ELSEVIER

Journal of Archaeological Science 32 (2005) 207–213

Journal of Archaeological SCIENCE

http://www.elsevier.com/locate/jas

Flint procurement strategies in the Late Lower Palaeolithic recorded by in situ produced cosmogenic ^{10}Be in Tabun and Qesem Caves (Israel)

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Received 10 June 2004; received in revised form 12 September 2004

Abstract

The in situ produced cosmogenic beryllium isotope, ^{10}Be, in flint artifacts from different layers in prehistoric caves can provide information on flint procurement. The buildup of ^{10}Be in a flint matrix is related to the exposure time of the flint to cosmic rays. Although this exposure history can be complex, the ^{10}Be content of flint assemblages can show whether the raw material was obtained from shallow mining and/or surface collection as opposed to sediments two or more meters below the surface. Flint artifact assemblages from two Palaeolithic caves in Israel, Tabun and Qesem, were analyzed.

In Tabun cave the flint artifacts from Lower Layer E (Acheulo-Yabrudian, around 400 000–200 000 yr) contain very small amounts of ^{10}Be, which is consistent with flint procured from sediments two or more meters deep. Artifacts from above and below Tabun Lower Layer E show a more complex distribution, as do artifacts from all layers of Qesem cave (Acheulo-Yabrudian). This is probably due to the fact that they were surface collected and/or mined from shallow (less than 2 m) depths. We show here that artifact assemblages have different concentrations of ^{10}Be, indicating different raw material procurement strategies.
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Keywords: Flint mining; Lower Palaeolithic; Cosmogenic isotopes; ^{10}Be; Acheulo-Yabrudian

1. Introduction

Stone artifacts, and in particular flint artifacts, have been extensively used in prehistory until the Bronze Age. Flint, a microcrystalline form of quartz, has been favored over other raw materials, because of its unique fracture properties. The manner in which the artifact was made can be reconstructed from a detailed study of its technological and typological properties, and chemical analysis of its composition can provide information on the provenience of the raw material [14]. It is, however, much more difficult to obtain information on the manner in which the raw material was procured. Vermeersch identified four possibilities: incidental collecting, intensive collecting, systematic quarrying and underground mining [19]. The inherent difficulty in

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0305-4403/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2004.09.001

investigating this aspect of stone industries is the need to find and characterize the locations of stone sources, which are often at some distances from occupation sites.

Quarrying and underground mining sites are well known from the Neolithic [1], but are almost unknown from older periods. The few quarries that have been identified from the Paleolithic are the Acheulian complex at Isampur (India) (ca. 1.0 Myr BP) [5], the Late Acheulian-Early Mousterian flint surface quarries at Mount Pua (Israel) (older than 200 000 BP) [2] and the Middle Palaeolithic flint quarry in Qena (Egypt) (ca. 50 000 BP) [19,20]. The Lower Palaeolithic site in Isampur has rich Acheulian cultural horizons with a large number of quarried limestone artifacts. Apparently the Acheulians exploited the source of limestone for preparing rough blocks that were then transported to the occupation site where they were shaped into handaxes [16]. The quarrying site in Mount Pua is located on the flat, narrow summit of a mountain where numerous flint nodules are exposed within limestone karrens. The site comprises hundreds of heaps of quarry debris, as well as prehistoric artifacts. Flint was extracted from the exposed limestone outcrops using the 'surface quarrying' technique [2] down to a maximum depth of 1 m. The site in Qena consists of irregular systems of open ditches and pits (max. depth 1.7 m) dug to extract flint cobbles. The site is unstructured and was intermittently exploited [19].

We recently developed a new approach for investigating procurement strategies of raw materials based on an in situ produced radioactive isotope of beryllium, ^{10}Be, in flint [21]. This approach takes advantage of the fact that ^{10}Be is produced inside rocks as a result of exposure to cosmic rays [12]. As these rays are significantly attenuated at depth of more than 2 or so meters, raw materials obtained from greater depths will not contain high amounts of ^{10}Be, as compared to those above 2 m or on the surface [8,13,17]. This however is on condition that the artifact once made, was deposited in a cave, where from the perspective of cosmic ray exposure, it was essentially reburied. The method thus makes possible a systematic investigation of procurement strategies using raw materials deposited in prehistoric cave sites. Using flint artifacts from caves not only increases significantly the chance of having suitable material for carrying out these studies, but also means that the results can be integrated into the archaeological context. In principle, all raw materials used for stone artifact production can be tested, provided that it can be proved that they are closed systems.

