 6.7 and 6.8). Individual plots of each artifact against the sources by its data

points are provided in Appendix 7 (Layer 8) and Appendix 8 (Layer 7). These provide clearer associations between the artifacts and sources than the averages. However, it should be noted that the close overlap of some sources in the western catchment area (35Q, WR) inhibit the association of some artifacts with either 35Q or WR and these are best described as originating from the general area.

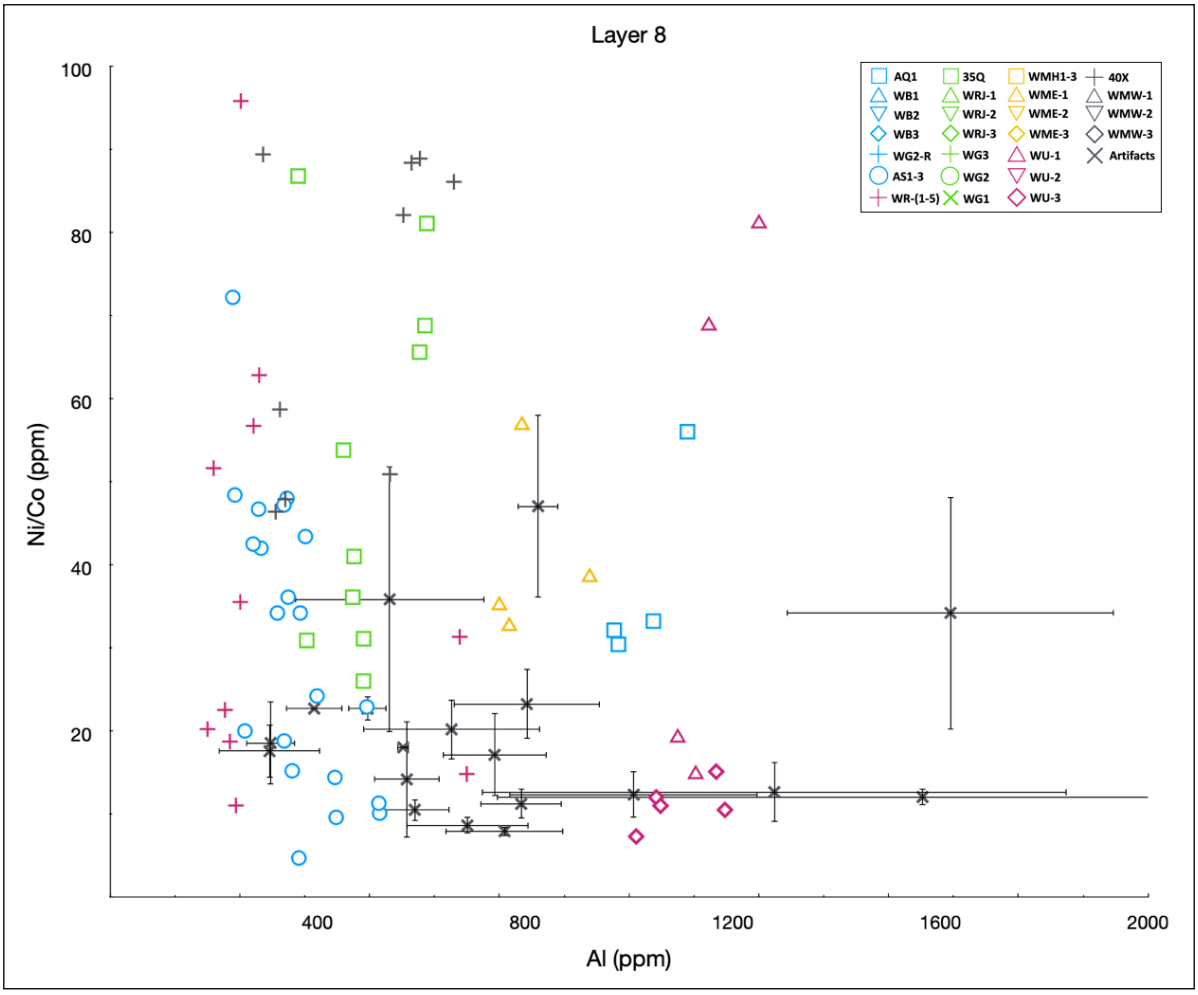


Figure 6.7: Scatterplot of sources (points) and artifacts (averages) from Layer 8 with renewed Ni/Co axis at 100 ppm. Individual plots of each artifact by its data points are provided in Appendix 7.

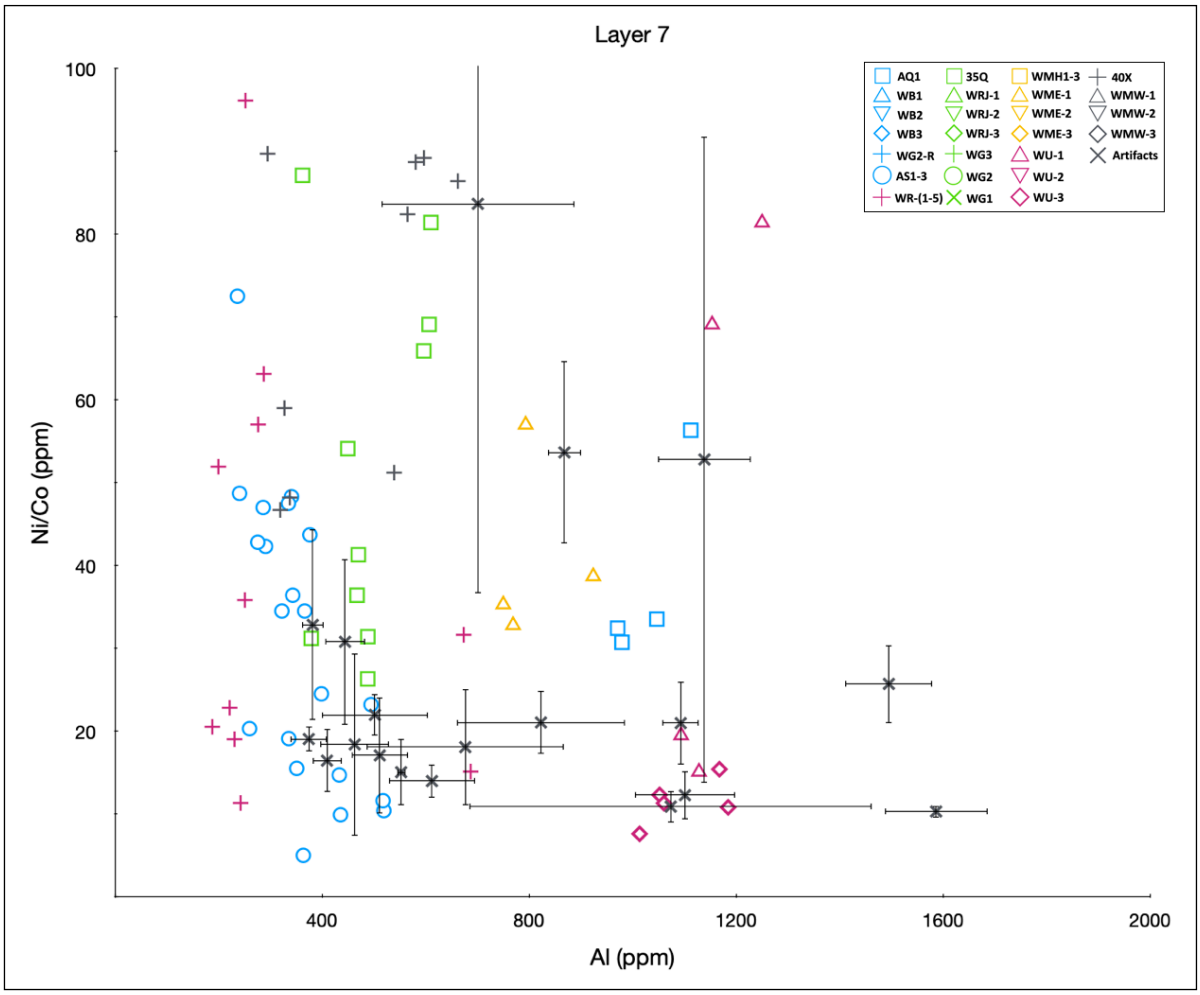


Figure 6.8: Scatterplot of sources (points) and artifacts (averages) from Layer 7 with renewed Ni/Co axis at 100 ppm. Individual plots of each artifact by its data points are provided in Appendix 8.

The artifacts are most suitably connected to sources of the URC Formation (Table 6.4). Most (n=12) artifacts originate from the ‘Ain Soda sources, the closest sources to SM1. Nearby SM1, the ‘Ain Qasiyya source was also exploited (n=1). To the west, many artifacts are consistent with the geochemical profiles of Wadi Rattama (n=7) and 35Q (n=1) and the collective profile of the on-site and western catchment areas (n=6). A group of artifacts are linked to Wadi Usaykhim (n=6) and Wadi al-Masayil (east) (n=2), which are located northeast of SM1 and Qa’ Azraq. Three artifacts could not be suitably connected to any sources included in the study. These exhibit significantly higher values of Al (1250-2000 ppm), which place them sufficiently outside the range

of any sources. Sánchez de la Torre et al. (2019) found high concentrations (1250-2000 ppm) of Al in samples from the URC (URC 03A-B), MCM (MCM 02), and WSC (WSC 07), indicating the possibility that these artifacts cannot (yet) be associated with a specific formation.

The results show that the two layers contain artifacts from similar sources, but in different frequencies (Tables 6.4-6.5). In Layer 8, five artifacts are connected to Wadi Rattama, while four artifacts are linked to the sources (WR and 35Q) in the western catchment area and four others to ‘Ain Soda. To the northeast of SM1, three artifacts are consistent with Wadi Usaykhim and one with Wadi al-Masayil (east). Finally, one artifact is consistent with 35Q and another has an unknown origin. In Layer 7, a large number (n=8) of the artifacts are associated with the ‘Ain Soda sources. To the west, two artifacts each are linked to Wadi Rattama and the broader western catchment sources (WR and 35Q). Several artifacts are also connected to sources in the northeast catchment area, specifically Wadi Usaykhim (n=3) and Wadi al-Masayil (east) (n=1). Lastly, a single artifact is consistent with ‘Ain Qasiyya and two have unknown origins.

Table 6.4: Associations between sources and artifacts by source.

Layer	Source	# of artifacts
Combined layers (n=38)	35Q	1
	‘Ain Qasiyya	1
	‘Ain Soda	12
	Wadi al-Masayil (east)	2
	Wadi Rattama	7
	Wadi Usaykhim	6
	Western catchment	6
	Unknown	3
Layer 8 (n=19)	35Q	1
	‘Ain Soda	4
	Wadi al-Masayil (east)	1
	Wadi Rattama	5
	Wadi Usaykhim	3
	Western catchment	4
	Unknown	1

Layer 7 (n=19)	‘Ain Qasiyya	1
	‘Ain Soda	8
	Wadi al-Masayil (east)	1
	Wadi Rattama	2
	Wadi Usaykhim	3
	Western catchment	2
	Unknown	2

Table 6.5: Geochemical association between artifacts and sources by artifact ID.

Layer	Artifact	Source
8 (n=19)	2947	Wadi Rattama
	3082	Western catchment
	3591	‘Ain Soda
	3711	Wadi Rattama
	3805	Wadi Usaykhim
	3806	Western catchment
	4033	‘Ain Soda
	4192	Wadi al-Masayil (east)
	4215	Wadi Rattama
	4278	35Q
	4396	Western catchment
	4425	‘Ain Soda
	4522	‘Ain Soda
	4548	Wadi Usaykhim
	4622	Wadi Usaykhim
	4651	Western catchment
	4671	Wadi Rattama
	4673	Wadi Rattama
	4826	Unknown
7 (n=19)	1200	‘Ain Soda
	1767	Western catchment
	2557	‘Ain Soda
	2941	Wadi Rattama

	3118	‘Ain Qasiyya
	3131	‘Ain Soda
	3468	Unknown
	3547	Wadi Usaykhim
	3603	‘Ain Soda
	3883	Unknown
	3912	‘Ain Soda
	4018	‘Ain Soda
	4038	‘Ain Soda
	4134	Wadi al-Masayil (east)
	4488	‘Ain Soda
	4495	Wadi Rattama
	4675	Wadi Usaykhim
	4751	Wadi Usaykhim
	4752	Western catchment

There are several additional observations that can be further stated in regard to the data. The general abundance of chert samples from the URC Formation clutters the plots and does not offer a distinct solitary URC profile in contrast to a WSC profile. This is expected, however, as the greater the number of sources included, the more likely a greater range of variability will be achieved. The results do not reflect a sampling bias towards sources that are closer (<10 km) to SM1, as there are multiple distant sources included. In addition, there are no artifacts securely linked to sources from the WSC Formation. This observation is not surprising, as sources from the WSC Formation are fairly distant from SM1.

There are no secure associations between any artifacts and the beds located at 40X. This lack of connection is partly expected, as the locale of sampling was recently exposed for road construction. It is not clear whether the generated geochemical data of the beds within this outcrop are representative of eroded material within the immediate vicinity or surrounding local landscape of 40X. The beds appear sequentially, representing the siliceous lithostratigraphy at this locality and demonstrating the vertical variability that can occur at the same outcrop of the URC Formation. It is apparent that beds within a sequence can exhibit drastically different geochemical profiles and should not be assumed to be similar simply because they share the same GPS coordinates.

There are also no artifacts that can be remotely associated with Wadi Rajil in the east. Clasts of an appropriate size for biface blanks are found in Wadi Rajil at a significant distance (27 km) from SM1. The primary sources of the material moved downstream within this *wadi* are located approximately 10-15 km east of Wadi Usaykhim and Wadi al-Masayil (east). There is some occasional overlap between the geochemical profiles of Wadi Rajil and Wadi Usaykhim, which may be tentatively representative of the horizontal distribution of chert in the northeastern portion of the central Azraq Basin.

In addition, no artifacts can be connected to the secondary sources of Wadi Butm, Wadi al-Masayil (west), or Wadi Ghadaf. The individual samples collected from these sources plot differently from each other, suggesting they are likely from unrelated parent sources.

6.4 Conclusion

Most provenance studies rely on individual attributes, which provide tentative associations between sources and artifacts. This observation is not to suggest there is no utility in such attributes, but to highlight that associations established through mineralogy or geochemistry are likely to be a more secure form of provenance (Brandl et al. 2011; Bustillo et al. 2009; Luedtke 1992). A trace element analysis of 38 artifacts from SM1 and 32 sources from within the central Azraq Basin provided a suitable discrimination and enabled the identification of geochemical consistencies between 35 artifacts and several sources. The majority (71%) of artifacts can be connected to sources <7.5 km of SM1 and others (21%) are consistent with distant sources (>15 km) located northeast of SM1. The interpretation of these results is explored in the next chapter, as is a consideration of procurement patterns with other sites in the region and the greater Levant.

CHAPTER 7: DISCUSSION

The comparison of geochemical profiles provided associations between 35 (of 38 tested) artifacts (handaxes, cleavers, cores). This chapter interprets these results within a larger comparative framework of existing ethnographic and archaeological data on hunter-gatherer mobility and foraging activities. It also includes a broader description of the risk-mitigation strategies practiced by hominins during occupation of the GAOA. Finally, it concludes with a discussion of the nature of lithic procurement within the Azraq Basin and greater Levant during the Lower-Middle Paleolithic.

7.1 Revisiting the hypotheses

The hypotheses posed in Chapter 5 can now be assessed. These are not mutually exclusive from one another and can be accepted or rejected in a variety of combinations. They also address the different provenance results between the two layers discovered at SM1. The discrimination of the geochemical profiles indicated that the artifacts could be connected to several sources within the Azraq Basin (Tables 6.4-6.5). In this case, the 19 lithics of Layer 8 are linked to several sources (here 5.3% is one artifact), namely WR (26.3%), AS (21.1%), western catchment (21.1%), WU (15.8%), 35Q (5.3%), WME (5.3%), and unknown (5.3%). By comparison, the 19 lithics of Layer 7 are linked to AS (42.1%), WU (15.8%), western catchment (10.5%), WR (10.5%), unknown (10.5%), WME (5.3%), and AQ (5.3%).

7.1.1 Effect of the environment

The first hypothesis addresses the relationship between the environment and the procurement strategies (Section 5.1.1). The regional climate, environment, and distribution of resources within the Azraq Basin have the potential to greatly affect the nature of lithic procurement strategies of hominins at SM1. The artifacts were discovered in two adjacent sedimentary units representing two different periods of occupation: Layers 8 and 7b-c (Figure 4.11). The units above Layer 7b-c and below Layer 8 were archaeologically sterile. These artifacts-bearing units were dated by OSL to approximately 266 +/- 40 kya (Layer 8) and 125 +/- 12 kya (Layers 7b) (Nowell et al. 2016). Their sedimentary composition indicates a warming and drying

trend that starts at the end of Layer 9 and continues through Layer 8 into Layer 7 (Nowell et al. 2016; Pokines et al. 2019). Over this time, there was a gradual reduction of water availability throughout the Azraq Basin to the point where GAOA was characterized by a series of marshy ponds and concentrated resources. The possibility that these changes, a continued drying, affected the procurement strategies is addressed in H1.

- H1) There is a relationship between the environment and procurement. If this is true, it is expected that the following conditions will be observed between the two layers:
  i) Lithics were procured from different sources.
  ii) Lithics were procured from the same sources, but in significantly different frequencies.

- $H1_{null}$) If there is no discernible relationship between the environment and procurement, then no differences are expected between layers.

The frequencies (%) of exploitation in the sources noted above exhibit some differences between Layers 8 and 7b-c, most notably an increase of artifacts linked to ‘Ain Soda sources and a decrease in the exploitation of Wadi Rattama. These patterns perhaps best correspond with conditions stated in H1-ii: the same sources are exploited, but some in different frequencies. At best, the correlated changes in the environment and procurement patterns between Layers 8 and 7b-c support the existence of a relationship between the two. However, due to the small sample size, this relationship is quite tentative.

7.1.2 Logistics of procurement

The second hypothesis addresses the nature of procurement in relation to the distance, scheduling, and raw material preferences (Section 5.1.2). It has been noted that such procurement tends to appear along a spectrum, from direct to embedded procurement (Binford 1978, 1982; Binford & O’Connell 1984). In relation to the provenance results, the most fitting hypothesis is H2b.

- H2b) The lithics were obtained through mostly embedded procurement. If this is true, it is expected that the following conditions will be observed:
  i) Most lithics were procured from sources within the assumed foraging radius or DET (e.g., 5-10 km).
  ii) Lithics were procured from a high number of sources (>4).
  iii) Lithics may appear in a range of quality.

- $H2_{null}$) If there is no discernible strategy of procurement, then it is expected that lithics are procured from a range of sources at various distances of all qualities.

Although the assemblages from each layer can be considered independently, their frequencies and can be discussed in unison. In Layer 8, the lithics originate from a high number of sources and are predominantly manufactured from sources within an assumed foraging radius or DET. In the subsequent Layer 7b-c, the lithics are connected to the same sources, but are mainly manufactured from sources within the foraging radius. For the artifacts, the quality of the chert in both layers ranges from medium to high, though it should be noted that the abundance of high quality chert in the Azraq Basin decreases the likelihood of low quality chert being utilized. Collectively, these patterns best correspond to the conditions associated with H2b, which suggests that lithic procurement in both layers occurred through a predominantly embedded strategy. Embedded procurement allows the individual to be provisioned with considerable convenience and limited planning. The presence of a discernable procurement strategy allows the null hypothesis to be rejected.

7.1.3 Forager mobility

The third hypothesis addresses the nature of forager mobility around the GAOA and within the Azraq Basin and how this changed diachronically (Section 5.1.3). An inquiry into forager mobility typically requires the identification of three locations: the site of deposition, the source(s) exploited, and the home base. However, this study only has two of the three locations and can only

relate the movement of material from source to site of deposition. The path of transport need not be linear (and likely never is) as these tools may have been carried to multiple destinations across the landscape for various tasks prior to their discard at SM1. A diachronic modification to foraging mobility would have two possibilities: a greater contraction around the GAOA or an expansion beyond its boundaries.

- H3a) Over time, the concentration of foraging shifted toward the GAOA. If this is true, it is expected that the following conditions will be observed:
  i) There is a greater frequency of lithics procured from sources within the GAOA in Layer 7 than in Layer 8.
  ii) There is a greater frequency of lithics procured from sources closer to the GAOA in Layer 7 than in Layer 8.

- $H3_{null}$) If there is no discernible change in foraging range or concentration over time, then no differences are expected between layers.

Several important observations must be made with respect to the provenance results of lithics from Layers 8 and 7b-c. The foremost observation is that the most distant sources, WME and WU, retain the same frequency of lithics in both layers. The sources in the western catchment area provide blanks for biface manufacture in both periods of occupation. There is a notable doubling in the frequency of lithics from AS from 21.1% in Layer 8 to 42.1% in Layer 7b-c. These collective patterns are most consistent with the conditions associated with H3a, as there is a greater frequency of lithics procured from sources within the GAOA in Layer 7b-c than in Layer 8. Since there is a discernable change, the null hypothesis is rejected.

7.2 Procurement ranges

Other than the basalt flows of the Harrat Ash-Shaam, the geology of the Azraq Basin mainly comprises sedimentary formations (Figures 4.4-4.5). The most extensive of these is the URC Formation, which generally contains repeating sequences of chert and calcareous beds with

multiple exposures throughout the region. The WSC and MCM formations are estimated to contain significantly less chert and have relatively limited exposures (Andrews 1992), particularly within the central Azraq Basin. A total of 32 sources were documented and sampled at 18 localities of varying distances from SM1. The results of the provenance analysis indicate that several sources were exploited for the manufacture of bifaces (Tables 6.4-6.5). These sources are found in three separate catchment areas (Figure 7.1): on-site (AQ, AS), western (35Q, WR), and northeastern (WU, WME). They are located at various distances from SM1 and can be described by traditional foraging/procurement ranges, namely on-site, local (western area), and regional (northeastern area).

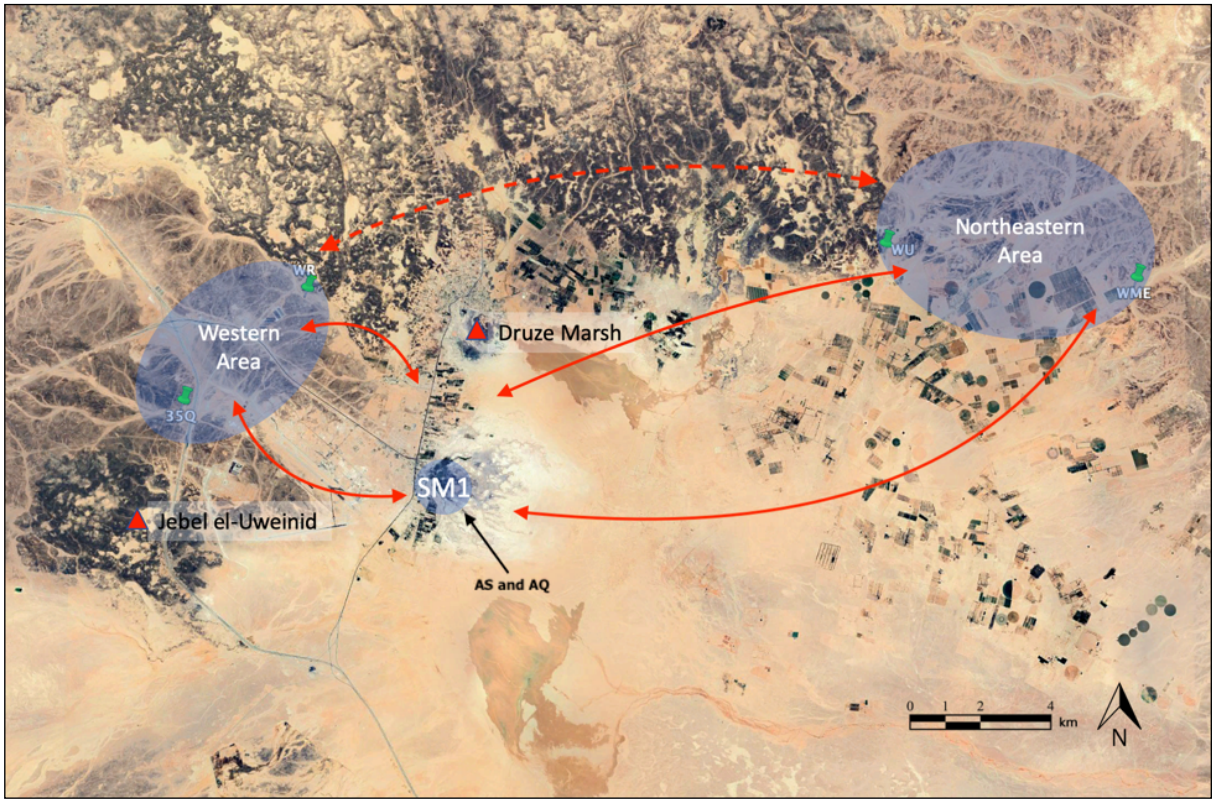


Figure 7.1: Sources within the Azraq Basin that were exploited. At center, SM1 (on-site catchment Figure created from Google Earth®.

7.2.1 On-site procurement within the Shishan Marsh

A total of 13 artifacts (34% of total assemblage) can be connected to sources within the Shishan Marsh, namely ʻAin Soda (n=12) and ʻAin Qasiyya (n=1). These sources are considered to be "on-site", as they range from the immediate vicinity of SM1 to 200 m away. The exploitation of ʻAin Soda and ʻAin Qasiyya represents a convenient and opportunistic form of procurement. These sources currently appear as small disembedded outcrops protruding from the sediment. Three such outcrops are included under the ʻAin Soda sources: AS1, AS2, and AS3.-The nature of their weathering and that of ʻAin Qasiyya may indicate the production of clasts of various sizes within the Shishan Marsh, though these do not appear in high abundance. While there may have been some exposed portions of these outcrops during hominin occupation, it is more probable that some freed clasts were scattered across this section of the Shishan Marsh. Some clasts, those of suitable size for a biface blank, could be moved through (perhaps seasonal) fluvial action within the wetlands and located within the immediate vicinity (~200 m radius) of the site. This availability presented the opportunity for quick on-the-spot collection of cobbles that could serve as blanks in a time of need. Hominins moving along the western margins of the Shishan Marsh could collect the cobbles upon encounter. This procurement would require little effort, especially as transport to SM1 would be negligible. However, these sources are not necessarily reliable, given their limited exposure and low supply of clasts. The relative scarcity of these clasts would account for the limited debitage from biface manufacture at SM1. Hominins utilizing such sources were certainly opportunistic and fortunate, given that the available raw material quality was medium-high. It does not appear that hominins were dependent upon these sources and likely recognized the need to bring bifaces or cores into the Shishan Marsh. A near complete reliance upon on-site raw material would be demonstrated by an overwhelming frequency (e.g., ~90%) of artifacts from the combined ʻAin Soda and ʻAin Qasiyya, but this scenario is not indicated with the provenance results.

7.2.2 Local movement from the western catchment area

A total of 14 artifacts (37% of assemblage) originate from the catchment area directly to the west of the Shishan Marsh, namely from sources along Wadi Rattama and at 35Q. Over time and *en route* to the GAOA, Wadi Rattama cuts through several chert beds of the URC Formation,

exposing them and permitting them to weather. Both the beds and the occurrence of clast sizes for biface blanks are located approximately 6.5 km upstream from the GAOA. Similarly, 35Q is an exposure of chert beds from the URC Formation along a segment of a *wadi*, located 7.5 km from SM1 and 4.8 km southwest from the sampling location of Wadi Rattama. The modern quarry at 35Q has exposed additional chert beds, but it is unlikely that these were accessible at the time of hominin occupation, since they are well below the elevation of the *wadi* into which the quarry now cuts. Clast movement, which could not be fully discerned due to industrial development, likely did not extend downstream further than the location of sampling.

The geochemical profiles of the chert beds at Wadi Rattama and 35Q are very similar and may be indicative of an extensive horizontal range and vertical sequence for the URC Formation in this area, although this must be assumed with caution. However, due to their overlap, six artifacts were linked to beds at both sampling locations. It is not known whether hominins exploited raw material from these specific locations, but rather it is more appropriate to state that lithic procurement occurred within the western catchment area, likely between 35Q and Wadi Rattama or within their vicinities. The distance (<10 km) raw material (or artifacts) moved from this catchment area to the Shishan Marsh can be classified as a local range (Binford 1978; Ekshtain et al. 2014; Kandel et al. 2016).

7.2.3 Regional movement from the northeast catchment area

A total of eight artifacts (21% of total assemblage) are geochemically consistent with sources (WU and WME) located in a catchment area northeast of the GAOA and larger Qa' Azraq. Multiple escarpments of the URC Formation are exposed in this area. Access to the chert beds can be difficult due to their isolation and the undulating landscape that surrounds them. Some are cut by *wadis* while others are situated along the heights of escarpments (Figure 7.2). Here an approach from below is safest, though it initially requires navigating along *wadi* sectors. The subsequent weathering and erosion of chert beds in this area results in the release of clasts into the Wadi Usaykhim and Wadi al-Masayil sectors. The numerous clasts in each *wadi* constitute a collective secondary source; one that brings material southwest toward Qa' Azraq, though only finer sediments reach the *qa'* in the present geomorphic context. However, these secondary sources are

full of a range of clasts representative of many chert beds. Three samples per *wadi*, possibly representing three different beds of the URC Formation to the north, were collected at the location where suitable blank sizes were found. The closest locations to SM1 for procuring material from this northeast area are 15 km (WU) and 21.5 km (WME). Although these locations are already significant distances from GAOA, the chert beds from which the clasts originate are a further >3 km upstream (as the crow flies) or farther if the meandering *wadi* is tracked. Traditionally, the movement of material over the aforementioned distances can be described as regional (Kandel et al. 2016).



Figure 7.2: Modern barren landscape in the northeastern catchment area. Note the rocky escarpment of the URC Formation on the right where several chert beds are exposed. Wadi Usaykhim runs along the line of green vegetation in the background. Photographs taken by the author.

7.3 Provisioning in the Azraq Basin

The setting of the GAOA within a landscape with a variable distribution of chert presented the hominins with many decisions in regards to which sources to exploit, where to manufacture tools, and whether to transport blanks or finished tools across the landscape. The provenance

results offer further insight into several paleoeconomic features of the foragers of SM1, which involves an intertwined system of provisioning.

The location(s) of biface manufacture from raw material procured in the northeast catchment area is(are) unknown. Conducting manufacture at the source allows foragers to carry lighter loads of finished implements (gear) to utilize for tasks encountered along their route or at their destination. The distances over which the collective raw material was moved may indicate that most were transported as finished tools. In this case, individuals provisioned themselves with specific toolkits in the northeastern area. From there, hominins moving into the GAOA were then predominantly outfitted with finished tools as personal gear—handaxes and cleavers.

It is possible that bifaces could be manufactured at the location of raw material extraction in the western area. Alternatively, the proximity of these sources to the western boundary of the GAOA would allow for convenient transport of the raw material as clasts or blanks to specific places on the landscape where manufacture could occur in preparation for their use in the Shishan Marsh. For example, raw material may have been brought to sites, such as C-Spring (Figure 1.3, Table 4.2), which operated as distinct knapping locales (Copeland 1991). Very few clasts are available within the vicinity of C-Spring and most material was likely brought in from the landscape to the west (e.g., 35Q, WR). Such knapping locales would serve to provision individuals (Kuhn 1992, 1995).

A consideration of the bifaces and broader lithic assemblage indicates a strategy to provision SM1 (or even the margins of the wetlands) as a place with abundant prepared tools and cores that could be used on demand for multiple tasks. The collective evidence indicates that SM1 is most consistent with a butchering site (Nowell et al. 2016; Pokines et al. 2019). The nearby site of ‘Ain Soda with nearly identical remains has also been interpreted in a similar manner (Lister et al. 2013; Rollefson et al. 1997a, 2006), which further supports the idea of carcass processing and meat acquisition directly within the wetlands (Nowell et al. 2016). The types of tools present and the protein residue discovered upon them securely demonstrate their use for butchering (Table 4.3), although not necessary who (hominins vs. predators) or what tools killed the animals. The small scattered lithic clasts in the wetlands provide raw material from which an assortment of tools (e.g., flakes, knives, scrapers) and small tools (< 5 cm) can be manufactured. These constitute a

proficient toolkit for hide and meat removal, while the bifaces may perform these tasks as well as bone breaking for marrow extraction. After their use, perhaps mainly butchering, these tools were "discarded", despite their good condition.

The bifaces exhibit varied amounts of use wear (Murray 2017), but cease to be part of the immediate toolkit. Instead, the continual "discard" of good condition tools at SM1 and within its vicinity (bifaces were also discovered at SM3, SM9, SM10, SM13, and 'Ain Soda – Rollefson et al. 1997b) allows a high number of different tools to accumulate in one locale of the Shishan Marsh. The action of discard was not so much a permanent rejection of the tool for further use, but rather a caching of it among others in that specific location. The hominins may have intentionally stockpiled various tools and cores at SM1 for later anticipated needs (Kuhn 1992, 1995).

7.4 Hominin movement and mobility

When coupled with the data from other archaeological sites, the occupation at SM1 and the results of the provenance analysis lend insight into the nature of long-term movement and seasonal mobility of hominins within the Azraq Basin.

7.4.1 Contraction toward the GAOA

During humid periods in the Azraq Basin, precipitation fell on the surrounding landscape, replenishing the aquifer and allowing water to accumulate in the heart of the basin. A large paleolake (or a collection of smaller lakes) was present at the heart of the basin during MIS 9 with a high lake stand dated to approximately 346-316 kya (Abed et al. 2008). The documented extent of the lake stretched (at least) from upstream Wadi Rattama in the northwest to Umari in the southeast, covering the GAOA (e.g., Layers 10 and 9 at SM1) and Qa' Azraq (Abed et al. 2008; Ames & Cordova 2015; Nowell et al. 2016). Hominin occupation corresponding to these conditions is mainly found in the southwestern Azraq Basin and is indicated by the extensive distribution of the DWA, estimated to be >300 kya, along the various *wadi* sectors (Table 4.2). The banks of the channels offered an attractive habitat for hominin groups that surrounded the lake margins, as did the wider grassland savannas and steppes of the Central Plateau (al-Nahar & Clark 2009).

Climatic shifts resulted in decreased precipitation in the Azraq Basin during MIS 8-6 and contributed to a long-term drying trend within the region (Ames et al. 2014a; Ames & Cordova 2015; Cordova et al. 2013). The lake margins receded into Qa' Azraq and the GAOA gradually transitioned to a series of marshy ponds (e.g., Layers 8 and 7b-c at SM1) by approximately 266 kya (Nowell et al. 2016). Water availability in the region was significantly reduced and concentrated in the GAOA and nearby *qa'*, although the latter was likely subject to seasonal evaporation. However, the oasis complex of the GAOA likely remained stable, as it was dependent on springs not direct precipitation. Hominin occupation corresponds to this reduction of water availability, as many sites appeared around and within the GAOA. These sites (Table 4.2), including SM1, contain a noticeably different and more recent toolkit than the DWA: the LAA facies (Copeland 1988). Arid conditions in the basin continue into MIS 6, as early Middle Paleolithic occupation is also discovered within the GAOA (Ames et al. 2014a; Ames & Cordova 2015).

There is a distinct trend with respect to long-term hominin movement in the Azraq Basin. Initially, the expansive coverage of the paleolake(s) forced hominins to reside at higher elevations among the landscape, particularly in the southwestern Azraq Basin. The paleolake(s) and *wadis* could have provided ample water and supported a host of various resources. The onset of arid conditions in the region caused the lake margins to recede and the hominins to contract with them. Contraction around the GAOA ensured access to fauna, flora, and water, as this spring-fed oasis complex remained a reliable locale of various resources amidst a largely open and dry landscape. Over time, hominins moved from the distant reaches of the Azraq Basin, attested by the DWA, inward to the periphery of the GAOA and *qa'*, as indicated by the LAA facies.

7.4.2 Seasonality and mobility

During the later Middle and early Upper Pleistocene, the gradual reduction of water availability within the larger Azraq Basin forced hominin groups to contract within the heart of the basin to ensure resource security (Ames et al. 2014a; Ames & Cordova 2015; Nowell et al. 2016; Pokines et al 2019). The GAOA provided a permanent concentration of vital resources, namely water and dense vegetation, both which also attracted animals. Contemporaneous sites to SM1,

such as Lion Spring and C-Spring (Figure 1.3), are located on the boundary of the GAOA and indicate foragers were active around it.

Although long-term occupation around the GAOA is evident, it is not necessarily clear how seasonal conditions influenced mobility within the central Azraq Basin. The reconstruction of mobility is complicated by the absence of home-bases or residence sites, if any were used at all. Mobility was certainly far reaching into the landscape that surrounded Qa' Azraq, as hominins could predictably find chert sources in the western and northeastern catchment areas (Figure 6.2). However, the provenance results provide direct evidence for unidirectional trips—from sources to SM1, but not from where hominins set out to procure their stone tools.

The high availability of material in the western catchment area provides ample opportunity for exploitation by hominins. From here, a trek to SM1 is 7.5-6.5 km, a distance that can be easily traversed in a single day. The trek from 35Q is gravelly and dusty underfoot, but with minimal elevation changes and topographic obstacles. The trek from Wadi Rattama could follow the *wadi* route itself, which moves downstream southeast and reaches Qa' Azraq in between the Druze and Shishan marshes (Figure 4.6). This chert-rich landscape and its close proximity to a resource-rich locale, such as the GAOA, offer an attractive area for repeated visits.

The northeastern catchment area provides a similar quality and distribution of raw material, but a greater distance (WU – 15 km, WME – 21.5 km) over which they were moved to SM1. At the average walking pace of an adult (5 km/hour), this trek can also be accomplished in a single day. However, this estimate excludes any search for and acquisition of non-lithic resources (e.g., vegetation, prey, organic material), as well as the collection of clasts or even the exploitation of beds, not to mention the time allotted for tool manufacture. A direct route from this chert-rich area to SM1 would pass over some undulating terrain until the boundary of Qa' Azraq is reached. Although an overall regional drying trend is documented, seasonal fluctuations could keep the *qa'* wet or make it too muddy to cross. During dry seasons, it is a fairly straight and gentle trek across the gravely-sandy surface of the *qa'* to the Shishan Marsh. A path over the *qa'* (shortest route) or around it to the west offers no additional chert clasts. Regardless of the conditions, it may have been more advantages to follow Wadi Usaykhim, as it cuts along the eastern edge of the igneous plateau. Although this route would include several extra kilometers, it would lead hominins closer

to the Druze Marsh, rather than bypassing it over the *qa'*. Today the Druze Marsh is dry, but, during the Middle-Upper Pleistocene, its wetlands would have presented another resource-rich locale to which hominins could deviate and exploit (Figures 1.3) (Ames et al. 2014a; Ames & Cordova 2015).

Foraging within these two areas aligns with seasonal hydrological conditions in the region, as they receive considerably more precipitation than the south and east (Copeland 1988). Hominins were more likely to occupy these areas during the wet season, as they likely offered sufficient resource security while the *qa'* flooded. During the dry season, it is likely that hominins prioritized a stationary resource—water—and perhaps its associated mobile resources (e.g., animals), over other permanent stationary resources (e.g., vegetation, lithic sources). Hominins would be tethered to the GAOA to a greater degree, making frequent visits to the margins of the wetlands. However, it cannot be established if SM1 reflects a dry season occupation, utilized when pond levels were lower or the spillover from the *qa'* had receded. Overall, SM1 appears as a frequented destination for hominins moving inward from the landscape surrounding Qa' Azraq and the GAOA.

7.5 Familiarity with landscape

A further consideration of the lithic resource landscape within the Azraq Basin provides insight into how hominins may have perceived the availability and distribution of raw material. The initial congregation around the Shishan Marsh brought the hominins into occasional contact with disembedded clasts, but a portion of procurement occurred outside the GAOA.

The procurement of chert was largely restricted by the intrusion of the Harrat Ash-Shaam basalt plateau (Oligocene-Pleistocene) into the Azraq Basin, as it served as a lithological cap (Figure 7.3), within which there was little (or no) access to chert. These igneous flows forced a division in the landscape between the sources available in the west (35Q and WR) and those in the northeast (WU and WME). Indeed, surveys along Wadi Enoqqiya, which cuts southeast through the basalt plateau and into Qa' Azraq, revealed no chert clasts larger than pebbles, yet an abundance of basalt cobbles. Portions of the basalt plateau in the Azraq Basin are overlain by layers of eolian sediment, while other parts are exposed rocky surfaces. It is possible that hominins may have had little reason to venture over it and preferred to forage among the lower elevation

and vegetation of the sedimentary landscapes. In fact, very few Paleolithic remains have been discovered among the plateau (Betts 1988).

The boundary of the plateau, which encapsulates the northwestern corner of Qa' Azraq, may appear an extensive topographic guide on the landscape. It could signal that lithic sources, or the *wadis* along which chert beds and clasts appear, are located on its southern (35Q and WR) and eastern flanks (WU and WME). Following and monitoring the *wadi* sectors may have been advantageous in guiding hominins towards or from the GAOA. Indeed, material collected by previous surveys indicate Paleolithic occupation along or nearby the major *wadi* sectors. Passing over the gently descending landscape of the various catchment areas until the *qa'* appears on the horizon would reinforce the direction of travel toward a collection of resources.

Even casual exploration throughout a region has additional benefits beyond the procurement of lithics, as it is also performed to acquire and maintain information about the landscape (Whallon 2006). It allows for monitoring herds, surveying for other hominin groups, and evaluating the status of other water resources (e.g., Druze Marsh). The immediate information collected serves to inform impactful decisions for the future of the group. For example, Jebel el-Uweinid, a large igneous bluff to the southwest of the GAOA (Figure 7.1), presents an elevated obstacle on the landscape. Exploration around Jebel el-Uweinid would later allow it to signal that access to chert was to its immediate north in the western catchment area, as there is no suitable chert available to its immediate south or east (Price & Garrard 1975).



Figure 7.3: Basalt boulders indicating the boundary and greater elevation of the Harrat Ash-Shaam along the Wadi Enoqiyya sector. Photograph taken by the author.

7.6 SM1 and lithic procurement in the Levant

The procurement strategies associated with bifaces from SM1 exhibit many similarities with those of other Paleolithic sites in the Levant, but also some distinctions. For example, on-site procurement and local movement of raw material are well documented and occur at many sites (e.g., Qesem Cave, Tabun Cave, Ar-Rasfa), including SM1. This frequent occurrence is largely enabled by the general abundance of chert within the Levant. It seems common that hominins in most geographic pockets of the Levant were opportunistic and took advantage of raw materials that were locally available, even if some are of lower quality. Raw material movement conducted over regional distances is also evident at SM1 and throughout the Levant (e.g., GBY, Tabun).

Since SM1 is a task-oriented site and not a residence, direct procurement was not detectable, as it was at Tor Foraj (Henry 1995a, 1995b, 2003). However, SM1 was well provisioned with numerous finished bifaces and cores for later reduction. This provisioning strategy enabled access to on-demand tools for various tasks, including butchering. These tools were moved across the landscape and cached at a strategic location on the margins of the wetlands. Although most sites considered to be provisioned are residences, typically cave sites, SM1 finds

notable parallels to ‘Ein Qashish. The remains at both open-air sites indicate a range of tasks were performed, including provisioning, knapping, and butchering (Ekshtain et al. 2014, 2019).

Quarrying activity and deep mining are not evident within the Azraq Basin and the former appears to be unique to the E&R complexes in the Galilee region of the Levant. However, a familiarity with the landscape of the surrounding region that the hominins of SM1 occupied was imperative to their survival. In this case, hominins likely utilized the extensive *wadi* channels or the contrast between igneous and sedimentary landscape for navigation.

7.7 Survival and risk-mitigation in the GAOA

As previously described, the landscape of the Azraq Basin during the Middle-Upper Pleistocene is largely represented by eolian sediments overtop a mosaic of igneous and sedimentary rock, with a predominance of scrub typical of hot deserts. The wetlands of the GAOA at the heart of the Azraq Basin are characterized by a transitional environment, from a receding lake to a series of marshy ponds, which were surrounded by aquatic vegetation (Nowell et al. 2016). The surrounding *wadis* that drain into the Qa’ Azraq would contribute to seasonally available sources of water. However, the wetlands are the stable source of water, as they are spring-fed and dependent on the groundwater of the aquifer. Even during the driest, most inhospitable periods, it is likely that the Druze and Shishan marshes of the GAOA retained seasonal ponds (Cordova et al. 2013). The transitional environment, from the highest lake stand to the desertification of the surrounding landscape, presented an increasingly harsher and riskier environment for hominins and other animals. The ability to adapt to specific pockets of concentrated resources throughout a generally resource-poor landscape was critical to the survival of hominins and was facilitated by risk-mitigation strategies (Nowell et al. 2016).

The collective need for water brought hominins into the inevitable contact of other animals within the wetlands. This contact provided opportunities to either hunt animals or scavenge their carcasses. Several medium- and large-sized herbivore taxa were discovered in the faunal assemblage of SM1 and similar species were discovered at the nearby sites of C-Spring and ‘Ain Soda, suggesting the presence of such herds in the region (Pokines et al. 2019). The hominins could prey on these species as they drank or ate the lush vegetation growing around the margin of

the wetlands and within it. Attacks and pursuit of prey occurring at the margins of the wetlands may have enable hunting success, as the water itself eliminated (at least) one direction of escape and tall vegetation may have enabled ambushes (Figure 4.8).

SM1 is most consistent with a butchering site, though it is unclear if it represents a *kill site*, where butchering occurred in the same place that the animal fell (Binford 1978, 1983). The remains of the butchered carcasses at SM1 would be attractive to predators, as would the hominins themselves, since hominins (and humans today) are not outside the diet of large felids (Brain 1981; Camaros et al. 2016; Patterson 1908). The presence of large, ferocious predators is accounted for in both the faunal record of the region and the serum evidence from SM1. Due to the tight aggregation and shared water resources, it was imperative that the hominins must have had effective strategies for protection of the carcass (if killed), the capture of the carcass (if scavenged), and for the general avoidance of predators (Nowell et al. 2016). The numerous prepared bifaces with which SM1 was provisioned and additional expedient tools were necessary for prey acquisition. As bifaces were continually brought in and accumulating, they could be accessed for on-the-spot tasks, including hunting and butchering. Groups of hominins were likely more effective and may have operated as specialized task groups to rapidly deflesh and process the carcass, something highly divergent from non-human primate foraging strategies (Nowell et al. 2016).

The hominins of SM1 also adopted an overall broader-based economy (from Layer 8 to 7) to ensure their survival (Hayden 1981; Nowell et al. 2016). This is evident in the continued exploitation of distant lithic sources and is well demonstrated by an expanded dietary breadth. Rather than restrict the foraging distance over time, hominins continued to venture well beyond a local range, moving material from the northeast catchment area to SM1. Furthermore, the presence of avian protein residue on stone tools from Layer 7b-c indicates that individuals of the Family Anatidae, likely duck (waterfowl), were butchered at the site (see Section 3.6.3). It is most probable that these waterfowl were hunted rather than scavenged (Nowell et al. 2016), as their small carcasses are unlikely to be abandoned by predators and would provide little return overall. Hunting waterfowl required a much different method than large mammals and a high degree of stealth, finesse, and planning (Nowell et al. 2016). This may have been best executed at night when

ducks are reluctant to leave their nests. Their acquisition may have been further facilitated by throwing nets, sticks, boomerangs, and possibly slings (Nowell et al. 2016), all implements that are not likely to preserve.

7.8 Conclusion

The results from the provenance analysis permit a reconstruction of the lithic procurement strategies at SM1 in the Azraq Basin. Lithics were procured in three main foraging areas: on-site, western, and northeastern. They were moved into the wetlands over local and regional distances, possibly in conjunction with the seasonal exploitation of the GAOA. Furthermore, when these strategies are combined with other lines of data from SM1, they collectively reveal risk-mitigation strategies enacted by the hominin occupants of the GAOA.

CHAPTER 8: CONCLUSION

The reconstruction of lithic procurement strategies from SM1 provides insight into the survival behavior in the Azraq Basin during the Middle-Upper Pleistocene. This chapter concludes this study. It stresses the contributions to growing bodies of knowledge on provenance and procurement strategies in the Azraq Basin and Levant, as well as the operation of the GAOA as a desert refugium. Furthermore, it discusses avenues for future research and the challenges they may encounter.

8.1 Summary of research

The information generated by this study can be well summarized by answering the questions initially posed in Section 1.4.

1) From which sources did the hominins procure raw material for the manufacture of lithic artifacts?

The bifaces and associated cores from SM1 exhibit several patterns in regards to its raw material. The hominins manufactured bifaces from raw material of medium-high quality, although some of medium-high quality were used as well. These cherts were procured from specific areas on the landscape that offered access to exposed beds, disembedded beds, and loose clasts. These sources appear directly to the west (6-7.5 km) and to the northeast (15-21.5 km) of SM1, albeit "as the crow flies". Additional exploited sources that were located on-site within the Shishan Marsh.

2) What are the long-term procurement strategies practiced by the hominins and how do these change over time (e.g., from the Middle to Upper Pleistocene)?

The hominins of SM1 obtained the raw material for their stone tools from catchment areas with abundant chert. Foraging in the western and northeastern catchments allowed hominins to obtain their lithics likely through embedded procurement. These tools (or raw material) were eventually moved over local and regional distances until their deposition at SM1. Over time, hominins may have afforded more time to foraging near the margins of the wetlands. This interpretation is supported by the frequencies in which artifacts originate from specific sources. The frequencies

change slightly from Layer 8 (Middle Pleistocene) to Layer 7b-c (Upper Pleistocene), but the same sources are exploited in both layers. Evidence of opportunistic procurement in the immediate vicinity of SM1 occurs in both layers, likely as drying conditions continued to provide a landscape of disembedded clasts throughout the wetlands. Several nearby chert sources to the west of SM1 were exploited, suggesting that foraging within a local range was common. In addition, the profiles of multiple artifacts were consistent with more distant sources.

3) How do the collective foraging strategies inform our perspective of hominin familiarity and interaction with the landscape?

The foraging strategies exhibited by the hominins of SM1 indicate that they likely had a high degree of familiarity with their regional landscape. The noted preference for high-quality cherts for tool manufacture also suggests knowledge of the distribution of certain resources. There is ample low-quality chert in the region, as well as dolostone and basalt, but these raw materials were ignored in favor of high-quality chert. Movement to and from the resource-rich locale of the GAOA would provide an exploration of the region and the opportunity to identify where chert could be exploited. From the GAOA, the various *wadis* could be tracked upstream to where chert beds were exposed and clasts were available. Foraging throughout the central Azraq Basin would cause hominins to encounter the dark basalt bluffs on the horizon, which could signal the lack of chert in that area of the landscape. Tracing *wadis* from the higher elevations of the igneous plateau and escarpments of the URC Formation towards the low-lying Qa' Azraq would bring hominins within sight of the green GAOA.

4) What is the response of the hominins of SM1 to increased aridity and water reduction in the region and how does it compare to that of contemporaneous hominin groups within the GAOA and Levant, as well as to those of modern hunter-gatherer (*Homo sapiens*) groups in similar environmental circumstances?

The response of hominins to the decreasing availability of water in the Azraq Basin is largely indicated by their mobility patterns. Initially, these environmental conditions likely pressured hominin groups to locate to the central Azraq Basin and contract around the stable water resource

of the GAOA. Winter precipitation and expansion of the *qa'* would likely allow hominins to subsist relatively well on the surrounding landscape. However, during the dry season, hominins were likely tethered to the dependable GAOA (Cane 1987; Gould 1969; Taylor 1964; Yellen 1976). This tethering could still permit routine foraging or even residence within the western and northeastern catchment areas, but indicates hominins remains fairly mobile.

8.2 Contributions of study

This study contributes to several field of knowledge. Some contributions are large while others add a small piece to the larger puzzle. These include provenance and procurement in the Azraq Basin and the Levant, as well as the operation of the GAOA as a desert refugium.

8.2.1 First geochemical characterization of chert sources within the Azraq Basin

The geochemical characterization of chert is often difficult due to the high potential heterogeneity of the raw material and, overall, there are limited provenance analyses on chert within archaeology. This dearth of investigation applied especially to the central Azraq Basin, where no in-depth geochemical characterization of the chert sources had been undertaken. Nevertheless, this present study indicated that, even in such a chert-rich region, various sources can be discriminated from one another based on their geochemistry. The selected technique, LA-ICP-MS, proved to be effective for generating consistent and constrained data within each source. The results indicate that not only could the sampled sources be discriminated from one another, but that the artifacts could be sufficiently connected to several sources based on selected elements. The provenance postulate, the idea that artifacts from a specific source will exhibit a more similar geochemical composition to that source than others and that these are identifiable (Glascock & Neff 2003; Weigand et al. 1977), is applicable for the selected sources of the Azraq Basin.

8.2.2 First investigation of lithic procurement within the GAOA

This study is the first systematic investigation into the nature of lithic procurement from a Paleolithic site within the GAOA. There is a rich record of Lower-Middle Paleolithic occupation within the Azraq Basin that is largely evident from lithic remains (e.g., Copeland 1988; Copeland

& Hours 1989a, 1989b). Most previous studies sought to establish the typology and assumed all lithic artifacts originated from collected clasts in *wadi* sectors or from those that were moved downstream into the GAOA and thus were within the immediate vicinity of each site (Ames et al. 2014a; Copeland 1989c; Rollefson 1980, 1983). These studies generally assumed procurement to have been opportunistic and to have occurred within the very locale in which the tools were later deposited. However, this present study suggests that the nature of procurement for certain tools (bifaces) is entangled with features of mobility and provisioning. The hominins of the central Azraq Basin likely practiced an embedded procurement strategy and maintained it during on-going changes in the regional climatic and environmental conditions. It demonstrates that hominins were fairly mobile about their regional landscape, exploiting chert sources in different and distant areas of the Azraq Basin and moving them to a destination that would be considered beyond a secure foraging range.

8.2.3 Operation of the GAOA as a desert refugium

The importance of the GAOA, the collective wetlands of the Druze and Shishan marshes, as a stable and localized pocket of resources highlights its operation as a desert refugium during periods of environmental stress (Cordova et al. 2013; Nowell et al. 2014, 2016). A *refugium* (plural: refugia) is a relatively small geographic area, typically with a concentration of resources, in which a population can find shelter and survive during a period of unfavorable and inhospitable conditions (Cordova et al. 2013; Haffer 1969). Such locales have been used to describe the contraction in the range of a species or a complete isolation of them from other members, often resulting in a genetic bottle-neck (Bennett & Provan 2008; Hawks et al. 2000). Refugia take many forms (see Bennett & Provan 2008), as populations of fauna and flora have managed to survive in under varied environmental conditions.

The concept of refugia readily applies to hominin populations. An often-cited example is the diachronous extinction of Neanderthals across Eurasia (Finlayson et al. 2006; Stewart & Stringer 2012). MIS 4-2 contained notable global cooling with several particularly cold episodes (e.g., Heinrich event 4 at 39 kya) that expanded the southern extent of the continental glaciers and coincided with the disappearance of Neanderthals from the fossil record (Bradtmöller et al. 2012;

Mellars 2006). Neanderthal groups were gradually pressed south into the glacial refugia of Mediterranean environments, most notably the Iberian Peninsula (Carrion et al. 2003; Finlayson et al. 2006). Their subsistence was enabled by a diverse range of fauna and flora among the interior woodlands and exterior coastlines, including sea mammals and mollusks (Carrion et al. 2003, 2008; Stringer et al. 2008). It is further speculated that Neanderthal groups may have been able to recover had the arrival of AMH into Eurasia (~40 kya) not coincided with such a vulnerable time (Banks et al 2008; Gilpin et al. 2016).

The GAOA is not the only refugium in the Levant, as other localized pockets of water and biodiversity that can be found during climatically adverse periods. For example, the former springs in the El Kowm Basin, Syria were able to sustain hominin occupation during the Middle Paleolithic (Hauck 2011; Kalbe et al. 2016; Le Tensorer et al. 2007). Similarly, smaller isolated and ephemeral water resources in the Levant may have served as more temporary refugia. This is exemplified by hominin occupation at the site of Quneitra, Israel, along the shoreline of a former seasonal lake (Davis et al. 1988; Hovers 1990; Oron & Goren-Inbar 2014), or among the small lakes or marsh habitats of large *wadi*/*nahal* systems, such as Wadi Hasa (Clark et al. 1988; Coinman 2004).

The geohydrological settings that provided these wetlands had significant implications for the survival (or extinction) of hominin groups in the Levant, particularly during dispersals. These stable sources of water likely contained a wealth of micro- and macro-nutrients for flora and fauna alike and allowed metapopulation stability for hominins (Brown et al. 2013). While other hominin groups affected by adverse climatic conditions underwent range contractions and local population extinctions, hominins within the Azraq Basin may have been less vulnerable. Their survival was enabled by the exploitation of the GAOA as a temporary desert refugium. Here hominins were likely restricted by their regional environment to an extent, but were still able to subsist relatively well with the available resources. Ultimately, the various refugia allowed the local groups to later expand into new founder populations and the metapopulation to persist within the Levant (Bey 2011; Finlayson 2013).

In addition, these refugia could also serve as locales for the meeting and interbreeding of hominin populations. For example, hominin groups moving from the Arabian Peninsula into the Levant may arrive in the Azraq Basin through the Azraq corridor (SE-NW). Other hominin groups

may move from the western Levant into the Azraq Basin, possibly with the directionality of precipitation (west to east). This latter movement could even correspond to the contraction associated with the DWA to LAA facies. In this scenario, two separate populations (or species) could be brought together and interact due to the shared necessity of finding stable sources of fresh water (Finlayson 2013). Given the dates at SM1 (Layer 8: 266 +/- 40 kya; Layer 7b: 125 +/- 12 kya) and the fossil record of the Levant and beyond (Table 4.1), there are several possibilities regarding which species may have been present in the GAOA. Layer 8 corresponds possibly with *Homo erectus*, but also early AMH and "Pre"-Neanderthals. Layer 7 corresponds with the Neanderthals and AMH timeframe, but is formed slightly earlier than the first interbreeding event (~100 kya) of the two species (Kuhlwilm et al. 2016). While this discussion highlights the potential refugia can play in hominin evolution, the conclusions are still speculative.

8.3 Future directions of research

Due to the inaugural nature of this study, it is apparent that there are several directions that future research could take. These revolve around the geochemical characterization of chert and networking of sites within the Azraq Basin, the nature of lithic procurement within the Levant, and the exploration of hominin occupation within the Azraq corridor.

8.3.1 Developing a larger provenance dataset in the Azraq Basin

The difficulty of this study was exacerbated by the lack of previous geochemical characterization in the Azraq Basin. No previous studies were available for guidance or reference to indicate which techniques, strategies, or elements were most effective for the discrimination of cherts in this region. For the present study, the contrast of selected elements and element ratios proved effective for establishing geochemical consistency between several sources and the artifacts. In such a chert-rich region, sufficient characterization involves the inclusion of numerous samples. The inclusion of multiple sources can clutter the data and increase the potential that unrelated sources have a similar geochemical profile, but it is necessary to identify the full range of variation in the region. An artifact could then be paired with several sources and additional steps of discrimination may be required. The sample size of artifacts is roughly 46% (38 of 82) of the

entire assemblage and can be considered representative of entire sample. Still, the question must be asked whether an increase in the sample size would change the interpretation? Given that Layers 8 and 7b-c have close similarities, it unlikely that the overall patterns would change significantly if the sample size doubled. An important discovery with a larger sample size may be the occasional artifact linked to a much more distant source. Artifacts with geochemical profiles consistent with sources from the southern or southwestern catchment areas (e.g., WG, WB) would provide the most significant modification to the results. Though still tentatively representative of long-term procurement trends, the interpretation may be adjusted by new data, such as the inclusion of additional sources or application of additional techniques.

The results of this study warrant a need further geochemical characterization of the chert within the Azraq Basin. Many chert sources in the Azraq Basin were left unsampled and thus were not included in this study. Additional survey and documentation would allow for a broader range of sources to be included and considered. Supporting characterization can be accomplished through additional techniques, such as thin section analysis or solution ICP-MS. The former will emphasize the fossil or mineralogical composition while the latter can provide a better resolution of the REEs in particular (Segal et al. 2005). However, destructive techniques are not always possible on certain artifacts, such as those included in the present study. Ultimately, greater reconnaissance, sampling, and characterization can strengthen the original results and further add to a growing dataset. A larger dataset of raw material composition permits more secure associations for any newly discovered artifacts.

There are multiple unexcavated sites within the GAOA, as indicated by survey and test trenches. They would serve to broaden the scope of procurement reconstruction within the GAOA and perhaps permit connections among sites in the Azraq Basin. The bifaces from previously excavated sites (Table 4.2), namely Lion Spring, C-Spring, and DM-8, require revisiting in order to establish a comparative nature of procurement within the GAOA. It may be possible that hominins groups around the Druze Marsh (north GAOA) exploited different sources and exhibit different procurement strategies than those of the Shishan Marsh (south GAOA). A consideration of the procurement patterns between the DWA and FAA facies would also present an interesting

avenue. These assemblages differ in typo-technological characteristics and were utilized during different region-wide environmental conditions.

8.3.2 Constructing a connected picture of lithic procurement in the Levant

The lithic procurement strategies in the Levant during the Pleistocene have largely been ignored and insufficiently investigated. This dearth of information is likely due to the recognized abundance of chert within the Levant, as it is often assumed that procurement is simply "local". The trend is changing as several studies, including this present one, indicate that this is not necessarily the case (e.g., Barkai et al. 2006; Ekshtain et al. 2014; Finkel et al. 2016, 2019). These recent investigations have demonstrated that there are more complex forms of procurement than previously assumed, some of which are not found outside the Levant until much later (e.g., deep mining, resource management). However, due to the nature of the sites and forms of analysis, there is a disconnected picture of lithic procurement in the Levant. Questions remain as to how contemporary occupation sites are linked to each other and how they further relate to sites of extraction. For example, is there a relationship between the provisioning observed at 'Ein Qashish and the exploitation of the quarries of Sede Ilan, as they are both in the Galilee region of Israel? Or were the deep-mined tools from Qesem and Tabun caves procured from deep beds or nodules of the quarries? How do lithic procurement strategies vary in different ecozones of the Levant (e.g., eastern desert vs. coastal plain)? These questions are currently unanswered due to limited provenance investigation. An identification and consideration of home bases or residences could further connect sites to the network of extraction sites (sources). This would also offer a broader picture of mobility patterns. Archaeologists often look to establish connections between sites on the basis of hominin species present or assemblage typology, but rarely by accessed sources of raw material or procurement patterns.

Many provenance studies of chert artifacts in the Levant are based on individual attributes with occasional support from petrography (e.g., Delage 2007b; Long & Julig 2007; Rollefson et al. 2007). In general, very little geochemical characterization has been conducted on chert in the Levant. Those of strictly geological inquiry focus on the depositional environment or formation pathways (e.g., Flexer 1971; Kolodny et al. 2005; Lewy 2010), which, depending on the

geochemical data, can be useful for provenance studies. No robust geochemical studies have been undertaken on chert provenance in Jordan, though there are some where a preliminary step has been taken (e.g., Al-Qudah 2007; Sánchez de la Torre et al. 2019). Several geochemical studies on the Eocene chert in the Galilee region of Israel have been conducted (e.g., Ekshtain et al. 2014, 2016; Finkel et al. 2019). However, there are multiple chert sources, both primary and secondary, that require characterization and distinction. To enable intra- and inter-regional comparisons, the characterization of cherts is best accomplished through a standardization of techniques and discrimination strategies.

While ethnoarchaeological inquiry of the 1970-80s produced very insightful studies (e.g., Binford 1978, 1982; Binford & O'Connell 1984; Gould & Saggers 1985), the literature on lithic procurement is not extensive and is almost completely built upon these initial efforts. Attempts to overlay models of modern hunter-gatherer behavior onto the data of Levantine assemblages have also been difficult. Most interpretations, including that of this study, fall somewhere along the embedded-direct procurement spectrum (e.g., Ekshtain et al. 2014; Finkel et al. 2019). Lithics are often caught in the gravitational pull of studies that examine the acquisition of other resources, namely prey and vegetation. Perhaps, lithics procurement can draw on models from other artifact types, such as clay (for ceramic manufacture), of which there is abundant literature and even on-going studies in the 21st century (e.g., Arnold 1985; Fowler et al. 2011, 2019; Gosselain 2002, 2008).

8.3.3 Exploring the Azraq corridor

A consideration of SM1 and the GAOA within the larger context of the Azraq Basin requires further inquiry into the archaeological and geohydrological connections with the associated sequential basins along the larger palaeohydrological corridor. The Azraq corridor stretches from the Azraq Basin, across the western portion of the "northern Arabian Desert barrier", to the interior of the Nefud Desert where it converges with the larger Tabuk corridor (Figure 4.2). Significant attention has been afforded to the Tabuk corridor, but much less to the Azraq corridor. Groups of hominins potentially dispersing from Africa through the Arabian Peninsula could move along the lake shorelines in the successive basins when paleolake levels

were sufficiently high. Movement along the Tabuk corridor is most promising given the distribution of remains and viability of the region during more humid interglacial episodes (e.g. MIS 9, 7, 5e), the nature of survival along it has only been reconstructed for a section of the Azraq Basin (Ames et al. 2014a; Ames & Cordova 2015; Cordova et al. 2013; Nowell et al. 2016; Pokines et al. 2019). Similar geohydrological investigation within the hypothesized string of lakes of the Wadi Sirhan depression can reconstruct the paleoshorelines and indicate the degree of water availability during various periods. If these basins (e.g., Al Qutb, Qa' Hazawa, Qurrayat) exhibit similar geohydrological settings to the Azraq Basin, then it is possible that desert refugia also existed within them. The identification of hominin occupation sites and the subsequent analysis of their material culture assemblages can lend further insight into the nature of survival within these locales. This can, in part, be investigated through a reconstruction of their lithic procurement strategies. Any behavioral similarities or changes can be monitored from subcatchment to subcatchment *en route* to the Levant.

8.4 Conclusion

This study has examined several aspects related to the survival of hominins in the Levant during the Middle-Upper Pleistocene. More specifically, the lithic remains from SM1 presented the opportunity to investigate the nature of procurement at a desert refugium during periods of environmental stress. It explored the strategies by which hominins procured their resources and mitigated risk and found parallels with modern hunter-gatherers in comparable circumstances. In seeking to understand how our behavior is similar to and different than our ancestors, it revealed that there are long standing behaviors in our hominin lineage. Further research has the potential to provide additional insight into the dispersal of hominins, namely AMH, out of Africa, through the Arabian Peninsula and into the Levant.

APPENDICES

Appendix 1: Description of lithic artifacts (3 tables).

