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Olivier Barge, Daa Albucaai, Manfred Boelke, Kévin Guadagnini, Emmanuelle Régagnon, et al.. New Arabian desert kites and potential proto-kites extend the global distribution of hunting mega-traps. *Journal of Archaeological Science: Reports*, 2022, 42, pp.103403. 10.1016/j.jasrep.2022.103403 . hal-03678385

HAL Id: hal-03678385

<https://hal.science/hal-03678385v1>

Submitted on 1 Jun 2022

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New Arabian desert kites and potential proto-kites extend the global distribution of hunting mega-traps

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Highlights:

- Recently discovered mega-traps are documented by a combination of satellite image analysis and fieldwork.
- A relative chronology could be established between a proto-kite form (the 'open kites') and the desert kites in the Khaybar region.
- Morphologically homogeneous groups of desert kites show a distinctive geographic distribution
- Mapping of morphologically distinct kites is proposed for the southern part of their geographic range.

Abstract:

New desert kites have been discovered over the past two years during the observation of satellite images of north-western Arabia. Great numbers of these large archaeological traps were known prior to this from the Aralo-Caspian zone to the Arabian Peninsula. Many of these recent discoveries are constructions without the same closed enclosures as kites, but which are nonetheless clearly related to kites as, like them, they comprise pit-traps. The study of all these 'open kites', based on the observation of satellite images, focused on the characterisation of their morphology, topographical location and comparisons of their geographical distribution with that of kites in the region. The analysis of these data was confirmed by a field study in Khaybar, Saudi Arabia, of a sample of open kites in the spring of 2021, during which elements of relative chronology were observed. Open kites are more rudimentary and less systematically organised than kites and represent a 'mega-trap' form that pre-dates the desert kites. Groups of kites were identified on the basis of morphological resemblances, using two different methods, resulting in the overall mapping of mega-traps in the southern part of the kite distribution range. These localised morphological variations probably reflect the evolution of the hunting technique using these traps. They provide new information, which, combined with chronological data from excavations, aims to record the spread of the kite phenomenon.

Keywords:

Desert kites, Saudi Arabia, typology, geographical distribution, mega-traps, hunting techniques

1. Introduction

In recent years, several field expeditions have contributed to documenting and excavating desert kites, these gigantic archaeological constructions that have long remained mysterious or subject to controversy. These teams, which include the Globalkites Project (see www.globalkites.fr), have proposed chronological markers showing that kites were used over a very long period of time, ranging from the late Neolithic to recent periods ([Abu-Azizeh et al., in press](#), [al Khasawneh et al., 2019](#), [Barge et al., 2016](#), [Brochier et al., 2014](#)). Furthermore, their function as hunting “mega-traps” for herds of wild ungulates has been clearly demonstrated ([Crassard et al., 2021](#)). The geographical range of kites is for its part documented by the observation of high-resolution satellite images. A total of 6,023 kites were counted in a recent study ([Barge et al., 2020](#)), extending from the Aralo-Caspian zone, the steppes and desert east of the Levant to western Arabia. However, new discoveries have been made in the past two years (2020 and 2021) in Saudi Arabia. They concern desert kites in sectors where they had never been identified before, and constructions with an original morphology which do not comply with the strict definition of a kite – a combination of long walls converging to an enclosure surrounded by peripheral pit-traps – because they are not closed structures in the same way as desert kites *stricto sensu*. However, they display many kite attributes and are undoubtedly related to them. We thus refer to these constructions as Arabian “open kites”. They were previously mentioned as “pseudo-kites” (see [Barge et al., 2020](#)), and their number has since increased from 320 to 835. The new and more complete corpus obtained from satellite imagery enables us to characterise their morphological features as well as their location in the landscape. Furthermore, the observation of several of these open kites during a field campaign in spring 2021 in Khaybar, western Saudi Arabia, and the implementation of remote sensing resulted in an enhanced description of this new type of construction. The observations made in Khaybar in 2021 confirm some first analyses on the satellite images. Here, we propose a preliminary assessment of the archaeological structures from the ground, and their patterns.

