Quantitative examination of lithic raw material variability and fracture predictability in the Middle and Upper Paleolithic assemblages in southern Jordan
（南ヨルダンの中部・上部旧石器石器群における石器石材の多様性と剥離予測性に関する定量的研究）

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Chapter 1. Introduction

1.1. Middle-to-Upper Paleolithic transition

The transition from the Middle Paleolithic (MP) to the Upper Paleolithic (UP) has long been an important issue in prehistoric archaeology (e.g., Garrod, 1951, 1955) and also gained greater attention recently. The Middle to Upper Paleolithic transition (hereafter the MP-UP transition) is known for its temporal proximity to key paleoanthropological processes, such as the wide geographic dispersal of *Homo sapiens* (ca. 50–40 ka) and their interaction and interbreeding with Neanderthals and Denisovans (Shea, 2013; Higham et al., 2014; Bosch et al., 2015; Bae et al., 2017; Dennell, 2020; Kuzmin et al., 2022; Vallini et al., 2022; Slimak, 2023). The MP-UP transition has been considered as an important topic in various fields. One of the main research issues is how paleoanthropological processes were related to archaeological records. Paleoanthropological studies (e.g., ancient DNA) alone cannot explain the factors and complicated processes of the major events in human history mentioned above, thus it is necessary to examine the archaeological record. Especially, some studies focused on cultural remains in the Levantine region, which was the beginning of *Homo sapiens* geographic dispersal across Eurasia (For the Levantine case studies, see Akazawa et al., 1998; Bar-Yosef, 2000; Henry, 2003; Shea, 2008; Meignen, 2012; Douka, 2013; Kadowaki, 2013; Rose and Marks, 2014; Belfer-Cohen and Goring-Morris, 2018; Abadi et al., 2020; Dennell, 2020; Stutz, 2020; Boaretto et al., 2021). Consequently, the MP-UP transition in the Levant is known for changes in a wide range of archaeological records, such as lithic technology, foraging practices, mobility patterns, and personal adornments (Marks, 1981, 1983b; Rabinovich, 2003; Kuhn et al., 2009; Belfer-Cohen and Hovers, 2010; Shea and Sisk, 2010; Douka, 2013; Stiner et al., 2013; Henry et al., 2017; Goder-Goldberger and Malinsky-Buller, 2022).

Several studies employed a taxonomic term of the "Initial Upper Paleolithic (IUP)" as a chronological framework in understanding these transitional archaeological records distributed over a wide geographical region (Kuhn and Zwyns, 2014; Kuhn, 2019; Goring-Morris and Belfer-Cohen, 2020; Hublin et al., 2020; Zwyns, 2021; Carvalho and Bicho, 2022; Kot et al., 2022). Moreover, the "Late Middle Paleolithic (LMP)" is chronologically distinguished before the IUP, and the "Early Upper Paleolithic (EUP)" is chronologically distinguished after the IUP. These chronological entities were defined using techno-typological criteria of many lithic assemblages in the Levant (Fig.1.1.; Garrod, 1951; Copeland, 1975, 2000; Marks and Volkman, 1983; Gilead, 1991; Richter et al., 2001; Pastoors et al., 2008; Meignen, 2012; Shea, 2013; Rose and Marks, 2014;

Kadowaki et al., 2019a, 2021; Goder-Goldberger, 2020; Goder-Goldberger and Mailnsky-Buller, 2022). More specifically, in the LMP (75–50 ka), the Levallois method is dominantly employed. Among the Levallois flaking modes, the unidirectional convergent mode is dominant, accompanied by the bidirectional and centripetal modes. Non-Levallois reduction methods include single platform cores, bladelet cores and cores on flakes. The retouched tool categories are characterized by abundant side-scrapers (Nishiaki et al., 2012; Malinsky-Buller et al., 2014; Sharon and Oron, 2014; Baykara et al., 2015; Goder-Goldberger and Bar-Matthews, 2019; Goder-Goldberger et al., 2020). In the IUP (50–35 ka), the lithic technology shifted to increasing occurrences of robust blades knapped with hard hammers. The retouched tool types are characterized by UP tool types, such as end-scrapers and burins. Elongated points, including typological Levallois points, are also found (Kuhn et al., 2009; Leder, 2016; Nishiaki, 2018; Kadowaki et al., 2019b, 2022a; Barzilai, 2022; Goder-Goldberger et al., 2023). Moreover, some studies proposed several distinct variants of IUP lithic industries based on the appearance of unique tool types, such as Emireh points and chamfered pieces (Goring-Morris and Belfer-Cohen, 2020). In the EUP (45–30 ka), bladelets increased, and their small striking platforms with fine overhang removals indicate the employment of soft-hammer percussion. Within the period of the EUP, many archaeologists recognize the subdivision of two techno-complexes, Ahmarian and Aurignacian. The Ahmarian, examined in this dissertation, is characterized by the composition of unique tool types, such as backed points and el-Wad points (Bar-Yosef and Befer-Cohen, 2019; Shea et al., 2019; Parow-Souchon et al., 2021; Abulafia et al., 2021; Shemer et al., 2023).

In contrast to these numerous studies on lithic techno-typology, little is known about whether any changes occurred in the use of lithic raw materials at the MP-UP transition in the Levant. At this stage, only a few studies have analyzed lithic raw material changes at the Levantine MP-UP transition in contrast to the other regions like Europe (For the European case studies, see Féblot-Augustins, 2009; Grimaldi et al., 2014; Aubry et al., 2016; Tomasso and Porraz, 2016; Negrino and Riel-Salvatore, 2018; Riel-Salvatore and Negrino, 2018; Holt et al., 2019). Therefore, this dissertation focuses on lithic raw material utilization at the MP-UP transition in the Levant. In the next section, I review the case studies of lithic raw material in the Levant from a methodological viewpoint and summarize some research problems.

1.2. Brief overview of lithic raw material studies in the Levantine Paleolithic

During the entire Levantine Paleolithic, chert (flint) is mainly used as raw material of flaked stone tools (Delage, 2003; Delage and Webb, 2020). Recent raw material studies actively adopted field surveys for chert outcrops and analyzed raw material samples collected at the outcrops in comparison to archaeological samples (Finkel et al., 2016, 2018, 2019, 2020b, 2022; Groucutt et al., 2017; Parow-Souchon et al., 2021). More specifically, Finkel et al. (2016, 2018, 2019, 2020b) aimed to identify extraction and reduction (E&R) complexes from the lithic assemblage composition collected from raw material sources. The field survey of raw material outcrops is often regarded as preliminary studies for identifying raw material sources.

Increasingly, the identification of raw material sources was conducted through various geochemical studies such as INAA (Julig et al., 2007), the measurement of ^{10}Be (Boaretto et al., 2009), ICP-MS (Ekshtain et al., 2014, 2017, 2019; Ekshtain and Tryon, 2019; Agam, 2020; Bellar et al., 2020; Finkel et al., 2020a, 2023; Ekshtain and Zaidner, 2022; Bellar, 2023), and petrographic analysis (Agam et al., 2020) of chert samples from outcrops and archaeological sites. Because the source identification analysis result is easily linked to lithic raw material procurement and exploitation strategies, Minimal Distance Analysis was performed by using ArcGIS (Parow-Souchon and Purschwitz, 2020). Some studies mentioned the raw material selectivity through the classification of chert's macroscopic aspects (Wilson et al., 2016; Agam, 2020; Agam et al. 2022) and the analyses of the quality (Delage, 2007; Hovers, 2009; Shimelmitz et al., 2020; Assaf, 2021) and use-wear (Agam and Zupancich, 2020) of chert artifacts. As described above, the classification of lithic artifacts by macroscopic aspects is still a primary step in examining the use of chert. Because geochemical analyses of lithic raw material can only be applied to a limited number of samples. On the other hand, the blind test about the macroscopic classification of chert types was also performed (Agam and Wilson, 2018). A few studies identified the sources of Paleolithic obsidian artifacts (Frahm and Hauck, 2017; Frahm and Tryon, 2019). From a wider perspective, some studies discussed lithic provisioning strategies at the UP (Kuhn, 2004) and the MP (Henry, 2011; Varoner et al., 2022).

Explaining the studies related to the MP–UP transition, Julig et al. (2007), conducted instrumental neutron activation analyses (INAA) to examine the changes in chert sources at the MP-UP transition, using geological samples and the lithic assemblage of Jerf al-Ajla Cave, Syria. They found that while MP inhabitants used local Eocene raw material almost exclusively, the use of more distant Cretaceous raw material increased in the Upper and Epipaleolithic periods. In Israel, the studies of 'Ein Qashish (Ekshtain et al., 2014), Amud Cave (Ekshtain et al., 2017), Skhul Cave (Ekshtain and Tryon, 2019) and

Nesher Ramla (Ekshtain and Zaidner, 2022) have recently revealed the raw material exploitation patterns in the MP. They indicate that MP inhabitants at these sites exploited lithic raw materials not only from local sources but also from mid-range or non-local sources.

In this way, lithic raw material studies in the Levantine Paleolithic are progressing in various themes, and focusing on the identification of raw material sources. In fact, to demonstrate Paleolithic raw material utilization, identifying raw material sources and considering models of raw material procurement and exploitation have been conducted as effective approaches in various regions (e.g., Shackley, 2008; Spinapolice, 2012; Ekshtain et al., 2014; Garvey, 2015; Aubry et al., 2016; Frahm and Hauck, 2017; Brandl et al., 2018; Soto et al., 2018; Agam, 2020; Gómez de Soler et al., 2020b; Valde-Nowak and Ciésla, 2020; Ekshtain and Zaidner, 2022). On the other hand, few studies focused on the capacity and availability of lithic raw material in the Levantine Paleolithic.

1.3. Aims and organization of the research

The problems mentioned above can be summarized as follows. Firstly, few Levantine studies focus on lithic raw material at the MP-UP transition. As mentioned above, a number of paleoanthropological research suggested that several major events in human evolution had occurred at the MP-UP transition. One of the further interests in this research topic is how material culture contributed to these events. Lithic artifacts are representative of the archaeological discussion of material culture in the Paleolithic. Moreover, lithic raw materials have a great influence on the production and modification of stone tools (Andrefsky, 1994, 2009). Lithic raw material studies play an important role in exploring prehistoric behavioral strategies because understanding how prehistoric people used lithic raw material can help us to explore their technological organization linked to mobility and land use (e.g., Binford, 1979; Nelson, 1991; Marks et al., 1991; Kuhn, 1995). Lithic raw material studies can provide us with the comprehension of the resource utilization at the MP-UP transition when material culture shifted. However, the discussion like mobility and land use is by no means abundant because of few lithic raw material studies in the Levant.

Secondly, these lithic raw material studies are slightly inclined toward the source identification. I think that due to the geological conditions in the Levant, where chert is mainly available as lithic raw materials, the variety of lithic raw material excavated from the sites is not abundant accordingly. The exiguity of lithic raw material variety has resulted in few opportunities for the research themes, which may have led to the paucity of case studies and the bias in analysis methods. In fact, the study in other region has adopted more various themes. For example, there are analyses of lithic raw material variability in use-wear formation (e.g., Lerner et al., 2014a, 2014b; Abrunhosa et al., 2019), raw material quality examination through quantifying mechanical properties (e.g., Webb and Domanski, 2008; Moník and Hadraba, 2016; Namen et al., 2022) and raw material transport patterns using cortex ratios (e.g., Lin et al., 2010, 2015, 2016). These methods can be sufficiently applied to the Levantine cases even if chert is only used for lithic raw material.

Here, this dissertation proposes a novel framework of lithic raw material study combining the macroscopic classification with the physical properties, which have not been analyzed extensively in the Levant. More specifically, I present analyses of four lithic assemblages of the LMP, IUP, and EUP (Ahmarian) excavated from the Jebel Qalkha area in southern Jordan to examine whether any changes occurred in raw material utilization at the MP-UP transition. The Jebel Qalkha sites are located close to each other within an area of 6 km^2, sharing essentially the same availability and accessibility of lithic raw materials. One significance of this dissertation is the diachronic examination of lithic raw material selection and procurement through three continuous phases over the MP-UP transition, a landmark period in human history.

To approach the above issues, this dissertation has performed two analyses. First of all, Chapter 2 introduces Paleolithic sites in the Jebel Qalkha area and geological settings around the study area. Chapter 3 classifies chert types by using several macroscopic and microscopic attributes. Chapter 3 also presents diachronic changes in chert-type frequencies from the LMP to the EUP and discusses the relation to techno-typological attributes. Chapter 3 was revised from the article published in *Archaeological Research in Asia* (Suga et al., 2022). Furthermore, Chapter 4 also examines how the differences in macroscopic appearances (chert types) that were conventionally used as criteria for the chert "quality", are related to some quantitative attributes in hardness involved in flaking lithics. Chapter 4 was also revised from the article published in *Journal of Paleolithic Archaeology* (Suga et al., 2023). Although the two publications include co-authors, the author of this dissertation (Suga, E.) had a major role in the studies and wrote the manuscripts. Based on Chapters 3 and 4 results, Chapter 5 presents the significance of this dissertation in the lithic raw material studies. Chapter 5 also shows further problems of this dissertation and presents some preliminary analyses and results to overcome these issues. Chapter 6 shows the conclusion of this dissertation.

Fig. 1.1. Map of the Levant region showing the LMP, IUP and EUP sites. A red circle shows study sites. Vector and raster map data are acquired from Natural Earth (https://www.naturalearthdata.com/). Site names, periods, and references are as follows.

1) Üçağızlı Cave (IUP–EUP): Kuhn et al., 2009. 2) Dederiyeh Cave (LMP): Nishiaki et al., 2012.
3) Wadi Kharar 16R (EUP): Kadowaki et al., 2015. 4) Hummal (LMP): Hauck, 2011.
5) Umm el-Tlel (IUP): Boëda and Bonilauri, 2006. 6) Abou Halka (IUP): Leder, 2016.
7) Ksar Akil (IUP): Bosch et al., 2015. 8) Antelias (EUP): Copeland, 2000.
9) Manot (EUP): Alex et al., 2017. 10) Nahal Mahanyeem Outlet (LMP): Kalbe et al., 2014.
11) Amud Cave (LMP): Ekshtain et al., 2017. 12) Tabun Cave (LMP): Ronen, 2017.

13) ‘Ein Qashish (LMP): Malinsky-Buller et al., 2014.
14) Kebara Cave (LMP–EUP): Meignen, 2019. 15) Mughr el-Hamamah (EUP): Shea et al., 2019.
16) Far’ah II (LMP): Goder-Goldberger et al., 2020.
17) Tor Sadaf (IUP): Fox and Coinman, 2004. 18) EHLPP1 (EUP): Clark et al., 2017.
19) Al-Ansab 1 (EUP): Schyle and Richter (Eds.), 2015.
20) Al-Ansab 2 (IUP): Schyle and Richter (Eds.), 2015.
21) Boker Tachtit (IUP): Boaretto et al., 2021. 22) Boker A (EUP): Marks, 1983a.
23) Boker BE (LMP): Marks, 1983a.
24) Rosh Ein Mor (LMP): Goder-Goldberger and Bar-Matthews, 2019.
25) N Nizzana XIII (EUP): Gilead and Bar-Yosef, 1993.
26) Qadesh Barnea (EUP): Goring-Morris and Davidson, 2006.
27) Lagama sites (EUP): Gilead, 1983. 28) Abu Noshra I & II (EUP): Phillips, 1988.
29) Tor Sabiha (LMP): Henry, 1995. 30) Tor Faraj (LMP): Henry, 2003.
31) Wadi Aghar (IUP): Kadowaki et al., 2019b. 32) Tor Fawaz (IUP): Kadowaki et al., 2022a.
33) Tor Hamar (EUP): Naito et al., 2022.

Chapter 2. Research materials

2.1. Lithic assemblages from the Jebel Qalkha area, Jordan

The initial investigations of the prehistoric sites in the Jebel Qalkha area were conducted by D. O. Henry as part of a long-term prehistoric project between 1976 and 1999. Systematic surveys and excavations at numerous prehistoric sites were conducted in several study areas with different elevational, topographic and biotic settings including the Mediterranean zone on the Ma'an Plateau, the Irano-Turanian steppe in the Judayid Basin, the Saharo-Arabian desert in the lowland of Wadi Hisma, and the Wadi Araba Rift Valley (Henry, 1989, 1994, 1995, 2003, 2012, 2017a, 2017b; Henry and Beaver, 2014; Henry et al., 2017). Since 2016, renewed investigation focusing on the Jebel Qalkha area has been conducted to refine the cultural-chronology and to increase human behavioral and paleoenvironmental records in the late Pleistocene (Hirose et al., 2022; Kadowaki and Henry, 2019; Kadowaki et al., 2019a, 2019b, 2021, 2022a, 2022b; Naito et al., 2022; Suga et al., 2022, 2023; Ichinose et al., 2023).

In previous studies of lithic raw materials in the Jebel Qalkha area, Henry (1995) suggested that chert raw material was transported to the MP site at Tor Faraj from sources 20 km away. Henry and Mraz (2020) also compared the use of lithic raw material between the LMP and Neolithic assemblages.

The current environment around the Jebel Qalkha area is arid with less than 50 mm annual precipitation. The vegetation is currently sparse at the transition between the Irano-Turanian and Saharo-Arabian phytogeographic zones. However, recent paleoclimatic studies suggest more humid conditions during MIS 4–3 (Torfstein et al., 2015; Miebach et al., 2019) that correspond to the Middle Paleolithic, Upper Paleolithic, and Epipaleolithic occupations in the Jebel Qalkha area. In addition, the pollen records from the dead sea indicate that a steppe corridor was widely distributed in southern Jordan (Richter et al., 2020). The analyses of pollens and phytoliths excavated from the Jebel Qalkha sites (Henry, 1995) indicate that a wider range of vegetation including arboreal and herbaceous plants was distributed during the Middle Paleolithic, Upper Paleolithic, and Epipaleolithic periods in agreement with the Dead Sea pollen records. In addition, some recent studies reported the luminescence ages in MIS 5 at wetland sediments in Wadi Gharandal (Al-Saqaret et al., 2020; Abbas et al., 2023).

This dissertation analyzes lithic assemblages collected in the renewed investigations at Tor Faraj, Wadi Aghar, Tor Fawaz, and Tor Hamar in Chapter 3 (Table 2.1.). These sites are located close to each other (less than 2 km apart) within the same geological settings characterized by extensive exposure of Umm 'Ishrin Sandstone (Figs. 2.1 and 2.2.)

(Rabb’a, 1987). Chert is the dominant lithic raw material at these sites. The appearance of chert made into artifacts varies in macroscopic features, such as color and texture, and their variations are generally similar among the sites (Fig. 2.3.). Thus, I assume that prehistoric inhabitants of the sites experienced similar availability and accessibility of lithic raw materials. The following section summarizes the basic information of the four sites (Fig.2.2.).

Tor Faraj

Tor Faraj (29◦ 56′ 19.9“N, 35◦ 19’ 33.6” E, 1000 m a.s.l.) is a rock shelter site (Fig. 2.2e.). Several radiometric dates (TL, AAR and U-series) between 43.8 and 69.0 kya were reported (Henry, 2003). The lithic technology is characterized by the dominant employment of Levallois technology encompassing various core-flaking methods (Henry, 2003; Demidenko and Usik, 2003; Kadowaki and Henry, 2019). Especially, unidirectional-convergent reduction is dominant, but bidirectional reduction is also relatively common, and centripetal reduction is rare (Groucutt, 2014; Groucutt et al., 2015). These characteristics correspond to the lithic technology in the LMP (Hovers, 2009; Shea, 2013; Sharon and Oron, 2014; Meignen, 2019; Malinsky-Buller et al., 2021).

Wadi Aghar

Wadi Aghar (29◦56′11.99” N, 35◦19′53.53″ E, 965 m a.s.l.) is a shallow rock shelter site (Fig. 2.2b.). The assemblage was dated to 45–40 ka by OSL and radiocarbon dating (Kadowaki et al., 2019b). The lithic assemblage includes typical UP tool types like end scrapers and burins. The core reduction technology is dominated by unidirectional flaking, and the core types are characterized by the predominance of volumetric cores with a few along-axis cores (Kadowaki et al. 2019b). In sum, the lithic assemblages from Wadi Aghar show IUP techno-typological characteristics (Kuhn and Zwyns, 2014; Nishiaki, 2018; Kadowaki et al., 2019a, 2019b, 2022a; Kuhn, 2019; Goder-Goldberger et al., 2023).