Table 1/3									
Artifact	Layer	Sublayer	Selected for LA-ICP-MS	Square	Quadrant	Datum	Type	Biface/Core Type	Manufacture Technology
152	8	N/A		D	SE		Handaxe		Bifacial Percussion
246	7	7 b		D	SW		Handaxe		Bifacial Percussion
331	8	N/A		D	NW		Handaxe		Bifacial Percussion
421	7	7 b		???	SE	43957	Handaxe	Ovate	Bifacial Percussion
437	8	N/A		F	NE		Handaxe		Bifacial Percussion
474	8	N/A		O1	SE	43894	Handaxe	Ovate	Bifacial Percussion
475	8	N/A		F	SW		Handaxe		Bifacial Percussion
556	7	7 c		T2	NE	0-1	Handaxe	Ovate	Bifacial Percussion
584	7	7 a-b		S2	SE	0-1	Handaxe	Ovate	Bifacial Percussion
925	7	7 a-b		T1	NW	0-1	Handaxe	Ovate	Bifacial Percussion
1121	7	7 a-b		R2	SW	43864	Handaxe	Discoid	Bifacial Percussion
1200	7	7 c	Yes	S2	NW	43832	Core	Bidirectional	Bifacial Percussion
1767	7	7 b	Yes	R2	SE	43864	Handaxe	Amygdaloid	Bifacial Percussion
1944	7	7 a-b		S2	NE	43894	Handaxe	Amygdaloid	Bifacial Percussion
2005	7	7 b		???	SE	43957	Handaxe	Ovate	Bifacial Percussion
2058	7	7 b		???	SE	43957	Handaxe	Cordiform	Bifacial Percussion
2123	7	7 a-b		M2	SW	43864	Handaxe	Fragment	Bifacial Percussion
2225	7	7 b		???	SE	43957	Handaxe	Triangular	Bifacial Percussion
2384	7	7 b		???	SE	43957	Handaxe	Fragment	Bifacial Percussion
2556	7	7 b		???	SE	43957	Handaxe	Preform	Bifacial Percussion
2557	7	7 a-b	Yes	N2	NW	43894	Handaxe	Ovate	Bifacial Percussion
2585	7	7 b		???	SE	43957	Handaxe	Ovate	Bifacial Percussion
2684	8	N/A		M2	NE	43957	Handaxe	Cordiform	Bifacial Percussion
2689	7	7 b		???	SE	43957	Handaxe	Ovate	Bifacial Percussion
2695	8	N/A		M2	NE	43957	Handaxe	Ovate	Bifacial Percussion

2706	8	N/A		M2	SW	43957	Handaxe	Amygdaloid	Bifacial Percussion
2716	8	N/A		M2	NW	43957	Handaxe	Early Stage	Bifacial Percussion
2743	7	7 b		R3	NW	43864	Handaxe	Fragment	Bifacial Percussion
2941	7	7 b	Yes	R3	NW	43894	Handaxe	Ovate	Bifacial Percussion
2947	8	N/A	Yes	Q3	NW	44052	Handaxe	Ovate	Bifacial Percussion
3076	8	N/A		Q3	NW	44052	Handaxe	Fragment	Bifacial Percussion
3082	8	N/A	Yes	P3	NE	44115	Handaxe	Ovate	Bifacial Percussion
3118	7	7 b	Yes	Q3	NE	44084	Handaxe	Ovate	Bifacial Percussion
3131	7	7 b	Yes	Q3	NE	44084	Handaxe	Ovate	Bifacial Percussion
3152	8	N/A		R3	NE	43926	Handaxe	Ovate	Bifacial Percussion
3153	8	N/A		R3	NE	43926	Handaxe	Cordiform	Bifacial Percussion
3227	8	N/A		R3	NW	43957	Handaxe	Fragment	Bifacial Percussion
3399	8	N/A		Q3	SE	44084	Cleaver	Ovate	Bifacial Percussion
3468	7	7 b	Yes	Q4	NE	43864	Biface	Ovate	Bifacial Percussion
3547	7	7 b	Yes	R3	SE	43894	Biface	Discoid	Bifacial Percussion
3591	8	N/A	Yes	P4	NE	43957	Core	Bidirectional	Bifacial Percussion
3603	7	7 b	Yes	Q4	NW	43864	Handaxe	Ovate	Bifacial Percussion
3711	8	N/A	Yes	Q5	NW	43926	Handaxe	Ovate	Bifacial Percussion
3738	8	N/A		P4	SE	43926	Handaxe	Early Stage	Bifacial Percussion
3747	7	7 b		O3	NE	43894	Handaxe	Ovate	Bifacial Percussion
3761	8	N/A		P4	SE	43926	Handaxe	Early Stage	Bifacial Percussion
3805	8	N/A	Yes	Q4	SE	43894	Cleaver	Ovate	Bifacial Percussion
3806	8	N/A	Yes	Q4	SE	43894	Handaxe	Discoid	Bifacial Percussion
3869	7	7 b		Q4	SW	43864	Handaxe	Preform	Bifacial Percussion
3882	7	7 b		P5	NE	43864	Handaxe	Ovate	Bifacial Percussion
3883	7	7 b	Yes	P5	NW	43864	Cleaver		Bifacial Percussion
3912	7	7 b	Yes	P5	SE	43864	Handaxe	Ovate	Bifacial Percussion
3966	8	N/A		O3	NW	43989	Handaxe	Fragment	Bifacial Percussion
4018	7	7 b	Yes	Q5	NE	43864	Handaxe	Preform	Bifacial Percussion
4033	8	N/A	Yes	P5	NW	43926	Handaxe	Ovate	Bifacial Percussion

4038	7	7 b	Yes	Q5	SW	43864	Handaxe	Ovate	Bifacial Percussion
4134	7	7 b	Yes	Q5	NW	43864	Handaxe	Ovate	Bifacial Percussion
4192	8	N/A	Yes	Q5	NW	43894	Handaxe	Ovate	Bifacial Percussion
4197	8	N/A		O3	SW	43926	Handaxe	Discoid	Bifacial Percussion
4215	8	N/A	Yes	O3	SW	43926	Handaxe	Ovate	Bifacial Percussion
4278	8	N/A	Yes	P5	SW	43957	Handaxe	Ovate	Bifacial Percussion
4330	7	7 b		O5	NE	43864	Handaxe	Preform	Bifacial Percussion
4396	8	N/A	Yes	O4	NW	43894	Handaxe	Discoid	Bifacial Percussion
4423	7	7 c		O5	SE	43926	Handaxe	Cordiform	Bifacial Percussion
4425	8	N/A	Yes	O5	NE	43894	Handaxe	Ovate	Bifacial Percussion
4488	7	7 b	Yes	O4	SE	43864	Handaxe	Ovate	Bifacial Percussion
4495	7	7 c	Yes	O5	SE	43957	Handaxe	Ovate	Bifacial Percussion
4522	8	N/A	Yes	O5	NE	43926	Handaxe	Ovate	Bifacial Percussion
4530	8	N/A		O5	NW	43926	Handaxe	Ovate	Bifacial Percussion
4539	8	N/A		O4	SW	43957	Handaxe	Preform	Bifacial Percussion
4548	8	N/A	Yes	O4	SE	43894	Handaxe	Ovate	Bifacial Percussion
4577	8	N/A		O4	SE	43926	Cleaver		Unidirectional Percussion
4622	8	N/A	Yes	O4	SE	43957	Handaxe	Ovate	Bifacial Percussion
4651	8	N/A	Yes	O5	NW	43926	Handaxe	Ovate	Bifacial Percussion
4671	8	N/A	Yes	O5	SW	43957	Handaxe	Ovate	Bifacial Percussion
4673	8	N/A	Yes	O5	SW	43957	Handaxe	Ovate	Bifacial Percussion
4675	7	7 b	Yes	N3	NW	0-1	Handaxe	Ovate	Bifacial Percussion
4709	7	7 b		N3	NW	43832	Handaxe	Cordiform	Bifacial Percussion
4733	7	7 b		N3	SE	0-1	Handaxe	Discoid	Bifacial Percussion
4751	7	7 b	Yes	O1	NE	43864	Handaxe	Discoid	Bifacial Percussion
4752	7	7 b	Yes	N3	SE	43832	Handaxe	Ovate	Bifacial Percussion
4826	8	N/A	Yes	N3	NE	43926	Handaxe	Ovate	Bifacial Percussion

Table 2/3										
Artifact	Raw Material	Material Quality	Previous State	Cortex %	Cortex Type	Element	Length (mm)	Width (mm)	Thickness (mm)	Context ID
152	Chert	Very good		11-40		Complete	128.8	80.1	25.8	
246	Chert	Good		11-40		Complete	86.5	79.2	27.9	
331	Chert	Very good		11-40		Complete	113.5	89	22.1	
421	Chert	Medium	Tabular Material	11-40	Primary Geologic	Complete	147.47	101.53	25.78	?? : SE : 5-6 : Layer 7b
437	Chert	Very good		1-10		Complete	83.1	65.1	24.9	
474	Chert	Good	Unknown	1-10	Primary Geologic	Complete	128.95	88.04	24.72	O1 : SE : 3-4 : Layer 8
475	Chert	Medium-good		1-10		Complete	153.5	114	23.5	
556	Chert	Medium	Tabular Material			Complete	152	106.08	58.12	T2 : NE : 0-1 : Layer 7c
584	Chert		Flake	41-60	Incipient Cone	Complete	83.95	66.42	22.3	S2 : SE : 0-1 : Layer 7a/b
925	Chert		Tabular Material	61-90	Primary Geologic	Complete	90.97	46.51	18.99	T1 : NW : 0-1 : Layer 7a/b
1121	Chert		Unknown	11-40	Primary Geologic	Complete	98.89	86.78	24.35	R2 : SW : 2-3 : Layer 7a/b
1200	Chert	Medium	Unknown			Complete	86.8	60.97	46.63	S2 : NW : 1-2 : Layer 7c
1767	Chert	Good	Tabular Material	11-40	Primary Geologic	Complete	122.27	80.08	27.7	R2 : SE : 2-3 : Layer 7b
1944	Chert		Tabular Material	11-40	Primary Geologic	Complete	96.82	73.2	26.41	S2 : NE : 3-4 : Layer 7a/b
2005	Chert		Unknown			Complete	129.5	92.7	25.1	?? : SE : 5-6 : Layer 7b
2058	Chert		Unknown	11-40	Primary Geologic	Complete	126.77		46.18	?? : SE : 5-6 : Layer 7b
2123	Chert		Flake, Late Core Reduction			Lateral	35.36	41.73	12.9	M2 : SW : 2-3 : Layer 7a/b
2225	Chert		Unknown	11-40	Primary Geologic	Complete	63.83	63.93	20.37	?? : SE : 5-6 : Layer 7b
2384	Chert		Unknown	11-40	Primary Geologic	Proximal				?? : SE : 5-6 : Layer 7b

2556	Chert		Tabular Material	61-90	Primary Geologic	Complete	96.7	66.8	20.8	?? : SE : 5-6 : Layer 7b
2557	Chert	Good	Cobble	11-40	Incipient Cone	Complete	92.89	64.17	25.22	N2 : NW : 3-4 : Layer 7a/b
2585	Chert		Tabular Material	11-40	Primary Geologic	Complete	113.7	78.55	29.26	?? : SE : 5-6 : Layer 7b
2684	Chert	Med-good	Unknown			Complete	125.44	80.9	32.04	M2 : NE : 5-6 : Layer 8
2689	Chert		Unknown			Complete	140.3	91.3	58.2	?? : SE : 5-6 : Layer 7b
2695	Chert	Very good	Tabular Material	11-40	Primary Geologic	Complete	115.44	88.23	22.66	M2 : NE : 5-6 : Layer 8
2706	Chert	Good	Tabular Material	11-40	Primary Geologic	Complete	110.67	72.86	33.77	M2 : SW : 5-6 : Layer 8
2716	Chert	Good	Tabular Material	41-60	Primary Geologic	Complete	137.77	79	41.62	M2 : NW : 5-6 : Layer 8
2743	Chert		Pebble	61-90	Primary Geologic	Fragment	47.07	35.2	14.33	R3 : NW : 2-3 : Layer 7
2941	Chert	Good	Unknown	11-40	Primary Geologic	Complete	97.45	66.49	25.48	R3 : NW : 3-4 : Layer 7
2947	Chert	Good	Unknown	11-40	Primary Geologic	Complete	105.06	83.25	33.74	Q3 : NW : 8-9 : Layer 8
3076	Chert		Tabular Material	41-60	Primary Geologic	Fragment	59.17	43.71	13.89	Q3 : NW : 8-9 : Layer 8
3082	Chert	Very good	Tabular Material	11-40	Primary Geologic	Complete	122.68	87.72	20.72	P3 : NE : 10-11 : Layer 8
3118	Chert	Very good	Cobble	41-60	Incipient Cone	Complete	112.62	94.93	32.61	Q3 : NE : 9-10 : Layer 7
3131	Chert		Tabular Material	41-60	Primary Geologic	Complete	89.57	59.84	22.2	Q3 : NE : 9-10 : Layer 7
3152	Chert		Unknown			Complete	118.31	76.39	29.11	R3 : NE : 4-5 : Layer 8
3153	Chert		Unknown			Complete	118.81	83.76	34.19	R3 : NE : 4-5 : Layer 8
3227	Chert		Unknown			Fragment	66.61	38.53	15.44	R3 : NW : 5-6 : Layer 8
3399	Chert	Medium	Flake			Complete	101.26	62.21	21.51	Q3 : SE : 9-10 : Layer 8

3468	Chert	Medium	Unknown			Complete	109.86	82.86	30.94	Q4 : NE : 2-3 : Layer 7
3547	Chert	Good	Unknown			Complete	82.4	72.51	36.44	R3 : SE : 3-4 : Layer 7
3591	Chert	Medium	Unknown	11-40	Primary Geologic	Complete	100.56	63.61	52.37	P4 : NE : 5-6 : Layer 8
3603	Chert	Very good	Tabular Material			Complete	92.66	61.47	23.76	Q4 : NW : 2-3 : Layer 7
3711	Chert		Tabular Material	11-40	Primary Geologic	Complete	97.74	75.98	30.99	Q5 : NW : 4-5 : Layer 8
3738	Chert	Good	Tabular Material	61-90	Primary Geologic	Complete	111.89	84.97	32.68	P4 : SE : 4-5 : Layer 8
3747	Chert	Medium	Tabular Material	41-60	Primary Geologic	Complete	100.72	60.28	25.43	O3 : NE : 3-4 : Layer 7
3761	Chert	Poor	Tabular Material	61-90	Primary Geologic	Complete	98.11	62.53	29.65	P4 : SE : 4-5 : Layer 8
3805	Chert	Good	Unknown			Complete	121.91	77.76	49.51	Q4 : SE : 3-4 : Layer 8
3806	Chert	Very good	Tabular Material	11-40	Primary Geologic	Complete	93.16	85.96	29.46	Q4 : SE : 3-4 : Layer 8
3869	Chert		Tabular Material	61-90	Primary Geologic	Complete	75.72	52.61	14	Q4 : SW : 2-3 : Layer 7
3882	Chert	Very good	Unknown	43840	Primary Geologic	Complete	102.19	76.93	30.92	P5 : NE : 2-3 : Layer 7
3883	Chert	Medium	Flake	61-90	Primary Geologic	Complete	88.82	61.27	20.9	P5 : NW : 2-3 : Layer 7
3912			Tabular Material	11-40	Primary Geologic	Complete	79.2	49.83	15.85	P5 : SE : 2-3 : Layer 7
3966	Chert		Unknown			Fragment	78.75	52.94	20.12	O3 : NW : 6-7 : Layer 8
4018	Chert	Good	Tabular Material	41-60	Primary Geologic	Complete	70.12	58.08	26.37	Q5 : NE : 2-3 : Layer 7
4033	Chert	Good	Flake	43840	Primary Geologic	Complete	144.05	95.31	27.31	P5 : NW : 4-5 : Layer 8
4038	Chert	Very good	Unknown	43840	Primary Geologic	Complete	95.56	59.09	29.84	Q5 : SW : 2-3 : Layer 7
4134	Chert	Good	Unknown	43840	Primary Geologic	Complete	95.1	63.29	28.71	Q5 : NW : 2-3 : Layer 7

4192	Chert	Good	Unknown	11-40	Primary Geologic	Complete	81.78	62.55	28.71	Q5 : NW : 3-4 : Layer 8
4197	Chert	Very good	Flake	1-10	Primary Geologic	Complete	140.39	77.71	27.02	O3 : SW : 4-5 : Layer 8
4215	Chert		Tabular Material	11-40	Primary Geologic	Complete	129.75	92.55	29.73	O3 : SW : 4-5 : Layer 8
4278	Chert	Good	Unknown	1-10	Primary Geologic	Complete	58.42	49.49	26.09	P5 : SW : 5-6 : Layer 8
4330	Chert		Tabular Material	11-40	Primary Geologic	Complete	70.03	53.18	19.9	O5 : NE : 2-3 : Layer 7
4396	Chert	Good	Unknown			Complete	126.98	103.16	29.9	O4 : NW : 3-4 : Layer 8
4423	Chert		Tabular Material	11-40	Primary Geologic	Complete	68.35	45.74	22.01	O5 : SE : 4-5 : Layer 7c
4425	Chert		Unknown			Complete	100.23	81.33	30.89	O5 : NE : 3-4 : Layer 8
4488	Chert	Good	Unknown			Complete	118.73	75.22	41.2	O4 : SE : 2-3 : Layer 7
4495	Chert	Good	Tabular Material	41-60	Primary Geologic	Complete	98.46	81.14	27.18	O5 : SE : 5-6 : Layer 7c
4522	Chert	Good	Unknown	1-10	Primary Geologic	Complete	105.9	75.75	31.06	O5 : NE : 4-5 : Layer 8
4530	Chert		Tabular Material	11-40	Primary Geologic	Complete	72.37	50.35	18	O5 : NW : 4-5 : Layer 8
4539	Chert		Tabular Material	41-60	Primary Geologic	Complete	85.78	74.53	25.71	O4 : SW : 5-6 : Layer 8
4548	Chert	Medium	Tabular Material	11-40	Primary Geologic	Complete	118.1	66.2	21.05	O4 : SE : 3-4 : Layer 8
4577	Chert		Tabular Material	61-90	Primary Geologic	Complete	82.68	57.97	17.96	O4 : SE : 4-5 : Layer 8
4622	Chert	Good	Unknown	41-60	Primary Geologic	Complete	111.28	98.32	33.11	
4651	Chert	Good	Flake			Complete	118.56	61.28	23.89	O5 : NW : 4-5 : Layer 8
4671	Chert		Unknown	1-10	Primary Geologic	Complete	71.9	61.63	22.72	
4673	Chert		Tabular Material	11-40	Primary Geologic	Complete	130.23	77.88	39.91	

4675	Chert	Medium	Tabular Material	11-40	Primary Geologic	Complete	84.75	58.7	33.83	N3 : NW : 0-1 : Layer 7
4709	Chert		Unknown	43840	Primary Geologic	Complete	61.15	47.95	14.52	
4733	Chert		Unknown	43840	Primary Geologic	Complete	48.53	49.4	14.82	
4751	Chert	Very good	Tabular Material	11-40	Primary Geologic	Complete	130.45	80.59	46.23	
4752	Chert	Good	Unknown	43840	Primary Geologic	Complete	107.83	73.18	43.95	
4826	Chert	Good	Tabular Material	11-40	Primary Geologic	Complete	119.1	86.03	26.77	

Table 3/3										
Artifact	UseWear Round	UseWear Polish	UseWear Micro Flaking	UseWear Loc_Lat	UseWear Loc_Dist	UseWear Loc_Prox	Tranchet	Residue	ThermAlt _CrBrk	ThermAlt _Potlid
152										
246										
331										
421										
437										
474	TRUE		TRUE	TRUE				TRUE		
475										
556	TRUE		TRUE	TRUE	TRUE			TRUE		
584	TRUE		TRUE	TRUE						TRUE
925	TRUE		TRUE	TRUE	TRUE					
1121	TRUE		TRUE	TRUE	TRUE					
1200		TRUE	TRUE	TRUE				TRUE		
1767	TRUE		TRUE	TRUE	TRUE					
1944		TRUE		TRUE				TRUE		
2005	TRUE		TRUE		TRUE					
2058			TRUE	TRUE	TRUE					
2123	TRUE		TRUE	TRUE	TRUE			TRUE		
2225			TRUE	TRUE			TRUE	TRUE		
2384			TRUE	TRUE	TRUE		TRUE	TRUE		
2556			TRUE	TRUE	TRUE		TRUE	TRUE		
2557			TRUE		TRUE		TRUE	TRUE		
2585										
2684	TRUE		TRUE	TRUE	TRUE			TRUE		
2689			TRUE	TRUE	TRUE			TRUE		
2695										
2706			TRUE	TRUE				TRUE		
2716	TRUE		TRUE	TRUE	TRUE			TRUE		

2743	TRUE		TRUE		TRUE			TRUE		
2941	TRUE	TRUE		TRUE	TRUE			TRUE		
2947	TRUE		TRUE	TRUE	TRUE			TRUE		
3076										
3082	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE		TRUE		TRUE
3118	TRUE		TRUE		TRUE			TRUE		
3131	TRUE	TRUE		TRUE	TRUE			TRUE		
3152										
3153										
3227	TRUE	TRUE	TRUE		TRUE				TRUE	TRUE
3399										
3468		TRUE	TRUE		TRUE			TRUE		
3547										
3591										
3603	TRUE		TRUE	TRUE			TRUE	TRUE		
3711	TRUE		TRUE	TRUE	TRUE	TRUE		TRUE		
3738	TRUE	TRUE	TRUE	TRUE	TRUE			TRUE		TRUE
3747										
3761	TRUE	TRUE	TRUE	TRUE				TRUE		
3805										
3806										TRUE
3869	TRUE		TRUE	TRUE			TRUE	TRUE		
3882	TRUE		TRUE					TRUE		
3883	TRUE			TRUE	TRUE	TRUE		TRUE		
3912									TRUE	TRUE
3966			TRUE	TRUE	TRUE			TRUE		TRUE
4018	TRUE		TRUE	TRUE	TRUE			TRUE		
4033	TRUE		TRUE	TRUE				TRUE		
4038										TRUE
4134	TRUE			TRUE						

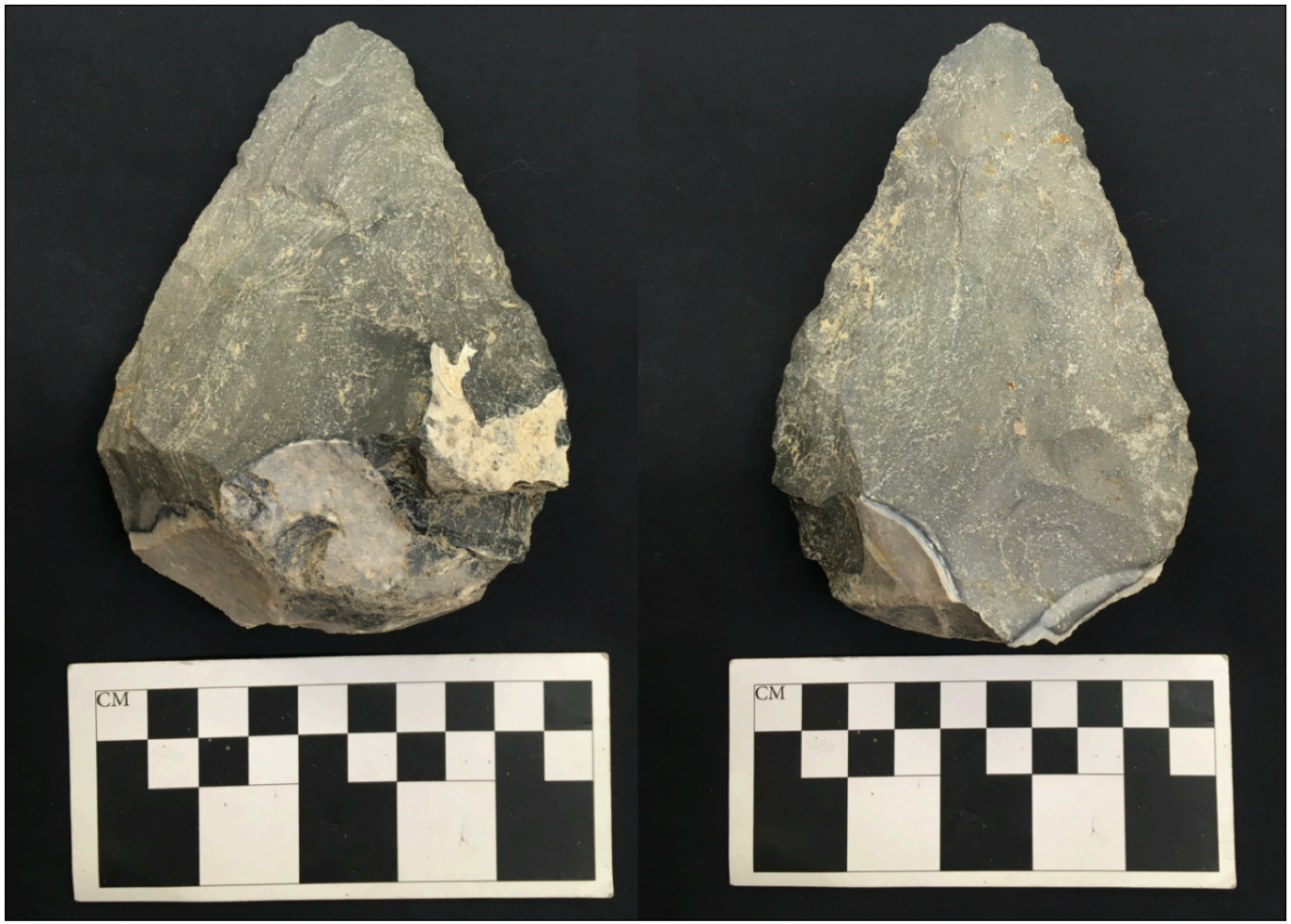
4192	TRUE		TRUE	TRUE	TRUE			TRUE		
4197			TRUE	TRUE	TRUE			TRUE		
4215										TRUE
4278	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE		TRUE		
4330										TRUE
4396		TRUE	TRUE	TRUE				TRUE		
4423	TRUE		TRUE		TRUE			TRUE		TRUE
4425	TRUE		TRUE	TRUE	TRUE			TRUE		TRUE
4488	TRUE	TRUE	TRUE		TRUE		TRUE	TRUE	TRUE	TRUE
4495	TRUE	TRUE	TRUE	TRUE	TRUE		TRUE	TRUE		
4522	TRUE		TRUE	TRUE	TRUE		TRUE	TRUE		
4530			TRUE		TRUE		TRUE	TRUE		TRUE
4539										
4548										
4577								TRUE		
4622										
4651	TRUE		TRUE	TRUE	TRUE			TRUE		
4671										
4673										
4675										
4709										
4733										
4751										
4752										
4826										

Appendix 2: Photographs of lithic artifacts from SM1 included in the provenance study. All photographs taken by the author.

Artifact 1200: bidirectional core



Artifact 1767: amygdaloid handaxe



Artifact 2557: handaxe



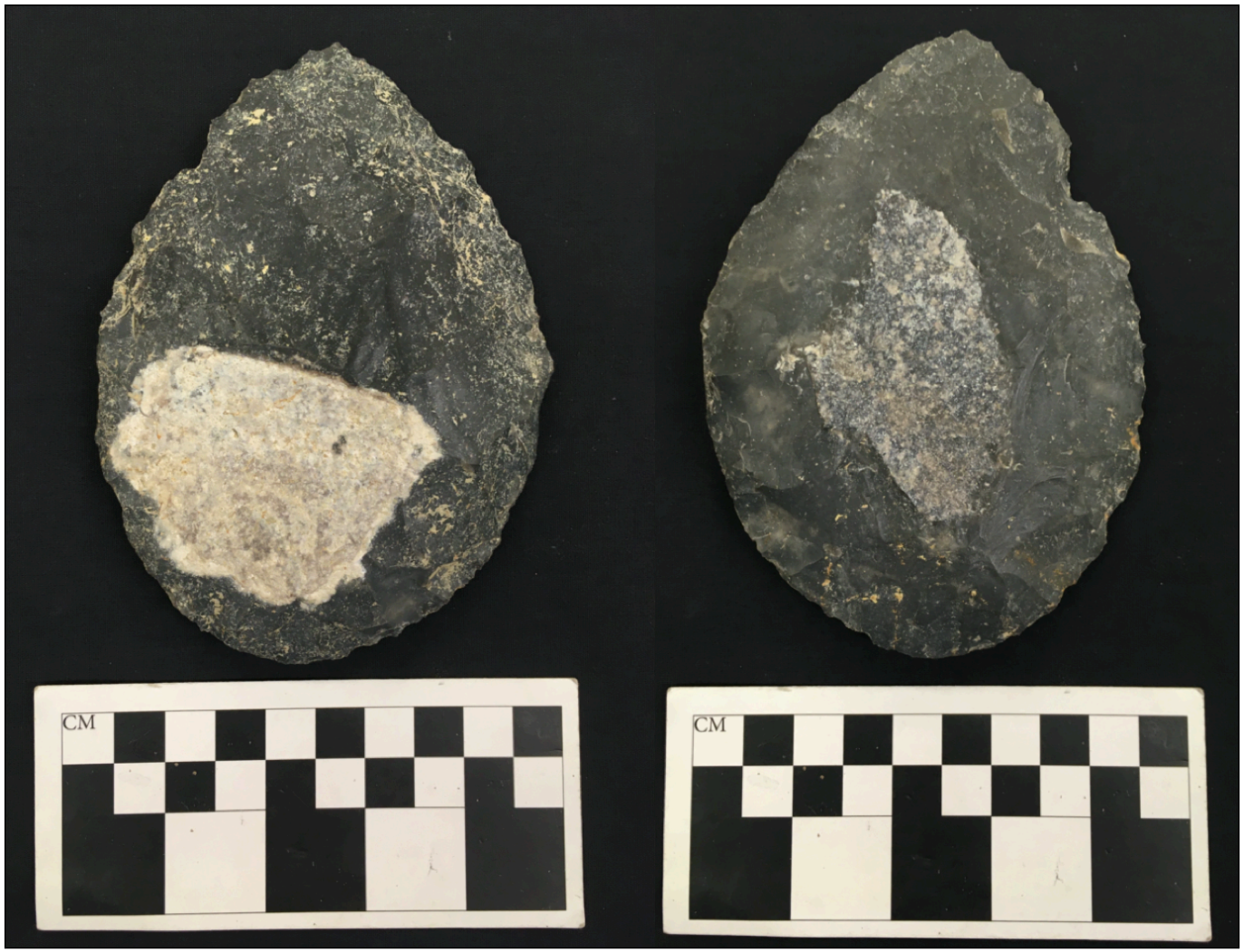
Artifact 2941: ovate handaxe



Artifact 2947: ovate handaxe



Artifact 3082: ovate handaxe



Artifact 3118: ovate handaxe



Artifact 3468: ovate handaxe



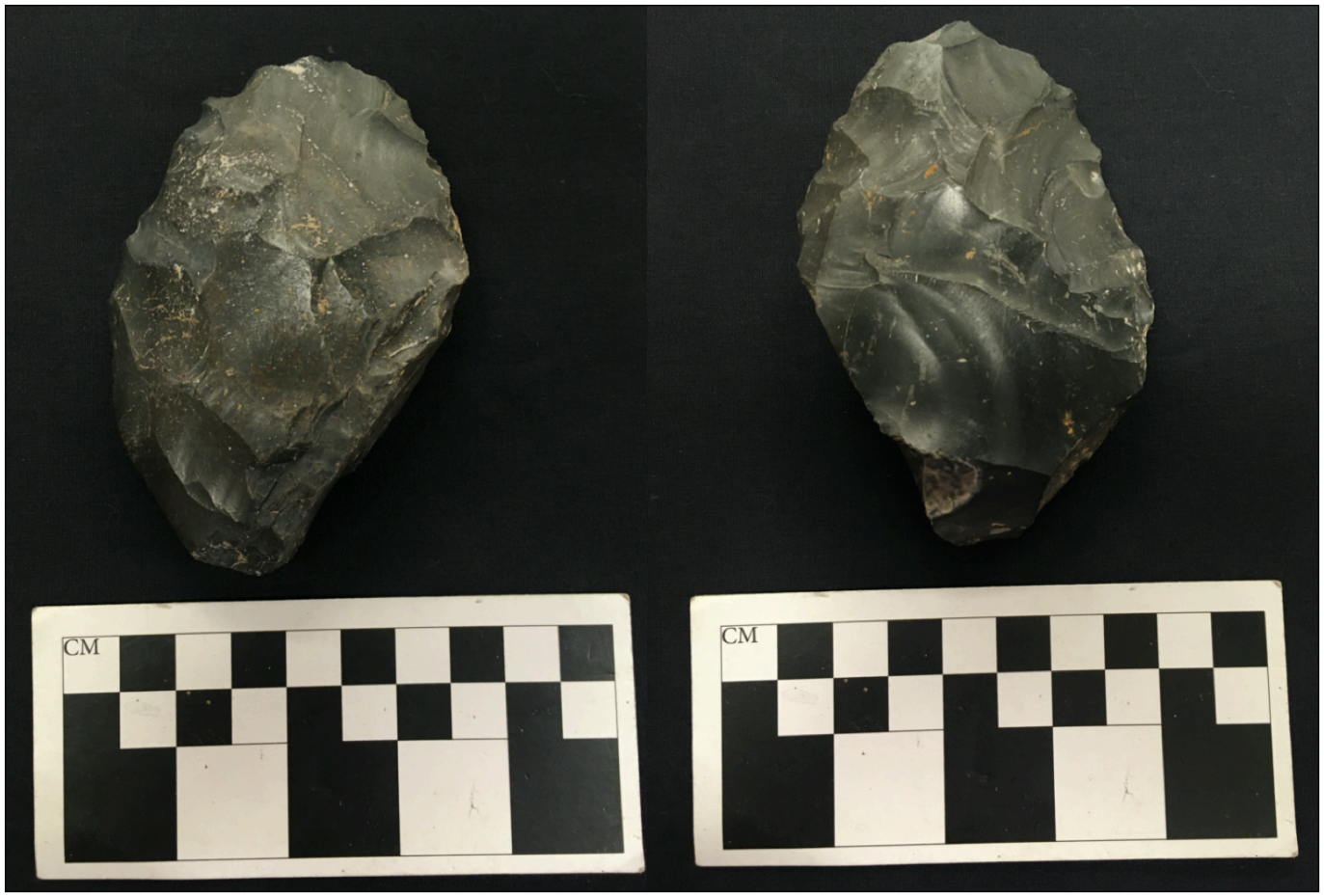
Artifact 3547: discoid handaxe



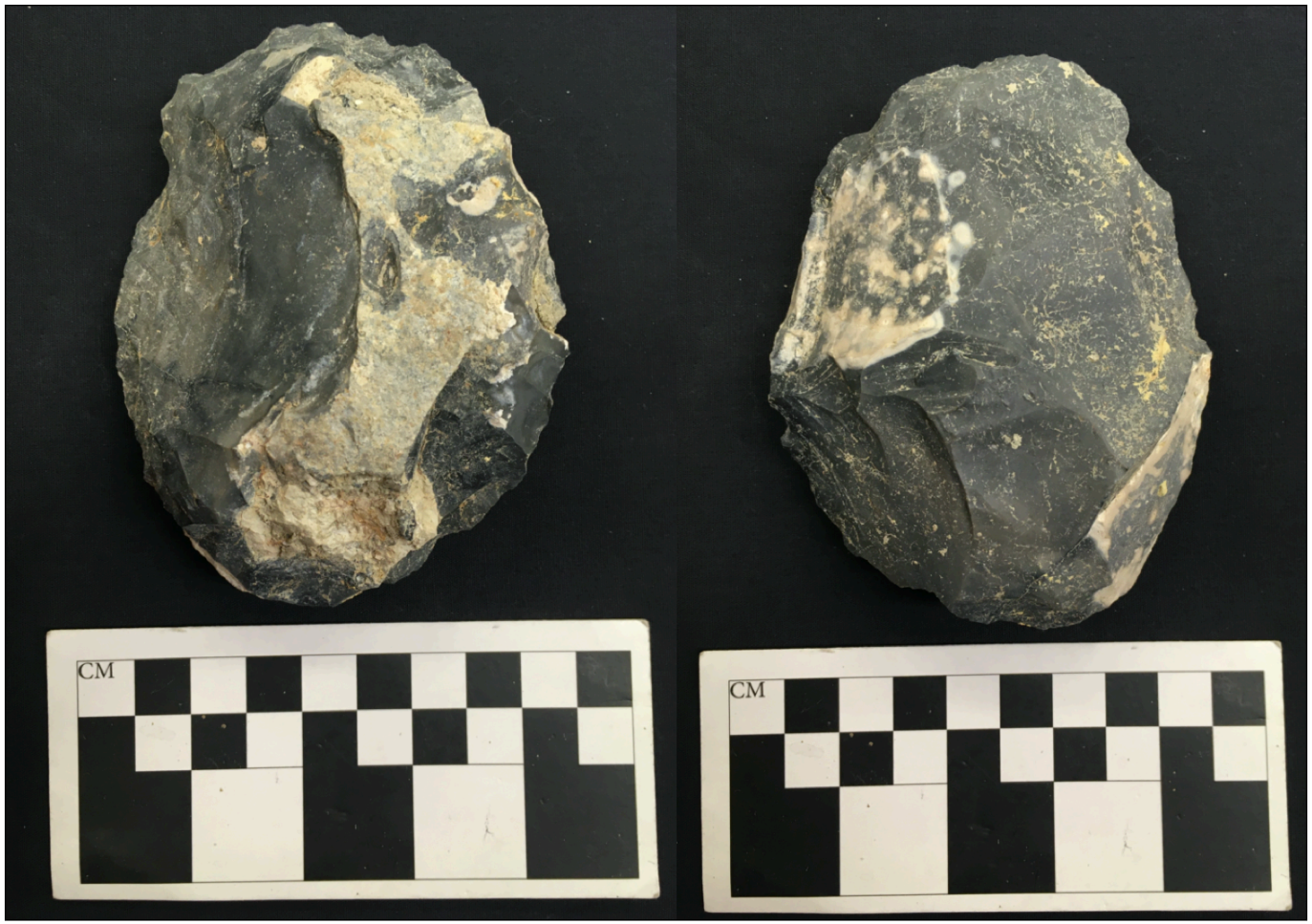
Artifact 3591: bidirectional core



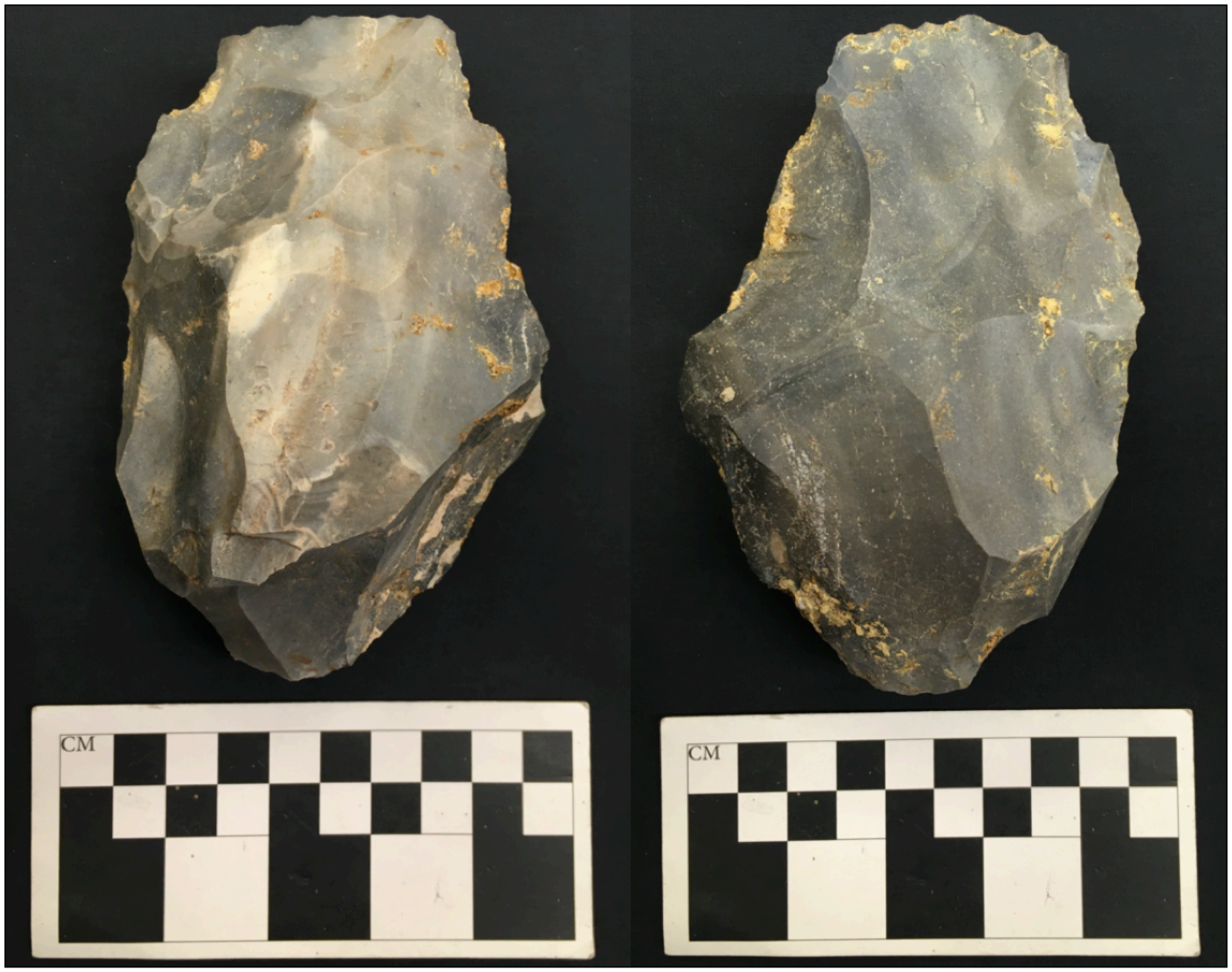
Artifact 3603: ovate handaxe



Artifact 3711: ovate handaxe



Artifact 3805: ovate cleaver



Artifact 3806: discoid handaxe



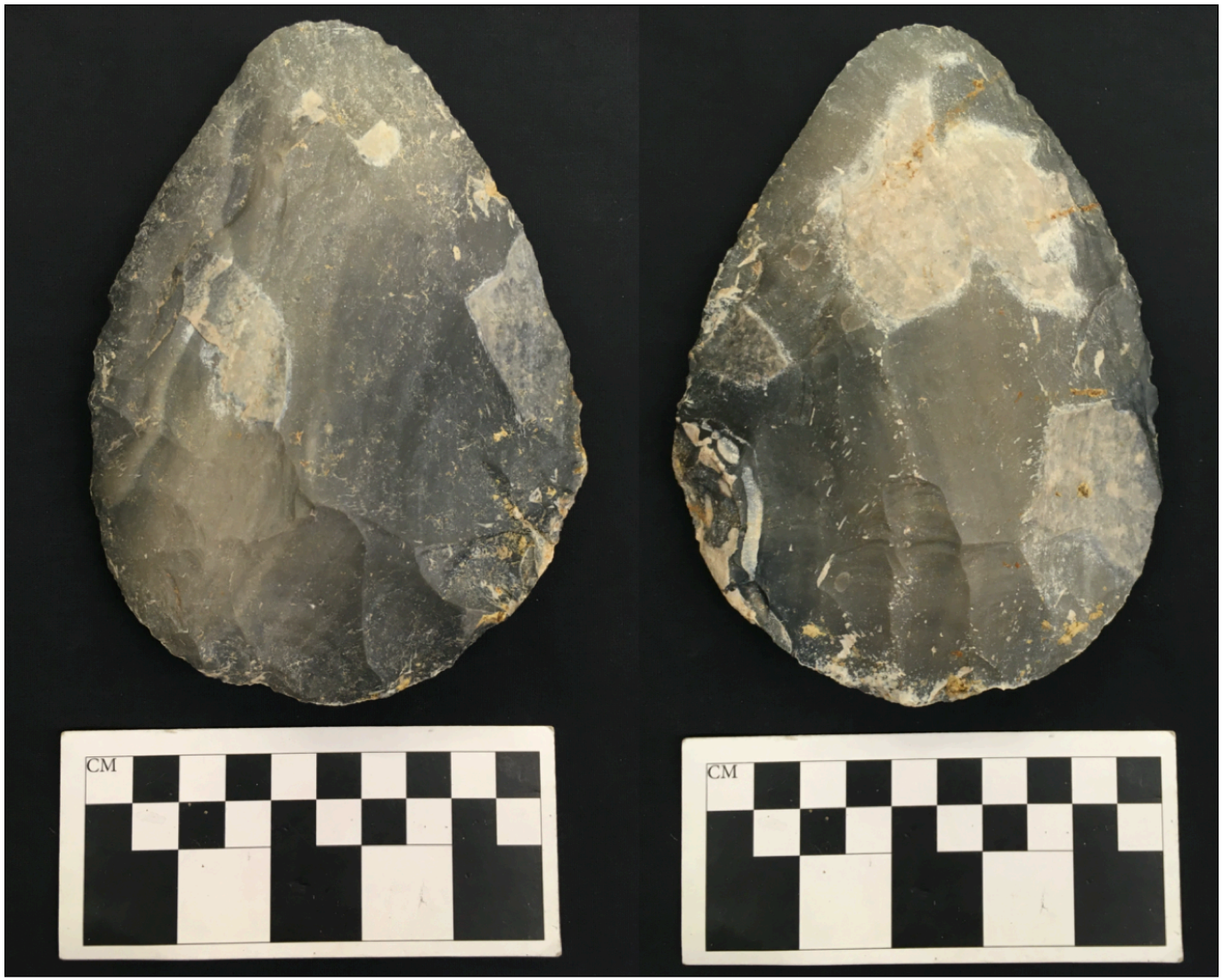
Artifact 3883: cleaver



Artifact 4018: biface preform



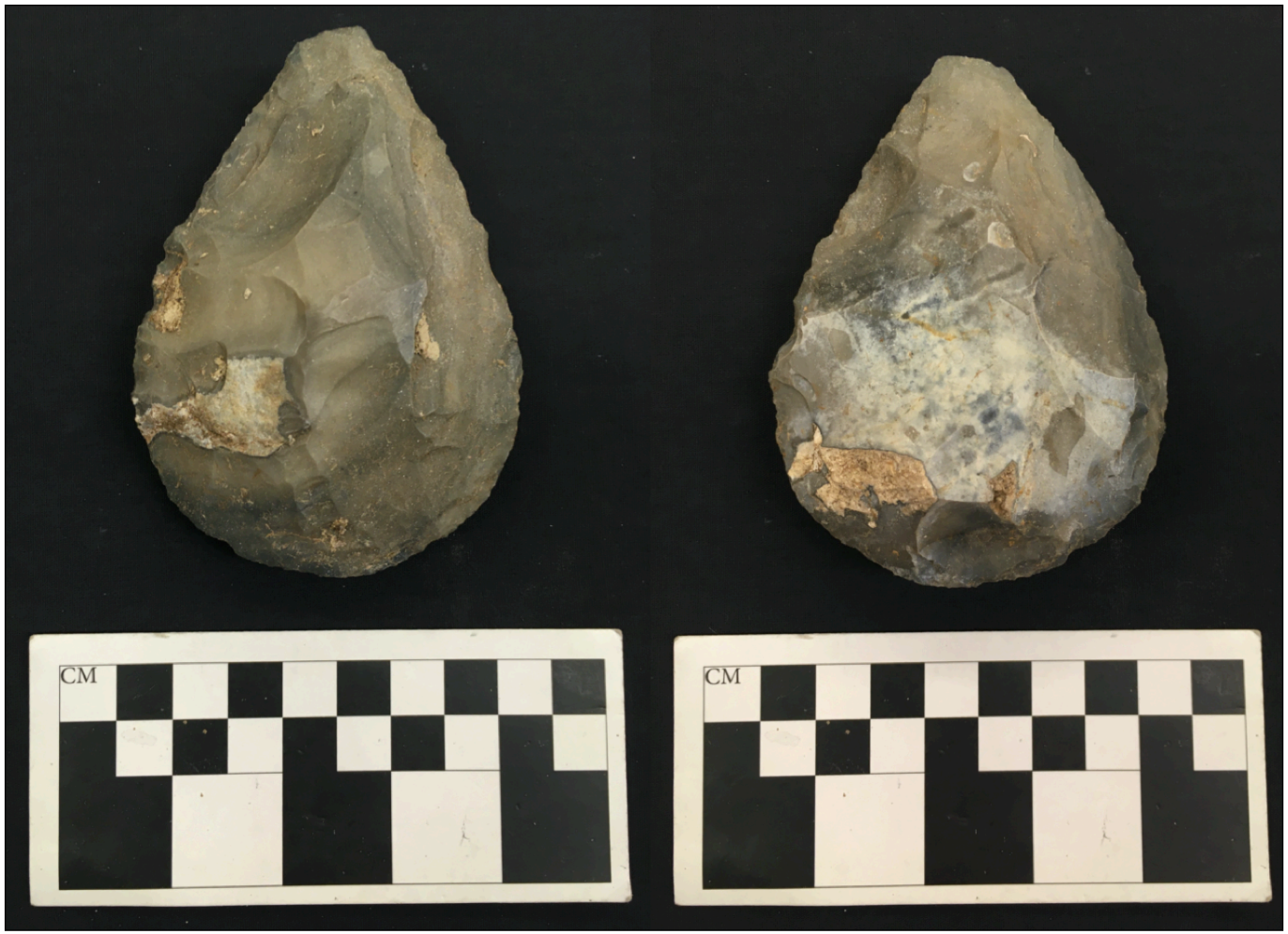
Artifact 4033: ovate handaxe



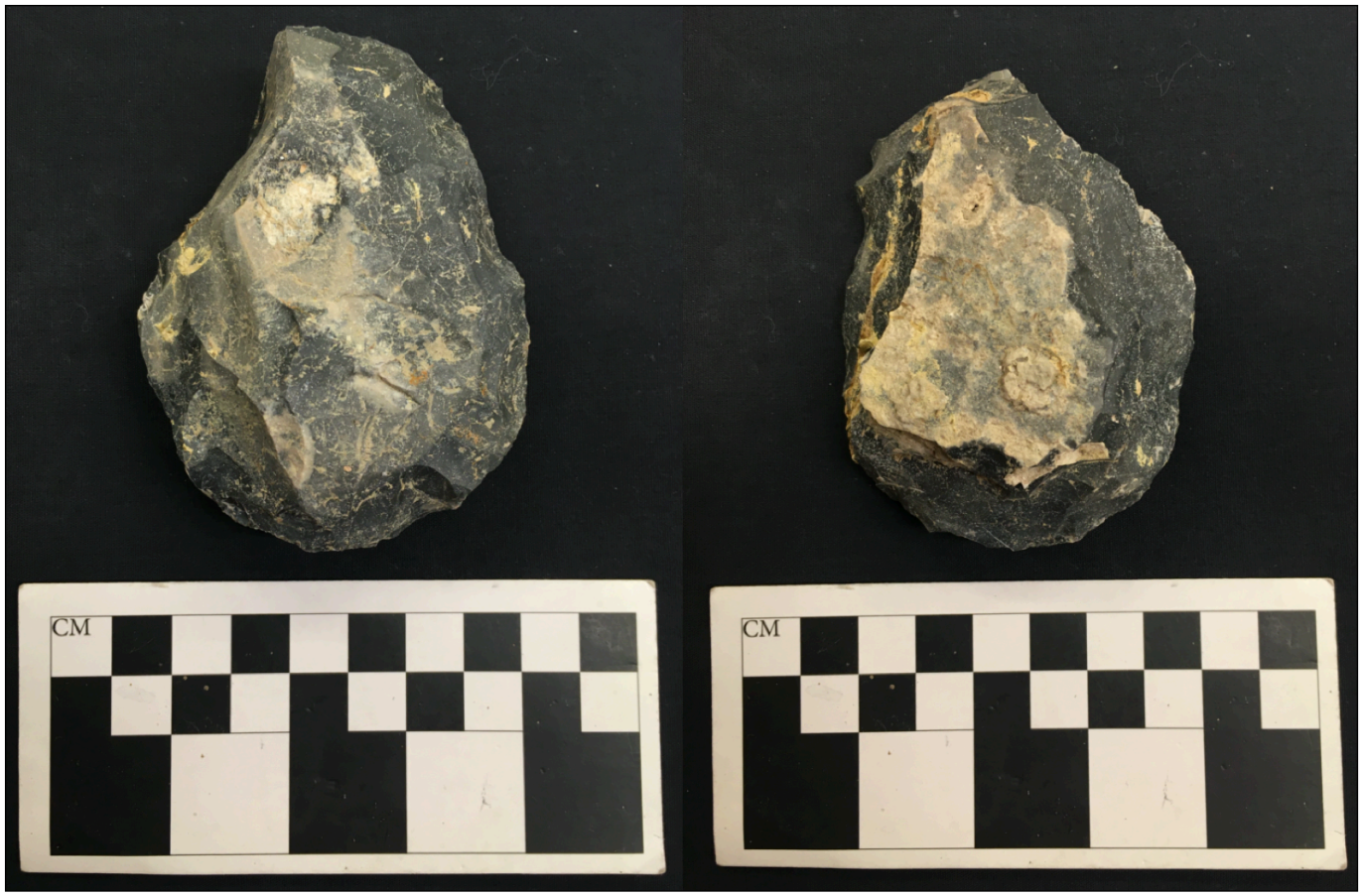
Artifact 4038: ovate handaxe



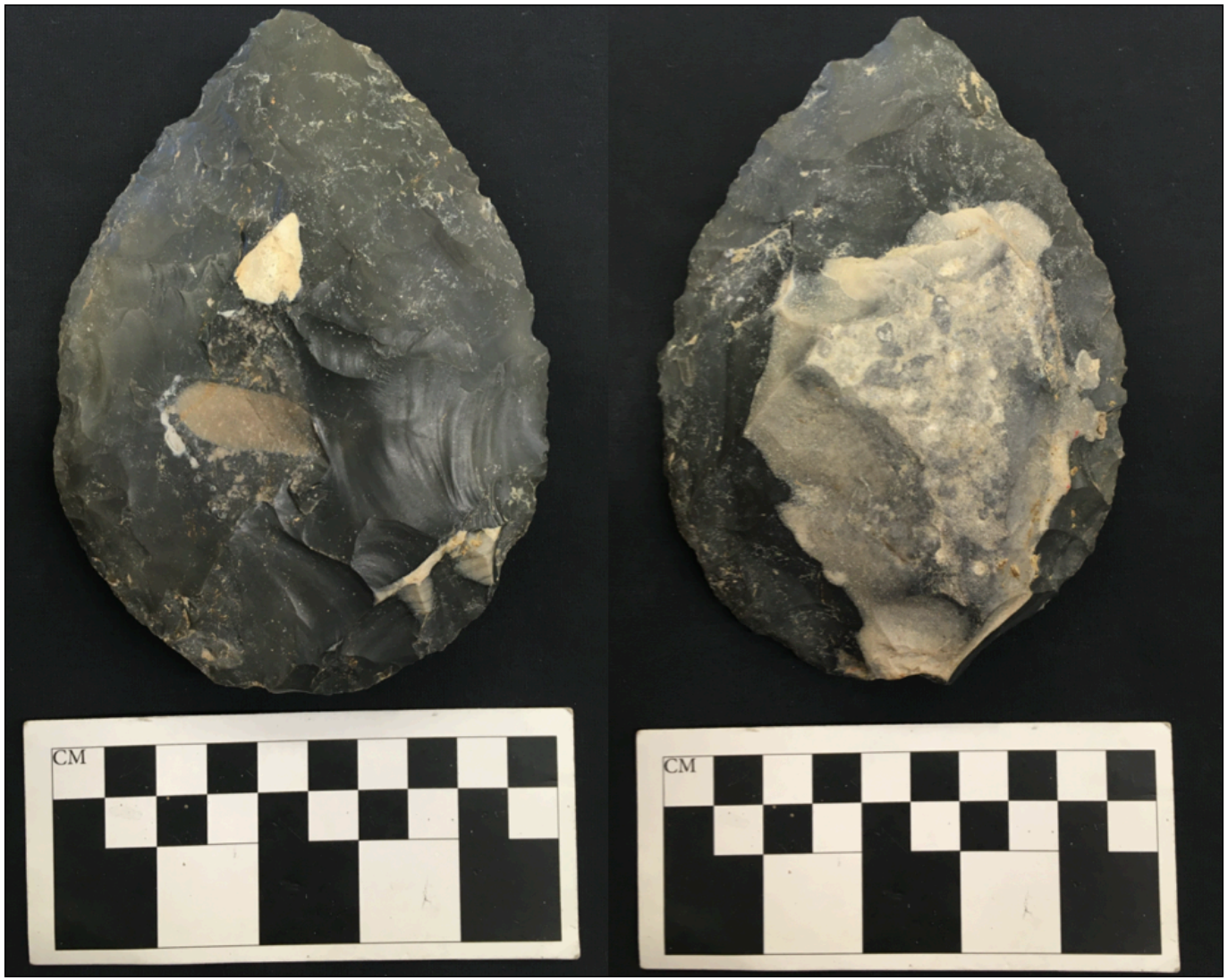
Artifact 4134: ovate handaxe



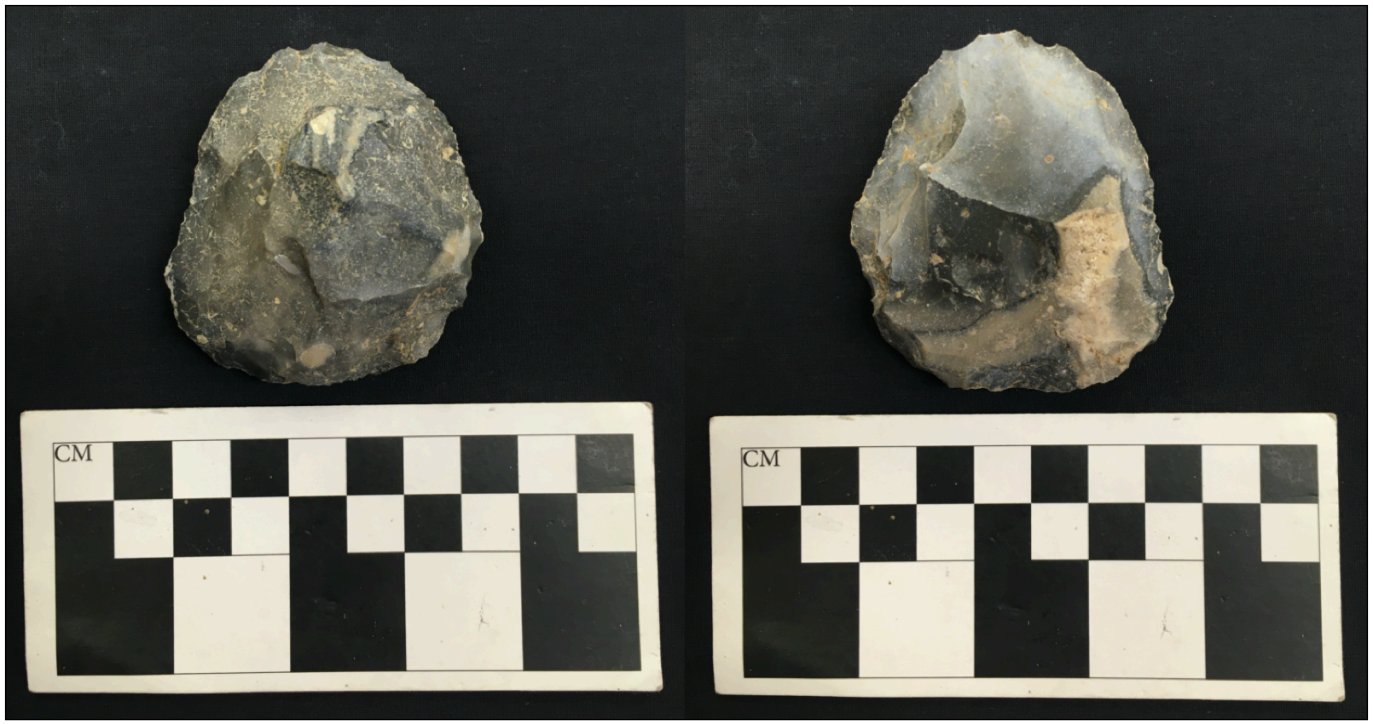
Artifact 4192: ovate handaxe



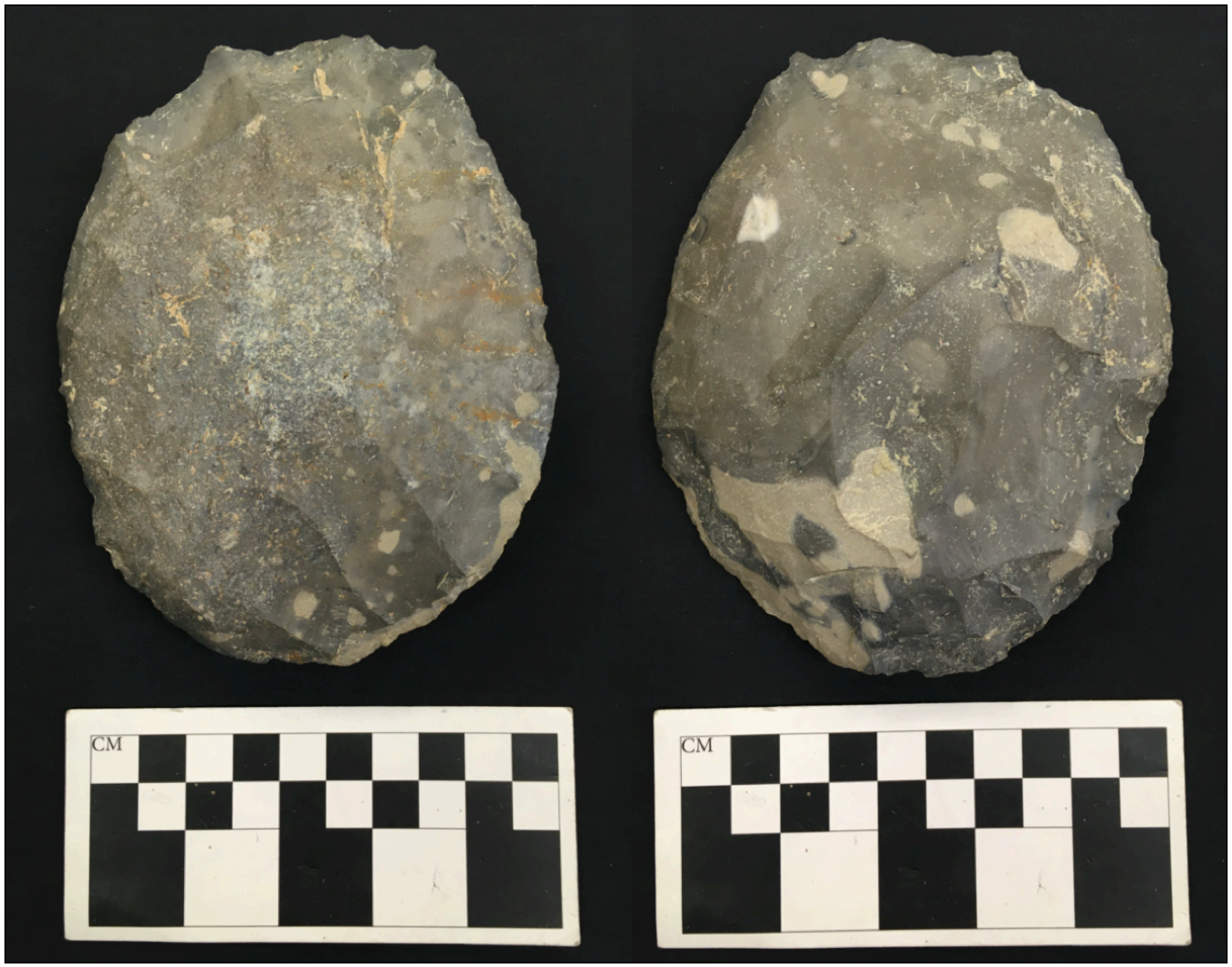
Artifact 4215: ovate handaxe



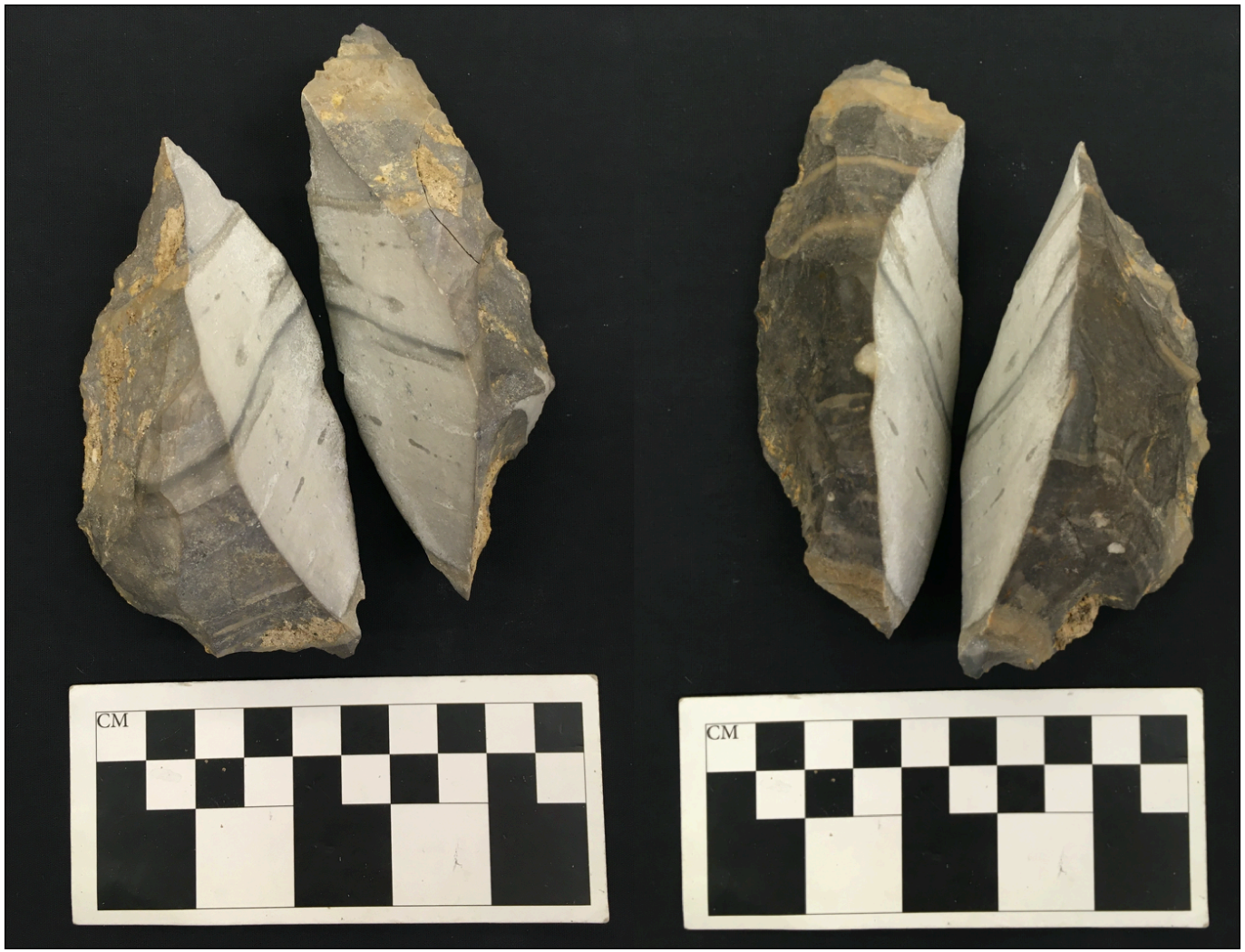
Artifact 4278: ovate handaxe



Artifact 4396: discoid biface



Artifact 4488: ovate handaxe



Artifact 4495: ovate handaxe



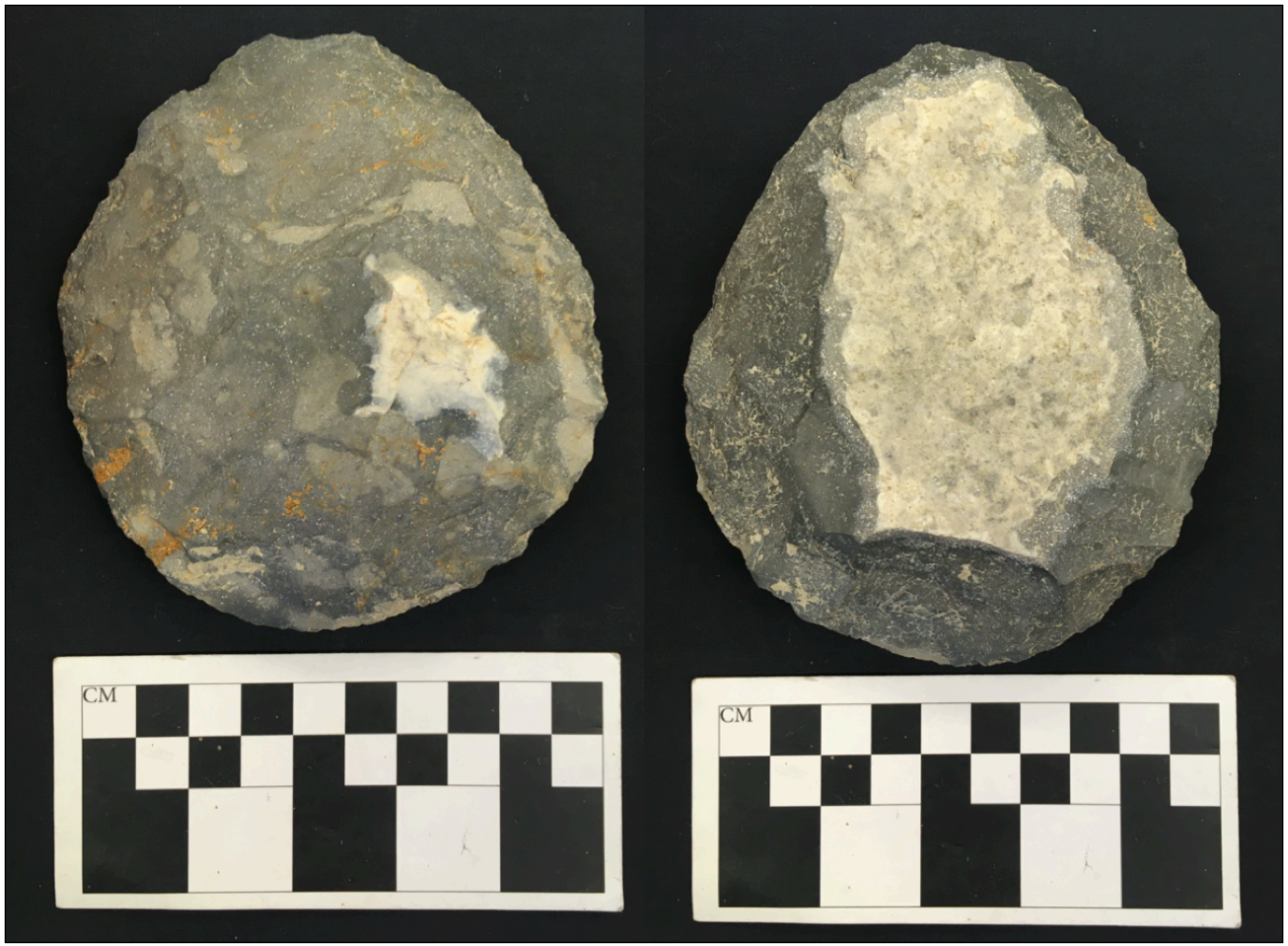
Artifact 4522: ovate handaxe



Artifact 4548: ovate handaxe



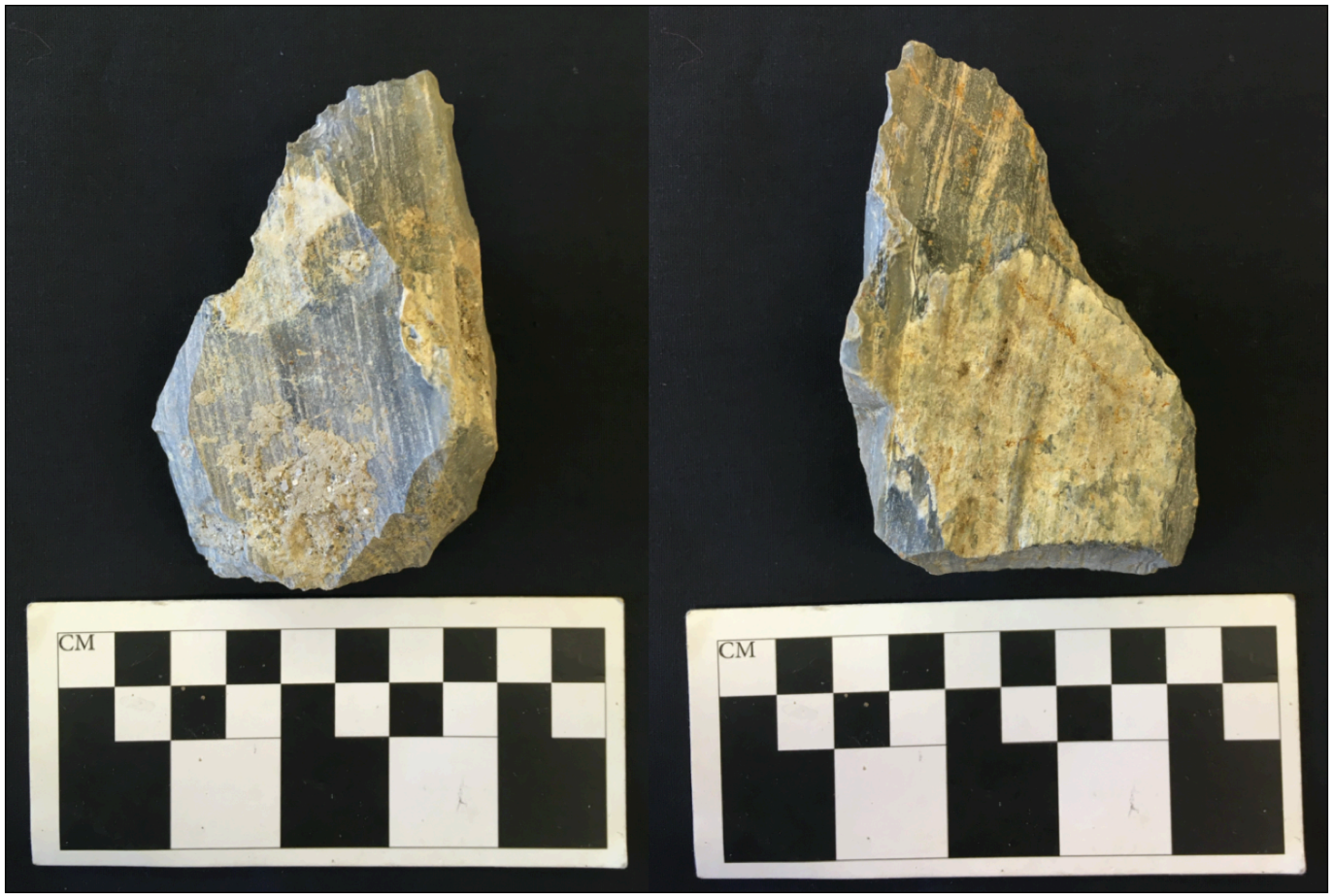
Artifact 4622: ovate handaxe



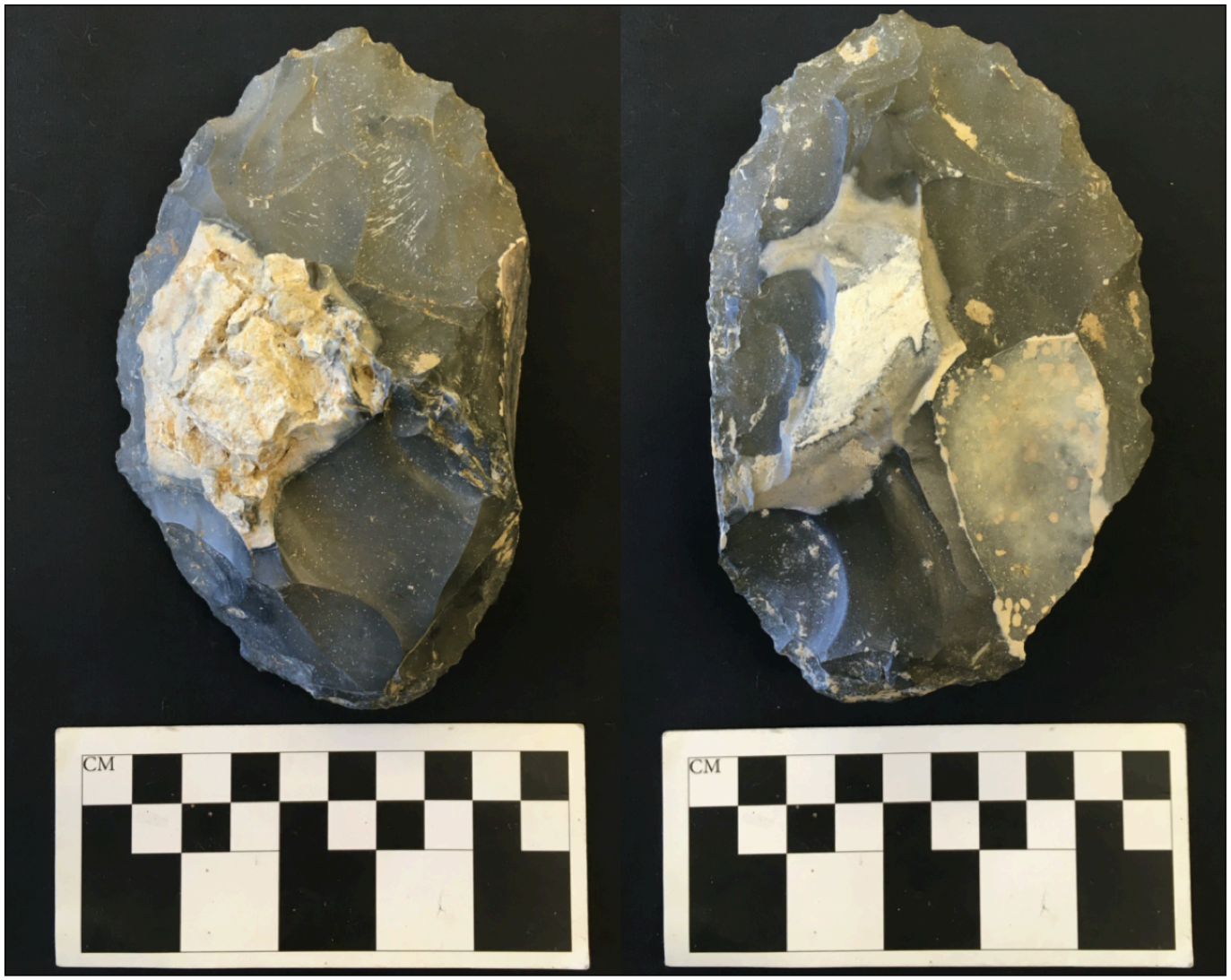
Artifact 4651: ovate handaxe



Artifact 4675: ovate biface



Artifact 4751: discoid handaxe



Artifact 4752: ovate handaxe



Artifact 4826: ovate handaxe



Appendix 3: Description of samples from chert sources in the Azraq basin (4 tables).