Desert kites *stricto sensu* comprise varied morphological characteristics ([Barge et al., 2015](#)) across the entire geographical area of extension, and intra-regional similarities have been distinguished. Yet, recent discoveries in Arabia do not only concern Arabian open kites, but also other desert kite types with sizes, shapes and layout details that can be linked to families of kites identified elsewhere. For this reason, these new desert kites are of great interest even if they are less numerous (n=87) than Arabian open kites.

A regionalization of kite families is now taking shape in Arabia, to the south of the geographical area of global kite distribution and is filling some previous gaps in regions between the Negev and Khaybar. On account of the scarcity of available absolute dating and the difficulties involved in obtaining dates ([Crassard et al., 2015](#)), this improved regionalization provides crucial data on the phenomenon of the diffusion of kites and associated hunting techniques.

2. Methods

The methods used here are based primarily on the identification and observation of kites on high-resolution satellite images. These images allow us to cover large areas and to analyse the spatial distribution of kites on a wide scale. With these images, it is also possible to obtain fine-scale information and thus to characterise kite morphology. It is even sometimes feasible to define a relative chronology in the case of reuse or overlapping with other archaeological structures. However, data from field investigations remain essential; they are complementary in terms of the scale and type of data collected and allow for a more detailed analysis of architectural traditions. Fieldwork is also crucial in order to better define the chronology of constructions. This is identifiable in particular by the search for dating elements or the observation of the state of preservation of the structure.

All this information must be based on a systematized methodology, in order to be perfectly applicable and comparable. This methodology has already been presented on several occasions, but requires restating here to avoid misunderstandings ([Groucutt and Carleton, 2021](#)). The Globalkites Project research team (e.g.: [Brochier et al., 2014](#); [Crassard et al., 2015](#); [Barge et al., 2015](#)) proposed the

following definition of a kite: it is composed of long walls or stone alignments (driving lines, or antennae) which converge towards an enclosure equipped with pits along the external periphery (pit-traps, or cells). It should be noted here that one of the objectives of the Globalkites Project was to examine the function of kites and that a functionally neutral terminology was therefore adopted at the outset of the project. As the function of kite components has now been established (Crassard et al., 2021), here we will use the terms “driving lines” and “pit-traps”. Based on the combined presence of these three components (driving lines, enclosure, pit-traps), it is possible to distinguish kites from other mega-traps known in the world from the Palaeolithic to the modern era (e.g.: Brink, 2005; Leondorf and Stone, 2006; Santiago and Salemme, 2016; O’Shea et al. 2013; Lemke, 2021; Imamura 1996; Sato 2012; Blehr 1987; Jordhøy 2008; Olsen 2013). This definition also backs up the hypothesis that kites are the material evidence of the diffusion of a hunting technique. An approximate definition would compromise the examination of this hypothesis by running the risk of integrating distinct devices and techniques. A strict definition does not, however, exclude exceptions, to be examined on a case-by-case basis. On the one hand, topographical configurations can make driving lines or enclosures superfluous, as is the case for some kites in Armenia (Barge et al., 2018) or on the Ustyurt Plateau, Kazakhstan (Barge et al. 2016). On the other hand, from the point of view of the diffusion phenomenon, the kite-hunting technique may have been adapted on a local or temporal scale to structures lacking one of the three attributes. Conversely, kites can be the result of earlier hunting techniques using traps with less systematic architecture. However, the pit-trap is a compulsory attribute. Indeed, the pit-trap has been clearly identified by excavations as the final trapping feature (Crassard et al., 2021). It cannot be defined as a small subsidiary enclosure (contra Groucutt and Carleton, 2021), but as a dug-out pit, which the inner side was carefully lined (or stone-faced) with rows of stones, and into which animals fell. It is therefore essential to the final function of the whole structure as a trap. The absence of the pit-trap from certain structures resembling kites, sometimes interpreted as trapping systems, therefore identifies constructions used in a very different manner to kites. The huge geographical distance separating structures or groups of structures comprising pit-traps from large clusters of desert kite concentrations may also be an additional parameter of distinction, notably in the case of constructions in the Atacama Desert in Chile (Barge et al. 2020), or those in South Africa (Lombard and Badenhorst, 2019), for example. In these cases, we can refer to technical convergence where the invention of the trapping concept using long walls-type system was reinvented in other regions. In this way, we propose the following classification of mega-traps identified on satellite images (Fig. 1):

- kites (*stricto sensu*),
- kite-like (equipped with at least one pit-trap but lacking the presence of a well-defined enclosure, as is the case for kites *stricto sensu*),
- other mega-traps.