Tor Fawaz

Tor Fawaz (29◦56′ 49.44” N, 35◦20′9.03″ E, 980 m a.s.l.) is a rock shelter site (Fig. 2.2c.). The age of IUP occupations was estimated to 45–36 ka (Kadowaki et al., 2022a). The lithic assemblage includes Levallois-like points with unidirectional convergent flaking, but many prismatic blade cores and flat-faced cores are observable. The blade technology is characterized by the production of robust blades with large platforms (Kadowaki et al., 2022a). In sum, the lithic assemblages from Tor Fawaz show IUP techno-typological characteristics (Kuhn and Zwyns, 2014; Nishiaki, 2018; Kadowaki et al., 2019a, 2019b, 2022a; Kuhn, 2019; Goder-Goldberger et al., 2023).

Tor Hamar

Tor Hamar (29◦56′17.34” N, 35◦19′8.90″ E, 985 m a.s.l.) is a rock shelter site (Fig. 2.2d.). The assemblage can be subdivided into three cultural periods: Middle Epi (Mushabian) in Layers A–E1 (15.5–15.2 ka), Early Epi (Qalkhan) in Layer E2 (24–18 ka) and Early UP (Ahmarian) in Layers F–G (38–37 ka) (Naito et al. 2022). I analyzed lithic assemblage in Layers F–G in this dissertation. The lithic assemblage from Layers F–G includes el-Wad points and is characterized by dominant production of bladelets typically from single-platform narrow-fronted cores. The techno-typological features show affiliation with the Ahmarian (Shea, 2013; Kadowaki et al., 2015; Goring-Morris and Belfer-Cohen, 2018; Richter et al., 2020; Abulafia et al., 2021; Kadowaki et al., 2021; Gennai et al., 2023; Shemer et al., 2023).

2.2. Geological settings in the Western Hisma Basin

Around the Jebel Qalkha sites, the Cambrian sandstone is dominantly exposed, and chert sources are generally limited (Rabb'a, 1987; Tarawneh, 2002, 2019). However, there are small, fragmented exposures of Cretaceous–Paleogene limestone sequences within 10 km from the Jebel Qalkha area, in which a few chert outcrops occur in small pockets (Fig. 2.1.; Kadowaki et al., 2022b; Ichinose et al., 2023). Some of the chert outcrops are distributed with numerous chert nodules and clasts suitable for the production of flaked stone tools (Fig. 2.4.). For example, the outcrop of the Miocene conglomerate at Humayma, only a few kilometers from the Jebel Qalkha area, is characterized by relatively small size of chert nodules (Fig. 2.2g). On the other hand, large chert nodules weighing over 30 kilograms are available at the Abbasiyah outcrop of Cretaceous–Paleogene limestone formations, located 6–7 km to the northeast of the Jebel Qalkha area, and at the Wadi Abu Sawwan outcrop of the Miocene conglomerate, located about 8 km to the southwest (Figs. 2.2f. and 2.2h.). In these chert sources, the survey found diagnostic Paleolithic artifacts, such as Levallois products and handaxes (Kadowaki et al., 2022b). The prehistoric exploitation of these outcrops is indicated by surface scatters of many lithic artifacts. This dissertation analyzes chert nodules collected from these outcrops in Chapter 4.

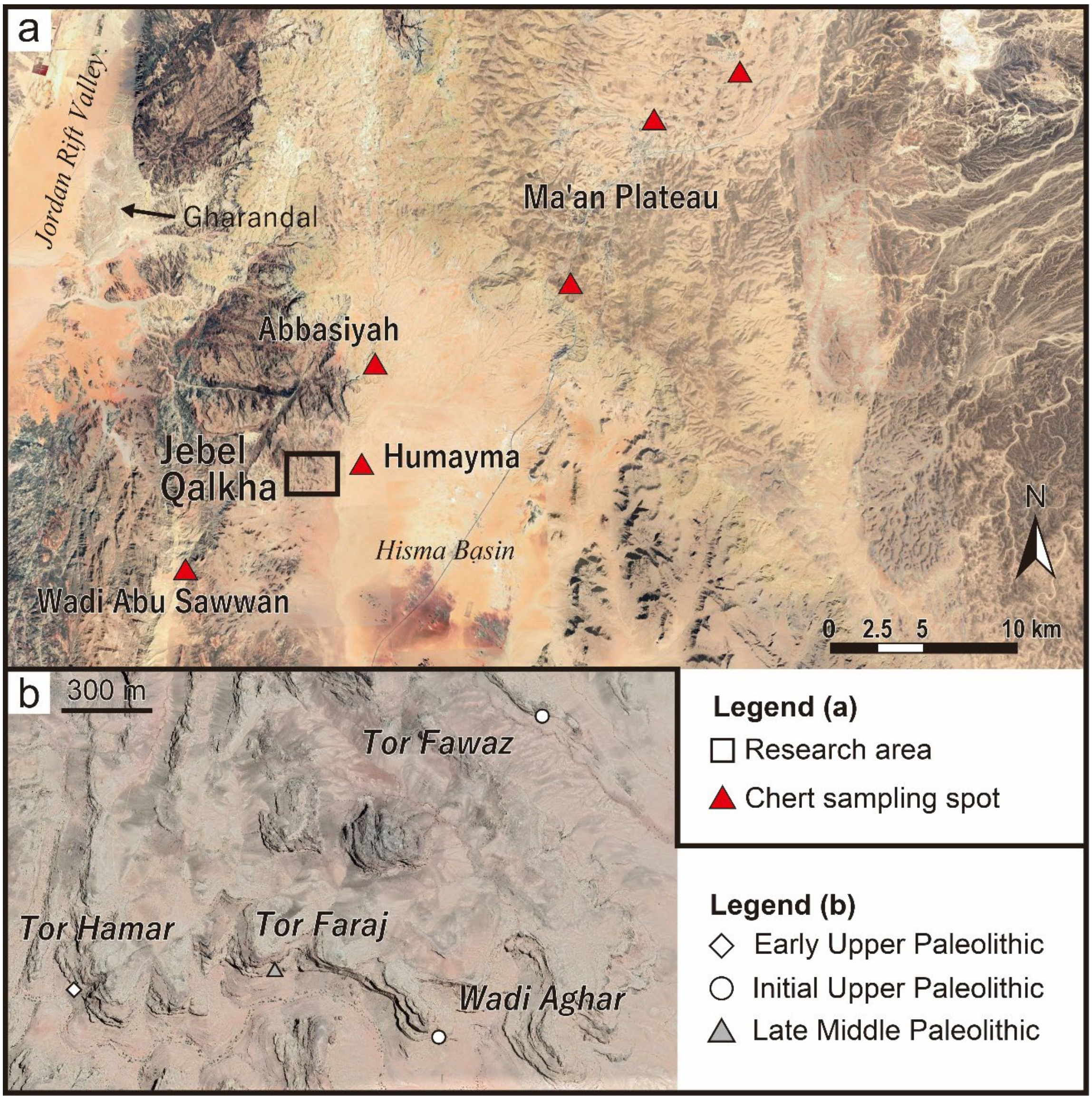


Fig. 2.1. a) Satellite image (acquired from Google Earth) of the western Hisma Basin in southern Jordan. b) Jebel Qalkha area, showing the locations of the Middle and Upper Paleolithic sites analyzed in this dissertation.

Fig. 2.2. Overviews of Paleolithic sites and chert outcrops around the Jebel Qalkha area. a) Jebel Qalkha area. b) Wadi Aghar. C) Tor Fawaz. D) Tor Hamar. E) Tor Faraj. F) Chert beds near Abbasiyah. G) A hillock strewn with chert nodules near Humayma. H) Conglomerate containing chert nodules near Wadi Abu Sawwan.

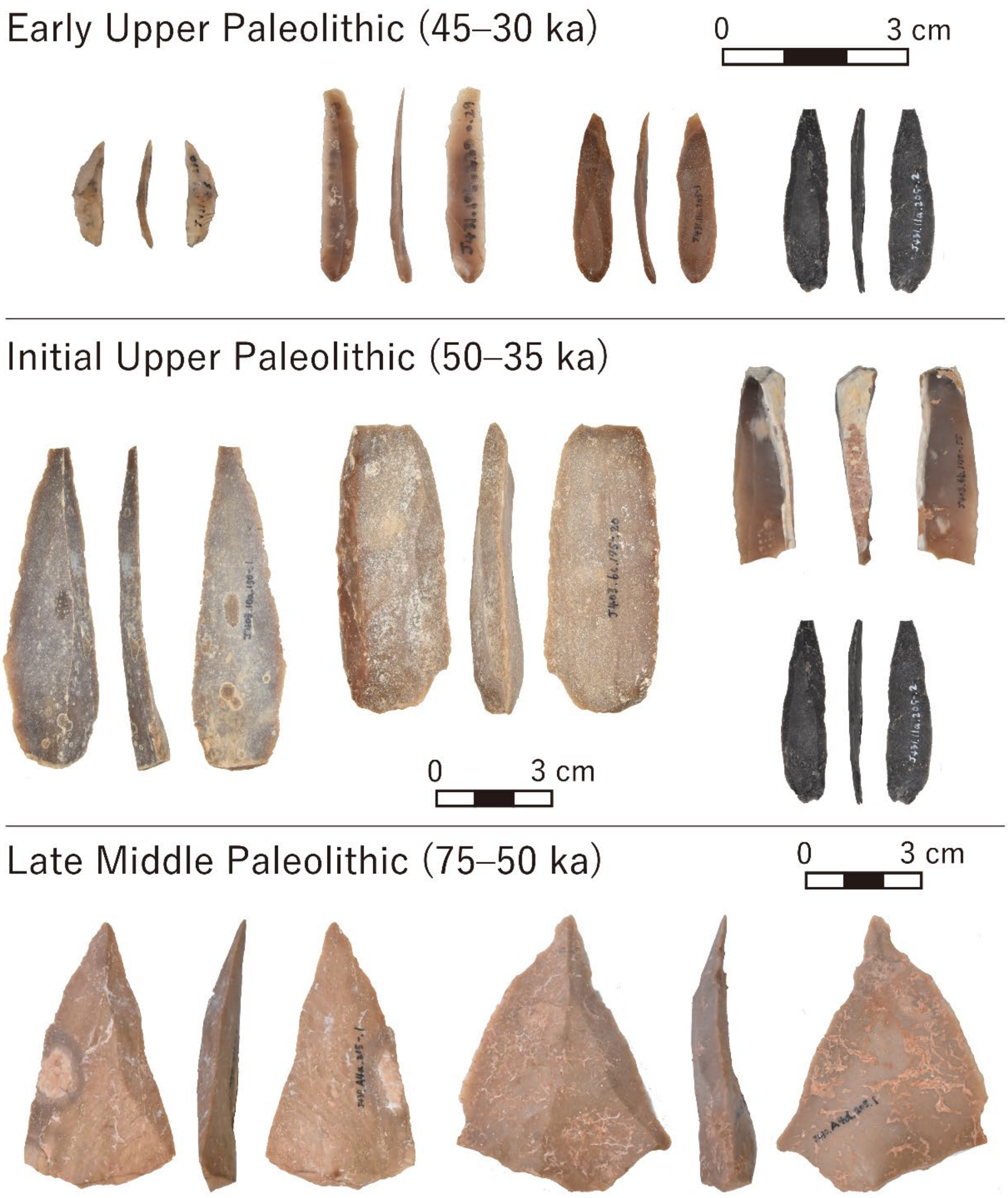


Fig. 2.3. Typical lithic artifacts analyzed in this dissertation.

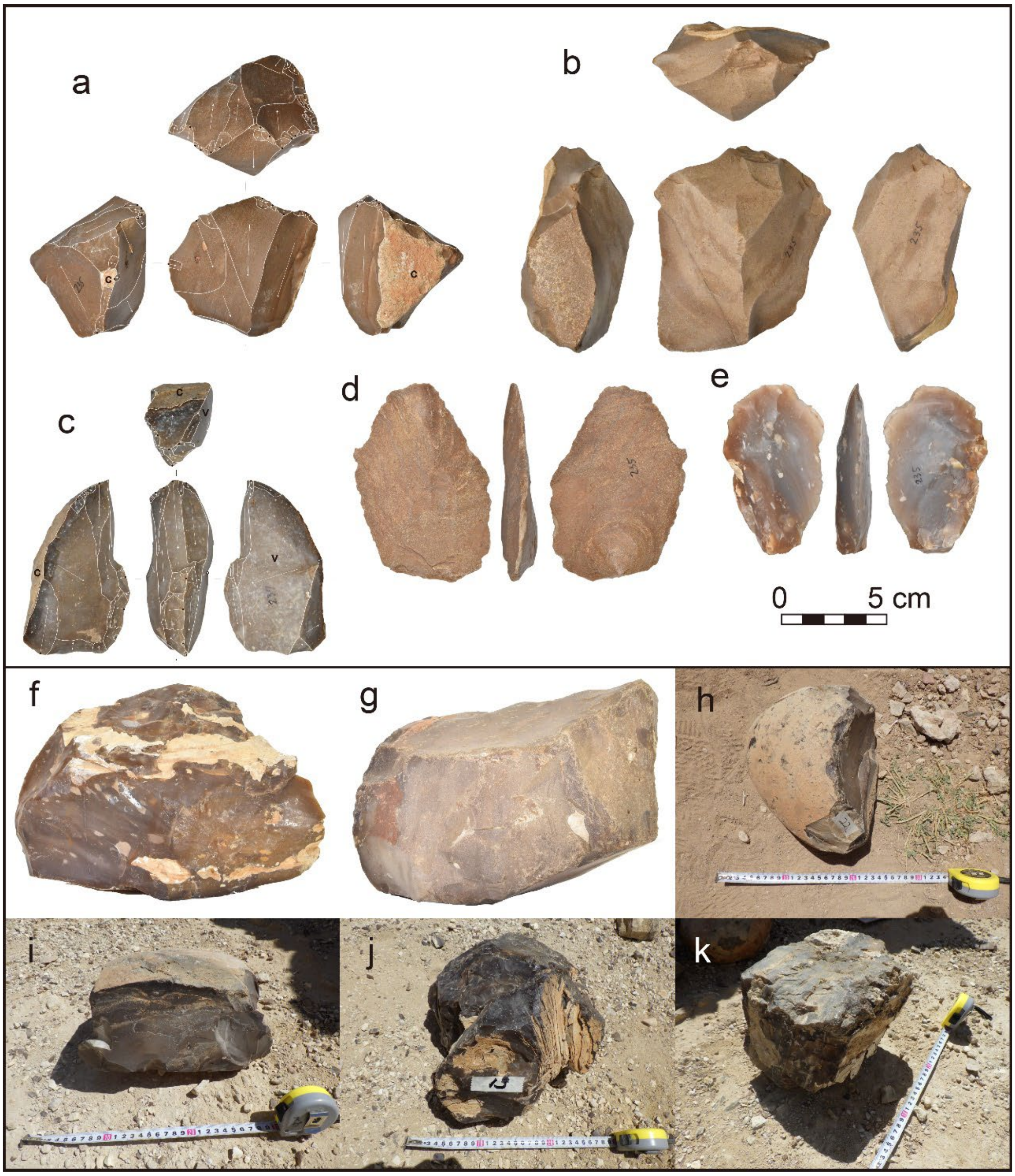


Fig. 2.4. Several photographs of lithic artifacts (a–e) and chert nodules (f–k) collected in the outcrops.

Table 2.1. General inventories of lithic artifacts analyzed in this study from Tor Faraj, Wadi Aghar, Tor Fawaz, and Tor Hamar in the Jebel Qalkha area, southern Jordan.

Site	Tor Faraj	Wadi Aghar	Tor Fawaz	Tor Hamar
Chrono-cultural entities	Late Middle Paleolithic	Initial Upper Paleolithic	Initial Upper Paleolithic	Early Upper Paleolithic (Ahmarian)
Excavation areas (Units)	A4, B2, B3, B4	100, 101, C, D, 83–1, 83–2	6, 7, 8, 9, 10	9, 10, 11
Layers	D2–E	B–D2	Surface, B2, C	F, G
Date	69–44 ka	45–40 ka	45–36 ka	38–37 ka
Core	11	13	82	63
Fully cortical debitage	24	28	334	83
Partially cortical debitage	76	79	673	300
Non-cortical debitage	331	232	1670	1617
Core trimming element	37	11	60	49
Retouched tool	24	38	189	137
TOTAL (without debris)	503	401	3008	2249
References	Henry, 2003 Kadowaki and Henry, 2019	Henry, 1995 Kadowaki et al., 2019b	Henry, 1995 Kadowaki et al., 2022a	Henry, 1995 Naito et al., 2022

Chapter 3. Diachronic changes in lithic raw material (chert) use

3.1. Methods

3.1.1. Macroscopic criteria of raw material classification

In the Levantine Paleolithic, the macroscopic attributes widely used to classify chert raw material include color, pattern, texture, cortex, luster, translucence, and inclusions (e.g, Delage, 2007; Wilson et al., 2016; Agam, 2020; Agam and Zupancich, 2020; Agam et al., 2022). In the Jebel Qalkha sites, Henry and Mraz (2020) employed a macroscopic raw material classification to compare the variability of lithic raw material between Tor Faraj (LMP) in the Jebel Qalkha area and Ayn Abū Nukhayla (Neolithic) in the Wadi Rum area. This study devised a new classification scheme suited to clarify the lithic raw material variations in the LMP, IUP and EUP assemblages of the Jebel Qalkha sites. For macroscopic examination of chert variability, several attributes were used, such as color, UV signature, texture, and translucence, which were also employed in the previous studies (Henry, 1995; Henry and Mraz, 2020). Chips and heavily weathered or burnt lithics were excluded from the analyses.

The translucency was determined as ‘high’ or ‘low’ according to the degree to which light passed through the lithic edges (> 1 mm in thickness) by placing them over a 1 cm hole backlit by the light of a 7 W LED bulb with 360 lm (NEC LED stand, HSD16002K-D12) (Fig. 3.1a.).

Colors of lithics were determined according to a Munsell Soil Color chart (e.g., Milne et al., 2009). Multiple colors were recorded for chert types with banded or gradient patterns (Fig. 3.1b.).

To obtain UV signatures of chert, I used a UV lamp (Nichia UVLED, SK375UV-002) and followed methods of Lyons et al. (2003) and Henry and Mraz (2020). The UV colors were determined according to Aubuchon’s classifications (Aubuchon’s, 2007), including Orange 590, Yellow 570, Violet 400, and Grey or White (Fig. 3.1c.).

Regarding the texture, this study made detailed measurements of the surface roughness as described in the next section.

3.1.2. Texture and the measurement of surface roughness (R_a)

Texture is usually recorded with ordinal scales such as fine, medium and coarse (e.g., Henry, 1995; Henry et al., 2014; Henry and Mraz, 2020). In this dissertation, a novel method was employed for the quantification of texture by measuring surface roughness (R_a values) by using Mitsutoyo SURFTEST SJ-210.

R_a is usually used for the inspection of cut and ground surfaces of industrial products (e.g., Whitehouse, 1997; Gökkaya and Nalbant, 2007; Jeyapoovan and Murugan, 2013). Some archaeological studies also employed the measurement of surface roughness in heat treatment of lithic raw material (Schmidt et al., 2017, 2020; Schmidt and Hiscock, 2019). The measurement is taken by scratching a surface with a micro-needle (Fig. 3.1d.). The radius of the needle's tip is 5 μm (Fig. 3.1e.). To obtain the R_a value, the influence of large undulations (e.g., macroscopic curvature or ripples) is removed to focus on the roughness that corresponds to the texture of the surface (See Bhushan, 2001 for the details of the measurement).

I used Mitsutoyo SURFTEST SJ-210 and followed the measurement basis of Japanese Industrial Standard 1994. The cut-off value was λc 0.8. The measurement speed was 0.5 mm/s, and the number of intervals was x5. To determine R_a, four measurements were made for each sample by using a flat, unweathered surface, which is either ventral or dorsal in the case of artifacts. The four measurements consist of two measurements for each of two perpendicular directions. The four R_a values were then averaged to determine the R_a value of each lithic sample. The ranges of R_a values in each sample are within 0.5 μm.

R_a values were measured for all retouched tools (n = 324) and their R_a values were compared among the four lithic assemblages to establish a quantitative criterion for assessing the surface roughness of chert artifacts. This criterion was then used to establish reference chert samples with known R_a values. The reference samples were then used to judge the texture of debitage pieces by touching them with a finger. Because the large sample size of debitage did not allow all the debitage pieces to be measured for R_a values, their texture was classified into two categories (i.e., medium and fine) by comparing their texture with the reference samples with known R_a values. The same method was applied to small lithics (e.g., retouched bladelet) that are difficult to measure with the instrument. In addition to lithic artifacts, the R_a values of chert samples were measured, which were collected from the local outcrops (n = 41) within 10 km of the sites, e.g., Humayma, Abasiyya, and Wadi Abu Sawwan.