The study of Verri et al. [21] proved in practice that flint is a raw material that can be used for this purpose as it is a closed system with respect to ^{10}Be. The study also reported the details of the extraction and analytical procedures. These were applied to flint samples collected from surface exposures, to some deeply buried flints and to knapped artifacts from Acheulo-Yabrudian layers in two caves in Israel, Tabun cave and Qesem cave. Surface collected flints have ^{10}Be contents that vary according to their exposure history prior to collection, and deeply buried flints have values at or very close to the detection limit. Here we report the results of a systematic analysis of flint artifacts from different stratigraphic layers in these caves and show that in Tabun cave there are interesting differences in the distribution of ^{10}Be concentrations, maybe related to procurement strategies at different times, whereas for Qesem cave the similarity of distributions may imply that the same strategies seem to have been used over the period in which the artifacts accumulated in the cave.

1.1. Principles of the method

The use of the in situ produced long-lived cosmogenic isotope ^{10}Be (mean life $\tau = 2.2 \times 10^6$ years) to differentiate between deep vs. shallow or surface procurement strategies is based on the fact that nuclear interactions between cosmic rays (mainly secondary neutrons) and oxygen in the flint matrix generate in situ ^{10}Be atoms when the flint is at or close to the surface. The production rate by this spallation process at high latitude and at sea level is 4.5–5.5 atoms/y/g [8,17]. ^{10}Be production however occurs to only a very small extent in flints buried at depths greater than about two meters, where the weak muonic production becomes dominant. At the surface the contribution of the muons is only $\sim$2% of the total production. The ^{10}Be produced in the flint matrix remains where it originated. Thus the flint is a closed system with respect to in situ produced ^{10}Be. Furthermore there is no contamination of the in situ produced isotope by the more abundant atmospheric produced ^{10}Be [21]. The amount of ^{10}Be in flint is proportional to the exposure time of flint to cosmic rays. Once the flint is left in a cave it stops accumulating ^{10}Be by the spallation mechanism, because it is shielded from the cosmic rays by the walls and the ceiling of the cave. ^{10}Be is a radioactive isotope and its decay should be taken into consideration for old samples ($>10^5$ yr). Erosion rate and thickness of the roof of the cave are parameters that should be considered in order to estimate the possible accumulation of ^{10}Be in the artifact after it was deposited in the cave. In our studies we estimate that the cave roofs both had thicknesses of several meters, providing a good screen for further production of ^{10}Be in the flint.

1.2. Sites analyzed

The analysis of Tabun cave artifacts enables a systematic investigation of the differences in ^{10}Be concentration, and hence flint procurement strategies, from different stratigraphic layers. These layers are representative of cultural complexes that flourished over a long period. The Qesem Cave samples, on the other hand, provide a detailed analysis of procurement strategies of a specific cultural complex, the Acheulo-Yabrudian. The comparison of the results from the two caves provides information on the development of flint procurement strategies in the region, with a particular focus on the Acheulo-Yabrudian complex.