		Attributes		
Kites		Pit-traps	Driving lines	Enclosure
Kite-like	V-shaped Kites (Negev)	1 pit-trap	Driving lines	
	Open kites (Arabia)	Pit-traps	Driving lines	
Other constructions	Crescent (Ustyurt, Kazakhstan)			Enclosure
	Long wall Constructions (Yemen)		Driving lines	
	V-shaped Constructions (Lybia)	Unfrequent presumed pit-traps	Driving lines	
	V-shaped Constructions (Chile)	Presumed pit-traps	Driving lines	
	Long wall Constructions (S. Africa)	Presumed pit-traps	Driving lines	

Figure 1: classification of mega-traps identified on satellite images

Based on this definition of a desert kite, it is possible to define variables that describe the morphology of each of the three constituent elements. These variables can be recorded for each kite by field observation and/or from satellite images. The potential acquisition of this information using these two data sources has validated the approach in the past. Apart from cases where the image is not sufficiently legible (poor image quality or poor kite preservation), it is possible to draw up an identity sheet for each kite by means of quantitative data, particularly measurements (enclosure size, length of driving lines, width of entrances, number and size of pit-traps), or by identifying morphological features (entrance shape, presence or absence of particular layouts) (Crassard et al., 2015; Supplementary data, 1). In five different regions of the area where kites are present, the field study of more than 150 kites confirmed the reliability of data obtained from satellite images. A few rare cases showed that measurements may be slightly underestimated, but these inaccuracies are negligible when working on hundreds of structures, which in any case remain comparable. In the case of open kites, where spatial organisation is less elaborate and systematic, the cumulative length of walls was measured, pit-traps were counted, contiguous pit-traps were identified and orientation was measured (Supplementary data, 1). These data, recorded in tables in a database, are analysed using univariate or multivariate statistical methods, allowing for comparisons between kites and between groups of kites.

Geographical coordinates are also associated with each kite. It is thus possible, using geomatics tools, to analyse the geographical context of constructions, and in particular their topographical context. Digital Terrain Models (DTM) available online (e.g.: SRTM, ASTER, ALOS PALSAR) can be used to characterise local slopes or orientations. Finally, Geographical Information Systems (GIS) help in the analysis of distributions and neighbourhoods, and generate mapping at different scales. The satellite images used come from freely available online platforms (Google Earth, Bing), the geomatics work was carried out with ArcGis Desktop 10.5 with the spatial analyst extension, and statistical analyses were carried out using Past software.

The present study is also based on a fieldwork season in Khaybar during the summer of 2021. No kites nor open kites have yet been excavated, but the structures were observed and photographed from the ground. In addition, drone photographs, combined with photogrammetry work, were systematically taken in the study zone. No archaeological material, such as lithics or pottery, was found on the surface of kites or open kites.

Based on our previous experience in excavating and surveying mega-trap structures, we developed a new research project in Saudi Arabia, the Khaybar *Longue Durée* Archaeological Project, in order to investigate the material cultures of mega-trap constructions and the associated occupation sites (potential settlements and hunter campsites).