Table 1/4								
Source	Code	Catchment area	LA-ICP-MS	Sample/strata		Formation	Age	Sector
35Q	35Q-1	Western	Raster	Top		URC	Early-Middle Eocene	
	35Q-2	Western	Raster	Middle		URC	Early-Middle Eocene	
	35Q-3	Western	Raster	Bottom		URC	Early-Middle Eocene	
40X	40X-1	Southwestern	Spot	1	Bottom	URC	Early-Middle Eocene	
	40X-2		Spot	2	Ascending	URC	Early-Middle Eocene	
	40X-3		Raster	3	Ascending	URC	Early-Middle Eocene	
	40X-4		Raster	4	Ascending	URC	Early-Middle Eocene	
	40X-5		Raster	5	Ascending	URC	Early-Middle Eocene	
	40X-6		Raster	6	Ascending	URC	Early-Middle Eocene	
	40X-7		Raster	7	Ascending	URC	Early-Middle Eocene	
	40X-8		Raster	8	Ascending	URC	Early-Middle Eocene	
	40X-9		Raster	9	Ascending	URC	Early-Middle Eocene	
	40X-10		Raster	10	Ascending	URC	Early-Middle Eocene	
	40X-11		Raster	11	Ascending	URC	Early-Middle Eocene	
	40X-12		Raster	12	Ascending	URC	Early-Middle Eocene	
	40X-13		Raster	13	Top	URC	Early-Middle Eocene	
‘Ain Qasiyya	AQ1	On-site	Spot	1		URC	Early-Middle Eocene	

‘Ain Soda	AS1	On-site	Spot	1		URC	Early-Middle Eocene	
‘Ain Soda	AS2	On-site	Spot	1		URC	Early-Middle Eocene	
‘Ain Soda	AS3	On-site	Spot	1		URC	Early-Middle Eocene	
Wadi al-Masayil (east)	WME-1	Northeastern	Raster	1		URC	Early-Middle Eocene	Wadi al-Masayil (east)
Wadi al-Masayil (east)	WME-2	Northeastern	Raster	2		URC	Early-Middle Eocene	Wadi al-Masayil (east)
Wadi al-Masayil (east)	WME-3	Northeastern	Raster	3		URC	Early-Middle Eocene	Wadi al-Masayil (east)
Wadi al-Masayil (west)	WMW-1	Northeastern	Raster	1		URC	Early-Middle Eocene	Wadi al-Masayil (west)
Wadi al-Masayil (west)	WMW-2	Northeastern	Raster	2		URC	Early-Middle Eocene	Wadi al-Masayil (west)
Wadi al-Masayil (west)	WMW-3	Northeastern	Raster	3		URC	Early-Middle Eocene	Wadi al-Masayil (west)
Wadi Butm	WB1	Southwestern	Spot			URC	Early-Middle Eocene	Butm
Wadi Butm	WB2	Southwestern	Spot			URC	Early-Middle Eocene	Butm
Wadi Butm	WB3	Southwestern	Spot			URC	Early-Middle Eocene	Butm
Wadi Enoqiyya	WE	N/A	N/A			Harrat Ash-Shaam	Oligocene-Pleistocene	Enoqiyya
Wadi Ghadaf	WG1	South	Spot			WSC	Middle-Late Eocene	Ghadaf
Wadi Ghadaf	WG2	South	Spot			WSC?	Middle-Late Eocene	Ghadaf
Wadi Ghadaf (Red)	WG2-R	South	Spot			WSC	Middle-Late Eocene	Ghadaf
Wadi Ghadaf	WG3	South	Raster			WSC	Middle-Late Eocene	Ghadaf
Wadi Mushash	WMH-1	Southwestern	Raster	1		WSC	Middle-Late Eocene	Mushash
Wadi Mushash	WMH-2	Southwestern	Raster	2		WSC	Middle-Late Eocene	Mushash

Wadi Mushash	WMH-3	Southwestern	Raster	3		WSC	Middle-Late Eocene	Mushash
Wadi Rajil	WRJ-1	Northeastern	Raster	1		URC	Early-Middle Eocene	Rajil
Wadi Rajil	WRJ-2	Northeastern	Raster	2		URC	Early-Middle Eocene	Rajil
Wadi Rajil	WRJ-3	Northeastern	Raster	3		URC	Early-Middle Eocene	Rajil
Wadi Rattama	WR-1	Western	Spot	1	Bottom	URC	Early-Middle Eocene	Rattama
Wadi Rattama	WR-2	Western	Spot	2	Ascending	URC	Early-Middle Eocene	Rattama
Wadi Rattama	WR-3	Western	Spot	3	Ascending	URC	Early-Middle Eocene	Rattama
Wadi Rattama	WR-4	Western	Spot	4	Ascending	URC	Early-Middle Eocene	Rattama
Wadi Rattama	WR-5	Western	Spot	5	Ascending	URC	Early-Middle Eocene	Rattama
Wadi Usaykhim	WU-1	Northeastern	Raster	1		URC	Early-Middle Eocene	Usaykhim
Wadi Usaykhim	WU-2	Northeastern	Raster	2		URC	Early-Middle Eocene	Usaykhim
Wadi Usaykhim	WU-3	Northeastern	Raster	3		URC	Early-Middle Eocene	Usaykhim

Table 2/4								
Source	Code	Coordinates		Elevation (m)	Distance from SM1	Source type	Stratum length (m)	Stratum height (m)
35Q	35Q-1	31°51’00.8”	036°44’30.6”	543	7.5 km	Primary	5	0.05
35Q	35Q-2	31°51’00.8”	036°44’30.6”	543	7.5 km	Primary	5	0.1
35Q	35Q-3	31°51’00.8”	036°44’30.6”	543	7.5 km	Primary	5	0.05
40X	40X-1	31°51′02.1″	036°40′22.3″	591	14 km	Primary	>25	0.25
40X	40X-2	31°51′02.1″	036°40′22.3″	591	14 km	Primary	>25	0.25
‘Ain Qasiyya	AQ1	31°50’01.2”	036°49’04.5”	510	200 m	Primary	3	0.25
‘Ain Soda	AS1	31°49′56.4″	036°49′07.3″	508	50 m	Primary	2.5	0.15
‘Ain Soda	AS2	31°49′58.5″	036°49′07.8″	508	50 m	Primary	2.5	0.1
‘Ain Soda	AS3	31°49′58.6″	036°49′07.3″	509	75 m	Primary	2	0.1
Wadi al-Masayil (east)	WME-1	31°52’57.8”	037°02’23.6”	580	21.5 km	Secondary		
Wadi al-Masayil (east)	WME-2	31°52’57.8”	037°02’23.6”	580	21.5 km	Secondary		
Wadi al-Masayil (east)	WME-3	31°52’57.8”	037°02’23.6”	580	21.5 km	Secondary		
Wadi al-Masayil (west)	WMW-1	31°53’50.3”	037°00’22.8”	574	19 km	Secondary		
Wadi al-Masayil (west)	WMW-2	31°53’50.3”	037°00’22.8”	574	19 km	Secondary		
Wadi al-Masayil (west)	WMW-3	31°53’50.3”	037°00’22.8”	574	19 km	Secondary		
Wadi Butm	WB1	31°47’57.3”	036°35’26.3”	565	22 km	Secondary		
Wadi Butm	WB2	31°47’47.9”	036°36’57.0”	558	19.5 km	Secondary		
Wadi Butm	WB3	31°47’46.3”	036°36’35.0”	560	20 km	Secondary		
Wadi Enoqiyya	WE	31°54'51.4"	036°50'03.2"	516	9 km	N/A		
Wadi Ghadaf	WG1	31°42’35.8”	036°48’24.5”	528	13 km	Secondary		
Wadi Ghadaf	WG2	31°34’49.1”	036°49’12.5”	587	28 km	Secondary		
Wadi Ghadaf (Red)	WG2-R	31°34’49.1”	036°49’12.5”	587	28 km	Secondary		
Wadi Ghadaf	WG3	31°41’27.8”	036°50’17.5”	530	16 km	Secondary		
Wadi Mushash	WMH-1	31°43’38.8”	036°29’26.8”	615	33 km	Primary		

Wadi Mushash	WMH-2	31°43’38.8”	036°29’26.8”	613	33 km	Primary		
Wadi Mushash	WMH-3	31°43’38.8”	036°29’26.8”	597	33 km	Primary		
Wadi Rajil	WRJ-1	31°45’06.8”	037°05’17.9”	551	27 km	Secondary		
Wadi Rajil	WRJ-2	31°45’06.8”	037°05’17.9”	551	27 km	Secondary		
Wadi Rajil	WRJ-3	31°45’06.8”	037°05’17.9”	551	27 km	Secondary		
Wadi Rattama	WR-1	31°52’49.1”	036°46’47.8”	523	6.5 km	Primary	5	0.25
Wadi Rattama	WR-2	31°52’49.1”	036°46’47.8”	524	6.5 km	Primary	10	0.25
Wadi Rattama	WR-3	31°52’49.1”	036°46’47.8”	525	6.5 km	Primary	15	0.25
Wadi Rattama	WR-4	31°52’49.1”	036°46’47.8”	525	6.5 km	Primary	15	0.25
Wadi Rattama	WR-5	31°52’49.1”	036°46’47.8”	526	6.5 km	Primary	20	0.25
Wadi Usaykhim	WU-1	31°53’31.6”	036°57’41.2”	530	15 km	Secondary		
Wadi Usaykhim	WU-2	31°53’31.6”	036°57’41.2”	530	15 km	Secondary		
Wadi Usaykhim	WU-3	31°53’31.6”	036°57’41.2”	530	15 km	Secondary		

Table 3/4							
Source	Code	Munsell color	Munsell code	Texture	Luster	Inclusions	Translucency
35Q	35Q-1	Brown	7.5YR 5/2	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Slightly translucent
35Q	35Q-2	Grayish brown	10YR 5/2	Mostly fine-grained	Slightly shiny		Slightly opaque
35Q	35Q-3	Brown	7.5YR 5/2	Fine-grained	Fairly shiny		Slightly translucent
40X	40X-1	Gray-brown	7.5YR 5-6/1-3	Fine- to coarse-grained	Dull	Very few calcareous grains (<1 mm)	Fairly opaque
40X	40X-2	Gray-brown; Reddish-brown	7.5YR 5-6/1-3; 2.5YR 5/4	Fine- to coarse-grained	Dull to slightly shiny	Very few calcareous grains (<1 mm)	Slightly opaque
‘Ain Qasiyya	AQ1	Gray-dark gray	5Y 5/1-4/1	Slightly coarse-grained	Fairly dull	Very few calcareous grains (<1 mm)	Fairly opaque
‘Ain Soda	AS1	Gray-dark gray	5Y 5/1-4/1	Slightly coarse-grained	Fairly dull	Very few calcareous grains (<1 mm)	Fairly opaque
‘Ain Soda	AS2	Gray-dark gray	5Y 5/1-4/1	Slightly coarse-grained	Fairly dull	Odd calcareous grain (~1 mm)	Fairly opaque
‘Ain Soda	AS3	Gray-dark gray	5Y 5/1-4/1	Slightly coarse-grained	Fairly dull	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi al-Masayil (east)	WME-1	Gray	Gley 2 7/5B-10B	Mostly fine-grained	Dull		Fairly opaque
Wadi al-Masayil (east)	WME-2	Light brownish gray	10YR 6/2	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Slightly translucent
Wadi al-Masayil (east)	WME-3	Grayish-brown	10YR 5/2	Slightly coarse-grained	Dull	Very few calcareous grains (<1 mm)	Slightly opaque
Wadi al-Masayil (west)	WMW-1	Light brownish gray	10YR 6/2	Fine-grained	Dull	Very few calcareous grains (<1 mm)	Slightly opaque

Wadi al-Masayil (west)	WMW-2	Gray	Gley 2 6/10BG	Fine-grained	Dull	Speckling of minute calcareous grains (<1 mm)	Opaque
Wadi al-Masayil (west)	WMW-3	Brown	7.5YR 5/2	Fine-grained	Fairly shiny		Slightly translucent
Wadi Butm	WB1	Brown	7.5YR 5/2-5/3	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi Butm	WB2	Brown	7.5YR 5/2-5/3	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi Butm	WB3	Brown	7.5YR 5/2-5/3	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi Enoqiyya	WE		N/A				
Wadi Ghadaf	WG1	Light gray	10YR 7/2	Mostly fine-grained	Dull	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi Ghadaf	WG2	Gray - Grayish brown	10YR 5/1-5/2	Fine-grained	Fairly shiny	Minute calcareous, speckled	Fairly opaque
Wadi Ghadaf (Red)	WG2-R	Reddish brown	2.5YR 5/4	Very fine-grained	Slightly shiny		Mostly translucent
Wadi Ghadaf	WG3	Pale brown	10YR 6/3	Fine-grained	Dull		Fairly translucent
Wadi Mushash	WMH-1	Light gray	10YR 7/2	Mostly fine-grained	Slightly shiny		Fairly opaque
Wadi Mushash	WMH-2	Light gray	10YR 7/2	Mostly fine-grained	Slightly shiny		Fairly opaque
Wadi Mushash	WMH-3	Brown	10YR 5/3	Mostly fine-grained	Slightly shiny		Slightly translucent
Wadi Rajil	WRJ-1	Pinkish gray	7.5YR 6/2	Slightly coarse-grained	Slightly dull	Very few calcareous grains (<1 mm)	Opaque
Wadi Rajil	WRJ-2	Brown	7.5YR 5/2	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Slightly translucent
Wadi Rajil	WRJ-3	Brown	7.5YR 5/2-4/2	Slightly coarse-grained	Slightly shiny		Fairly opaque

Wadi Rattama	WR-1	Reddish gray-brown	2.5Y 5/1	Fine-grained	Slightly shiny	Very few calcareous grains (<1 mm)	Slightly translucent
Wadi Rattama	WR-2	Gray	Gley 2 7-5/5BG-5PB	Slightly coarse-grained	Dull	Numerous calcareous grains (<1 mm)	Opaque
Wadi Rattama	WR-3	Gray	Gley 2 6/10BG-10B	Mostly fine-grained	Dull	Very few calcareous grains (<1 mm)	Opaque
Wadi Rattama	WR-4	Gray	7.5YR 5/1	Fine-grained	Dull	Very few calcareous grains (<1 mm)	Opaque
Wadi Rattama	WR-5	Gray	Gley 2 6/10BG-10B	Fine-grained	Dull	Very few calcareous grains (<1 mm)	Opaque
Wadi Usaykhim	WU-1	Reddish gray-brown	5YR 5/2-5/3	Fine-grained	Dull	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi Usaykhim	WU-2	Brown	7.5YR 5/2	Fine-grained	Dull	Very few calcareous grains (<1 mm)	Fairly opaque
Wadi Usaykhim	WU-3	Reddish gray-brown	5YR 5/2-5/3	Fine-grained	Dull	Very few calcareous grains (<1 mm)	Fairly opaque

Table 4/4							
Source	Code	Matrix	Quality	# of chert strata in outcrop	Scarcity (15-30 cm range)	Extraction cost	Secondary clast sizes (Wentworth)
35Q	35Q-1	Slightly homogenous	High	3	Abundant	Medium	Mostly cobbles and pebbles
35Q	35Q-2	Heterogenous - laminations	High	3	Abundant	Medium	Mostly cobbles and pebbles
35Q	35Q-3	Fairly homogenous	High	3	Abundant	Medium	Mostly cobbles and pebbles
40X	40X-1	Fairly heterogenous (irregular bands and patches)	Med-high	13	Abundant	Medium	
40X	40X-2	Fairly heterogenous (irregular bands and patches)	Med-high	13	Abundant	Medium	
ʻAin Qasiyya	AQ1	Fairly homogenous	Med-high	1	Moderate	Low	Boulder-cobbles-pebbles
ʻAin Soda	AS1	Fairly homogenous	Med-high	1	Moderate	Low	Small boulder-cobbles-pebbles
ʻAin Soda	AS2	Fairly homogenous	Med-high	1	Moderate	Low	Small boulder-cobbles-pebbles
ʻAin Soda	AS3	Fairly homogenous	Med-high	1	Moderate	Low	Small boulder-cobbles-pebbles
Wadi al-Masayil (east)	WME-1	Heterogenous – some “pin-striping”	High		Scarce	Low	Majority is pebbles. Odd cobble
Wadi al-Masayil (east)	WME-2	Fairly homogenous	High		Scarce	Low	Majority is pebbles. Odd cobble
Wadi al-Masayil (east)	WME-3	Fairly homogenous	High		Scarce	Low	Majority is pebbles. Odd cobble
Wadi al-Masayil (west)	WMW-1	Mostly homogenous	High		Very scarce	Low	Majority is pebbles. Odd cobble
Wadi al-Masayil (west)	WMW-2	Fairly homogenous	High		Very scarce	Low	Majority is pebbles. Odd cobble
Wadi al-Masayil (west)	WMW-3	Slightly heterogenous – some “splotches”	High		Very scarce	Low	Majority is pebbles. Odd cobble
Wadi Butm	WB1	Fairly homogenous	High		Abundant	Low	Mostly cobbles and pebbles

Wadi Butm	WB2	Fairly homogenous	High		Abundant	Low	Mostly cobbles and pebbles
Wadi Butm	WB3	Fairly homogenous	High		Abundant	Low	Mostly cobbles and pebbles
Wadi Enoqiyya	WE						
Wadi Ghadaf	WG1	Fairly homogenous	High			Low	
Wadi Ghadaf	WG2	Homogenous	High		Moderate	Low	Mostly cobbles and pebbles
Wadi Ghadaf (Red)	WG2-R	Homogenous	High			Low	Mostly cobbles and pebbles
Wadi Ghadaf	WG3	Somewhat heterogenous (bands)	Med-high			Low	Mostly cobbles and pebbles
Wadi Mushash	WMH-1	Fairly heterogenous (irregular bands)	High		Scarce	Low	Some boulders; mainly cobbles, many pebbles
Wadi Mushash	WMH-2	Fairly heterogenous (irregular bands)	High		Abundant	Low	Some boulders; mainly cobbles, many pebbles
Wadi Mushash	WMH-3	Fairly heterogenous (irregular bands)	Medium		Scarce	Low	Some boulders; mainly cobbles, many pebbles
Wadi Rajil	WRJ-1	Fairly homogenous	Medium		Moderate	Low	Mostly cobbles and pebbles
Wadi Rajil	WRJ-2	Fairly homogenous	Med-high		Moderate	Low	Mostly cobbles and pebbles
Wadi Rajil	WRJ-3	Heterogenous - laminations	Medium		Moderate	Low	Mostly cobbles and pebbles
Wadi Rattama	WR-1	Fairly homogenous	High	5	Abundant	Medium	Some boulders; plenty of cobbles and pebbles
Wadi Rattama	WR-2	Slightly homogenous	Med-high	5	Abundant	Medium	Some boulders; plenty of cobbles and pebbles
Wadi Rattama	WR-3	Fairly homogenous	High	5	Abundant	Medium	Some boulders; plenty of cobbles and pebbles
Wadi Rattama	WR-4	Fairly homogenous	High	5	Abundant	Medium	Some boulders; plenty of cobbles and pebbles
Wadi Rattama	WR-5	Fairly homogenous	High	5	Abundant	Medium	Some boulders; plenty of cobbles and pebbles
Wadi Usaykhim	WU-1	Fairly homogenous	High		Semi-scarce	Low	Cobbles and pebbles and smaller.
Wadi Usaykhim	WU-2	Fairly homogenous	High		Semi-scarce	Low	Cobbles and pebbles and smaller.

Wadi Usaykhim	WU-3	Fairly homogenous	High		Semi-scarce	Low	Cobbles and pebbles and smaller.

Appendix 4: Photographs of chert sources in the Azraq basin.

35Q, western area



35Q, western area. 35Q-1 (top), 35Q-2 (middle), and 35Q-3 (bottom)



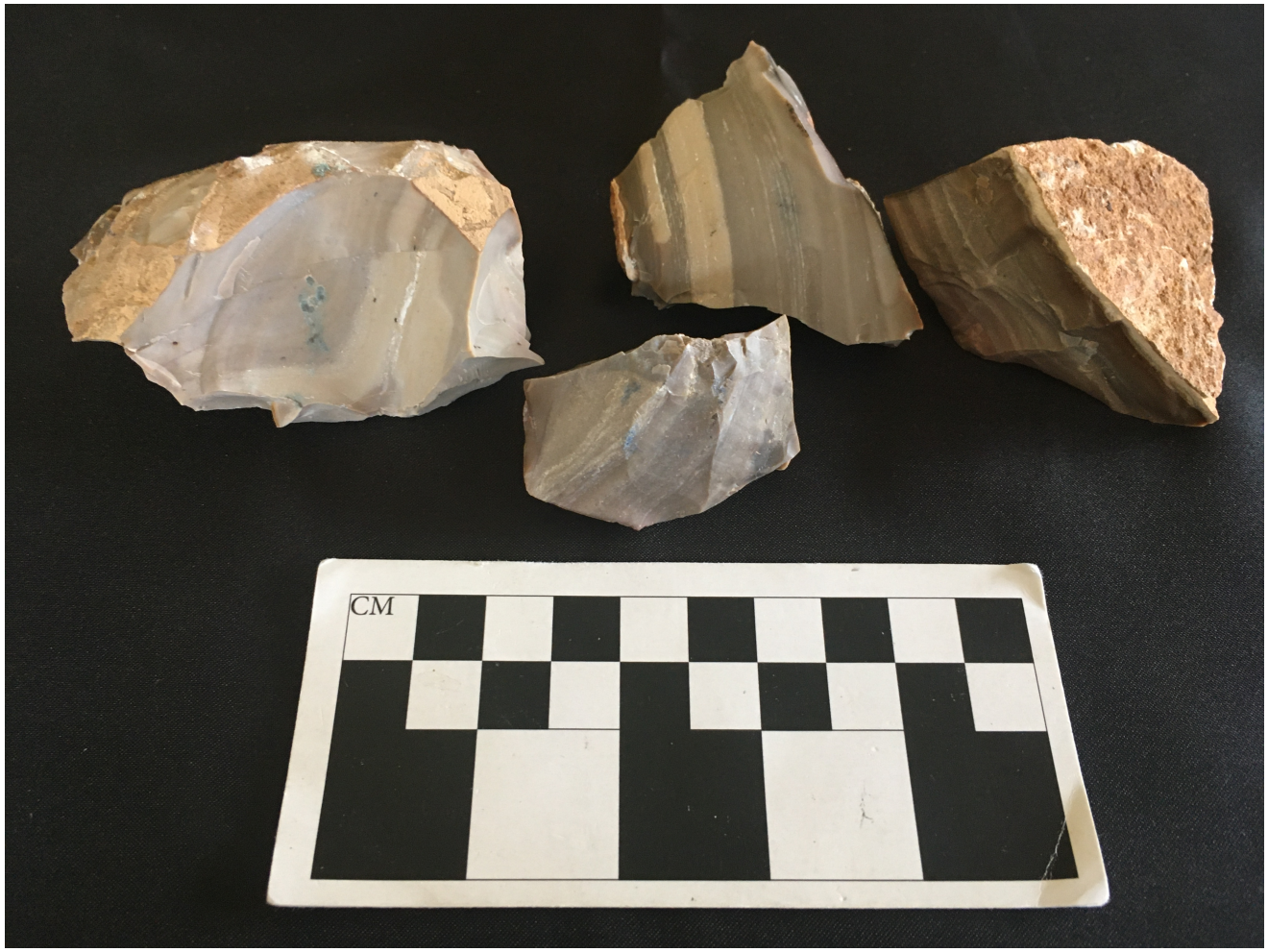
35Q, western area. 35Q-1 (top), 35Q-2 (middle), and 35Q-3 (bottom)



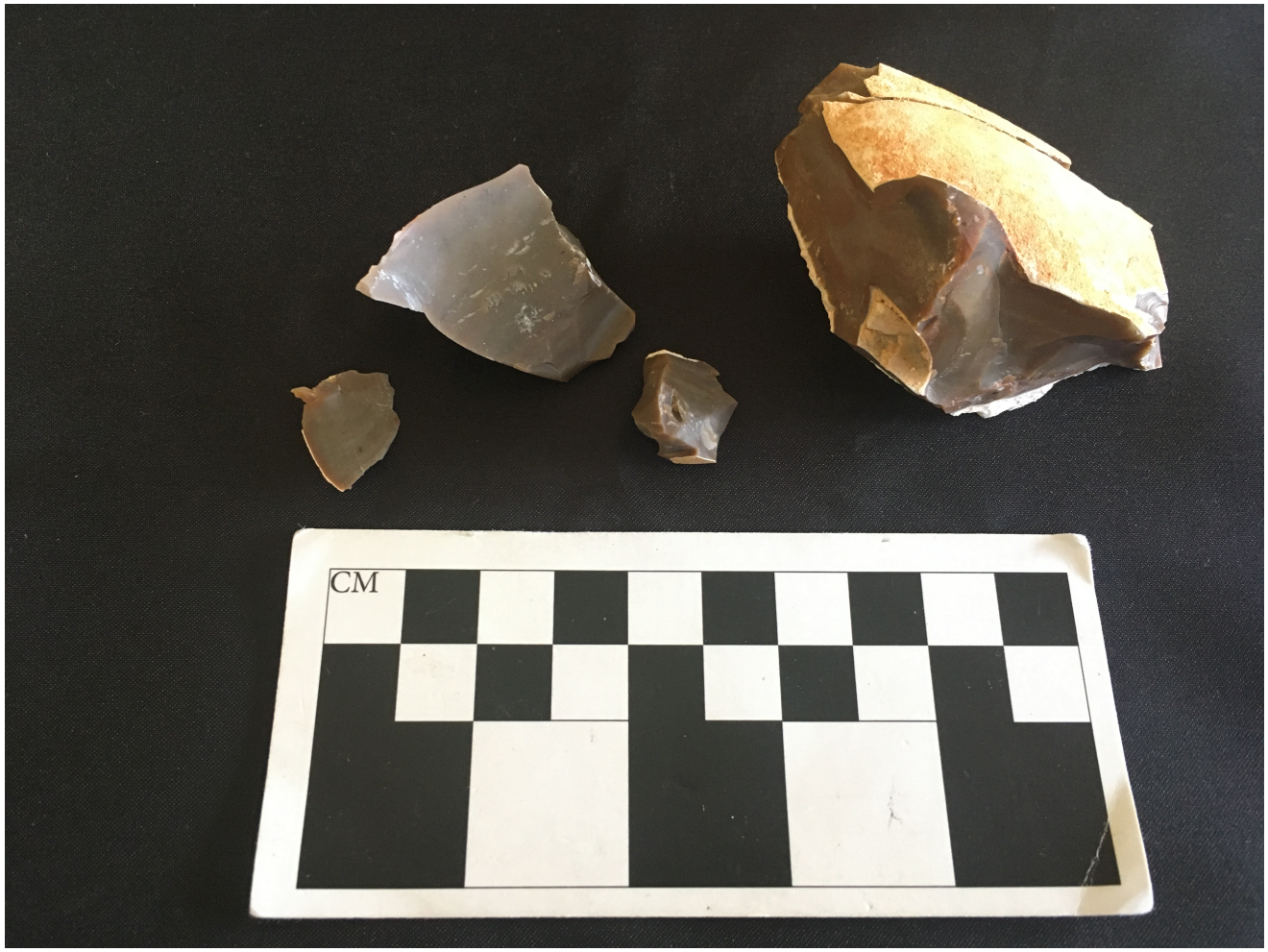
35Q-1



35Q-2



35Q-3



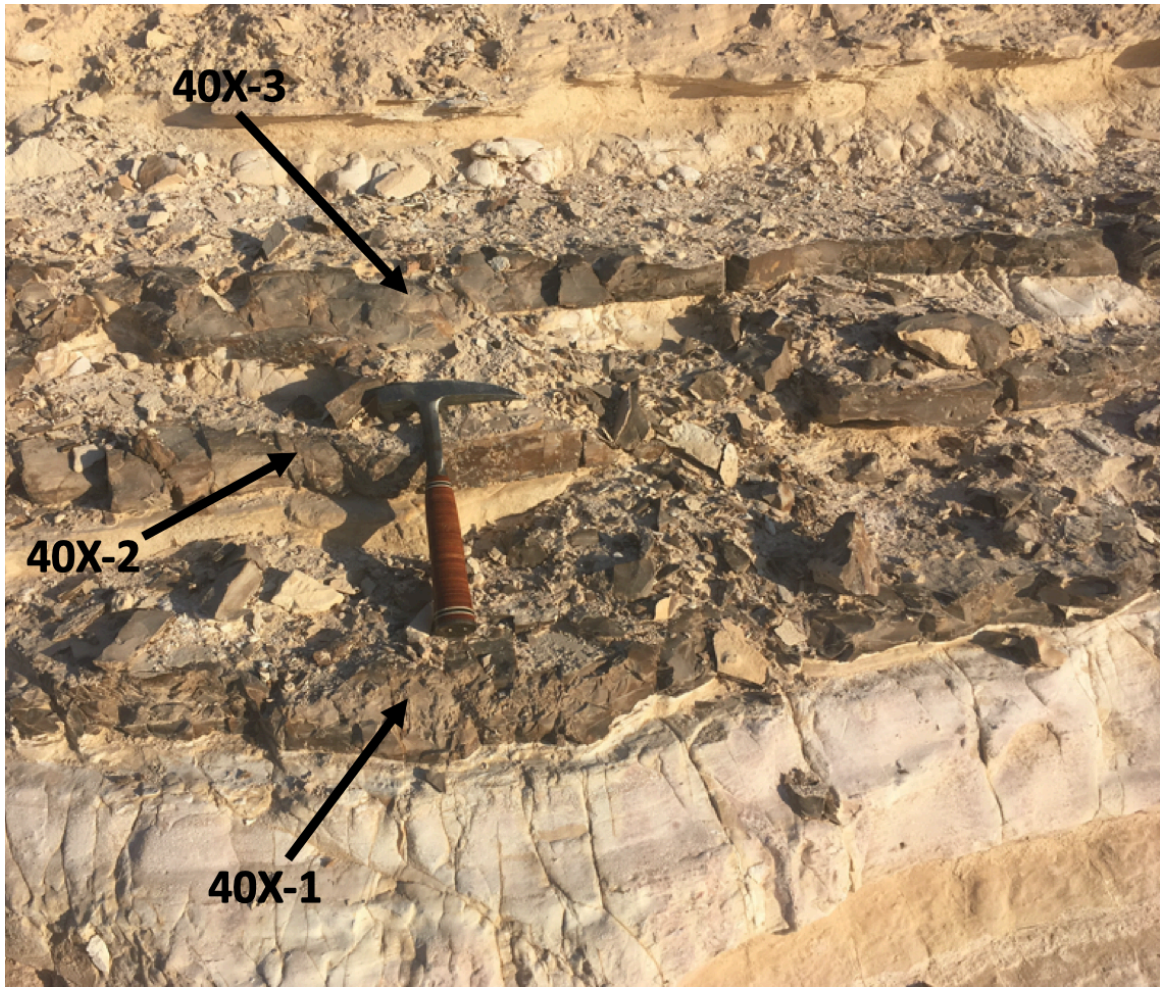
40X, southwestern area



40X locality sampled along line indicated (13 beds)



40X-1 (bottom), 40X-2 (middle), and 40X-3 (top)