To evaluate the validity of this new method for measuring chert texture, major chemical composition and the abundance/preservation of microfossils were also analyzed. Then, their correlations were examined with the ratio-scale data (R_a values) of surface roughness. This chapter demonstrates the validity of the new measurement of surface roughness by showing that ratio-scale data (R_a values) of the surface roughness are correlated in reasonable ways to the major chemical composition and the abundance/preservation of microfossils. Then, this chapter presents a new classification scheme designed to characterize diachronic changes in the chert variability observed in the LMP, IUP and EUP assemblages in the Jebel Qalkha sites. The relationship is also examined between the chert variability and the techno-typological attributes of lithic artifacts.

3.1.3. Microfossil inclusion and preservation

The previous classification of chert from the Jebel Qalkha sites noted varying amounts of microfossils (Henry, 1995). The observation of microfossils can be useful for characterizing lithic raw material variations in combination with macroscopic attributes (Browne and Wilson, 2011). For the observation of microfossils, chert samples (n = 92) were selected from the lithic assemblages and outcrops around the Jebel Qalkha sites including a wide range of color, texture, and translucency. From the selected samples, thin sections were made to observe the amount and preservation of microfossils under a polarizing microscope.

Chert samples were characterized by recording “fossil scores” (0–7) that are ordinal scales based on the abundance and the preservation of microfossils in chert (see Ichinose et al., 2023 for the definition of the fossil score). The observation of microfossils in thin-sections is not precise enough for the reliable identification of the species that would allow the age determination of rocks. For reliable identification, microfossils need to be isolated from chert, and this attempt is in progress as another study. Thus, this study focuses on the observations of quantity and preservation of microfossils. These records are used not for the identification of geological sources of chert but for the examination of their correlation (n = 53) with R_a values that are newly introduced as the surface roughness measurement. The analyses were conducted by Dr. Kazuhiro Tsukada (Nagoya University Museum) and Ms. Natsuki Ichinose (Graduate School of Environmental Studies, Nagoya University).

3.1.4. Measurement of major chemical composition

The chemical composition of chert was measured using an Energy Dispersive X-ray spectrometer linked with the Scanning Electron Microscope (SEM-EDX) to examine its correlations with R_a values, a new measurement for chert texture. For this purpose, chert samples (n = 33) were selected from the Tor Fawaz assemblage, including a wide range of color, texture, and translucency. Multiple measurements were made on different spots for each sample and used the mean value to average the internal variation of chemical composition (SEM, Hitachi S-3400 N). The oxide concentration was used for comparison, and various components were detected, such as SiO_2, CaO, P_2O_5, Al_2O_3, K_2O, Na_2O, and MgO. Their total amount was normalized as 100% following Tsukada (2018). The ranges of major chemical components in each sample are within 5%. The detected components were dominated by SiO_2 and CaO while the other components accounted for less than 1.5%. I focused on the major components, i.e., SiO_2 and CaO, to examine their correlations with the surface roughness (R_a values). The Mann–Whitney U test was conducted to evaluate whether the chemical composition differs significantly between the visual chert types.

3.1.5. Techno-typological comparison among the chert types

The chert classifications, as established by the methods above, were used to examine diachronic changes in the use of lithic raw material in the LMP, IUP, and EUP assemblages of the Jebel Qalkha sties. The relative amounts of the chert types were calculated by the number and the weight of lithics. In addition, I examined whether the chert types established in this study show any correlation with flaking methods or lithic morphologies (e.g., Wilson et al., 2016; Agam, 2020; Sánchez de la Torre et al., 2020). For this purpose, I compared techno-typological attributes, particularly several techno-typological indices used in some previous studies (Inizan et al., 1999; Tostevin, 2012; Kot et al., 2020; Abulafia et al., 2021), among the chert types.

3.2. Results

3.2.1. Classification of chert types based on macroscopic attributes

Based on the macroscopic attributes, the chert artifacts were classified into ten raw material types (Fig. 3.2.; Table S1 in Appendix). I employed a method of taxonomic classification (Banning, 2020) and used texture as a top criterion for classification because it is the most quantitative and objective attribute among the macroscopic attributes used in this study. I identified two textural categories: medium and fine. A criterion for this division was established from the distribution of the surface roughness values (R_a) measured on retouched tools (Fig. 3.3.). The distributions of R_a values are similar among Tor Faraj, Wadi Aghar and Tor Fawaz while that of Tor Hamar is distinct with a mode at 1.5–2 in R_a values. Based on this observation, R_a value 2 was set as a boundary between medium and fine textures. The geological chert samples from the local sources showed a similar range of R_a values to those of the lithic assemblages in the Jebel Qalkha sites. Moreover, the distribution is similar to those of the Tor Faraj, Wadi Aghar and Tor Fawaz assemblages.

Fine texture lithics were subdivided by the variation of translucency, for which were identified into two sub-categories, i.e., low and high translucency. Each of the sub-categories was further divided by color variations. All medium texture lithics showed low translucency. Thus, they were subdivided by color variations and then UV signatures.

While ten chert types were identified, as described above, their correlations with petrographic and geochemical attributes suggested three major type-groups (Types M, FL and FH). The following describes how the three type-groups are related to petrographic and geochemical characteristics.

- Type M is the first group consists of all the chert artifacts with medium texture. Its color varies from brown to orange and shows various patterns of color bands and gradients. Because both color and its pattern vary gradually within individual samples, they cannot be effective criteria for the subdivision of Type M chert. Cortex is thin (< 1 mm) and worn, and its color is white to brown.

- Type FL is the second group includes the chert artifacts with fine texture and low translucency. The color variations do not differ from those of Type M, but Type FL characteristically includes white and black colors. The variety of cortex is also similar to Type M chert.

- Type FH is the chert in the third group also has fine texture but has high translucency. Two major color groups in Type FH are dark brown (Dk. Dusky, Red) and light brown (Red Grey, Weak Red). The cortex is thinner than that of Type M. Some samples show white surface layers of 1–2-mm thickness, which likely resulted from weathering called "white alteration" (Thiry et al., 2014; Caux et al., 2018).

3.2.2. Petrographic and geochemical analysis

According to the microscopic observations of thin-sections of the lithics, Type FH generally includes only a few microfossils, while Type M includes numerous microfossils. Type FL is intermediate in microfossil abundance between Type FH and Type M (Fig. 3.4.). In addition, microfossils in Type FH and Type FL are poorly preserved or merged with the matrix, those in Type M are, on the contrary, preserved well enough to show clear skeletal structures.

More quantitatively, Fig. 3.5. shows the relationship between microfossil abundance/preservation and the texture of chert. The surface roughness (R_a) and fossil scores generally show a positive correlation. This suggests that chert with greater surface roughness, i.e., higher R_a values, tends to include a greater amount and preservation of microfossils. The Spearman's correlation coefficient is 0.518 (p-value <0.001).

Fig. 3.6. shows the relationship between the texture of the lithics (R_a values) and SiO_2 concentration for the samples. The two attributes show a negative correlation. This means that chert artifacts with a medium/coarse texture (higher R_a values), i.e., Type M, tend to be lower in SiO_2 concentration than those of finer texture, i.e., Types FL and FH. The Spearman's correlation coefficient between them is 0.523 (p-value = 0.002).

3.2.3. Diachronic trends and techno-typological characteristics by the chert types

Fig. 3.7. shows the relative frequencies of the three type-groups of chert (Types M, FL and FH) in the four lithic assemblages, representing the LMP, IUP and EUP periods. The LMP (Tor Faraj) and IUP (Wadi Aghar and Tor Fawaz) assemblages are characterized by a greater proportion of Type M than the EUP (Tor Hamar) that instead shows a higher proportion of Type FH. Type FH accounts for nearly 50% of the Tor Hamar assemblage. The increase of Type FH from the IUP to the EUP is statistically significant (chi-square value = 21.883, p-value <0.001 between Tor Fawaz and Tor Hamar; chi-square value = 11.554, p-value = 0.009 between Wadi Aghar and Tor Hamar). Thus, the EUP can be differentiated from the IUP/LMP in the decrease of Type M and the concomitant increase of Type FH. Based on this observation, I focus on the comparison between Type M and Type FH in the following results.

To examine whether Type FH chert was associated with any specific lithic techno-morphological categories, the lithic assemblages from the four sites were divided into six general categories, including cortical debitage, partially cortical debitage, non-cortical debitage, core trimming elements, cores, and retouched tools. Then, relative frequencies of the six lithic classes were compared between Type M and Type FH for each of the sites (Fig. 3.8.). The results show that the EUP assemblage (Tor Hamar) is characterized by higher proportions of non-cortical debitage than the LMP/IUP assemblages. Although this observation applies to both Types M and FH, Type FH shows a slightly greater proportion of non-cortical debitage than Type M.

Fig. 3.9. shows the relative frequencies of five blank morphologies, including blade, flake, point, spall and bladelet, by Type M and Type FH in the four sites. The EUP site is characterized by greater ratios of bladelets than the LMP/IUP in both of Type M and Type FH, reflecting the development of bladelet technology (Kadowaki et al., 2021). On the other hand, the four sites commonly show greater proportions of bladelets in Type FH than those in Type M. The proportion of bladelets in Type FH is particularly high at Tor Hamar, accounting for 43.44%.

Table 3.1. compares Type M and Type FH in several measurements of complete artifacts from the four sites. The measurements include length, width, thickness, weight, elongation, and flattening. Because all the measurement data are not distributed normally, the Mann–Whitney U test was conducted to assess the significance of difference between Type M and Type FH. Length, width, thickness and weight of Type M are generally greater than those in Type FH in each of the lithic assemblages. In addition, lithics made on Type FH are generally more elongated than those made on Type M although this difference is statistically significant only in the Tor Hamar assemblage. As for flattening, no significant difference was observed between Type M and Type FH. These patterns are the most prominent in the EUP assemblage at Tor Hamar. Collectively, lithics in Type M chert tend to be larger than those in Type FH in each of the LMP, IUP, and EUP assemblages. Additionally, some other techno-typological attributes were also compared, such as retouched tool types, core morphology, dorsal scar patterns, dorsal-distal shapes, platform types, and overhang removal, among Types M, FL, and FH. However, no clear difference was observed among the three chert type-groups.

3.3. Discussion

3.3.1. Three chert type-groups, M, FL, and FH

As shown in the results, this study identified ten raw material types using macroscopic criteria of texture, translucency, color and UV signature (Fig. 3.2.). The texture was quantified through the measurement of R_a values, which showed reasonable and expectable correlations with major chemical components (SiO_2 and CaO) and the abundance/preservation of microfossils in chert (Figs. 3.5 and 3.6.). Thus, I suggest that R_a values can be reliable ratio-scale data for the surface roughness of chert.

Translucency was evaluated as the degree of fixed light passing through the edges of lithics. In contrast, I found color variations more difficult to define consistently as they gradually change and vary even in the same sample. Additionally, UV signature may be influenced by the degree of weathering although heavily weathered surfaces were avoided. As a result, clear diachronic trends could not be observed in the relative frequencies of the ten chert types. Thus, I focused on texture and translucency as principal criteria in the taxonomic classification of chert types because they were based on more quantitative and objective measurements. These attributes were likely recognizable to the prehistoric inhabitants in the Jebel Qalkha area. In fact, a clear diachronic trend was observed in the three type-groups (Types M, FL, and FH) as described in the Result section (Chapter 3.2.3.). This shows that the three chert type-groups are sufficient to highlight diachronic changes in the use of lithic raw materials over the LMP, IUP, and EUP.

In this study, I did not examine whether the three type-groups of chert represent specifically different geological sources. However, it is at least clear that all three chert type-groups are locally available within the 10 km radius of the Jebel Qalkha area, as shown by the distribution of R_a values of the chert samples (Fig. 3.3.). Thus, I suggest that there was no significant difference in availability among the three chert type-groups for the prehistoric inhabitants in the Jebel Qalkha area. This indicates that the diachronic changes in the proportions of the three chert type-groups were related to changes in the selection of lithic raw materials according to lithic technology that changed over the LMP, IUP, and EUP, as discussed in the following sections.

Further research needs more geologic chert samples from potential sources around the sites and needs to examine their optical, surface profile, petrographic, and geochemical information. Comparison with these geological data can help us establish the chert classification related to geological sources and will allow us to discuss raw material provisioning behaviors (e.g., Browne and Wilson, 2011; Agam, 2020).

3.3.2. Increase of type FH chert in the EUP

A clear change in the relative frequencies of the three chert type-groups (i.e., Types M, FL, and FH) was detected in the EUP, which showed a higher frequency of Type FH than the IUP and LMP. The increase of Type FH in the EUP could possibly reflect a change in chert sources. However, according to the geological surveys around the Jebel Qalkha area, the variability of cherts at several local outcrops includes Types M, FL, and FH. This is illustrated by a wide range of the surface roughness (R_a values) of chert samples from outcrops in the Jebel Qalkha area (Fig. 3.3.). Thus, Type FH does not necessarily correspond to a specific chert source. On the other hand, this is indicated by differences in chemical compositions of some EUP chert artifacts from those of the LMP and IUP in the Jebel Qalkha area (Ichinose et al., 2023). However, the possibility of changes in raw material sources is not exclusive from the intentional selection of Type FH chert that was suitable for the production of bladelets.

On the other hand, the increase of Type FH chert in the EUP assemblage from Tor Hamar could have been caused by an increased selection for Type FH chert at outcrops. One of the reasons for favoring Type FH may be related to the production of bladelets that increased in the EUP (Kadowaki et al., 2021). As shown in Fig. 3.9., more bladelets are made on Type FH than Type M not only in the EUP but also in the IUP and LMP. In addition, lithic artefacts made on Type FH chert material are generally smaller than those on Type M in all the periods (Table 3.1.). Thus, I suggest that small lithic artifacts, particularly bladelets, tended to be produced from Type FH chert. Importantly, the association between Type FH chert and small lithics applies to all three periods despite diachronic changes in lithic technology, and the increase of Type FH in the EUP was clearly associated with the development of bladelet technology and concomitant decrease in the size of lithics in the EUP. In Chapter 4, the more detailed discussion based on the mechanical properties is described.

3.3.3. Reasons for the association between type FH chert and bladelets

The development of bladelet technology in the EUP can be evaluated as a phenomena of “lithic miniaturization” in which the production of small stone tools is a dominant knapping mode in lithic assemblages (Shea and Pargeter, 2019; Shipton, 2023). In addition, these studies suggested that miniaturized stone tools include several functional advantages like compound tools, arrow tips, scarification, and shaving. The increase of Type FH chert in the EUP is likely to have been related to the concomitant lithic miniaturization in general. One of the possible reasons for this association is the size of chert raw materials. Fig. 3.10. shows the scatterplot of length and width of cobbles/nodules (n = 38) that were sampled at chert outcrops around the Jebel Qalkha area. The size of cobbles/nodules, represented by length multiplied by width, is significantly greater in Type M than Type FH (p-value of the Mann–Whitney U = 0.006).

Given this size difference, the larger volume of Type M chert is likely to have been more suited than Type FH for Levallois core reduction in the LMP and the production of robust blades in the IUP. On the other hand, the production of bladelets in the EUP may not have required as large cobbles or nodules but could use a wider range of size, including smaller cobbles of Type FH. In this way, the increase of Type FH chert in the EUP is likely to reflect a wider range of chert selection, in terms of size, for the bladelet production. However, the dimensional data of chert cobbles/nodules at the outcrops are based on a small samples size that needs to be verified with more systematic collections in future.

On the other hand, it is also possible that Type FH was favored in the EUP because of its fine texture in relation to bladelet production. This idea is consistent with some patterns in the Epipaleolithic raw material use in the Levant, where fine-grained flint or chalcedony was preferred for the production of microliths whereas larger tools, such as scrapers, were made on coarse-grained cherts (Henry, 1989; Delage, 2007). Marder and Goring-Morris (2020) have also reported preferential use of translucent chalcedony in the Epipaleolithic assemblages in the Negev and suggested less brittleness of chalcedony as one of possible reasons for the preference. Assuming that 'fine-grained chert' and 'chalcedony' are similar to chert with fine texture in this study, these observations indicate that the association between cherts with fine texture and small lithics, such as bladelets and microliths, is a broader phenomena in the Upper and Epipaleolithic periods in the Levant. Chapter 4 will analyze of physical characteristics between fine and medium-coarse texture chert and delve into the reasons for this association.

3.4. Summary

This chapter presented a rare study of changes in lithic raw material use at the MP-UP transition in the Levant. This study took advantages of a unique condition in the Jebel Qalkha area, southern Jordan, where the LMP, IUP, and EUP sites are located close to each other, sharing essentially the same availability and accessibility of lithic raw materials.

The raw material (chert) variations were analyzed in four lithic assemblages from the Jebel Qalkha sites. While the chert variations were classified into ten types on the basis of several macroscopic attributes, more general type-groups (Types M, FL and FH) were established by focusing on two criteria (i.e., texture and translucency) that were established objectively through quantification. Differences in texture and translucency of chert were likely recognizable to prehistoric inhabitants in the Jebel Qalkha area. The relative frequencies of the three type-groups in the four assemblages in the Jebel Qalkha sites showed an increase of Type FH in the EUP assemblage (Tor Hamar).

This result means that a clear change in lithic raw material was observed not at the classical boundary between the MP and UP, but between the IUP and EUP. The increase of Type FH in the EUP was clearly associated with the development of bladelet technology and concomitant decrease in the size of lithics in the EUP. Because the varieties of locally available chert near the Jebel Qalkha area include all of Types M, FL, and FH, the increase of Type FH in the EUP may not reflect a fundamental change in chert sources. Instead, it is more likely to reflect a change in the selection of chert, possibly related to the size of nodules/ cobbles or the fine texture. This interpretation needs to be verified with other EUP lithic assemblages like Tor Aeid and Jebel Humeima in the Jebel Qalkha area (Henry, 1995).

Although this study did not detect a clear change in lithic raw material between the LMP and IUP, it does not necessarily mean that no change occurred in lithic raw material procurement or use over these periods. Any change in chert variations could be detectable by using other classification methods, such as employing an RGB color scale or identifying the chert sources more specifically. Thus, further studies are necessary to clarify the changes in lithic raw material and their behavioral implications at the MP-UP transition in the Levant.

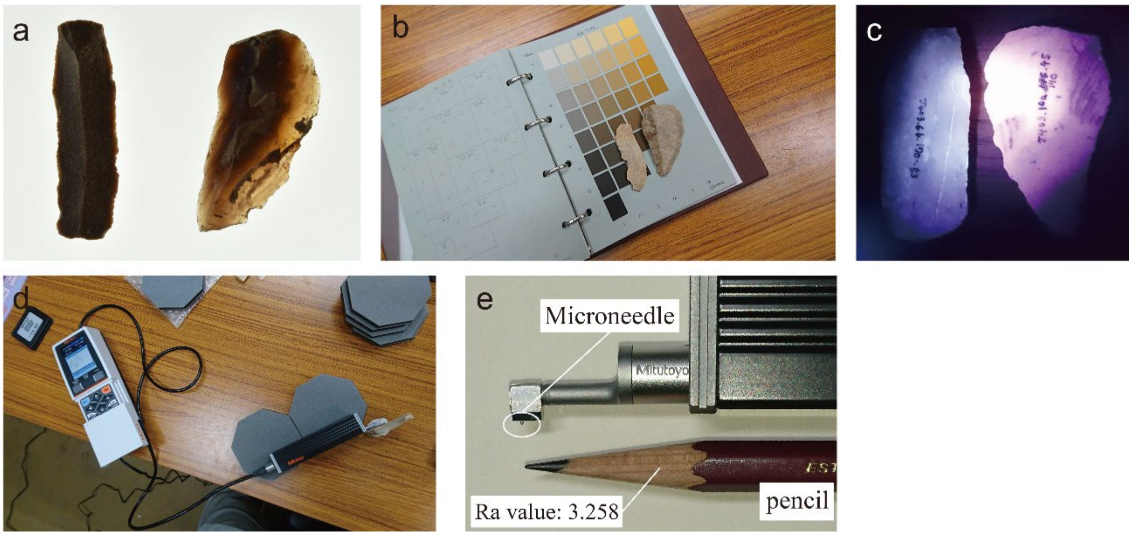


Fig. 3.1. Images showing the methods and instruments used for the measurements of macroscopic attributes of chert artifacts. (a) Translucency. (b) Munsell Soil Color Chart. (c) UV color signatures. (d) Device for measuring average surface roughness (Mitsutoyo SURFTEST SJ-210). (e) Microneedle for measuring average surface roughness. The picture shows the R_a values of a pencil as a reference.