1.2.1. Tabun cave

Tabun cave is situated on the western edge of Mount Carmel, about 3.5 km from the present Mediterranean coast and 20 km south of Haifa. The cave originally had three chambers; an inner, intermediate and outer chamber. The latter was also the largest, but its roof has since collapsed. The inner chamber, connected to the outer by the intermediate chamber, has a hole in the ceiling. The cave takes its name from this ‘chimney’ as it resembles an oven, in Arabic. Tabun Cave is an important site, as its long stratigraphic section serves as a reference for other prehistoric caves in the Levant. The cave was excavated in 1929 and 1931–1934 by Garrod [7] and in 1967–1972 by Jelinek. It is currently being excavated by A. Ronen. Garrod and Jelinek excavated two partly overlapping sections; the main differences between the two excavations are due to various depositional discontinuities in the cave. These discontinuities create ambiguities in correlating the two excavations. Fig. 1 shows the base of the section. Garrod divided the cultural sequences into the following strata: Layer G, Tayacian (due to its similarities with the European Tayacian); Layer F, Upper Acheulian; Layer E, Acheulo-Yabrudian; Layers D and C, Lower Levallois-Mousterian; Layer B, Upper Levallois-Mousterian; Layer A, historic period. Jelinek’s cultural subdivision in stratigraphic units is similar to Garrod’s, even though the interpretation is not always the same. Jelinek divided the cultural sequences as follows: Unit XIV, Upper Acheulian [9–11,15]; Units XIII-X, Acheulian, Acheulo-Yabrudian and Yabrudian (Mugharan), corresponding to Layer E; Unit IX-I, Mousterian, corresponding to Layers D–B.

1.2.2. Qesem cave

Qesem cave is a newly discovered cave 12 km east of Tel-Aviv (Fig. 2) [3]. The cave consists of a single chamber, which was revealed when the ceiling was destroyed by recent road construction. The stratigraphic sequence of this cave (7.5 m of sediments) is attributed to the Acheulo-Yabrudian complex of the terminal Lower Paleolithic. The dating of speleothems [3] suggests that the Acheulo-Yabrudian occupation complex started prior to 380 kyr and ceased some time around 200 kyr ago.

2. Materials and methods

2.1. Materials

Table 1 lists the samples analyzed and the depths and/or stratigraphic settings of the samples in Qesem and in Tabun caves. Flint artifacts from four layers of Tabun cave were analyzed: three samples from the Tayacian Layer G; five from the Upper Acheulian Lower Bed XIV; five from the Acheulo-Yabrudian Lower Layer E and six from the Yabrudian Upper Layer E. Most samples were flakes, and the rest cores, flint debris and blades. Only three samples were

Fig. 1. The steeply dipping layers of the lower (layer G, F and Lower E) stratigraphy in Tabun Cave.

Fig. 2. The remains of Qesem cave after roof destruction during recent road construction. Some of the stratigraphic layers are roughly horizontal.

analyzed from Layer G, because large enough artifacts for analysis in this layer were not available. The Upper and Lower parts of Layer E in Tabun are considered contemporary with the sequence found in Qesem cave. Note that the depth below datum in Tabun does not correlate directly with the stratigraphy, as at the base of the section the layers dip steeply (Fig. 1).

The samples from Qesem cave are from four stratigraphic units: the first is approximately 7–8 m below datum, the second about 6–7 m, the third 3.8 m and the fourth at the top of the Acheulo-Yabrudian sediments, at about 1–2 m below datum.

2.2. Sample preparation for ^{10}Be analysis

The procedures are described in detail in [21]. They are briefly summarized here. A sample with a minimum weight of 10–20 g is crushed into powder (grain size < 50 μm) and carbonates and organic material are removed by treatment with HCl and HNO_3. Successive cleaning and etching steps are performed with 1% HF to remove any meteoric ^{10}Be. The powder is then dissolved with HF (40%) and $HClO_4$ and 0.5 mg Be carrier is added. After selective removal of Ca and Fe, Be and Al are separated with a cation exchange column. BeOH is then precipitated and baked for 2 h. The BeO obtained is then crushed into a powder and mixed with Nb. The mixture is inserted into copper holders to be measured by Accelerator Mass Spectrometer (AMS). The samples were measured at the 14UD Pelletron Koffler accelerator of the Weizmann Institute (Israel) [4] and at the EN Tandem Accelerator of ETH/PSI (Switzerland). For details see [6], [18] and [21].

After each of the etching steps a fraction (0.3–1 g) of the flint sample was put aside for Induced Coupling Plasma (ICP) analysis. The sample was dissolved completely with 40% HF and $HClO_4$. After fuming three times with HNO_3, the sample was then diluted in 15 ml 1 N HCl and analyzed by ICP (Geological Survey of Israel).