40X-1



40X-2



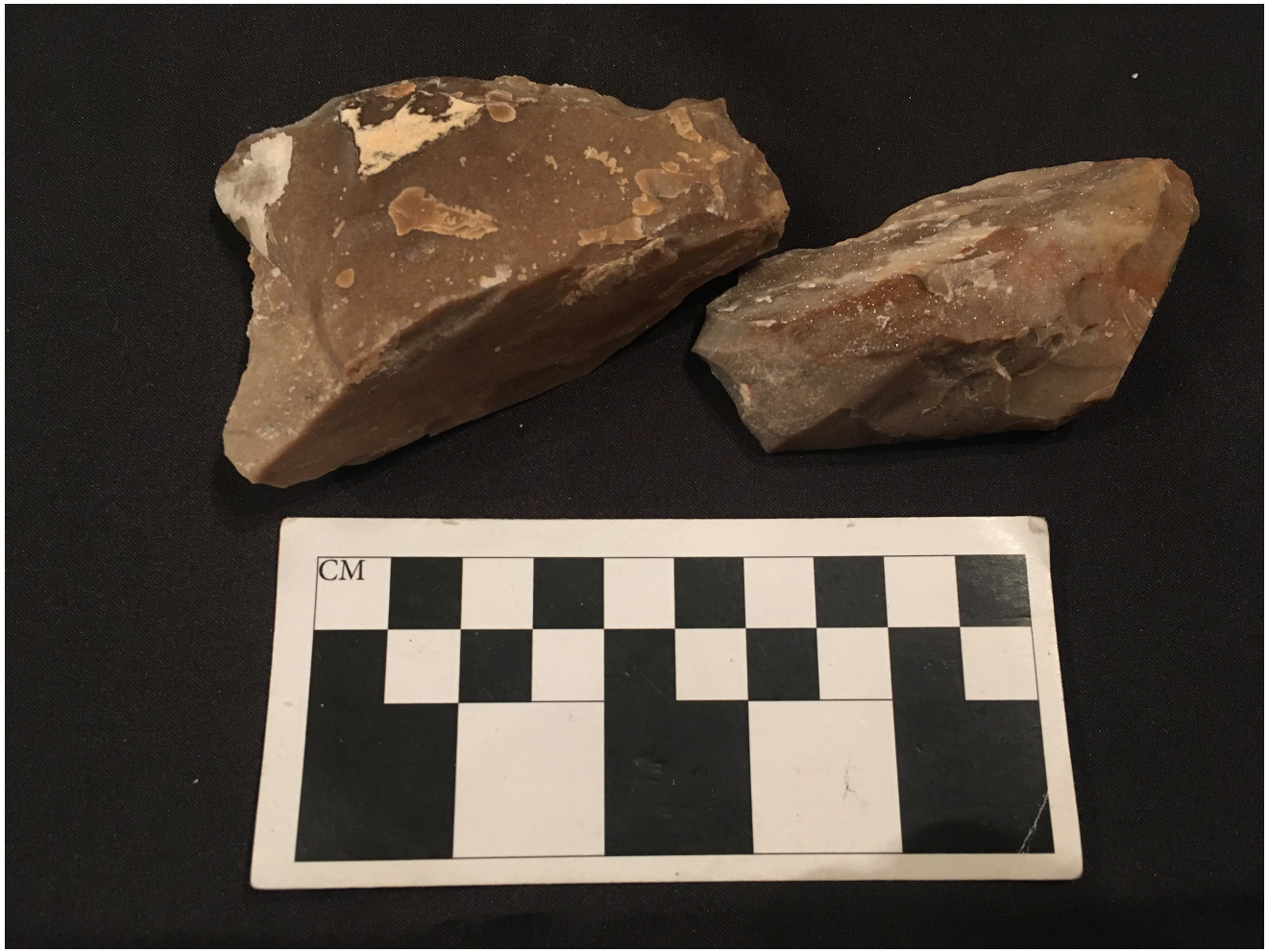
40X-3



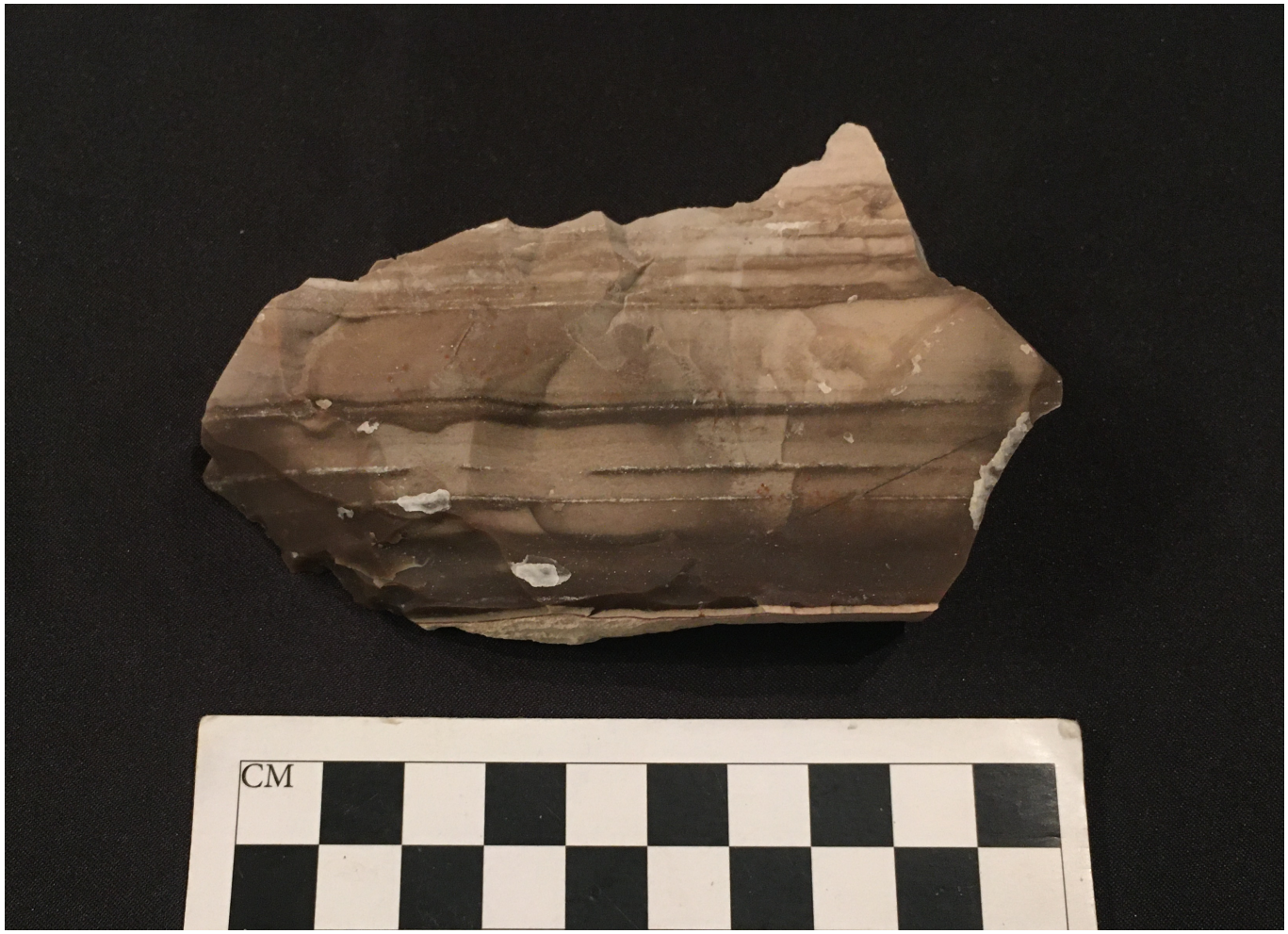
40X-4



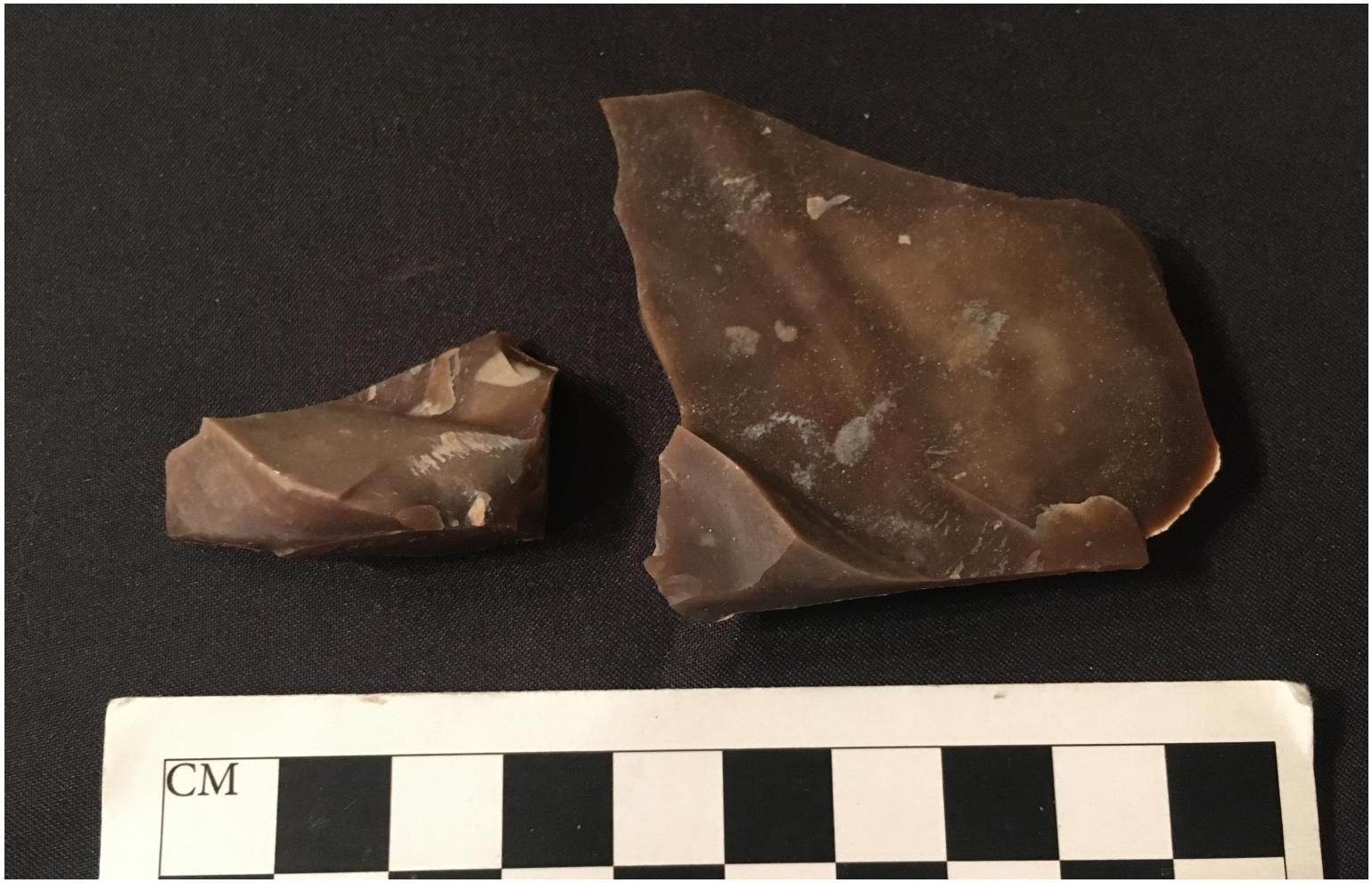
40X-5



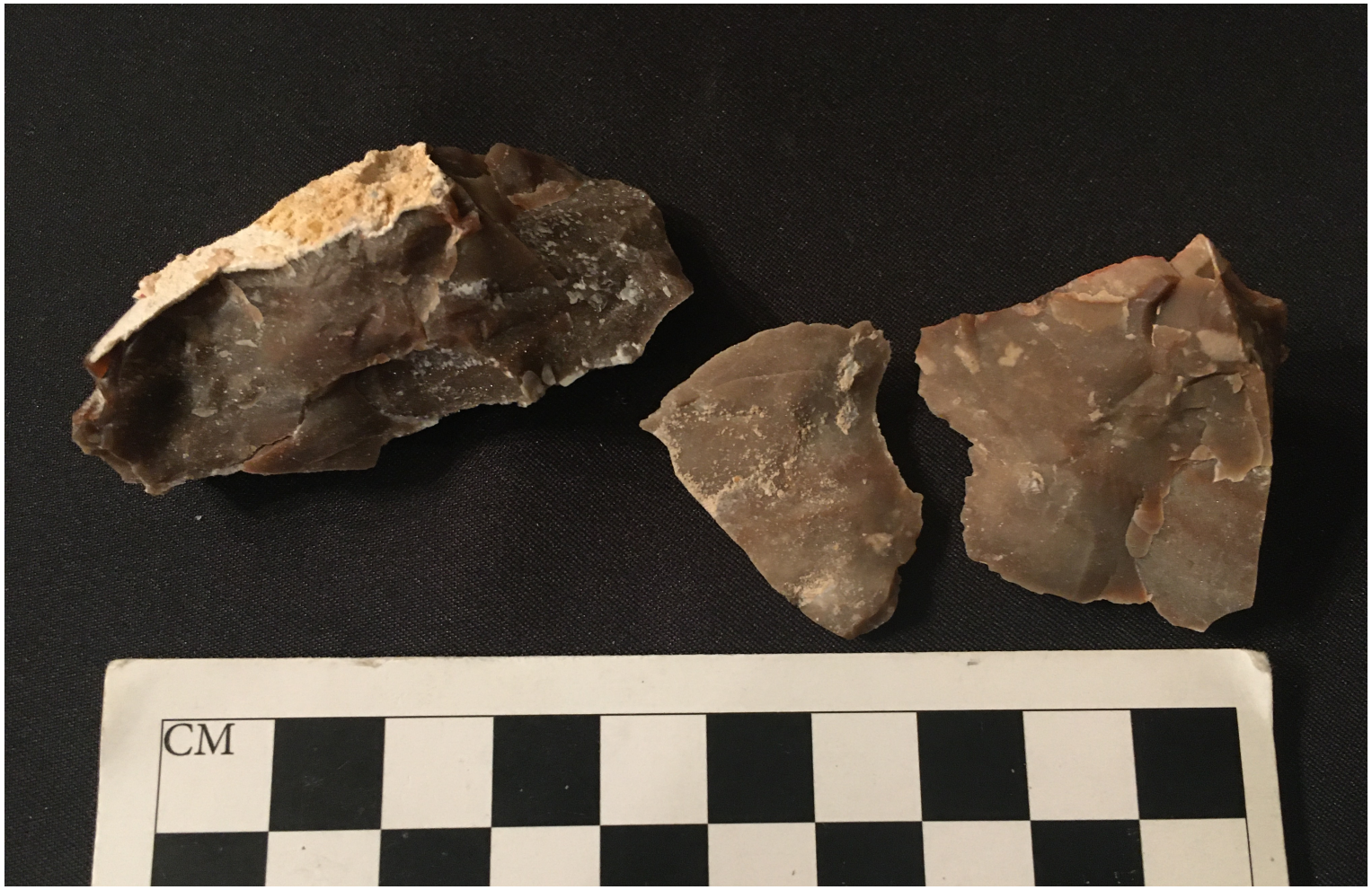
40X-6



40X-7



40X-8



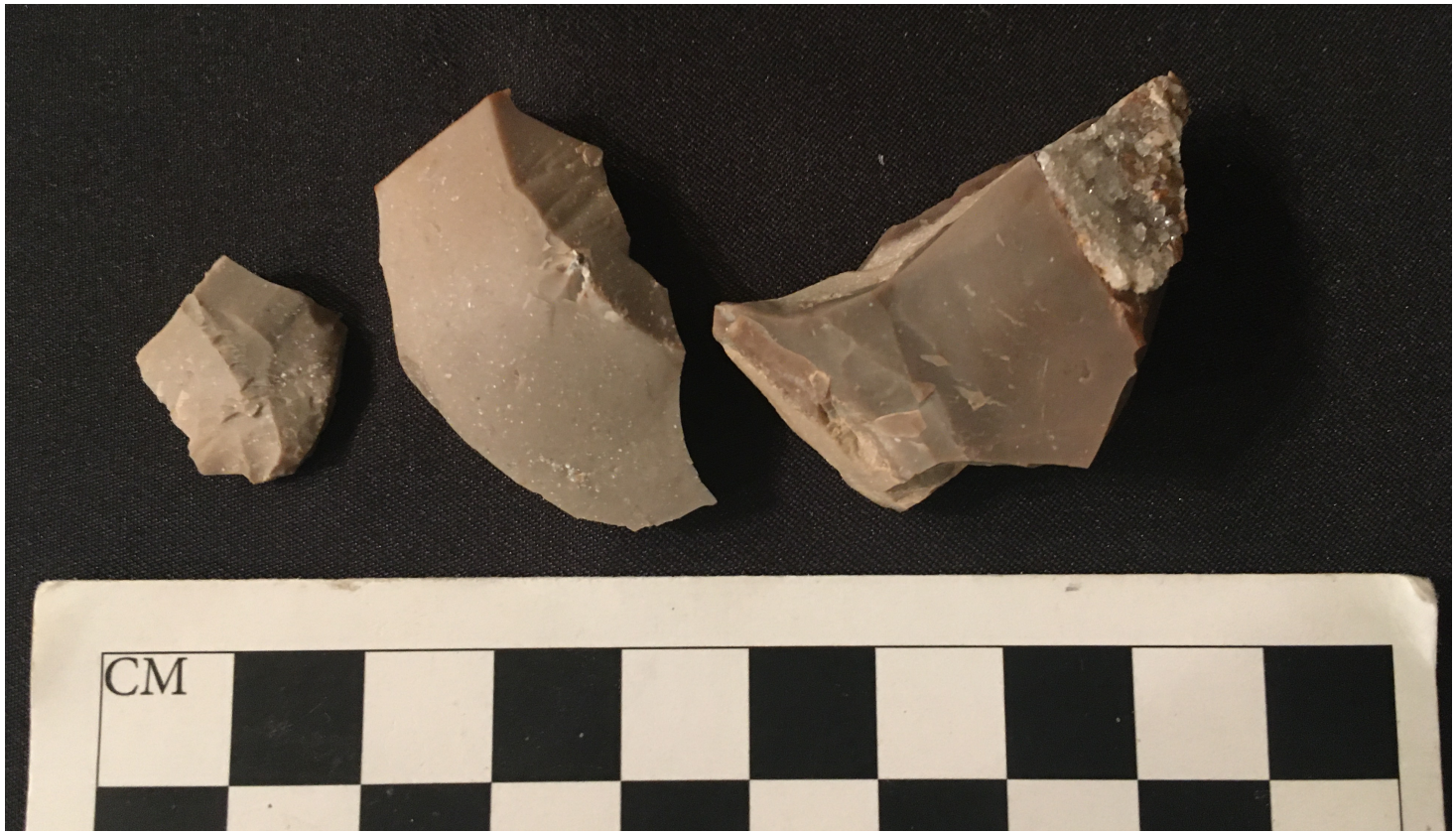
40X-9



40X-10



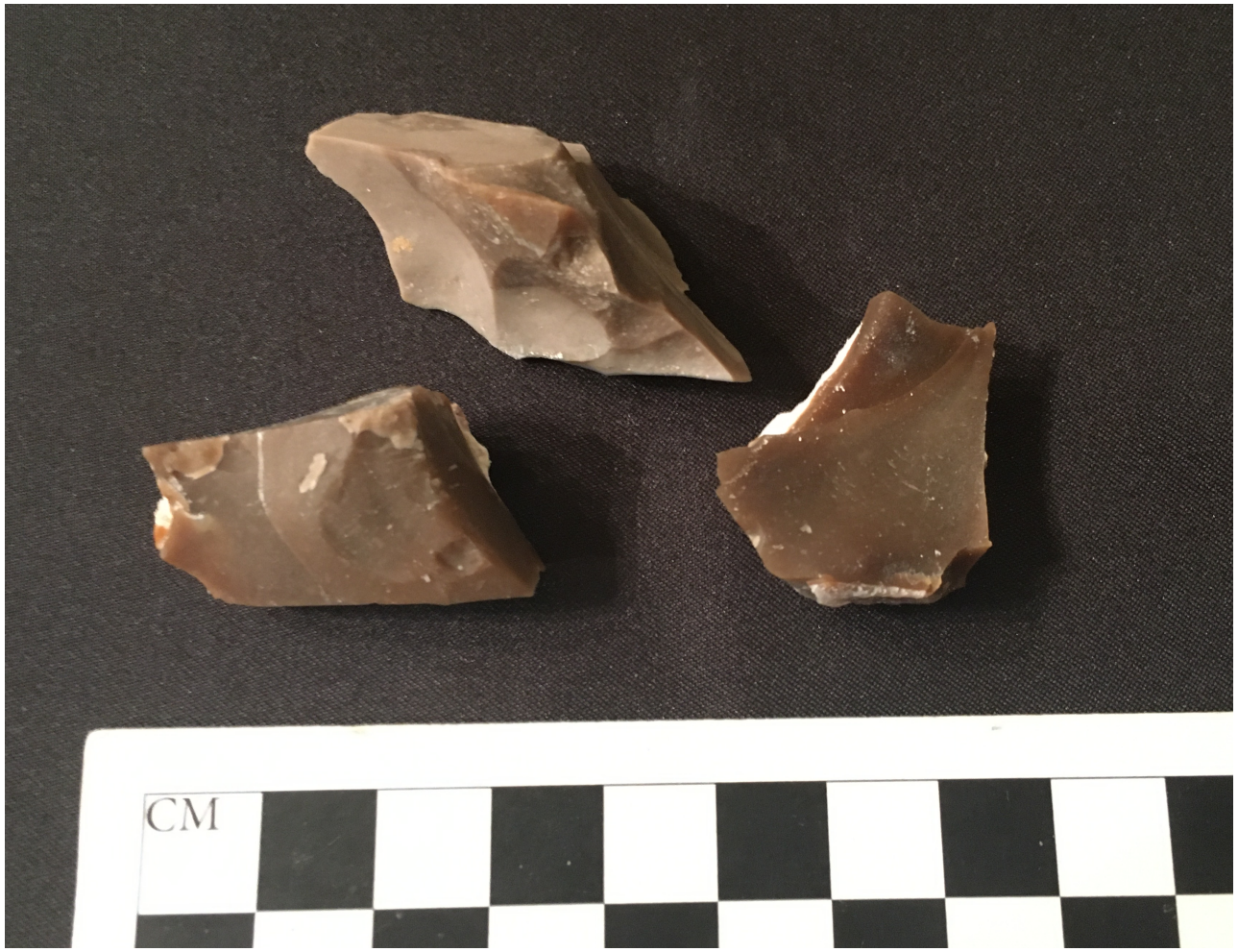
40X-11



40X-12



40X-13



‘Ain Qasiyya 1, Shishan Marsh



‘Ain Qasiyya 1, Shishan Marsh



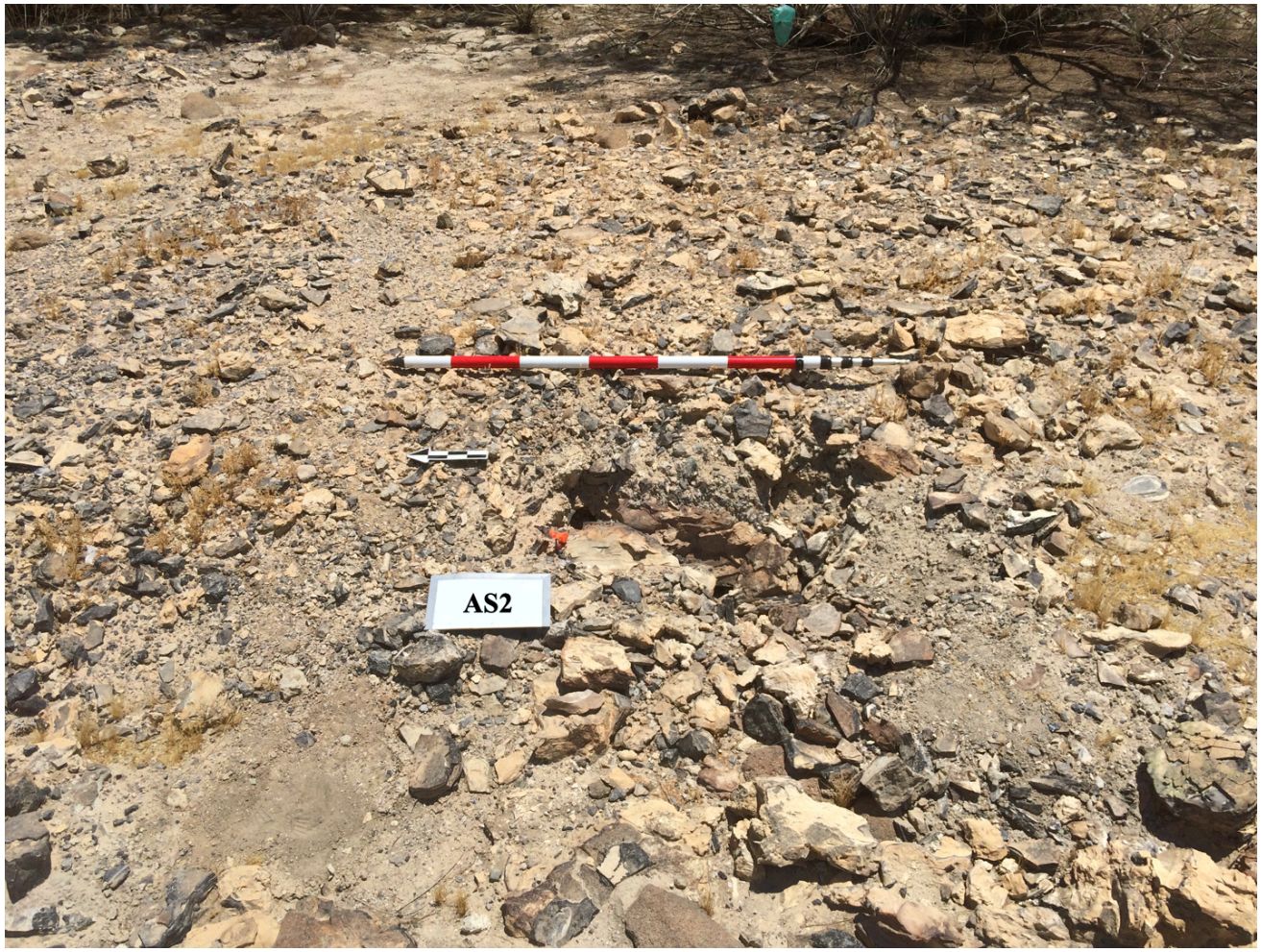
‘Ain Soda 1, Shishan Marsh



‘Ain Soda 1, Shishan Marsh



‘Ain Soda 2, Shishan Marsh



‘Ain Soda 2, Shishan Marsh



‘Ain Soda 3, Shishan Marsh



‘Ain Soda 3, Shishan Marsh



Wadi al-Masayil (east), northeastern area



Wadi al-Masayil (east), northeastern area



Wadi al-Masayil (east), northeastern area



From left to right: WME-1, WME-2, and WME-3



Wadi al-Masayil (west), northeastern area



From left to right: WMW-1, WMW-2, and WMW-3



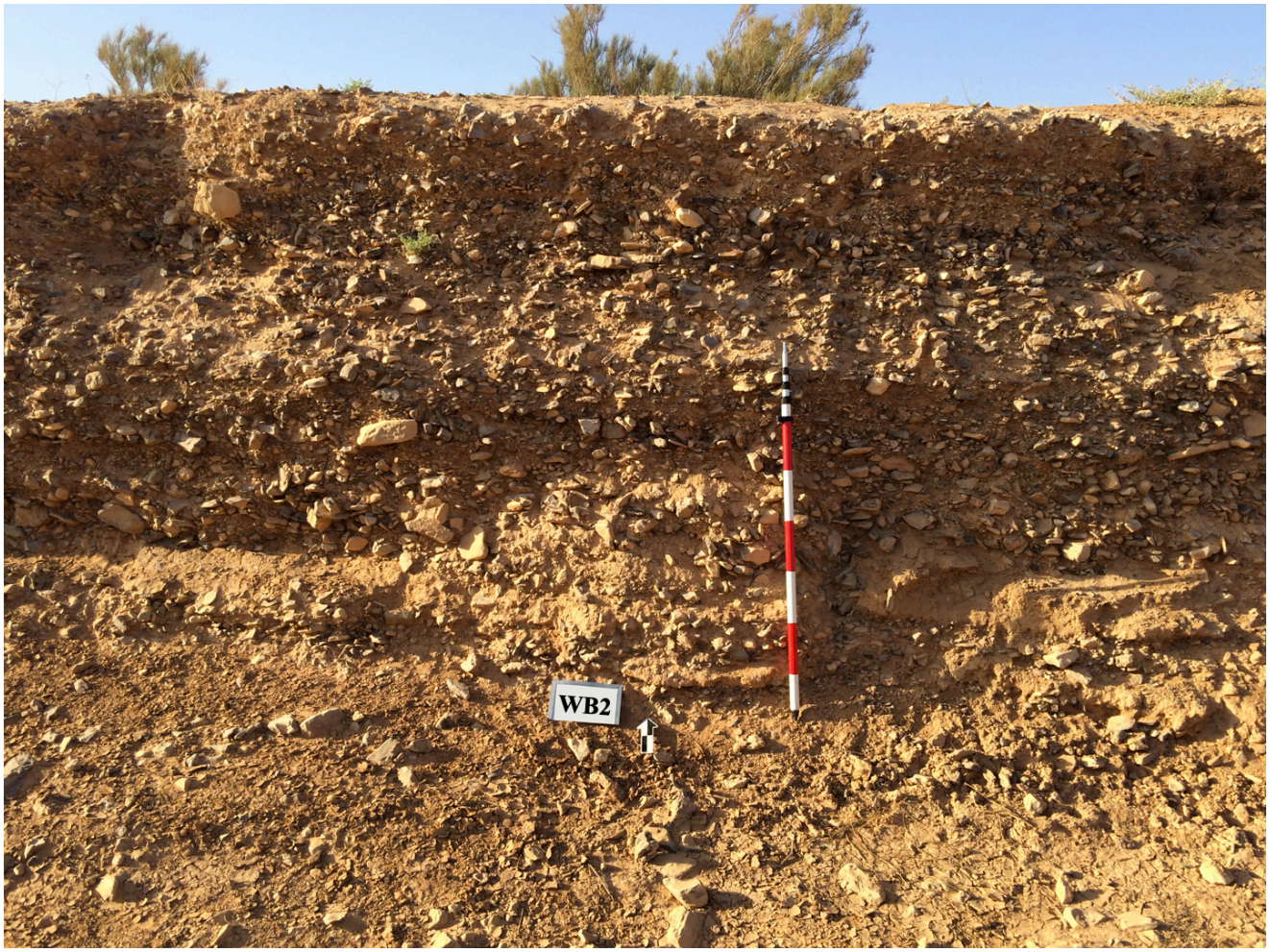
Wadi Butm 1, southwestern area



Wadi Butm 1, southwestern area



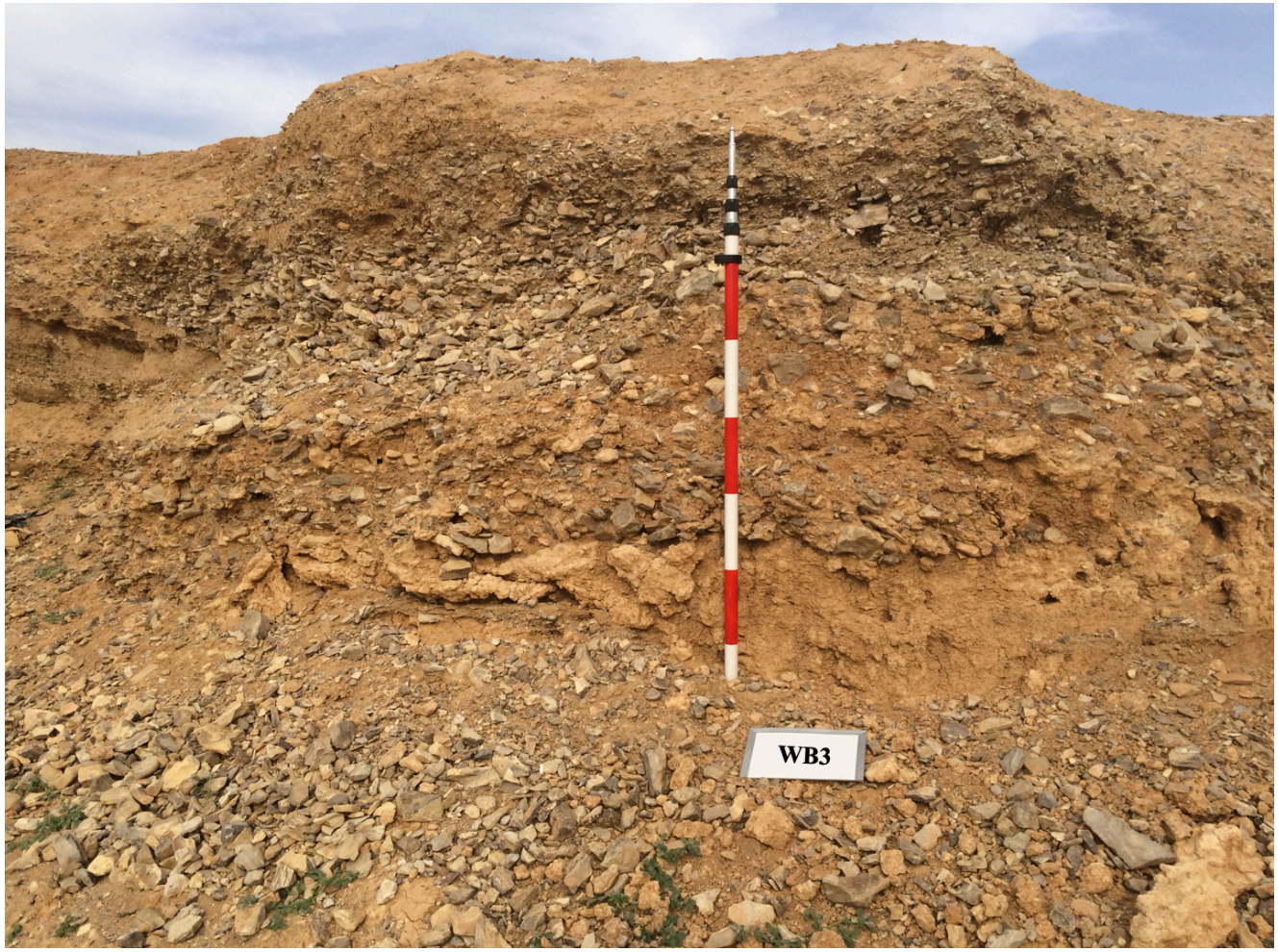
Wadi Butm 2, southwestern area



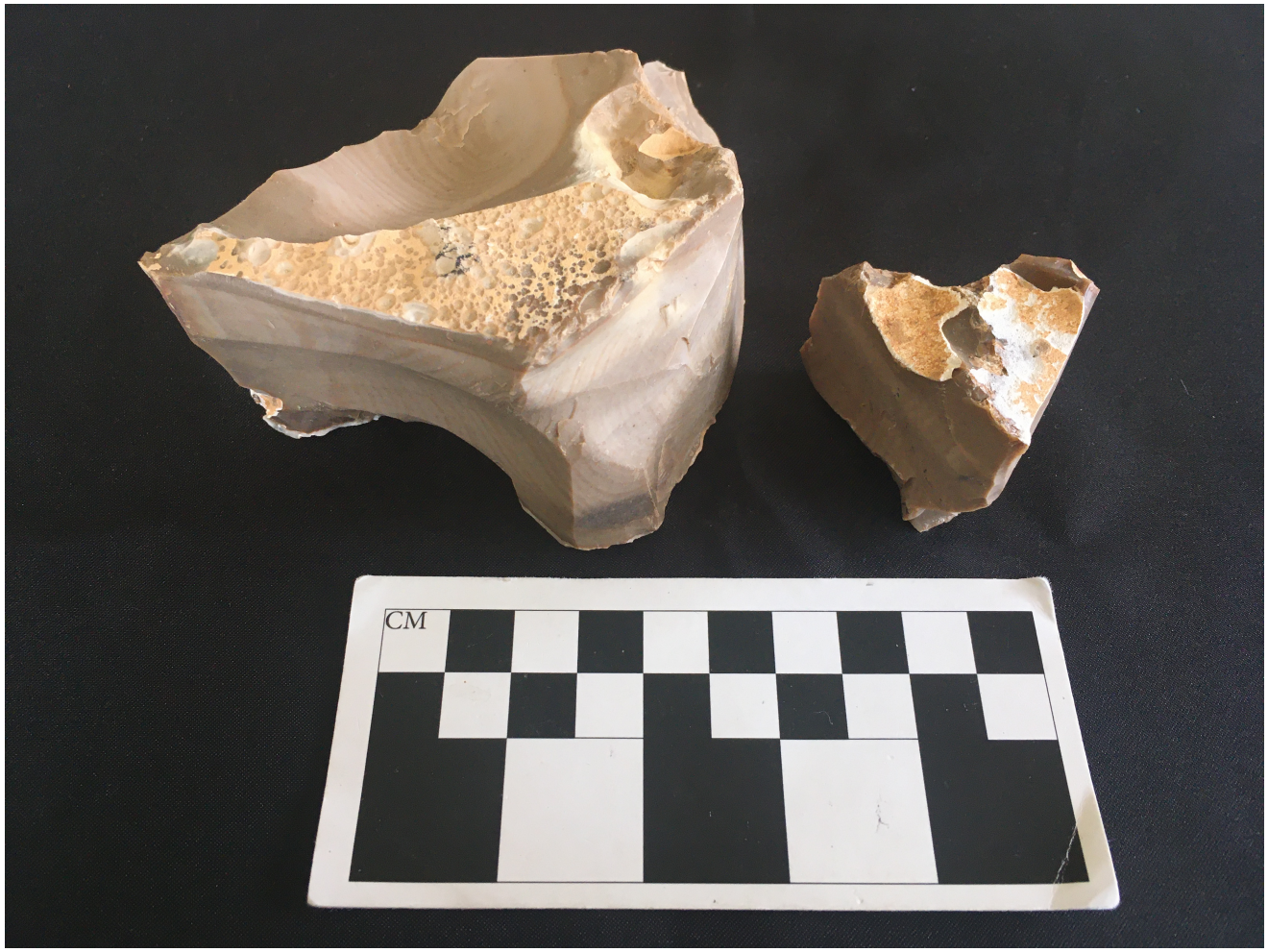
Wadi Butm 2, southwestern area



Wadi Butm 3, southwestern area



Wadi Butm 3, southwestern area



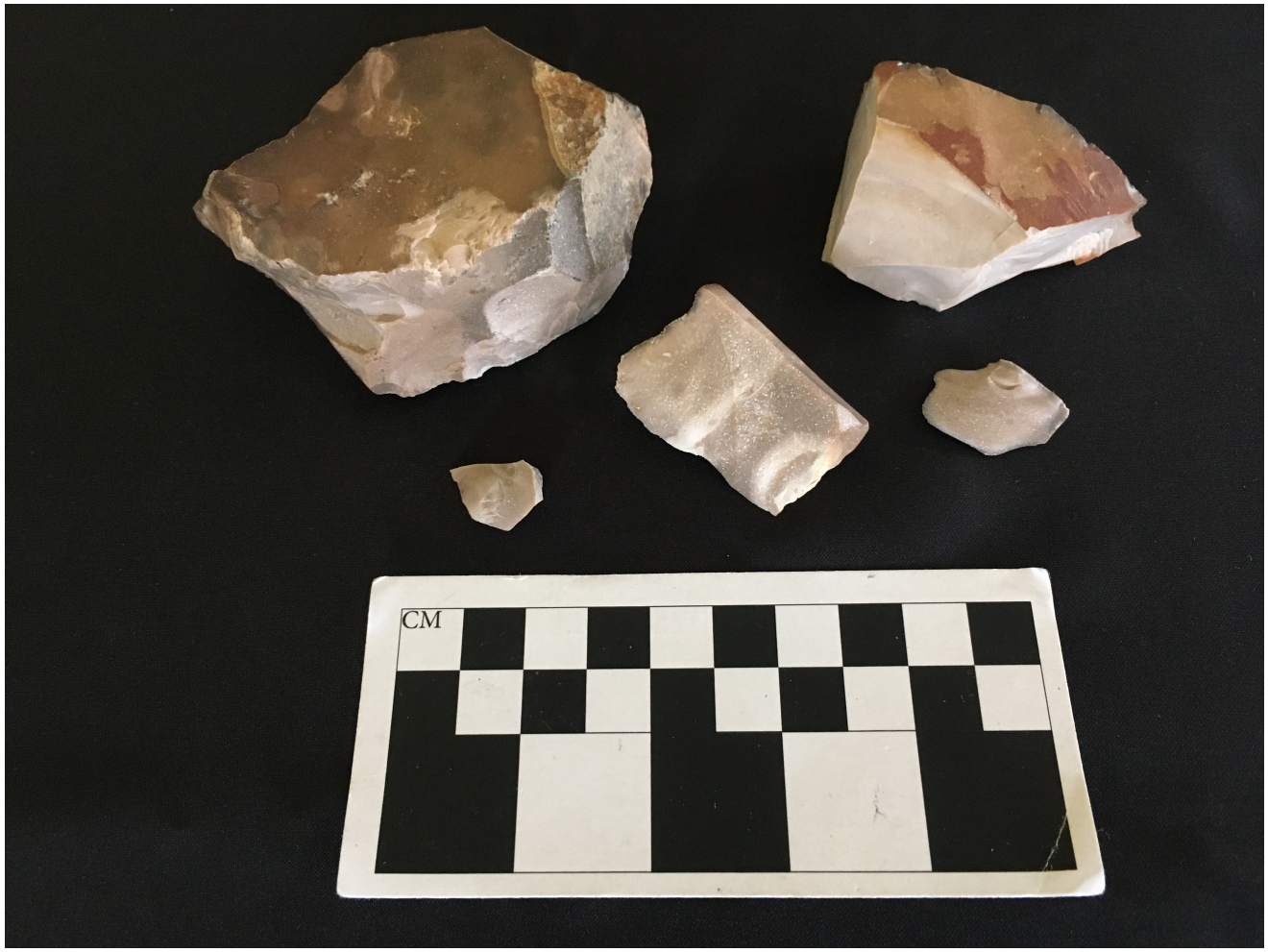
Wadi Enoqiyya, northwestern area



Wadi Ghadaf 1, southern area



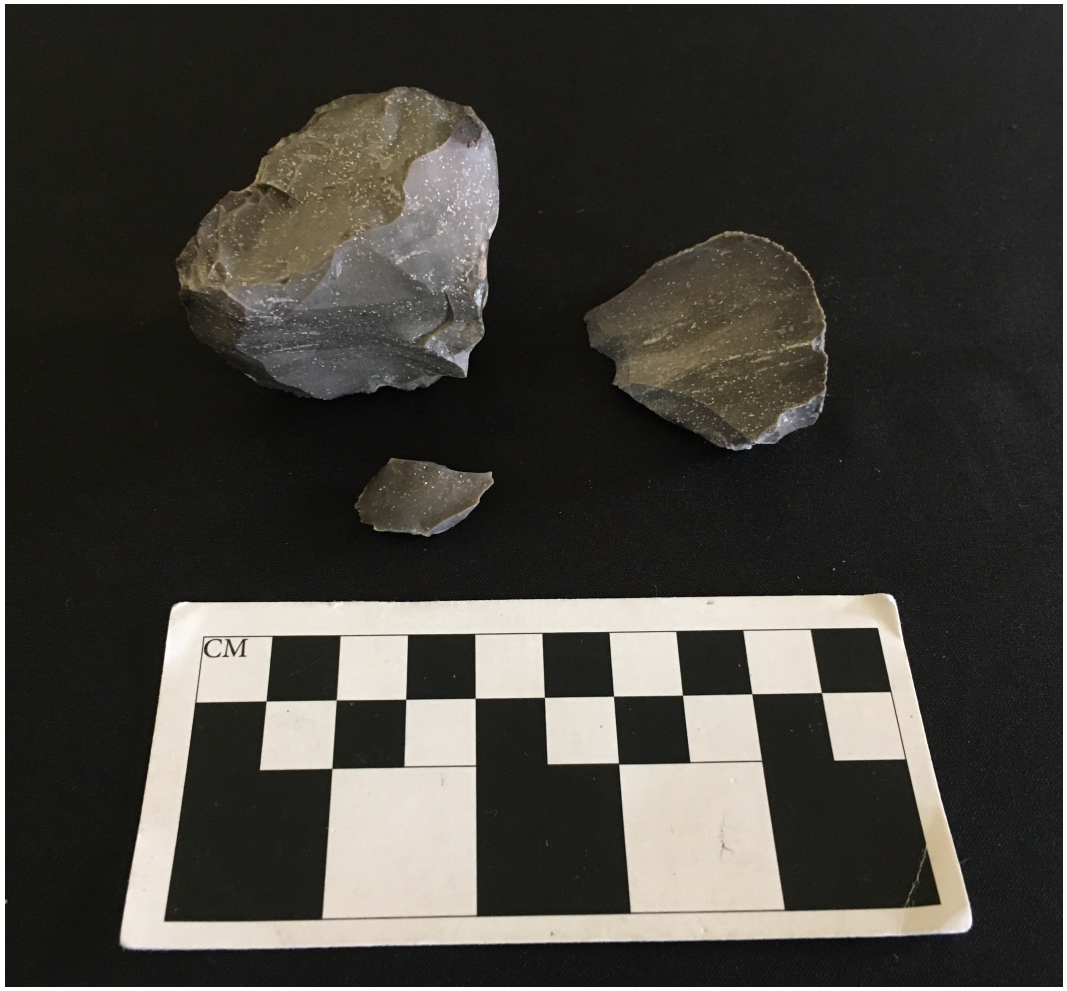
Wadi Ghadaf 1, southern area



Wadi Ghadaf 2, southern area



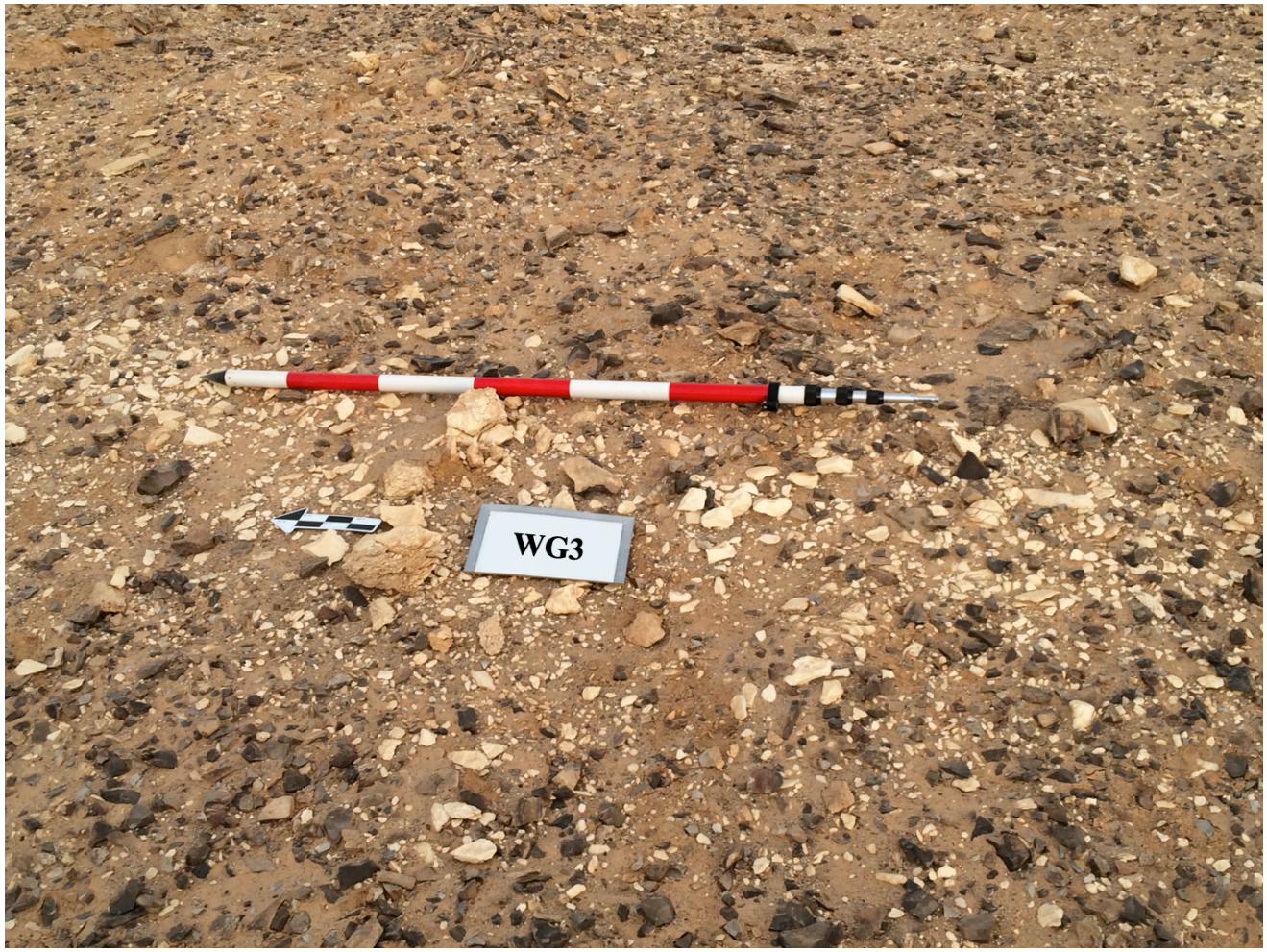
Wadi Ghadaf 2, southern area



Wadi Ghadaf 2-Red, southern area



Wadi Ghadaf 3, southern area



Wadi Ghadaf 3, southern area



Wadi Mushash, southwestern area



Wadi Mushash, southwestern area



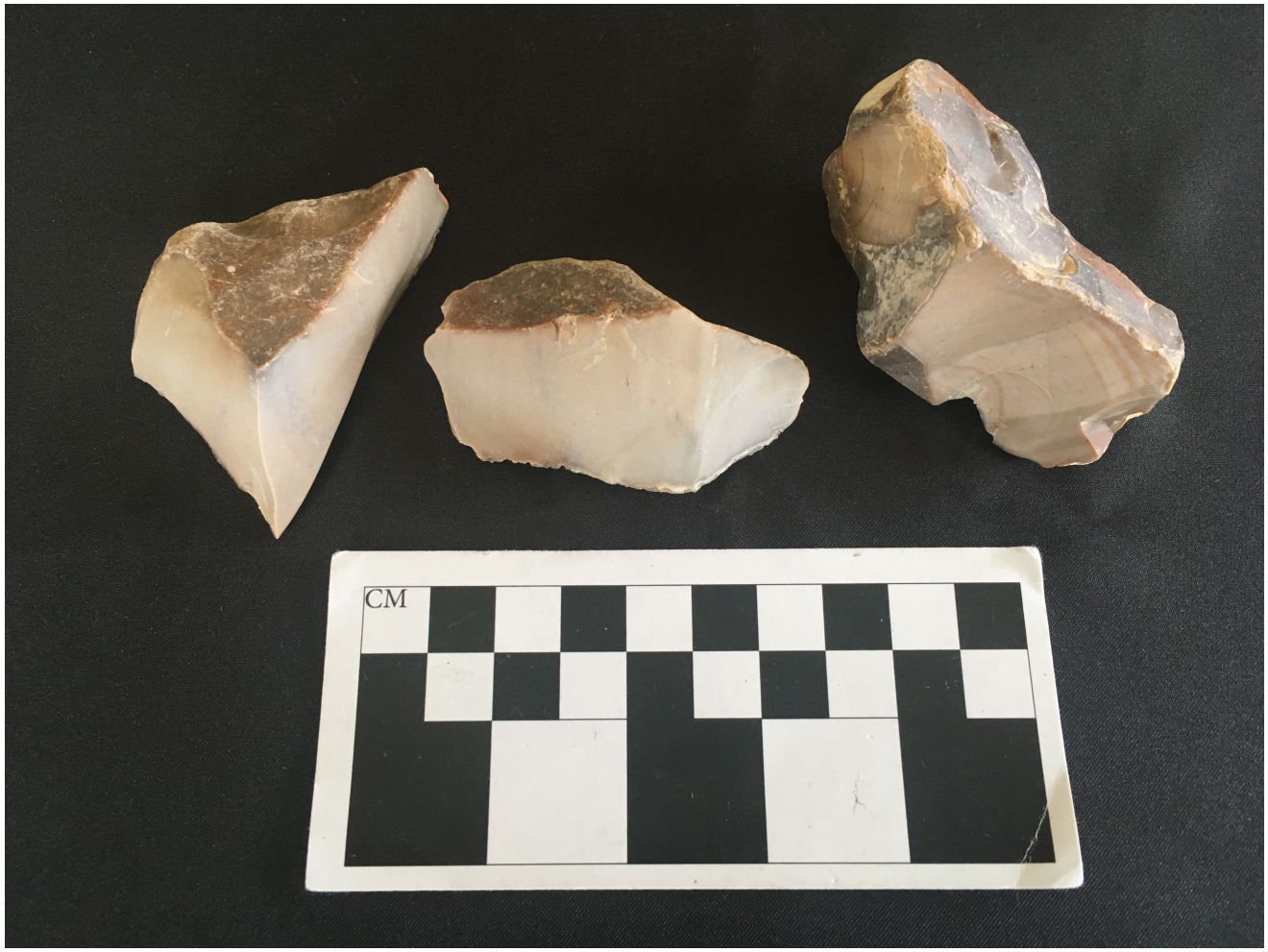
Wadi Mushash, southwestern area



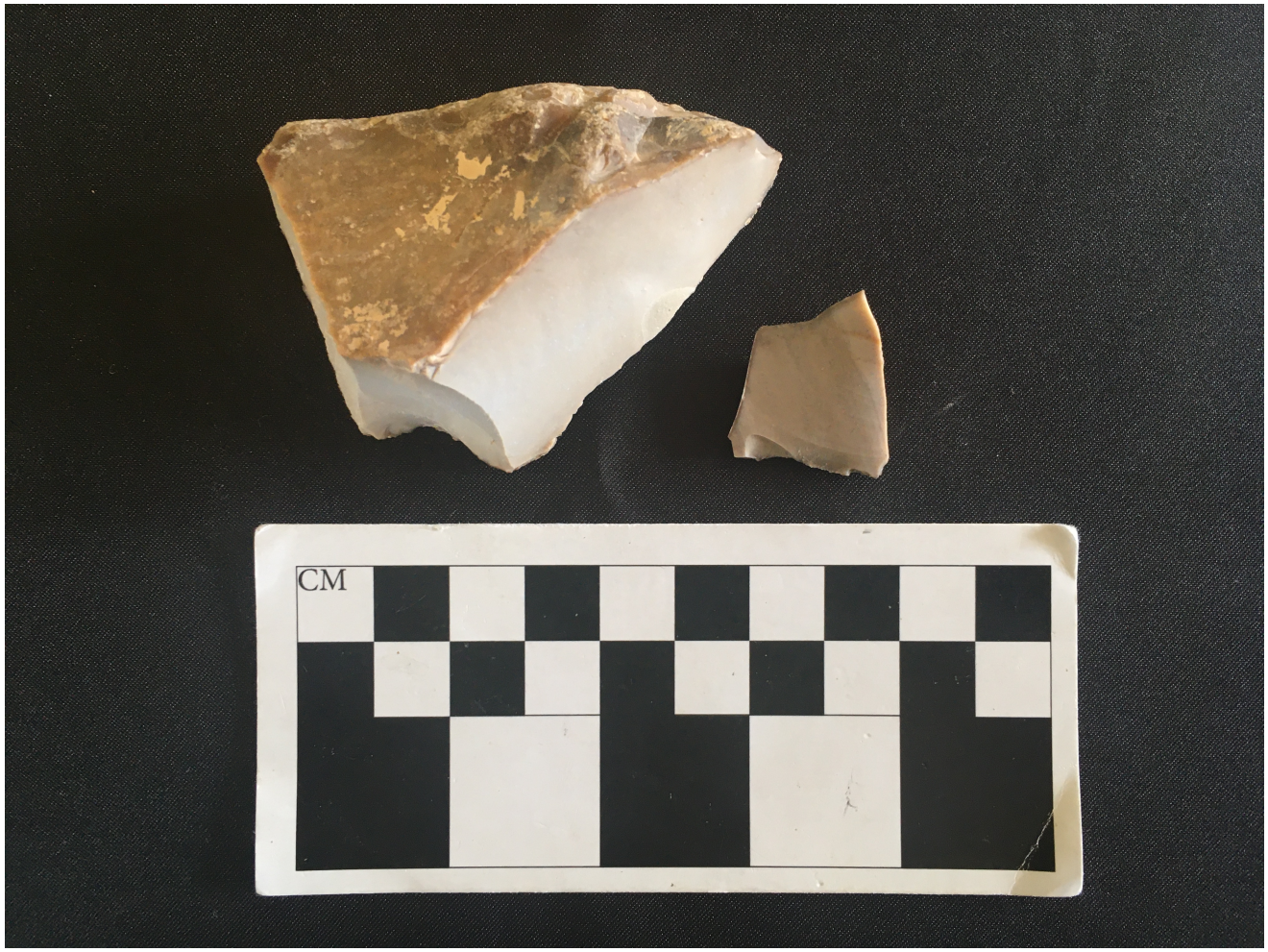
Wadi Mushash, southwestern area



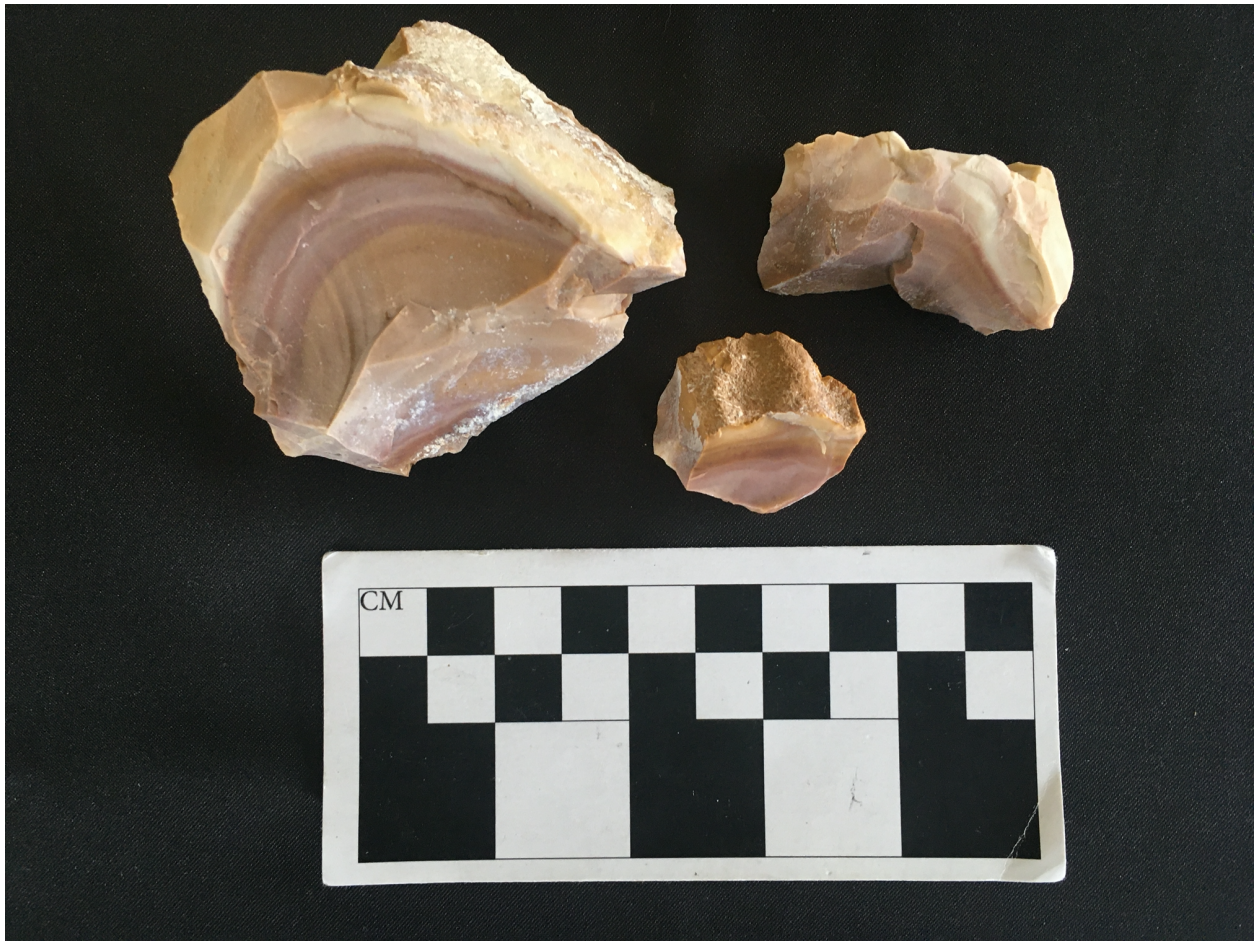
WMH-1



WMH-2



WMH-3



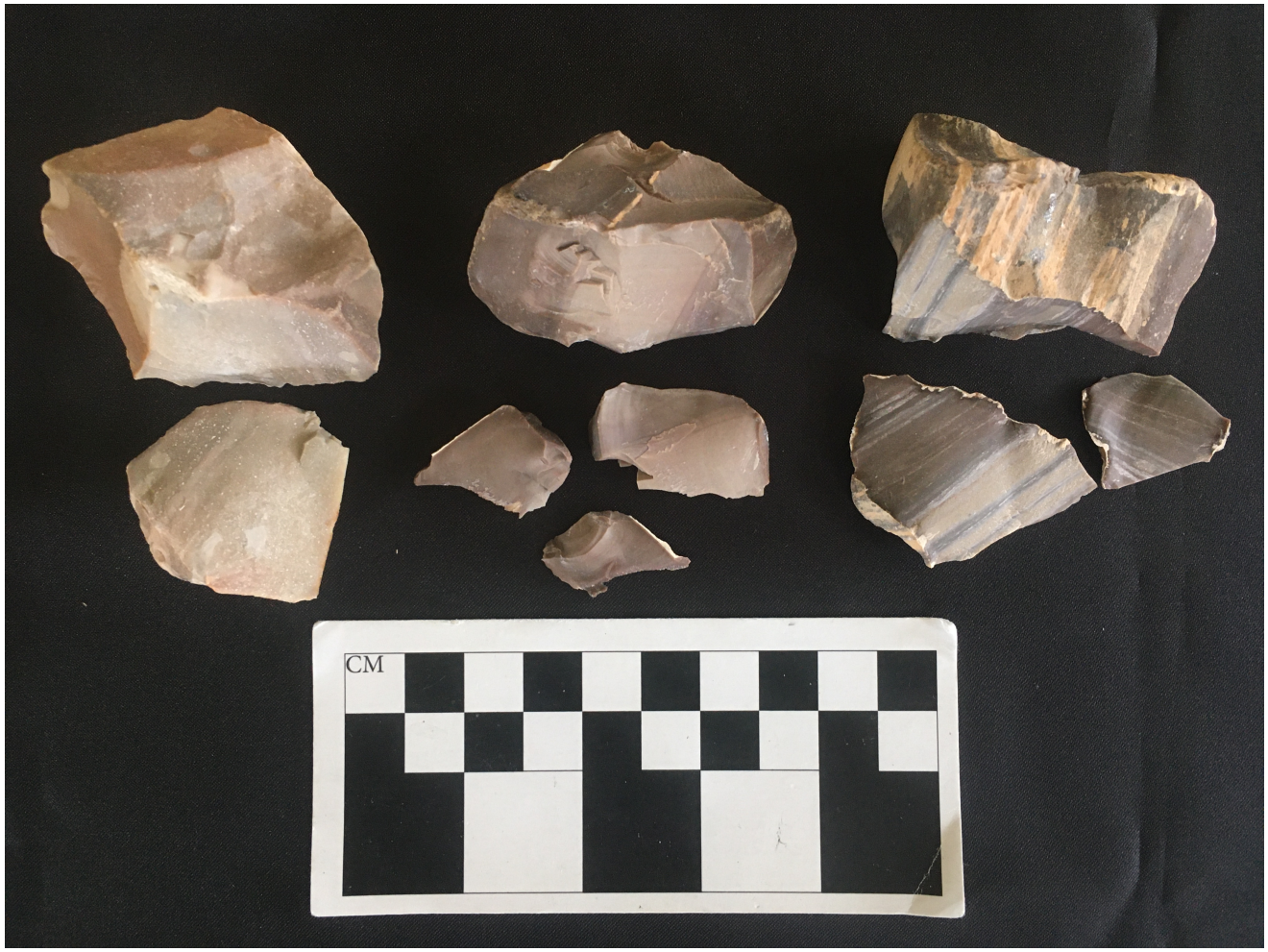
Wadi Rajil, northeastern area



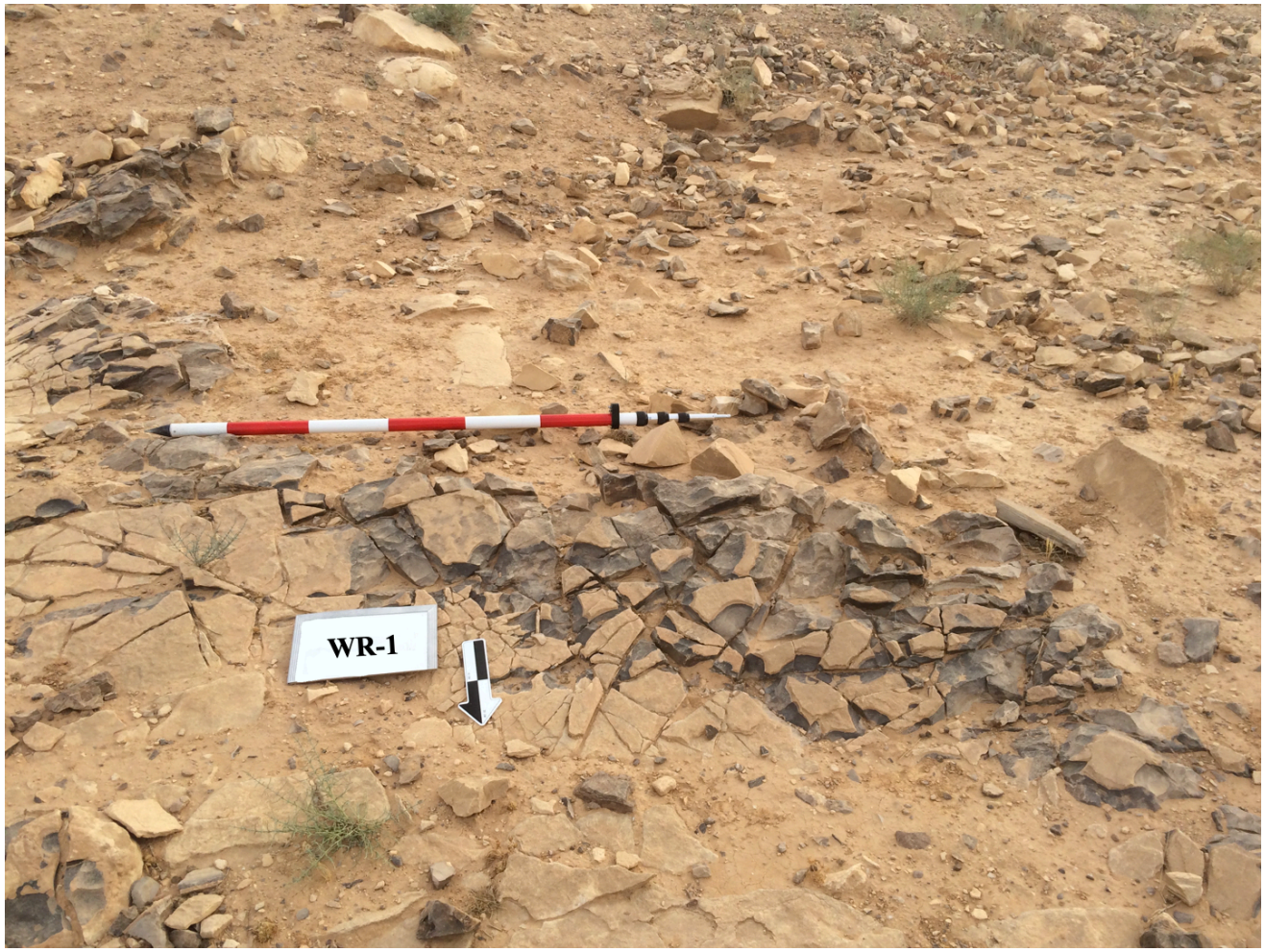
Wadi Rajil, northeastern area



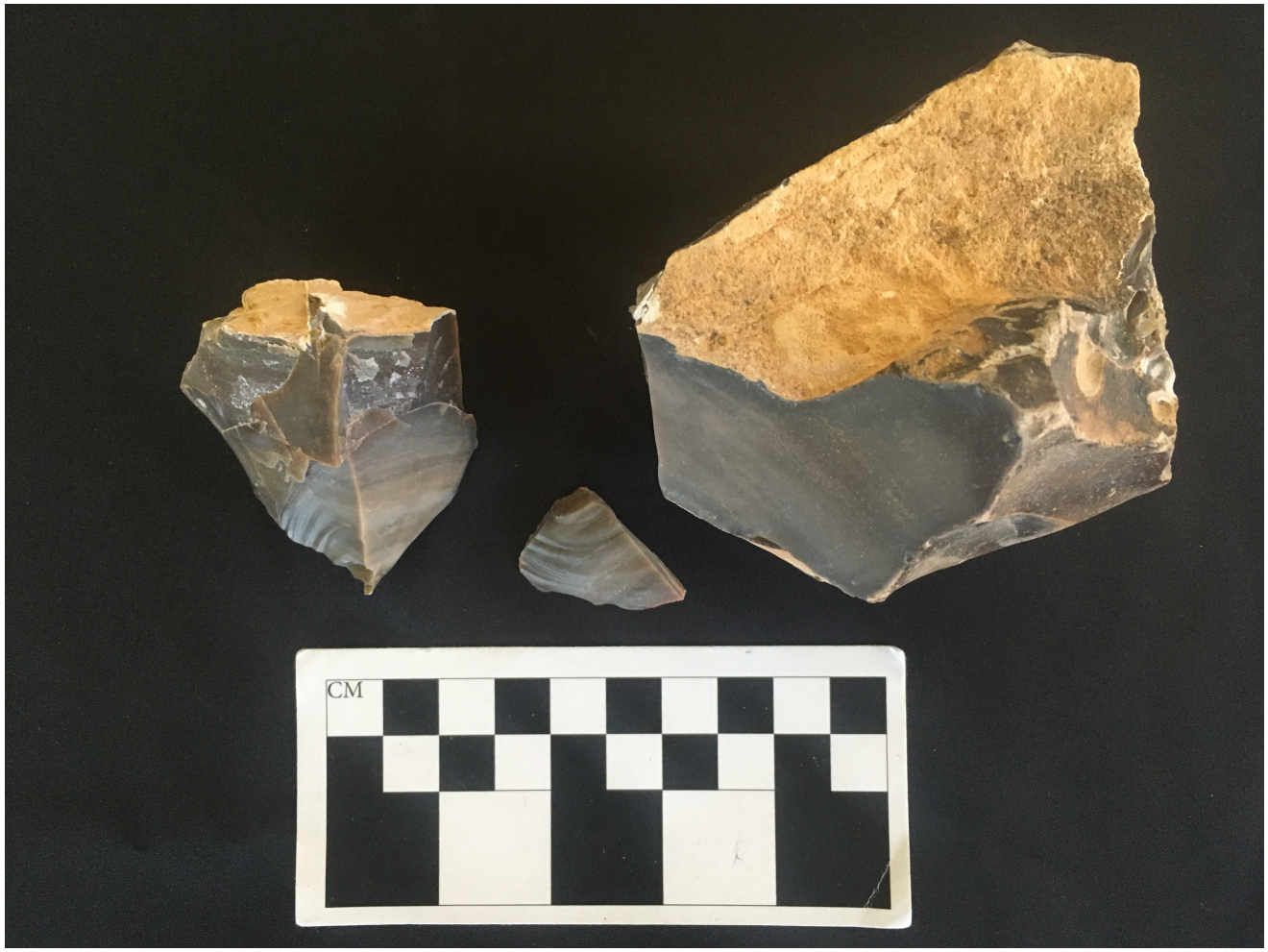
From left to right: WRJ-1, WRJ-2, and WRJ-3



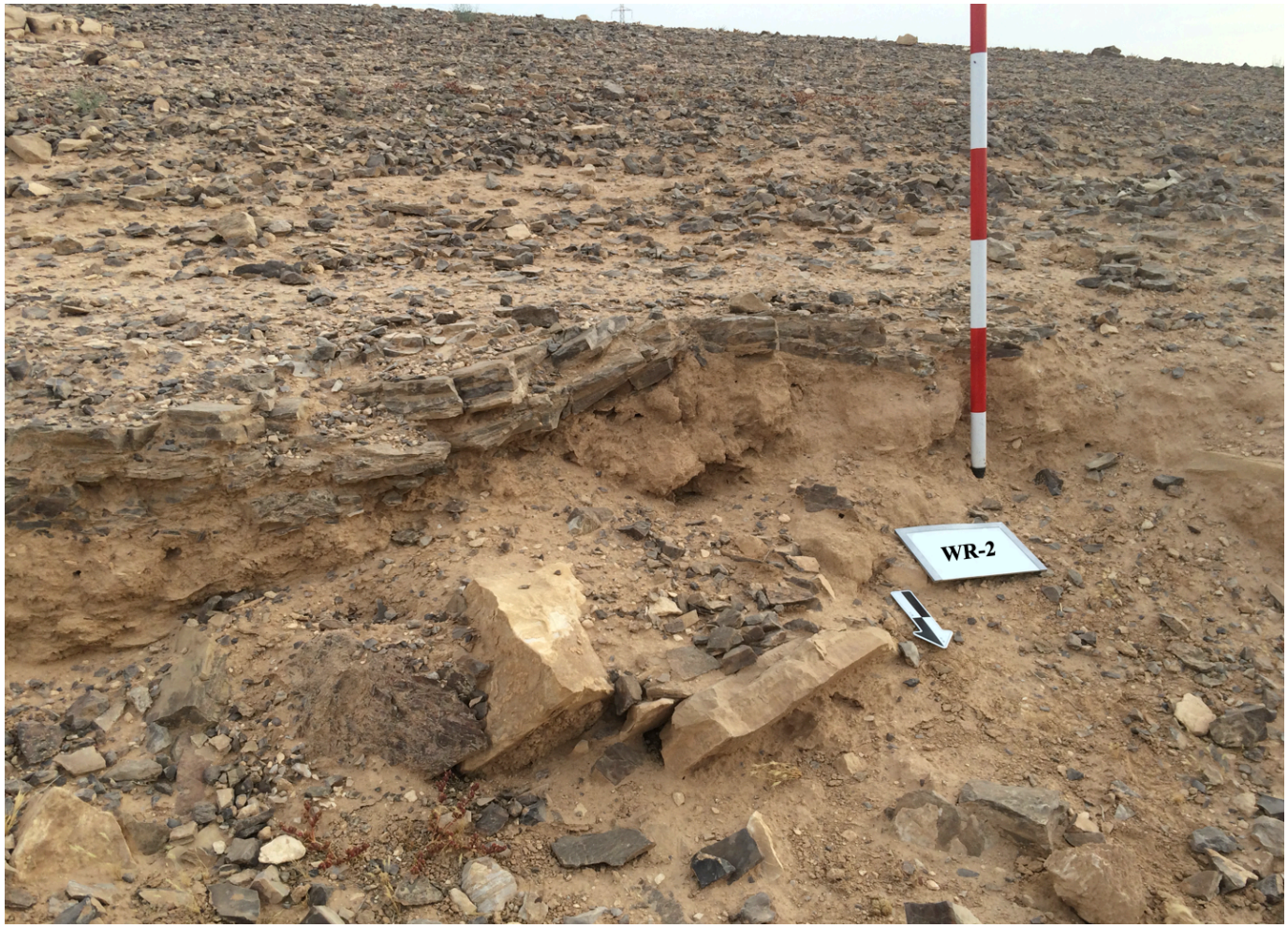
Wadi Rattama-1, western area



Wadi Rattama-1, western area



Wadi Rattama-2, western area



Wadi Rattama-2, western area



Wadi Rattama-3, western area



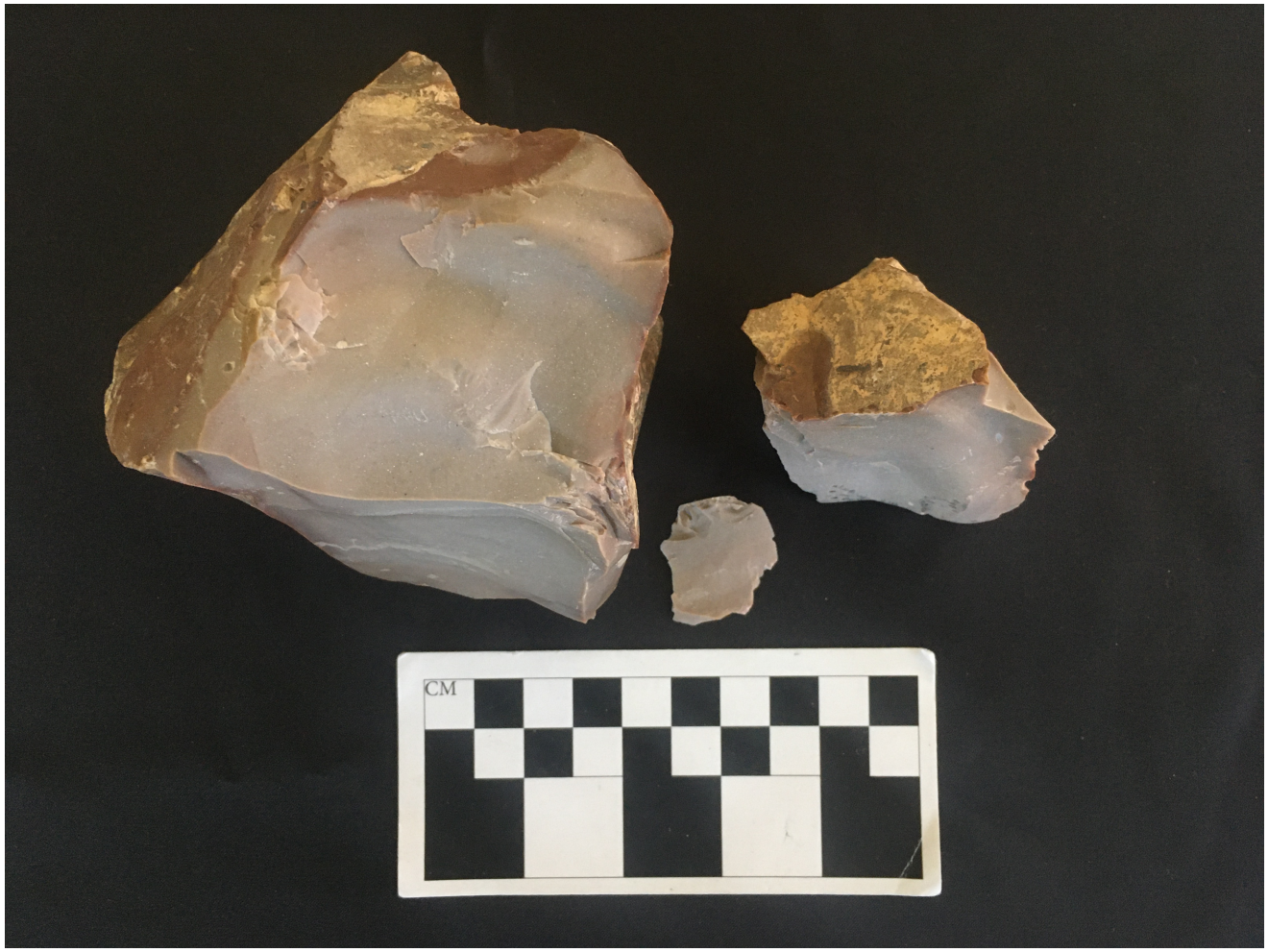
Wadi Rattama-3, western area



Wadi Rattama-4, western area



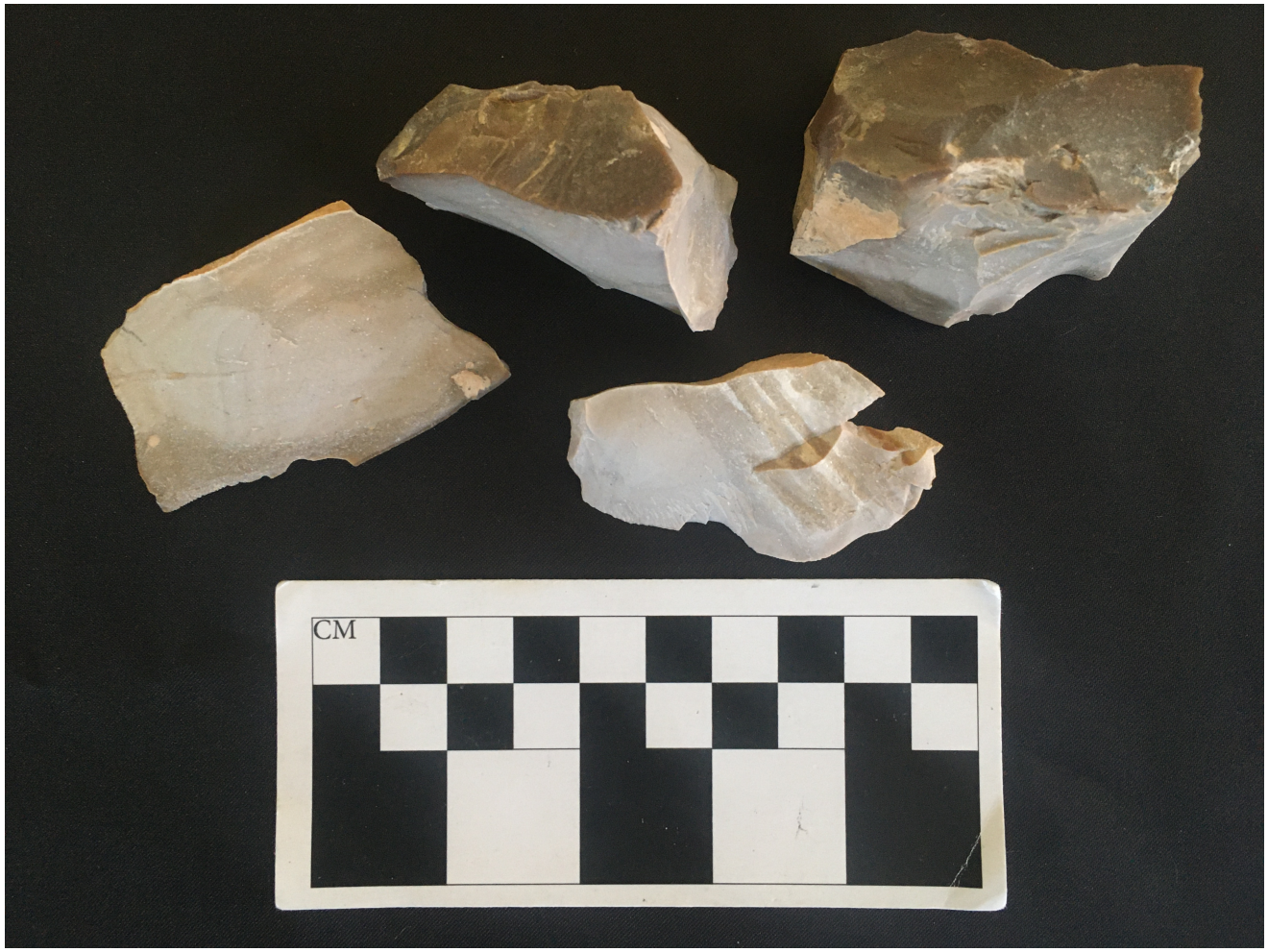
Wadi Rattama-4, western area



Wadi Rattama-5, western area



Wadi Rattama-5, western area



Wadi Usaykhim, northeastern area



Wadi Usaykhim, northeastern area



From left to right: WU-1, WU-2, and WU-3



Appendix 5: Geochemical data (ppm) of sources (4 tables).

Table 1/4 (sample ablated by * line raster; ** immobile laser)												
Formation	Source	Li	Be	B	Na	Mg	Al	Si	K	Ca	Sc	Ti
Umm Rijam Chert-Limestone Formation	35Q-1*	7.522	0.455	61.489	376.085	22.375	470.136	464330.081	224.49	1695.564	5.38	60.618
	35Q-1	6.518		61.291	425.574	34.154	467.489	460677.83	225.882	4971.356	5.836	41.156
	35Q-1	6.573		59.017	384.862	25.498	488.473	463549.082	230.235	2293.806	5.533	49.923
	35Q-1	6.412	0.126	60.747	404.964	27.143	488.214	462645.628	232.24	3207.408	5.886	53.068
	35Q-1	5.04	0.257	59.647	370.338	23.523	449.714	464075.95	252.491	1956.351	5.884	46.271
	35Q-2*	10.024	0.142	40.946	599.435	32.451	606.704	459400.871	347.138	5463.31	5.177	35.574
	35Q-2	6.586	0.26	40.639	535.866	42.137	610.37	460210.104	325.096	4912.399	5.228	54.429
	35Q-2	9.911	0.269	42.086	509.436	32.799	596.464	461637.282	310.116	3005.606	5.034	65.859
	35Q-2	7.939	0.586	47.038	424.487	17.022	378.992	464005.143	221.651	1997.775	5.759	35.022
	35Q-2	8.175	0.31	42.246	487.6	34.682	485.638	459278.534	262.21	4405.805	5.321	39.867
	35Q-3*	10.694	0.542	66.758	317	15.034	351.224	465028.081	181.264	1057.974	5.403	31.192
	35Q-3	9.925	0.527	71.557	357.427	26.277	416.098	462985.313	209.024	2763.132	5.536	40.122
	35Q-3	9.207	0.309	71.708	314.525	17.283	362.225	464598.818	183.851	1515.808	5.218	32.277
	35Q-3	7.677	0.296	71.252	302.241	18.929	357.442	464429.396	185.375	1557.208	5.026	33.643
	35Q-3	5.764		66.327	441.734	18.721	376.704	463650.692	195.529	1786.423	5.722	40.304
	40X-1**	30.888	0.155	31.13	1365.707	460.608	964.368	457837.727	349.94	7393.969	4.431	75.333
	40X-1	29.884	0.349	24.417	537.872	327.222	870.217	466428.778	149.618		4.263	58.681
	40X-1	29.84	0.232	34.19	1353.335	412.849	1100.245	459597.674	438.549	5172.955	4.363	105.229
	40X-1	33.406	0.288	32.704	1216.656	410.229	937.931	460333.946	328.387	5499.357	4.25	32.812
	40X-1	37.782	0.23	28.624	1332.894	352.533	856.758	460923.697	385.035	5238.785	4.163	60.034

	40X-2**	14.898	0.364	23.06	2479.624	461.869	1179.519	445538.789	483.403	20027.094	4.112	80.572
	40X-2	15.383	0.605	20.449	1886.946	384.023	888.362	449951.356	366.576	16116.658	4.106	71.78
	40X-2	15.939	0.424	20.348	1840.896	404.767	993.313	448067.929	449.901	17899.626	4.05	53.657
	40X-3*	1.669	0.345	60.275	871.906	50.47	414.16	462438.244	179.72	3449.569	2.46	31.088
	40X-3	1.898	0.435	56.678	974.836	54.517	494.353	460320.984	226.34	5370.352	2.636	31.975
	40X-3	2.043	0.636	59.275	857.044	46.461	510.824	463655.506	224.957	2179.857	2.336	28.397
	40X-4*	1.632	0.368	49.442	594.459	136.448	327.182	453860.593	164.837	11507.223	2.515	22.324
	40X-4	1.758	0.373	48.478	398.632	101.027	319.09	461498.668	151.591	4532.112	2.568	140.189
	40X-4	1.622	0.324	47.797	393.622	104.386	337.569	461136.346	157.128	5131.629	2.587	26.509
	40X-5*	8.088	0.185	42.879	711.285	88.76	756.467	461888.013	333.574	4114.844	2.601	36.649
	40X-5	4.313	0.363	47.907	594.941	93.286	596.877	462959.103	275.529	3287.421	2.399	41.642
	40X-5	5.969	0.163	51.104	570.974	109.744	662.405	459314.489	295.356	6406.564	2.621	33.033
	40X-6*	5.282	0.471	50.367	631.82	74.986	580.754	464315.112	247.301	1722.196	2.442	37.872
	40X-6	5.473	0.499	51.831	649.2	63.989	539.269	464261.275	222.494	1692.704	2.511	49.85
	40X-6	4.212		59.664	709.804	63.386	581.262	463817.495	234.739	2181.917	2.563	33.927
	40X-7*	3.5	0.344	46.874	653.57	88.803	565.145	459677.877	262.823	5985.721	2.607	33.717
	40X-7	4.55	0.14	48.493	652.759	88.663	499.718	462861.346	245.304	3000.889	2.526	37.268
	40X-7	4.407	0.356	51.935	665.623	84.803	450.679	462010.232	195.748	3738.873	2.521	31.545
	40X-8*	12.2	0.24	49.33	1279.31	45.09	294.76	458247.26	140.41	8052.15	2.69	24.82
	40X-8	22.08		46.46	1158.14	31.13	337.51	461863.75	150.07	4762.42	2.63	18.74
	40X-8	12.35	0.27	44.09	1173.33	36.32	300.2	462392.87	142.52	3885.9	2.7	36.85

	40X-9*	10.865	0.223	44.125	819.318	82.731	652.239	462485.109	294.522	3053.537	2.493	45.763
	40X-9	6.037	0.258	56.708	870.265	79.766	597.173	462822.66	297.644	2833.084	2.54	29.745
	40X-9	5.745	0.265	52.124	897.098	65.477	440.334	464006.148	273.199	1923.389	2.713	32.209
	40X-10*	10.3	0.201	38.053	638.139	61.848	843.499	462056.54	306.144	3667.542	2.675	47.551
	40X-10	11.421	0.256	38.347	655.031	64.862	692.405	461694.233	273.908	3896.202	2.61	42.031
	40X-10	9.464	0.129	39.521	700.824	82.223	759.363	461098.62	276.803	4567.529	2.626	40.603
	40X-11*	7.132	0.131	43.806	755.095	70.454	406.762	460984.953	193.246	5176.523	2.59	21.965
	40X-11	6.059	0.176	44.288	706.113	66.055	370.122	463128.138	173.991	2944.173	2.616	27.921
	40X-11	7.643	0.128	39.364	732.142	72.83	424.402	461274.957	277.746	4594.47	2.603	40.298
	40X-12*	5.244	0.203	54.808	981.272	122.266	625.936	456770.649	263.712	8188.98	2.611	50.754
	40X-12	4.869	0.15	58.289	879.705	98.677	557.11	462630.589	228.44	3216.354	2.638	31.45
	40X-12	5.459	0.39	51.445	876.227	105.864	638.14	461057.393	259.164	4620.047	2.555	30.679
	40X-13*	9.593	0.319	43.291	916.393	79.783	634.492	461153.355	267.035	4249.449	2.46	43.695
	40X-13	10.984	0.125	41.87	864.704	85.26	671.595	463338.746	271.072	2627.855	2.521	38.032
	40X-13	6.197	0.14	48.501	792.501	91.42	651.463	463494.147	287.549	2253.238	2.572	33.958
	AQ1**	38.057	0.81	37.437	905.022	85.535	1112.41	453079.342	444.394	10131.441	5.473	59.401
	AQ1	37.08	0.352	44.061	853.579	80.796	979.408	450187.936	460.612	11184.918	5.609	68.522
	AQ1	35.832	0.507	40.757	750.376	65.039	971.119	454141.335	418.086	7937.633	5.02	34.502
	AQ1	35.609	0.604	43.061	841.457	55.07	1046.817	459392.02	501.798	4962.261	4.865	73.778
	AQ1	38.691	0.485	45.858	944.475	53.608	905.669	458512.945	423.919	4499.737	5.196	41.534
	AQ1	34.153	0.487	42.171	875.354	80.621	973.774	453782.116	489.169	8831.796	4.91	49.474
	AS1**	3.623	0.327	62.33	352.96	344.373	519.278	461276.891	532.79	1810.836	2.45	327.394

	AS1	5.199	0.289	50.848	353.751	240.886	517.763	461276.158	486.165	2112.82	2.239	22.947
	AS1	4.858	0.554	52.592	372.719	209.459	494.589	461898.701	447.929	1736.979	2.615	36.692
	AS1	4.867	0.463	47.907	370.295	55.639	435.638	463391.702	279.048	1444.811	2.63	19.107
	AS1	4.798	0.219	51.949	338.801	36.851	433.218	462883.438	262.972	1109.737	2.49	23.078
	AS2**	5.56	0.243	34.471	467.054	44.199	366.348	458998.556	163.893	5693.398	5.561	53.246
	AS2	5.403	0.168	33.094	598.116	52.124	398.677	455016.932	195.657	7795.562	5.438	20.499
	AS2	7.348	0.303	29.563	408.486	23.421	363.673	444504.458	167.289	2178.948	5.441	16.362
	AS2	8.686	0.299	35.411	459.428	35.881	376.325	458632.941	201.95	3639.506	5.391	16.118
	AS2	5.464	0.309	38.689	437.805	38.271	340.853	460696.667	184.954	4721.052	5.384	29.214
	AS2	4.583	0.183	40.235	485.076	41.445	334.971	458209.364	176.007	5919.295	5.42	23.829
	AS2	4.179	0.37	37.507	322.724	37.121	350.918	460482.168	174.605	5098.158	4.736	21.575
	AS3**	3.502	0.536	57.787	287.375	24.19	286.087	464662.363	164.085	1676.709	2.997	16.987
	AS3	2.783	0.369	65.604	285.063	26.862	236.354	462955.061	148.268	3027.747	3.145	41.363
	AS3	3.338	0.381	66.335	352.281	19.19	335.579	465139.595	208.559	693.031	3.156	13.566
	AS3	3.878	0.566	63.188	351.141	27.5	322.326	464890.606	190.412	1127.425	2.938	10.258
	AS3	3.497	0.325	65.319	363.179	19.166	343.238	464817.747	193.006	701.4	3.046	14.95
	AS3	2.648	0.24	40.565	456.469	39.828	259.792	457322.684	138.897	8080.72	3.045	21.487
	AS3	3.024	0.147	42.149	292.008	29.278	290.698	461541.21	152.645	4568.363	2.933	22.053
	AS3	3.626		39.27	252.704	21.143	240.447	463521.248	132.318	2875.293	3.127	19.307
	AS3	2.522	0.209	42.38	299.904	29.224	272.219	460946.023	142.811	5191.104	3.024	20.505
	AS3	2.808	0.162	40.582	277.629	23.118	275.641	463065.891	146.098	3273.702	2.941	19.071
	WR-1**	13.989	1.012	36.062	532.974	95.769	919.243	460993.431	426.522	5687.619	12.652	45.397
	WR-1	13.817	0.91	39.02	479.239	119.929	996.156	455180.27	433.88	12664.597	11.506	85.879
	WR-1	15.27	0.989	31.888	703.22	130.012	1108.367	455923.289	510.605	10444.688	10.215	52.026
	WR-1	17.521	0.862	31.153	590.251	135.265	1288.865	457356.731	622.194	8794.282	9.861	73.499

	WR-1	12.942	0.658	33.683	495.261	98.529	918.924	461355.249	469.512	5089.465	9.73	45.453
	WR-1	10.395	0.903	34.11	363.855	56.421	633.225	464054.016	299.082	2480.454	9.159	24.247
	WR-1	15.911	0.631	32.195	586.055	131.524	1171.243	458613.858	581.214	7206.166	9.375	68.771
	WR-2**	9.998	0.264	55.142	379.381	98.123	538.469	463941.765	230.211	1937.979	4.942	29.463
	WR-2	11.21	0.369	65.735	407.344	121.505	673.609	464164.893	276.392	1193.975	5.069	42.113
	WR-2	10.588		63.118	483.062	102.11	687.165	463466.948	334.769	2234.032	5.371	51.005
	WR-3*	0.941	0.131	82.518	1064.305	90.739	242.53	460537.343	166.04	4106.012	4.816	17.896
	WR-3	0.865	0.43	83.991	1033.771	120.573	230.838	461007.547	150.45	3492.021	5.289	29.483
	WR-3	0.776	0.136	72.694	700.97	111.45	221.31	459130.713	151.078	5922.296	5.003	18.614
	WR-4*	5.636	0.32	49.4	150.107	25.601	287.269	465671.339	167.279	1034.872	2.965	14.38
	WR-4	6.09	0.588	47.786	160.852	26.364	251.944	465859.688	124.007	795.836	3.186	21.633
	WR-4	6.555	0.234	41.093	197.659	35.169	291.07	462904.765	139.567	2719.679	3.135	35.202
	WR-4	6.258	0.229	37.879	202.937	33.481	276.362	463774.074	138.06	2701.629	3.09	13.445
	WR-4	7.415	0.292	42.084	161.091	25.288	250.738	466032.552	119.974	759.099	3.22	17.324
	WR-5*	1.405	0.274	53.075	220.594	67.285	187.85	464198.728	123.332	1975.213	5.172	11.878
	WR-5	1.85	0.403	55.084	252.059	76.384	238.191	462718.496	145.243	3927.548	5.074	15.532
	WR-5	1.034		57.284	344.091	70.749	199.533	458441.128	131.601	7005.772	5.07	18.512
Wadi Shallala Chalk Formation	WMH-1**	5.753	0.464	12.412	130.061	47.571	465.812	465089.159	284.26	747.196	3.669	32.751
	WMH-1	5.069	0.21	11.367	125.404	32.827	427.9	465920.881	265.207	614.046	3.578	25.57
	WMH-1	4.205	0.357	11.953	142.395	35.938	453.943	465167.324	271.542	1150.849	3.718	28.07
	WMH-2**	5.045		12.114	126.985	35.685	381.676	466233.818	286.907	488.02	3.452	24.836
	WMH-2	5.317	0.438	11.223	135.751	44.976	391.476	465778.847	286.77	783.95	3.55	23.151

	WMH-2	4.733	0.661	11.292	127.568	32.33	431.84	466058.777	301.899	607.857	3.608	34.126
	WMH-3**	15.484	0.557	16.208	335.961	50.811	691.842	459470.122	342.453	3633.219	3.486	46.816
	WMH-3	19.428	0.432	17.604	393.305	54.891	798.603	460817.183	376.051	4600.429	3.393	43.848
	WMH-3	12.062	0.206	17.462	308.39	45.088	630.795	460049.976	297.449	3897.81	3.341	51.005
Secondary sources	WME-1*	18.648	0.221	23.142	386.224	77.858	793.396	460242.497	343.243	5032.9	2.908	46.16
	WME-1	17.151	0.109	24.295	424.653	92.335	924.013	457728.908	407.685	7715.108	2.881	45.209
	WME-1	13.81	0.259	26.346	578.464	140.845	750.086	449042.003	341.036	15979.075	2.95	44.304
	WME-1	15.342	0.26	22.418	475.041	95.765	769.058	455477.136	349.21	9833.842	2.905	59.748
	WME-2*	7.07	0.564	30.079	427.537	48.125	843.412	463629.919	378.529	1580.736	2.668	41.635
	WME-2	5.875	0.585	32.624	575.237	77.864	806.807	456993.878	375.61	8052.771	2.847	37.892
	WME-2	6.392	0.62	29.116	433.471	50.074	719.138	462131.981	371.484	3602.994	2.743	30.949
	WME-2	6.223	0.655	31.5	442.158	46.496	726.237	463132.908	401.224	2573.466	2.706	36.681
	WME-3*	8.083	0.273	30.287	404.712	95.226	1132.078	463900.982	558.988	1376.279	2.7	107.466
	WME-3	6.306	0.513	31.144	377.4	37.967	662.335	464487.76	324.168	1006.714	2.799	36.894
	WME-3	7.618	0.292	28.842	413.297	49.877	782.564	464236.433	407.842	1720.793	2.734	34.338
	WME-3	6.831	0.12	31.116	424.786	112.528	1015.821	461401.304	427.342	1374.198	2.647	54.643
	WMW-1*	4.756	0.291	43.508	406.64	31.425	471.453	462345.938	243.368	3115.101	4.905	36.301
	WMW-1	3.632	0.525	42.734	492.796	41.722	527.939	459976.653	303.979	5405.317	5.474	41.702
	WMW-1	5.314	0.131	43.118	469.544	42.544	559.808	458583.759	275.336	5440.49	5.665	68.839
	WMW-1	3.817		43.279	481.461	48.317	508.999	458227.417	245.614	7262.018	5.294	35.36
	WMW-1	5.191	0.574	33.046	472.833	36.623	634.599	462225.793	359.559	3329.28	5.057	44.213
	WMW-2*	4.002	0.253	38.873	397.316	33.19	554.746	463167.882	273.889	2803.645	5	35.152

	WMW-2	3.65	0.53	36.93	393.287	32.272	555.603	463201.127	273.133	2587.57	5.21	35.017
	WMW-2	5.011	0.659	42.724	342.199	23.206	526.567	464833.394	232.506	1084.682	5.036	27.492
	WMW-2	4.22	0.667	40.762	447.17	33.372	509.246	461356.767	282.678	3728.38	5.735	47.194
	WMW-2	3.318	0.129	38.554	379.75	26.465	536.213	464142.134	275.049	1647.45	5.293	95.716
	WMW-3*	8.012		33.084	223.172	29.833	236.912	462167.398	158.592	4211.506	5.966	24.551
	WMW-3	8.339	0.127	28.19	232.362	26.931	271.64	463348.113	167.363	2835.839	5.82	23.355
	WMW-3	9.264		33.034	248.161	33.822	268.85	463167.529	177.569	3088.226	5.768	20.126
	WMW-3	6.823		33.988	304.615	40.379	282.077	459586.15	194.047	6190.771	5.87	41.952
	WMW-3	8.844		29.964	268.109	36.453	200.214	460399.438	146.735	5474.373	5.648	22.969
	WB1**	11.956	0.341	41.835	662.908	47.208	765.197	463901.554	316.263	2402.199	6.088	46.047
	WB1	11.3	0.183	44.113	643.24	64.466	731.651	459390.387	316.405	6794.822	5.947	68.855
	WB1	10.971	0.413	43.267	741.838	59.323	776.206	461595.801	326.148	4571.229	5.431	54.286
	WB1	15.135	0.268	44.79	691.353	98.274	829.652	462424.762	442.338	3363.683	5.585	76.233
	WB1	11.831	0.403	41.986	508.749	81.618	753.443	463074.989	362.331	2819.407	5.078	69.169
	WB1	13.184	0.543	41.571	711.007	57.4	661.033	463785.447	308.586	2271.473	5.118	52.713
	WB2*	11.781	0.577	66.127	871.764	290.009	805.365	458671.976	407.867	5523.131	6.257	111.186
	WB2	12.797	0.201	64.026	833.163	243.524	669.466	461875.707	346.059	3372.471	6.235	73.974
	WB2	13.715	0.737	60.634	779.794	279.091	752.063	461613.166	350.323	3376.792	6.17	63.176
	WB2	11.643	0.247	68.184	852.326	313.579	758.615	457293.568	368.758	7047.767	5.76	54.319
	WB2	13.331	0.255	59.017	846.021	334.664	806.731	448546.782	369.769	8239.602	5.968	50.288
	WB2	12.328	0.53	61.143	887.079	368.043	832.289	454060.44	462.84	7443.219	5.317	107.763
	WB2	12.115	0.138	65.462	816.592	339.162	705.549	457720.336	372.469	5670.924	5.477	108.45
	WB2	12.715	0.724	68.498	981.96	356.694	786.291	453798.557	407.099	9505.365	5.358	64.839
	WB3*	11.556	0.514	70.064	848.255	409.39	765.876	458865.326	364.92	6227.414	2.779	45.531

	WB3	13.047	0.395	67.944	809.953	444.348	812.738	457885.154	378.683	7106.759	2.932	64.02
	WB3	12.723	0.354	61.686	811.231	408.563	777.116	458509.637	369.572	6480.771	2.89	58.871
	WB3	10.676	0.616	65.01	783.165	378.518	739.652	456352.842	350.107	5013.92	2.812	51.285
	WB3	11.736	0.471	63.383	747.177	459.592	753.744	455833.738	357.368	8628.135	3.043	80.549
	WG1**	18.018	0.529	19.741	583.94	199.511	664.268	463051.15	351.939	640.287	3.871	54.174
	WG1	16.581	0.312	19.761	411.389	278.609	599.145	462756.053	391.382	1355.989	3.872	48.386
	WG1	13.307	0.773	19.014	494.832	226.34	627.152	463209.599	324.49	963.986	3.709	78.377
	WG1	18.224	0.134	19.678	611.824	296.913	722.467	464187.983	376.105	949.603	3.635	46
	WG1	19.062	0.343	20.34	493.688	165.247	643.625	465290.944	358.279	536.66	3.808	38.215
	WG1	19.654	0.334	19.379	580.659	284.608	779.442	463713.92	455.211	562.526	3.575	35.985
	WG2*	17.369		32.786	346.302	386.045	404.611	458656	138.116	10066.35	5.411	43.402
	WG2	13.213		32.046	279.678	326.404	354.784	455200.6	105.905	15669.22	5.348	39.955
	WG2	15.672	0.221	31.763	295.72	347.278	425.39	456023	123.107	14675.34	5.375	124.954
	WG2	13.154		31.827	286.122	342.352	343.392	453001.4	106.606	18766.24	5.935	66.031
	WG2	14.584		32.423	302.071	326.178	391.874	457554.7	112.915	9516.968	5.238	90.12
	WG2-R*	4.41	2.665	20.034	531.694	72.037	899.787	462285.1	281.411	2761.402	5.773	50.736
	WG2-R	4.705	4.147	19.99	506.399	102.799	936.922	461910.2	260.792	3101.936	5.727	55.285
	WG2-R	5.055	2.826	21.426	551.853	120.833	935.967	458384.8	263.148	7080.894	5.9	67.304
	WG2-R	5.234	3.304	20.712	508.663	79.516	899.71	462661.1	244.183	2433.237	5.683	51.623
	WG2-R	5.221	3.762	21.662	470.438	103.528	814.132	463163.1	241.81	2149.71	5.537	70.769
	WG3*	15.376	0.168	18.131	379.824	137.132	735.032	463808.3	329.735	1921.801	5.546	75.451
	WG3	15.589		17.97	428.532	198.401	945.165	462814.8	449.81	1863.295	6.139	61.43
	WG3	15.219		18.584	444.657	148.587	702.336	460068.6	333.644	5070.305	6.164	45.198
	WG3	15.825	0.217	19.237	387.995	137.955	671.785	463439.5	341.434	2146.815	6.048	50.41

	WG3	15.478		22.435	397.339	183.504	784.024	461922.8	313.336	2867.821	5.449	88.65
	WRJ-1*	24.039	0.295	58.073	511.222	46.275	1209.098	464001	500.716	874.931	5.153	40.942
	WRJ-1	23.779	0.433	53.325	596.713	82.525	1471.166	458110.932	603.831	4742.961	5.322	87.257
	WRJ-1	29.416		46.859	564.786	67.737	1357.188	460917.02	567.024	1887.217	4.808	124.904
	WRJ-1	27.009	0.148	45.875	530.868	64.827	1400.717	460845.79	526.152	2538.212	5.044	85.066
	WRJ-1	17.315		54.738	479.158	49.365	1076.801	462857.708	391.069	1979.196	4.744	52.243
	WRJ-2*	25.601	0.144	15.68	517.769	105.752	1169.516	457193.222	502.238	2858.254	5.446	62.664
	WRJ-2	25.305	0.137	53.973	771.274	64.301	1210.268	461258.205	615.483	1509.013	5.226	125.008
	WRJ-2	27.831	0.268	53.642	620.76	72.962	1282.976	455421.594	601.615	1930.103	5.266	90.371
	WRJ-2	29.731	0.27	51.455	726.981	119.832	1942.119	458952.294	945.9	2626.474	5.393	175.468
	WRJ-2	23.987	0.144	19.373	354.438	92.438	1098.611	461703.029	459.554	2576.716	5.759	59.934
	WRJ-3*	29.044	0.241	46.455	596.932	55.213	1101.087	461168.78	558.334	2773.633	5.659	87.269
	WRJ-3	26.444	0.137	49.625	564.433	45.888	999.163	462827.067	508.457	1025.15	5.175	70.079
	WRJ-3	27.546	0.141	14.35	355.95	90.707	1007.597	461878.36	491.792	1330.69	5.249	68.856
	WRJ-3	21.686	0.162	19.889	340.546	110.437	1023.125	458101.995	467.909	2150.221	5.376	69.56
	WRJ-3	27.927	0.149	52.131	548.966	75.138	1078.476	462544.116	491.591	2201.317	5.328	81.044
	WU-1*	17.779		32.023	606.991	53.401	1128.328	461040.663	596.768	1170.945	5.986	106.948
	WU-1	20.108		30.27	625.004	45.235	1093.718	461050.658	577.474	1897.119	6.931	86.189
	WU-1	27.588	0.4	33.36	647.857	47.321	1153.665	461354.451	648.816	1145.124	6.623	81.784
	WU-1	27.017	0.2	34.746	722.369	53.992	1250.193	461115.132	670.397	2861.686	6.923	73.45
	WU-1	19.541	0.542	106.102	558.632	126.689	2479.16	453604.986	648.167	8005.97	5.645	102.968
	WU-2*	19.935	0.245	14.516	522.018	79.276	1678.129	459445.537	1007.006	3796.114	7.427	70.311
	WU-2	22.617	0.331	20.117	426.874	66.386	1462.972	461270.842	823.53	2481.273	6.796	79.685