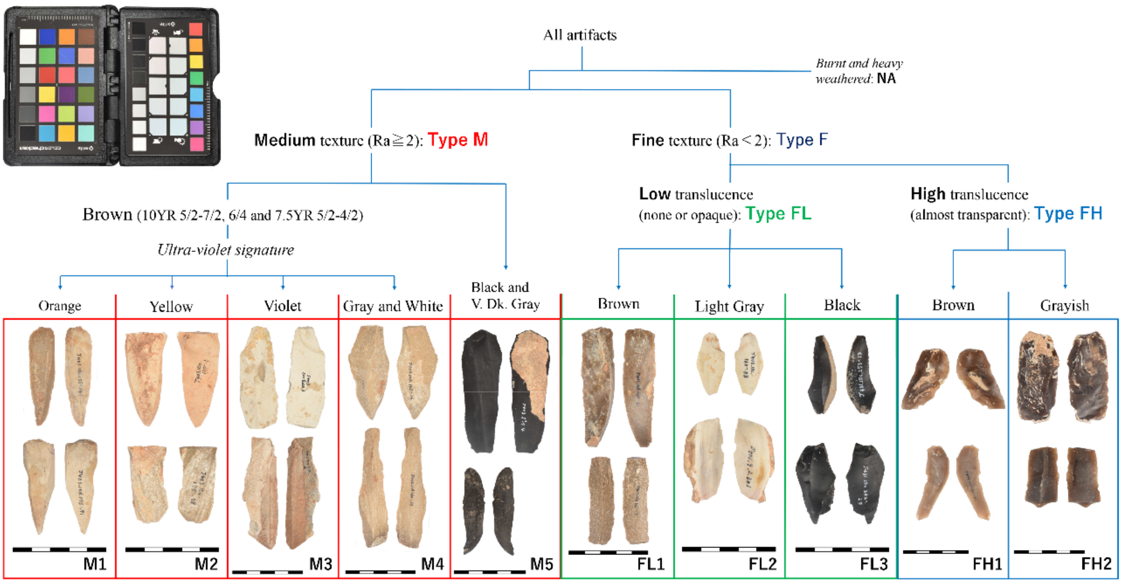
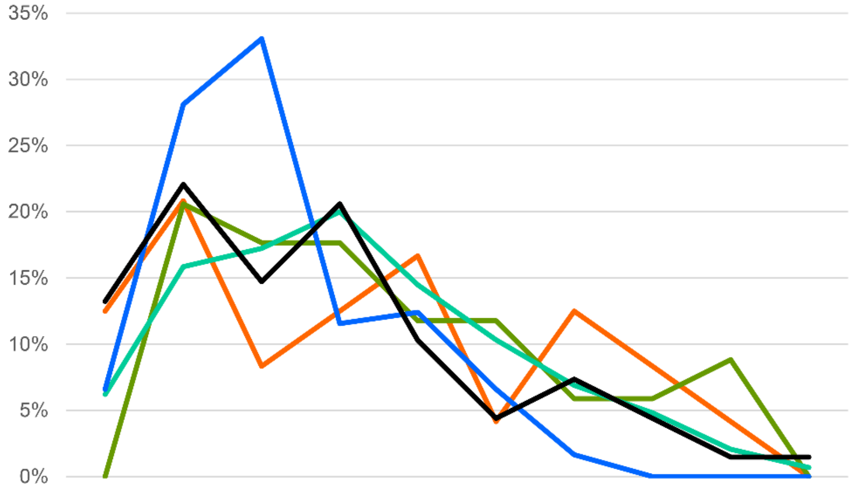


Fig. 3.2. A taxonomic classification of chert artifacts from Tor Faraj, Wadi Aghar, Tor Fawaz, and Tor Hamar assemblages on the basis of several macroscopic attributes.



	–1.0	–1.5	–2.0	–2.5	–3.0	–3.5	–4.0	–4.5	–5.0	–5.5	total
🟦 Tor Hamar	6.61%	28.10%	33.06%	11.57%	12.40%	6.61%	1.65%	0.00%	0.00%	0.00%	100% (n = 121)
🟩 Tor Fawaz	6.21%	15.86%	17.24%	20.00%	14.48%	10.34%	6.90%	4.83%	2.07%	0.69%	100% (n = 145)
🟩 Wadi Aghar	0.00%	20.59%	17.65%	17.65%	11.76%	11.76%	5.88%	5.88%	8.82%	0.00%	100% (n = 34)
🟧 Tor Faraj	12.50%	20.83%	8.33%	12.50%	16.67%	4.17%	12.50%	8.33%	4.17%	0.00%	100% (n = 24)
⬛ chert samples	13.24%	22.06%	14.71%	20.59%	10.29%	4.41%	7.35%	4.41%	1.47%	1.47%	100% (n = 68)

Fig. 3.3. Distribution of R_a values of chert artifacts from the four sites in the Jebel Qalkha area and geological local chert samples from nearby chert outcrops (within 10 km of the sites). Relative frequencies of retouched tools and chert samples are shown by intervals of 0.5 in the R_a value.

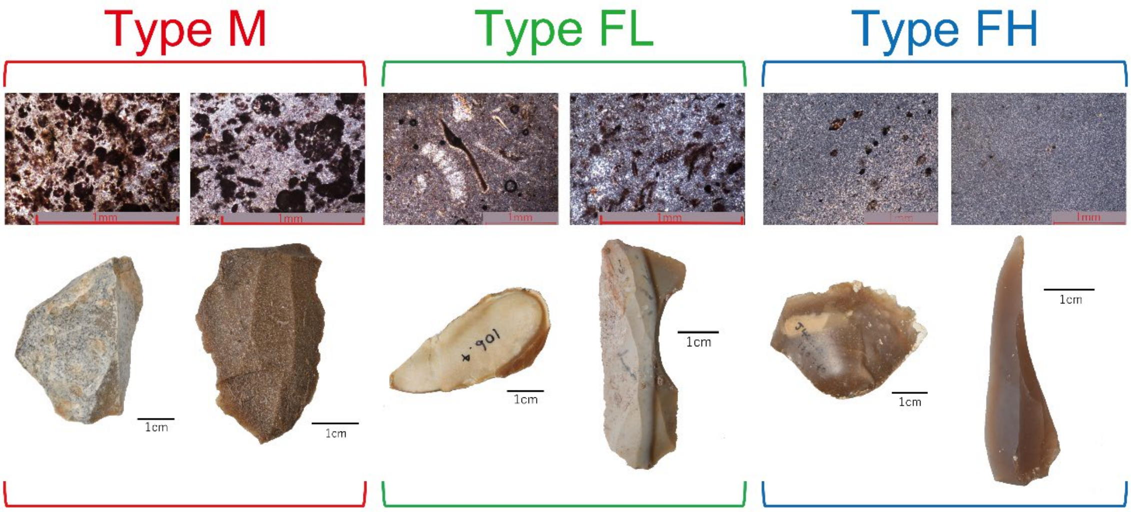


Fig. 3.4. Photomicrographs of several chert artifacts from the Jebel Qalkha sites under a polarizing microscope (all photos are under crossed polars). The selected artifacts represent the three chert type-groups (Types M, FL, and FH) identified in this study. Note differences in the abundance of microfossils among the three chert type-groups.

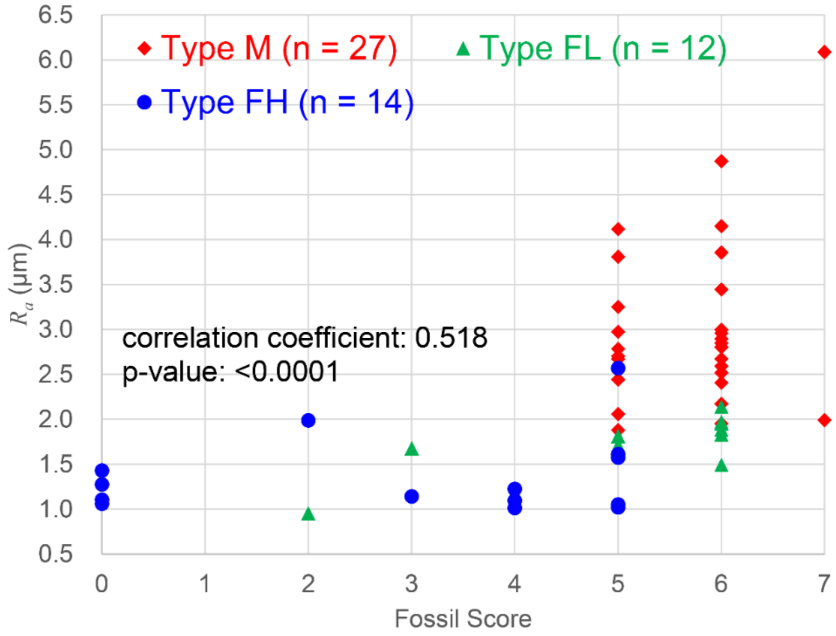


Fig. 3.5. *R_a* values (µm) vs. fossil scores diagram for the lithic samples (n = 53) from the Jebel Qalkha sites by the three chert type-groups (Types M, FL, and FH).

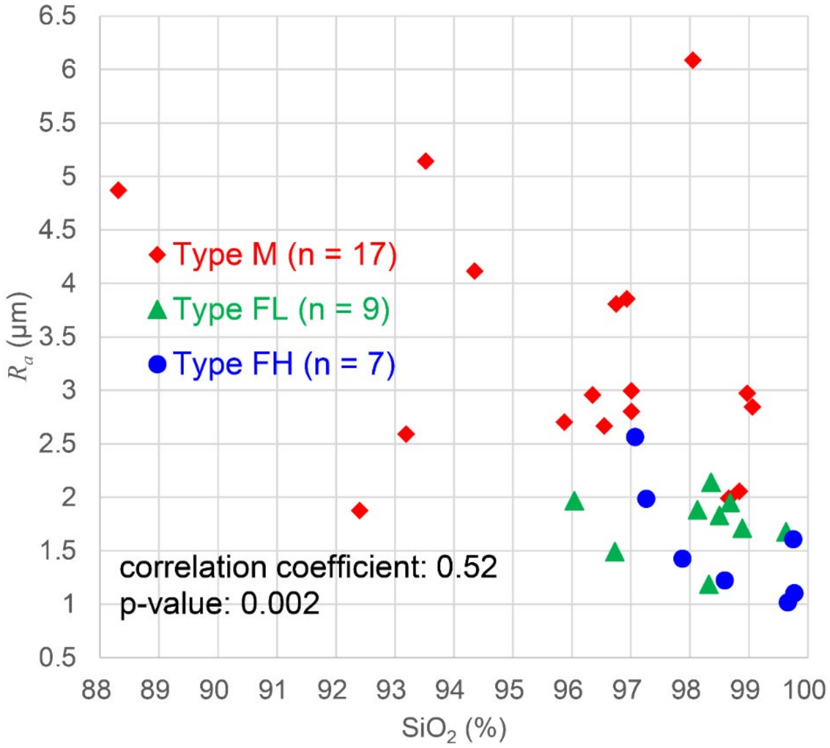


Fig. 3.6. SiO_2 vs. *R_a* values (µm) diagram for the chert samples (n = 33) from the Tor Fawaz lithic assemblage. The plots are marked differently according to the three chert type-groups (Types M, FL, and FH).

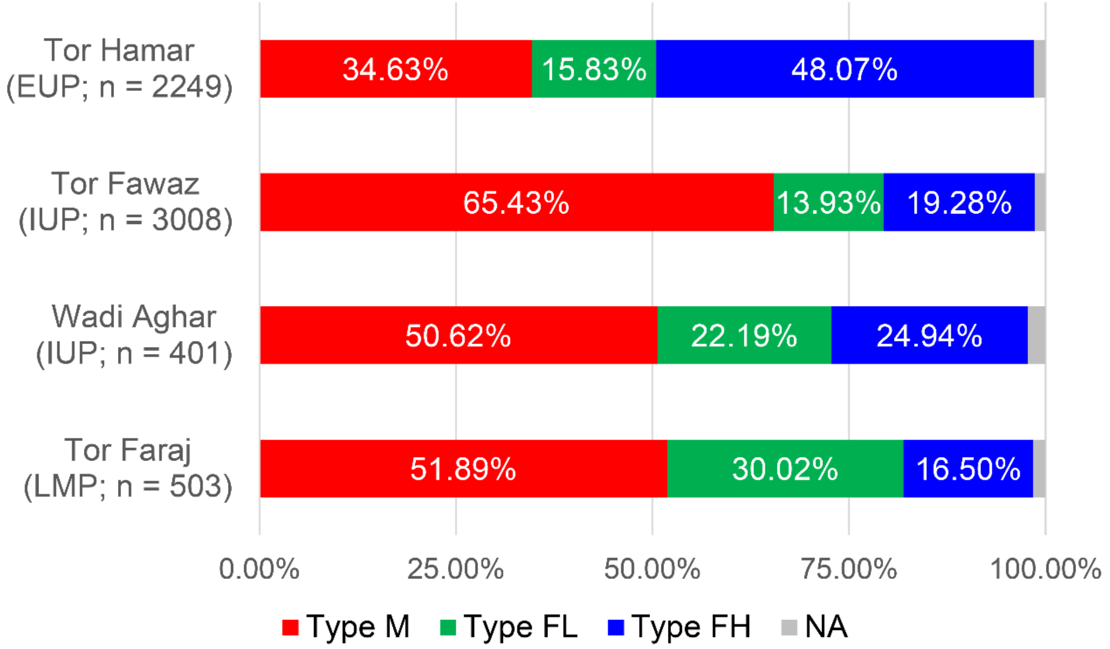


Fig. 3.7. Relative frequencies of the three chert type-groups (Types M, FL, and FH) in the five lithic assemblages in the Jebel Qalkha area.

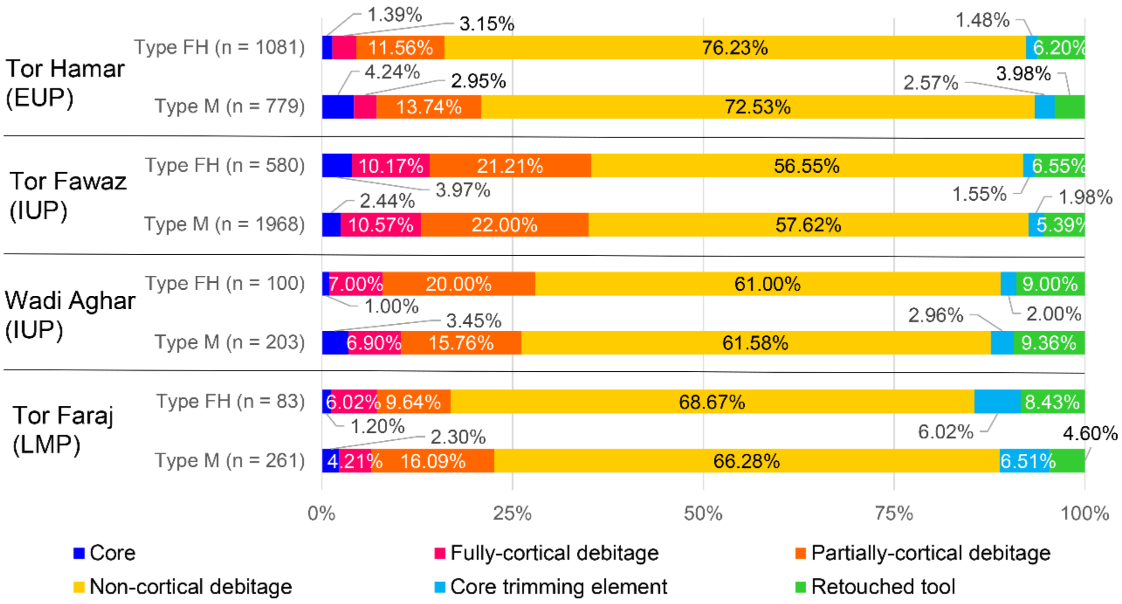


Fig. 3.8. Relative frequencies of six general categories of lithic artifacts by the two chert type-groups (Type M and Type FH) in the four lithic assemblages in the Jebel Qalkha area.

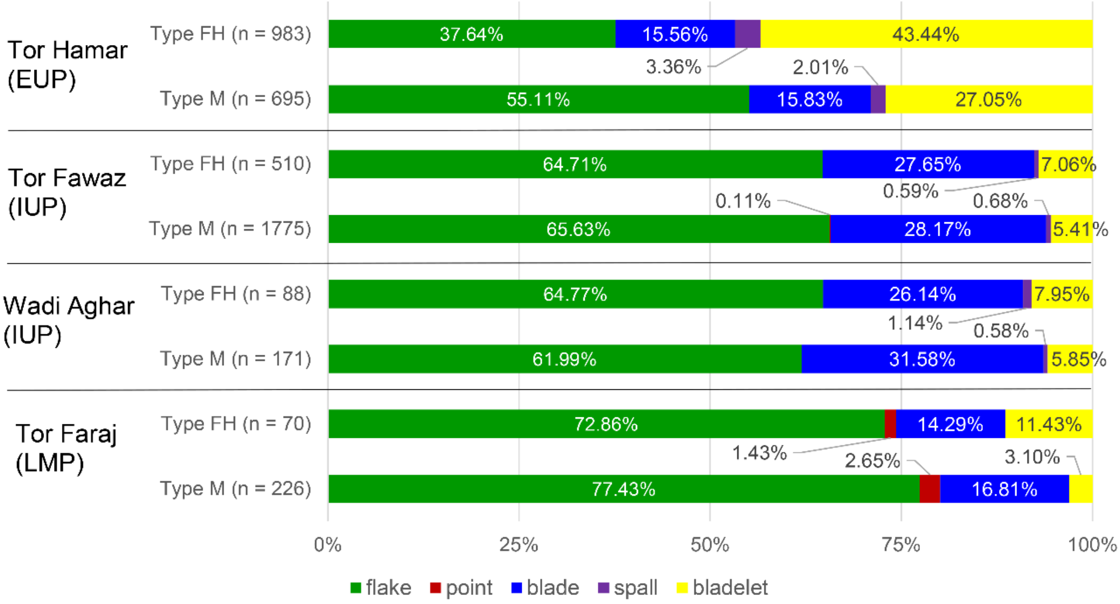


Fig. 3.9. Relative frequencies of five blank morphologies, including blade, flake, point, spall and bladelet, by the two chert type-groups (Type M and Type FH) in the four assemblages in the Jebel Qalkha area.

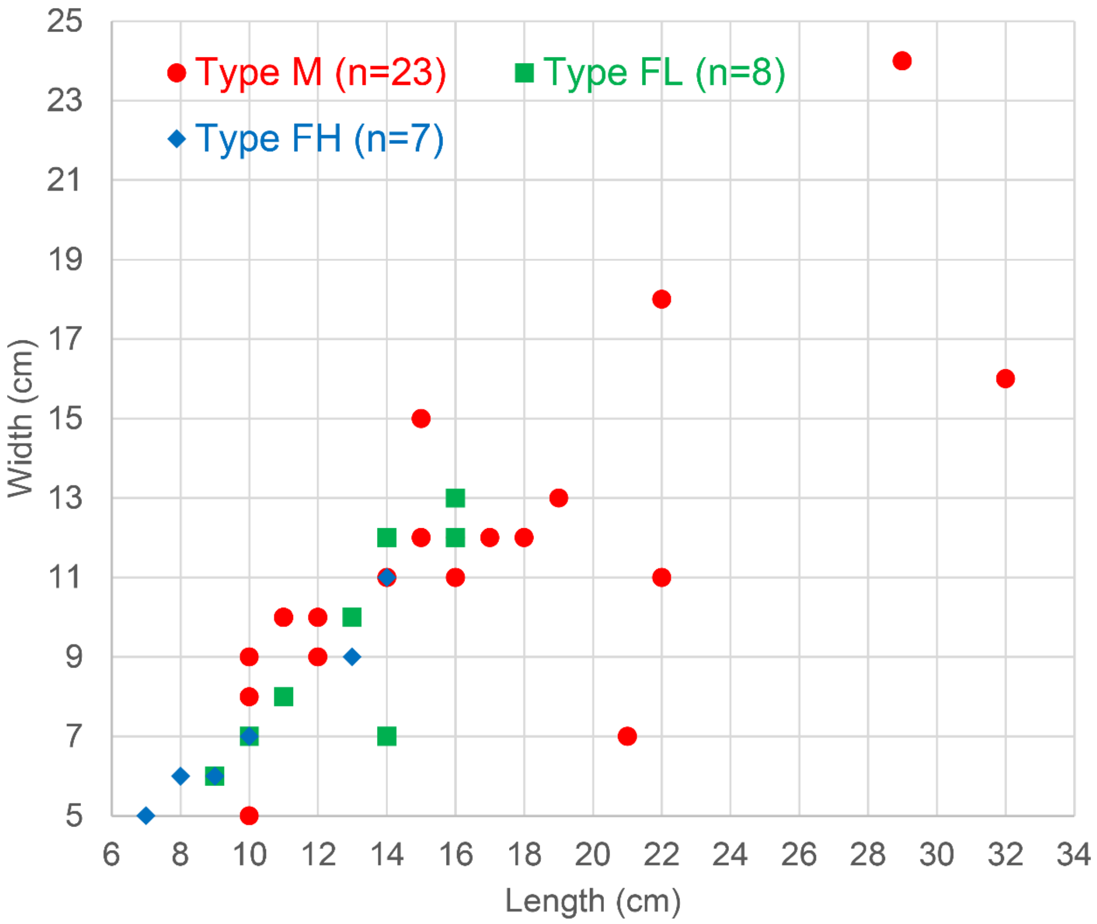


Fig. 3.10. Scatterplots of length and width of cobbles/nodules (n = 38) sampled at chert outcrops located around the Jebel Qalkha area. The plots are marked differently according to the three chert type-groups (Types M, FL, and FH).