3. New discoveries in Arabia

Most of the desert kites *stricto sensu*, and kite-like structures identified over the last two years are located in north-western Arabia (Fig. 2). Some of these constructions have been presented elsewhere (Groucutt and Carleton, 2021), but their initial description appears to be rather approximate and the comparisons poorly documented. Here, we present a much more complete inventory. Many of these new discoveries are open kites, and their numbers have increased considerably, especially in basaltic plateau areas (*harrat* is the Arabic word to describe these lava fields; Kennedy et al. 2015), such as in Harrat Nawasif, Harrat Kishb and Harrat Rahat. New open kites have also been identified in Harrat Khaybar and Al-Hait region, albeit in a more limited way. Large numbers of open kites are now known and their distribution is well defined, suggesting much more massive hunting activity with these traps than previously thought. The distribution of open kites south of the previously documented area of global desert kite distribution further extends the scope of the kite phenomenon. However, the temporality of these southernmost structures has yet to be more clearly defined.

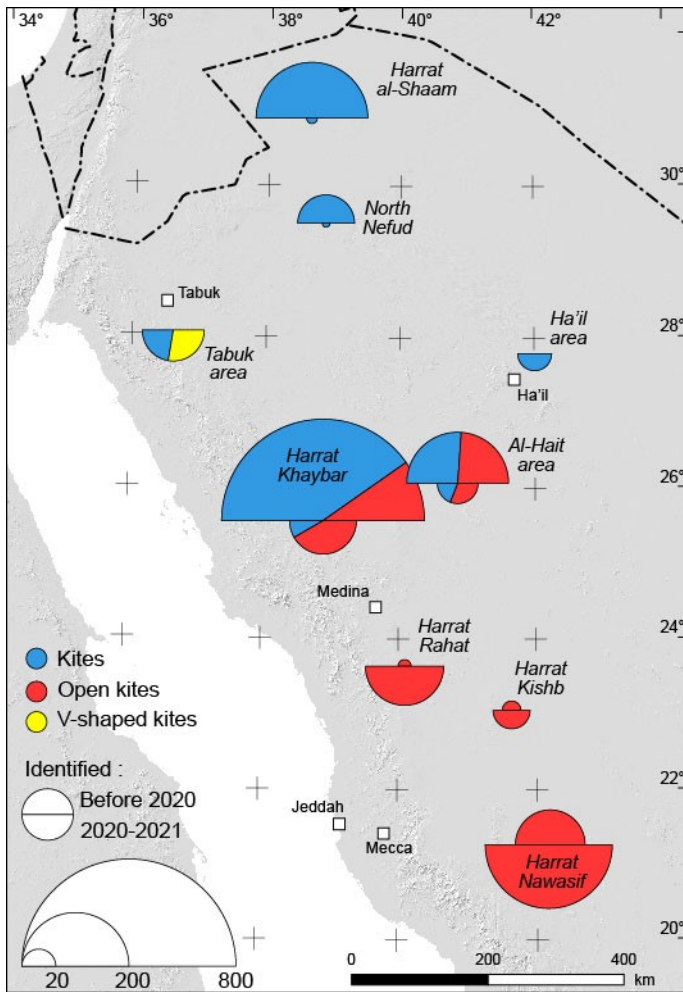


Figure 2: Kites and kite-like structures discovered before and after 2020 in Saudi Arabia

In the Tabuk area, just south of the city, 37 constructions with all the characteristics of the Negev V-shaped kites (Holzer et al. 2010; Nadel et al. 2013) extend over an area of about 300 km in length from northwest to southeast. They consist of two driving lines converging directly into a single pit-trap (Fig. 3). These driving lines are between 100 m and 400 m long. The topographies and orientations of these V-shaped kites are varied, but the pit-trap is frequently hidden by a slope break.

Meanwhile, the numbers of kites *stricto sensu* has remained almost stable in northern Saudi Arabia, in Harrat-al-Shaam south extension and in the northern confines of the Nefud. Similarly, little change is observed in Harrat Khaybar and the Al-Hait regions. In contrast, other kites have recently been identified at a latitude between 27 and 28.5 degrees north, i.e., in an area between the northern Nefud and the Khaybar region, which was previously thought to be a hiatus. They are divided into two concentrations. The first is located to the west, south of the town of Tabuk, in the area with V-shaped kites, but over a smaller area of about 40 km by 40 km. They are clearly different from the latter. They are small in size, but consist of driving lines, an enclosure and pit-traps and are therefore kites *stricto sensu*. The second concentration, to the east, is

divided into four sub-groups to the north and east of the town of Ha'il, over a 120-kilometre-long area. The numbers of these structures are quite low in both regions (30 in Tabuk region, 20 in Ha'il region) but these desert kites are of particular interest as their morphology resembles that of other known kites further north, notably in the Jordanian and Syrian parts of Harrat al-Shaam.