	WU-2	19.614	0.388	17.779	439.609	80.054	1532.088	458936.298	846.44	4557.512	6.637	175.775
	WU-2	15.374	0.588	17.146	441.973	70.059	1527.467	460707.419	827.031	3435.736	6.596	62.95
	WU-2	18.17	0.303	18.458	512.868	112.325	1912.701	457335.281	1064.861	6067.37	6.955	70.454
	WU-3*	25.246		28.038	571.211	53.052	1184.614	460094.213	578.69	1383.535	5.608	127.748
	WU-3	19.075	0.247	32.688	538.945	42.462	1013.584	462406.083	497.893	998.41	5.55	114.435
	WU-3	20.256		36.507	556.611	39.959	1052.204	462687.24	513.064	923.606	6.111	59.429
	WU-3	19.058	0.402	34.444	605.575	45.85	1060.594	461163.534	562.413	1494.489	5.979	65.361
	WU-3	18.159	0.281	29.853	627.326	48.828	1167.809	463140.007	596.797	1159.249	5.832	114.979
**Precision (1 sigma NIST 613)		9%	3%	13%	13%	1%	2%	3%	4%	2%	2%	6%
Limit of detection (ppm)		0.008	0.001	5.85	27.7	0.064	0.487	36699.0957	121.8	64.548	0.306	0.096
*Precision Test on NIST 613 glass	NIST 613	48.86	32.48	56.39	118776.18	53.68	9075.89	331682.57	77.29	78113.48	36.59	34.92
	NIST 613	51.53	36.17	54.15	126355.56	56.18	9116.95	328666.39	76.79	75466.32	36.28	39.16
	NIST 613	51.20	32.39	51.69	120800.38	49.96	8853.61	332377.48	77.25	75523.48	33.98	35.77
	NIST 613	49.09	31.03	65.57	124403.40	54.03	8877.39	330792.64	83.99	74265.45	34.59	34.43
	NIST 613	47.99	32.98	44.88	112774.45	51.24	8760.94	341956.75	68.82	69186.25	31.06	34.36
	NIST 613	45.86	35.74	42.13	116755.66	52.42	8902.00	336223.63	66.34	73798.90	32.67	36.05
	NIST 613	44.21	33.71	43.36	116016.49	51.94	9278.92	334148.11	71.78	77009.20	35.32	37.82
	NIST 613	43.75	28.61	38.41	116047.20	52.78	9173.81	334596.51	69.16	76559.12	34.30	37.55
	NIST 613	43.92	31.92	38.20	112940.55	54.44	9414.58	334465.03	68.02	79404.35	34.61	37.89
	NIST 613	44.58	31.95	41.84	117729.65	54.06	9502.65	330495.52	72.41	80685.42	35.30	37.41
	NIST 613	44.10	34.76	38.70	112334.10	55.93	9761.20	333315.08	67.08	81223.00	35.44	39.56
	average	46.83	32.88	46.85	117721.24	53.33	9156.18	333519.97	72.63	76475.91	34.56	36.81
	rsd	0.06	0.07	0.19	0.04	0.04	0.03	0.01	0.08	0.05	0.05	0.05
	Preferred values	40.2	37.5	34.3	101633.753	68	10743.3111	337042.603	62.3	85048.5021	39.9	44

Table 2/4 (sample ablated by * line raster; ** immobile laser)													
Formation	Source	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	Rb	Sr
Umm Rijam Chert-Limestone Formation	35Q-1*	9.124	17.415	3.998	106.321	0.093	3.824	26.002	18.06	0.608	1.295	0.443	13.603
	35Q-1	11.388	17.66	3.303	102.056	0.106	3.842	20.838	16.781	0.861	1.203	0.3	38.81
	35Q-1	11.116	19.066	14.808	129.662	0.191	5.966	22.133	16.037	0.66	1.156	0.422	18.824
	35Q-1	9.039	16.498	3.665	79.995	0.143	3.738	19.988	13.221	0.73	1.241	0.461	25.572
	35Q-1	10.876	16.445	7.42	132.426	0.114	6.139	21.914	15.855	0.746	1.323	0.577	16.291
	35Q-2*	12.101	25.368	2.382	99.484	0.085	5.86	23.968	12.621	3.018	1.073	0.636	57.614
	35Q-2	17.079	31.933	5.387	248.54	0.089	7.23	25.247	16.963	1.189	0.72	0.753	38.837
	35Q-2	74.978	40.969	14.456	1082.395	0.244	16.037	32.678	39.202	1.703	0.782	0.539	34.448
	35Q-2	8.743	13.661	3.691	64.855	0.086	2.668	19.552	9.153	0.74	0.961	0.353	17.992
	35Q-2	146.524	42.369	7.893	2116.093	0.114	24.829	35.116	57.586	1.005	1.373	0.449	38.459
	35Q-3*	16.033	17.519	1.531	320.098	0.067	6.784	32.641	24.767	0.447	1.295	0.262	7.05
	35Q-3	12.917	15.002	1.179	238.433		4.15	34.851	22.511	0.644	1.33	0.469	18.752
	35Q-3	10.952	11.721	0.986	199.788	0.061	5.299	38.582	22.55	0.585	0.821	0.27	9.827
	35Q-3	15.549	10.116	1.547	348.848	0.051	6.003	37.708	25.613	0.54	1.143	0.255	11.575
	35Q-3	38.782	30.508	2.559	712.902	0.323	36.364	43.182	30.625	0.559	1.25	0.36	13.248
	40X-1**	228.656	181.308	9.132	1735.144	0.356	81.62	40.38	139.747	1.491	1.078	1.187	56.503
	40X-1	155.391	47.609		150.859		17.632	5.808	18.675		0.605		28.125
	40X-1	198.178	126.52	4.387	1184.899	0.153	54.331	25.002	98.069	1.103	0.982	1.178	57.043
	40X-1	171.41	63.218	1.665	530.6	0.131	26.93	13.898	51.596	0.942	0.76	0.771	56.441
	40X-1	142.61	30.693		108.588	0.024	7.132	7.82	22.023	0.665	0.727	0.726	53.24
	40X-2**	177.329	71.466	1.82	394.665	0.088	14.006	28.063	44.167	3.604	0.445	1.477	149.044
	40X-2	174.74	58.012		384.608	0.075	11.245	24.057	40.695	2.849	0.575	0.684	119.519

	40X-2	189.836	65.953	1.952	590.329	0.105	19.555	28.798	53.079	2.898	0.593	0.973	137.917
	40X-3*	42.403	19.21	0.364	54.468	0.025	2.705	19.779	43.35	0.447	0.555	0.354	44.981
	40X-3	46.183	31.502	1.172	145.688	0.039	6.154	13.809	41.888	0.674	0.624	0.514	66.724
	40X-3	44.939	29.465	0.591	116.475	0.028	3.826	49.701	44.229	0.463	0.595	0.495	36.468
	40X-4*	96.024	21.379	1.977	145.62	0.084	4.941	10.187	36.836	0.474	0.531	0.26	100.405
	40X-4	96.662	24.231	5.855	164.352	0.075	3.488	7.2	33.76	0.371	0.628	0.27	40.85
	40X-4	96.189	21.776	1.202	181.546	0.143	6.871	6.63	37.235	0.318	0.445	0.308	46.796
	40X-5*	99	22.534	1.596	499.383	0.113	12.192	14.137	42.338	0.441	0.558	0.608	57.711
	40X-5	75.063	19.317	0.775	221.32	0.063	5.609	9.911	35.508	0.544	0.679	0.701	52.393
	40X-5	82.301	16.204	0.713	207.722	0.069	5.945	13.189	37.558	0.637	0.716	0.676	65.823
	40X-6*	56	17.478	1.155	163.336	0.044	3.896	15.581	30.528	0.378	0.747	0.55	36.497
	40X-6	75.869	18.508	1.333	381.356	0.169	8.614	16.663	42.209	0.427	0.889	0.421	33.479
	40X-6	58.758	22.404	0.728	195.503	0.061	7.362	14.329	36.894	0.427	0.325	0.453	42.082
	40X-7*	70.677	38.43	0.817	118.573	0.041	3.371	20.195	79.037	0.496	0.844	0.728	60.99
	40X-7	89.233	43.133	0.924	494.69	0.087	10.295	16.324	64.674	0.345	0.843	0.565	37.3
	40X-7	108.304	40.439	0.683	609.25	0.078	11.62	20.198	67.761	0.385	0.872	0.472	43.066
	40X-8*	21.08	34.26	1.31	212.93	0.08	7.16	18.75	22.86	0.43	2.03	0.47	79.45
	40X-8	14.23	24.79	0.73	108.62	0.04	5.58	13.01	17.59	0.34	1.97	0.42	57.05
	40X-8	31.17	60.83	1.93	408.07	0.06	13.22	23.9	35.52	0.4	2.37	0.42	52.22
	40X-9*	42.908	35.147	1.298	382.903		10.196	12.55	50.015	0.314	1.065	0.661	36.951
	40X-9	31.304	15.222	0.566	81.878		1.968	15.228	30.816	0.328	1.1	1.21	27.029

	40X-9	32.86	17.202	0.627	139.342		3.853	11.411	32.677	0.284	0.943	0.483	22.368
	40X-10*	37.933	20.673	0.4	313.001	0.036	5.854	18.38	47.965	0.345	0.616	0.736	49.853
	40X-10	46.51	20.623	0.489	348.784	0.043	8.71	18.874	66.219	0.355	0.776	0.564	53.152
	40X-10	42.414	16.977	0.552	286.254		5.887	22.905	53.8	0.333	0.817	0.517	58.816
	40X-11*	27.763	21.098	0.638	143.387		4.526	10.262	28.553	0.547	1.539	0.651	38.29
	40X-11	30.279	18.455	0.471	123.673		3.717	13.17	32.244	0.434	1.409	0.355	29.301
	40X-11	33.377	32.671	0.919	212.736	0.028	7.032	12.178	32.438	0.464	1.369	0.472	44.278
	40X-12*	60.284	74.616	2.92	711.024	0.061	26.881	31.017	76.235	0.525	0.699	0.725	99.242
	40X-12	36.839	28.471	0.681	235.248		8.354	17.753	47.894	0.431	0.482	0.499	36.957
	40X-12	38.07	38.051	0.782	397.927		10.685	21.354	48.284	0.403	0.758	0.706	48.384
	40X-13*	45.567	51.101	3.143	618.347	0.081	15.192	14.365	50.279	0.446	1.15	0.469	48.877
	40X-13	26.386	20.751	2.076	183.418	0.036	5.215	9.612	34.039	0.363	1.096	0.744	31.081
	40X-13	32.943	30.084	1.778	324.569	0.062	7.755	14.575	40.032	0.425	1.189	0.818	35.048
	AQ1**	51.077	22.287		516.805	0.085	4.756	76.985	8.136	146.287	0.435	0.516	243.699
	AQ1	99.485	25.506		861.423	0.298	9.057	79.911	18.085	228.375	0.465	0.48	350.761
	AQ1	76.626	18.759		654.325	0.186	5.963	67.184	9.495	197.099	0.462	0.493	230.965
	AQ1	67.598	26.188		674.661	0.305	10.137	65.473	11.634	30.542	0.435	0.67	59.304
	AQ1	76.006	23.465	1.781	970.899	0.138	18.83	56.087	8.525	90.512	0.495	0.496	113.378
	AQ1	67.196	32.773	1.976	918.63	0.053	6.273	39.498	9.658	137.325	0.526	0.469	225.034
	AS1**	112.005	20.416	12.855	655.43	0.767	7.851	9.872	15.77	13.159	0.505	1.502	47.944
	AS1	104.126	16.758	5.131	628.257	0.574	6.564	9.472	19.095	12.507	0.503	0.858	51.484
	AS1	82.074	14.802	6.315	554.371	0.257	5.915	6.882	20.2	6.456	0.646	0.848	42.854

	AS1	61.559	10.528	1.503	289.383	0.319	3.083	5.746	16.225	4.72	0.464	0.402	32.49
	AS1	135.481	23.066	1.595	480.233	0.578	8.406	13.321	16.325	9.258	0.497	0.449	46.373
	AS2**	22.729	15.766		310.562	0.164	5.621	12.069	8.765	135.753	0.454	0.231	158.098
	AS2	17.889	16.789		172.782	0.224	5.446	18.025	15.294	218.069	0.409	0.287	245.354
	AS2	19.704	17.341		258.569	1.237	5.908	20.654	18.37	1318.403	0.486	0.176	597.157
	AS2	21.745	15.707		354.335	0.126	5.484	19.881	11.233	231.616	0.536	0.187	195.072
	AS2	19.4	15.833		142.345	0.102	4.911	12.345	23.248	71.3	0.573	0.248	95.029
	AS2	18.132	16.403		125.545	0.104	4.922	10.647	18.861	147.97	0.561	0.192	180.557
	AS2	21.734	16.154		358.118	0.726	11.114	13.041	4.99	51.204	0.519	0.2	84.57
	AS3**	31.424	7.732		106.261	0.043	2.011	7.934	8.769	2.125	0.47	0.201	30.57
	AS3	72.828	16.026	0.41	205.012	0.06	4.336	9.02	12.933	3.959	0.626	0.168	46.515
	AS3	42.512	6.028		229.504	0.194	3.665	13.767	6.975	5.911	0.333	0.219	30.022
	AS3	39.956	5.262		142.665	0.073	2.507	12.172	7.545	5.171	0.322	0.175	33.629
	AS3	121.202	11.313	0.255	354.709	0.235	8.5	16.329	14.698	7.273	0.454	0.209	33.502
	AS3	12.427	11.784	0.682	70.027	0.099	1.993	12.105	8.174	4.026	0.533	0.187	75.204
	AS3	17.362	17.451	0.848	161.686	0.084	3.533	14.418	5.674	1.703	0.512	0.247	34.914
	AS3	18.692	18.367	0.433	95.68	0.081	3.931	14.137	5.225	1.247	0.612	0.151	24.65
	AS3	9.46	8.522	0.521	59.327	0.041	39.331	11.931	5.435	1.056	0.45	0.156	36.612
	AS3	7.224	7.45	0.399	53.202	0.042	1.791	10.216	5.829	1.579	0.504	0.188	25.339
	WR-1**	29.336	55.694	5.674	345.718	0.12	18.862	13.322	23.627	1.679	0.924	0.804	36.516
	WR-1	29.262	50.244	7.909	352.931	0.151	17.343	13.556	20.228	4.292	1.034	0.835	90.236
	WR-1	29.715	56.927	5.231	367.911	0.112	15.838	14.764	21.382	2.025	0.872	1.012	60.818
	WR-1	25.946	82.467	4.114	223.93	0.117	12.998	11.346	17.197	1.992	1.007	1.483	53.75
	WR-1	23.843	62.48	4.698	212.591	0.068	13.663	9.67	16.6	1.56	0.799	1.029	31.36
	WR-1	38.768	31.801	10.018	572.537	0.142	20.333	13.403	26.525	1.164	0.667	0.275	18.198

	WR-1	37.077	90.298	9.765	398.474	0.172	17.807	15.815	22.356	2.097	1.162	1.268	43.137
	WR-2**	28.129	12.412	2.369	381.062		12.861	17.775	32.307	0.471	0.307	0.318	16.751
	WR-2	41.958	218.298	7.398	712.832	0.593	18.589	21.713	54.741	0.532	0.599	0.664	9.324
	WR-2	8.707	9.967	0.924	97.484	0.254	3.769	15.603	17.676	0.496	0.403	0.707	16.753
	WR-3*	29.866	12.223	28.465	166.512	0.375	4.119	29.812	24.166	0.487	0.371	0.253	168.555
	WR-3	90.609	49.092	48.712	584.368	0.55	10.263	44.086	40.455	0.519		0.173	101.179
	WR-3	49.17	26.83	38.867	303.646	0.275	6.196	33.453	31.336	0.467	0.357	0.296	104.638
	WR-4*	7.672	6.944	1.733	89.394	0.038	2.386	14.96	17.998	0.684	0.287	0.307	9.723
	WR-4	18.145	15.122	2.852	245.562	0.069	6.609	30.12	27.719	0.381	0.366	0.185	5.812
	WR-4	100.271	59.134	9.711	1582.848	0.242	33.751	46.885	74.723	0.502	0.369	0.212	14.331
	WR-4	12.386	10.145	2.455	163.884	0.067	3.796	46.404	30.612	0.45	0.315	0.183	17.62
	WR-4	6.52	4.914	2.681	68.6	0.055	1.95	40.253	27.203	0.392	0.284	0.176	5.584
	WR-5*	26.468	8.935	19.934	193.652	0.282	5.689	21.468	20.722	0.37	0.236	0.161	25.976
	WR-5	16.785	6.087	13.579	72.938		2.069	19.91	20.845	0.648		0.166	32.623
	WR-5	19.969	10.809	10.172	121.185	0.067	3.458	16.769	18.326	0.774	0.245	0.188	59.891
Wadi Shallala Chalk Formation	WMH-1**	33.148	73.01	5.811	1079.422	0.031	29.96	20.539	51.876	0.603	0.549	0.566	7.01
	WMH-1	9.715	32.634	1.826	277.027		8.892	13.909	13.392	0.397	0.34	0.457	5.645
	WMH-1	13.606	39.314	3.018	432.585	0.043	12.122	15.63	19.255	0.381	0.535	0.503	8.112
	WMH-2**	5.29	21.325	5.575	82.875		3.465	11.198	7.516	0.377	0.341	0.468	4.636
	WMH-2	9.026	72.251	0.711	203.688	0.024	6.655	14.681	12.966	0.399	0.347	0.605	6.124
	WMH-2	7.191	27.527	0.579	114.171		4.586	11.341	9.216	0.377	0.327	0.646	4.726

	WMH-3**	23.279	47.273	1.609	299.425	0.101	4.762	18.808	12.079	35.811	0.9	0.538	264.969
	WMH-3	12.411	36.086	1.018	87.007	0.03	1.839	14.703	6.185	4.655	0.845	0.518	63.274
	WMH-3	86.65	48.667	15.145	1277.37	0.275	23.503	29.754	55.462	15.866	1.206	0.342	121.856
Secondary sources	WME-1*	59.35	68.566	5.085	576.731	0.166	9.434	15.241	28.483	2.374	0.954	0.979	49.756
	WME-1	46.085	48.872	3.961	276.117	0.113	4.348	11.007	17.404	2.096	0.962	1.302	60.795
	WME-1	42.465	39.45	3.902	222.101	0.122	4.281	13.514	16.125	2.128	1.1	0.995	115.611
	WME-1	36.94	32.774	3.666	125.65	0.079	2.578	14.925	12.394	1.843	1.135	0.92	72.483
	WME-2*	51.784	21.38	2.512	660.962	0.048	11.427	14.859	19.318	3.47	1.409	0.873	34.468
	WME-2	36.759	22.844	2.022	359.787	0.038	9.733	16.18	16.317	1.187	1.157	0.821	59.703
	WME-2	32.24	17.373	1.425	243.229		6.392	17.94	14.91	0.988	1.048	0.62	28.687
	WME-2	40.971	21.109	1.699	429.823	0.029	8.359	13.833	15.602	0.998	1.064	0.71	22.85
	WME-3*	35.698	32.108	1.84	390.266	0.058	12.931	18.361	23.219	1.199	1.129	1.881	15.181
	WME-3	82.256	23.21	3.313	949.124	0.027	17.401	15.646	29.922	1.112	1.063	0.552	20.339
	WME-3	20.718	19.137	1.149	128.741	0.042	5.24	11.895	11.77	1.093	0.976	0.816	17.486
	WME-3	329.814	44.427	12.894	3935.888	0.171	66.554	27.712	81.643	1.308	1.547	0.872	18.836
	WMW-1*	43.678	15.982	1.84	696.209		21.001	28.011	42.976	1.203	0.527	0.243	20.406
	WMW-1	29.662	15.668	1.116	374.551	0.059	7.804	24.226	22.419	0.981	0.651	0.495	31.302
	WMW-1	50.208	30.024	3.361	1004.03	0.226	19.539	21.515	41.845	18.107	0.833	0.428	70.202
	WMW-1	17.732	19.218	0.879	179.691	0.04	5.717	16.734	15.056	0.852	0.772	0.322	45.972
	WMW-1	21.385	9.253	1.086	291.232		4.88	18.98	12.529	0.92	0.451	0.489	21.546
	WMW-2*	10.197	10.541	0.488	91.533		3.121	20.267	11.255	0.943	0.374	0.481	18.811
	WMW-2	25.008	13.52	0.856	322.574		10.115	21.971	22.3	0.926	0.628	0.439	17.414
	WMW-2	16.281	23.758	1.666	342.761	0.162	8.043	21.463	18.428	0.958	0.432	0.264	9.568

	WMW-2	50.93	23.332	2.164	942.844	0.052	29.281	26.966	50.384	1.52	0.392	0.289	28.269
	WMW-2	33.576	9.778	1.389	479.386	0.063	10.271	22.394	22.462	1.679		0.444	13.835
	WMW-3*	24.895	31.896	0.755	149.382		5.262	27.593	19.684	0.991	0.729	0.277	31.068
	WMW-3	22.906	26.49	1.052	161.259		5.39	28.313	16.996	0.85	0.457	0.238	24.434
	WMW-3	14.704	20.502	0.672	82.283		4.585	31.554	18.763	0.611	0.701	0.256	24.707
	WMW-3	23.788	33.727	1.132	119.472	0.048	6.098	27.982	18.681	1.096	0.995	0.343	44.404
	WMW-3	34.864	39.169	1.288	321.46	0.055	8.002	20.988	19.221	0.96	0.764	0.232	43.339
	WB1**	42.307	39.739		398.238	0.029	7.566	25.828	19.966	1.775	0.834	0.546	24.163
	WB1	42.673	49.454		405.012	0.053	8.697	57.404	20.367	1.939	0.72	0.497	51.521
	WB1	29.63	36.128		265.598	0.048	7.627	29.937	16.944	1.63	0.649	0.609	39.11
	WB1	25.775	44.906	3.251	347.502	0.122	10.101	26.884	20.054	1.857	0.707	0.987	30.329
	WB1	35.668	54.36	2.235	492.453	0.086	13.3	28.106	24.429	1.533	0.701	0.867	26.351
	WB1	17.248	26.713		221.216	0.093	6.693	19.059	12.591	3.6	0.781	0.491	23.478
	WB2*	21.486	43.03	1.366	398.151		10.302	47.587	19.143	0.87	0.512	0.75	39.122
	WB2	15.758	31.11	0.971	313.807		7.585	34.558	12.179	1.074	0.565	0.513	21.527
	WB2	10.832	26.403	0.655	176.135		5.138	33.537	9.185	0.669	0.503	0.587	24.738
	WB2	29.571	51.558	1.956	630.198	0.049	12.742	49.912	26.709	12.256	0.752	0.566	82.654
	WB2	12.925	39.863	0.822	147.033		4.275	33.165	10.769	184.169	0.363	0.628	546.46
	WB2	199.414	202.805	14.548	3991.104	0.222	74.824	130.925	134.456	0.775	0.639	0.835	48.869
	WB2	42.012	63.363	2.176	922.465	0.054	19.613	49.518	30.103	19.54	0.623	0.573	67.402
	WB2	22.208	42.097	1.188	391.175	0.043	10.036	36.905	16.211	7.043	0.468	0.611	87.827
	WB3*	11.978	26.899	1.206	203.064	0.035	4.816	15.623	10.221	0.564	0.369	0.509	43.047
	WB3	12.68	28.632	0.912	213.66	0.023	5.586	16.399	8.859	0.747	0.414	0.599	49.496
	WB3	12.611	29.093	1.155	209.713		5.403	16.594	9.736	0.602	0.316	0.52	43.602

	WB3	12.38	28.062	0.649	201.873		5.131	14.136	9.22	40.098	0.335	0.489	211.189
	WB3	17.203	36.896	1.08	340.048		7.374	19.391	14.979	14.376	0.414	0.563	116.179
	WG1**	84.54	51.918	24.543	1556.906	0.135	29.368	27.833	70.88	62.234	0.287	0.506	41.264
	WG1	38.492	22.663	6.456	498.417	0.062	11.011	18.671	24.997	90.862	0.284	0.446	61.147
	WG1	77.829	29.055	20.478	1381.783	0.195	23.518	30.791	68.755	49.277	0.36	0.349	44.653
	WG1	39.404	23.61	10.362	553.949	0.05	13.127	20.795	28.748	16.97	0.264	0.687	21.35
	WG1	22.958	15.456	6.805	244.766	0.048	7.228	12.025	15.373	6.695		0.557	18.387
	WG1	20.615	14.181	4.015	216.562	0.025	6.013	13.59	13.263	65.628	0.136	0.765	52.199
	WG2*	14.306	19.687	2.997	397.73		5.695	32.932	18.56	0.412		0.245	26.085
	WG2	19.434	18.557	4.001	612.504	0.054	7.426	30.963	19.498	0.333	0.293	0.143	37.627
	WG2	6.497	6.653	1.361	74.4		1.936	28.803	10.315	0.39	0.419	0.257	34.898
	WG2	21.165	27.334	4.718	805.843		13.751	32.116	17.698	0.315	0.416	0.183	42.075
	WG2	54.457	46.673	7.837	1732.906	0.099	17.059	40.29	34.463	0.457	0.312	0.232	29.141
	WG2-R*	28.968	16.009	8.478	625.394		4.65	22.714	57.946	3.392	1.333	0.954	26.223
	WG2-R	35.511	24.291	18.373	928.096	0.09	10.168	27.055	60.766	2.152	1.326	1	25.27
	WG2-R	36.813	25.823	20.097	853.954	0.126	9.779	25.315	59.851	1.67	1.527	0.763	39.728
	WG2-R	36.446	24.343	15.892	855.121	0.091	9.437	24.611	59.514	1.599	1.682	0.725	22.174
	WG2-R	32.682	19.791	8.017	689.467	0.072	7.595	23.528	60.871	1.203	1.878	0.919	19.67
	WG3*	6.02	13.33	0.394	148.965	0.045	4.952	12.679	8.926	2.651	0.317	0.568	19.977
	WG3	20.327	56.106	1.117	722.967	0.077	16.598	20.811	26.198	9.6	0.555	1.345	28.728
	WG3	17.611	22.05	0.741	492.416		7.866	21.27	14.872	1.77	0.562	0.627	38.466
	WG3	6.275	13.958	0.519	153.931	0.053	5	15.881	9.207	2.812	0.301	0.62	22.38
	WG3	32.221	55.662	0.916	1223.263	0.099	20.69	18.879	34.357	2.07	0.529	0.666	23.523

	WRJ-1*	46.154	26.437	3.673	375.982	0.073	8.195	23.967	18.348	2.483		2.1	17.783
	WRJ-1	96.789	45.936	8.048	864.989	0.078	12.92	51.781	39.908	11.227	0.426	1.674	142.442
	WRJ-1	74.698	53.287	10.048	748.784	0.084	10.688	27.22	27.958	22.904	0.39	1.371	113.741
	WRJ-1	110.319	59.538	20.391	1540.18	0.058	17.602	34.262	52.432	14.105	0.502	1.273	100.373
	WRJ-1	55.634	30.82	6.866	598.437	0.044	9.858	26.426	23.881	1.178	0.282	0.759	17.786
	WRJ-2*	199.941	107.212	10.243	1017.63	0.079	23.761	50.019	83.306	58.059	2.592	1.691	260.967
	WRJ-2	97.614	55.946	15.231	1318.08	0.101	15.959	23.401	34.795	15.914		1.197	133.509
	WRJ-2	100.359	52.721	12.004	1225.818	0.053	17.539	32.012	38.261	112.441	0.363	1.326	226.259
	WRJ-2	120.035	83.676	12.613	1187.203	0.067	18.736	48.898	48.817	25.608	0.537	3.128	114.202
	WRJ-2	152.119	84.065	6.231	688.945	0.128	16.005	46.446	61.206	5.945	1.34	1.145	40.913
	WRJ-3*	103.309	52.967	6.53	764.367	0.047	13.149	26.437	31.818	3.902		1.246	34.351
	WRJ-3	90.886	38.511	8.035	923.962	0.041	12.379	20.453	27.167	11.272	0.234	0.947	42.755
	WRJ-3	176.595	89.69	6.145	688.349	0.118	21.981	65.173	72.092	28.476	1.212	1.33	110.262
	WRJ-3	162.815	97.665	4.906	478.023	0.12	17.584	68.714	64.149	61.601	0.818	1.498	470.079
	WRJ-3	99.584	52.592	7.386	774.645	0.075	12.282	25.548	30.927	1.293	0.351	0.92	17.996
	WU-1*	161.682	83.151	626.465	3033.073	4.166	62.181	47.066	144.701	7.29	0.498	1.317	26.078
	WU-1	55.666	35.095	74.571	634.135	0.555	10.705	20.392	36.97	38.055	0.307	1.071	100.804
	WU-1	37.917	30.538	20.356	727.825	0.113	7.782	28.796	38.468	36.534		1.371	39.471
	WU-1	20.264	26.443	4.453	231.254	0.049	3.977	28.79	19.35	12.682	0.378	1.537	35.722
	WU-1	39.364	50.018	60.282	746.743	0.927	13.59	216.377	51.429	62.65	0.404	1.924	189.165
	WU-2*	71.007	46.661	2.408	1171.623		25.007	42.069	46.335	1.134	0.964	1.998	26.998
	WU-2	78.426	49.269	2.263	1283.033	0.049	30.144	56.459	56.368	0.934	1.505	1.335	18.551
	WU-2	44.755	72.95	2.706	659.215		20.05	32.915	42.974	4.798	1.059	1.812	41.39
	WU-2	36.484	37.456	1.421	549.572		13.527	26.656	24.617	0.993	0.871	1.793	24.335

	WU-2	31.976	40.236	1.22	452.376		13.028	40.768	27.353	1.258	0.95	2.357	41.57
	WU-3*	48.619	38.62	141.183	1092.661	1.316	13.99	23.087	47.386	72.219		1.314	298.49
	WU-3	45.282	35.749	195.351	811.436	2.165	16.106	24.273	44.557	36.062		1.055	97.622
	WU-3	46.953	32.168	137.482	785.879	1.035	12.514	21.336	43.322	31.455	0.296	1.032	71.289
	WU-3	68.146	38.574	252.669	1220.98	1.681	18.692	26.94	67.499	33.912		1.056	104.148
	WU-3	48.699	38.757	128.835	874.928	0.912	13.855	22.372	43.192	2.049	0.466	1.419	11.865
**Precision (1 sigma NIST 613)		1%	3%	3%	4%	2%	2%	5%	4%	5%	2%	3%	4%
Limit of detection (ppm)		0.036	0.375	1.646	21.133	0.004	0.080	0.037	0.020	0.006	0.108	0.0127	0.0007
*Precision Test on NIST 613 glass	NIST 613	45.98	45.15	38.11	65.63	35.48	40.22	42.62	39.75	41.47	48.40	38.01	72.98
	NIST 613	46.78	43.13	39.45	66.80	37.02	44.74	44.08	40.64	40.94	47.98	39.83	71.87
	NIST 613	45.20	41.09	36.30	58.79	35.84	43.84	39.20	41.15	41.73	47.41	38.41	71.36
	NIST 613	43.11	41.40	36.78	66.34	35.92	43.54	42.19	38.62	40.79	49.12	41.99	71.86
	NIST 613	40.41	39.52	35.89	64.07	34.30	40.70	39.69	38.20	37.06	39.81	33.34	62.52
	NIST 613	41.79	39.98	36.90	67.01	37.38	41.77	39.71	40.47	39.10	45.04	36.05	69.65
	NIST 613	44.47	40.32	39.08	65.63	37.64	42.88	41.01	43.94	40.95	47.16	39.00	75.19
	NIST 613	43.09	39.73	37.89	65.92	37.48	42.28	39.06	41.11	40.51	45.78	37.62	72.75
	NIST 613	42.16	39.28	38.75	63.46	36.08	42.15	38.58	43.41	39.08	45.28	37.09	75.65
	NIST 613	43.10	41.10	39.03	62.98	36.95	42.48	39.05	42.52	42.28	46.99	37.68	75.82
	NIST 613	43.23	39.79	38.68	62.80	36.33	42.32	38.32	41.62	39.66	45.06	37.73	77.36
	average	43.57	40.96	37.90	64.49	36.40	42.45	40.32	41.04	40.32	46.19	37.89	72.45
	rsd	0.04	0.04	0.03	0.04	0.03	0.03	0.05	0.04	0.04	0.05	0.06	0.06
	Preferred values	38.8	36.4	38.7	51	35.5	38.8	37.8	39.1	36.9	36.1	31.4	78.4

Table 3/4 (sample ablated by * line raster; ** immobile laser)														
Formation	Source	Y	Zr	Nb	Ag	Sn	Sb	Ba	La	Ce	Pr	Nd	Sm	Eu
Umm Rijam Chert-Limestone Formation	35Q-1*	2.043	4.411	0.353	3.078	0.118	0.036	30.132	0.806	0.333	0.125	0.404	0.096	
	35Q-1	6.858	5.041	0.328	3.499	0.196	0.097	51.94	2.495	0.929	0.347	1.423	0.293	0.071
	35Q-1	2.933	4.548	0.332	3.549	0.127	0.137	39.299	1.081	0.536	0.187	0.616	0.143	0.032
	35Q-1	4.412	4.862	0.35	3.726	0.148	0.059	45.584	1.529	0.841	0.257	1.047	0.258	0.062
	35Q-1	2.872	4.932	0.268	4.291	0.092	0.093	43.299	1.093	0.576	0.165	0.563	0.091	0.034
	35Q-2*	5.366	3.815	0.252	4.682	0.163	0.053	243.623	1.706	0.865	0.264	1.319	0.213	0.08
	35Q-2	5.081	7.306	0.253	4.735	0.132	0.149	81.01	1.825	0.968	0.281	1.283	0.134	0.051
	35Q-2	3.199	4.869	0.237	3.888	0.125	0.503	147.21	1.071	0.623	0.199	0.672	0.085	
	35Q-2	2.068	3.774	0.188	2.499	0.16	0.068	48.505	0.67	0.308	0.095	0.301	0.069	
	35Q-2	4.723	6.637	0.174	3.407	0.189	1.022	77.821	1.644	0.696	0.201	0.925	0.11	0.046
	35Q-3*	1.385	2.877	0.266	0.802	0.27	0.2	12.822	0.368	0.311	0.069	0.288	0.064	
	35Q-3	3.655	3.345	0.291	1.02	0.276	0.148	23.431	1.275	0.663	0.182	0.731	0.114	0.069
	35Q-3	1.602	3.275	0.323	0.776	0.209	0.116	15.98	0.606	0.383	0.098	0.519		
	35Q-3	2.068	3.186	0.303	0.717	0.189	0.213	15.04	0.629	0.452	0.13	0.426	0.07	
	35Q-3	2.188	3.652	0.356	1.866	0.244	0.35	23.041	0.761	0.482	0.166	0.482	0.12	0.037
	40X-1**	0.539	7.884	0.527	10.786	1.564	0.155	10.216	0.637	1.564	0.155	0.494	0.071	0.018
	40X-1	0.963	8.5	0.448	10.271		0.043		0.328		0.043	0.216	0.064	0.001
	40X-1	1.957	8.949	0.602	10.98	0.456	0.125	15.612	0.644	0.456	0.125	0.549	0.11	0.042
	40X-1	1.722	7.187	0.277	8.867	0.365	0.107	13.655	0.613	0.365	0.107	0.556	0.105	0.029
	40X-1	2.158	7.024	0.299	9.325	0.62	0.166	10.734	0.906	0.62	0.166	0.769	0.172	0.041
	40X-2**	6.398	8.849	0.317	15.092	0.879	0.37	87.607	2.564	0.879	0.37	1.493	0.376	0.089
	40X-2	5.132	8.056	0.302	18.343	0.669	0.277	65.851	1.874	0.669	0.277	1.15	0.264	0.077

	40X-2	5.573	7.851	0.317	18.624	0.876	0.316	76.133	2.304	0.876	0.316	1.442	0.254	0.074
	40X-3*	3.366	4.697	0.203	12.074	0.23	0.132	13.111	1.324	0.44	0.183	0.722	0.139	0.037
	40X-3	5.644	5.294	0.183	15.672	0.273	0.108	22.655	1.973	0.669	0.299	1.365	0.287	0.077
	40X-3	2.189	4.692	0.179	14.743	0.198	0.106	9.997	0.871	0.404	0.111	0.553	0.111	0.039
	40X-4*	4.783	2.716	0.151	4.256	0.22	0.167	34.944	1.681	0.57	0.216	0.915	0.18	0.063
	40X-4	2.227	2.599	0.171	3.893	0.189	0.132	15.022	0.816	0.427	0.101	0.445	0.057	0.022
	40X-4	2.14	3.535	0.155	3.725	0.171	0.232	15.929	0.868	0.569	0.142	0.422	0.085	0.028
	40X-5*	1.096	3.63	0.288	4.602	0.264	0.433	13.204	0.423	0.212	0.068	0.219	0.062	0.014
	40X-5	1.175	2.823	0.238	3.788	0.262	0.2	10.564	0.825	0.747	0.15	0.416	0.061	0.016
	40X-5	2.789	5.408	0.242	3.515	0.27	0.191	22.228	1.095	0.54	0.149	0.657	0.137	0.036
	40X-6*	0.877	5.204	0.153	7.522	0.729	0.193	7.496	0.379	0.199	0.055	0.206	0.044	0.01
	40X-6	0.738	6.154	0.276	7.232	0.192	0.351	6.729	0.345	0.201	0.062	0.221	0.041	0.01
	40X-6	1.003	5.251	0.177	9.715	0.173	0.271	8.227	0.405	0.221	0.071	0.268	0.049	0.016
	40X-7*	4.041	2.999	0.177	6.476	0.178	0.076	18.69	1.987	1.68	0.296	1.324	0.241	0.065
	40X-7	1.652	2.907	0.202	7.169	0.205	0.265	10.121	0.682	0.298	0.105	0.454	0.092	0.02
	40X-7	2.367	2.93	0.146	5.856	0.187	0.537	13.579	1.837	1.892	0.283	1.029	0.168	0.038
	40X-8*	4.81	2.99	0.21	2.68	0.25	0.15	35.65	1.95	0.61	0.28	1	0.22	0.05
	40X-8	1.94	2.79	0.17	2.69	0.27	0.12	24.9	0.84	0.31	0.12	0.49	0.12	0.03
	40X-8	1.61	2.94	0.23	2.97	0.24	0.46	21.33	0.68	0.4	0.1	0.43	0.08	0.02
	40X-9*	2.01	4.699	0.246	2.977	0.161	0.234	12.439	0.771	0.392	0.115	0.454	0.102	0.017
	40X-9	1.896	3.739	0.172	1.998	0.179	0.024	11.181	0.72	0.274	0.122	0.514	0.07	0.018

	40X-9	1.175	3.266	0.126	2.455	0.141	0.059	7.597	0.485	0.187	0.065	0.262	0.087	0.021
	40X-10*	1.761	7.291	0.304	5.458	0.186	0.288	15.375	1.054	0.997	0.163	0.626	0.15	0.022
	40X-10	2.064	7.165	0.343	5.728	0.123	0.401	14.443	0.865	0.578	0.139	0.564	0.104	0.038
	40X-10	2.836	7.662	0.345	5.966	0.15	0.327	18.656	1.225	0.593	0.187	0.763	0.178	0.027
	40X-11*	2.146	3.981	0.225	0.699	0.181	0.09	17.856	0.921	0.5	0.142	0.565	0.064	0.03
	40X-11	1.39	3.933	0.239	0.925	0.118	0.093	12.579	0.973	0.843	0.147	0.559	0.115	0.022
	40X-11	2.206	4.773	0.324	1.013	0.179	0.141	17.162	0.838	0.4	0.118	0.51	0.081	0.025
	40X-12*	3.716	3.911	0.249	4.515	0.262	0.751	26.494	1.551	0.737	0.226	0.882	0.136	0.039
	40X-12	1.498	2.976	0.191	4.207	0.269	0.246	12.128	0.671	0.381	0.097	0.397	0.059	0.022
	40X-12	2.05	2.727	0.193	4.758	0.252	0.301	15.085	0.929	0.478	0.138	0.489	0.112	0.024
	40X-13*	2.225	3.222	0.283	5.721	0.247	0.95	17.203	0.934	0.437	0.13	0.538	0.087	0.028
	40X-13	0.962	3.671	0.237	3.138	0.177	0.387	10.073	0.406	0.267	0.063	0.244	0.052	0.008
	40X-13	0.986	3.586	0.229	4.699	0.185	0.359	9.652	0.462	0.34	0.07	0.245	0.049	0.017
	AQ1**	4.3	11.362	0.361	4.828	0.217	0.539	3818.733	1.492	0.702	0.222	1.078	0.269	0.273
	AQ1	4.69	10.934	0.438	8.256	0.259	0.937	6102.693	1.459	0.741	0.287	1.258	0.283	0.376
	AQ1	3.289	10.45	0.211	4.326	0.283	1.049	5376.402	1.217	0.836	0.233	0.86	0.153	0.297
	AQ1	2.359	12.209	0.367	4.289	0.19	1.186	793.36	0.774	0.576	0.155	0.677	0.134	0.103
	AQ1	2.214	11.272	0.335	4.431	0.299	1.122	2499.917	0.739	0.438	0.113	0.571	0.087	0.152
	AQ1	3.959	10.249	0.292	7.169	0.23	0.917	4014.025	1.277	0.729	0.229	1.034	0.222	0.226
	AS1**	0.849	3.156	0.27	0.65	0.176	0.405	1601.323	0.352	0.678	0.054	1.226	0.065	0.026
	AS1	1.798	1.886	0.184	1.076	0.16	0.423	1306.717	0.756	1.111	0.12	0.52	0.122	0.06
	AS1	1.357	1.957	0.23	1.293	0.231	0.377	904.197	0.551	0.639	0.108	0.421	0.232	0.049

	AS1	1.335	1.932	0.126	1.112	0.122	0.272	643.582	0.55	0.433	0.089	0.404	0.081	0.035
	AS1	0.753	1.894	0.157	1.065	0.2	0.567	1439.817	0.324	0.364	0.053	0.99	0.05	0.046
	AS2**	2.607	4.531	0.224	3.776	0.302	0.407	3472.781	0.834	0.449	0.126	0.685	0.103	0.227
	AS2	4.142	4.451	0.159	5.215	0.282	0.297	5939.421	1.404	0.707	0.225	0.999	0.201	0.345
	AS2	1.1	3.367	0.171	5.054	0.294	0.367	31531.636	0.404	0.168	0.059	0.318	0.107	1.416
	AS2	2.15	4.386	0.146	7.071	0.268	0.415	6509.752	0.776	0.473	0.114	0.58	0.105	0.321
	AS2	2.088	4.619	0.213	3.838	0.234	0.357	1797.3	0.758	0.378	0.121	0.503	0.153	0.098
	AS2	3.113	4.913	0.207	3.182	0.27	0.381	4139.032	1.149	0.648	0.187	0.908	0.151	0.186
	AS2	2.601	3.639	0.173	4.16	0.207	0.579	1372.97	0.987	0.474	0.135	0.676	0.141	0.106
	AS3**	2.077	1.024	0.102	1.323	0.392	0.136	247.827	0.833	0.392	0.136	0.545	0.113	0.034
	AS3	4.152	1.547	0.176	1.134	0.706	0.271	464.868	1.7	0.706	0.271	1.126	0.214	0.072
	AS3	0.784	2.177	0.162	1.063	0.167	0.057	741.446	0.299	0.167	0.057	0.184	0.052	0.032
	AS3	1.423	2.096	0.124	1.074	0.271	0.086	627.198	0.524	0.271	0.086	6.862	0.066	0.033
	AS3	0.796	2.154	0.128	0.932	0.174	0.055	908.307	0.342	0.174	0.055	0.261	0.049	0.023
	AS3	3.863	3.747	0.19	1.893	0.68	0.216	766.02	1.506	0.68	0.216	0.982	0.17	0.058
	AS3	2.091	3.677	0.238	1.832	0.357	0.12	159.326	0.811	0.357	0.12	0.448	0.097	0.029
	AS3	1.306	3.447	0.242	1.53	0.222	0.073	125.88	0.529	0.222	0.073	0.274	0.057	0.018
	AS3	2.546	4.031	0.214	1.729	0.41	0.185	99.961	0.981	0.41	0.185	0.649	0.119	0.041
	AS3	1.491	3.682	0.245	1.651	0.252	0.11	165.65	0.553	0.252	0.11	0.314	0.063	0.022
	WR-1**	2.595	4.197	0.206	1.866	0.33	0.226	27.809	0.726	0.486	0.128	0.769	0.148	0.06
	WR-1	5.023	4.691	0.234	1.831	0.33	0.208	98.281	1.531	0.734	0.285	1.347	0.271	0.111
	WR-1	4.407	4.312	0.219	1.849	0.286	0.155	38.262	1.432	0.716	0.246	1.185	0.266	0.087
	WR-1	3.767	4.409	0.28	1.94	0.271	0.086	38.389	1.222	0.686	0.215	0.825	0.285	0.069
	WR-1	2.175	3.773	0.212	1.301	0.242	0.112	25.182	0.659	0.485	0.113	0.601	0.184	0.036
	WR-1	1.102	2.971	0.154	1.01	0.252	0.423	16.538	0.348	0.171	0.052	0.296	0.086	0.018

	WR-1	2.881	5.253	0.243	2.287	0.271	0.223	38.525	0.94	0.696	0.169	0.778	0.181	0.05
	WR-2**	0.979	7.056	0.381	0.992	0.086	0.298	12.821	0.3	0.143	0.038	0.258		
	WR-2	0.407	7.104	0.336	1.954	0.108	0.542	11.724	0.129	0.118	0.024	0.093		
	WR-2	1.273	8.862	0.345	1.828		0.098	15.305	0.388	0.213	0.071	0.241	0.043	
	WR-3*	1.172	0.821	0.032	1.595	0.147	0.079	23.493	0.342	0.192	0.062	0.144	0.031	
	WR-3	0.966	0.991	0.121	1.63	0.125	0.181	24.823	0.308	0.166	0.046	0.206		
	WR-3	1.689	1.091	0.131	1.95		0.091	27.09	0.504	0.218	0.077	0.346	0.097	
	WR-4*	0.67	1.446	0.075	1.066	0.23	0.06	39.974	0.255	0.153	0.038	0.175	0.03	0.012
	WR-4	0.463	1.705	0.145	1.028	0.31	0.17	8.371	0.162	0.081	0.028	0.106	0.032	0.003
	WR-4	1.448	1.531	0.245	1.31	0.34	0.8	12.165	0.564	0.259	0.071	0.325	0.088	0.02
	WR-4	1.931	1.522	0.072	1.196	0.28	0.14	14.488	0.707	0.294	0.101	0.43	0.092	0.024
	WR-4	0.428	1.412	0.083	1.07	0.25	0.1	7.585	0.167	0.108	0.025	0.116	0.026	0.004
	WR-5*	0.548	1.086	0.121	1.432	0.077	0.17	15.741	0.171	0.144	0.04	0.15	0.054	
	WR-5	0.731	1.623	0.113	1.93	0.096	0.054	32.162	0.256	0.121	0.036	0.157	0.042	
	WR-5	2.848	1.485	0.105	1.513	0.087	0.079	51.669	1.016	0.473	0.162	0.546	0.098	0.05
Wadi Shallala Chalk Formation	WMH-1**	1.815	2.35	0.135	4.825	0.15	0.06	26.801	0.869	0.519	0.136	0.545	0.118	0.032
	WMH-1	1.425	2.53	0.118	4.975	0.16	0.09	19.549	0.66	0.296	0.106	0.43	0.083	0.024
	WMH-1	4.115	2.517	0.102	4.836	0.18	0.12	13.185	2.157	1.096	0.41	1.507	0.291	0.072
	WMH-2**	1.161	2.238	0.13	4.477	0.19	0.09	10.253	0.566	0.332	0.1	9.377	0.078	0.022
	WMH-2	1.735	2.003	0.115	5.003	0.23	0.04	11.355	0.834	0.418	0.147	0.567	0.096	0.029
	WMH-2	1.086	4.344	0.141	5.209	0.18	0.49	11.181	0.51	0.276	0.088	0.319	0.066	0.02

	WMH-3**	3.701	3.306	0.227	1.15	0.32	0.82	3991.776	1.584	0.614	0.219	0.978	0.196	0.088
	WMH-3	5.015	2.982	0.203	1.085	0.27	0.2	491.038	2.03	0.76	0.272	1.169	0.241	0.054
	WMH-3	4.208	3.083	0.201	1.131	0.33	0.28	1891.386	1.998	1.114	0.266	1.001	0.216	0.07
Secondary sources	WME-1*	3.059	4.679	0.327	6.81	0.449	0.169	206.589	1.296	0.449	0.169	0.804	0.138	0.051
	WME-1	4.55	4.654	0.239	6.434	0.742	0.268	169.336	1.999	0.742	0.268	1.135	0.227	0.066
	WME-1	8.114	4.529	0.248	6.111	0.981	0.47	209.472	3.38	0.981	0.47	2.052	0.407	0.113
	WME-1	5.678	4.803	0.289	6.229	0.8	0.349	159.599	2.37	0.8	0.349	1.351	0.304	0.077
	WME-2*	0.833	7.662	0.26	18.361	0.196	0.069	402.038	0.346	0.196	0.069	0.218	0.062	0.02
	WME-2	4.37	7.357	0.273	19.878	0.838	0.308	54.601	1.806	0.838	0.308	1.42	0.251	0.09
	WME-2	1.768	5.972	0.229	17.366	0.345	0.133	41.201	0.786	0.345	0.133	0.537	0.092	0.037
	WME-2	1.299	6.082	0.239	18.301	0.422	0.099	41.8	0.648	0.422	0.099	0.448	0.103	0.019
	WME-3*	1.323	5.866	0.343	19.525	0.966	0.177	46.287	0.808	0.966	0.177	0.691	0.153	0.035
	WME-3	0.453	6.285	0.246	16.183	5.063	0.359	41.892	1.838	5.063	0.359	1.269	0.188	0.044
	WME-3	0.818	5.624	0.184	20.077	0.475	0.087	46.171	0.418	0.475	0.087	0.29	0.064	0.021
	WME-3	0.788	8.354	0.423	22.566	1.168	0.102	51.869	0.683	1.168	0.102	0.38	0.074	0.024
	WMW-1*	1.973	7.311	0.384	4.921	0.197	1.027	61.762	0.716	1.33	0.078	0.587	0.088	
	WMW-1	3.442	6.248	0.332	5.172	0.149	0.546	45.782	1.208	0.557	0.164	0.9	0.155	0.041
	WMW-1	3.813	9.866	0.695	5.461	0.179	1.4	1139.594	1.292	0.718	0.176	0.845	0.103	0.064
	WMW-1	3.706	6.185	0.231	4.989	0.133	0.299	45.3	1.315	0.543	0.198	0.872	0.183	0.057
	WMW-1	1.623	12.827	0.351	4.522	0.189	0.243	43.404	0.609	0.273	0.075	0.393	0.046	
	WMW-2*	1.559	11.74	0.28	3.729	0.144	0.095	39.206	0.634	0.367	0.101	0.502	0.08	
	WMW-2	1.44	7.926	0.394	3.822	0.265	0.312	40.785	0.58	0.379	0.084	0.381	0.031	
	WMW-2	0.634	11.565	0.43	3.543	0.165	0.413	34.957	0.235	0.323	0.038	0.169		

	WMW-2	2.23	8.067	0.482	4.726	0.153	0.963	104.36	0.856	0.349	0.111	0.558	0.105	
	WMW-2	0.939	11.601	0.331	3.034	0.131	0.698	75.358	0.336	0.178	0.061	0.186	0.081	
	WMW-3*	2.679	2.002	0.048	3.383	0.16	0.09	85.359	0.916	0.364	0.128	0.527	0.163	
	WMW-3	2.474	0.473	0.113	3.13	0.143	0.092	68.934	0.778	0.343	0.118	0.533	0.06	0.04
	WMW-3	2.466	0.809	0.037	2.976	0.172	0.042	56.494	0.774	0.438	0.147	2.782	0.082	0.037
	WMW-3	4.962	1.001	0.113	2.944	0.165	0.097	87.747	1.694	0.621	0.204	1.318	0.133	0.039
	WMW-3	5.311	0.66	0.085	2.656	0.139	0.154	93.958	1.699	0.652	0.234	0.86	0.205	0.059
	WB1**	2.082	3.464	0.201	6.632	0.229	0.094	41.276	0.589	0.33	0.119	0.489	0.08	0.032
	WB1	6.045	3.899	0.227	6.979	0.161	0.107	43.073	2.035	1.195	0.402	1.641	0.335	0.077
	WB1	4.819	4.522	0.214	6.749	0.181	0.127	37.052	1.467	0.754	0.271	1.234	0.274	0.071
	WB1	2.933	3.359	0.326	7.029	0.266	0.126	45.383	0.936	0.681	0.206	0.72	0.113	0.055
	WB1	2.349	3.759	0.253	6.19	0.164	0.2	37.458	0.776	0.834	0.129	0.592	0.127	0.041
	WB1	1.881	4.699	0.141	5.785	0.158	0.049	92.374	0.524	0.478	0.093	0.399	0.075	0.022
	WB2*	6.831	13.274	0.656	1.147	0.188	0.158	40.004	2.514	1.037	0.384	1.317	0.265	0.083
	WB2	3.135	11.221	0.449	1.084	0.193	0.157	44.733	1.163	0.511	0.194	0.663	0.087	0.037
	WB2	3.903	34.641	0.41	1.166	0.207	0.07	23.46	1.434	0.496	0.196	0.888	0.215	0.044
	WB2	6.232	13.164	0.381	1.218	0.232	0.178	898.284	2.647	0.964	0.358	1.336	0.349	0.097
	WB2	7.121	12.661	0.352	1.142	0.2	0.06	12750.439	2.65	1.002	0.371	1.602	0.268	0.275
	WB2	7.53	12.291	0.692	1.623	0.173	1.106	40.05	2.665	1.189	0.366	1.49	0.376	0.079
	WB2	4.88	12.555	0.487	1.179	0.155	0.531	1481.863	1.703	0.752	0.27	0.972	0.217	0.099
	WB2	10.511	12.472	0.361	1.228	0.229	0.271	731.477	4.029	1.419	0.606	2.095	0.376	0.167
	WB3*	6.087	9.035	0.277	1.015	0.737	0.31	36.457	2.438	0.737	0.31	1.359	0.267	0.075
	WB3	6.03	12.517	0.365	1.086	0.805	0.344	69.608	2.345	0.805	0.344	1.439	0.293	0.077
	WB3	5.477	10.183	0.32	0.948	0.931	0.317	45.409	2.266	0.931	0.317	1.349	0.232	0.071

	WB3	4.285	10.533	0.338	0.972	0.663	0.231	6402.819	1.72	0.663	0.231	1.026	0.174	0.107
	WB3	5.796	11.866	0.368	1.031	0.821	0.305	2072.468	2.278	0.821	0.305	1.303	0.273	0.074
	WG1**	1.682	3.984	0.523	5.107	0.203	1.335	1751.784	0.749	0.762	0.138	0.567	0.129	0.114
	WG1	3.865	3.597	0.414	5.645	0.19	0.383	2686.041	1.751	0.782	0.336	1.449	0.338	0.183
	WG1	2.737	4.314	0.897	6.016	0.249	1.29	1412.225	1.192	0.82	0.234	1.065	0.33	0.104
	WG1	3.878	5.118	0.369	5.533	0.243	0.419	462.552	1.665	0.747	0.314	1.39	0.296	0.105
	WG1	1.36	4.352	0.344	5.817	0.196	0.23	181.386	0.629	0.514	0.128	0.531	0.081	0.042
	WG1	1.053	5.025	0.331	5.595	0.192	0.167	2162.762	0.488	0.515	0.118	0.421	0.092	0.124
	WG2*	1.411	5.029	0.262	2.174	0.189	0.175	13.488	0.632	0.291	0.083	0.411	0.076	
	WG2	1.099	5.674	0.279	1.882	0.221	0.257	13.115	0.464	0.265	0.066	0.288	0.07	
	WG2	1.069	5.774	0.48	2.311	0.182	0.089	14.473	0.48	0.468	0.05	0.281	0.07	
	WG2	1.012	6.107	0.349	1.932	0.221	0.236	13.481	0.554	0.252	0.065	0.2	0.035	0.033
	WG2	2.24	6.258	0.582	2.132	0.148	0.798	18.144	0.997	0.524	0.166	0.596	0.208	0.046
	WG2-R*	3.638	2.965	0.187	0.111	0.141	0.102	121.777	1.41	0.669	0.196	1.012	0.175	0.06
	WG2-R	2.607	3.084	0.187	0.101	0.092	0.168	39.184	1.107	0.501	0.175	6.927	0.133	0.052
	WG2-R	8.174	3.368	0.259	0.14	0.198	0.198	21.005	3.265	1.365	0.55	2.287	0.392	0.118
	WG2-R	2.768	2.817	0.111	0.103	0.197	0.228	18.037	1.056	0.533	0.159	0.833	0.104	0.044
	WG2-R	2.144	2.64	0.273	0.116	0.177	0.192	26.514	0.996	0.799	0.165	0.773	0.105	
	WG3*	2.492	6.245	0.469	5.147	0.087	0.08	111.664	0.852	0.49	0.136	0.501	0.145	
	WG3	2.77	6.707	0.544	5.645	0.141	0.533	393.59	0.92	0.647	0.163	0.673	0.095	0.05
	WG3	7.969	6.143	0.371	3.994	0.117	0.689	91.521	2.984	1.202	0.466	1.85	0.371	0.1
	WG3	2.849	5.452	0.257	5.169	0.072	0.121	199.118	1.147	0.619	0.196	0.712	0.162	0.051
	WG3	4.039	11.168	0.353	5.279	0.157	0.854	90.362	1.544	0.731	0.246	1.001	0.243	0.069

	WRJ-1*	0.633	2.652	0.172	3.535	0.208	0.196	241.749	0.313	0.413	0.049	0.212		
	WRJ-1	6.562	3.527	0.272	5.098	0.233	0.552	1317.965	3.017	2.179	0.498	4.253	0.284	0.129
	WRJ-1	1.966	5.445	0.343	5.54	0.171	0.55	2136.623	1.151	2.4	0.179	0.732	0.112	0.067
	WRJ-1	1.482	5.546	0.345	5.876	0.215	0.864	1183.51	0.846	0.68	0.149	0.609	0.14	0.054
	WRJ-1	2.017	4.86	0.218	3.735	0.13	0.425	82.78	0.746	0.559	0.113	0.692	0.083	
	WRJ-2*	3.411	1.71	0.082	2.359	0.085	0.48	5122.787	1.716	0.974	0.26	0.938	0.283	0.092
	WRJ-2	1.405	5.243	0.348	4.825	0.175	0.755	1610.278	0.532	0.727	0.091	0.301	0.054	0.046
	WRJ-2	2.402	4.058	0.243	4.242	0.182	0.729	9560.371	1.376	0.795	0.333	1.148	0.19	0.249
	WRJ-2	3.426	5.208	0.649	4.872	0.217	0.778	1778.571	1.803	1.234	0.419	1.468	0.424	0.109
	WRJ-2	3.466	1.408	0.192	2.267	0.101	0.386	477.922	1.467	2.247	0.297	1.128	0.295	0.063
	WRJ-3*	2.848	3.725	0.339	6.594	0.221	0.665	357.644	0.976	0.643	0.158	2.577	0.18	
	WRJ-3	0.876	4.201	0.374	4.436	0.102	0.651	1057.771	0.381	0.686	0.082	1.363	0.032	0.041
	WRJ-3	1.223	1.036	0.192	2.724	0.217	0.365	1995.418	0.481	0.403	0.106	0.31	0.055	0.059
	WRJ-3	2.56	1.052	0.248	2.093	0.207	0.309	5905.041	1.301	1.309	0.281	1.068	0.153	0.188
	WRJ-3	1.517	3.57	0.406	5.569	0.208	0.608	87.75	0.648	0.835	0.15	0.48	0.082	
	WU-1*	1.128	9.613	0.957	10.465	0.305	3.556	412.475	0.591	0.841	0.119	0.475	0.1	0.056
	WU-1	2.25	9.435	0.626	11.398	0.231	0.606	2289.566	0.98	0.866	0.222	0.78	0.12	0.107
	WU-1	1.274	9.486	0.594	10.156	0.159	0.538	3004.058	0.648	0.658	0.163	0.459	0.134	0.073
	WU-1	2.753	10.274	0.62	11.061	0.147	0.138	775.996	1.283	1.339	0.273	1.187	0.189	0.088
	WU-1	3.027	16.218	0.912	9.974	0.534	0.977	3527.445	1.831	1.296	0.301	1.259	0.418	0.093
	WU-2*	3.933	7.22	0.523	10.177	0.264	0.788	23.238	1.741	0.865	0.291	1.191	0.225	0.094
	WU-2	3.204	6.169	0.458	11.091	0.226	0.854	18.835	1.498	0.721	0.219	1.014	0.228	0.043
	WU-2	5.922	6.593	0.674	11.261	0.582	0.832	217.082	2.59	1.039	0.439	1.586	0.388	0.093
	WU-2	3.769	6.097	0.409	11.238	0.188	0.417	36.331	1.852	0.841	0.301	1.269	0.254	0.05

	WU-2	7.216	7.255	0.398	10.915	0.215	0.276	28.297	3.106	1.306	0.558	2.056	0.445	0.111
	WU-3*	1.199	7.396	0.88	10.424	0.146	0.855	3551.182	0.677	0.726	0.138	0.475	0.087	0.109
	WU-3	0.916	7.649	0.973	8.901	0.328	0.769	1823.673	0.452	0.564	0.101	0.356	0.078	0.039
	WU-3	0.695	7.488	0.718	8.153	0.144	0.741	1645.428	0.384	0.297	0.054	0.218	0.083	0.077
	WU-3	1.761	9.714	0.733	11.686	0.244	1.221	2027.537	0.858	0.841	0.152	0.662	0.159	0.061
	WU-3	1.318	9.962	1.033	10.639	0.231	0.784	116.498	0.499	0.577	0.212	0.482	0.157	0.13
**Precision (1 sigma NIST 613)		2%	1%	2%	5%	7%	6%	7%	4%	5%	8%	8%	9%	10%
Limit of detection (ppm)		0.001	0.001	0.001	0.0044	0.027	0.018	0.001	0.001	0.001	0.001	0.001	0.001	0.001
*Precision Test on NIST 613 glass	NIST 613	32.54	31.56	36.12	27.15	48.20	39.79	37.33	33.63	38.90	35.82	30.85	34.54	34.09
	NIST 613	32.07	32.52	36.15	28.31	46.63	41.12	37.03	32.53	37.45	35.21	31.47	32.94	31.05
	NIST 613	32.05	32.34	35.25	27.42	48.25	40.85	37.50	31.82	38.45	35.28	31.78	33.59	31.79
	NIST 613	31.65	30.57	35.47	27.16	50.28	41.68	37.97	31.77	38.56	35.32	31.50	32.84	32.61
	NIST 613	27.71	28.13	32.86	24.53	37.77	33.68	32.12	27.56	33.15	30.01	27.50	27.88	27.16
	NIST 613	30.60	30.86	35.16	26.39	42.25	36.91	35.11	30.43	36.42	33.42	30.12	31.24	31.03
	NIST 613	33.20	33.17	37.53	27.03	44.12	41.30	38.41	33.53	39.88	36.22	32.35	34.59	33.70
	NIST 613	32.35	32.46	37.24	26.29	42.80	38.90	37.11	32.26	38.20	35.75	32.71	34.21	32.48
	NIST 613	33.82	32.90	37.54	26.56	43.02	40.27	39.02	33.38	39.16	36.95	33.47	35.17	33.77
	NIST 613	34.23	35.02	38.13	26.27	43.62	40.56	39.65	34.10	39.79	37.23	33.93	35.60	33.71
	NIST 613	34.41	35.02	38.16	26.12	42.11	38.74	39.41	34.83	39.73	37.93	34.54	36.31	35.24
	average	32.24	32.23	36.33	26.66	44.46	39.44	37.33	32.35	38.15	35.38	31.84	33.54	32.42
	rsd	0.06	0.06	0.04	4%	8%	6%	6%	6%	5%	6%	6%	7%	7%
	Preferred values (ppm)	38.3	37.9	38.9	22	38.6	34.7	39.3	36	38.4	37.9	35.5	37.7	35.6

Table 4/4 (sample ablated by * line raster; ** immobile laser)												
Formation	Source	Gd	Dy	Yb	Lu	Pb	Th	U	Al/(Al+Mn+Fe)	Fe/Ti	Ni/Co	Total REEs
Umm Rijam Chert-Limestone Formation	35Q-1*	0.098	0.134	0.105		0.304	0.055	3.12	0.81	1.754	41.1	2.101
	35Q-1	0.408	0.495	0.465	0.069	0.285	0.08	4.496	0.82	2.48	36.2	7.055
	35Q-1	0.18	0.205	0.183	0.039	0.382	0.079	3.419	0.77	2.597	31.2	3.202
	35Q-1	0.253	0.381	0.299	0.041	0.283	0.095	4.097	0.85	1.507	26.1	5.013
	35Q-1	0.145	0.199	0.237	0.037	0.344	0.06	3.468	0.76	2.862	53.9	3.14
	35Q-2*	0.385	0.43	0.362	0.092	0.423	0.111	3.252	0.86	2.797	68.9	5.807
	35Q-2	0.589	0.388	0.347	0.069	0.412	0.119	3.3	0.71	4.566	81.2	5.979
	35Q-2	0.188	0.262	0.173	0.048	2.179	0.16	2.692	0.35	16.435	65.7	3.349
	35Q-2	0.089	0.143	0.164	0.033	0.218	0.036	1.84	0.85	1.852	31	1.872
	35Q-2	0.257	0.317	0.327	0.062	3.915	0.073	3.196	0.19	53.079	217.8	4.642
	35Q-3*	0.083	0.09	0.087		0.471	0.043	5.18	0.52	10.262	101.3	1.36
	35Q-3	0.218	0.293	0.261	0.04	0.459	0.073	6.533	0.63	5.943		3.878
	35Q-3	0.081	0.158	0.133		0.443	0.044	5.765	0.64	6.19	86.9	1.978
	35Q-3	0.155	0.164	0.115		0.513	0.04	5.94	0.5	10.369	117.7	2.141
	35Q-3	0.173	0.197	0.132	0.025	0.615	0.04	6.204	0.34	17.688	112.6	2.575
	40X-1**	0.123	0.084	0.073	0.014	2.085	0.161	3.348	0.36	23.033	229.3	3.238
	40X-1	0.029	0.106	0.094	0.017		0.101	2.493	0.85	2.571		0.917
	40X-1	0.167	0.185	0.208	0.031	0.399	0.143	3.776	0.48	11.26	355.1	2.543
	40X-1	0.11	0.221	0.175	0.03	0.191	0.092	4.048	0.64	16.171	205.6	2.34
	40X-1	0.275	0.253	0.163	0.033	0.105	0.137	4.754	0.89	1.809	297.2	3.426
	40X-2**	0.555	0.747	0.761	0.127	0.23	0.14	6.552	0.75	4.898	159.2	8.045
	40X-2	0.379	0.577	0.527	0.104	0.329	0.126	5.872	0.7	5.358	149.9	5.969

	40X-2	0.525	0.523	0.583	0.131	0.548	0.122	6.224	0.63	11.002	186.2	7.115
	40X-3*	0.206	0.244	0.19	0.031	0.334	0.063	6.496	0.88	1.752	108.2	3.551
	40X-3	0.394	0.476	0.317	0.056	0.292	0.07	6.179	0.77	4.556	157.8	5.97
	40X-3	0.174	0.162	0.139	0.019	0.385	0.059	6.197	0.81	4.102	136.6	2.606
	40X-4*	0.318	0.389	0.338	0.054	18.471	0.058	12.876	0.69	6.523	58.8	4.772
	40X-4	0.129	0.16	0.137	0.028	4.55	0.051	13.783	0.65	1.172	46.5	2.345
	40X-4	0.123	0.178	0.145	0.026	4.084	0.052	12.746	0.65	6.848	48	2.603
	40X-5*	0.099	0.105	0.078	0.011	0.455	0.036	7.928	0.6	13.626	107.9	1.305
	40X-5	0.084	0.093	0.084	0.011	0.221	0.07	8.809	0.73	5.315	89	2.506
	40X-5	0.169	0.213	0.206	0.035	0.439	0.079	9.616	0.76	6.288	86.2	3.268
	40X-6*	0.064	0.07	0.066	0.009	0.532	0.039	5.278	0.78	4.313	88.5	1.113
	40X-6	0.086	0.069	0.039	0.007	0.619	0.043	5.401	0.58	7.65	51	1.089
	40X-6	0.087	0.109	0.064	0.012	0.271	0.052	5.027	0.75	5.762	120.7	1.317
	40X-7*	0.28	0.345	0.239	0.043	0.454	0.115	10.557	0.83	3.517	82.2	6.547
	40X-7	0.118	0.115	0.084	0.017	0.6	0.057	9.417	0.5	13.274	118.3	2.004
	40X-7	0.151	0.213	0.147	0.031	1.037	0.129	10.296	0.42	19.314	149	5.815
	40X-8*	0.34	0.38	0.31	0.05	0.36	0.08	2.83	0.58	8.579	89.5	5.23
	40X-8	0.16	0.16	0.12	0.02	0.32	0.06	1.96	0.76	5.796	139.5	2.39
	40X-8	0.15	0.12	0.09	0.02	0.67	0.06	2.44	0.42	11.074	220.3	2.11
	40X-9*	0.157	0.171	0.161	0.03	0.247	0.078	5.494	0.63	8.367		2.395
	40X-9	0.123	0.175	0.138	0.02	0.294	0.041	6.914	0.88	2.753		2.193

	40X-9	0.111	0.102	0.079	0.013	0.277	0.034	6.06	0.76	4.326		1.425
	40X-10*	0.125	0.16	0.088	0.023	0.898	0.09	2.674	0.73	6.582	162.6	3.424
	40X-10	0.15	0.184	0.125	0.023	1.011	0.093	2.904	0.66	8.298	202.6	2.785
	40X-10	0.238	0.228	0.167	0.027	0.909	0.099	3.119	0.73	7.05		3.664
	40X-11*	0.142	0.161	0.152	0.024	0.162	0.068	5.681	0.74	6.528		2.725
	40X-11	0.094	0.113	0.111	0.012	0.24	0.081	5.826	0.75	4.429		3.006
	40X-11	0.169	0.164	0.177	0.033	0.277	0.055	5.432	0.67	5.279	251.1	2.542
	40X-12*	0.249	0.31	0.242	0.043	0.693	0.093	1.679	0.47	14.009	440.7	4.457
	40X-12	0.107	0.099	0.098	0.018	0.558	0.077	1.381	0.7	7.48		1.97
	40X-12	0.121	0.144	0.152	0.03	0.601	0.09	1.537	0.62	12.971		2.647
	40X-13*	0.167	0.18	0.148	0.023	0.938	0.084	3.421	0.51	14.151	187.6	2.693
	40X-13	0.073	0.107	0.073	0.015	0.673	0.059	3.279	0.78	4.823	144.9	1.318
	40X-13	0.064	0.098	0.073	0.011	0.627	0.078	3.43	0.67	9.558	125.1	1.443
	AQ1**	0.51	0.47	0.446	0.062	4.586	0.117	7.324	0.68	8.7	56	5.582
	AQ1	0.734	0.501	0.417	0.07	7.119	0.136	8.173	0.53	12.571	30.4	6.189
	AQ1	0.451	0.258	0.293	0.042	5.472	0.076	5.361	0.6	18.965	32.1	4.688
	AQ1	0.23	0.292	0.237	0.053	4.655	0.114	5.869	0.61	9.144	33.2	3.269
	AQ1	0.218	0.24	0.187	0.033	6.602	0.289	5.318	0.48	23.376	136.4	2.804
	AQ1	0.489	0.428	0.398	0.074	5.942	0.126	7.403	0.51	18.568	118.4	5.162
	AS1**	0.031	0.059	0.06		0.684	0.029	1.092	0.44	2.002	10.2	2.551
	AS1	0.109	0.155	0.116	0.022	3.841	0.034	0.995	0.45	27.379	11.4	3.112
	AS1	0.144	0.116	0.114	0.017	0.397	0.03	0.985	0.47	15.109	23	2.41