Table 3.1. Median values of dimensional and morphological measurements of complete lithics from the four sites by the two chert type-groups (Type M and Type FH). '>' means statistically significant difference indicated by the Mann–Whitney U test.

	Tor Faraj (LMP)			Wadi Aghar (IUP)			Tor Fawaz (IUP)			Tor Hamar (EUP)		
	Type M		Type FH	Type M		Type FH	Type M		Type FH	Type M		Type FH
	n = 146		n = 47	n = 69		n = 37	n = 489		n = 146	n = 263		n = 367
Length (mm)	34.01		33.41	49.89		43.00	42.83	>	35.50	31.05	>	29.45
Width (mm)	26.58	>	24.15	27.80	>	21.02	25.19	>	22.48	18.05	>	14.42
Thickness (mm)	4.79	>	3.79	7.26		5.97	8.19	>	6.86	4.83	>	3.72
Weight (g)	4.27		3.07	10.25	>	5.19	8.47	>	5.49	2.81	>	1.62
Elongation (Length/Width)	1.34		1.52	1.84		2.12	1.68		1.64	1.92	<	2.29
Flattening (Width/Thickness)	5.34		5.10	3.62		3.38	3.11		3.08	3.50		3.79

Chapter 4. Quantitative examination of chert mechanical properties and fracture predictability

4.1. Background of fracture predictability

Given the fracture mechanics of flaked stone tools, percussion of vitreous rocks is understood as cracks similar to glass. Some glass engineering experiments suggest that some kinds of cracks could have been observed when fracture stress is applied to glass (Cook and Pharr, 1990). Among these cracks, the intentional production of conical (conchoidal) crack, called Hertz cone, detached flaked stone tools (Speth, 1972; Cotterell and Kamminga, 1987; Odell, 2004; McPherron et al., 2020; Lawn, 2021). There are two different cone cracks: an inner one, occurring simultaneously with the impact loading, and an outer one, produced shortly after release of impact loading (Ligkovanlis, 2022). In fact, the two cone cracks can be observed on the ventral surface of stone tools. Although the detailed mechanism remains unclear, Hertz cone is widely recognized as explaining the function of pressure and striking in flaking stone tools by archaeologists. This chapter will discuss the difference in fracture force between lithic raw material types.

In archaeology, the "quality" of lithic raw material is often evaluated on the degree of its easiness to be flaked. In numerous studies of lithic raw material, an issue of raw material "quality" has often been discussed. The "quality" of raw material can be an important basis in the selection of raw material. Besides, the raw material "quality" is used for establishing the models that quantify attractiveness of raw material sources and estimate kinds of lithic tools produced (e.g., Andrefsky, 1994, 2009; Wilson, 2007; Browne and Wilson, 2011). On the other hand, most of the discussions on raw material "quality" were qualitative. Flaked stone tools are often made of sedimentary and volcanic rocks, such as obsidian and chert, which are rich in silica content and are microcrystalline and glassy. A common recognition among archaeologists is that these properties increase the "quality" of lithic raw material (e.g., Bradbury et al., 2008; Sharon, 2008). The "quality" of chert raw material is usually evaluated on the basis of macroscopic characteristics. More specifically, archaeologists often evaluated that fine-grained (textured) chert is high quality, and medium/coarse-grained (textured) is low quality (Goring-Morris and Davidson, 2006; Delage, 2007; Neeley, 2007; Bustillo et al., 2009; Gómez de Soler et al., 2020b; Marder and Goring-Morris, 2020; Parow-Souchon and Purschwitz, 2020; Tomasso and Rots, 2021).

Several studies use the term "fracture predictability" based on the degree to which the flaking outcome can be predicted for a specific type of lithic raw material (Braun et al., 2009; Eren et al., 2014; Moník and Hadraba, 2016; Caruana and Mtshali, 2018; Egeland et al., 2019; Williams et al., 2019; Lewis et al., 2022). The flakes knapped from lithic raw materials with the high fracture predictability (high quality) tend to have sharp edges suitable for knives or scrapers (Harmand, 2009; Terradillos-Bernal and Rodríguez-Álvarez, 2017). Some previous studies from the viewpoint of fracture predictability examined several physical attributes including brittleness, elasticity, isotropy, homogeneity, continuity, and granularity (Cotterell and Kamminga, 1987; Luedtke, 1992; Whittaker, 1994; Inizan et al., 1999; Sharon, 2008; Bamforth, 2009; Eren et al. 2011; Goldman-Neuman and Hovers, 2012; Garvey, 2015; Moník and Hadraba, 2016; Rodríguez-Rellán, 2016; Herrero-Alonso et al., 2021; Namen et al., 2022). These attributes can be classified into two group: a group of structural properties (e.g., isotropy, homogeneity, continuity and granularity) and a group of mechanical properties (e.g., brittleness and elasticity).

As for the structural properties, the high fracture predictability was linked to some petrographic characteristics, such as little or no crystalline macrostructure, few impurities (e.g., organic inclusions, void space, secondary quartz, and phenocrysts), and an overall small size of crystals (Luedtke, 1992; Domanski et al., 1994; Braun et al., 2009; Eren et al., 2014; Egeland et al., 2019). These characteristics were considered to facilitate fracture propagation inside the rock with little interference and thus increase the predictability of flaking, resulting in the feeling of "easiness" in stone knapping (Cotterell et al., 1985; Cotterell and Kamminga, 1987; Brantingham et al., 2000; Bamforth, 2009; Braun et al., 2009). Moreover, some studies approached the fracture predictability through petrographic analyses by observing macroscopic attributes and microscopic features in thin section (Brantingham et al., 2000; Stout et al., 2005; Sherwood et al., 2018). These studies aimed to quantify the fracture predictability by calculating the average size of phenocrysts and the ratio of impurities in flaking removals. Recently, some studies quantified the amount of impurities within chert specimens through loss on ignition me (LOI) method (William et al., 2019; Lewis et al., 2022).

As for the mechanical properties, several studies aimed to quantify the fracture predictability of heat-treated raw material by measuring their mechanical properties (Domanski and Webb, 1992, 2007; Domanski et al., 1994; Domanski et al., 2009; Yonekura, 2010; Schmidt et al., 2012, 2019; Zhou et al., 2014; Mraz et al., 2019; Moník et al., 2021; Nickel and Schmidt, 2022). Some studies explained that the heat-treatment of silica rocks increase their quality due to the formation of new Si–O–Si bonds that make the fracture path less meandering (Schmidt et al., 2012, 2019). In addition to heat treatment, some studies examined the fracture predictability of different kinds of lithic raw material by comparing mechanical properties (Goodman, 1944; Webb and Domanski, 2008; Tsobgou and Dabard, 2010; McPherron et al., 2014; Moník and Hadraba, 2016; Rodríguez-Rellán, 2016; Namen et al., 2022). These studies mainly measured strength, elasticity and toughness as key indicators. These mechanical properties are used not only in petrology but also in materials science. However, in their application to lithic studies in archaeology, it is important to be aware that most methods for measuring mechanical properties of tool stones do not exactly replicate actual stone knapping (e.g., angles of force). In addition, only a few studies present explicit models that explain how the mechanical properties influence stone knapping and lithic production (Nickel and Schmidt, 2022). The following section summarizes current archaeological views on how strength, elasticity, and toughness are related to stone knapping and flaking phenomena.

Strength Strength is the absolute value of fracture stress when objects break down. Lithic raw materials with high strength can be useful in its use for producing flakes as it prevents shattering of flakes' striking platforms (Doelman et al., 2001). On the other hand, a previous study pointed out potential fluctuations in the strength value of brittle materials with internal cracks and indicated an importance of using appropriate kinds of tests and sufficient numbers of rock samples (Tsirk, 2014). More specifically, many studies employed compressive or tensile strength as parameters of lithic raw material strength (Domanski et al., 1994; Webb and Domanski, 2008; Yonekura and Suzuki, 2009; Zhou et al., 2014; Nickel and Schmidt, 2022).

Elasticity Elasticity is the characteristic of objects returning to the original form after their plastic deformation. Lithic raw materials behave elastically at a macroscopic scale, and elasticity is a useful index that represents flexibility. Previous studies quantified elasticity by measuring Young's modulus (Domanski et al., 1994; Schmidt et al., 2019; Moník et al., 2021; Namen et al., 2022). The higher value of Young`s modulus means greater resistance to deformation (Luedtke, 1992; Braun et al., 2009).

Toughness Toughness is the degree of resistance of a material to crack opening, and this characteristic is used for brittle materials with internal cracks. Previous studies quantified toughness by measuring fracture toughness (K_{IC}) (Domanski and Webb, 1992; Domanski et al., 1994; Webb and Domanski, 2008; Domanski et al., 2009; Schmidt et al., 2019; Moník et al., 2021; Namen et al., 2022; Nickel and Schmidt, 2022). Raw materials of flaked stone tools, such as obsidian and chert, are similar to glass, and they often have microscopic cracks inside the rocks. When these internal cracks receive certain load (fracture stress), they induce a sudden breakage of the material. Fracture toughness is considered a useful parameter to evaluate raw materials of flaked stone tools (Tsirk, 2014).

Geological studies suggest that the above three mechanical properties are correlated mutually in general (Sachpazis, 1990; Zhang, 2002; Yasar and Erdogan, 2004; Aydin and Basu, 2005). In addition, the mechanical properties can be discussed in relation to the petrographic characteristics (Namen et al., 2022). Here I summarize some previous studies' predictions about how the mechanical properties of rocks influence stone flaking. Firstly, high strength and elasticity of tool stones are considered to facilitate the propagation of fracture forces and thus allows for predictable flaking (Braun et al., 2009; Egeland et al., 2019). Secondly, low fracture toughness makes rocks to be flaked with less forces, facilitating the preparations of core ridges and platforms (Doelman et al., 2001). On the other hand, when fracture toughness (K_{IC}) is too large, the raw material is too tough to work (Tsirk, 2014). The lithic grade scale proposed by Callahan (1979) suggests that lithic raw materials of better workability (high fracture predictability) have large values of elasticity and modest values of toughness (K_{IC}). Recently, Nickel and Schmidt (2022) proposed a mathematical model in which a combination of low fracture resistance (K_{IC}) and high tension stress reduces the size of a critical crack required to induce stone flaking, i.e., "Griffith" crack length, leading to high knapping quality of rocks.

Based on the previous studies, I estimate that lithic raw materials with high fracture predictability are rocks with high strength and elasticity but low toughness. To evaluate some of these mechanical properties, this study focuses on two types of properties that, are explained below.

4.2. Methods

4.2.1. Schmidt Hammer

Schmidt Hammer (N-type) is the instrument for measuring rebound hardness (Q-value). Despite the term of "hardness", the measurement by Schmidt Hammer is also related to elastic behavior of material because it measures the distance of elastic rebound applied under a controlled impact (2.207 Nm) on a rock surface. A spring-loaded piston makes an impact onto a plunger that transfers a force to a rock surface (Fig. S1 in Appendix). This measurement mechanism is somewhat similar to the indirect percussion in stone knapping. Schmidt Hammer has been used in some archaeological studies to compare the rebound hardness among several lithic raw materials (Braun et al., 2009; Eren et al., 2014; Egeland et al., 2019).

Schmidt Hammer is used in some engineering and geological studies to measure strengths of buildings and roads, and degrees of weathering of rock surfaces. The geological studies explained the measurement mechanism of Schmidt Hammer in detail (Betts and Latta, 2000; Goodie, 2006; Aydin, 2009; Winkler and Matthews, 2014; Ghorbani et al., 2022; Matthews and Winkler, 2022). As for the mechanical properties above-mentioned, many geological studies suggested that rebound hardness is positively correlated with strength (compressive strength) and elasticity (Young's modulus) (Winkler, 1975; Katz et al., 2000; Yasar and Erdogan, 2004; Aydin and Basu, 2005; Goudie, 2006; Yagiz, 2009; Bilen, 2021; Teymen, 2021).

In particular, the relationship with elasticity can be understood as follows. A rock with high elastic modulus is less deformable, and it rebounds with less absorption of the impact, resulting in higher rebound hardness. In fact, Callahan (1979) suggested that the high elastic modulus of lithic raw materials facilitates the control of flaking. Some archaeological studies used Schmidt Hammer to measure rebound hardness measured as a proxy for the fracture predictability because lithic raw materials that are often recognized easy to knap, like obsidian and chert, tend to show high rebound hardness (Braun et al., 2009; Brown et al., 2009; Eren et al., 2014; Egeland et al., 2019).

The measurement (Q-value) of rebound hardness with Schmidt Hammer can be performed quickly. All procedure can be carried out in the field. Moreover, the preparation of raw material samples is not required. The Schmidt Hammer measurement (Silver Schmidt OS8200 N) was performed under the following conditions and procedures (Table 4.1. and Fig. 4.1.) by referring to methods in previous studies in material sciences.

1. Chert nodules of a certain size (> 4 kg) were collected from the outcrops in the study area. The smallest dimensional limit was set in order to reduce fluctuations, errors and outliers of measurement values (c.f., Demirdag et al., 2009).

2. Size and mass of chert samples were recorded prior to the measurement of rebound hardness. Chert samples were classified into the chert types (Types M, FL and FH) based on the appearance and the texture of fractured surface.

3. Flakes removed from the nodules were collected as samples to be studied in the laboratory. R_a values and translucency were measured at the laboratory, and the chert samples were classified into the chert types by the methods of Chapter 3.

4. Ten measurements (Q-values) were obtained for each chert sample, and the average of the largest five Q-values was calculated and used for the comparisons (c.f., Anikoh et al., 2015; Brown, 1981).

5. As comparative samples, the rebound hardness of obsidian was measured, which is a typical raw material suited for the production of flaked stone tools. Obsidian nodules were obtained from Shirataki, Japan. As another kind of comparative samples, the rebound hardness of andesite was also measured, which is not suited for flaking but often used for ground stone tools. Archaeological materials of grinding querns made of andesite, were obtained from Hokkaido, Japan.

4.2.2. Rockwell Hardness (HRC)

Rockwell Hardness (HRC) is another kind of parameters for hardness. It is a static method and an indentation test in contrast to Schmidt Hammer that is a dynamic method and measurement of elastic rebound (Ghorbani et al., 2022). In the HRC measurement, a conical diamond indenter is pressed against an object twice: the first time with a smaller load (10 kgf, 98.07 N) and the second time with a large load (150 kgf, 1471 N), and a difference between the two depths of penetrations is used to determine the hardness (Fig. S2 in Appendix). Higher HRC values represent greater hardness (i.e., resistance against deformation). This measurement is mainly used for metal materials. The detailed mechanism is explained in geological and materials science studies (Broitman, 2017; Ghorbani et al., 2022).

In archaeological studies, the measurement of Rockwell Hardness was applied to pottery (Simon and Coghlan, 1989) and hard hammers used for lithic production (Magnani et al., 2014). Besides, some archaeological studies employed other indentation hardness tests for measuring lithic raw materials (Yonekura and Suzuki, 2009; Tsobgou and Dabard, 2010; Schmidt et al., 2019; Moník et al., 2021; Namen et al., 2022). The procedure of Rockwell hardness test is less complicated than those of other indentation hardness tests.

Rockwell Hardness is measured by deforming samples in a small scale. When it is applied to metals, it causes their plastic deformation. However, I expected that brittle materials, like obsidian and chert, would behave differently from metals. To confirm this idea, microscopic observations of indented areas were made on the samples after Rockwell Hardness tests.

In the measurement, Mitsutoyo ATK-600 (installed at the Graduate School of Science/School of Science Equipment Development Support Section, Nagoya University) was used under the following conditions and procedures (Table 4.1. and Fig. 4.2.).

1. Chert nodules from the outcrops were cut and polished into slabs (20 mm in thickness). Two to three slab samples were made from one nodule. 16 slab samples were measured in total.

2. In the measurement, a conical diamond indenter was pressed perpendicularly to a flat surface of the slab sample.

3. Ten measurements were made for each of the slab sample to deal with the variations of measurement values.

4. In addition to two chert types (Type M and Type FH), obsidian (from Shirataki, Japan) and a glass block (length: 70 mm, width: 40 mm, thickness: 35 mm) were also measured as comparative samples.

4.3. Results

4.3.1. Schmidt rebound hardness

Fig. 4.3. shows the distributions of the average Q-values, each of which was obtained from each rock sample. Shapiro-Wilk tests show that these values are normally distributed in the four raw material types. The Q-values of the andesite samples are distinctively lower than the other raw material types. In contrast, the values of the other types (Type FH chert, Type M chert, and obsidian) overlap with each other within a narrow range of 73–85, which are close to the values reported for flint and obsidian in previous studies (Eren et al., 2014; Egeland et al., 2019).

The t-test does not indicate significant difference in Q-values among Type M chert, Type FH chert and obsidian (Table 4.2.). However, it is notable that obsidian shows the highest mean value, which is followed by Type FH and then Type M.

As for the distributions of Q-value (Fig. 4.4.), those in Type FH chert are narrower than Type M chert. The Kurtosis of Type FH chert (-0.424) is larger than Type M chert (-0.873) meaning that the values of Type FH chert tend to be concentrated in a narrower range of than those of Type M chert.

The relationship was also examined between the Q-value and the mass of raw materials (Fig. 4.5.) and conducted regression analyses for Type M chert, Type FH chert and obsidian respectively. Table 4.3. summarizes linear regression equations, R^2 values, and p-values for each lithic raw material. The R^2 values of Type M chert and Type FH chert are high, and the p-values are below 0.05. Thus, the linear regressions of the two chert types are reasonable. The y-intercepts of the regression lines for Type M chert and Type FH chert differ from each other by more than 3 in Q-values. On the other hand, the R^2 value of obsidian is low, and the p-value is higher than 0.05, probably due to the small sample size. The y-intercept of the regression line for obsidian is close to Type FH chert, and the slope of the regression line is close to Type M chert.

4.3.2. Rockwell Hardness

After the Rockwell Hardness test, indented spots on the glass block showed conchoidal fractures that are apparently similar to flaking scars created by stone knapping (Fig. 4.6.). Below the indent, two vertical semicircular fractures were visible inside the glass. These fractures clearly differ from plastic deformation of metals. The indented areas of chert and obsidian also showed conchoidal fractures similar to those of the glass block, indicating that these materials experienced similar cracking processes.

Fig. 4.7. shows the distributions of Rockwell Hardness values. Shapiro-Wilk tests show that a normal distribution applies to the measurement data of only Type M chert. The values of Type FH chert are distributed more widely than those of Type M. Besides, the values of obsidian are distributed more widely than Type FH chert. As for the medians of Rockwell Hardness values, Type M chert has the highest value (40.7), followed by Type FH chert (27.2), and the obsidian value is noticeably lower (7.9). As a result of Mann-Whitney's U test, the three lithic raw materials differ from each other significantly (Table 4.4.).

4.4. Discussion

4.4.1. Schmidt rebound hardness

As a result of Schmidt Hammer measurement, andesite of grinding querns showed low rebound hardness values. Grinding tools are often made from porous or inhomogeneous raw materials that expose rough surfaces suitable for pulverizing materials. The andesite specimens used in this study typically include crystallites of various sizes that make the rock less stable in response to the percussion than obsidian or chert. In fact, the rebound hardness range of andesite is wider than those of obsidian and chert (Fig. 4.3.).

On the other hand, chert and obsidian showed higher rebound hardness values. This means that these rocks rebounded most of impact forces, probably because of their homogeneous and microcrystalline structure. Such structures suitable for stone flaking differ from those of stones used for grinding tools, and the differences between them are manifested in the Schmidt Hammer measurements.