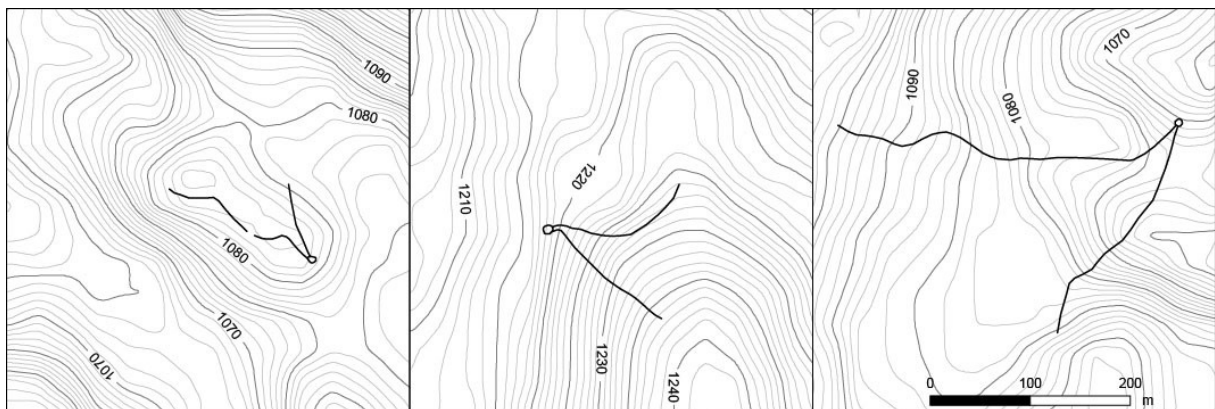


Figure 3: Examples of V-shaped kites in the region south of Tabuk

4. Open kites

4.1. Geographical distribution

The geographical range of the 835 recorded Arabian open kites extends for about 700 km from north to south, from Harrat Khaybar to Harrat Nawasif (Fig. 4: A). Their location is limited to basaltic areas, mostly on the periphery of lava fields. They are particularly abundant in Harrat Khaybar (n=320) and around Harrat Nawasif (n=368), and rather more scattered elsewhere. They are generally found grouped together, a few hundred metres apart, sometimes with gaps of several dozens of kilometres between the groups (Fig. 5 and supplementary data, 2). In Harrat Khaybar, open kites are located in the same areas as desert kites, and the latter are more numerous (n=693). The geographical extension of kites does not go beyond Harrat Khaybar to the south, whereas open kites extend over nearly 500 kilometres further south (Fig. 4). Harrat Khaybar is thus a unique region where kites *stricto sensu* (and especially very characteristic Khaybar-type kites) spatially coexist with open kites.