	AS1	0.108	0.108	0.074	0.02	0.192	0.027	0.941	0.6	15.145	9.7	1.916
	AS1	0.056	0.058	0.054		0.385	0.023	0.839	0.47	20.809	14.5	2.005
	AS2**	0.471	0.257	0.215	0.044	2.035	0.041	10.832	0.54	5.833	34.3	3.448
	AS2	0.521	0.358	0.325	0.075	1.719	0.056	11.771	0.7	8.429	24.3	5.217
	AS2	0.623	0.104	0.079	0.016	1.638	0.074	7.528	0.58	15.803	4.8	3.308
	AS2	0.375	0.232	0.172	0.03	1.872	0.034	10.821	0.52	21.984	43.5	3.203
	AS2	0.196	0.19	0.18	0.041	1.465	0.041	12.06	0.71	4.872	48.1	2.652
	AS2	0.348	0.295	0.298	0.042	1.695	0.067	12.467	0.73	5.269	47.3	4.246
	AS2	0.286	0.243	0.267	0.05	2.376	0.046	11.016	0.49	16.599	15.3	3.396
	AS3**	0.165	0.196	0.155	0.022	0.16	0.033	0.974	0.73	6.255	46.8	2.614
	AS3	0.37	0.381	0.245	0.047	0.205	0.056	1.363	0.54	4.956	72.3	5.181
	AS3	0.057	0.087	0.05	0.01	0.233	0.018	0.888	0.59	16.918	18.9	1.005
	AS3	0.103	0.108	0.106	0.018	0.201	0.022	0.947	0.69	13.908	34.3	8.194
	AS3	0.051	0.056	0.063	0.011	0.27	0.025	0.915	0.49	23.726	36.2	1.093
	AS3	0.274	0.317	0.265	0.047	0.293	0.045	8.753	0.79	3.259	20.1	4.56
	AS3	0.135	0.147	0.11	0.021	0.323	0.034	6.649	0.64	7.332	42.1	2.293
	AS3	0.065	0.114	0.084	0.021	0.352	0.024	6.057	0.71	4.956	48.5	1.468
	AS3	0.143	0.187	0.174	0.031	0.303	0.046	7.392	0.82	2.893	959.3	2.947
	AS3	0.111	0.112	0.096	0.019	0.237	0.027	6.207	0.84	2.79	42.6	1.668
	WR-1**	0.321	0.255	0.256	0.049	0.182	0.08	5.994	0.72	7.615	157.2	3.239
	WR-1	0.626	0.555	0.501	0.071	0.405	0.132	6.84	0.73	4.11	114.9	6.111
	WR-1	0.478	0.477	0.471	0.071	0.292	0.118	6.797	0.75	7.072	141.4	5.504
	WR-1	0.46	0.431	0.387	0.063	0.187	0.143	6.703	0.85	3.047	111.1	4.693
	WR-1	0.301	0.24	0.197	0.036	0.211	0.091	5.538	0.81	4.677	200.9	2.88
	WR-1	0.098	0.116	0.072	0.014	0.844	0.031	3.818	0.52	23.613	143.2	1.279

	WR-1	0.28	0.331	0.255	0.059	0.218	0.138	6.236	0.74	5.794	103.5	3.777
	WR-2**	0.107				0.252	0.03	4.154	0.58	12.934		0.846
	WR-2		0.038			0.283	0.032	4.842	0.48	16.927	31.3	0.402
	WR-2	0.096	0.166	0.09		0.154	0.072	5.075	0.87	1.911	14.8	1.308
	WR-3*	0.114	0.128	0.056		0.514	0.029	7.986	0.55	9.304	11	1.069
	WR-3	0.05	0.102	0.105		0.493		8.283	0.27	19.821	18.7	0.983
	WR-3	0.047	0.091	0.123		2.121		9.515	0.39	16.313	22.5	1.503
	WR-4*	0.045	0.045	0.042	0.008	0.407	0.025	5.829	0.76	6.217	62.8	0.809
	WR-4	0.041	0.043	0.044	0.006	0.644	0.023	6.14	0.5	11.351	95.8	0.551
	WR-4	0.092	0.116	0.105	0.017	1.483	0.039	6.434	0.15	44.965	139.5	1.671
	WR-4	0.193	0.168	0.121	0.022	0.79	0.036	6.377	0.62	12.189	56.7	2.173
	WR-4	0.034	0.042	0.043	0.004	0.704	0.017	6.413	0.78	3.96	35.5	0.574
	WR-5*	0.048		0.041		0.32		7.481	0.47	16.303	20.2	0.648
	WR-5		0.054	0.04		0.363		8.029	0.73	4.696		0.706
	WR-5	0.195	0.232	0.145	0.035	0.561	0.031	8.392	0.6	6.546	51.6	2.98
Wadi Shallala Chalk Formation	WMH-1**	0.179	0.193	0.138	0.023	0.338	0.031	3.084	0.3	32.958	966.5	2.777
	WMH-1	0.145	0.125	0.122	0.014	0.203	0.038	3.181	0.61	10.834		2.022
	WMH-1	0.431	0.38	0.294	0.047	0.233	0.089	3.679	0.51	15.411	281.9	6.744
	WMH-2**	0.116	0.124	0.076	0.013	0.138	0.038	3.338	0.81	3.337		10.821
	WMH-2	0.149	0.175	0.12	0.021	0.181	0.048	3.557	0.66	8.798	277.3	2.576
	WMH-2	0.121	0.097	0.088	0.013	0.164	0.043	3.534	0.79	3.346		1.617

	WMH-3**	0.29	0.306	0.245	0.038	0.305	0.075	3.531	0.7	6.396	47.1	4.597
	WMH-3	0.302	0.417	0.305	0.053	0.247	0.071	3.673	0.9	1.984	61.3	5.652
	WMH-3	0.363	0.334	0.279	0.04	0.774	0.067	3.121	0.33	25.044	85.5	5.722
Secondary sources	WME-1*	0.24	0.248	0.181	0.029	0.39	0.086	4.308	0.58	12.494	56.8	3.638
	WME-1	0.404	0.352	0.313	0.053	0.302	0.126	4.798	0.77	6.108	38.5	5.612
	WME-1	0.652	0.706	0.511	0.09	0.397	0.114	5.767	0.77	5.013	35.1	9.46
	WME-1	0.488	0.501	0.378	0.06	0.378	0.134	5.313	0.86	2.103	32.6	6.741
	WME-2*	0.071	0.077	0.061	0.013	0.787	0.065	5.611	0.56	15.875	238.1	1.146
	WME-2	0.421	0.426	0.307	0.056	0.496	0.159	6.906	0.69	9.495	256.1	5.978
	WME-2	0.177	0.209	0.109	0.019	0.385	0.071	5.585	0.75	7.859		2.473
	WME-2	0.118	0.124	0.122	0.019	0.458	0.065	5.736	0.63	11.718	288.2	2.139
	WME-3*	0.155	0.156	0.105	0.022	0.434	0.074	4.155	0.74	3.632	222.9	3.291
	WME-3	0.057	0.046	0.034	0.007	3.255	0.551	4.567	0.41	25.726	644.5	8.914
	WME-3	0.069	0.067	0.068	0.014	0.155	0.057	4.598	0.86	3.749	124.8	1.584
	WME-3	0.104	0.074	0.052	0.01	6.455	0.054	4.721	0.2	72.029	389.2	2.684
	WMW-1*	0.076	0.092	0.138		10.427	0.039	8.517	0.4	19.179		3.105
	WMW-1	0.286	0.285	0.209	0.027	0.36	0.119	8.45	0.58	8.982	132.3	3.873
	WMW-1	0.308	0.355	0.338	0.045	0.272	0.154	8.404	0.36	14.585	86.5	4.279
	WMW-1	0.191	0.419	0.247	0.044	0.238	0.072	8.625	0.74	5.082	142.9	4.11
	WMW-1	0.15	0.153	0.099		0.257	0.054	7.451	0.68	6.587		1.798
	WMW-2*	0.22	0.14	0.071		0.252	0.053	8.085	0.86	2.604		2.115
	WMW-2	0.092	0.129	0.097		0.248	0.051	8.285	0.63	9.212		1.773
	WMW-2	0.086				0.207	0.035	7.092	0.6	12.468	49.6	0.851

	WMW-2	0.174	0.237	0.143		0.336	0.056	8.629	0.35	19.978	563.1	2.56
	WMW-2	0.09	0.103	0.078		0.407	0.035	7.77	0.53	5.008	163	1.113
	WMW-3*	0.18	0.197	0.146	0.029	0.529	0.047	2.274	0.61	6.085		2.676
	WMW-3	0.2	0.09	0.132	0.025	0.625		2.432	0.63	6.905		2.319
	WMW-3	0.194	0.209	0.169	0.025	0.38	0.028	3.662	0.76	4.088		4.857
	WMW-3	0.318	0.448	0.211	0.045	0.372	0.048	3.224	0.7	2.848	127	5.068
	WMW-3	0.336	0.414	0.316	0.059	1.171	0.053	3.355	0.38	13.995	145.5	4.875
	WB1**	0.153	0.207	0.176	0.037	0.522	0.073	3.974	0.66	8.649	260.9	2.234
	WB1	0.512	0.674	0.581	0.094	0.624	0.158	5.693	0.64	5.882	164.1	7.618
	WB1	0.441	0.507	0.424	0.078	0.292	0.128	5.868	0.75	4.893	158.9	5.58
	WB1	0.306	0.315	0.282	0.05	0.551	0.115	3.423	0.7	4.558	82.8	3.713
	WB1	0.224	0.22	0.207	0.04	0.443	0.084	2.971	0.6	7.12	154.7	3.234
	WB1	0.154	0.162	0.17	0.025	0.137	0.057	2.533	0.75	4.197	72	2.122
	WB2*	0.377	0.418	0.38	0.069	0.588	0.071	6.799	0.67	3.581		6.899
	WB2	0.202	0.272	0.2	0.031	0.449	0.062	5.722	0.68	4.242		3.395
	WB2	0.229	0.285	0.24	0.042	0.45	0.104	6.87	0.81	2.788		4.109
	WB2	0.451	0.454	0.446	0.083	0.71	0.103	6.884	0.55	11.602	260	7.249
	WB2	0.774	0.578	0.424	0.08	0.392	0.147	6.928	0.85	2.924		8.094
	WB2	0.416	0.529	0.473	0.07	2.252	0.128	7.483	0.17	37.036	337	7.718
	WB2	0.384	0.44	0.361	0.067	0.795	0.097	6.462	0.43	8.506	363.2	5.308
	WB2	0.77	0.848	0.598	0.118	0.573	0.106	8.208	0.67	6.033	233.4	11.151
	WB3*	0.372	0.442	0.381	0.051	0.381	0.088	6.114	0.79	4.46	137.6	6.487
	WB3	0.454	0.466	0.356	0.062	0.28	0.111	6.497	0.79	3.337	242.9	6.702
	WB3	0.383	0.41	0.318	0.055	0.292	0.096	6.625	0.79	3.562		6.393

	WB3	0.296	0.291	0.236	0.037	0.235	0.088	6.279	0.79	3.936		4.822
	WB3	0.434	0.451	0.376	0.064	0.379	0.094	6.275	0.69	4.222		6.436
	WG1**	0.237	0.173	0.179	0.034	1.591	0.105	3.105	0.3	28.739	217.5	3.104
	WG1	0.589	0.444	0.304	0.04	0.572	0.126	3.507	0.54	10.301	177.6	6.288
	WG1	0.302	0.371	0.243	0.044	1.603	0.145	3.334	0.31	17.63	120.6	4.767
	WG1	0.433	0.47	0.298	0.065	0.511	0.182	3.039	0.56	12.042	262.5	5.843
	WG1	0.198	0.159	0.126	0.021	0.639	0.089	2.935	0.72	6.405	150.6	2.453
	WG1	0.212	0.124	0.106	0.017	0.213	0.07	2.985	0.78	6.018	240.5	2.232
	WG2*	0.14	0.104	0.087		0.708	0.063	4.251	0.5	9.164		1.824
	WG2	0.087	0.054	0.081		1.247	0.032	4.062	0.37	15.33	137.5	1.375
	WG2	0.059	0.074	0.086		0.379	0.07	3.642	0.85	0.595		1.568
	WG2	0.069	0.05	0.106		1.326	0.06	4.133	0.3	12.204		1.364
	WG2	0.143	0.201	0.18	0.032	3.191	0.104	4.694	0.18	19.229	172.3	3.093
	WG2-R*	0.271	0.202	0.21	0.044	0.964	0.106	14.26	0.59	12.326		4.281
	WG2-R	0.214	0.305	0.262	0.038	0.985	0.096	14.462	0.5	16.787	113	9.744
	WG2-R	0.574	0.686	0.539	0.095	1.13	0.215	15.181	0.52	12.688	77.6	9.971
	WG2-R	0.173	0.234	0.165		0.978	0.073	13.72	0.51	16.565	103.7	3.329
	WG2-R	0.19	0.172	0.162	0.026	0.837	0.116	15.215	0.54	9.743	105.5	3.388
	WG3*	0.183	0.213	0.141	0.031	0.208	0.085	1.525	0.83	1.974	110	2.721
	WG3	0.17	0.173	0.18	0.031	0.435	0.08	1.692	0.57	11.769	215.6	3.14
	WG3	0.701	0.719	0.503	0.09	0.41	0.13	2.646	0.59	10.895		9.076
	WG3	0.226	0.207	0.214	0.041	0.147	0.065	1.739	0.81	3.054	94.3	3.604
	WG3	0.414	0.395	0.272	0.046	0.509	0.107	1.968	0.39	13.799	209	5.011

	WRJ-1*		0.052	0.057		0.386	0.064	1.121	0.76	9.183	112.3	1.096
	WRJ-1	0.377	0.493	0.348	0.069	0.99	0.227	4.79	0.63	9.913	165.6	11.712
	WRJ-1	0.236	0.165	0.11	0.032	0.825	0.281	2.743	0.64	5.995	127.2	5.184
	WRJ-1	0.193	0.158	0.134		1.407	0.155	2.014	0.47	18.106	303.5	2.991
	WRJ-1	0.118	0.181	0.078		0.583	0.105	2.458	0.64	11.455	224	2.57
	WRJ-2*	0.263	0.264	0.181		1.417	0.132	2.697	0.53	16.239	300.8	4.971
	WRJ-2	0.156	0.116	0.061		1.371	0.126	1.726	0.48	10.544	158	2.084
	WRJ-2	0.33	0.297	0.161		1.865	0.118	2.219	0.51	13.564	330.9	4.916
	WRJ-2	0.293	0.353	0.232	0.045	1.545	0.227	2.667	0.62	6.766	279.6	6.425
	WRJ-2	0.226	0.384	0.217	0.025	0.954	0.129	2.9	0.61	11.495	125	6.391
	WRJ-3*	0.147	0.219	0.135	0.026	1.184	0.144	3.497	0.59	8.759	279.8	5.061
	WRJ-3	0.06	0.067	0.047		1.42	0.074	1.62	0.52	13.185	301.9	2.759
	WRJ-3		0.075	0.067		1.25	0.062	1.64	0.59	9.997	186.3	1.556
	WRJ-3	0.283	0.281	0.133		0.983	0.09	2.122	0.68	6.872	146.5	5.031
	WRJ-3	0.142	0.158	0.102		1.071	0.151	2.542	0.58	9.558	163.8	2.597
	WU-1*	0.214	0.146	0.071		2.535	0.117	1.282	0.24	28.36	14.9	2.613
	WU-1	0.392	0.255	0.231	0.027	0.509	0.201	1.748	0.61	7.357	19.3	4.01
	WU-1	0.139	0.124	0.095		0.472	0.096	1.488	0.61	8.899	68.9	2.526
	WU-1	0.279	0.298	0.177	0.029	0.419	0.199	2.05	0.84	3.148	81.2	5.191
	WU-1	0.631	0.3	0.127	0.038	2.608	0.313	1.822	0.75	7.252	14.7	6.337
	WU-2*	0.304	0.296	0.28	0.046	1.442	0.144	5.254	0.59	16.663		5.378
	WU-2	0.295	0.235	0.26	0.037	1.478	0.119	4.465	0.53	16.101	615.2	4.588
	WU-2	0.545	0.593	0.347	0.062	0.545	0.158	5.295	0.7	3.75		7.754
	WU-2	0.29	0.27	0.24	0.055	0.794	0.124	5.171	0.73	8.73		5.474

	WU-2	0.607	0.663	0.508	0.078	0.76	0.214	6.504	0.81	6.421		9.526
	WU-3*	0.148	0.173	0.079		0.843	0.132	1.868	0.49	8.553	10.6	2.612
	WU-3	0.086	0.077	0.069		0.796	0.127	1.952	0.5	7.091	7.4	1.822
	WU-3		0.083	0.081		0.568	0.069	1.818	0.53	13.224	12.1	1.277
	WU-3	0.269	0.196	0.156		0.775	0.137	2.081	0.42	18.681	11.1	3.354
	WU-3	0.122	0.193	0.151	0.122	0.698	0.223	1.684	0.54	7.609	15.2	2.748
**Precision (1 sigma NIST 613)		8%	9%	10%	12%	14%	13%	15%				
Limit of detection (ppm)		0.001	0.001	0.001	0.001	0.003	0.0005	0.0002				
*Precision Test on NIST 613 glass	NIST 613	33.72	31.72	33.37	31.95	48.74	33.45	47.30				
	NIST 613	32.72	29.20	31.00	30.63	47.77	31.91	44.10				
	NIST 613	29.78	30.67	31.02	31.07	48.23	32.91	46.53				
	NIST 613	31.68	30.52	33.09	31.51	51.08	32.60	46.98				
	NIST 613	27.51	26.01	27.57	25.93	40.78	27.74	37.27				
	NIST 613	31.29	28.79	30.95	29.26	47.33	31.29	41.85				
	NIST 613	34.89	32.19	34.21	32.59	50.83	34.00	46.38				
	NIST 613	33.10	31.33	32.57	31.02	48.13	33.10	43.13				
	NIST 613	34.19	32.17	34.42	32.88	47.44	34.60	43.90				
	NIST 613	34.46	32.02	34.98	33.13	48.94	35.46	46.07				
	NIST 613	35.55	33.23	35.19	33.57	48.13	35.59	45.30				
	average	32.63	30.71	32.58	31.23	47.95	32.97	44.44				
	rsd	7%	7%	7%	7%	6%	7%	7%				
	Preferred values (ppm)	37.3	35.5	39.2	37	38.57	37.79	37.38				

Appendix 6: Geochemical data (ppm) of artifacts (3 tables).

Table 1/3																
Layer	Artifact	Li	Be	B	Na	Mg	Al	Si	K	Ca	Sc	Ti	V	Cr	Mn	Fe
8	2947-a	6.2	0.3	36.1	383.1	31	574.7	462393.3	353	3087	2	36.2	14.2	16.7	0.7	309.5
	2947-b	6.1	0.2	41.7	351.4	16.8	551.5	464691.4	226.9	1298.6	2.3	29.2	8.5	10.9		131.4
	2947-c	4.4	0.5	42.3	443.3	30.8	568	462485.5	279.1	3252.1	2.3	36.5	14	20.5	0.4	138.7
	3082-a	2.3	0.4	41.3	271.4	86.1	291.6	462462.6	556.8	1958.1	2.9	56.1	26.1	64.1	1.9	806.3
	3082-b	2.7	0.4	36.6	274	34.8	217.7	465433.3	181	729.2	2.8	16.2	9.7	14	0.9	208.7
	3082-c	6.2	0.3	39.6	528.1	162.4	412.2	458819.1	353.4	3048.3	3.3	25.1	33.8	34.5	5.9	2598
	3591-a	18.1	0.1	4.6	480.4	84.4	388.7	447451.2	343.3	15287.5	2	156.4	51	109.3	4.6	1420
	3591-b	15.7	0.1	4.4	240.5	70.4	339.9	451073.7	189.9	15120.9	2.1	100.9	35.1	119.4	4	636.3
	3591-c	23.3	0.2	6.7	230.9	45.3	451	458154.2	205.9	8699.9	2	38.7	19.9	65.1	2.6	366.9
	3711-a	5.9		43.3	468.8	74.4	652	462223.7	554.2	1441	2.3	59.7	91	35.3	2.7	790.7
	3711-b	6.1	0.2	39.4	676.7	152.9	932.5	451297.4	704.5	10330.2	2.4	83.1	107	68.7	3	1671.4
	3711-c	5.9	0.2	39.9	512.8	87.7	824.4	452316.2	1012.8	3132.2	2.1	71.5	149.7	78	3.5	2155.2
	3805-a	14.6	0.2	38.6	463	272.9	889.8	460395.2	1170.8	1092.7	2.1	68.2	76.4	111.7	4.5	2605.9
	3805-b	14.9	0.2	43.8	370.2	263.5	1023.7	461570.1	1003.8	1082.1	2.4	120.2	78.8	104.8	13.8	1820.4
	3805-c	16.7		40.6	675.9	454.8	1925.8	451416.2	3328.8	1307.5	2.2	231.1	243.3	160.1	11.8	8131.9
	3806-a	7.2	0.1	54.8	477.4	43	819.6	463931.7	411.7	713	2.7	51.5	30.4	16.4	3.1	633.6
	3806-b	6.9	0.2	57.5	429.4	57.5	666.9	463592.2	362.7	873	2.8	35.1	64	23.4	2.8	915.1
	3806-c	7.2	0.1	61.2	396.3	32.5	585.2	464548.8	336.6	696.7	2.9	29.6	14.8	14	1.6	491.1

	4033-a	2.4		32.2	184.6	49.5	359.8	463971.3	714.1	885.3	2.5	37.7	28.8	37.9	2.6	737.9
	4033-b	1.9	0.2	34.5	158.9	25.8	303.1	464844.3	223	1289	2.8	39.9	13.1	25.7	1.5	267.7
	4033-c	1.4		36.2	228.6	42.8	265.3	464514.7	204.5	1425	2.7	49.8	15.4	14.4	0.7	249.7
	4192-a	17.7		31.4	406.8	67.8	793.3	463642.6	517.6	1009.2	2.8	73.2	77	40.8	1.7	545.8
	4192-b	18.1		30.2	504.2	84.9	811.5	461646.3	669.7	1920.1	2.7	127.9	130.2	67.5	2.3	1120.4
	4192-c	19.7		28.2	407.3	55.5	869.6	461649.4	559.9	1142.7	2.8	52.9	110.8	39.7	2.6	1298.1
	4215-a	6.4	0.5	20.4	461.5	318	866.6	456568.5	867.2	6235.6	2.8	91.1	81	55	4.2	1100.4
	4215-b	5.9	0.3	18.9	341.4	168.9	775.6	462935.3	526.9	1653.4	2.7	53.8	48.7	38.8	2.3	548.9
	4215-c	4.3	0.3	19	335.9	113.7	638.3	463115.9	465.9	1890.9	2.6	42.2	24.8	35.3	0.9	533.6
	4278-a	5.6	0.8	44.2	496.3	124	493.8	452989	863.9	5776.1	3	101.2	124.1	74.6	3.6	1420
	4278-b	20.2	0.2	19.9	419.4	136.1	739.2	459807.1	670.2	3273.1	2.6	47.5	72.6	61.7	3.3	1474.8
	4278-c	3.3	0.9	43.7	340.4	58.5	383.4	458298.4	345.4	6090.3	2.5	22.8	34.4	33.5	3.5	584.5
	4396-a	7.3	0.2	38	497.1	55.4	539.7	461787.4	439.3	3680.2	2.7	40.9	17.4	36.3	4.1	262.8
	4396-b	7	0.2	37.4	413.1	40.4	471.5	462446.9	267.5	3306.4	2.7	34	15	114	0.9	134.1
	4396-c	6	0.3	39.9	428.2	42.6	476.7	461172.8	223.5	4067.6	2.6	36.2	20.2	40.9	1.6	561.3
	4425-a	40.2		14.4	268.2	53.2	636	461922.3	414.3	1918.3	2.7	71.3	39.9	68.5	4	863
	4425-b	39	0.1	15	249	23.1	509.9	463972.4	263.9	1016.8	2.8	46.1	19.5	23	3.5	809.6
	4425-c	33.2	0.2	17.2	263	40.5	575.6	462874.1	195.3	906.6	2.6	56.4	14.8	20.9	4.8	1654.8
	4522-a	4.3	0.2	41	295.5	84.9	516.5	463835.6	501.9	633	2.3	59.8	26.8	31.2	1.2	561.7
	4522-b	3.9	0.1	39	330.4	152.9	651.8	462075.4	621.8	819.8	2.3	492.7	53.9	74.3	14.5	1225.1
	4522-c	3.8	0.3	38.8	333.4	104.5	592.6	463665.1	455.4	945.4	2.2	57	32	39.1	2	632.6

	4548-a	21.1	0.2	41.1	757.7	645.1	1889.7	455957.9	1863.3	1006.6	3	205.3	176.7	171.5	8.6	4578.9
	4548-b	20.9	0.6	44.1	826.7	785	2870.3	452830.2	1474.5	945	3.8	277.5	219.6	175.7	6.3	7278.4
	4548-c	21.4	0.2	43.1	555.7	262.3	1241.2	459531.2	1056.1	882.8	3	125.2	96.1	119	5.5	2863.9
	4622-a	2.1	0.3	29.8	387.1	295.5	990.1	460596.8	928.9	2143.2	2.5	104.9	75.4	85.6	5.1	1000.2
	4622-b	2	0.6	31.6	309.7	161.5	779.1	463028	646.3	1578.7	2.5	92.4	51.2	62.4	3.3	658.3
	4622-c	2.9	0.7	29.4	461.4	437	1257.9	458322	1184	3024.6	2.2	329.8	105.9	184	13.2	1880.2
	4651-a	9.8	0.3	32	420.8	157.9	848.2	461770.5	459.5	2506.7	2	56.6	29.7	40.3	2.1	514
	4651-b	8.3	0.2	39.1	484.1	96.9	608.3	462650.3	497.6	1983.8	2.3	51	27.6	46.1	1.7	486.8
	4651-c	8.2		42.4	440.7	31.7	517.2	463812.4	301.9	1678.5	2.4	32.9	38.2	29.4	0.5	481.4
	4671-a	5.1	0.1	26.7	337.2	172.4	703.9	462029.1	492.8	2007.1	2.9	88.5	85.7	58.2	6.3	1012.4
	4671-b	5.8	0.2	24.7	395.1	189.2	818.8	462331.7	575.7	1726.5	2.9	138.1	68.7	56.3	3	1023.1
	4671-c	5	0.1	25.2	307.4	155.9	853.4	461441.8	557.7	1570.3	2.8	97.8	96.7	41.6	2.1	871.5
	4673-a	7.8	0.2	44.3	545.3	161.1	853.4	453945.9	631.2	7405.9	2.4	180.2	109.6	77.2	4.6	1267.2
	4673-b	10.4	0.2	42.2	523.4	130.3	710.2	462188.1	362.8	2736.7	2.5	60.5	29.3	24.2	1.6	316.8
	4673-c	9.5	0.1	41.9	425	95.7	658.5	461115.8	381.7	3202.1	2.5	181.6	30	28.8	3.2	491.8
	4826-a	21.3	0.3	20.4	787.6	125.2	1939.5	458597.6	999.2	3963.5	2.8	143.2	89.5	152.3	2.5	1001.5
	4826-b	23.5	0.3	18.2	923	116.9	1609.1	456331.6	878.1	6540.6	2.7	120.3	70.3	98.4	1.5	1082.7
	4826-c	20.3	0.1	20.3	675.1	91	1308.9	459361.3	736.6	4760	2.6	123.6	32.8	87.5	1.2	421.9
7																
	1200-a	22.3		8.5	178	82.4	389.1	460628.8	213.8	5314.8	2.1	46.6	55.9	56.2	1.7	850.8
	1200-b	16.4	0.2	8.2	202.9	84.6	429.8	457910.6	379.5	7505.6	2.2	80.2	47.5	75.9	3.4	1073.7

	1767-a	18.2	0.2	31.8	307	23.2	406.6	461803.6	212.7	2274.1	6.2	86.2	36	56.2	0.8	1282.4
	1767-b	17.5		32.6	270.3	12.2	370.9	464829.7	174	979.6	6.3	23.5	6.5	8.1	0.2	229.1
	1767-c	16.2		35.6	278.4	22.2	368.5	462663.3	164.7	2111.4	6.2	63	53.4	43.4	1	757.6
	2557-a	17.9	0.1	26.1	553.2	46.4	436.4	460322.8	298.9	2686.1	2.4	31	58.4	18.8	1.2	386.4
	2557-b	17.3	0.1	25.9	334.5	78.7	414.3	461772.5	376.6	2119.2	2.3	23.8	22.3	14.7	0.9	467.5
	2557-c	22.1		28.7	405.4	65.6	538.5	463183.6	581.1		2.5	47.2	75.9	52.1	4.3	432.8
	2941-a	8.6	0.5	59.4	550.4	76.1	783.2	451974.2	502.2	9593	2.9	57.8	39.3	29.9	2.9	500.5
	2941-b	3.9	0.2	91.5	522.7	56.5	683.8	460611.5	674.4	2951	2.8	36.2	54.1	54.6	1.4	1303
	2941-c	8.3	0.4	49.6	855.2	170.7	1001.9	439617.1	902.5	18822.8	3	72.6	89.5	50.4	1.7	2123.3
	3118-a	13.3	0.2	49.4	518.8	53.7	1040.3	462032.4	582.8	1187	2.8	51.7	29.3	57.4	1.9	839.1
	3118-b	15.6	0.3	40.3	547	60.9	1158	453478.6	618.5	3008.4	2.7	65.4	115.4	100.8	2	3891.2
	3118-c	14.8	0.1	50.3	570	53	1218.2	458284.2	670	2371.3	2.8	77.1	38.1	57.2	0.8	590.1
	3131-a	8.9	0.1	47.6	334.9	63.9	551.8	463952.3	363.1	695.1	2.1	53.3	72.2	27.4	0.9	895.6
	3131-b	9.3	0.1	43.9	316.6	40.1	544.7	463978.6	331.4	802.4	2.2	48.8	45.9	14.9	0.9	841.1
	3131-c	8.9		45	378	65.2	561.7	464045.6	354.6	661.4	2.4	67.3	48.4	25.4	1.2	649.8
	3468-a	23.3		14.9	464	61.6	1401.4	454669.8	638.7	955.7	2.6	64.4	71.4	29.4	0.8	555.4
	3468-b	24		13.5	457.7	74.5	1563.3	461494.5	636.1	856.5	2.7	78.6	99.2	41.2	2.6	1463.1
	3468-c	23.4		14.7	426.8	68.5	1521.3	463330.8	644.6	561.6	2.6	98.8	81.7	30.7	1.1	535.5
	3547-a	42	0.3	20	435.2	64.5	1129.9	455928.8	392.6	6848.2	2.2	149.7	22.7	34.8	1.7	200.3
	3547-b	41.9	0.7	20.9	374.2	37.4	1059.3	456509	324.6	7043.5	2.2	72.8	21.6	33.8	4.1	319.9
	3547-c	41.7	0.2	20.6	443.3	36.7	1089.9	452325.7	349.6	10969.5	2.1	24.3	17.6	26	2.8	295.6

	3603-a	7.4	0.2	49.2	500.4	35.5	455.9	459023.8	342.3	1574	2.3	37.5	121.2	59.2	3.4	1120.1
	3603-b	6.9	0.1	45.8	530.1	29	567.3	459915.2	365	1883.1	2.2	37.7	94.4	46.9	1.2	1018.9
	3603-c	6.1	0.2	50.4	495	20.7	511.3	459796.2	235.3	2647.4	2.3	78.9	42.1	26.4	1.2	475.2
	3883-a	13	0.3	24.3	669.8	255	1502.1	459763.7	1214.7	2594	2.4	88.9	78.1	71.2	2.4	1323.6
	3883-b	15	0.4	20.1	881.1	403.5	1561.3	450958.3	1347	9984	2.6	122.9	102.2	90.4	5.9	2427.8
	3883-c	14	0.3	22.9	577.8	280.5	1696.3	459547.6	1315.1	2426.6	2.1	167.2	71.8	80	5.4	1326.8
	3912-a	11.1	0.2	34.8	482.1	29.5	468.5	462924.5	277.9	2662.3	6.5	23.7	12	14.9	0.5	72.3
	3912-b	10.2		35.3	530	32.3	618.2	462070	396.9	3048.3	6.4	25.9	13.1	14.9	0.6	102.1
	3912-c	11	0.2	39.5	360.2	20.8	419.4	464728.3	218.4	1376.9	6.3	24.3	8.3	10.8	0.5	39.3
	4018-a	3.6	0.4	85.5	443.9	39.8	485.6	459355.5	216	4879.6	2.4	25.5	31.9	10.9	1.2	303.9
	4018-b	10	0.3	62.4	655.9	33.7	821.9	458065.6	388.3	3739	2.5	61.5	58	44	1.3	510.5
	4018-c	10.5	0.2	54.9	629.1	36.1	795.4	453856.8	402.6	6668.6	2.6	61.8	89.4	45.5	2.3	750
	4038-a	9.5	0.4	29.9	470.3	45.9	708	461493.6	359.9	3223.3	2.1	48.8	41.7	29	1.6	583.9
	4038-b	9.4	0.1	33.4	383.8	30.4	574.2	463259.5	275.3	2613.9	2.2	45.6	17.9	12.3	0.9	114.9
	4038-c	10.9	0.2	30.4	319.7	17.6	554.7	463854.5	245.1	1350.5	2.2	43.3	58.3	24.5	1	481.8
	4134-a	17.4	0.1	35.3	688.7	57.2	887.3	460807.2	402.4	3363.2	4.7	68.1	32.8	52.4		121.7
	4134-b	16.7	0.2	32.0	592.4	73.3	904.2	455699.3	410.2	6027.7	4.4	56.4	55.9	65.8		229.2
	4134-c	15.2	0.2	31.5	667.4	87.4	837.5	457135.8	378.6	8861.0	4.5	49.1	45.8	66.8		160.4
	4134-d	14.8	0.1	28.2	580.4	44.8	844.3	462700.0	312.5	2935.9	4.1	40.1	27.1	29.7		85.6
	4488-a	2.7	0.1	35.7	385.1	120.1	339.8	457641.7	1089.1	1904.8	2.7	39.7	159.5	133.4	3.5	2607.2
	4488-b	2.1	0.2	30.6	331.9	73.9	371.8	461540.1	453.6	1472.2	2.7	59.3	88.9	84.9	1.7	1516
	4488-c	2.8	0.1	48.7	385.4	139.2	411.1	461003.3	462.7	791.1	2.9	34.5	105.6	108.1	2.2	2429.2

	4495-a	5.2	0.3	50.8	420	88.6	564.1	458855.4	392.7	5522.3	2.4	47.6	95	43.1	4.5	928.6
	4495-b	5.4	0.3	53.2	349.6	82.8	569	462685.2	455.2	2799.2	2.4	56.9	64.3	28.8	3.8	320.6
	4495-c	7.6	0.3	52.5	457.9	214	897	461370.6	1309.1	1810.3	2.3	111.3	159.1	65.2	5.6	1529.9
	4675-a	6.3	0.3	30.7	1062	324	860.4	453087	1596.6	1808.5	2.3	103.2	179.7	151.2	6.6	4102.4
	4675-b	4.8	0.1	38.4	1054.6	463.5	837.3	450266.1	1525.5	2926.5	2.1	128.8	327.8	188.4	5.2	5753.5
	4675-c	5.4	0.2	40.4	1698.1	838.8	1523.5	436595.4	2649	3224.6	2.5	371.1	626.2	349.6	17.9	13906.1
	4751-a	15	0.1	50.2	931.5	222.9	1158.8	457533.8	1010.6	2019.8	2.4	137.8	129	91.1	5.5	3130.7
	4751-b	11.5	0.2	45.9	468.6	245.7	1155.9	457967.9	946	1516.4	2.2	117.5	119.4	68.1	2.5	3684.7
	4751-c	10.1	0.2	47.8	540.8	229.5	988.9	456849.9	998.3	1607.8	2.4	296.6	134.6	73.9	4	3529.4
	4752-a	4.7		45.6	458.4	42.9	485.7	460650	299.9	4020.7	2.1	58	53.6	28.3	2.7	601.5
	4752-b	5	0.2	44.8	338.4	27.8	406	462320.5	225.4	2424.7	2.1	32.3	96.5	41.5	2.6	603.9
	4752-c	5.7	0.1	42.2	350.7	33.7	441.4	463338.3	276.9	1570.4	2	32.8	47.2	21.1	2.9	824.2
Precision (1 sigma NIST 613)		11%	10%	7%	14%	7%	1%	4%	4%	8%	3%	3%	12%	7%	9%	4%
Limit of detection (ppm)		0.1	0.1	0.8	53.6	0.8	10.8	1970.0	147.0	509.0	0.6	0.4	0.1	4.7	0.4	2.3

Table 2/3																		
Layer	Artifact	Co	Ni	Cu	Zn	Ga	Ge	Rb	Sr	Y	Zr	Nb	Ag	Sn	Sb	Ba	La	Ce
8	2947-a	0.1	1.8	2.4	5.3	1	1.1	0.3	25.3	3.2	7.6	0.2	6.9	0.1	0.1	62.7	1.3	0.7
	2947-b		1.7	1.7	4.7	0.7	1.1	0.4	15.5	1.3	7	0.2	6.3	0.1	0.1	46.8	0.5	0.3
	2947-c		1.8	2.5	6.3	0.9	0.9	0.5	26.3	3.4	6.4	0.2	8	0.1	0.2	89.8	1.2	0.8
	3082-a	0.2	2.9	3.9	14.7	8.5	0.9	0.7	62.8	3.2	1.2	0.1	2.9	0.2	0.1	1028.8	1.2	3.6
	3082-b	0.1	2.1	2.9	4.7	1.7	0.8	0.4	55.4	0.9	1	0.1	3	0.2	0.1	208.8	0.5	1.3
	3082-c	0.3	5.3	4.8	12.1	9.9	0.6	0.5	106.5	3.5	0.9	0.1	3.3	0.2	0.2	1159.7	1.7	3
	3591-a	0.5	20.1	21.6	42.8	3.5	2.1	0.8	123.4	3.4	1.3	0.3	3.4	0.2	1.5	701.6	1.9	1.7
	3591-b	0.3	16.6	23.5	28.4	2.5	2.9	0.6	123.8	6.1	1.9	0.3	3.9	0.2	2.1	303.5	2.8	1.7
	3591-c	0.2	9.8	14.6	13.9	2.4	1.7	0.5	71.4	2.1	4.7	0.1	2.9	0.2	1.1	338.6	0.9	0.6
	3711-a	0.3	7.4	15.4	16.4	7.7	0.4	1.3	63.8	2	4.1	0.2	3.1	0.1	0.8	923.9	1.7	3.3
	3711-b	0.7	13	36.1	34.8	9.2	0.5	1.7	125.6	12.7	4.5	0.2	3.9	0.1	1.5	1413.4	6.5	7.2
	3711-c	0.5	13.4	26.2	34.4	51.8	0.8	2.1	344.6	4.1	4.4	0.4	3.3	0.2	1.3	7962.9	2.2	13.8
	3805-a	0.4	4.8	6.6	10.8	3.1	2	2.3	31.5	3.4	10.5	0.4	0.7	0.2	0.2	326.8	3	9.9
	3805-b	0.4	6.8	4.1	13.1	2.2	2	2.7	28.5	4.2	31.4	0.7	0.7	0.4	0.3	238.8	3.4	8.1
	3805-c	1	9.9	10.6	27.5	4.7	2.5	5	61.4	2.4	10.1	0.6	0.7	0.4	0.2	472.2	5.6	15.8
	3806-a	0.2	1.6	2.9	4.8	1.7	0.3	0.7	14.1	2.5	6.6	0.3	1.6	0.1	0.1	176.8	1.9	2.7
	3806-b	0.9	8.9	8.2	14	1.3	0.4	0.6	11.8	3.4	5.6	0.3	2	0.1	0.4	108.9	2.1	2.5
	3806-c	0.3	2.5	4.3	5.9	1.6	0.4	0.5	17.3	2.9	5.1	0.3	2.2	0.1	0.1	184.5	2	2.8
	4033-a	0.2	3.6	12	14	0.9		0.9	6.3	0.9	1	0.1	1.8	0.2	0.3	66.1	0.4	0.2
	4033-b	0.1	2.4	5	9	0.7	0.4	0.4	10.4	1.3	1	0.1	1.7	0.2	0.1	50.9	4.3	8

	4033-c	0.1	1.4	4.5	5.2	0.5		0.3	4.1	1.3	1.8	0.1	0.8	0.1	0.1	21.3	0.5	0.3
	4192-a	0.2	7	15.3	17.1	1.6	0.6	1	15.2	0.9	4.4	0.3	4.8	0.1	0.2	115.8	0.5	1.7
	4192-b	0.2	11.7	23.1	33.9	1.9	0.4	1.6	20.7	1.7	4.6	0.4	5	0.1	0.7	157.7	0.9	2.1
	4192-c	0.2	9.6	20.4	25.6	18.3	0.4	0.9	89.9	1.1	5.4	0.3	5.3	0.2	0.5	1394.4	0.6	0.9
	4215-a	0.7	5.4	7.3	21.2	6.2	1.3	2.8	67.1	9.8	3.3	0.6	2.6	0.3	0.2	773	4.8	2.4
	4215-b	0.4	3	8	18.5	4.1	1	1.6	22.4	3.8	3	0.3	2.3	0.2	0.1	459.6	1.9	1.6
	4215-c	0.2	1.7	6.2	6.9	1.7	1.2	1.3	22	4.3	3.4	0.2	2.4	0.2	0	171.8	2.1	1.5
	4278-a	1	32.9	11.6	85.7	6.8	0.4	3.2	59.9	3.6	3.6	0.2	4.9	0.2	0.4	657.6	1.6	3.2
	4278-b	0.9	18.9	12.7	93	5.3	0.3	2.1	28.5	2.5	1.7	0.2	4.1	0.1	0.4	202.9	1.1	0.7
	4278-c	0.2	10.8	5.8	36.4	0.9	0.4	0.6	41.4	5.9	4.2	0.2	4.9	0.2	0.2	46.2	2.1	0.8
	4396-a	0.2	4.4	6.6	9.6	1	1.1	0.9	27.8	2.4	4.4	0.2	1.2	0.2	0.1	53.2	1.5	2.7
	4396-b	0.2	4.9	4.4	8	1.1	1.3	0.7	26.8	2.5	4.2	0.2	1.1	0.1	0.1	54.3	1	3.5
	4396-c	0.3	6.6	6	12.9	3.5	1.3	0.4	30.1	3.2	5.4	0.2	1.3	0.2	0.2	53.3	1.3	1.4
	4425-a	0.5	5.5	13.5	9.1	7.2		1.5	23.8	10.3	7.1	0.4	1.5	0.1	0.2	561.8	6.1	3
	4425-b	0.3	6.7	6.9	106.6	0.4	0.3	0.7	7.5	5	6.5	0.3	1.5	0.1	0.2	31	2.9	1.6
	4425-c	1	9.1	4.1	49.1	0.4		0.3	7.9	2.9	7.3	0.2	1.7	0.1	0.2	40.4	2.3	1.7
	4522-a	0.2	2.4	6.1	7.9	9.8	0.5	1.2	32.6	2.1	2.4	0.2	1.8	0.1	0.2	1498.2	1.5	2.6
	4522-b	0.5	4.9	10.2	9.1	11.2	0.7	1.5	51.4	2.7	5.7	1.1	1.9	0.4	0.4	1802.2	1.7	2.3
	4522-c	0.3	2.9	5.6	9.4	5.6	0.5	1.7	26.9	3.8	3.4	0.2	3.3	0.2	0.2	866	2.2	2.6
	4548-a	1	11.5	15.5	41.2	7.7	0.7	4	58.4	1.1	8.7	0.7	2.3	0.3	1	809.2	1.2	4.3
	4548-b	0.9	10.4	7.5	30.9	6.8	0.6	4.3	45.3	2.1	7.5	0.8	2.3	0.4	0.5	524.1	1.5	4.6

	4548-c	0.6	8	6.2	32.4	6.1	0.4	1.8	49.2	1.3	16	0.5	2.2	0.2	0.2	647.2	1.4	2.9
	4622-a	0.6	6.8	7.9	17.1	10.7	1	1.9	64.1	3.4	2.6	2.4	14.8	0.2	0.2	1248.5	2.4	5.1
	4622-b	0.4	6.2	6.5	15.2	2.8	0.9	1.3	21.9	3	2.5	0.2	11.4	0.2	0.1	185.5	2.1	4.5
	4622-c	1	10.1	17.2	27.2	2.6	0.9	2.9	34.3	4.8	2.3	0.5	10.9	0.3	0.2	599.4	3.9	9
	4651-a	0.2	4.5	8.7	15	4.7	1.2	1.3	70.9	2.6	2.2	0.2	13.9	0.4	0.4	709	2.1	9.2
	4651-b	0.2	3.2	6	9	3.9	1.7	0.9	57.3	2.5	2.7	0.2	11	0.2	0.3	591.2	1.2	4.1
	4651-c	0.1	2.2	4.4	3.9	1.5	1.4	0.6	21	1.7	2.6	0.3	10.1	0.1	0.3	205.5	0.9	3.3
	4671-a	0.4	4.1	5.8	11.3	7	0.7	2.1	39.3	5.1	4.7	0.6	1.3	0.2	0.2	803.4	3.1	4.6
	4671-b	0.5	5	6.7	11.8	4.8	0.6	1.4	33	4	3.2	0.3	1.3	0.1	0.2	610.1	2.5	3.1
	4671-c	0.3	4	4.8	8.8	17.2	0.7	1.3	66.7	4.7	3.6	0.4	1.2	0.2	0.2	2376.8	2.8	3.9
	4673-a	0.6	6.9	29.1	18.8	16.2	0.7	1.9	217.6	8.2	3.9	0.4	2.5	0.2	0.4	2180.4	3.4	1.8
	4673-b	0.1	2.2	15.6	6.3	4.8	0.4	0.6	45.5	3.2	3.7	0.3	4.5	0.2	0.1	627.2	1.3	0.8
	4673-c	0.3	5.5	10.7	5.6	2.9	0.5	0.7	48	3.6	4.9	0.8	2.6	0.1	0.1	396.4	1.7	1.6
	4826-a	2	47.4	21.8	37.9	1.1	0.5	4.6	27.1	2.6	8.4	0.6	31.4	0.2	0.7	47.5	1.5	1.3
	4826-b	0.7	19.5	20.3	35.6	1.1	0.5	2.4	46.1	3.9	7.4	1.1	41.6	0.2	0.6	64.7	2	1.2
	4826-c	0.1	5.1	7.8	11.4	1	0.6	1.8	34.5	2.6	6.4	0.5	31.5	0.2	0.2	62.2	1.4	0.9
7																		
	1200-a	0.6	11.4	7.8	25.2	4.7	1.1	0.9	79.8	1.9	2.1	0.1	2.5	0.2	0.3	645.7	0.9	1.4
	1200-b	1.2	16.2	35.8	49.1	4.2	1.1	2.3	91	3.3	2.4	0.1	2.8	0.2	0.4	560.3	1.5	1.2
	1767-a	0.3	13.7	26	12.4	7.9	0.7	0.4	34.1	4.7	6.5	0.6	0.7	0.2	0.3	423.2	2.2	2.3
	1767-b	0.1	2.7	18.6	6.3	7.1	0.9	0.3	24.1	2.8	5.7	0.1	0.7	0.2	0.1	408.2	1.5	1.9

	1767-c	0.6	14.7	25.9	16	8.1	1	0.2	31.9	2.6	6.2	0.4	0.7	0.3	0.3	482.7	1	0.4
	2557-a	0.3	3.8	2.7	8.2	3.9	0.8	1.3	35.7	3.1	6	0.2	0.5	0.3	0.1	456.4	1.2	1.2
	2557-b	0.2	6.3	1.7	7.5	3.8	0.7	0.6	34.2	5	6	0.2	0.6	0.2	0.2	478.7	2.3	2
	2557-c	0.7	6.8	6.2	15	2.8	0.9	2.5	13.3	0.5	4.3	0.2	0.6	0.3	0.2	271.8	0.6	2.2
	2941-a	0.2	3.3	8.5	12.8	24.8	0.6	0.6	221.7	5.7	25.5	0.4	2.7	0.2	0.1	3067.3	2.4	3
	2941-b	0.5	12	10.8	47.2	1.8	0.5	0.7	24.2	1.2	23.7	0.4	1.7	0.2	0.4	144.8	0.8	1.6
	2941-c	0.3	6.4	24.2	19.4	27.6	0.6	1.4	203.5	7.6	21.1	0.5	3.8	0.2	0.6	3279.8	3.2	3.1
	3118-a	0.1	3.2	11.6	16.7	8		1	59.7	0.6	3.5	0.2	3.7	0.2	0.2	856.1	0.3	0.6
	3118-b	2.5	67.7	30.9	32.9	23.8	0.3	1.2	202.2	1.8	3	0.3	3.6	0.2	1.3	3494.2	0.9	0.9
	3118-c	0.1	9.8	8.4	15	43.2	0.3	1.6	324	1.3	5.3	0.2	3	0.2	0.2	5349	0.6	0.5
	3131-a	0.3	4.6	10.1	14.9	1	0.7	0.7	9.7	0.8	3.6	0.2	1.6	0.1	1.2	67	0.4	1
	3131-b	0.6	5.9	8.2	10.7	1.9	0.6	0.8	23.7	1.2	4.1	0.2	2	0.1	1	260.7	0.5	0.6
	3131-c	0.2	3.8	3.9	12.3	6.3	0.7	1.2	26.2	1.1	3.7	0.2	2	0.2	0.8	706.1	0.5	0.6
	3468-a	0.1	2.6	8.2	14.8	90.6	0.8	1.3	706.9	0.4	4.8	0.2	4.6	0.1	0.5	12166.2	0.5	1
	3468-b	0.2	4.1	8.6	21.2	2.7	0.8	1.3	35.4	0.6	7.3	0.3	4.4	0.1	2	338.9	0.4	0.9
	3468-c	0.1	3	8.2	15.5	3.4	0.6	1.2	36	0.5	7.6	0.3	4.2	0.1	0.9	363.5	0.3	0.6
	3547-a	0.3	5.9	1.4	15.9	1.6	0.4	1	50.1	3.3	8.5	0.5	9.2	0.2	0.2	312.4	1.6	0.7
	3547-b	0.3	7.9	1.2	19.7	1.6	0.5	0.9	26.4	3.6	7.9	0.2	8.9	0.3	0.3	142.2	1.6	0.7
	3547-c	0.5	7.8	2.2	15.9	1.8	0.4	0.7	31.3	5.1	8	0.2	10	0.3	0.2	119.5	2.2	0.9
	3603-a	0.7	10.9	17.5	16.8	26.8	0.7	0.7	75.3	1.9	9.6	0.2	1.6	0.2	0.5	4214.8	0.8	0.6
	3603-b	0.3	7.3	11	20.4	17.5	0.7	0.5	61.8	2.8	10.3	0.2	1.5	0.5	0.5	2578.3	1.2	0.5

	3603-c	0.2	2	6.3	9.5	18.5	0.7	0.5	70.9	4.3	9.6	0.7	1.9	0.2	0.1	2884.4	1.7	0.8
	3883-a	0.7	6.6	11.2	20.5	4.7	0.5	2.5	39	4.7	10.9	0.6	37.7	0.3	0.2	640.1	3.4	5.9
	3883-b	0.7	7.5	15.2	33.5	2.9	0.4	4.8	74.1	12.9	11.3	0.6	40.6	0.3	0.2	280.4	9	13.7
	3883-c	1.1	10.4	11.3	31.6	2.9	0.5	3.7	28.5	4.5	11.5	0.7	43.8	0.3	0.1	213.7	3.7	5.2
	3912-a	0.3	6.8	16.5	10.4	1.3	1.2	0.5	21.9	7.5	8.3	0.3	0.6	0.2	0.1	48.6	3.1	1.3
	3912-b	0.4	7.5	16.1	9.2	1.2	1.5	0.6	29.4	8.2	7.7	0.3	0.6	0.1	0.1	51.5	4	2.1
	3912-c	0.2	4.7	19.7	11.7	1.1	1.4	0.3	11.6	3.5	7.1	0.2	0.5		0	40.1	1.4	0.6
	4018-a	0.1	3	10.1	28.1	8.9	0.7	0.4	47.7	1.8	11.1	0.2	2.4	0.1	0.2	717.6	1.2	3.6
	4018-b	0.1	10.1	26.3	32.9	32.8	0.6	0.8	77.7	1.7	10.9	0.4	6.5	0.2	0.6	3956.6	0.7	0.5
	4018-c	0.1	11.9	36.2	38.6	35.9	0.6	0.5	143.2	3.5	8	0.3	7.3	0.2	0.9	5139.4	1.5	1
	4038-a	0.4	6.5	9	31.6	3.8	1	0.9	34.3	4.2	7.9	0.3	2.9	0.1	0.2	602.6	3.6	4.5
	4038-b	0.2	2.7	8	17.4	0.4	0.8	0.5	19.7	3.6	7.4	0.3	2.9	0.1	0.1	43	1.4	0.6
	4038-c	0.9	10.4	14	33	1.7	0.9	0.4	20.5	2	8.5	0.3	2.5	0.2	0.3	227.7	0.9	0.6
	4134-a	0.1	5.6	11.7	266.0	80.5	0.4	0.9	85.4	4.1	5.9	0.3	2.5	0.2	0.8	2102.7	1.3	0.6
	4134-b	0.2	7.1	12.3	13.4	281.7	0.5	0.8	276.4	6.7	5.0	0.3	2.6	0.2	1.4	6011.8	2.2	1.0
	4134-c	0.1	6.1	8.9	10.0	8.3	0.4	0.7	68.3	10.5	4.5	0.2	2.2	0.2	0.9	207.9	3.3	1.3
	4134-d	0.1	4.0	7.8	12.6	13.5	0.3	0.6	39.2	3.5	6.8	0.3	2.9	0.2	0.3	351.6	1.1	0.5
	4488-a	0.4	6.9	5.6	32.4	1	0.5	1.7	14.6	2.6	4	0.3	0.5	0.2	0.4	32.6	2.1	12.6
	4488-b	0.3	6.1	5.6	17.2	1	0.4	0.7	10.1	1.4	3.9	0.3	0.8	0.1	0.3	33.6	1.2	2.7
	4488-c	0.3	5.7	3.1	17.7	1	0.5	1.2	6.5	1.7	3	0.2	0.7	0.3	0.4	33.9	1.4	8
	4495-a	0.9	18.1	8.2	41.8	0.9	1.2	0.9	41	8.7	4.4	0.2	2.2	0.2	0.6	64	3.7	1.6

	4495-b	0.3	7.2	3.5	22.3	0.6	1	1	20.7	4.6	4.7	0.3	1.8	0.1	0.1	45.4	2	0.9
	4495-c	1	9.5	7.9	29.8	0.9	1.3	4.5	15.7	2.4	4.4	0.3	1.6	0.4	0.2	47.1	1.1	7.2
	4675-a	0.8	10	12.8	48.7	1.8	0.9	3.1	83.9	3.6	3.1	0.3	0.9	0.3	0.5	540.9	2.6	10.3
	4675-b	1.6	13.8	9.5	43.5	2.6	0.8	4.4	27	2.8	2.2	0.3	0.8	0.4	0.7	207.2	1.5	4.6
	4675-c	2.6	26.6	21.7	83.1	2.6	1.6	8.4	26.4	3.2	3.4	0.6	0.5	0.4	1.3	61.7	2.3	7.9
	4751-a	0.8	12.3	16.7	26.4	1.6	0.6	2.7	22.8	2.9	10.4	0.5	4.2	0.2	1.1	131	1.6	4.1
	4751-b	0.8	8.8	10.5	29.4	2.2	1	1.7	28.7	2.3	11.9	0.5	4.4	0.3	1	192.8	1.2	2.5
	4751-c	0.7	6.9	13	23.2	12.2	1	2.5	83.9	2.8	11.6	1	4.9	0.2	0.9	1844.4	1.7	2.5
	4752-a	0.3	7.9	7.9	20.2	1.4	0.4	0.8	31.4	4.5	4.8	0.3	4.5	0.2	0.6	180.8	1.7	1.3
	4752-b	0.3	12.7	9	33.4	5.1	0.5	0.4	31.5	2.8	4.7	0.3	4.6	0.2	0.9	711.6	1	0.5
	4752-c	0.4	9.5	5.9	19.3	0.9	0.6	0.5	14.7	1.8	4.4	0.2	3.9	0.2	0.6	120.1	0.8	0.5
Precision (1 sigma NIST 613)		5%	3%	2%	1%	11%	9%	15%	11%	6%	7%	9%	2%	14%	8%	15%	10%	13%
Limit of detection (ppm)		0.04	0.6	1.0	0.1	0.0	0.3	0.2	0.2	0.01	0.01	0.01	0.01	0.03	0.03	3.0	0.01	0.01

Table 3/3																
Layer	Artifact	Pr	Nd	Sm	Eu	Gd	Dy	Yb	Lu	Pb	Th	U	Al/(Al+Fe+Mn)	Fe/Ti	Ni/Co	Total REEs
8	2947-a	0.2	0.9	0.2	0.1	0.3	0.3	0.2		0.3	0.1	9.7	0.65	8.55	18	4.2
	2947-b	0.1	0.3	0.1	0	0.1	0.1	0.1		0.2	0.1	8.3	0.81	4.5		1.6
	2947-c	0.2	0.9	0.2	0	0.3	0.3	0.2		0.2	0.1	10.7	0.8	3.8		4.1
	3082-a	0.3	1	0.1	0.1	0.2	0.2	0.1		1	0.1	6.3	0.27	14.37	14.5	6.8
	3082-b	0.1	0.3	0.1	0	0.1	0.1	0.1		0.3	0	4.8	0.51	12.88	21	2.6
	3082-c	0.4	1.3	0.2	0.1	0.3	0.3	0.2		1.4	0.3	7.4	0.14	103.51	17.67	7.5
	3591-a	0.3	1	0.2	0.1	0.3	0.3	0.3		0.6	0.1	3.6	0.21	9.08	40.2	6.1
	3591-b	0.4	1.6	0.3	0.1	0.5	0.5	0.5	0.1	0.3	0.2	2.9	0.35	6.31	55.33	8.6
	3591-c	0.5	0.6	0.1	0	0.1	0.2	0.2		0.2	0.1	1.3	0.55	9.48	49	3.2
	3711-a	0.3	0.9	0.2	0.1	0.2	0.3	0.1		0.5	0.1	11.5	0.45	13.24	24.67	7.1
	3711-b	1.1	4.5	0.7	0.4	0.9	1	0.9	0.1	0.8	0.2	22.2	0.36	20.11	18.57	23.4
	3711-c	0.8	1.9	0.6	0.2	0.5	0.4	0.3		1	0.1	14.6	0.28	30.14	26.8	20.8
	3805-a	0.5	1.7	0.3	0.1	0.3	0.4	0.2		1.3	0.2	3.3	0.25	38.21	12	16.4
	3805-b	0.7	2.5	0.6	0.1	0.5	0.5	0.5	0.1	1.4	0.7	3.9	0.36	15.14	17	17.1
	3805-c	0.7	1.9	0.3	0.1	0.3	0.3	0.2		1.7	0.3	6.1	0.19	35.19	9.9	25.2
	3806-a	0.3	1.2	0.3	0.1	0.3	0.3	0.1		0.5	0.1	4.4	0.56	12.3	8	7.2
	3806-b	0.3	1.4	0.2	0.1	0.3	0.3	0.2		0.8	0.1	4.4	0.42	26.07	9.89	7.4
	3806-c	0.3	1.3	0.3	0.1	0.4	0.3	0.2		0.7	0.1	4	0.54	16.59	8.33	7.7
	4033-a	0	0.2	0	0	0	0.1	0.1		5.5	0	3.9	0.33	19.57	18	1
	4033-b	0.7	2.1	0.2	0	0.1	0.1	0.1		0.4	0.1	4.6	0.53	6.71	24	15.6

	4033-c	0.1	0.3	0.1	0	0.1	0.1	0.1		0.3	0	5.8	0.51	5.01	14	1.6
	4192-a	0.1	0.3	0.1	0	0.1	0.1	0.1		0.6	0.1	2.2	0.59	7.46	35	3
	4192-b	0.1	0.6	0.1	0	0.2	0.1	0.1		2.2	0.1	2.7	0.42	8.76	58.5	4.2
	4192-c	0.1	0.3	0.1	0	0.1	0.1	0.1		1	0.1	2	0.4	24.54	48	2.3
	4215-a	0.5	2.3	0.5	0.1	0.6	0.8	0.7	0.1	0.7	0.1	6.2	0.44	12.08	7.71	12.9
	4215-b	0.2	1.1	0.2	0.1	0.2	0.3	0.2		0.7	0.1	5	0.58	10.2	7.5	5.8
	4215-c	0.3	1.1	0.2	0.1	0.3	0.3	0.2		0.5	0.1	5.3	0.54	12.64	8.5	6.1
	4278-a	0.2	0.8	0.1	0.1	0.2	0.3	0.2		2.5	0.1	11.4	0.26	14.03	32.9	6.7
	4278-b	0.2	0.5	0.1	0	0.1	0.2	0.1		2.4	0.1	5.6	0.33	31.05	21	3
	4278-c	0.3	1.2	0.2	0.1	0.4	0.4	0.4	0.1	1	0.1	10.7	0.39	25.64	54	6.1
	4396-a	0.3	0.9	0.3	0.1	0.2	0.2	0.2		0.4	0.1	3.7	0.67	6.43	22	6.4
	4396-b	0.2	0.8	0.2	0	0.2	0.2	0.2		0.3	0.1	3.8	0.78	3.94	24.5	6.3
	4396-c	0.3	1	0.2	0.1	0.2	0.3	0.2		1.8	0.1	5.4	0.46	15.51	22	5
	4425-a	1	4	0.9	0.3	1.1	1	0.4	0.1	0.7	0.1	4.9	0.42	12.1	11	18.1
	4425-b	0.5	2.3	0.5	0.1	0.6	0.5	0.3		0.7	0.1	3.7	0.39	17.56	22.33	9.4
	4425-c	0.5	2	0.3	0.1	0.4	0.4	0.2		0.3	0	3.2	0.26	29.34	9.1	8
	4522-a	0.3	1	0.2	0.1	0.3	0.2	0.1		0.6	0	4.9	0.48	9.39	12	6.3
	4522-b	0.3	1	0.2	0.1	0.3	0.2	0.1		1.1	0.1	5.6	0.34	2.49	9.8	6.2
	4522-c	0.3	1.2	0.2	0.1	0.3	0.3	0.2		0.6	0.1	5.6	0.48	11.1	9.67	7.4
	4548-a	0.2	0.8	0.1	0.1	0.2	0.2	0.2		4.4	0.2	6	0.29	22.3	11.5	7.3
	4548-b	0.4	1.6	0.3	0.1	0.3	0.3	0.2		1.6	1.3	6.8	0.28	26.23	11.56	9.3

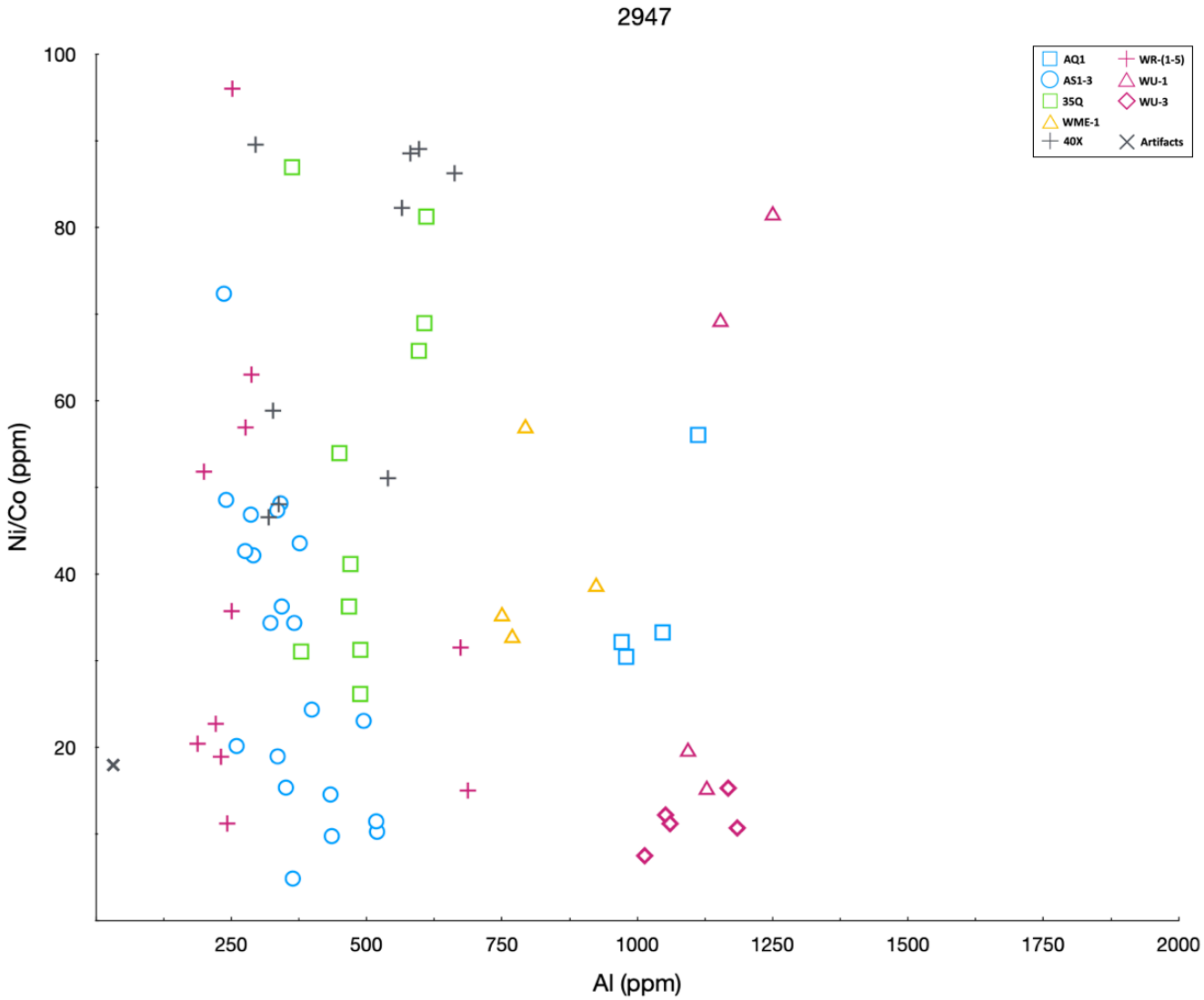
	4548-c	0.3	1.1	0.2	0.1	0.2	0.2	0.1		2.2	0.5	4	0.3	22.87	13.33	6.5
	4622-a	0.5	1.5	0.3	0.1	0.4	0.3	0.2		1.4	0.1	18.6	0.5	9.53	11.33	10.9
	4622-b	0.4	1.6	0.3	0.1	0.4	0.3	0.2		1	0	16.7	0.54	7.12	15.5	9.9
	4622-c	0.8	3.5	0.5	0.1	0.4	0.4	0.3		3.5	0.2	19.2	0.4	5.7	10.1	19
	4651-a	0.8	2.2	0.4	0.2	0.3	0.4	0.2		1.3	0.2	5.3	0.62	9.08	22.5	15.8
	4651-b	0.2	0.8	0.2	0.1	0.2	0.2	0.2		0.9	0.1	5.2	0.55	9.55	16	7.2
	4651-c	0.6	0.6	0.2	0.1	0.1	0.2	0.1		0.4	0.1	4.5	0.52	14.63	22	6.1
	4671-a	0.5	2	0.4	0.1	0.5	0.5	0.3		1.2	0.1	2.8	0.41	11.44	10.25	12.1
	4671-b	0.4	1.5	0.3	0.1	0.4	0.4	0.2		0.8	0.1	2.4	0.44	7.41	10	8.9
	4671-c	0.4	1.8	0.3	0.1	0.4	0.4	0.3		1.8	0.1	2.5	0.49	8.91	13.33	10.5
	4673-a	0.5	1.8	0.4	0.1	0.5	0.6	0.5	0.1	0.7	0.1	3	0.4	7.03	11.5	9.8
	4673-b	0.2	0.8	0.2	0.1	0.2	0.3	0.2		0.3	0.1	1.9	0.69	5.24	22	4.1
	4673-c	0.2	0.9	0.2	0.1	0.2	0.3	0.3		0.6	0.1	1.9	0.57	2.71	18.33	5.5
	4826-a	0.3	0.9	0.2	0.1	0.3	0.3	0.2		0.3	0.2	2.5	0.66	6.99	23.7	5.1
	4826-b	0.3	1.3	0.3	0.1	0.3	0.4	0.3		0.4	0.2	3.5	0.6	9	27.86	6.2
	4826-c	0.2	0.9	0.2	0.1	0.2	0.2	0.2		0.3	0.2	2.5	0.76	3.41	51	4.3
7																
	1200-a	0.1	0.6	0.2		0.2	0.1	0.1		0.9	0.2	2.1	0.31	18.26	19	3.6
	1200-b	0.2	0.9	0.1	0.1	0.2	0.3	0.2		1.2	0.1	2.4	0.29	13.39	13.5	4.7
	1767-a	0.3	1.3	0.2	0.1	0.5	0.4	0.4	0.1	0.8	0.1	10.6	0.24	14.88	45.67	7.9
	1767-b	0.3	1.1	0.1	0.1	0.3	0.3	0.2		0.5	0.1	7.9	0.62	9.75	27	5.8

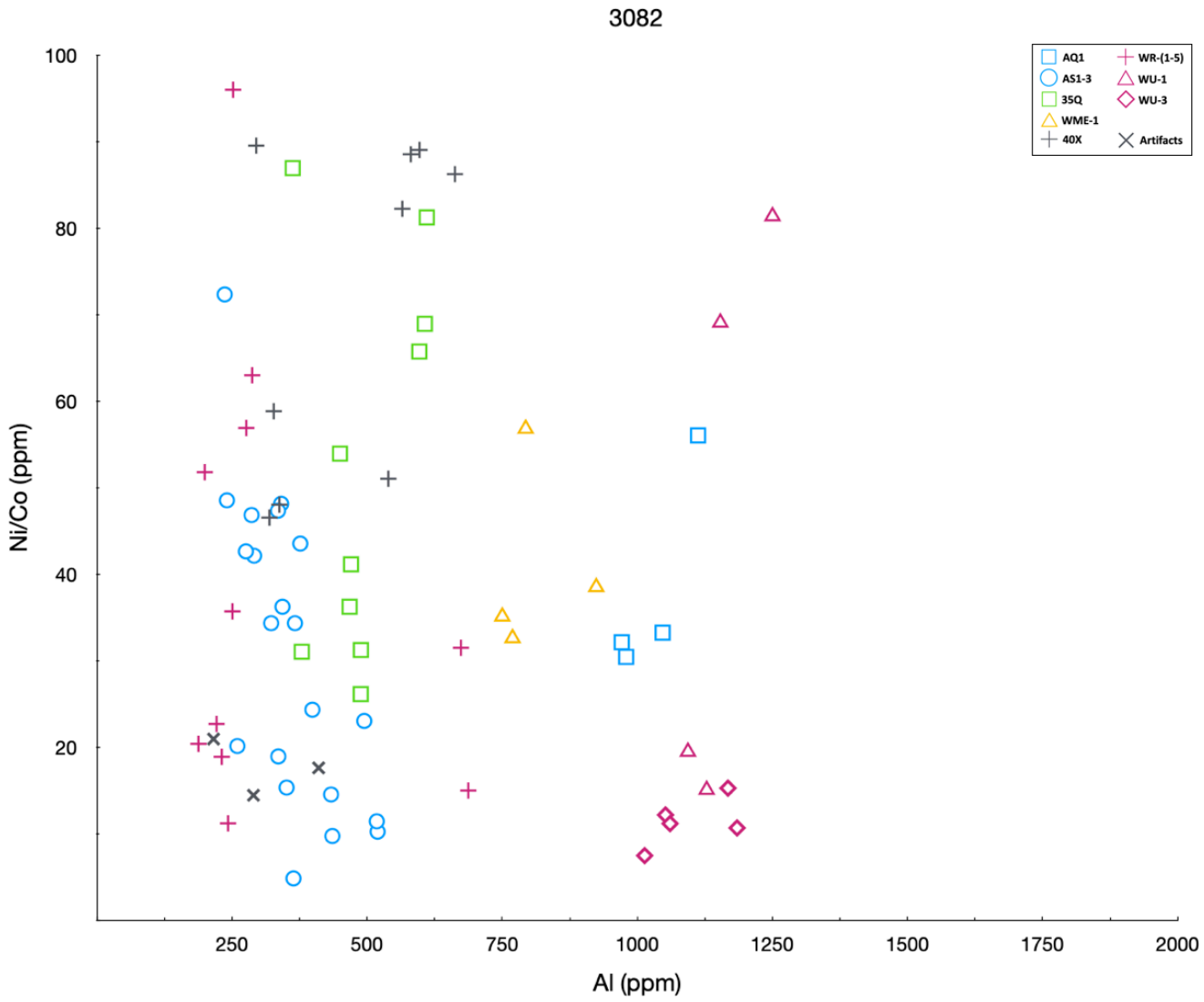
	1767-c	0.1	0.6	0.1	0.1	0.3	0.2	0.2		0.7	0.1	9	0.33	12.03	24.5	3
	2557-a	0.2	0.8	0.2		0.2	0.2	0.2		0.4	0.1	11.6	0.53	12.46	12.67	4.2
	2557-b	0.2	1	0.2	0.1	0.4	0.4	0.3		0.5		10.1	0.47	19.64	31.5	6.9
	2557-c	0.2	0.6	0.1		0.1	0.1			1.6	0.1	6.3	0.55	9.17	9.71	3.9
	2941-a	0.3	1.3	0.3	0.1	0.4	0.4	0.4	0.1	0.2	0.1	3.8	0.61	8.66	16.5	8.7
	2941-b	0.1	0.3	0.1		0.1	0.1	0.1		0.2	0.1	1.6	0.34	35.99	24	3.2
	2941-c	0.4	1.8	0.4	0.2	0.5	0.5	0.5	0.1	1.1	0.1	5.5	0.32	29.25	21.33	10.8
	3118-a	0.1	0.2	0.1		0.1	0.1			0.5	0.1	1.9	0.55	16.23	32	1.5
	3118-b	0.2	0.6	0.2	0.1	0.2	0.2	0.1		2.3	0.2	2.4	0.23	59.5	27.08	3.4
	3118-c	0.1	0.4	0.1	0.1	0.1	0.1	0.1		0.2	0.2	2.4	0.67	7.65	98	2.1
	3131-a	0.1	0.3	0.1		0.1	0.1	0.1		0.6	0.1	5.6	0.38	16.8	15.33	2.2
	3131-b	0.1	0.4	0.1		0.1	0.1	0.1		0.5	0.1	6.4	0.39	17.24	9.83	2
	3131-c	0.1	0.4	0.1		0.1	0.1	0.1		0.5	0.1	5.5	0.46	9.66	19	2
	3468-a	0.1	0.3	0.1	0.2	0.1				0.3	0.1	1.5	0.72	8.62	26	2.3
	3468-b	0.1	0.4	0.1		0.1	0.1			1	0.1	1.4	0.52	18.61	20.5	2.1
	3468-c	0.1	0.3	0.1		0.1	0.1	0.1		0.4	0.1	1.2	0.74	5.42	30	1.7
	3547-a	0.2	0.9	0.2		0.3	0.3	0.2		0.1	0.1	5.7	0.85	1.34	19.67	4.4
	3547-b	0.2	1	0.2	0.1	0.3	0.3	0.3		0.3	0.1	8.1	0.77	4.39	26.33	4.7
	3547-c	0.3	1.4	0.3	0.1	0.4	0.4	0.4	0.1	0.1	0.1	5.1	0.79	12.16	15.6	6.6
	3603-a	0.1	0.5	0.1	0.1	0.2	0.2	0.2		0.4	0.1	3.8	0.29	29.87	15.57	2.8
	3603-b	0.2	0.7	0.1	0.1	0.2	0.2	0.2		0.6	0.1	4.4	0.36	27.03	24.33	3.4

	3603-c	0.2	1.1	0.2	0.1	0.3	0.4	0.3		0.1	0.1	4.7	0.52	6.02	10	5.1
	3883-a	0.8	3.1	0.6	0.2	0.8	0.6	0.4	0.1	1	0.2	4.3	0.53	14.89	9.43	16
	3883-b	1.8	6.6	1.3	0.4	1.7	1.5	0.9	0.1	2.1	0.4	7.6	0.39	19.75	10.71	37.2
	3883-c	0.7	2.2	0.5	0.2	0.5	0.5	0.3		1.6	0.2	5.7	0.56	7.94	9.45	13.9
	3912-a	0.5	2.2	0.4	0.1	0.7	0.6	0.4	0.1	0.4	0.1	6.1	0.87	3.05	22.67	9.5
	3912-b	0.7	3	0.7	0.1	0.7	0.8	0.5	0.1	0.4	0.1	6.2	0.86	3.94	18.75	12.8
	3912-c	0.2	1.1	0.2	0.1	0.3	0.3	0.2		0.3		4.6	0.91	1.62	23.5	4.4
	4018-a	2.9	0.6	0.1	0.1	0.1	0.2	0.1		0.5	0	9.6	0.61	11.92	30	8.9
	4018-b	0.1	0.4	0.1	0.1	0.2	0.1	0.1		0.3	0.1	5.2	0.62	8.3	101	2.3
	4018-c	0.2	0.9	0.2	0.1	0.3	0.3	0.2		0.5	0.2	6.9	0.51	12.14	119	4.7
	4038-a	0.7	2.5	0.5	0.1	0.4	0.4	0.3		0.4	0.2	9.3	0.55	11.97	16.25	13.1
	4038-b	0.2	0.9	0.2	0	0.3	0.3	0.3		0	0.1	8.5	0.83	2.52	13.5	4.2
	4038-c	0.1	0.5	0.1	0	0.2	0.2	0.1		0.2	0.1	8	0.53	11.13	11.56	2.7
	4134-a	0.2	0.9	0.2	0.1	0.3	0.4	0.3	0.1	0.8	0.1	6.4	0.9	1.8	66.4	4.5
	4134-b	0.3	1.6	0.3	0.3	0.7	0.6	0.6	0.1	1.7	0.1	10.3	0.8	4.1	39.6	7.8
	4134-c	0.5	2.2	0.4	0.1	0.8	1.0	0.9	0.1	1.2	0.2	13.4	0.8	3.3	51.9	10.8
	4134-d	0.2	0.7	0.1	0.1	0.2	0.3	0.3	0.1	0.5	0.1	4.7	0.9	2.1	57.1	3.6
	4488-a	0.6	1.6	0.3	0.1	0.2	0.3	0.2		0.7		8.8	0.12	65.67	17.25	18
	4488-b	0.2	0.6	0.1		0.2	0.1	0.1		0.6		5.7	0.2	25.56	20.33	5.2
	4488-c	0.5	1.1	0.2	0.1	0.2	0.1	0.1		0.9		6.8	0.14	70.41	19	11.7
	4495-a	0.5	2.3	0.4	0.1	0.6	0.7	0.6	0.1	0.3	0.1	2.9	0.38	19.51	20.11	10.7

	4495-b	0.3	1.2	0.2	0.1	0.3	0.4	0.3		0.3	0.1	2.4	0.64	5.63	24	5.8
	4495-c	0.2	0.7	0.1		0.2	0.2	0.2		1	0.1	2.8	0.37	13.75	9.5	9.9
	4675-a	0.7	1.9	0.4	0.1	0.4	0.3	0.2		3.8	0.2	17.5	0.17	39.75	12.5	16.9
	4675-b	0.3	1	0.2	0.1	0.4	0.4	0.2		1.9	0.2	16.1	0.13	44.67	8.63	8.7
	4675-c	0.6	1.9	0.3	0.1	0.4	0.3	0.2		4.2	0.3	30.4	0.1	37.47	10.23	14
	4751-a	0.3	1.2	0.2	0.2	0.2	0.2	0.2		1.5	0.1	3.7	0.27	22.72	15.38	8.2
	4751-b	0.3	1.2	0.4	0.1	0.2	0.2	0.2		1.6	0.2	3.5	0.24	31.36	11	6.3
	4751-c	0.4	1.1	0.2	0.1	0.3	0.3	0.2		1.8	0.2	4.5	0.22	11.9	9.86	6.8
	4752-a	0.3	1	0.2	0.1	0.3	0.3	0.3	0.1	0.2	0.1	6	0.45	10.37	26.33	5.6
	4752-b	0.2	0.6	0.1		0.2	0.2	0.2		0.5	0.1	5.6	0.4	18.7	42.33	3
	4752-c	0.2	0.4	0.1		0.1	0.1	0.1		0.3	0.1	4.8	0.35	25.13	23.75	2.3
Precision (1 sigma NIST 613)		13%	14%	12%	13%	9%	13%	14%	12%	16%	13%	23%				
Limit of detection (ppm)		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01				

Appendix 7: Individual Ni/Co vs. Al plots of Layer 8 artifacts.