In addition, Schmidt Hammer values are likely to be influenced by conditions of raw material nodules. More specifically, during the Schmidt Hammer measurements at the chert outcrops in Jordan, I observed that some nodules of Type FH chert were not suitable for flaking due to many internal flaws that were extensively caused by geological processes like folding and faulting (Fig. 4.8.). Because the geological deposition process like folding and faulting at the outcrops caused the internal flaws. Thus, even if large chert nodules are available, only small parts of them are actually usable for flaking. Nevertheless, the Q-values of Type FH chert nodules are distributed in a higher and narrower range than those od Type M chert.

4.4.2. Rockwell hardness value

The Rockwell indentation caused conchoidal fractures on glass, obsidian, and chart in contrast to metals that deform plastically (Fig. 4.6.). Such fractures occurred as a result of forces that exceeded fracture toughness of glass, chert, and obsidian, and they represent essentially the same phenomena as cracks that occur on chert in the Vickers hardness test (Tsobgou and Dabard, 2010; Schmidt et al., 2019; Moník et al., 2021; Namen et al., 2022). Thus, here I interpret that the Rockwell Hardness values of chert, obsidian, and glass, principally represent the scale of fractures/cracks caused by a pressure from the indenter.

From this viewpoint, the low HRC values of the glass indicate that the large scale of fractures occurred in comparison with the chert and obsidian samples. The increasing order of HRC values from glass to obsidian then chert is consistent with the easiness of flaking I felt in knapping them. Previous studies also suggested that the chert cores required more force to detach flakes than glass and obsidian cores (Dogandžić et al., 2020;

Li et al., 2022).

Based on these observations, it is notable that the HRC values of Type FH chert are significantly lower than Type M because this difference means that the indentation caused larger scale of fracture in Type FH than in Type M. This in turn indicates that Type FH requires less force to fracture. The "knapping force requirement" is considered a significant factor contributing to knapping quality of lithic raw materials (Nickel and Schmidt, 2022). In addition to indentation fracture toughness, Nickel and Schmidt (2022) also take into account tensile strength to estimate the size of a critical crack required to induce stone flaking, i.e., "Griffith" crack length. In their model, a combination of smaller fracture toughness and greater strength leads to smaller length of Griffith cracks, i.e., easiness of flaking. Although this study did not measure tensile strength, rebound hardness measured by Schmidt Hammer has been shown to be positively correlated with compressive strength and elasticity (Young's modulus) (Winkler, 1975; Katz et al., 2000; Yasar and Erdogan, 2004; Aydin and Basu, 2005; Goudie, 2006; Yagiz, 2009; Bilen, 2021; Teymen, 2021). Despite the absence of statistical significance, the results showed an increasing order of rebound hardness from Type M to Type FH then obsidian, which implies greater strength of Type FH than Type M. This observation is principally in accord with the model by Nickel and Schmidt (2022).

4.4.3. Factors of fracture predictability difference between chert types

Why are the appearance of the chert, in this case of surface roughness (R_a value) and translucency, related to the force required for flaking lithics? The previous study suggested that the surface roughness (R_a value) of chert in southern Jordan is positively correlated with the preservation and the abundance of carbonate microfossils such as foraminifers and calcareous algae in chert (Suga et al., 2022). In other words, the R_a value (surface roughness) is increased by better preservation and greater abundance of microfossils. As to the translucency, highly translucent chert contains only a few microfossils that are often poorly preserved and cannot be observed well even under the microscope (Ichinose et al., 2023; Suga et al., 2022). Type FH chert contains few impurities, such as microfossils, and is enriched in SiO_2 (Suga et al., 2022). These properties are expected to make Type FH chert more homogeneous and brittle than Type M, increasing the similarity of Type FH to obsidian and chert. This expectation is consistent with the measurement results of Schmidt Hammer and Rockwell Hardness that indicates greater fracture predictability of Type FH than Type M. However, the relationship between the petrographic features (e.g., microfossils) and mechanical properties is still speculative and requires further studies.

4.4.4. Raw material selectivity of lithic knapping at the Jebel Qalkha area

Based on the above observations about the differences in mechanical properties related to fracture predictability between Type FH and M chert, here I discuss the reasons for the increase in the use of Type FH in the EUP assemblage at the Jebel Qalkha area. As mentioned above, both Type FH and Type M chert are available in local chert outcrops, and I expect that the increase in Type FH chert primarily reflect the changes in raw material selection by prehistoric inhabitants in this area.

As discussed above, I suggest that the knapping force requirement is smaller in Type FH than in Type M. This means that, in the production of flaked stone tools, the strength of percussion can be smaller. Its behavioral implication is that the swing of a hammer can be smaller or slower. A small or slow swing allows a knapper to control the movement of a hammer and thus increase the precision of striking. This should have been particularly beneficial for producing bladelets with tiny platforms in the EUP (i.e., Ahmarian industry). The previous study showed that the tiny platform types such as the linear and punctiform increased in the EUP assemblage in southern Jordan (Kadowaki et al., 2021). In addition, it is widely recognized that the detachment of bladelets with small platforms was achieved by soft-hammer percussion (Ohnuma and Bergman, 1990; Kuhn et al., 2009; Meignen, 2012). This is likely another factor that favored the use of Type FH chert because of its greater fracture predictability that requires less force than Type M. In this way, I suggest that the use of Type FH chert increased because it was more suitable for the production of bladelets that increased in the EUP.

It is also possible that the use of Type FH chert increased in the EUP (Ahmarian) as a result of changes in raw material sources. This is indicated by differences in chemical compositions of some EUP chert artifacts from those of the LMP and IUP in the Jebel Qalkha area (Ichinose et al., 2023). However, the possibility of changes in raw material sources is not exclusive from the intentional selection of Type FH chert that was suitable for the production of bladelets.

In addition, I suggest that the difference in durability of cutting-edge between the chert types influenced the selection of lithic raw materials. More specifically, intentional selection of more durable chert types reduces the consumption of lithic raw materials. Lerner et al. (2007) indicated that wear accrual rates of lithic assemblages were influenced by relative hardness of lithic raw materials. The study of Oldowan stone tools in South Africa suggested that vein quartz predominated Oldowan assemblages because the cutting-edge of vein quartz is more durable than other raw materials (Caruana and Mtshali, 2018). Moreover, Moník and Hadraba (2016) mentioned some possible relations among fracture predictability/brittleness, edge sharpness and durability of edges. However, durability test has not been conducted yet for the lithic samples from southern Jordan.

However, the above discussion cannot explain why Type FH chert was not used frequently in the LMP and IUP despite the high predictability of fracture. One possible reason is the frequent occurrences of internal flaws in Type FH chert. The presence of internal flaws practically reduces the useful portion of chert for lithic production. Such actual macroscale conditions in the occurrences of Type FH chert may have limited its usefulness for the production of large blanks, such as Levallois flakes and robust blades, in the LMP and IUP. On the other hand, Type M chert does not show as frequent flaws as Type FH. In addition, the nodules and clasts of Type M chert tend to be larger than those of Type FH in the Jebel Qalkha area (Suga et al., 2022). The internal flaws in Type FH may not have been as problematic for the production of small artifacts like bladelets. In fact, some previous studies suggested an advantage of small lithic production that enables the use of raw materials in various sizes (Close, 2002; Vujević et al., 2017). Thus, actual selection of lithic raw material was likely governed by multiple factors including not only fracture predictability but also the presence/absence of flaws, the size of nodules, the size and function of tools to be manufactured, and flaking techniques/methods to be applied. Such multiple factors are likely to have been involved in various complicated uses of lithic raw materials since the Lower Paleolithic (Agam et al., 2022; Finkel et al., 2023).

4.4.5. Relation to lithic miniaturization

The general chert classification of this study (Type M and Type FH) has been widely recognized for lithic assemblages in the Levant (see Chapter 3.3.3.). The previous observations are consistent with the results of this study suggesting that fine-grained chert (Type FH) tend to be preferentially used for flaking miniature lithics (e.g., microliths). To my knowledge, this study is the first case that explains the increase of fine-grained chert from the IUP to EUP (Ahmarian) in the Levant. However, in Europe, it is known that the use of high quality (finer grained) flint increased in the Early Upper Paleolithic in association with the production of blades and bladelets by soft marginal percussion (Moník and Hadraba, 2016; Tomasso and Porraz, 2016). Although the shift to "high quality flint" tends to be taken for granted by archaeologists, it is actually a cultural process that need to be explained. For this purpose, the examination of fracture predictability can be a useful approach as it provides a testable hypothesis through quantitative measurements.

4.5. Summary

This chapter examined how differences in mechanical properties may have influenced the Paleolithic raw material selection. Type FH chert with high fracture predictability increased in tandem with the increase in bladelet production in southern Jordan. To explain lithic miniaturization like bladelets, Pargeter and Shea (2019) suggested a significance of understanding variability in raw material package sizes and quality within specific foraging radii. The examination of fracture predictability can be a useful approach in explaining the selection of lithic raw materials in relation to lithic technology.

Further examinations are necessary to test the validity of these methods. In this study, the chert with high translucency and low surface roughness showed high fracture predictability. In other regions, some chert assemblages are similar to the samples in southern Jordan (e.g., Ghasidian and Heydari-Guran, 2018; Schmidt and Morala, 2018; Kolobova et al. 2021; Aubry et al., 2022), and the measurement of the fracture predictability between different chert types may be applicable to other regions. In addition, it is necessary to examine fracture predictability of other sedimentary rocks and volcanic rocks. The workability of lithic raw material may need to be examined by combining measurement values with impressions of modern knappers. In this way, further studies are necessary in modelling the relationship among key mechanical properties as well as in conducting flaking experiments (e.g., Bradbury et al., 2008; Harmand, 2009).

Quantification of the fracture predictability has an advantage that it can be easily combined with other quantitative lithic data. For example, fracture predictability can be incorporated into multivariate analyses conducted by 3D morphology (e.g., Valletta et al., 2020; Archer et al., 2021; Herzlinger et al., 2021; Radinović and Kajtez, 2021; Muller et al., 2022). Fracture predictability can also be combined with the model that quantifies attractiveness of raw material sources, as mentioned in Introduction (Wilson et al., 2007; Browne and Wilson, 2011). Moreover, its wider applications are expected to facilitate objective comparisons of lithic raw materials between different regions.

Fig. 4.1. a) Schmidt Hammer used in this study. b) Punch marks on obsidian, left by Schmidt Hammer after measurement. c) Scene during the use of Schmidt Hammer on a grinding quern made of andesite.

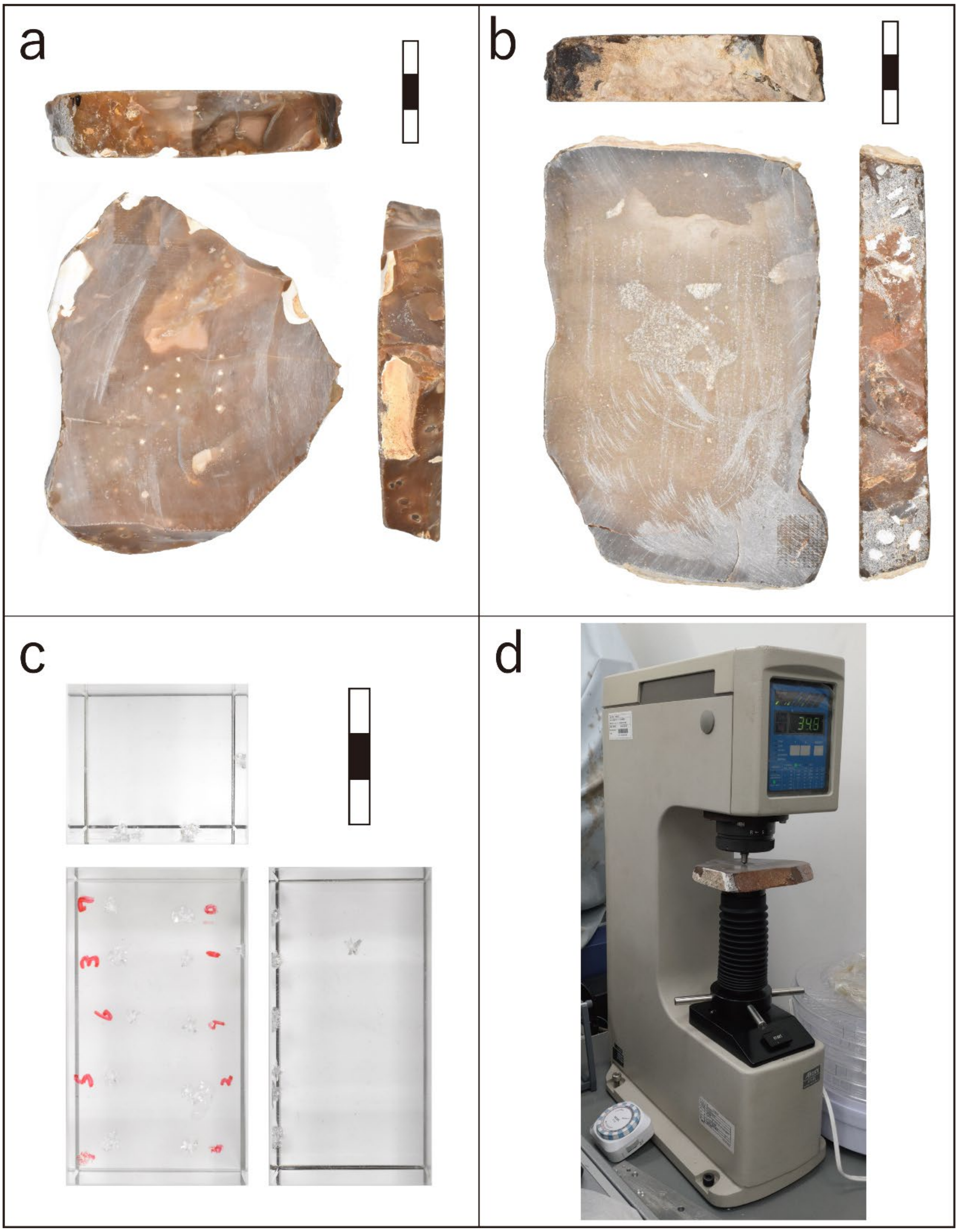


Fig. 4.2. Samples used for Rockwell Hardness test. A) Slab of Type FH chert. b) Slab of Type M chert. c) Glass block. d) Rockwell Hardness tester during its use for the measurement of a chert sample.

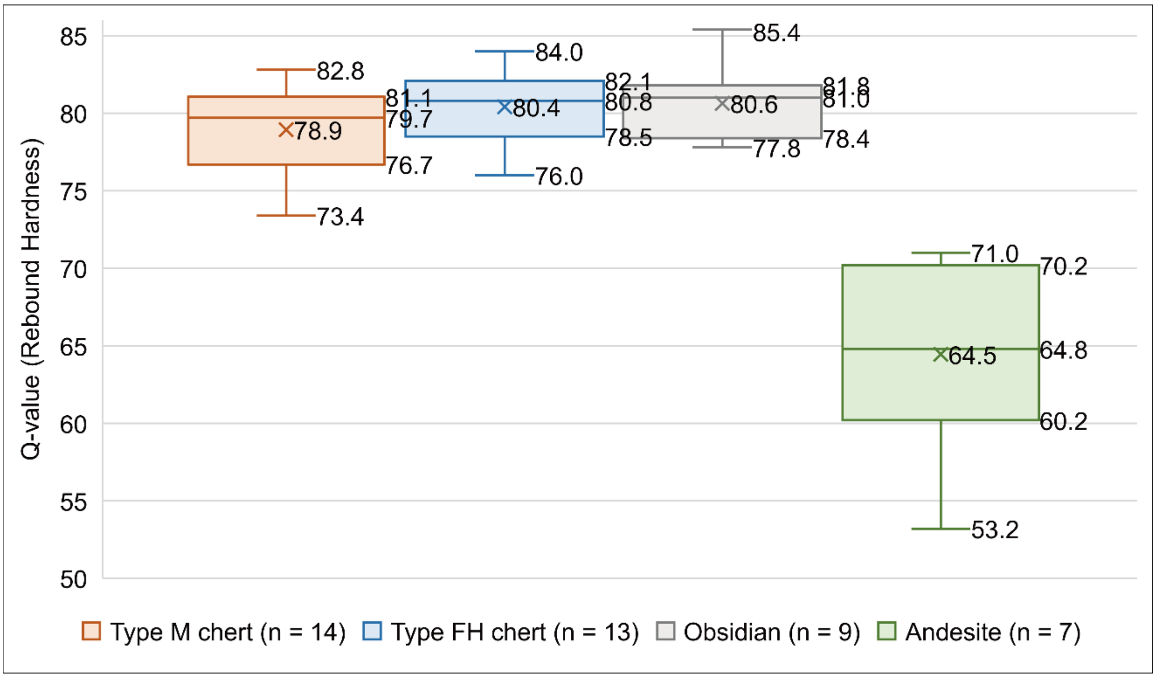


Fig. 4.3. Boxplots showing the Q-values of Type M chert, Type FH chert, Obsidian and Andesite. See Appendix Table S2 for data sources.

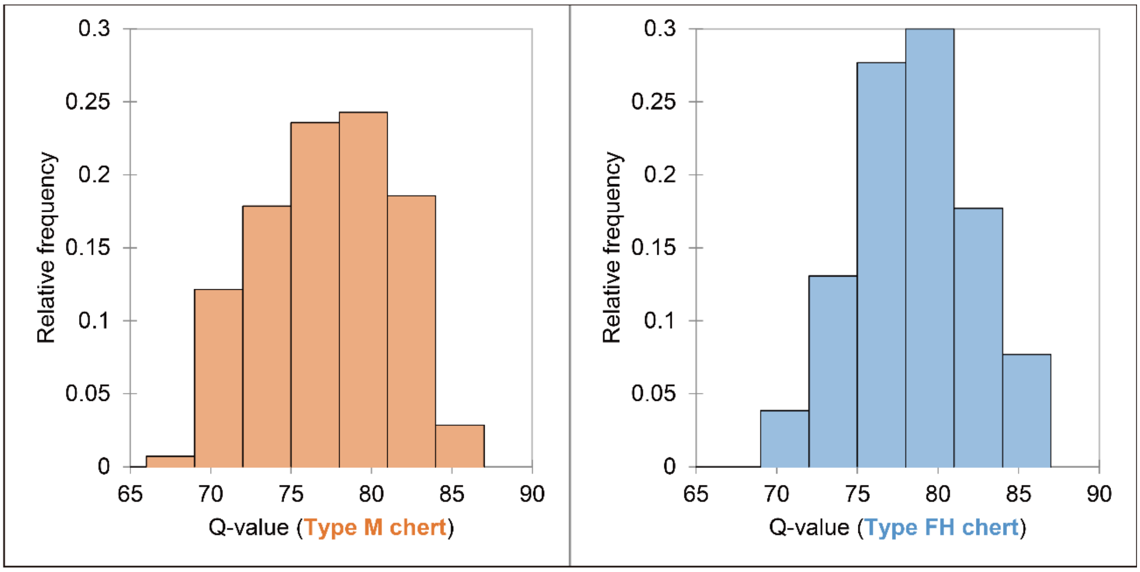


Fig. 4.4. Relative frequency histograms of Q-values of Type M chert and Type FH chert. The Kurtosis, that indicates whether distribution is concentrated near average value, is -0.873 for Type M chert and -0.424 for Type FH chert. See Appendix Table S2 for data sources.

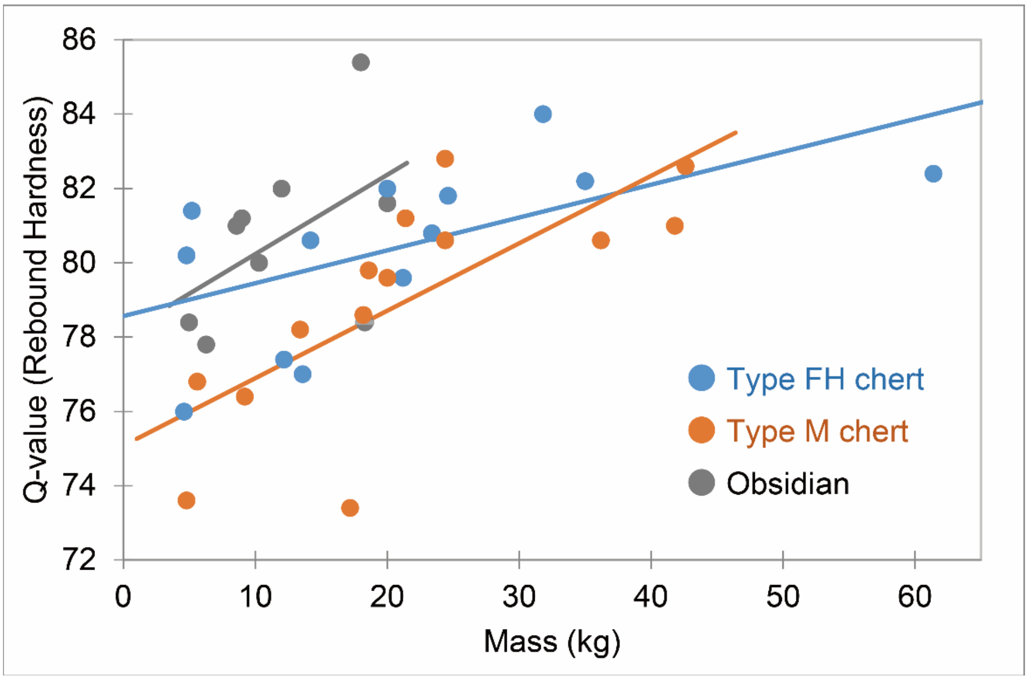


Fig. 4.5. Scatterplots and regression lines of Q-values and mass of chert and obsidian samples. The plots are marked differently according to Type M chert, Type FH chert and Obsidian. See Appendix Table S2 for data sources.