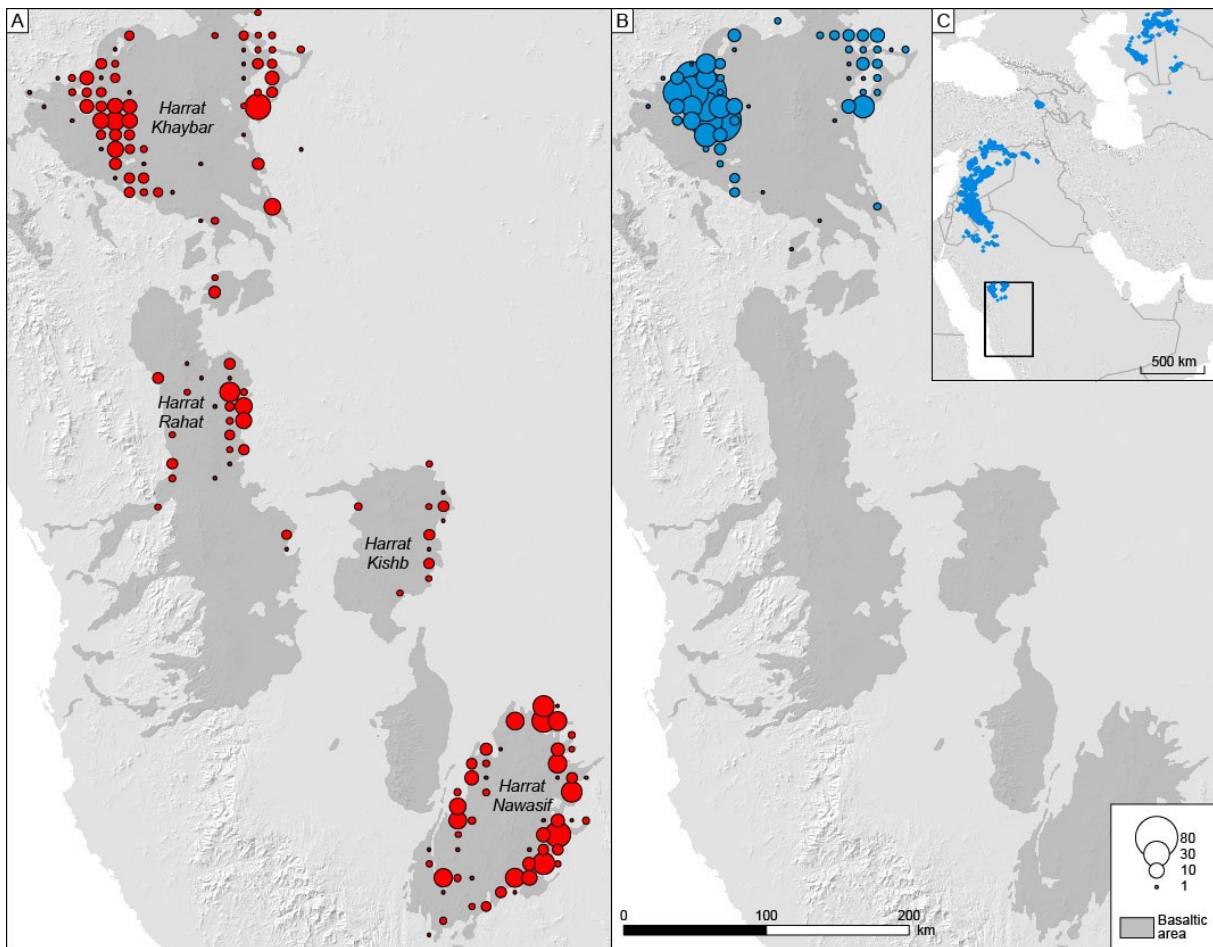


Figure 4: Distribution area of open kites (A) and kites (B) in Western Arabia. Circles are proportional to the number of constructions counted in 10-km-square grids. Location of the study area in the geographical range of kites (C) (supplementary data, 3).