3082
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
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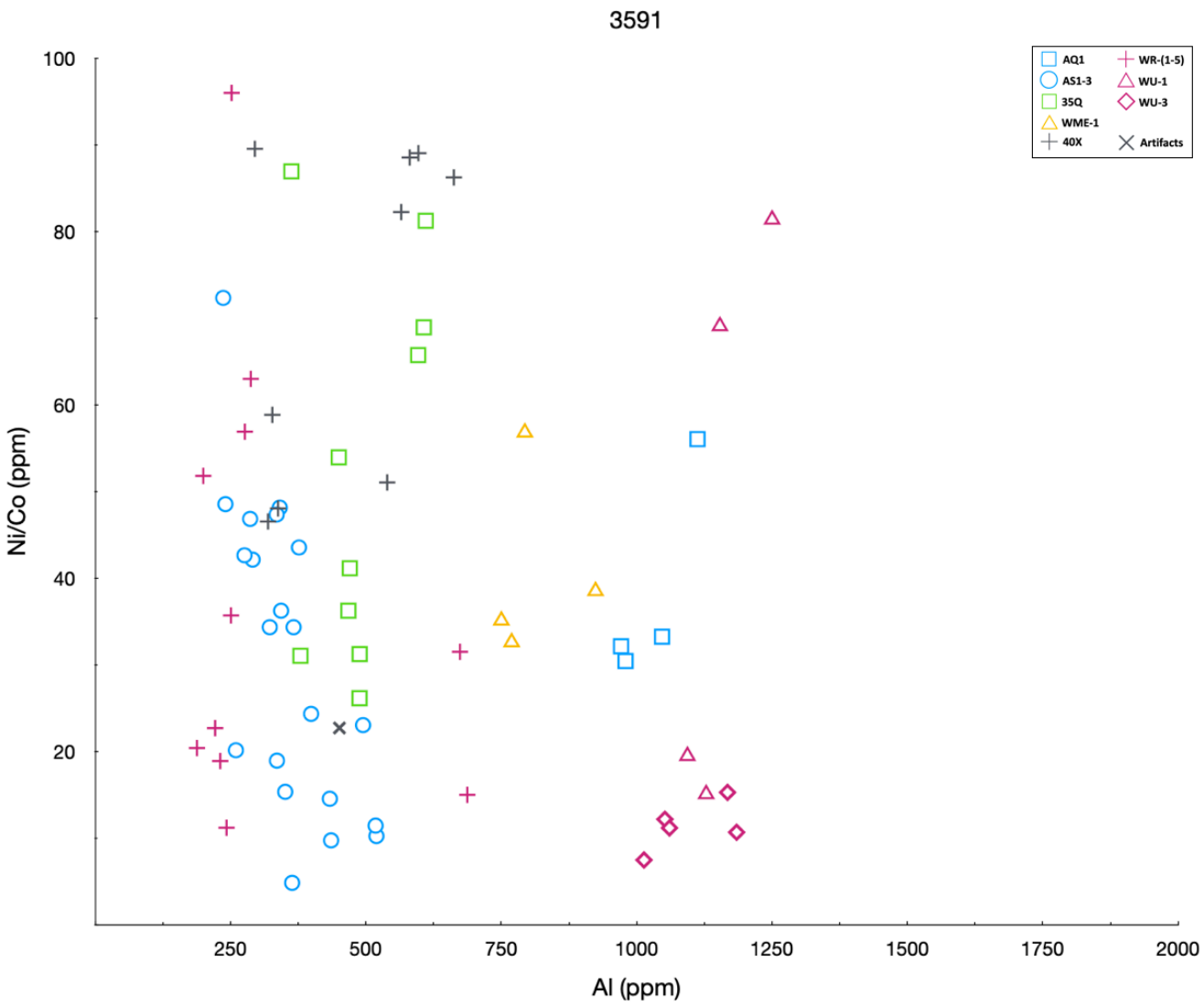
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


3591
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
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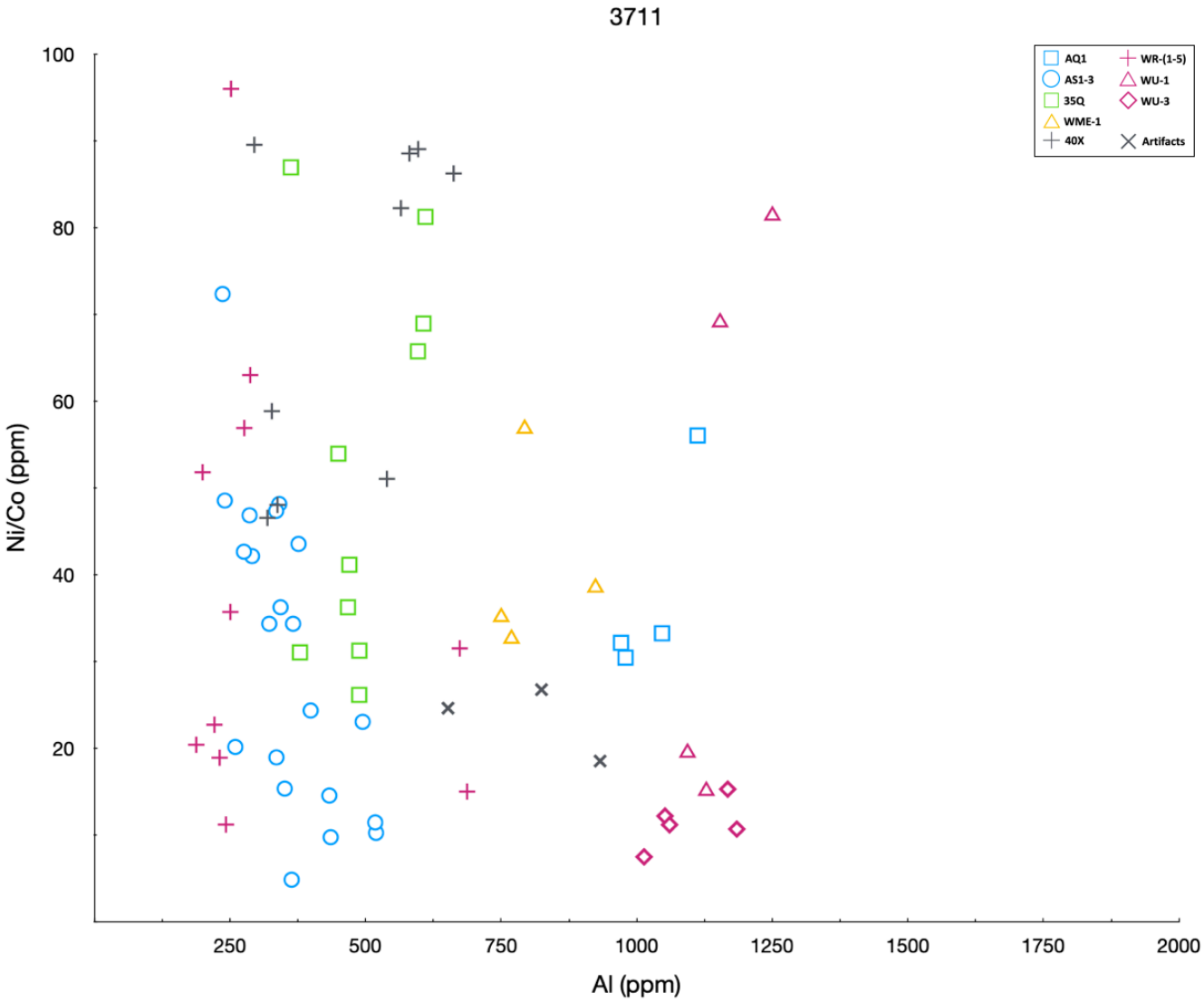
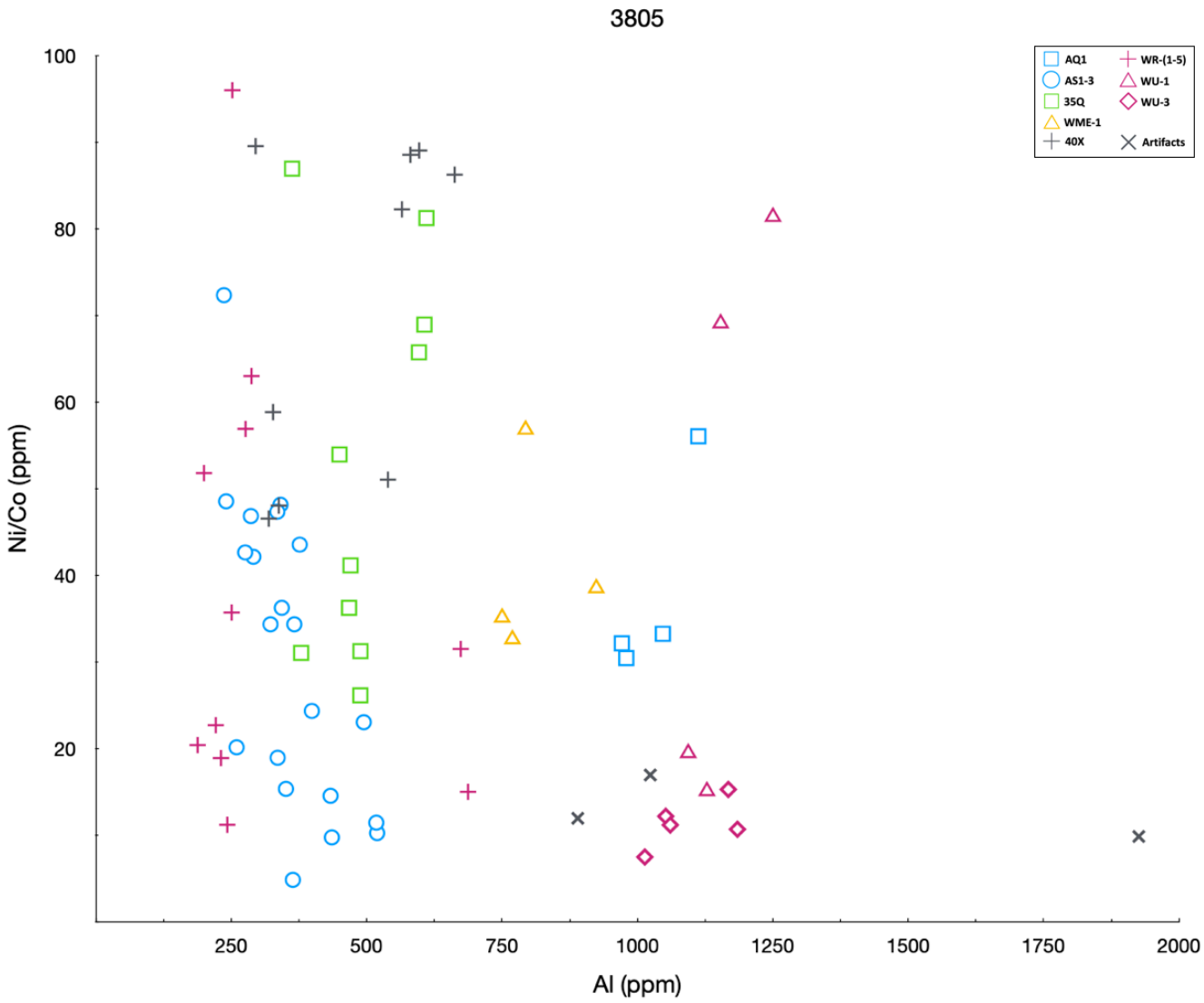
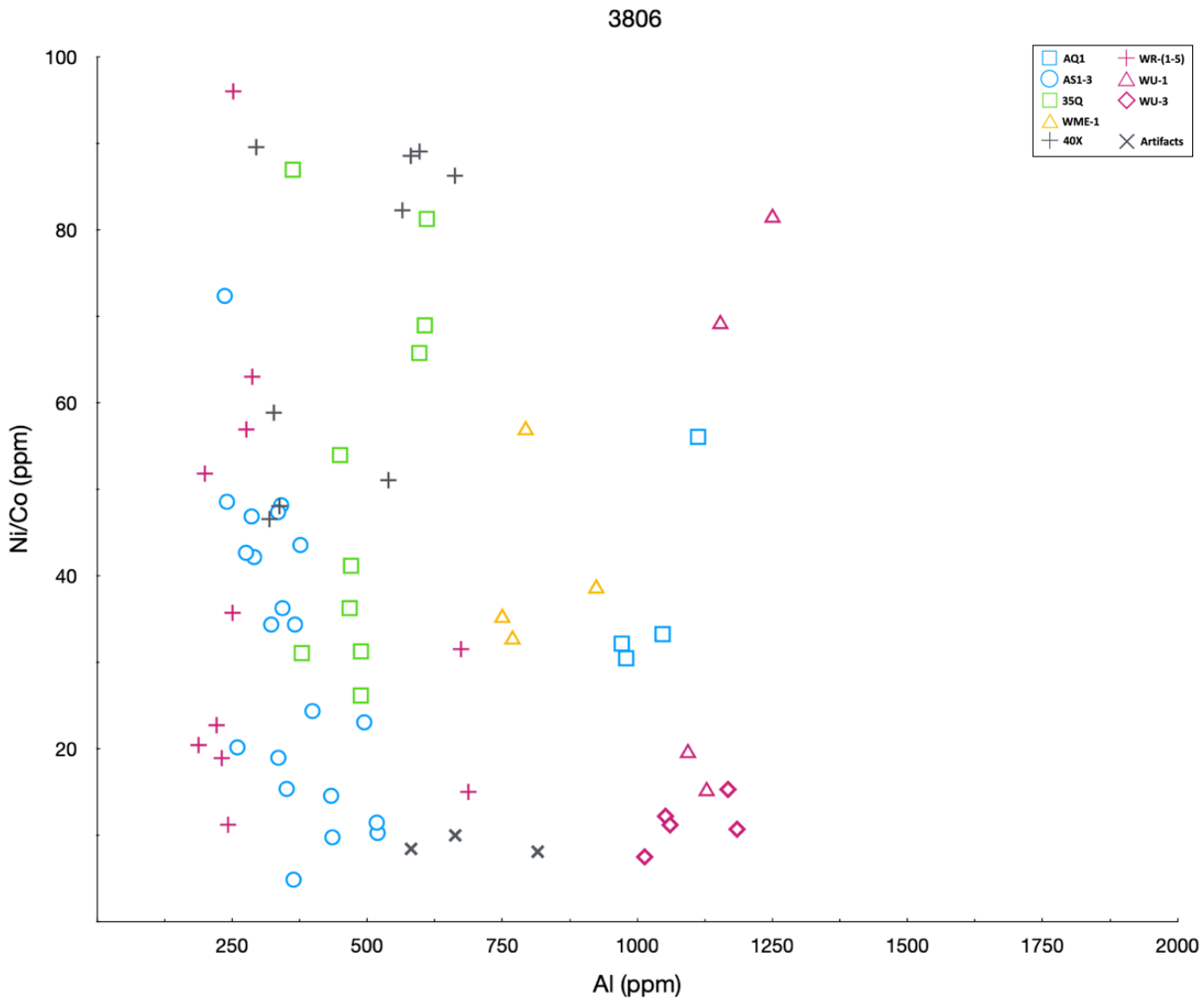
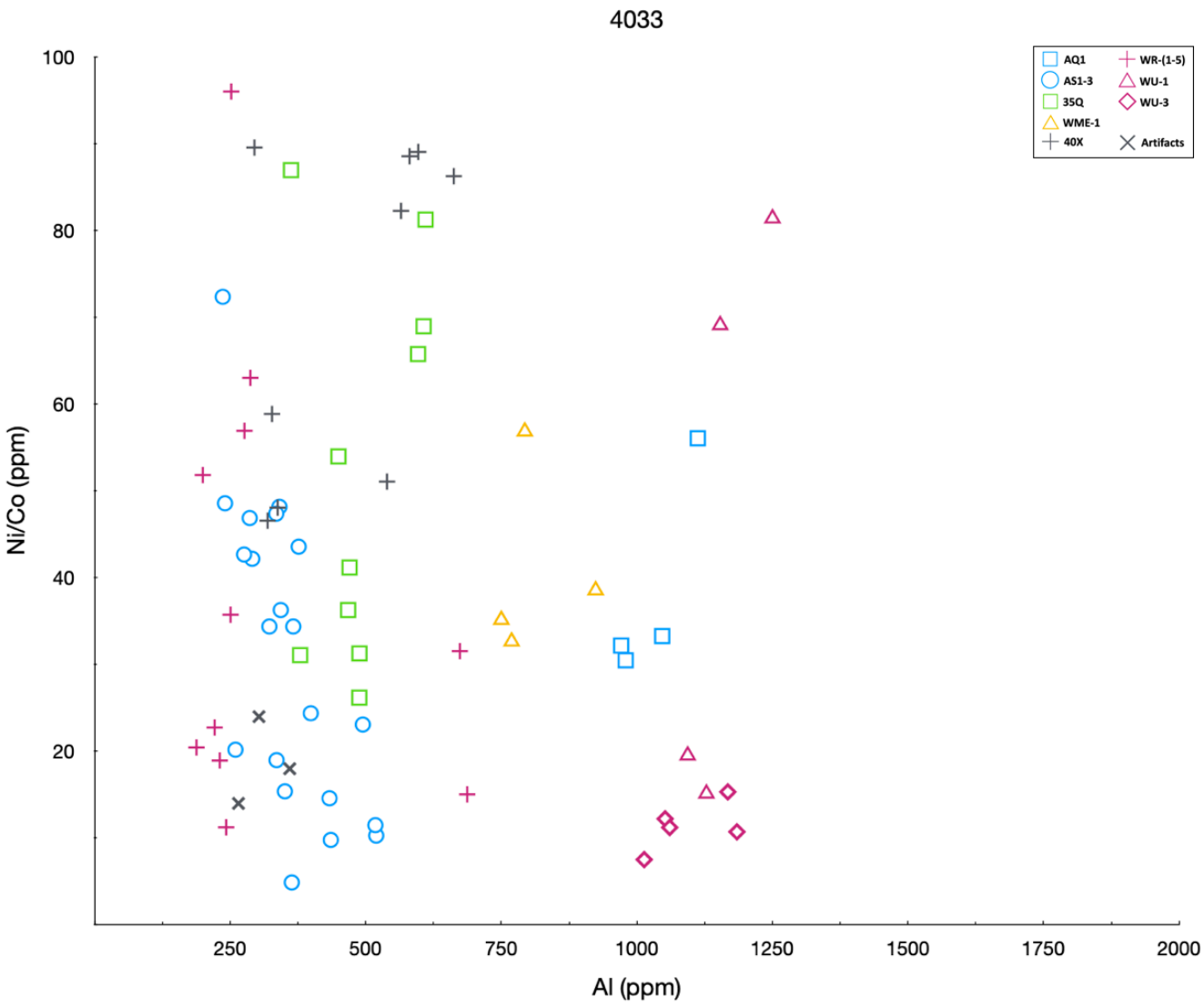
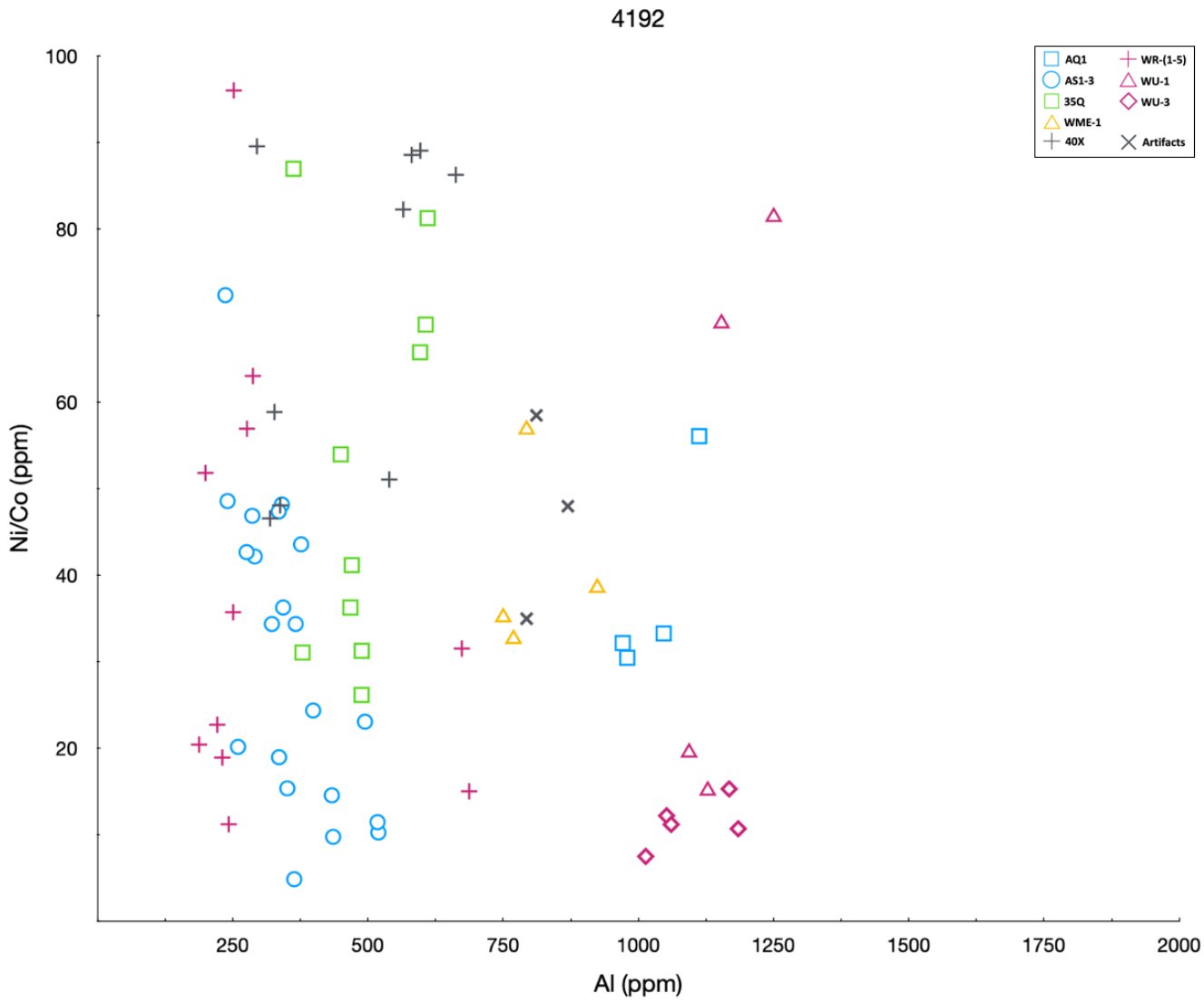
60
40
20
250
500
750
1000
1250
1500
1750
2000

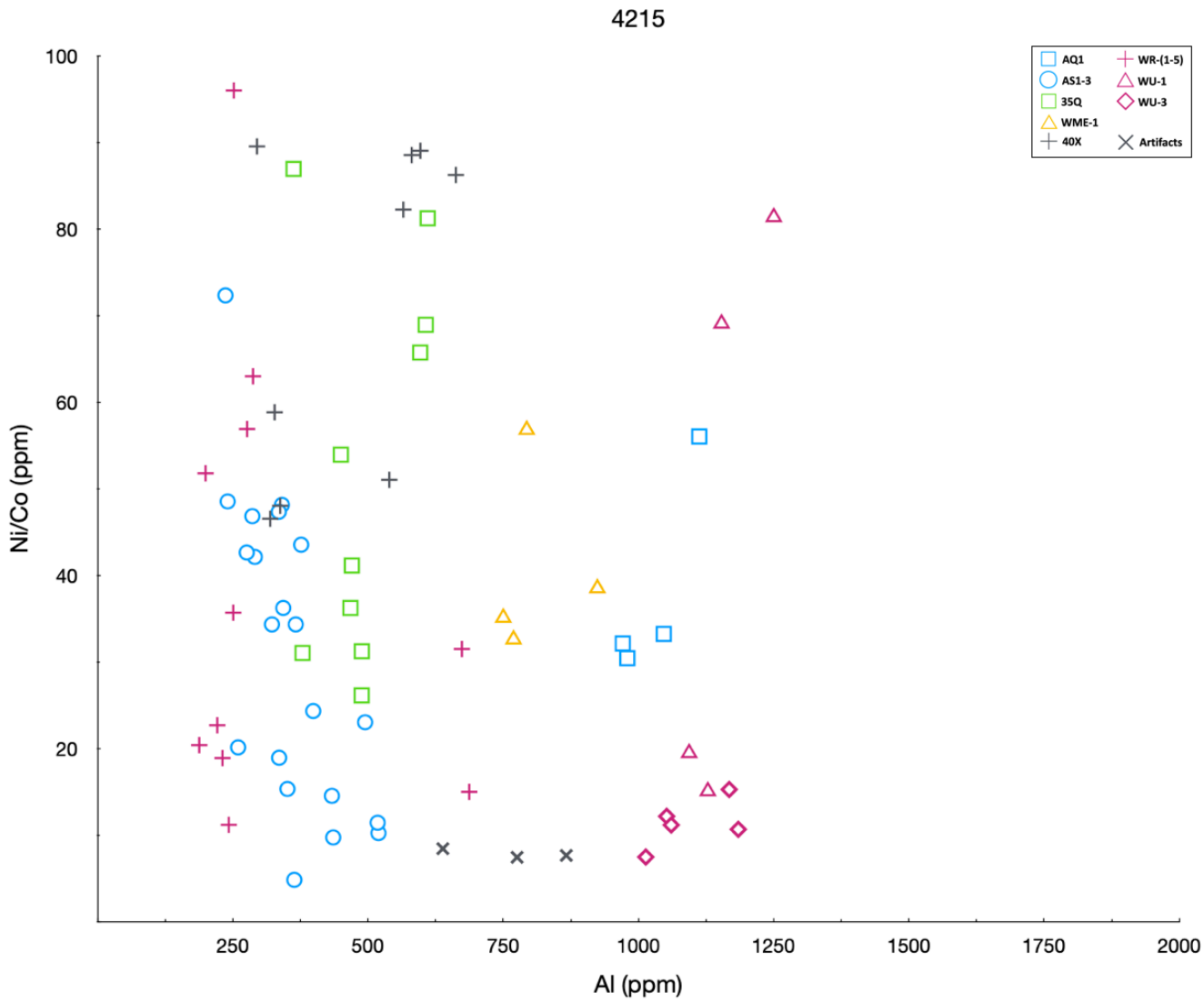

3711
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

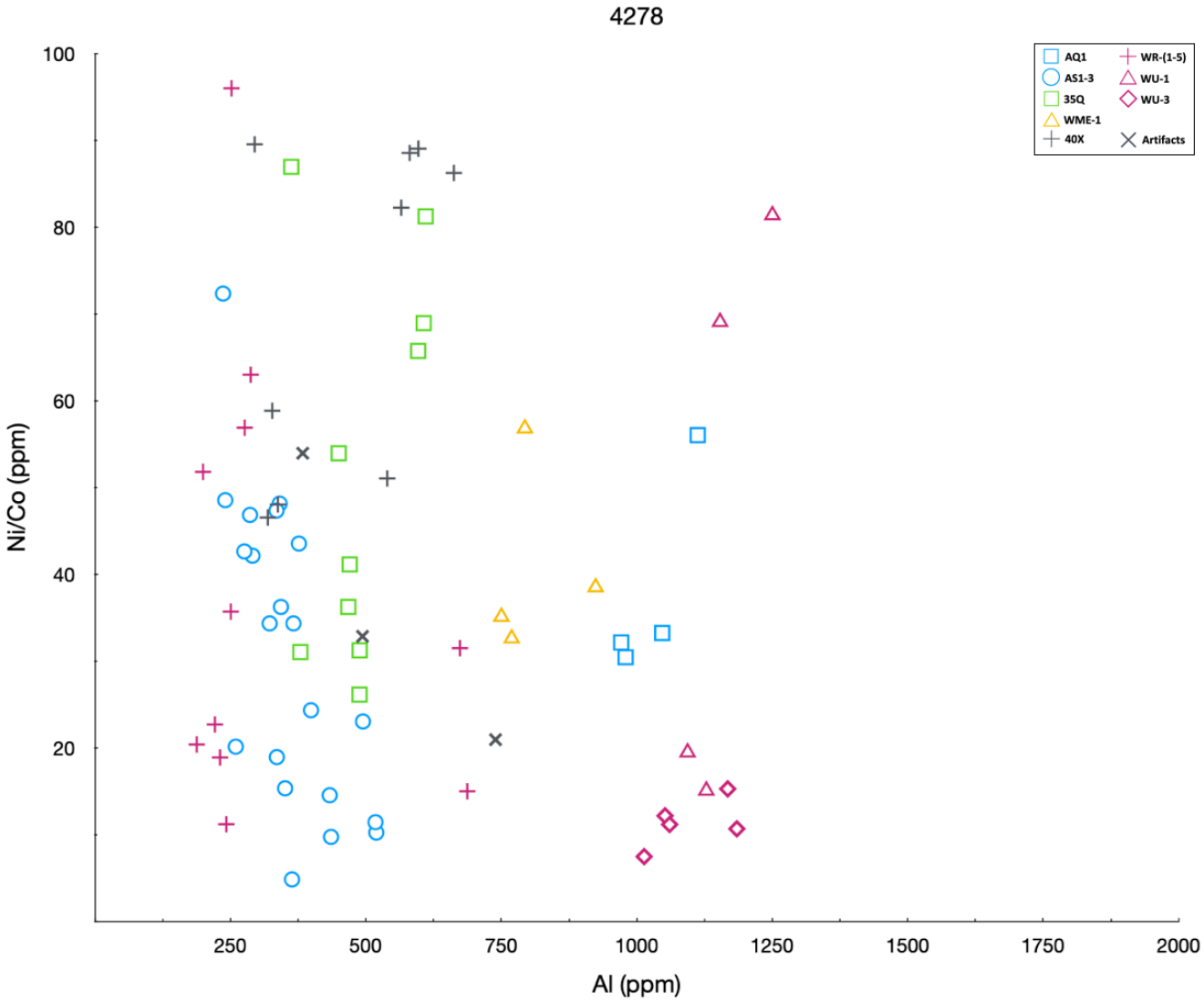

3805
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

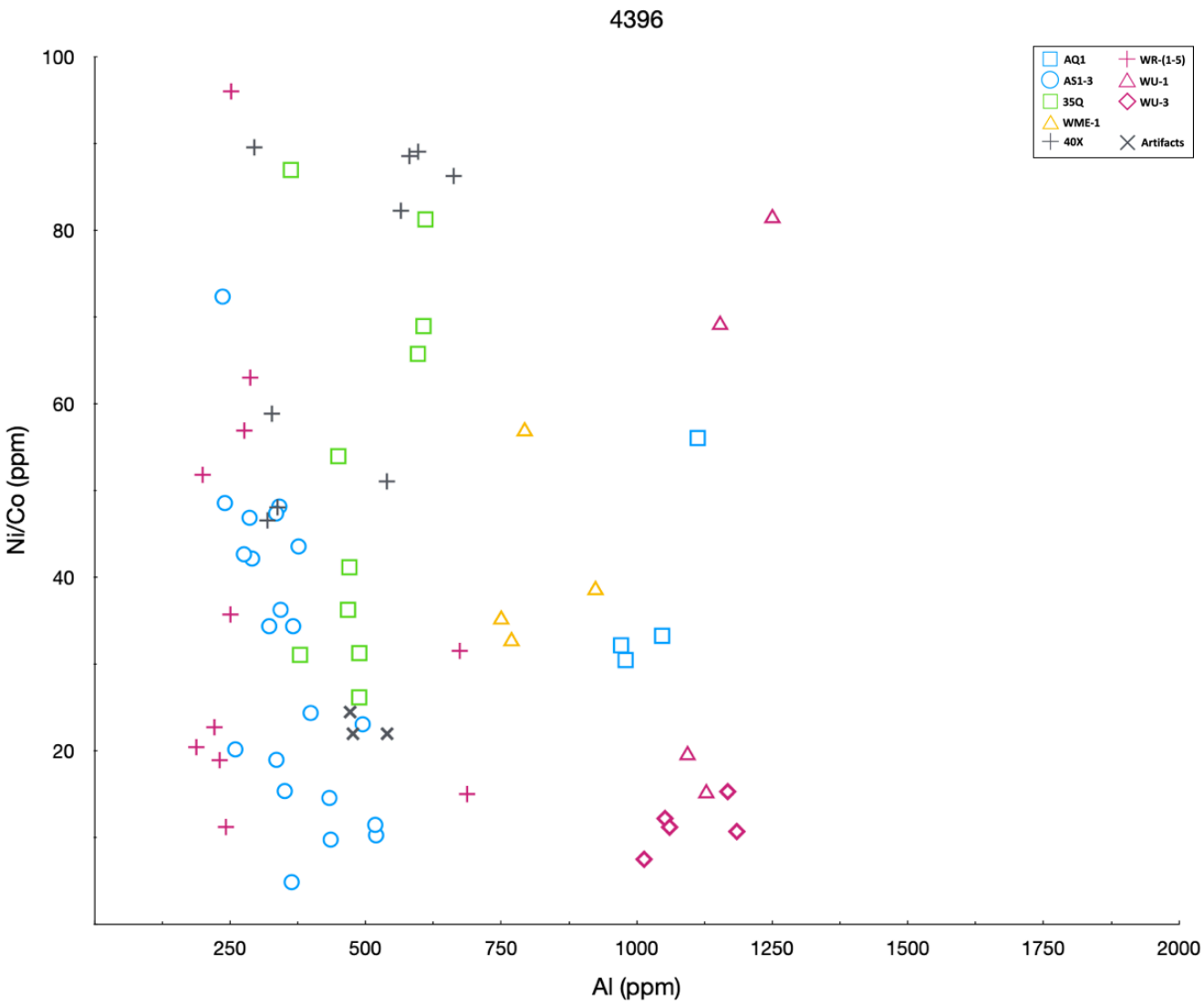

3806
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

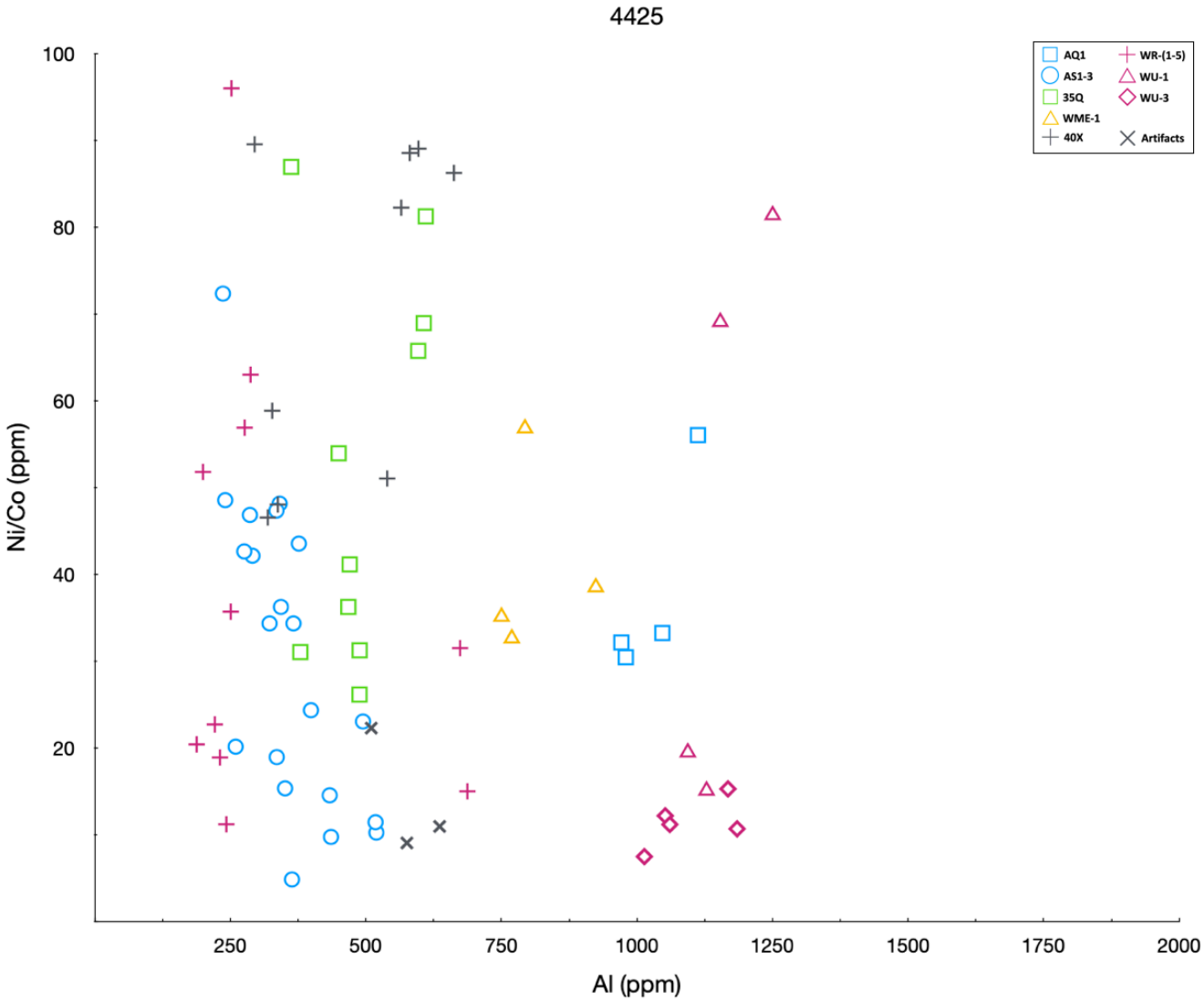

4033
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

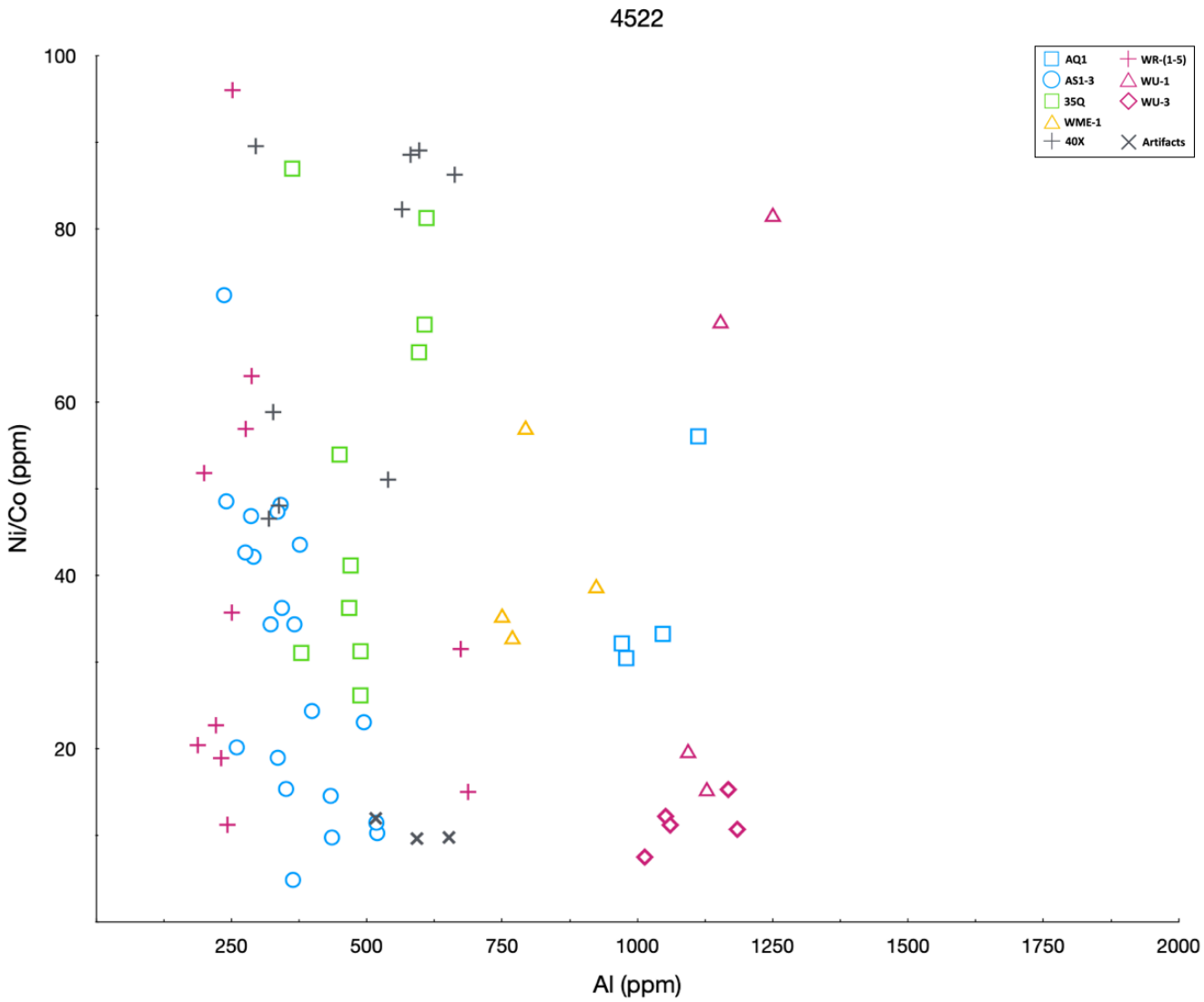

4192
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

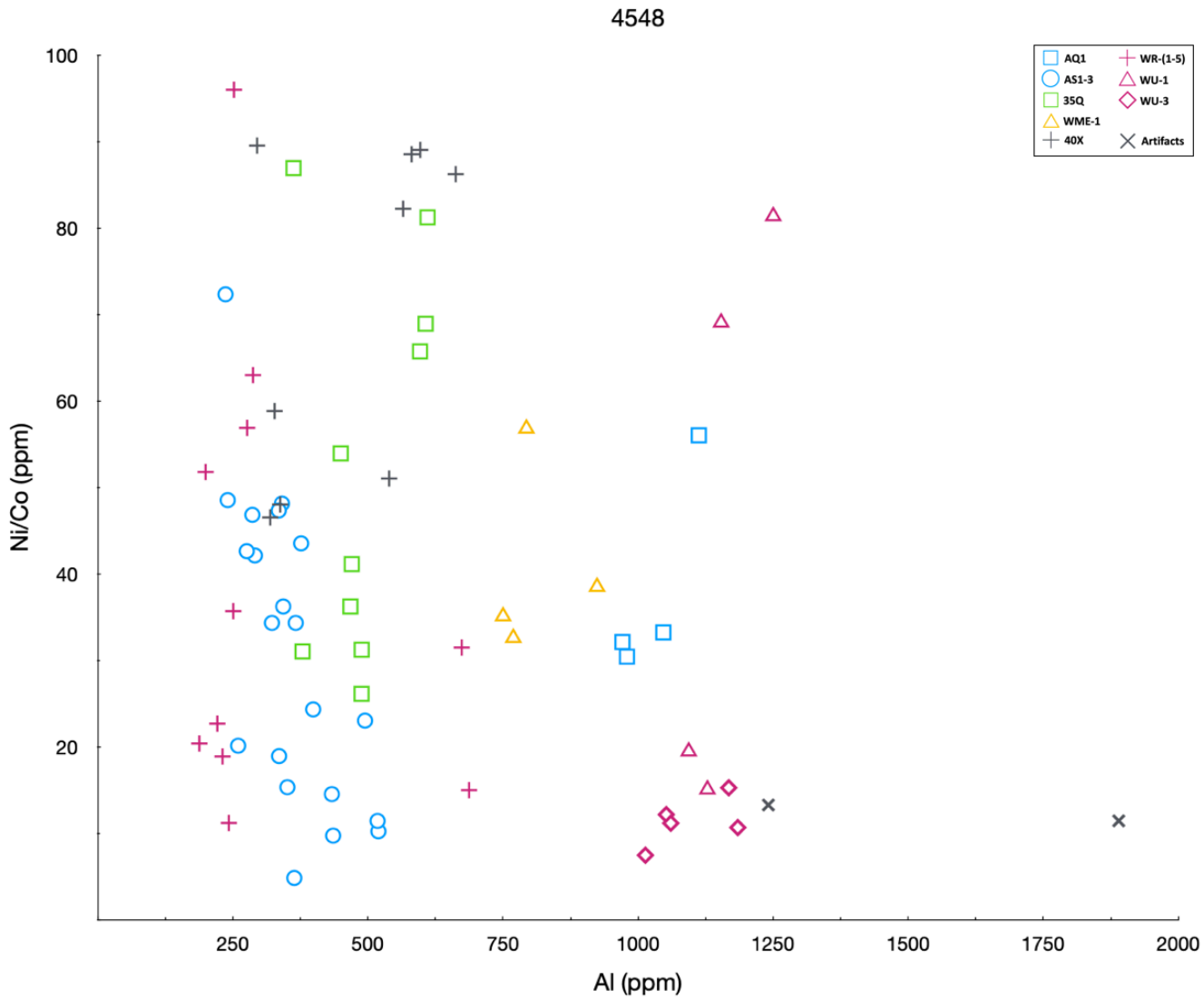

4215
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

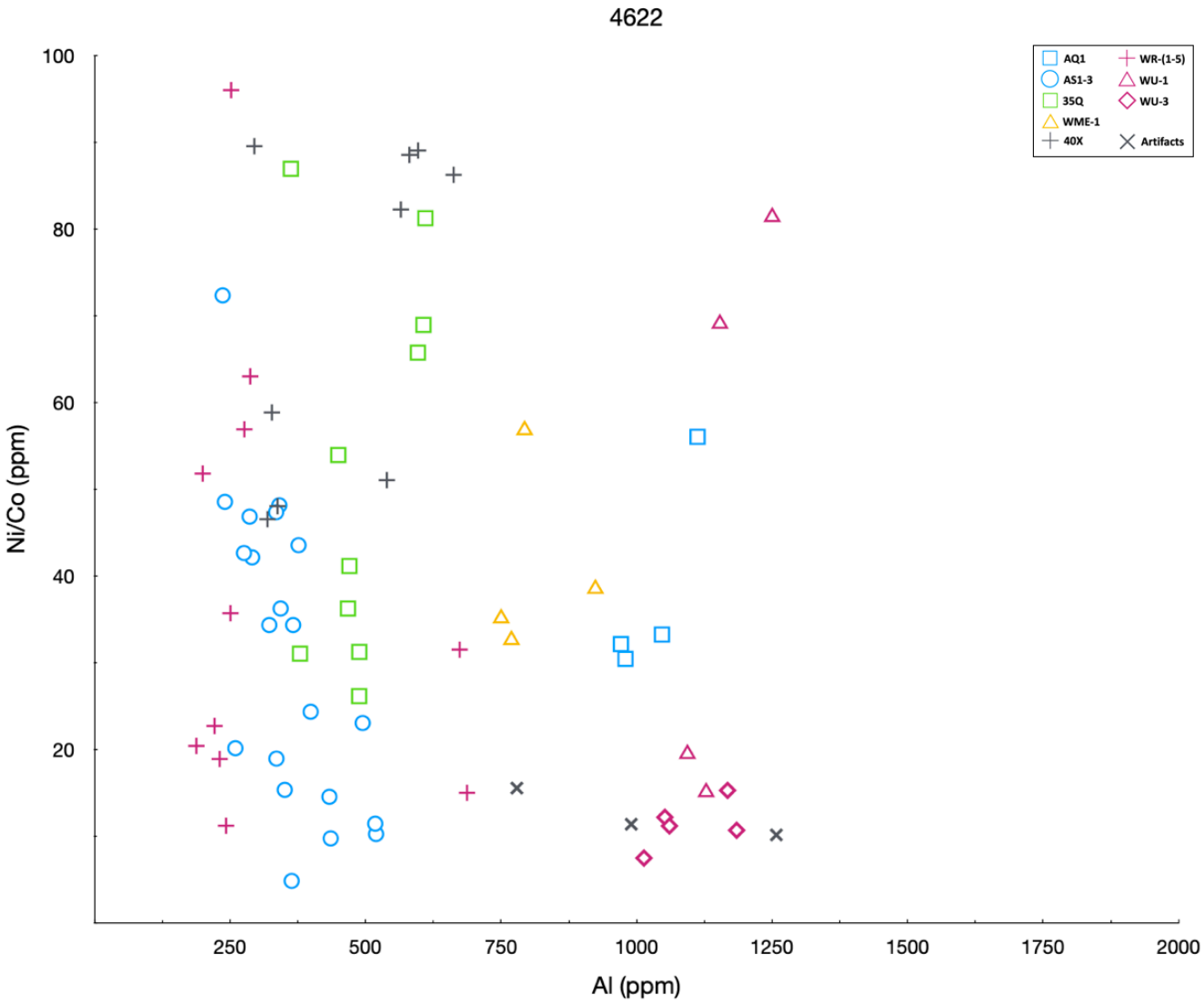

4278
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

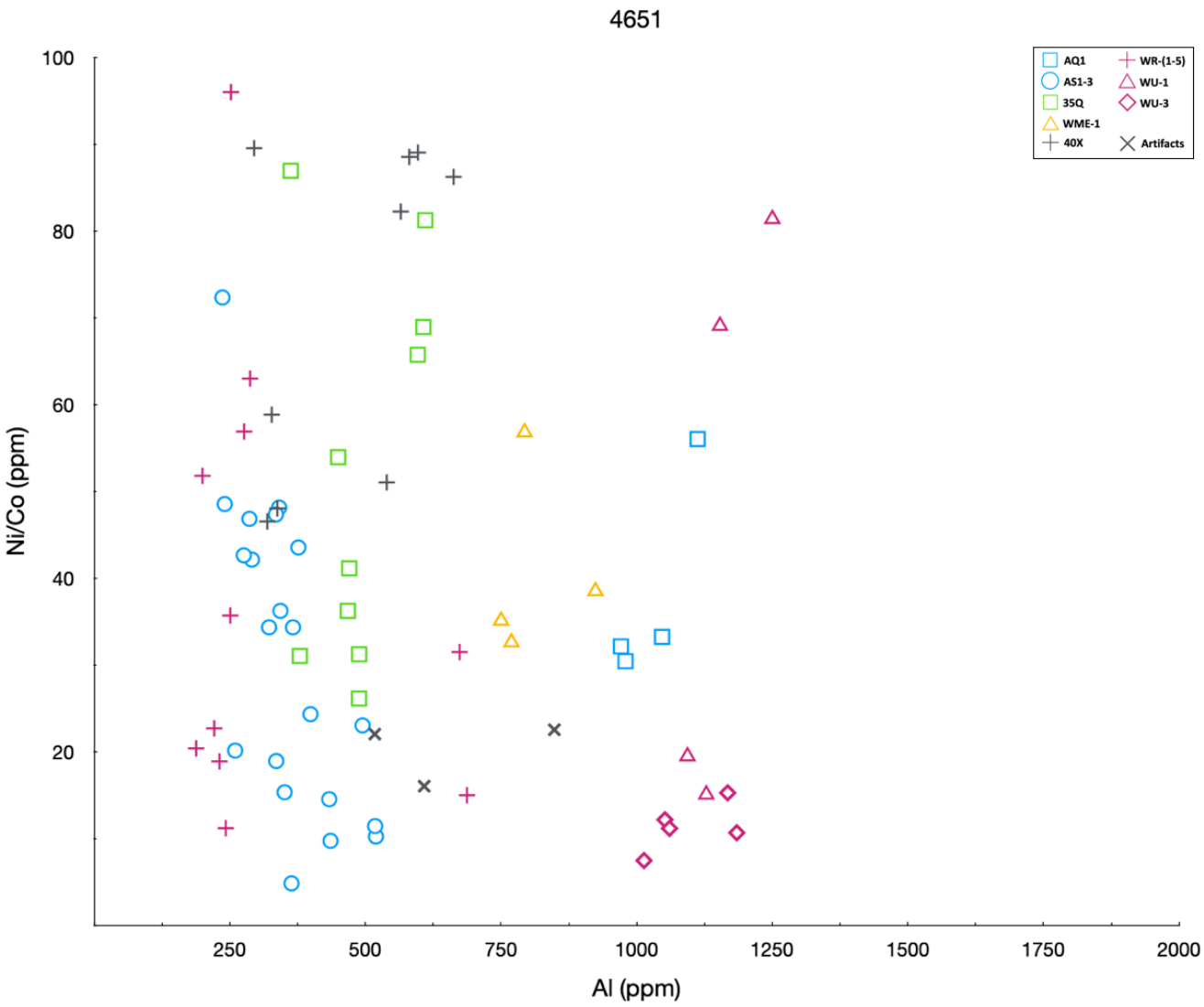

4396
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

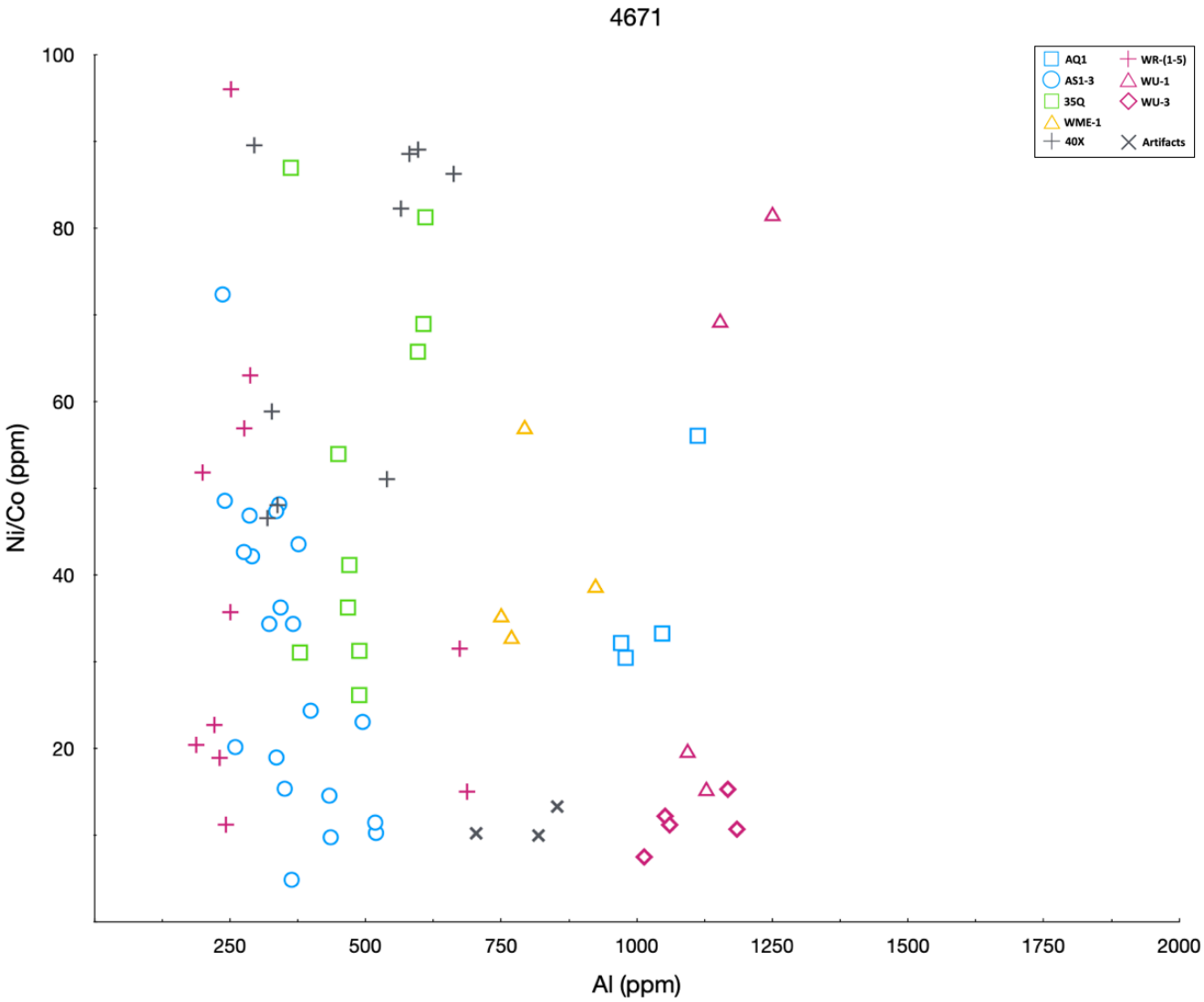

4425
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

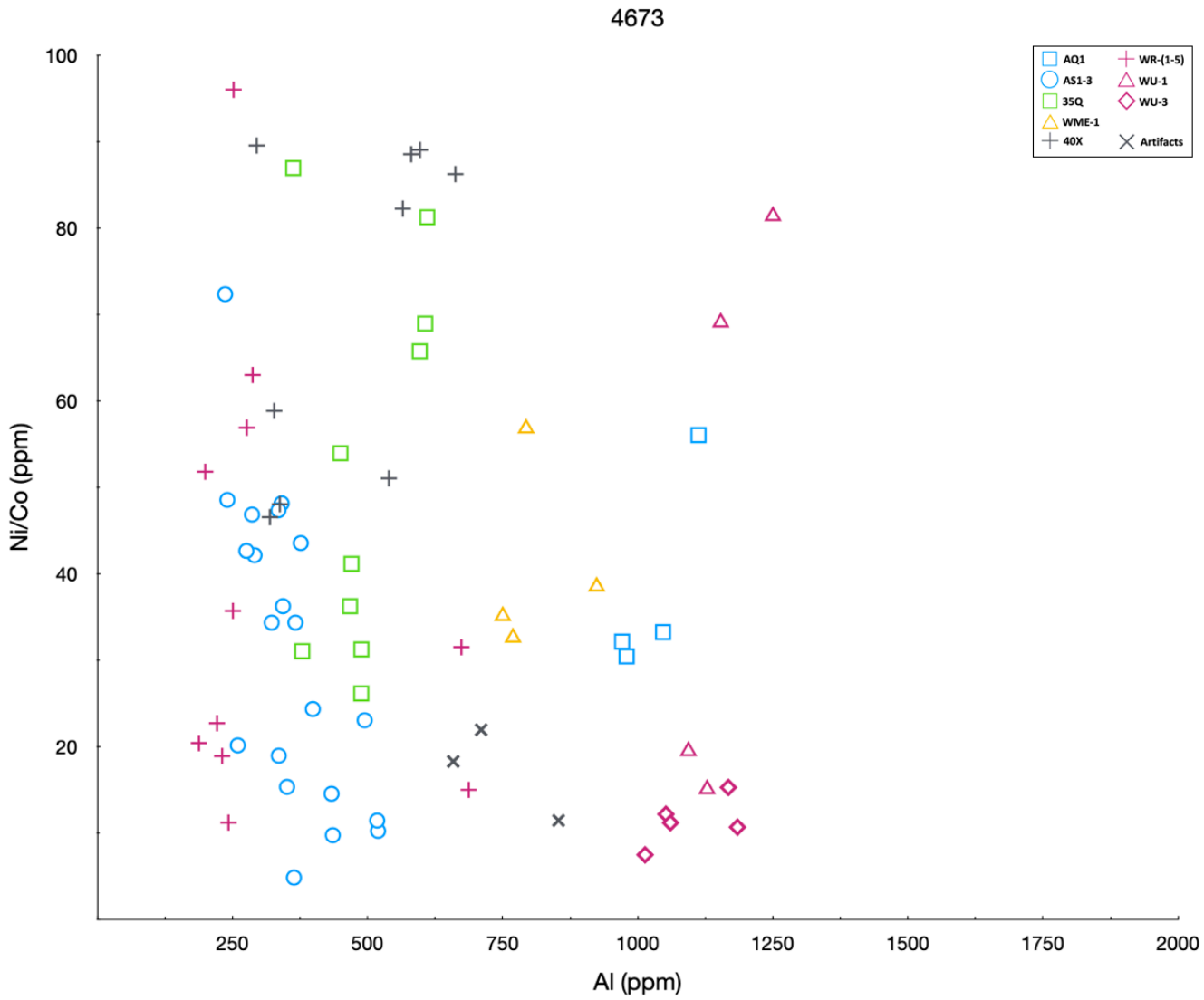

4522
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

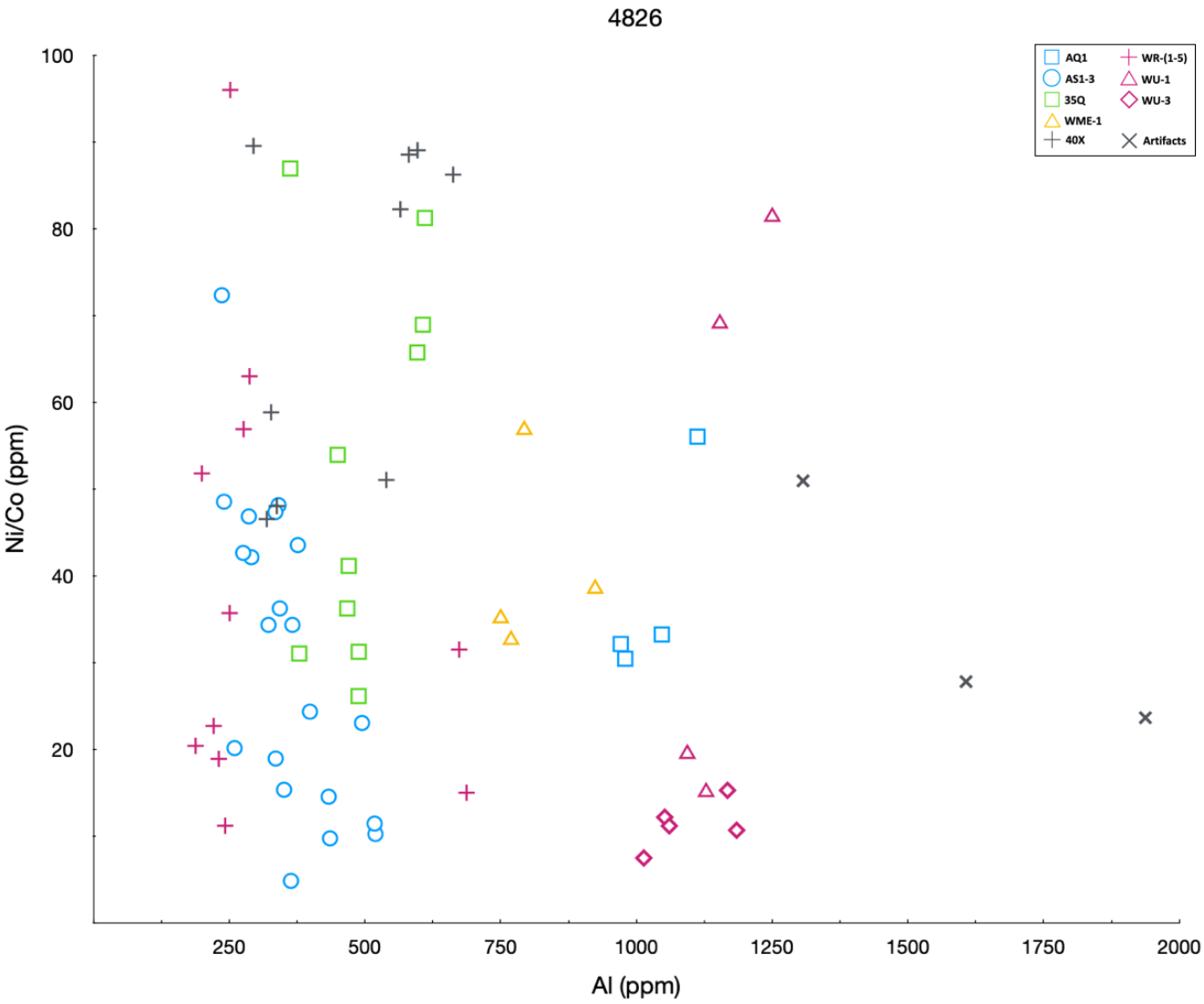

4548
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4622
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