3. Results

3.1. ^{10}Be results

The results of the Tabun Cave samples (Table 1) are plotted in Fig. 3. Each set of samples from a single stratigraphic layer is presented in order of ascending concentration of ^{10}Be. Due to the steeply dipping strata in Tabun (Fig. 2) a stratigraphic representation according to depths below datum is not possible. The samples from Lower Bed XIV and Layer G have a wide range of ^{10}Be contents, which is consistent with surface collection and/or shallow mining. The layer above Bed XIV, namely, Lower layer E, has flints that have very small amounts of ^{10}Be. This is consistent with a deep mining procurement strategy. Most of the flints in the Upper layer E also have small amounts of ^{10}Be, except for two that have significantly higher contents. Here the interpretation with regard to procurement strategy is equivocal. The ^{10}Be contents of the three Layer G (approximately the same age as Bed XIV) samples, corrected for decay, show a trend that may be reminiscent of Lower Bed XIV samples. More samples need to be analyzed to determine the procurement strategy during this period.

Table 1
Details of each flint analyzed

Specimen	Stratigraphic layer	Culture	Specimen type	Depth (cm)	^{10}Be (10^6 atoms/g)
Tabun Cave					
TB45B	Upper Layer E	Yabrudian		510	0.75±0.10
TB46B	Upper Layer E	Yabrudian		530	0.23±0.04
TB47B	Upper Layer E	Yabrudian		533	0.67±0.07
TB35	Upper Layer E	Yabrudian		654	0.21±0.02
TB37b	Upper Layer E	Yabrudian		703	0.07±0.01
TB36	Upper Layer E	Yabrudian		760	0.14±0.02
TB1 1mg	Lower Layer E	Acheulo-Yabrudian		811	0.12±0.07
TB4	Lower Layer E	Acheulo-Yabrudian		813	0.08±0.09
TB3	Lower Layer E	Acheulo-Yabrudian		813	0.09±0.08
TB22	Lower Layer E	Acheulo-Yabrudian		965	0.10±0.08
TB21	Lower Layer E	Acheulo-Yabrudian		1090	0.14±0.10
TB28b	Lower Bed XIV	Upper Acheulian		970	0.36±0.05
TB29	Lower Bed XIV	Upper Acheulian		978	0.45±0.03
TB30b	Lower Bed XIV	Upper Acheulian		987	0.25±0.03
TB32b	Lower Bed XIV	Upper Acheulian		991	0.19±0.03
TB31b	Lower Bed XIV	Upper Acheulian		999	0.19±0.03
TB50	Layer G			1160	0.13±0.03
TB13	Layer G			1575	0.21±0.02
TB40	Layer G			1576	0.09±0.05
Qesem Cave					
QC21		Acheulo-Yabrudian	Chunk	140–150	0.12±0.02
QC23		Acheulo-Yabrudian	Chunk	150–155	0.23±0.03
QC24		Acheulo-Yabrudian	Overshot (blade core)	165–170	0.27±0.03
QC26		Acheulo-Yabrudian	Retouched flake	170–175	0.29±0.03
QC27		Acheulo-Yabrudian	Retouched flake	170–180	0.46±0.06
QC22		Acheulo-Yabrudian	Flake	170–180	0.81±0.05
QC25		Acheulo-Yabrudian	Flake	185–190	2.15±0.08
QC5		Acheulo-Yabrudian	Flake	365–370	0.18±0.06
QC1		Acheulo-Yabrudian	Core	375–380	0.41±0.05
QC8		Acheulo-Yabrudian	Blade	590–610	0.15±0.04
QC10		Acheulo-Yabrudian	Flake	615–620	0.32±0.05
QC12		Acheulo-Yabrudian	Core	595–640	0.46±0.05
QC13		Acheulo-Yabrudian	Blade	665–670	0.67±0.06
QC16		Acheulo-Yabrudian	Flake	670–675	1.39±0.08
QC36		Acheulo-Yabrudian	Flake	745–750	0.12±0.02
QC35		Acheulo-Yabrudian	Chunk (broken flake)	760–765	0.45±0.04
QC33		Acheulo-Yabrudian	Blade	765–770	0.21±0.02
QC32		Acheulo-Yabrudian	Primary flake	765–770	0.33±0.04
QC30		Acheulo-Yabrudian	Primary flake	775–780	0.35±0.06
QC37		Acheulo-Yabrudian	Blade	775–780	0.36±0.04
QC14		Acheulo-Yabrudian	Core trimming element	780–810	0.53±0.06
QC31		Acheulo-Yabrudian	Primary flake	825–830	1.34±0.08
QC34		Acheulo-Yabrudian	Flake	830–835	0.62±0.04
QC7		Acheulo-Yabrudian	Flake	750–840	0.17±0.04