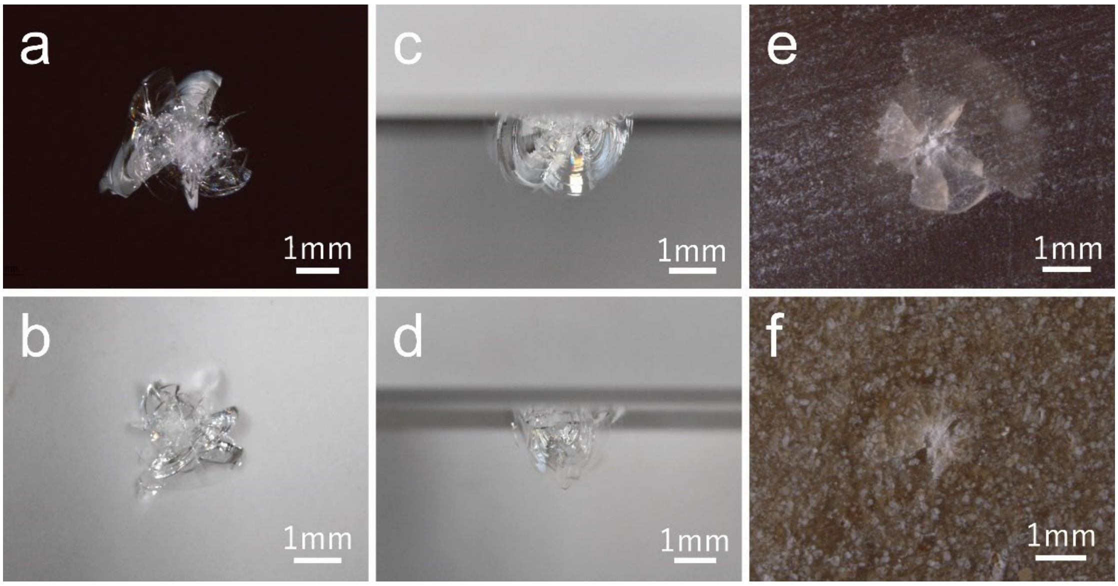


Fig. 4.6. Fractures caused by indentations of Rockwell Hardness test. a–b) plan views of fractures on glass blocks. c–d) profile views of fractures inside glass blocks. e) plan view of fractures on Type FH chert. f) plan view of fractures on Type M chert.

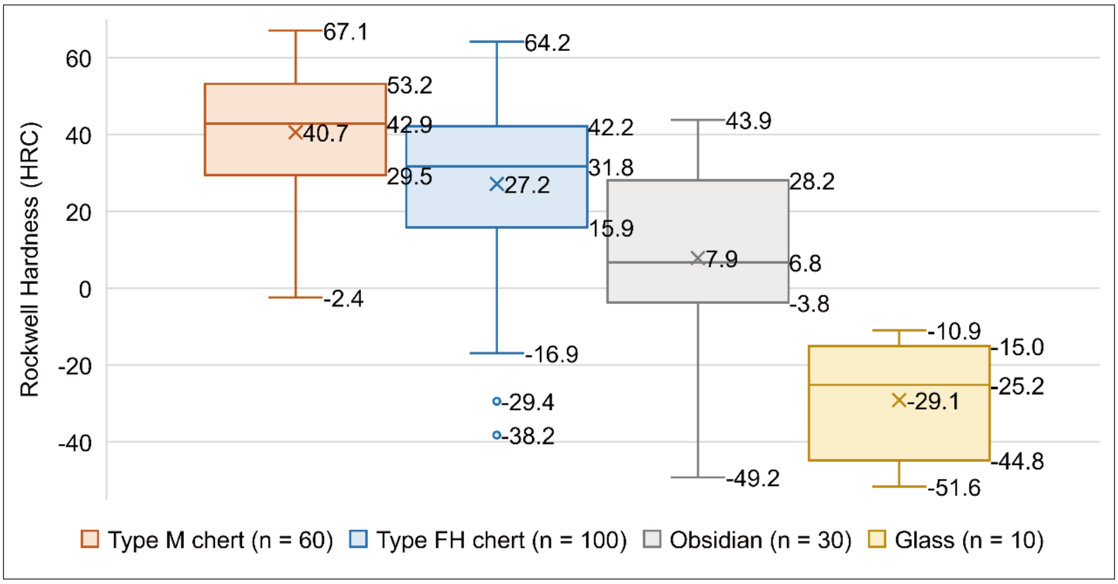


Fig. 4.7. Boxplots showing Rockwell Hardness values of Type M chert, Type FH chert, Obsidian and Glass. See Appendix Table S3 for data sources

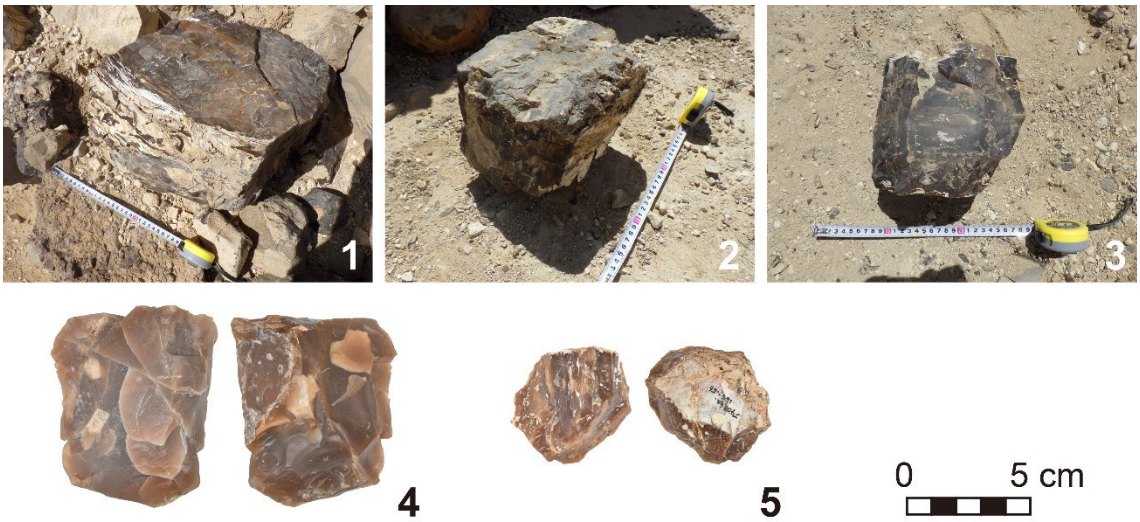


Fig. 4.8. Examples of Type FH chert nodules (1–3) and lithics (4–5) with internal flaws

Table. 4.1. Number of samples by raw material types and by measurement methods.

	Type M chert	Type FH chert	Obsidian	Glass	Andesite
Schmidt Hammer	14	13	9	0	7
Rockwell Hardness (HRC)	6	10	3	1	0

Table. 4.2. Results of t-tests for pairwise comparisons of rebound hardness.

Compared pair of raw material		p-value
Type FH chert	Type M chert	0.169
Type FH chert	Obsidian	0.825
Type FH chert	Andesite	<0.001
Type M chert	Obsidian	0.163
Type M chert	Andesite	<0.001
Obsidian	Andesite	<0.001

Table. 4.3. Statistical values of linear regressions of mass (kg) vs. Q-value.

Raw material	Linear regression	R^2	p-value
Type FH chert	$y = 0.09x + 78.56$	0.345	0.035
Type M chert	$y = 0.18x + 75.08$	0.538	0.003
Obsidian	$y = 0.21x + 78.10$	0.251	0.170

Table. 4.4. Results of Mann-Whitney's U tests of Rockwell Hardness values for pairwise comparisons of raw material types.

Compared pair of raw material		p-value
Type FH chert	Type M chert	<0.001
Type FH chert	Obsidian	<0.001
Type M chert	Obsidian	<0.001

Chapter 5. Discussion

5.1. Quantitative characterization of lithic raw material variations and fracture predictability

This dissertation is one of the case studies that employ a quantitative approach to examine raw material changes accompanied by lithic miniaturization. Previous studies in the Levant suggested a connection between microlithic production and high knapping quality raw material (fine-grained chert) in the Epipaleolithic (Delage, 2007; Marder and Goring-Morris, 2020). This dissertation suggested that the connection had already appeared in the EUP (Ahmarian). The employment of the quantitative approach allowed this study to show a raw material change in the earlier period than previous studies. In this dissertation, lithic raw material (chert) was classified based on objective attributes (Chapter 3), and the difference of knapping force requirement between the chert types was quantified by the mechanical properties (Chapter 4). On the other hand, some studies explained raw material knapping force requirement from the lithic raw material macroscopic observation, and their explanation is rather similar to a description of their impressions. The quantitative method enabled a precise detection of the timing when raw material change began to appear. A unique contribution of this dissertation is a precise illustration of lithic raw material change through the employment of the quantitative approach.

Another unique feature of this dissertation was to discuss empirically the resource utilization in the Paleolithic through mechanical hardness of lithic raw material. In Chapter 4.1., I described some archaeological case studies that analyzed the fracture predictability mechanically and explained mechanical properties employed in these cases. However, most of these studies were carried out in the context of examining the influence of heat treatment on lithic raw material or examining the differences between high knapping quality raw material (e.g., obsidian) and low knapping quality raw material (e.g., andesite, basalt) recognized commonly among archaeologists. The former examination is based on the hypothesis that the heat treatment increases the predictability of flaking, and a few studies did not consider specific archaeological records. The latter examination is also not empirical because these studies did not analyze archaeological raw materials excavated from the same site. In other words, most of the archaeological studies with mechanical hardness have not considered the actual archaeological record. This dissertation began with an analysis of raw material of lithic assemblage excavated from sites and employed the concept of the fracture predictability in order to interpret the differences in the relative frequencies of the chert types in four lithic assemblages.

Therefore, this dissertation examined fracture predictability using mechanical hardness based on actual archaeological records.

5.2. Changes in the raw material selection at the MP-UP transition

As for the lithic technology of the period covered by this dissertation, the IUP lithic assemblages in the Levant are known for the transitional characteristics between the Middle Paleolithic and the Upper Paleolithic (Meignen, 2012; Goring-Morris and Belfer-Cohen, 2020; Goder-Goldberger and Malinsky-Buller, 2022). Namely, the change from the LMP to the IUP is considered to have been gradual. On the other hand, Kuhn et al. (2009) pointed out the "saltational technological shift" between the IUP and the EUP (Ahmarian), and Goring-Morris and Belfer-Cohen (2018) suggested that it is difficult to derive the lithic industry of the Ahmarian from the IUP assemblage. This dissertation did not detect a transitional shift of lithic raw material between the LMP and the IUP but showed a clear change between the IUP and the EUP. Several studies suggested an influence of raw material knapping quality on the organization of lithic technology (Bamforth, 1986; Andrefsky, 1994, 2009; Kuhn, 2020), thus the suitable resource utilization may have caused an innovation of the lithic technology between the IUP and the EUP.

This dissertation examined lithic raw material changes in southern Jordan of the Levant region in connection with lithic miniaturization. In the previous studies, the phenomena of lithic miniaturization is characterized by the systematic production and utilization of miniature stone tools (Pargeter and Shea, 2019; Shipton, 2023). The lithic miniaturization has long been recognized among archaeologists in various regions and was addressed as a special issue of *Archaeological Papers of the American Anthropological Association* (Kuhn and Elston, 2002 and papers therein). Recently, a lithic raw material change with lithic miniaturization was also reported in the European Upper Paleolithic (Ahmarian/Aurignacian) (e.g., Moník and Hadraba, 2016; Tomasso and Porraz, 2016) and the Middle to Later Stone Age transition in Africa (Shipton et al., 2018, 2021). Considering these examples, it is possible to hypothesize that the raw material change with lithic miniaturization is one of the Paleolithic adaptive behaviors that can occur in any region, depending on the site and resource conditions (e.g., site location, distance from raw material sources, assumed hunting behavior, etc.). The interpretation is that appropriate resource utilization made miniaturization possible. In order to explain this hypothesis as a general cultural process, it is necessary to increase similar case studies in other regions. In addition, it is also necessary to explain the process and factor that caused the raw material change, for example, why the best lithic raw material was not used at the beginning. As for such factors, this dissertation referred to the difference in the size of cobbles/nodules and frequent occurrences of internal flaws. The actual situation of resource utilization in the Paleolithic can be clarified by analyzing not only the easiness of flaking but also various aspects of lithic raw material. This dissertation is also one of case studies to generalize the resource utilization pattern with lithic miniaturization and their connection to specific lithic raw material.

5.3. Further research issues

As presented separately in Chapters 3 and 4, this dissertation leaves many further research issues. Here I highlight a few of these issues and present some preliminary analyses and results to overcome these issues.

5.3.1. Frequency of chert types in the Epipaleolithic

One of the remaining issues is a paucity of raw materials data in the EUP lithic assemblage that showed a change in the relative frequencies of chert types. The EUP lithic assemblage in this dissertation is only the assemblage from Layer F–G at Tor Hamar. Accordingly, it is difficult to determine whether the prehistoric people at Tor Hamar were unique or whether the increase of Type FH chert in the EUP is a general phenomena. To examine this issue, I made a preliminary study to see whether the predominant trend of Type FH chert continues in later periods (the Epipaleplithic). Here the assemblage from Layer E2 at Tor Hamar was additionally analyzed. This layer reported radiocarbon dates around 24–18 ka cal. BP (Naito et al., 2022). Previous studies (Kadowaki and Henry, 2019; Naito et al., 2022) expected that the lithic industry from Layer E2 corresponds to "Qalkhan". The Qalkhan, like the Ahmarian of Layer F-G, is also a lithic industry dominated by bladelets (Henry, 1995; Olszewski, 2006). Based on the same method as in Chapter 3, the lithic artifacts were classified by the three chert type-groups, and their relative frequencies were compared with those of the other lithic assemblages in the Jebel Qalkha area.

Fig. 5.1. shows the relative frequencies of the three chert type-groups in the five lithic assemblages. The Epipaleolithic assemblage (Tor Hamar Layer E2) is characterized by a greater proportion of Type FH chert than the EUP assemblage (Tor Hamar Layer F–G). As a result, the dominant use of Type FH chert not only occurred in Layer F–G (Ahmarian) but also in Layer E2 (Qalkhan). This result supports the adaptive behavior of selecting Type FH chert for the production of bladelets, although it is necessary to verify the results with EUP lithic assemblages other than Tor Hamar.

5.3.2. Linking mechanical and structural properties of chert: Loss on ignition

In Chapter 4, the difference in Rockwell hardness between the chert types was statistically significant. However, no other studies have employed Rockwell hardness measurement to examine the fracture predictability, thus it is difficult to assess the result in comparison with other studies. Moreover, this dissertation employs mechanical approaches, but it is necessary to relate the results to the structural approach. Therefore, a preliminary analysis was made to measure the SiO_2 content by XRF and the amount of impurities within chert samples by Loss on ignition (LOI) in the same method as the previous studies (Williams et al., 2019; Lewis et al., 2022). The impurities within chert samples stem from in situ volatile elements and secondary mineralization (Lewis et al., 2022). Silica, the main component of chert, is not considered a volatile compound. Thus, the SiO_2 content of chert is inversely proportional to the amount of impurities. In previous studies (Williams et al., 2019; Lewis et al., 2022), fracture predictability is represented by the Euclidean distance converting %LOI value and %SiO_2 value. As a result, a scatter plot can illustrate the distance from a theoretically "perfect" chert sample with 100% SiO_2. The previous studies analyzed chert artifacts excavated from the Paleoindian sites based on the above theory and compared the degrees of fracture predictability by chert sources or various periods. This dissertation followed their theory and used Rockwell hardness chert nodule samples ($n = 6$) for the XRF and LOI measurements. The analyses were conducted by Dr. Koshi Yamamoto (Nagoya University Museum) and Mr. Bayart Nadmid (Graduate School of Environmental Studies, Nagoya University).

As a result, the measurement values of %SiO_2 and %LOI are shown in a scatter plot (Fig. 5.2.). This dissertation did not calculate the Euclidean distance because the purpose is to make simple comparisons and see correspondences among the measurement values. The scatter plot shows that the distribution range of Type FH chert is different from Type M chert. Type FH chert has a higher value of %SiO_2 and is closer to a "perfect" chert than Type M chert. Although a few samples of this dissertation cannot show statistically significant differences, this result is consistent with the previous studies. On the other hand, the measurement values of both %SiO_2 and %LOI are distributed in a narrower range than the previous studies. Thus, this dissertation discussed a slighter difference of the fracture predictability than the previous studies. This result may explain why differences in the Schmidt Hammer hardness were not significant between Type FH and Type M chert.

In addition, Fig. 5.3. shows the relationship between Rockwell hardness values and %SiO_2. Rockwell hardness and the SiO_2 content show a negative correlation. This result suggests that the SiO_2 content of chert influences the knapping force requirement. However, these results have to be verified by additional analyses of more samples.

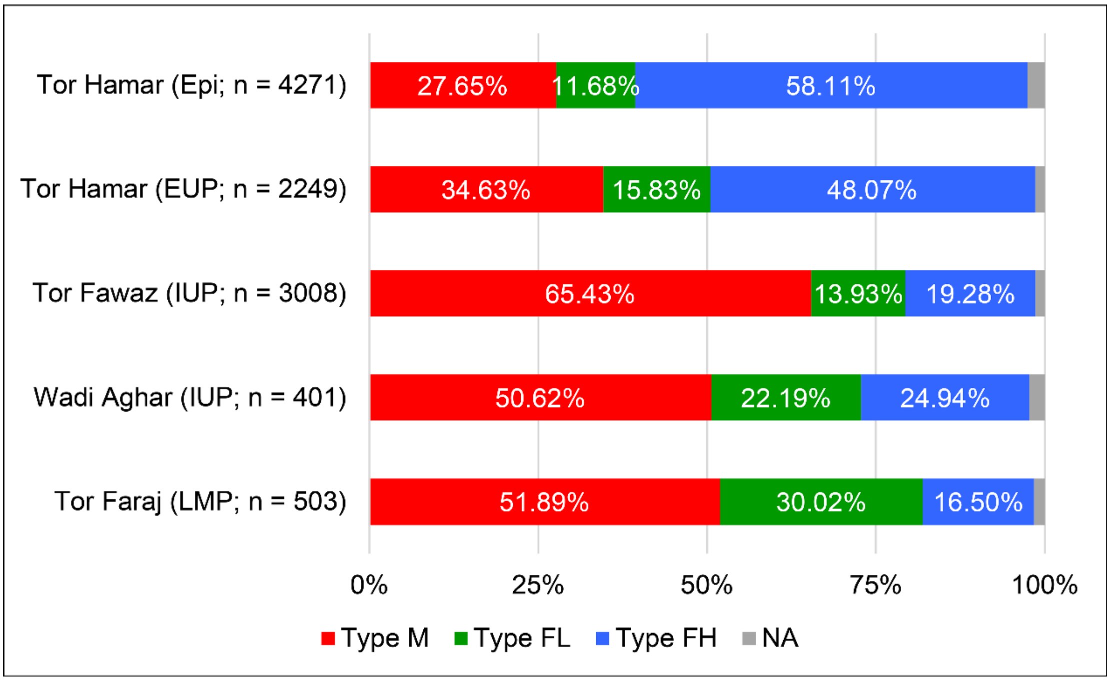


Fig. 5.1. Diachronic changes in the use of lithic raw material (chert) from the MP to the Early Epipaleolithic (Qalkhan) in southern Jordan.