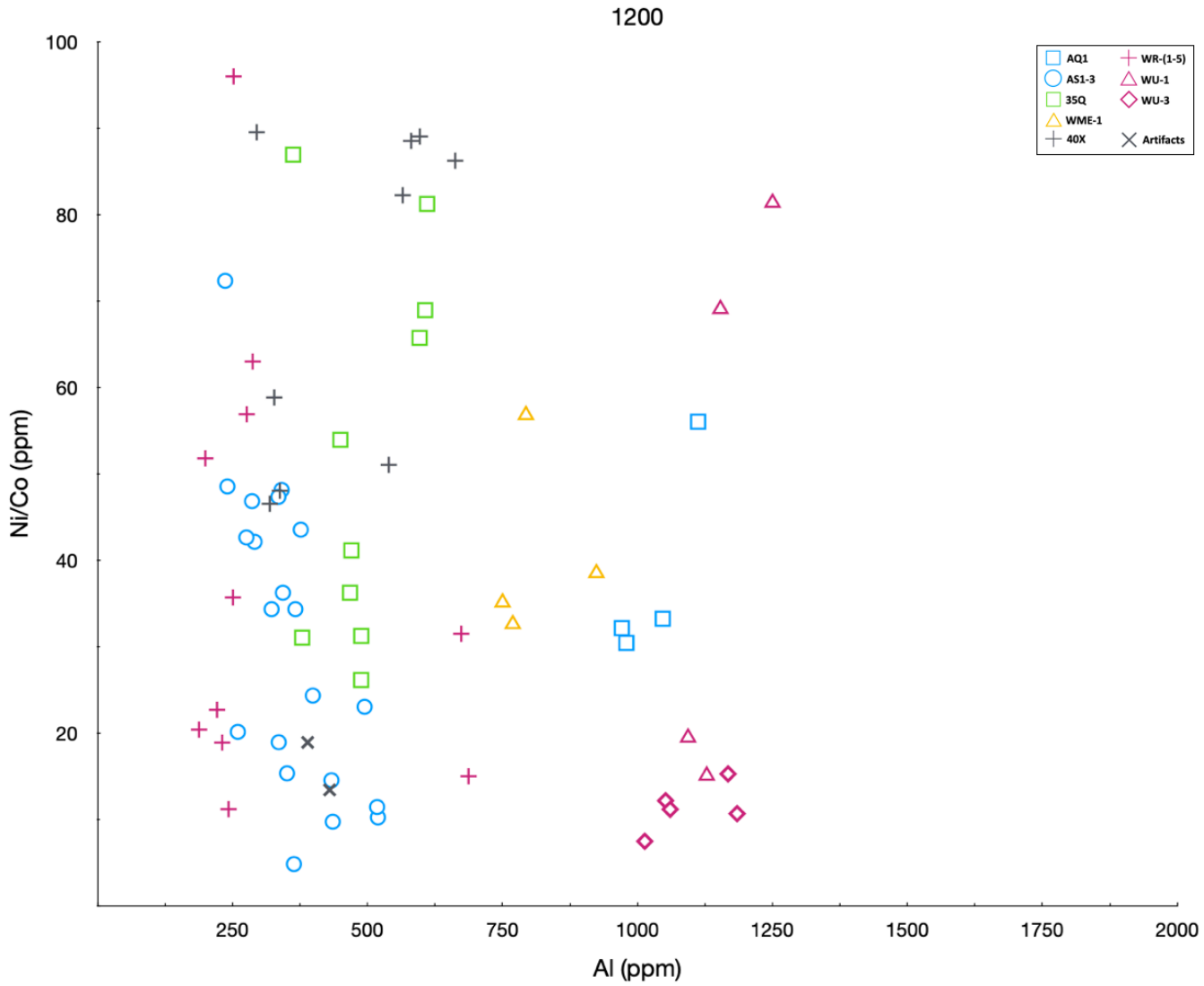

4651
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

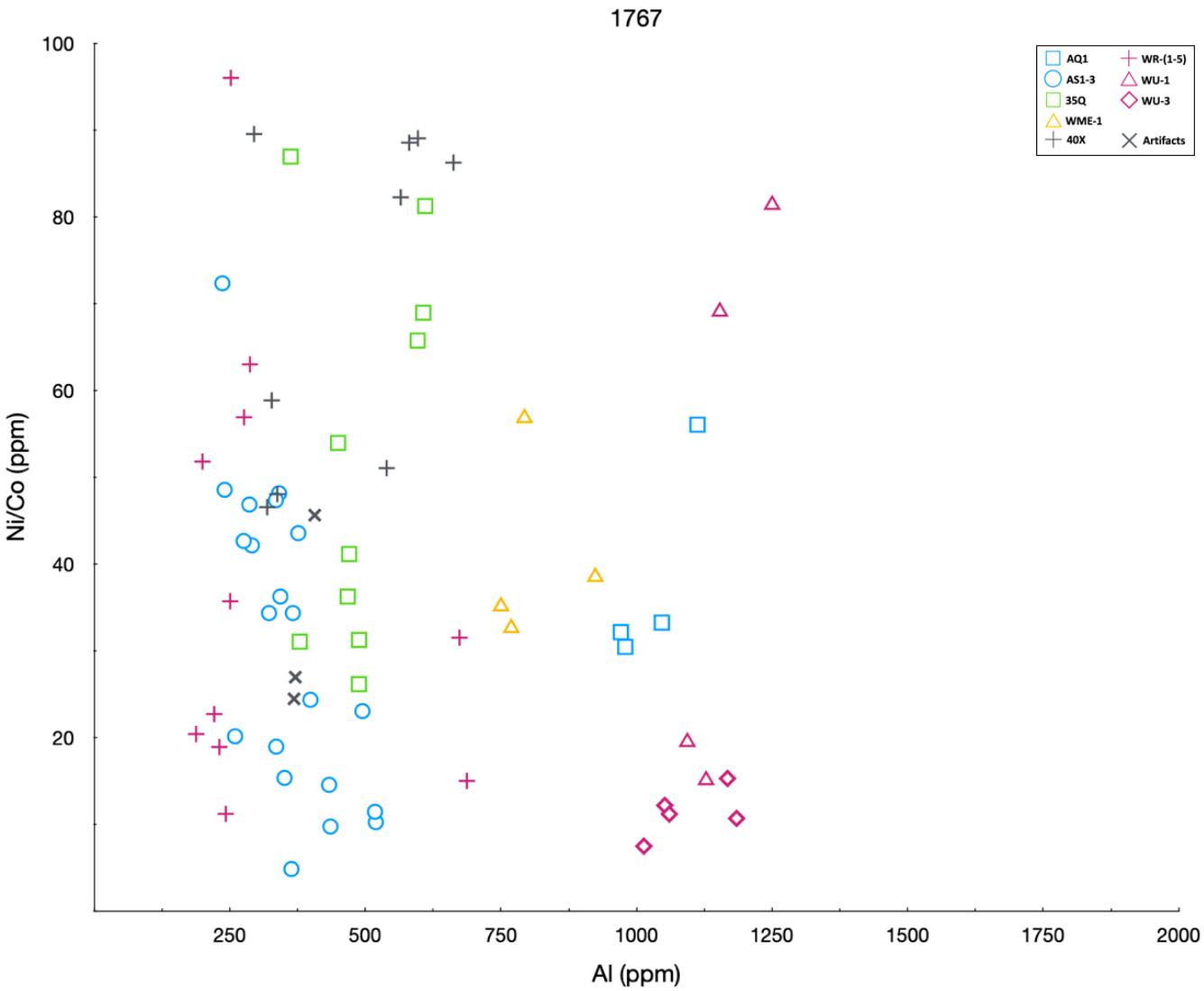

4671
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

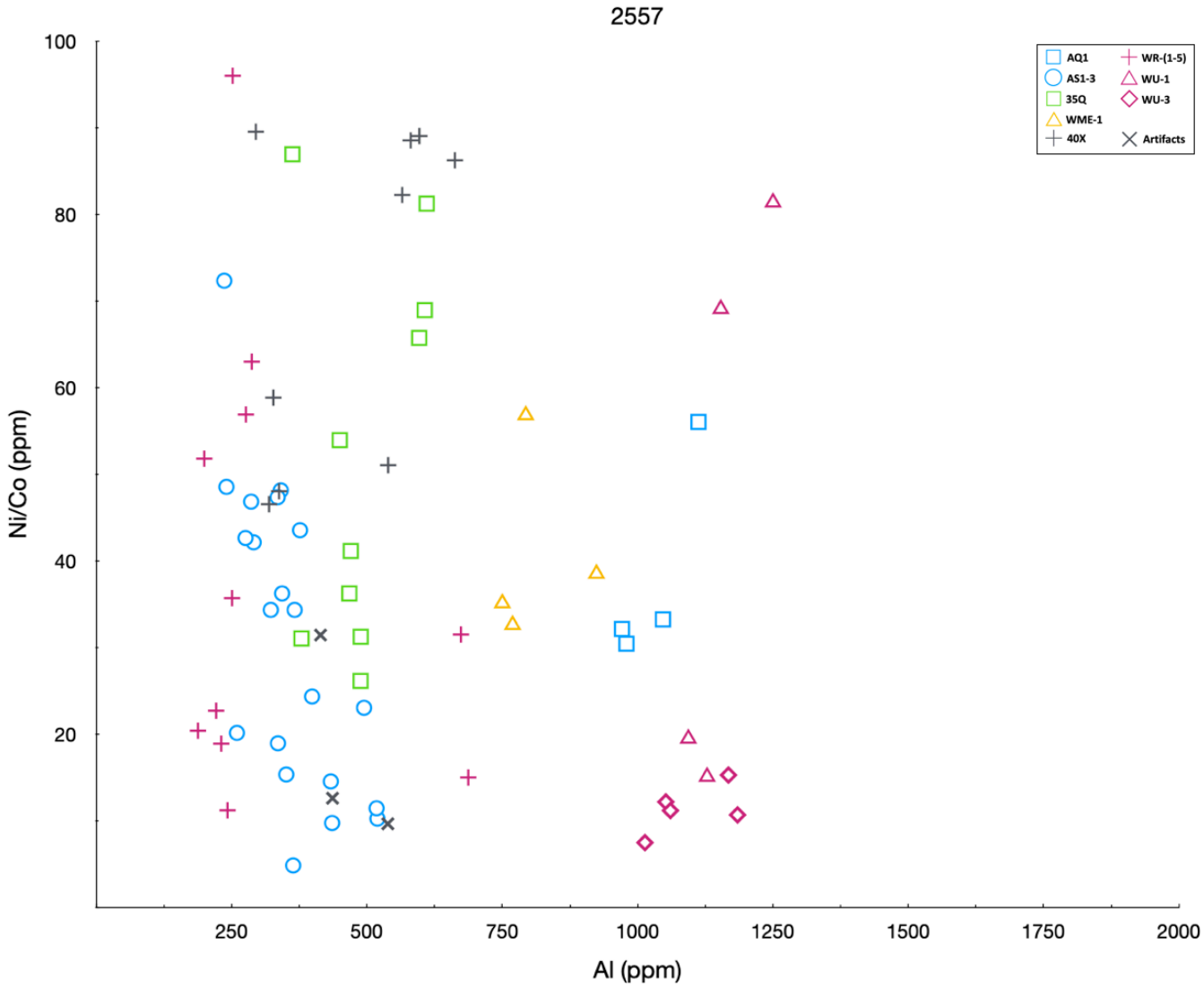

4673
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

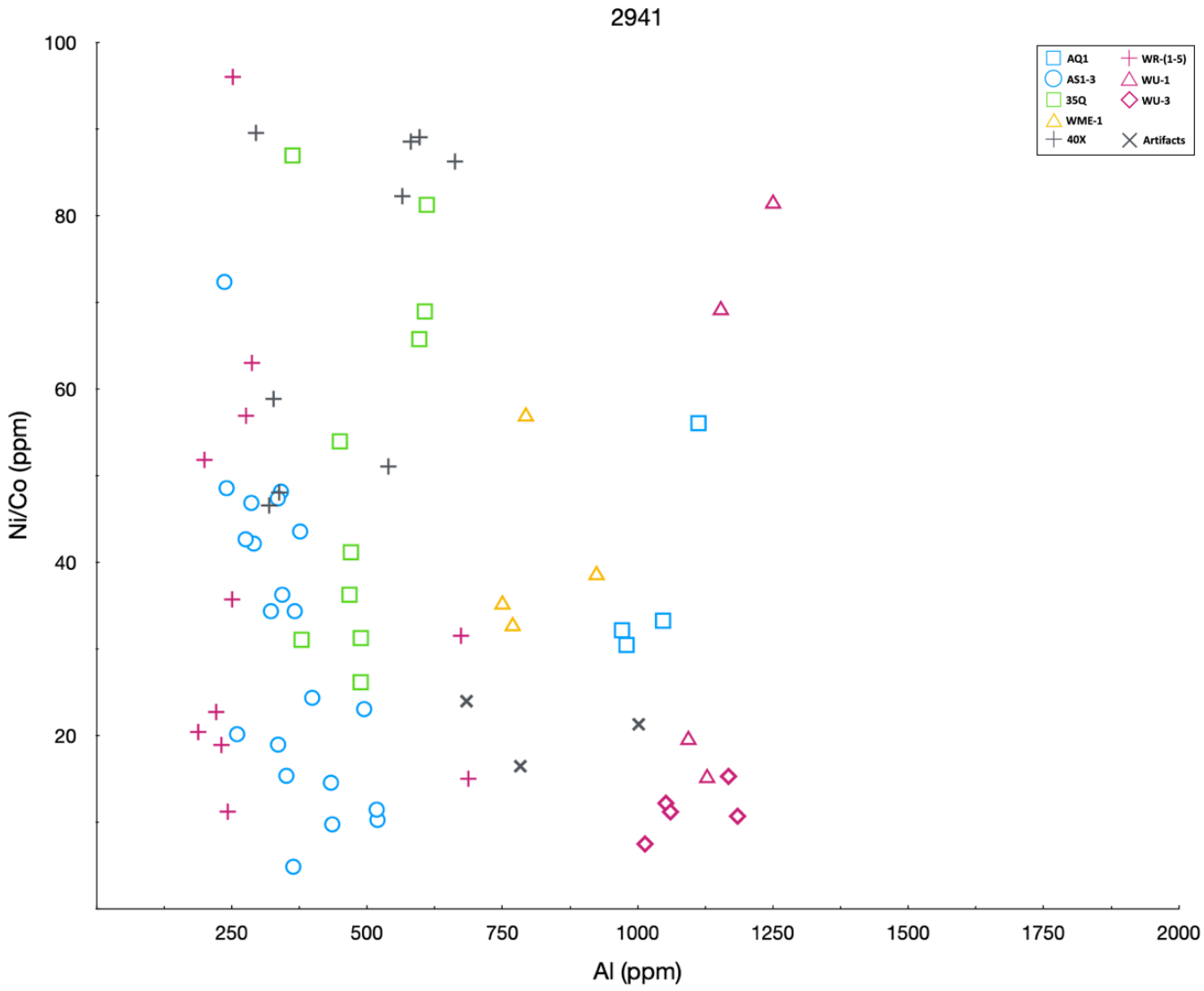

4826
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

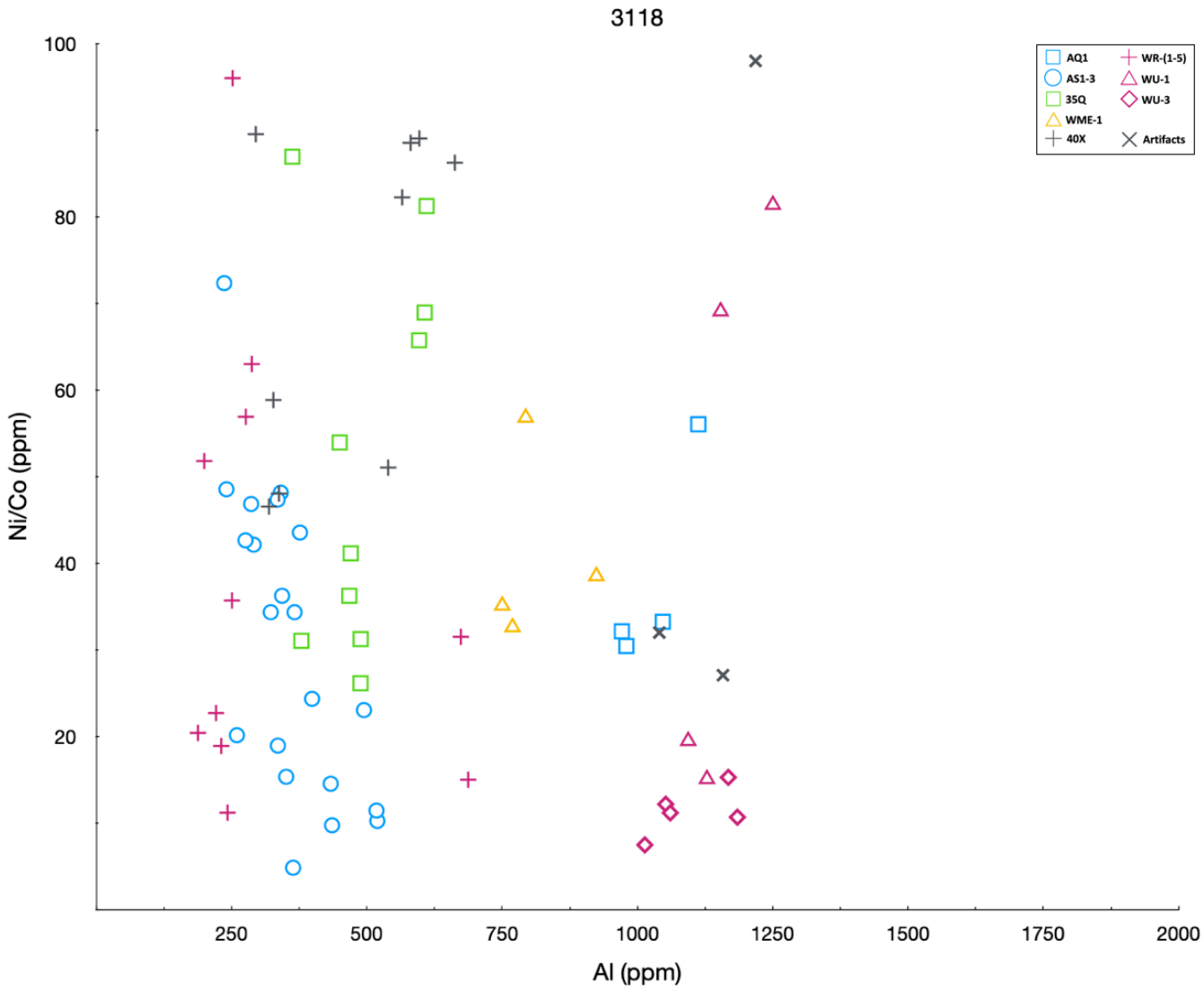
Appendix 8: Individual Ni/Co vs. Al plots of Layer 7 artifacts.

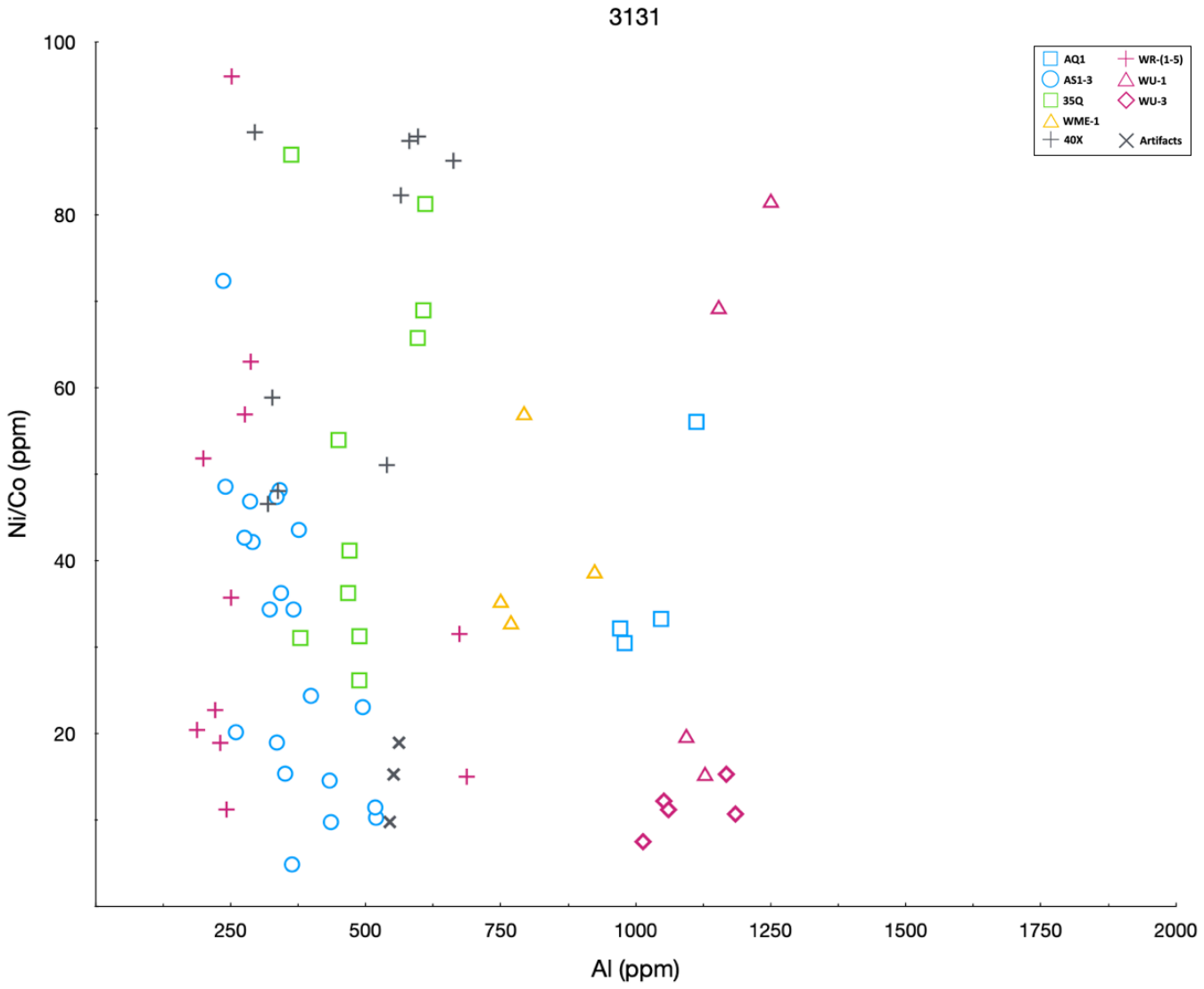


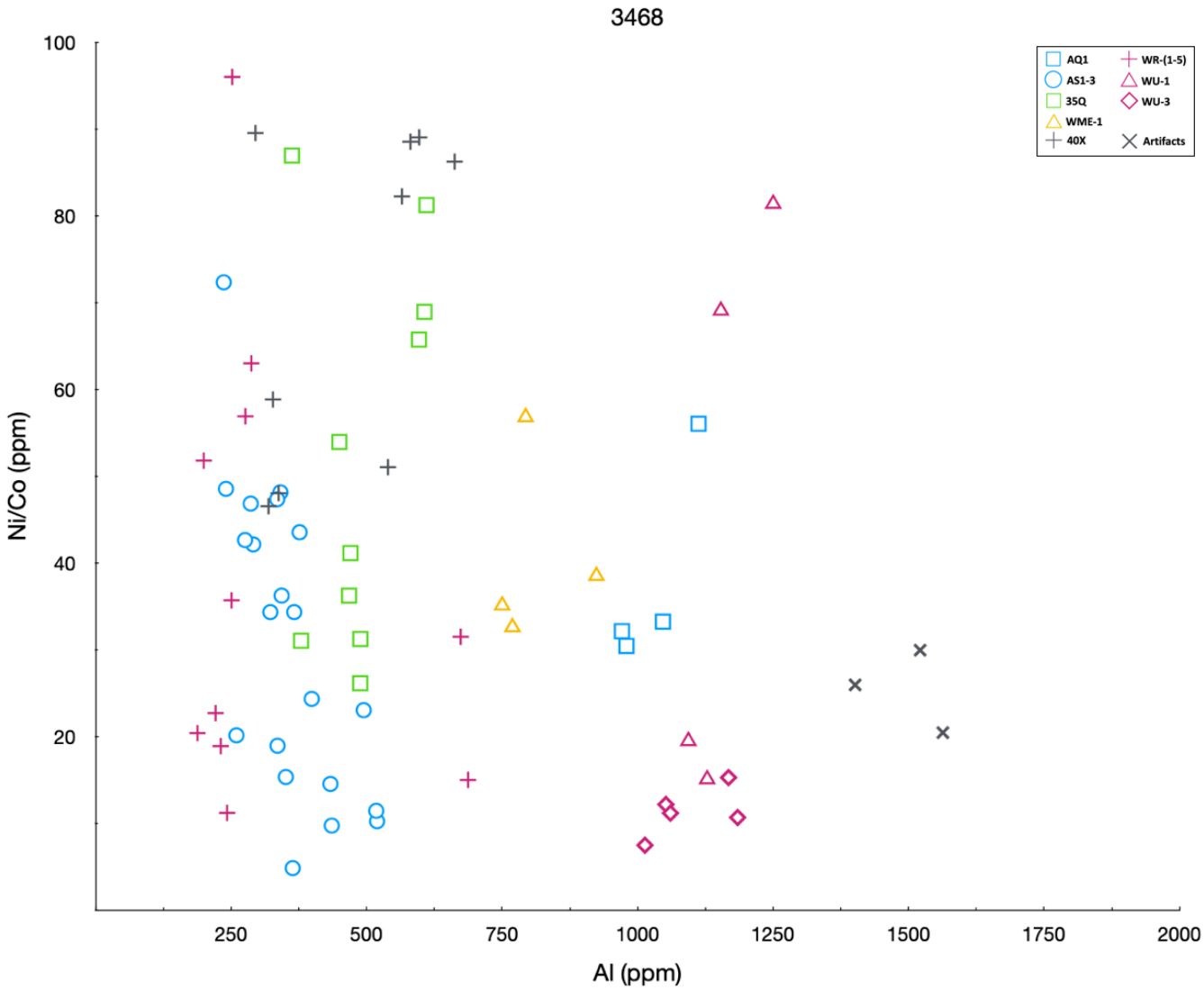

1767
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

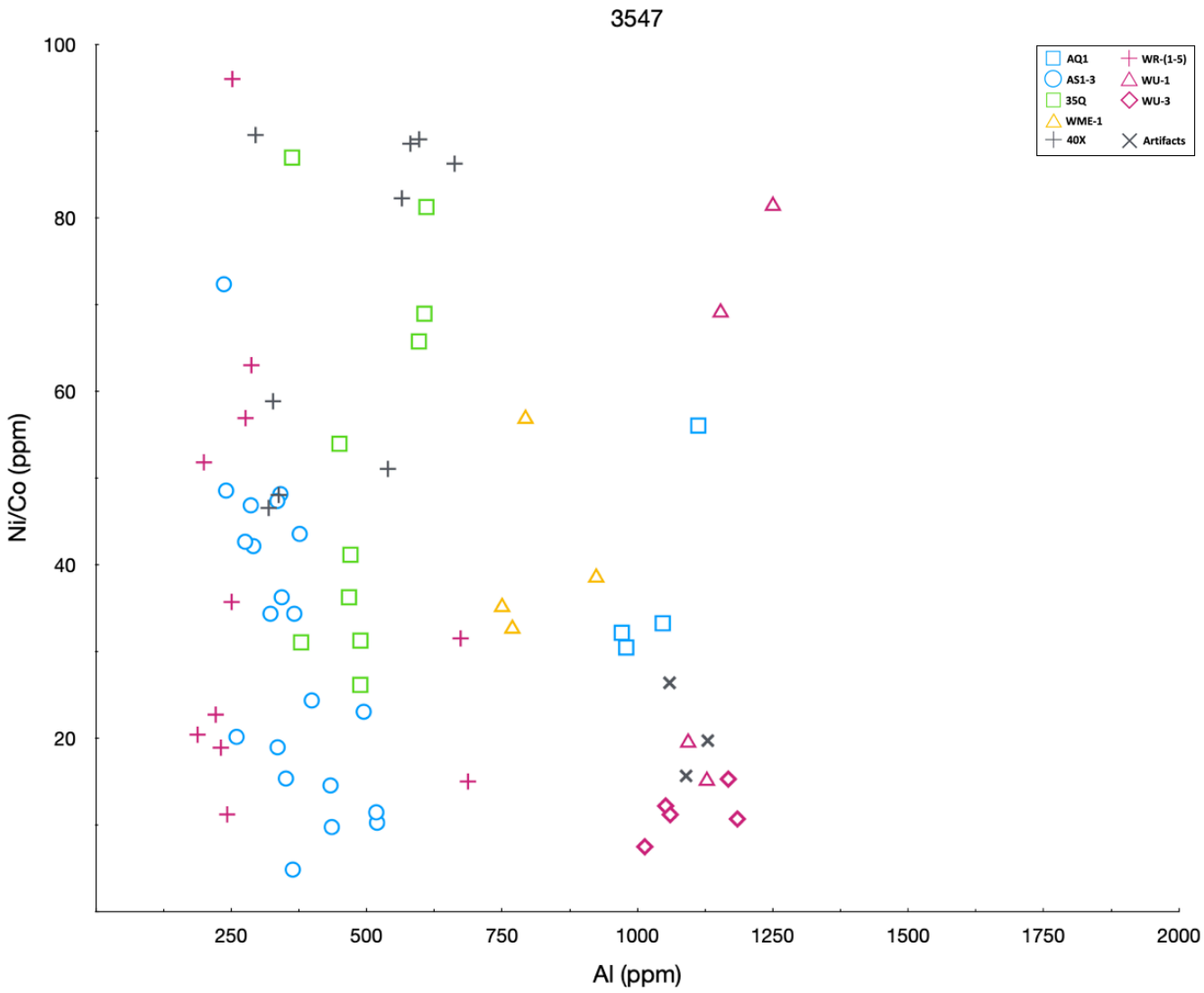

2557
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

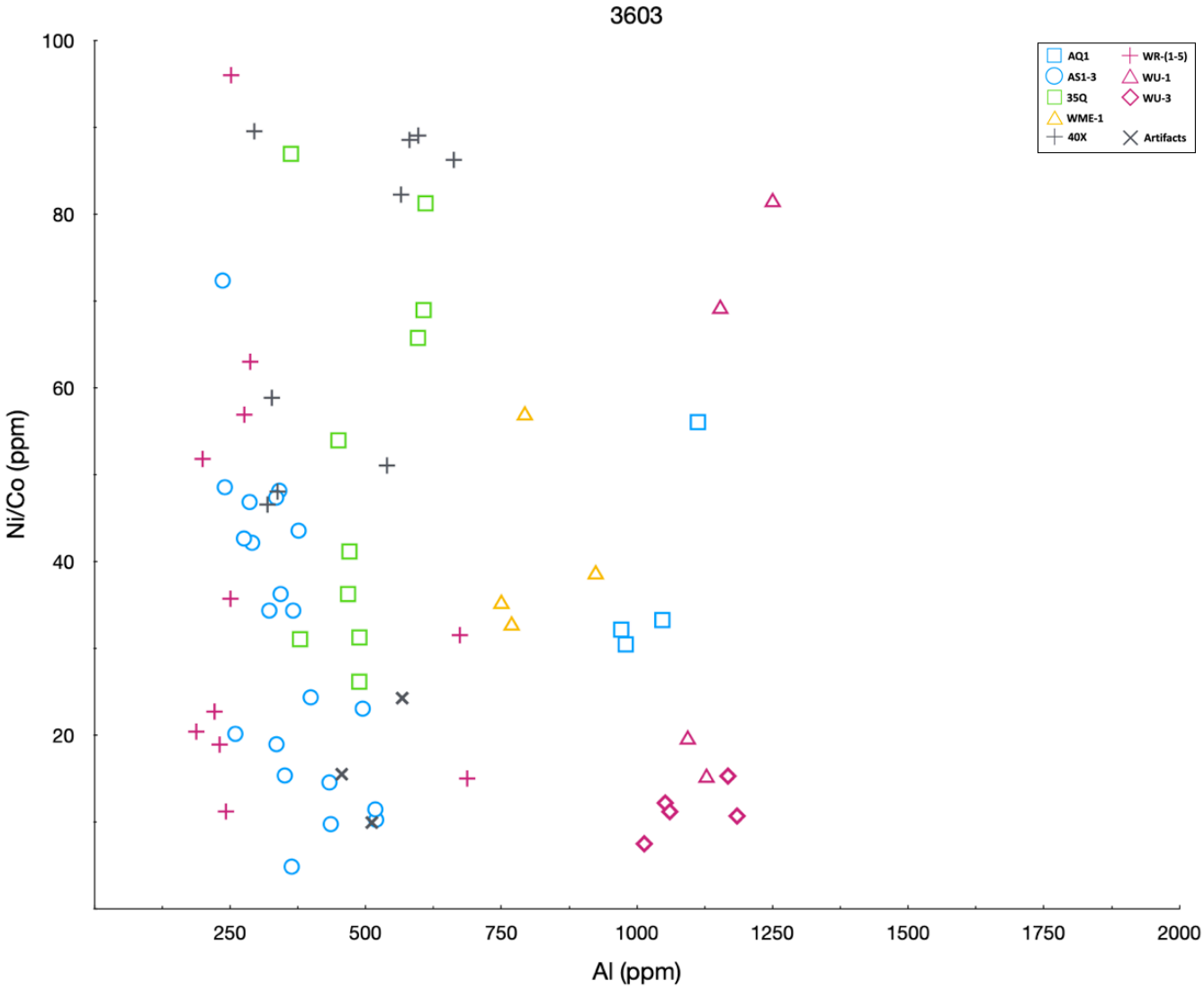

2941
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

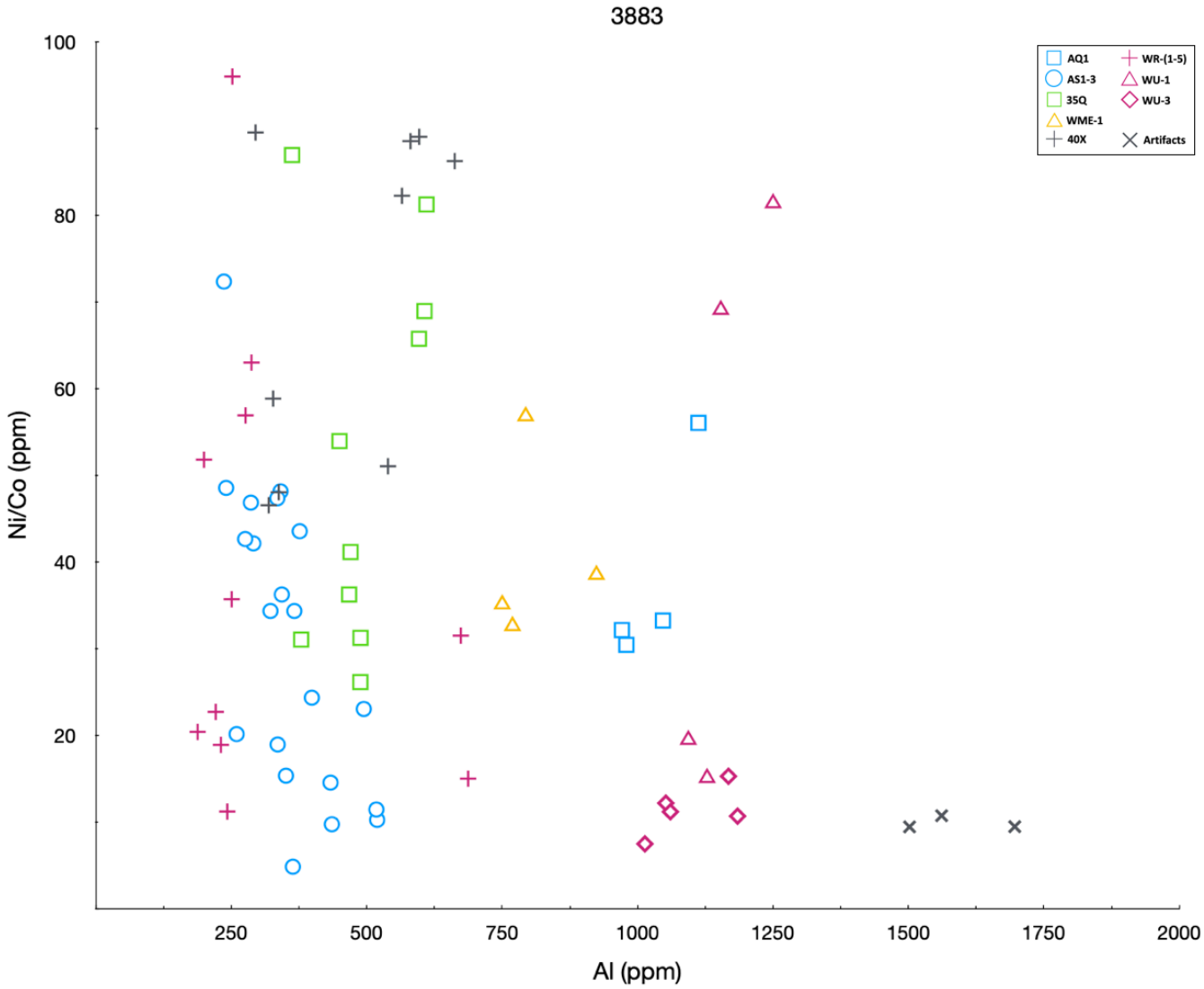

3118
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

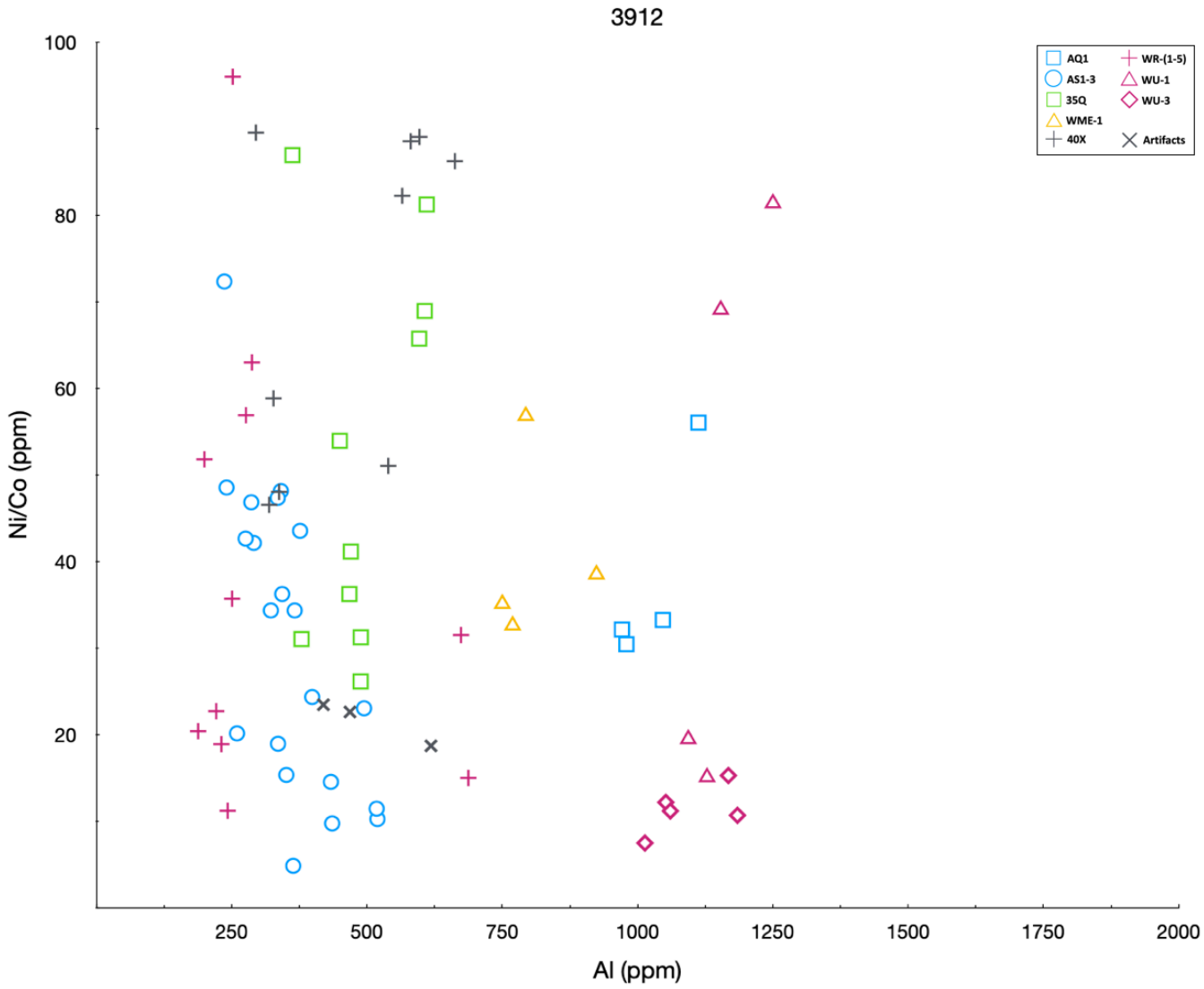

3131
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

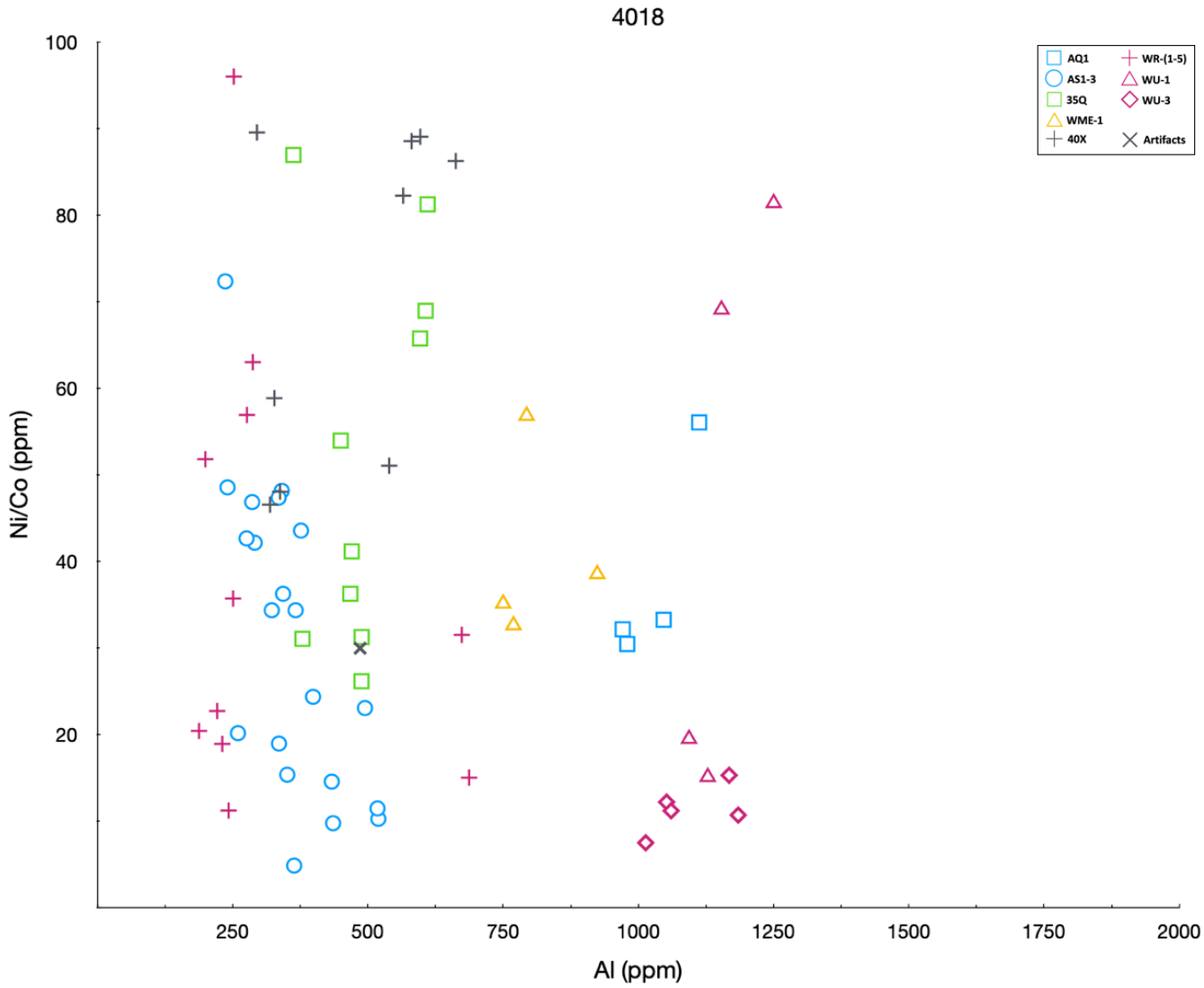

3468
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

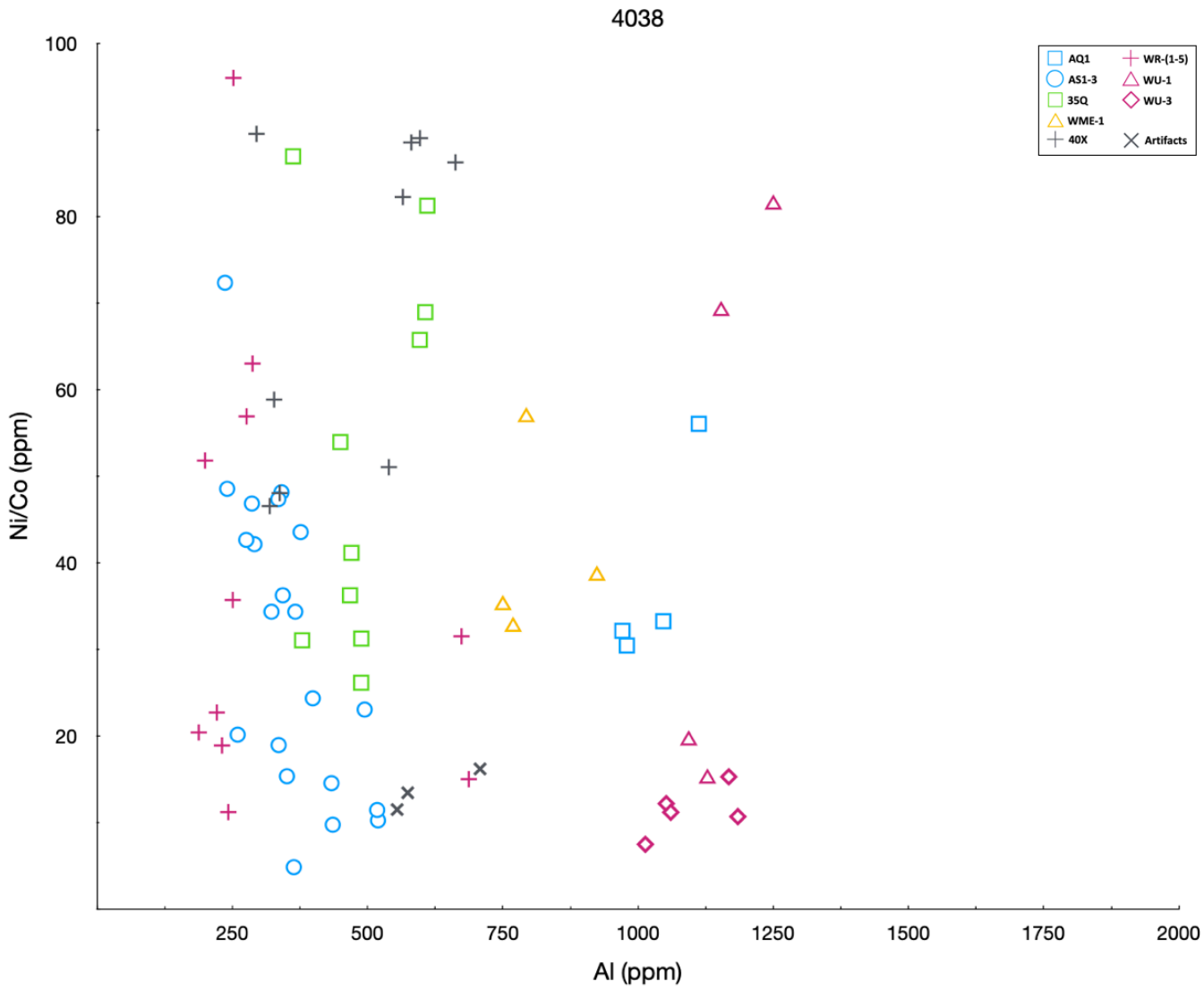

3547
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

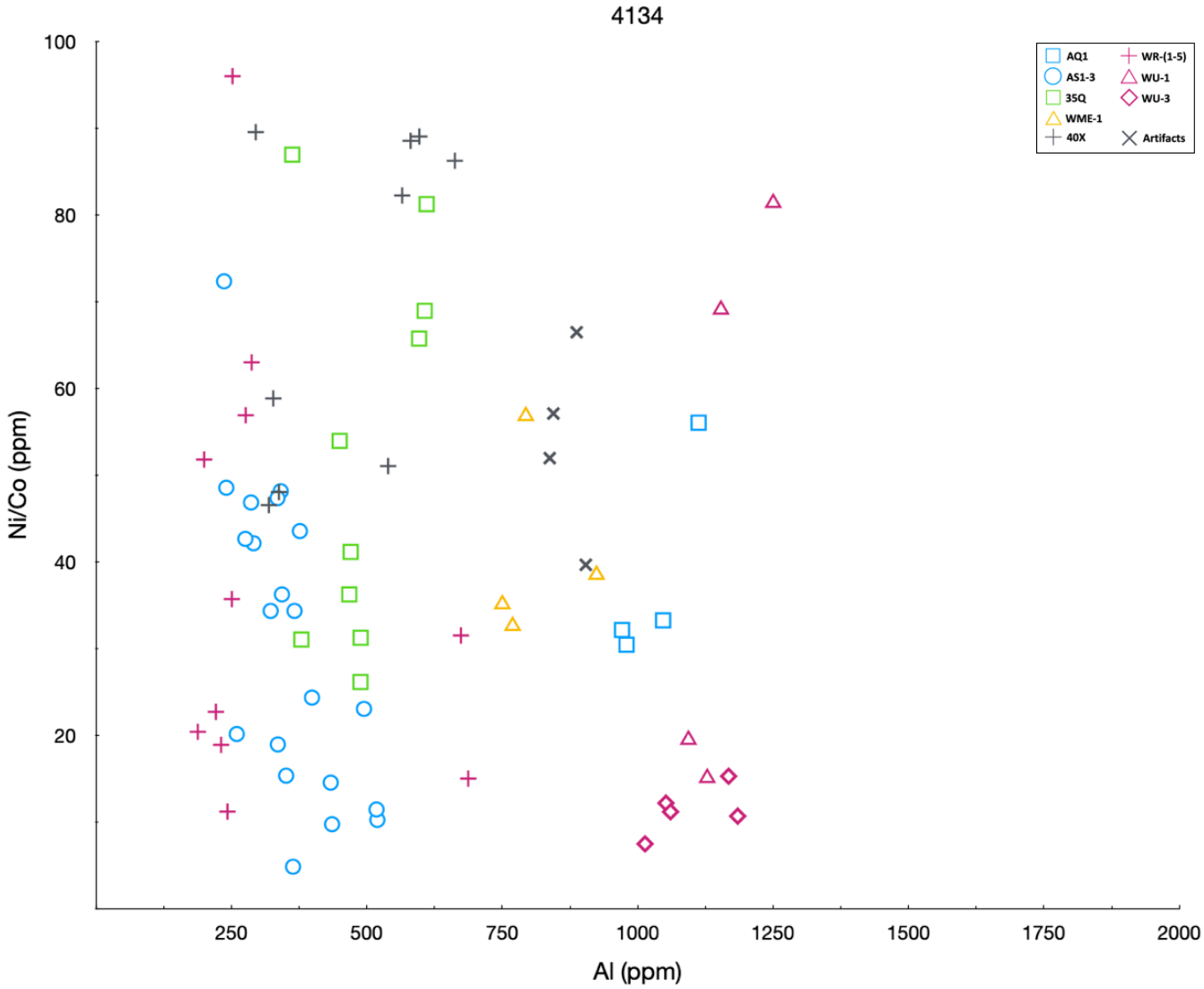

3603
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

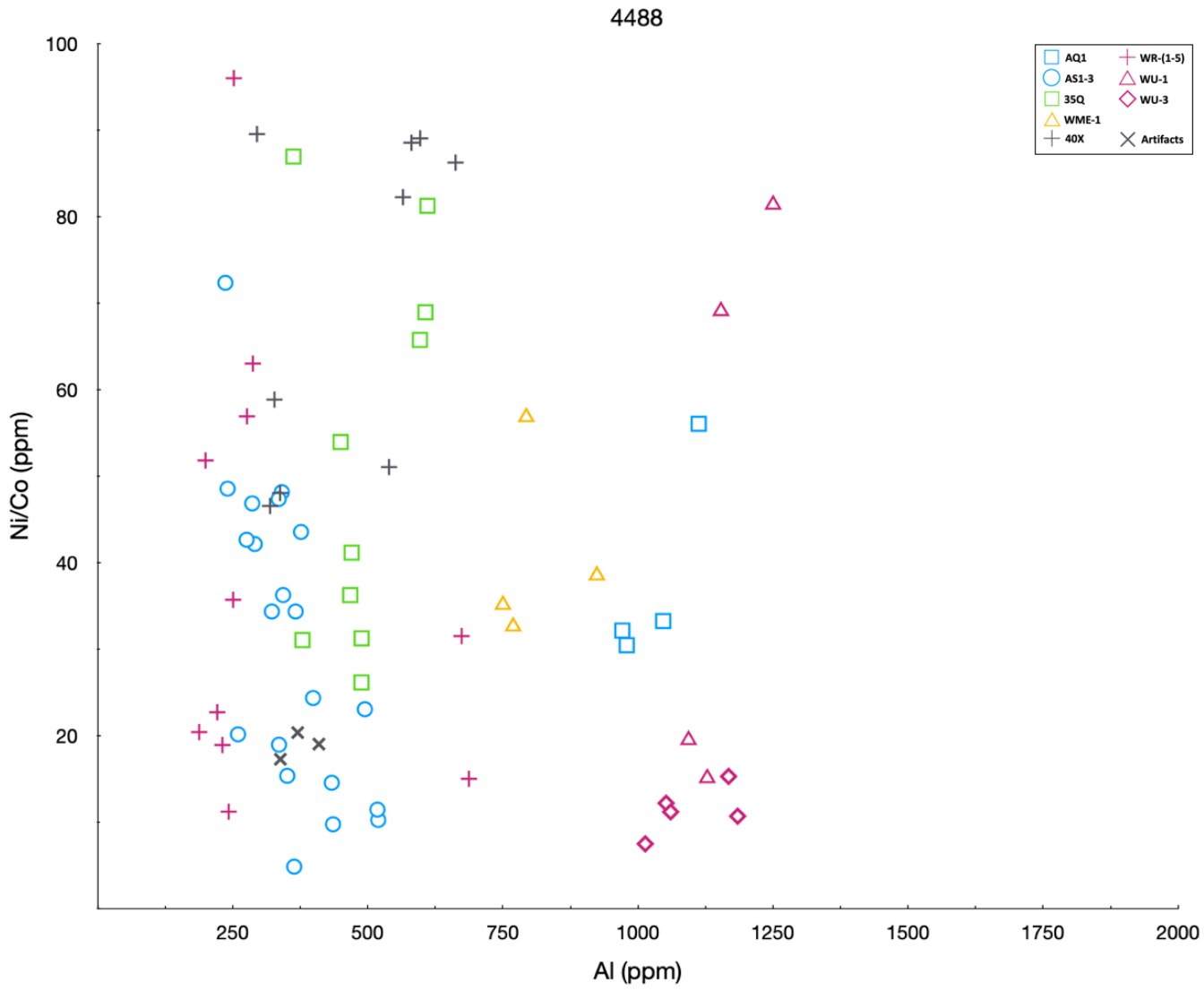

3883
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

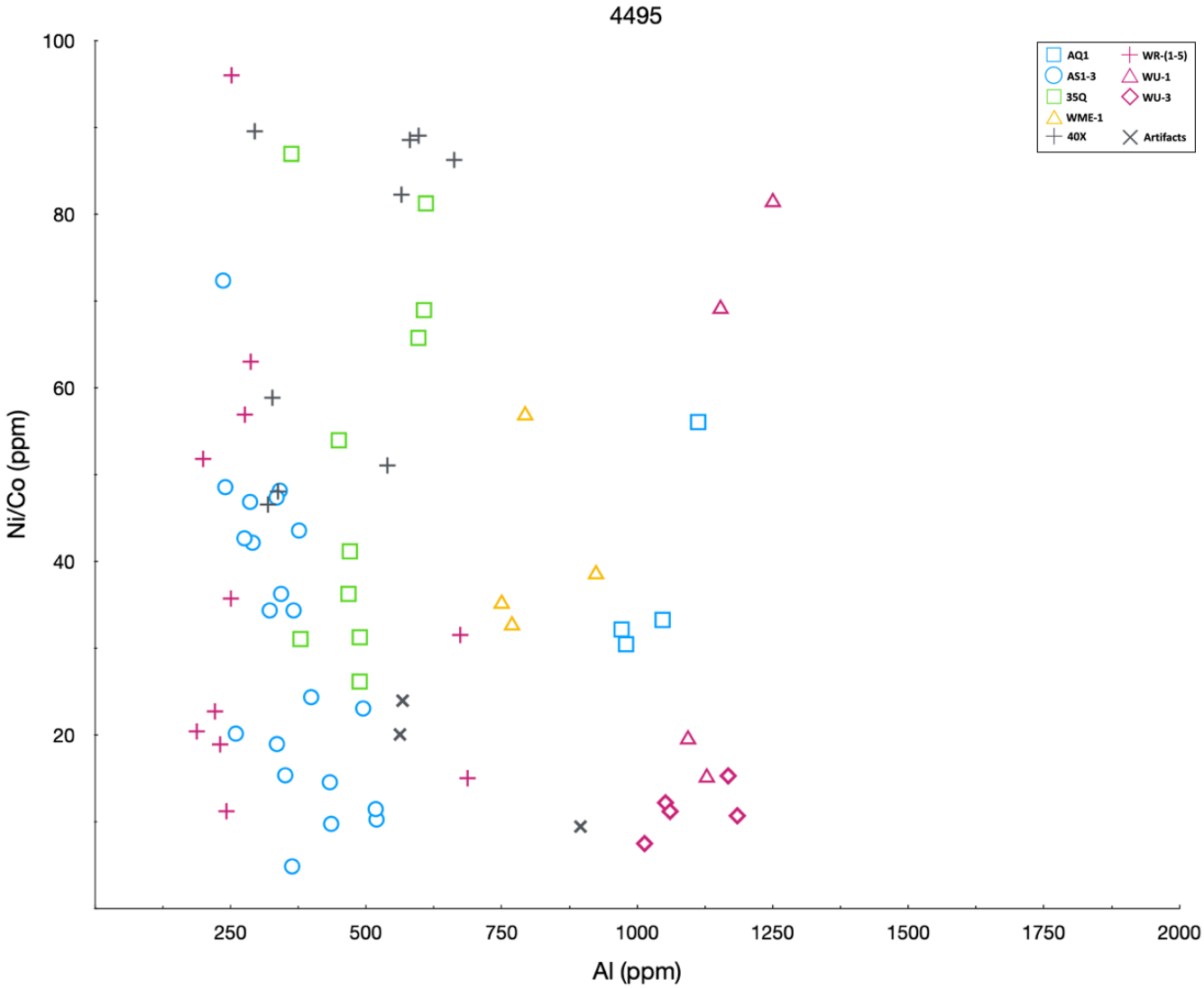

3912
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4018
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4038
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4134
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4488
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000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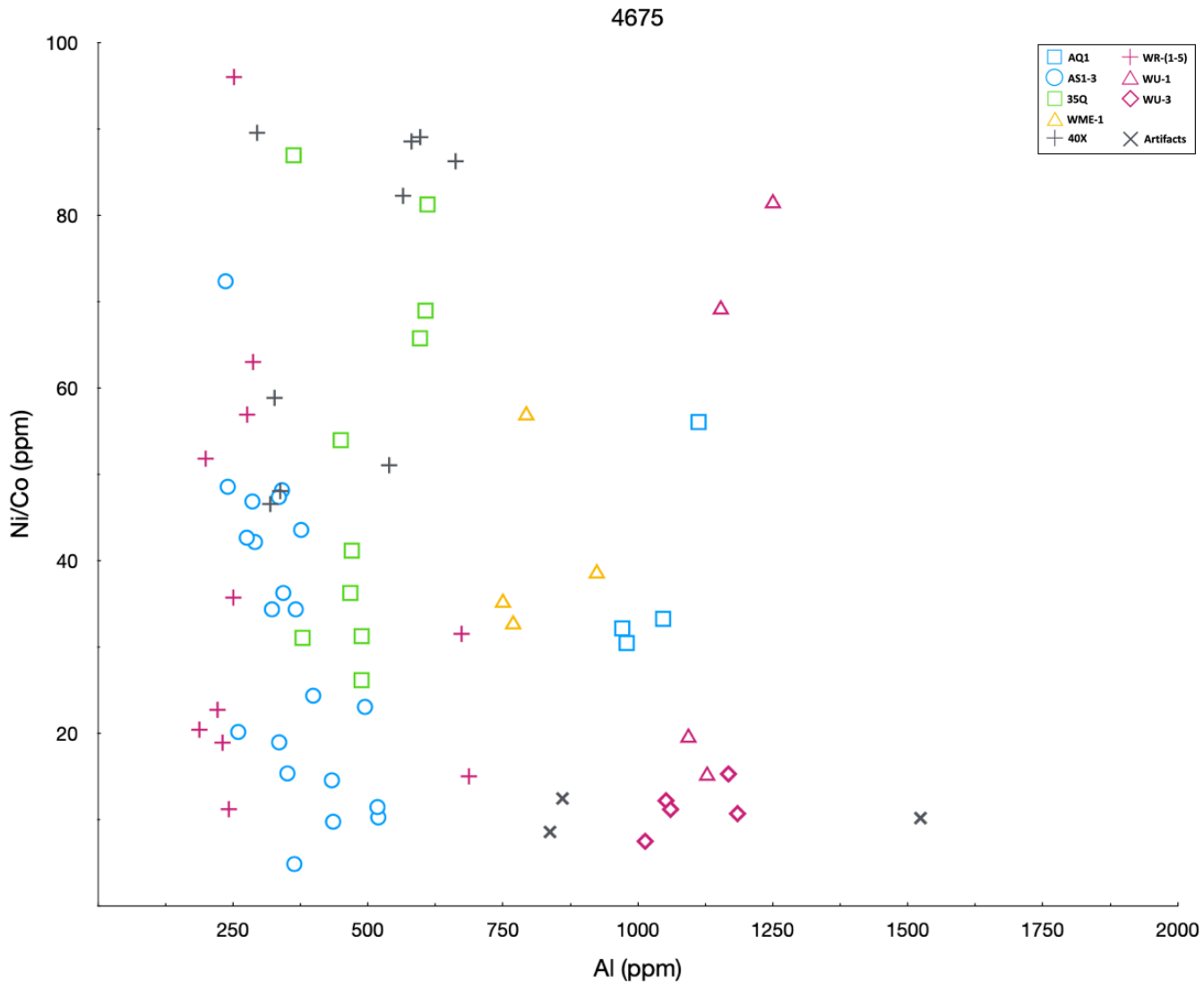
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4675
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
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60
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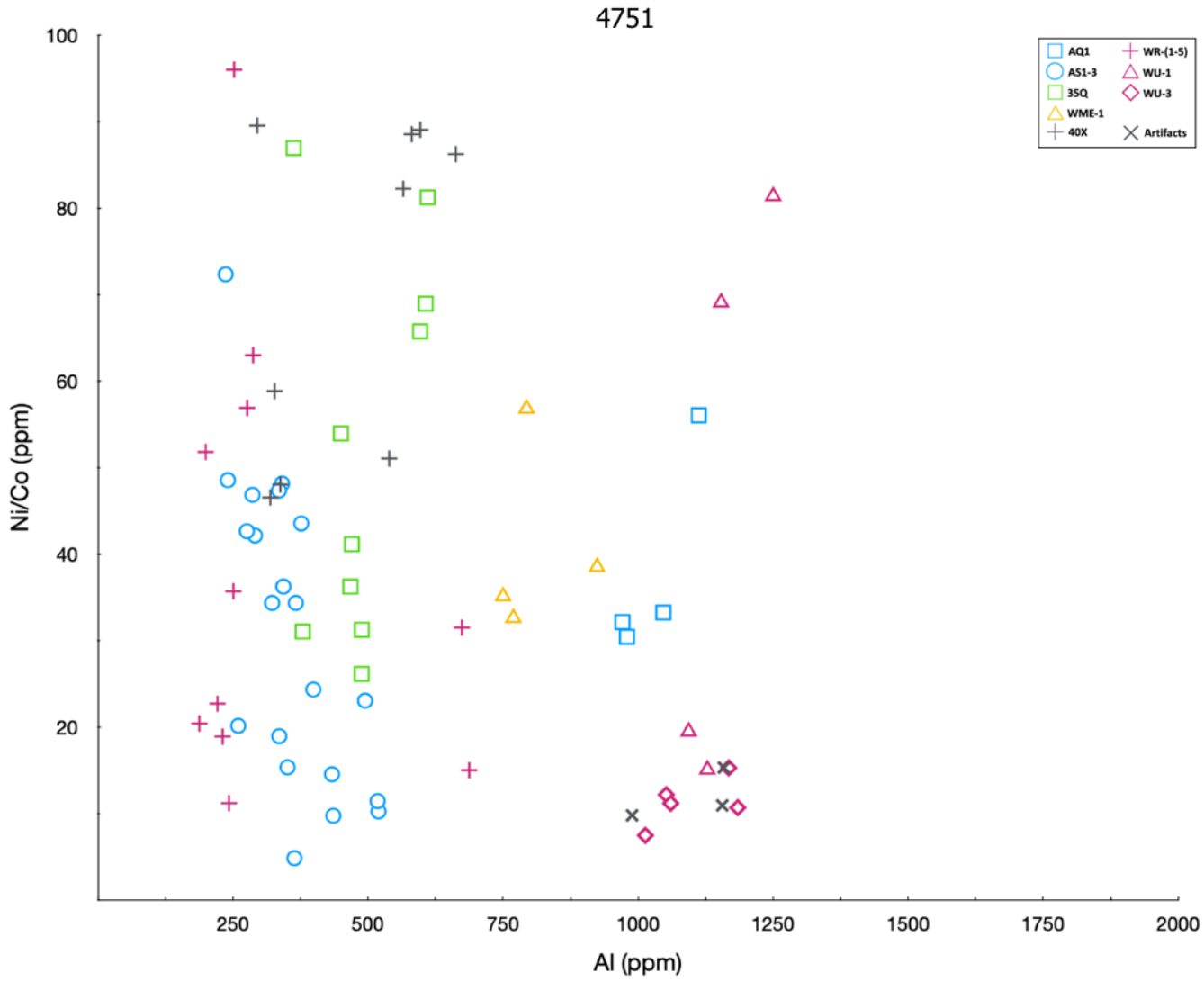
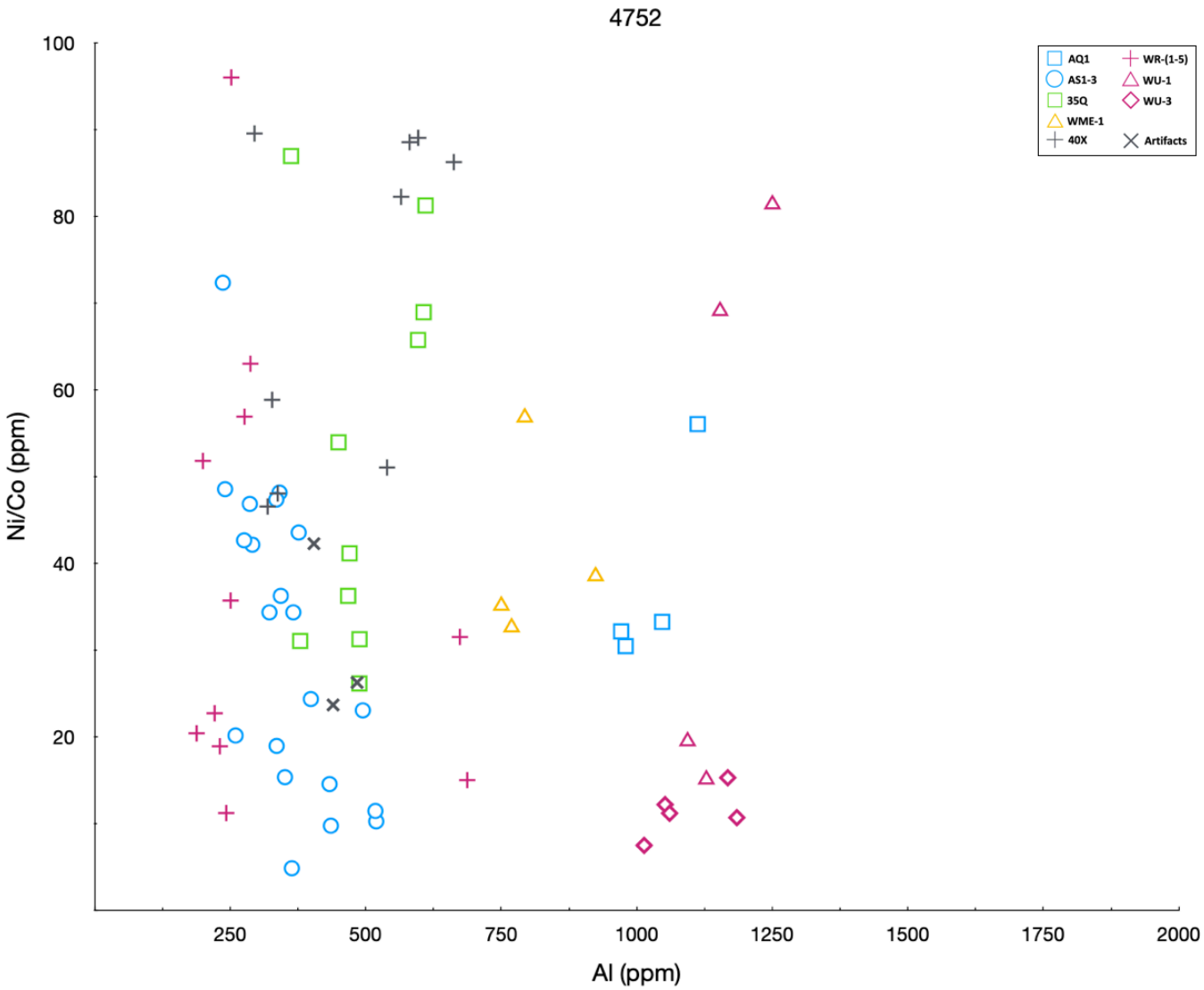
750
1000
1250
1500
1750
2000


4751
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000


4752
AQ1
AS1-3
35Q
WME-1
40X
WR-(1-5)
WU-1
WU-3
Artifacts
Ni/Co (ppm)
Al (ppm)
100
80
60
40
20
250
500
750
1000
1250
1500
1750
2000

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