The depth is below datum. The amount of ^{10}Be is per gram of initial flint. The values are background subtracted.

The more detailed stratigraphy of Qesem cave provides a different view of flint procurement strategies in the Acheulo-Yabrudian. Fig. 4 shows the results of ^{10}Be concentrations in artifacts from Qesem cave. The range of concentrations is much wider as compared to Tabun Cave for all of the stratigraphic units analyzed. Note that the outlier (QC25 Table 1) is a sample made of especially poor quality flint included in the analysis as a control sample. The distributions in Qesem cave are consistent with surface and/or shallow mining of raw material combined with deep mining. It thus seems that in Qesem cave, throughout the sequence, deep mined flint was a small component of the lithic assemblage while the rest was surface collected or shallow mined. On the other hand Tabun Cave showed at least one stratigraphic unit in which flint procurement was dominated by deep mining only.

3.2. ICP analyses

The ICP analyses of a suite of elements are from the fractions of the flint artifacts that had been subjected to

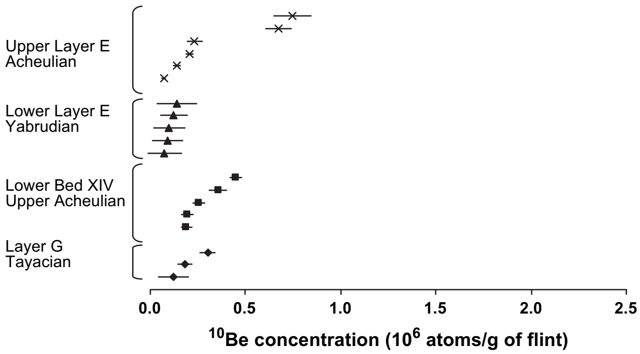

Fig. 3. ^{10}Be concentrations per gram of flint for Tabun Cave are displayed on the x-axis. The y-axis represents the different cultures according to the stratigraphy. The concentrations are represented in ascending stratigraphic order.

extensive etching by hydrofluoric acid. They thus represent the trace element content of only the microcrystalline quartz fraction. A few samples from the Acheulo-Yabrudian of Hayonim Cave (Layer F) were also included. Hayonim cave is located north of Tabun Cave in the western Galilee. A multi-parameter analysis of the data that produces the widest spread of values in order to detect possible groupings, only showed a clear-cut separation between Qesem and Tabun-Hayonim caves. The analysis did not differentiate between flint samples containing low ^{10}Be and high ^{10}Be contents. Samples from the same layer in each cave have a large spread. In conclusion, the trace element contents of the samples can only distinguish between two broad geographical regions, but do not provide information on the procurement strategies themselves. See doi: 10.1016/j.jas.2004.10.003 for the table of the ICP analyses of the samples analysed.

4. Discussion

The results of ^{10}Be analyses from Tabun and Qesem caves provide interesting information on flint procurement strategies of humans in the Levant over a considerably long time interval. Following the basic premise that deep mined flint from depths greater than 2 m will contain small amounts of ^{10}Be, whereas flints collected from the surface or from depths shallower than 2 m will have higher ^{10}Be contents according to their exposure history, we can deduce that different flint procurement strategies, including deep mining, were used at least as early as the Late Lower Paleolithic.