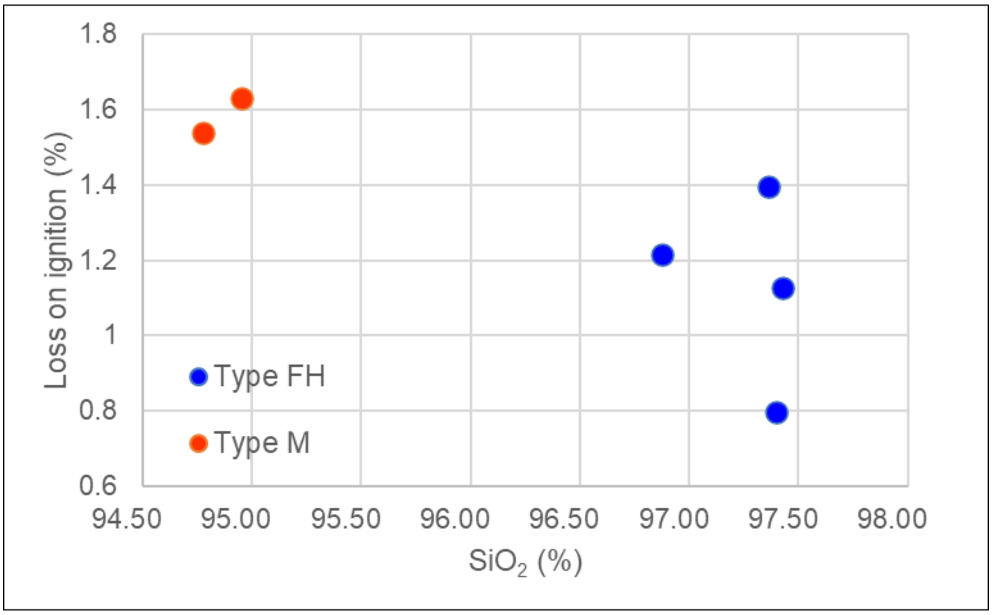


Fig. 5.2. Scatterplot of the percentages of SiO₂ (silica) and the loss on ignition for each chert sample of Rockwell Hardness (HRC). See Appendix Table S3 for data sources.

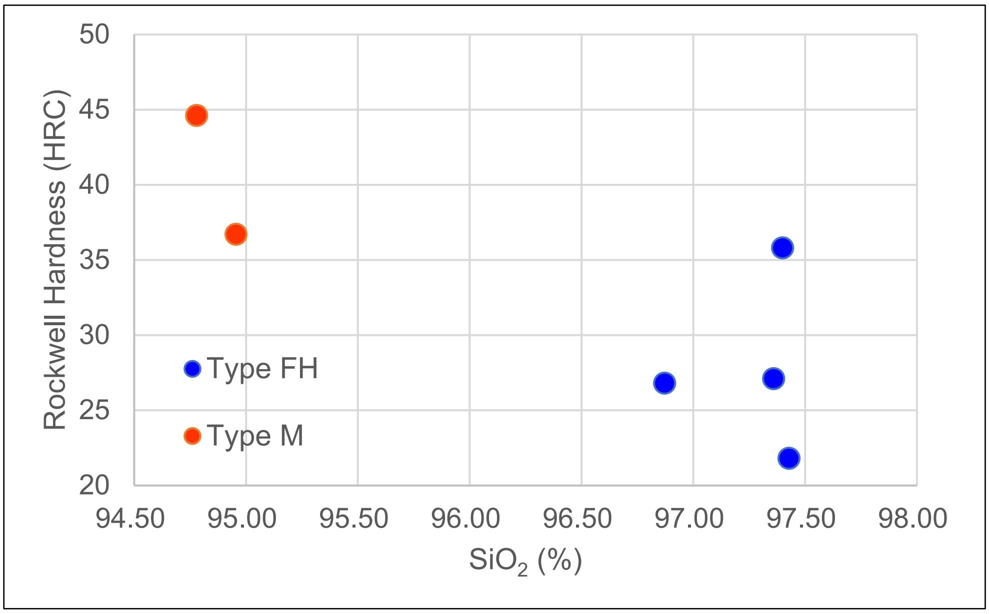


Fig. 5.3. Scatterplot showing the correlation between Rockwell Hardness values and the percentage of SiO_2 (silica). Rockwell Hardness values are the average values for each mother nodule. See Appendix Table S3 for data sources.

Chapter 6. Conclusion

This dissertation aimed at diachronic examinations of the selection and utilization of lithic raw material at the MP-UP transition, which is known for the key paleoanthropological processes. Firstly, I analyzed the raw material (chert) variations in the four lithic assemblages that represent the LMP, the IUP and the EUP in the Jebel Qalkha area, southern Jordan. More specifically, three major chert types (Types M, FL and FH) were established based on two macroscopic criteria (texture and translucency) that correlate with microfossil contents and major chemical compositions. As a result, the relative frequencies of the three chert types in the four lithic assemblages showed an increase in Type FH in the EUP assemblage. As for this increase, I also hypothesized that the physical properties of Type FH chert are different from those of the other chert types (Type FL and M). Secondly, I examined the fracture predictability between Type FH and Type M through the measurement of two mechanical properties, i.e., the rebound hardness by Schmidt Hammer and the Rockwell Hardness (HRC), by using chert samples from raw material sources. The results indicate that Type FH chert needs less knapping force requirement and is particularly suitable for the production of bladelets. On the other hand, Type FH chert in southern Jordan suffers from abundant internal fractures and was not used as often as medium-grained chert for Levallois products and robust blades in the LMP and IUP. Depending on end products, specific chert may have been selected at raw material sources where various chert types could be collected. The general discussion presented some implications of this dissertation and several remaining issues. As for the latter, some preliminary analyses and results were presented as further research directions.

This dissertation aimed at contributing to better comprehension of the changes in cultural remains at the MP-UP transition when significant paleoanthropological processes occurred, such as the wide geographic dispersal of *Homo sapiens* and their interaction and interbreeding with Neanderthals and Denisovans. As a result, a clear change in lithic raw material was not found at the conventional MP-UP boundary but detected at a little later phase between the IUP and EUP. However, this result is only for the Jebel Qalkha area. The discussion of behavioral change throughout the MP-UP transition requires investigations in the other region.

At present, the comprehension among archaeologists is still limited regarding the utilization of lithic raw material resource and the mechanical properties of raw material in the Paleolithic. However, this dissertation provided a novel perspective on these issues to make contributions to the further development of the research on prehistoric resource utilization.

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Appendix

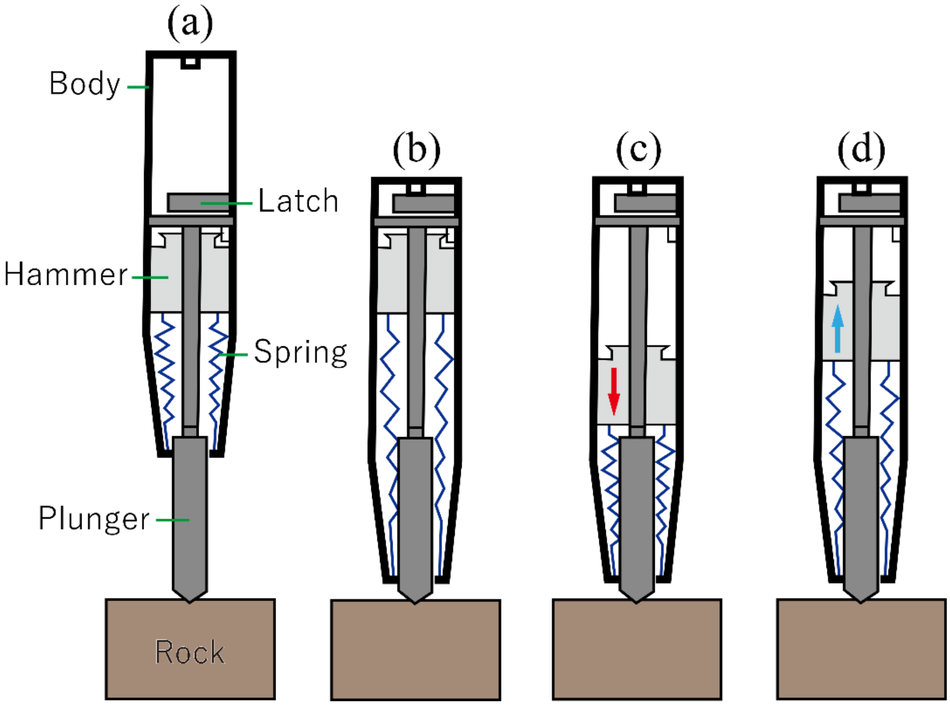

Fig. S1. Schmidt Hammer mechanism. (a) The instrument is ready for test. (b) A body pushed toward a rock sample and a spring is stretched. (c) A steel hammer is released and the rock sample is loaded. (d) The steel hammer rebounds.

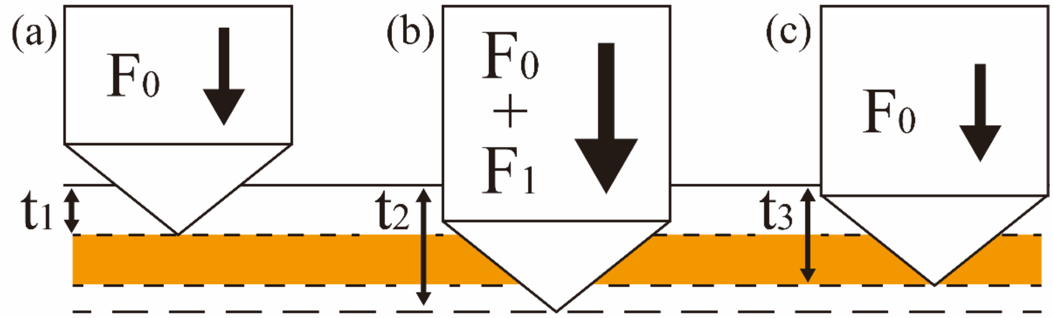

Fig. S2. Rockwell Hardness (HRC) mechanism. (a) The surface of rock sample is pushed by a diamond conical indenter with reference load (98.07 N). (b) The indenter pushed with test load (1471 N). (c) The difference in groove depth caused by the two loads is measured.

Table S1. Macroscopic, microscopic, and chemical attributes of chert types defined in this study for the lithic assemblages from the Jebel Qalkha area.

Type	M1	M2	M3	M4	M5
Texture (R_a value)	Medium (≥2)	Medium (≥2)	Medium (≥2)	Medium (≥2)	Medium (≥2)
Translucence	Medium-Low	Medium-Low	Medium-Low	Medium-Low	Low
Color	Light Gray L. Brn. Gray Grayish Brn. L. Ye. Orange Dull Orange Dull Brown Brown	Light Gray L. Brn. Gray Grayish Brn. L. Ye. Orange Dull Orange Dull Brown Brown	Light Gray L. Brn. Gray Grayish Brn. L. Ye. Orange Dull Orange Dull Brown Brown	Light Gray L. Brn. Gray Grayish Brn. L. Ye. Orange Dull Orange Dull Brown Brown	Black V. Dk. Gray
Munsell Notation	7.5 YR 8/2-4/2 7.5 YR 8/3-4/3	7.5 YR 8/2-4/2 7.5 YR 8/3-4/3	7.5 YR 8/2-4/2 7.5 YR 8/3-4/3	7.5 YR 8/2-4/2 7.5 YR 8/3-4/3	10YR 2/1–3/1
UV signature	Orange 590	Yellow 570	Dk. Violet 400	Yellow 550	Dk. Violet 400
Microfossils	Much-Few	Much-Few	Much-Few	Much-Few	Much-Few
SiO_2 content	High-Medium	High-Medium	High-Medium	High-Medium	High-Medium
CaO content	Little	Little	Little	Little	Little
Chert Variety No. by Henry and Mraz, 2020	1 or 3	2 or 4	NA	NA	5

Table S1. (Continued)

Type	FL1	FL2	FL3	FH1	FH2	NA
Texture (R_a value)	Fine (below 2)	Fine (below 2)	Fine (below 2)	Fine (below 2)	Fine (below 2)	Heavy burned or weathered Quarzite Other Catchall
Translucence	Medium-Low	Medium-Low	Low	High	High	
Color	Light Gray Grayish Brn.	Brn. Gray Grayish Ye. Brwon	Black V. Dk. Gray	Dk. Dusky Red	Red Gray Weak Red	
Munsell Notation	10 YR 5/2-7/2	10 YR 5/1-4/1 10 YR 5/2-4/2	10YR 2/1–3/1	5 YR 3/3-5/3	5-10 YR 4-5/2	
UV signature	Indigo 450	Indigo 450	Dk. Violet 400	Indigo 450	Orange 590	
Microfossils	Few–None	Few–None	Few–None	None	None	
SiO_2 content	High–Medium	High–Medium	High–Medium	High	High	
CaO content	Little–None	Little–None	Little–None	None	None	
Chert Variety No. by Henry and Mraz, 2020	7	NA	NA	6	9	10 or 11

Table S2. Measurement values of rebound hardness. Some samples are not included in the list because they broke during the measurement and could not be measured 10 times.

No.	Outcrops	Raw Material type	Mass (kg)	Measurement values									
				1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	Abbasiya	Type M chert	21.4	71	81	75	80	70	82	81	71	78	82
2	Abbasiya	Type FH chert	61.4	84	83	78	80	80	75	73	82	83	80
3	Abbasiya	Type M chert	20.0	75	78	72	79	80	81	76	80	77	78
4	Abbasiya	Type FH chert	20.0	85	82	83	80	79	78	74	78	77	80
5	Abbasiya	Type M chert	9.2	68	69	78	73	78	75	76	70	72	75
7	Abbasiya	Type M chert	24.4	84	84	82	81	81	75	81	82	82	82
8	Abbasiya	Type FH chert	23.4	80	80	81	81	79	81	74	80	81	79
9	Abbasiya	Type M chert	17.2	73	71	71	70	69	70	73	70	72	78
10	Abbasiya	Type M chert	24.4	72	82	75	78	81	79	74	74	77	83
11	Abbasiya	Type FH chert	24.6	85	85	76	75	72	80	78	75	76	81
13	Abbasiya	Type FH chert	13.6	72	80	73	73	79	75	71	77	74	73
14	Abbasiya	Type FH chert	12.2	79	73	72	69	75	69	76	77	76	79
15	Abbasiya	Type FH chert	31.8	86	85	84	77	77	82	83	77	80	82
16	Abbasiya	Type M chert	18.6	80	73	82	78	77	81	74	78	73	77
17	Abbasiya	Type FH chert	21.2	76	75	77	78	81	75	78	76	80	81
18	Wadi Abu Sawwan	Type M chert	18.2	70	75	76	70	79	81	75	76	73	81
19	Wadi Abu Sawwan	Type M chert	41.8	82	78	76	81	82	79	74	75	78	81
21	Wadi Abu Sawwan	Type M chert	42.6	86	84	83	77	78	76	80	80	79	80
22	Wadi Abu Sawwan	Type M chert	13.4	73	74	79	75	72	78	77	78	79	75
23	Wadi Abu Sawwan	Type M chert	36.2	78	79	82	83	75	78	80	79	74	77
26	Humayma	Type FH chert	35.0	86	84	79	81	77	77	76	80	77	80

Table S2. (Continued)

No.	Outcrops	Raw Material type	Mass (kg)	Measurement values									
				1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
29	Ma'an Plateau	Type FH chert	14.2	76	82	78	79	82	75	77	75	78	82
30	Abbasiya	Type FH chert	5.2	84	82	75	76	76	80	76	78	83	76
31	Wadi Abu Sawwan	Type FH chert	4.8	79	79	79	80	77	81	75	81	75	80
32	Abbasiya	Type FH chert	4.6	71	74	79	74	74	73	79	73	74	71
34	Humayma	Type M chert	5.6	78	77	77	75	71	77	73	74	75	75
35	Ma'an Plateau	Type M chert	4.8	73	72	75	71	73	71	72	75	71	72
40	Hokkaido	Obsidian	8.6	84	83	82	79	77	75	75	74	68	67
41	Hokkaido	Obsidian	18.3	82	78	78	77	77	76	76	74	71	71
42	Hokkaido	Obsidian	6.3	81	80	78	76	74	73	65	61	54	45
43	Hokkaido	Obsidian	12.0	84	83	82	81	80	79	71	69	69	61
44	Hokkaido	Obsidian	10.3	83	81	80	78	78	67	67	66	61	59
45	Hokkaido	Obsidian	5.0	79	79	79	78	77	77	74	73	73	70
46	Hokkaido	Obsidian	20.0	84	82	81	81	80	79	76	76	66	64
47	Hokkaido	Obsidian	18.0	87	86	85	85	84	83	82	81	78	66
48	Hokkaido	Obsidian	9.0	86	80	80	80	80	77	71	68	60	47
49	Hokkaido	Andesite	19.9	63	63	59	59	57	56	54	53	51	47
50	Hokkaido	Andesite	17.0	71	70	70	69	69	68	68	68	68	66
51	Hokkaido	Andesite	15.7	66	66	65	64	63	63	62	62	59	59
52	Hokkaido	Andesite	11.5	65	62	61	61	61	58	58	54	50	51
53	Hokkaido	Andesite	6.0	71	71	71	69	69	67	67	66	64	57
54	Hokkaido	Andesite	12.9	57	54	53	52	50	49	46	45	44	42
55	Hokkaido	Andesite	14.7	72	72	71	71	69	68	67	64	61	56

Table S3. Measurement values of Rockwell Hardness (HRC), and SiO_2 and loss on ignition (LOI) percentage.

No.	Raw Material Type	Mother rock ID	SiO_2 (wt.%)	LOI (wt.%)	Outcrop	Measurement value									
						1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
1	Type FH chert	A	97.34	1.40	Ma'an Plateau	38.7	36.5	44.2	26.4	46.1	48.9	30.7	37.3	19.9	-8.0
2	Type FH chert	A	97.34	1.40	Ma'an Plateau	-11.0	33.3	43.1	14.8	39.7	5.9	-3.2	44.7	53.2	1.5
3	Type FH chert	B	96.67	1.21	Ma'an Plateau	39.6	15.1	42.1	9.6	-10.2	42.2	11.9	35.7	27.5	33.7
4	Type FH chert	B	96.67	1.21	Ma'an Plateau	23.7	16.6	45.9	31.7	17.7	7.2	18.1	16.2	30.8	20.0
5	Type FH chert	B	96.67	1.21	Ma'an Plateau	44.5	24.3	1.9	43.0	40.2	21.9	44.8	31.8	28.3	48.5
6	Type FH chert	C	97.41	0.80	Humayma	15.8	46.5	40.4	31.9	22.8	25.6	34.1	-5.6	52.0	20.0
7	Type FH chert	C	97.41	0.80	Humayma	44.3	52.1	43.5	31.6	53.0	52.0	46.5	62.7	53.8	-6.8
8	Type FH chert	D	97.39	1.13	Abbasiya	32.9	31.1	-16.9	-2.5	33.7	33.2	-38.2	33.3	-29.4	26.0
9	Type FH chert	D	97.39	1.13	Abbasiya	22.7	38.7	35.8	34.7	13.6	64.2	39.9	29.7	3.4	39.3
10	Type FH chert	D	97.39	1.13	Abbasiya	39.0	-10.4	43.9	11.2	21.9	36.7	9.3	27.7	52.5	-2.8
11	Type M chert	E	94.93	1.63	Humayma	57.5	29.1	46.0	57.8	62.4	50.2	29.2	51.7	42.8	45.4
12	Type M chert	E	94.93	1.63	Humayma	26.3	31.6	36.4	23.3	39.4	29.1	46.5	37.0	56.0	42.9
13	Type M chert	E	94.93	1.63	Humayma	1.6	41.0	25.4	26.2	33.0	23.4	34.5	11.6	47.6	15.7
14	Type M chert	F	94.74	1.54	Humayma	67.1	-2.4	55.5	64.3	53.2	59.2	65.8	34.6	58.6	52.4
15	Type M chert	F	94.74	1.54	Humayma	59.2	12.6	22.4	33.8	51.8	57.3	43.1	51.7	63.1	53.2
16	Type M chert	F	94.74	1.54	Humayma	50.9	46.7	35.8	30.2	54.1	51.8	10.6	36.1	30.8	35.1
17	Obsidian	—	—	—	Hokkaido	-45.3	-10.4	34.0	2.8	-7.8	31.6	-2.4	36.9	23.4	1.9
18	Obsidian	—	—	—	Hokkaido	3.6	-40.5	12.9	-2.3	8.7	37.1	43.9	-49.2	28.0	15.0
19	Obsidian	—	—	—	Hokkaido	25.8	4.8	-1.0	-7.8	-10.7	28.7	18.8	22.4	0.0	34.0
20	Glass block	—	—	—	—	-42.6	-16.1	-11.6	-25.6	-51.6	-24.7	-37.6	-10.9	-51.3	-18.8