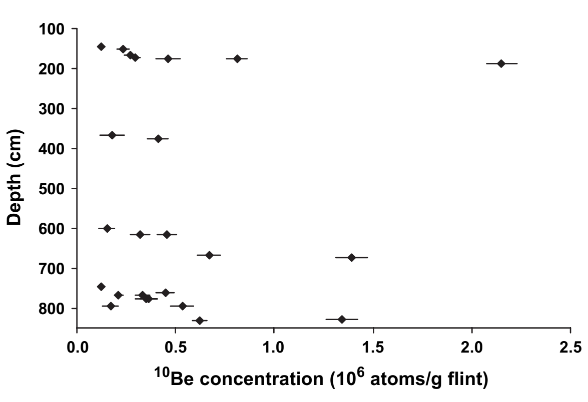

Fig. 4. ^{10}Be concentrations per gram of flint are displayed on the x-axis for Qesem cave. The y-axis represents the depths below datum where the artifacts were collected.

The simplest explanation of the data is that during the Upper Acheulian (Lower Bed XIV) the inhabitants of Tabun cave were collecting flint from the surface or shallow quarries, whereas in the younger Acheulo-Yabrudian (Lower Layer E), the Tabun occupants were deep mining for flint. In the same period, however, in Qesem cave, the inhabitants were collecting flint from the surface or from shallow quarries and if they used deep mined flint, it was to a lesser extent. No layer in Qesem cave reproduces the distribution found in Lower Layer E of Tabun cave.

The situation is, however, more complicated. In Upper layer E of Tabun Cave four out of the six samples analyzed have very low ^{10}Be contents, suggesting that they too could have been deep mined. Two have high contents and could be from the surface or from shallow mining. From this perspective Upper Layer E is similar to the distributions observed in Qesem Cave. In general layers that have a distribution of ^{10}Be concentrations in flints from close to background to high levels cannot be interpreted unequivocally. The flints that have high concentrations must have been derived from the surface or from shallow mining. Those that have very low concentrations are most likely to have been derived from deep mining. Verri et al. [21], however, showed that a few surface collected flints also have low concentrations of ^{10}Be. We do note, however, that the flint at Qesem Cave is in general of high quality and fresh appearance, possibly being derived from primary geological sources, and there is little evidence of rolled material. It is thus clear that for a definitive interpretation of all the ^{10}Be data, additional information is required, as well as analyses of as many samples as possible from each stratigraphic layer.

Our attempt to resolve at least part of these ambiguities by using trace element contents to subdivide the flints into groups according to their chemical compositions was not helpful. The only subdivision we could identify was between relatively large-scale geographic regions. It is possible that by analyzing selected technological (blanks) and typological (tool types) artifacts rather than the debitage analyzed here, some of these ambiguities could be resolved. It is also possible that if both ^{10}Be and ^{26}Al, which is another cosmogenic isotope with a different half-life, are analyzed then more specific information on the depth of mining assuming a reasonable erosion rate, could be obtained.

5. Conclusions

^{10}Be contents can shed light on procurement strategies of flint in the past. The interpretation of the results is simplest when the distribution of ^{10}Be contents in a given stratigraphic layer is uniform. When it is not, the interpretation is complex, and more independent information is needed to obtain an unequivocal explanation of the data. Future studies should involve the analysis of as many samples as possible per stratigraphic layer, the use of selected artifacts rather than casual debitage, and include as many natural flint samples collected from the area around the locality under investigation.

When looked at from an anthropologically oriented perspective, the information obtained from the ^{10}Be analyses on Paleolithic flints indicates that Acheuleo-Yabrudian flint knappers were aware of the major differences in properties and knapping potential between surface collected and deep mined nodules. Flint mining in the Levant is thus known at least since the Late Lower Paleolithic reflecting familiarity with geological sources, technological know how, and skills required for manipulating concealed natural resources.

Acknowledgements

This project was funded by the Minerva Foundation and an Israel Science Foundation grant to S.W. S.W. holds the Dr. Walter and Dr. Trude Borchardt Professorial Chair in Structural Biology. S.W. also gratefully acknowledges the generous financial help from Mr. George Schwartzman. G.V. was a recipient of a Lady Davis Fellowship at the Hebrew University. The Qesem Cave project is supported by the Israel Science Foundation (820/02), the Leakey Foundation and the Irene Levy Sala CARE Archaeological Foundation.

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