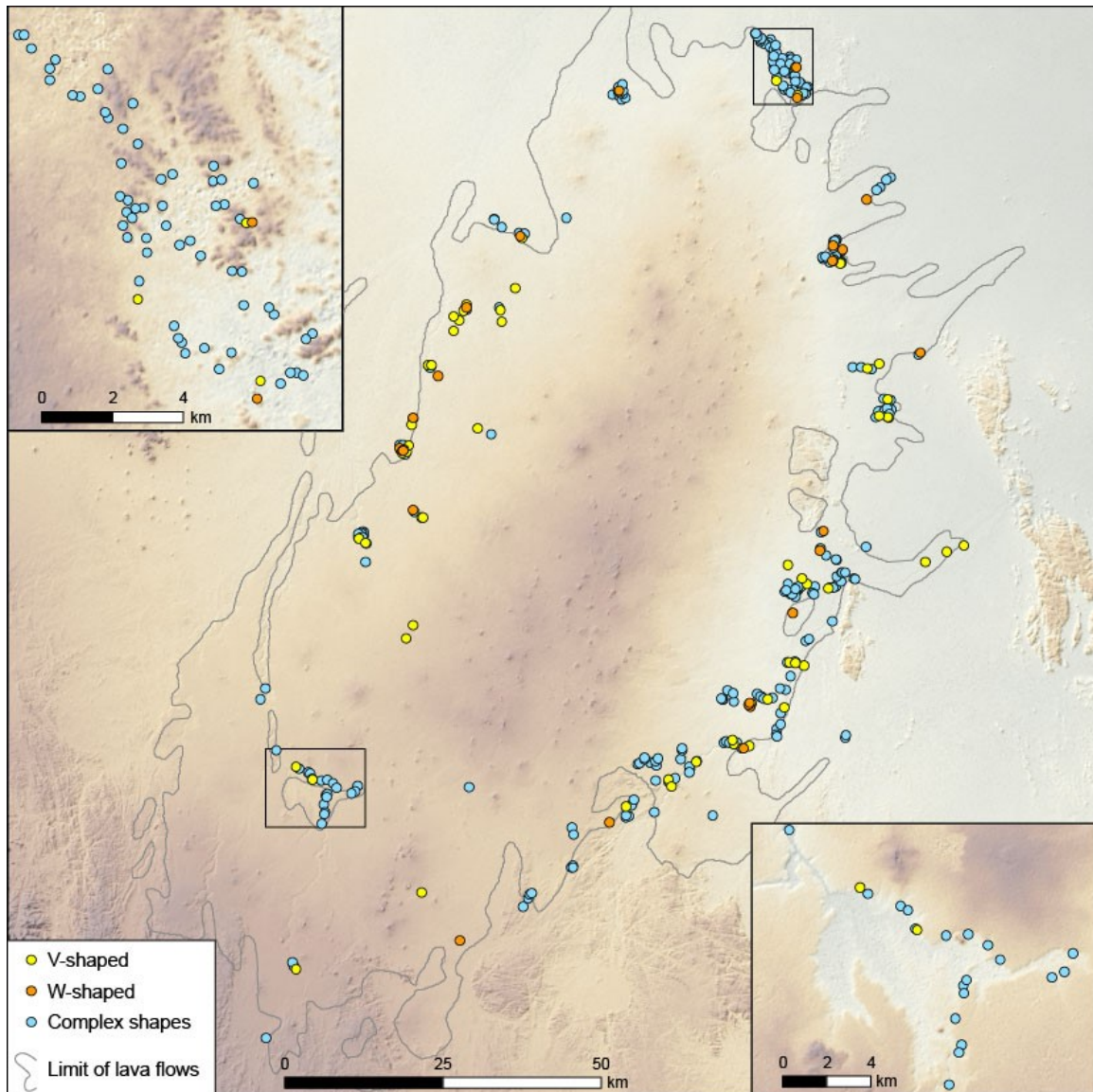


Figure 5: Open kites types in Harrat Nawasif.

4.2. Morphology

Open kites do not comprise all three attributes of desert kites (driving lines, enclosure, pit-traps): they do not delimit a closed area and therefore do not encompass an enclosure. They consist of long walls or stone alignments that resemble kite driving lines, but which are usually shorter and do not always converge. Open kites are made up of sections of walls of varying length that connect variable numbers of pit-traps (Fig. 6). A distinction can be made between different types of open kites:

- those with only one pit-trap (or with a single group of contiguous pit-traps) at the end of two converging walls forming a point (Fig. 6: A; n=203 of this type). They are comparable to the Negev “V-shaped” kites (Holzer et al. 2010; Nadel et al. 2013), with however more variability in driving line length and the angle formed by them. The distinction with the latter is also based on their spatial distribution, which suggests making them a subtype of open kites,
- those made up of the juxtaposition of several of these pointed shapes (Fig. 6: B; n=92 of this type), outlining a W shape,
- those that combine walls and pit-traps in a complex manner without any discernible recurring shape (Fig. 6: C, D, E, F, G and H). The latter are by far the most frequent (n=540).

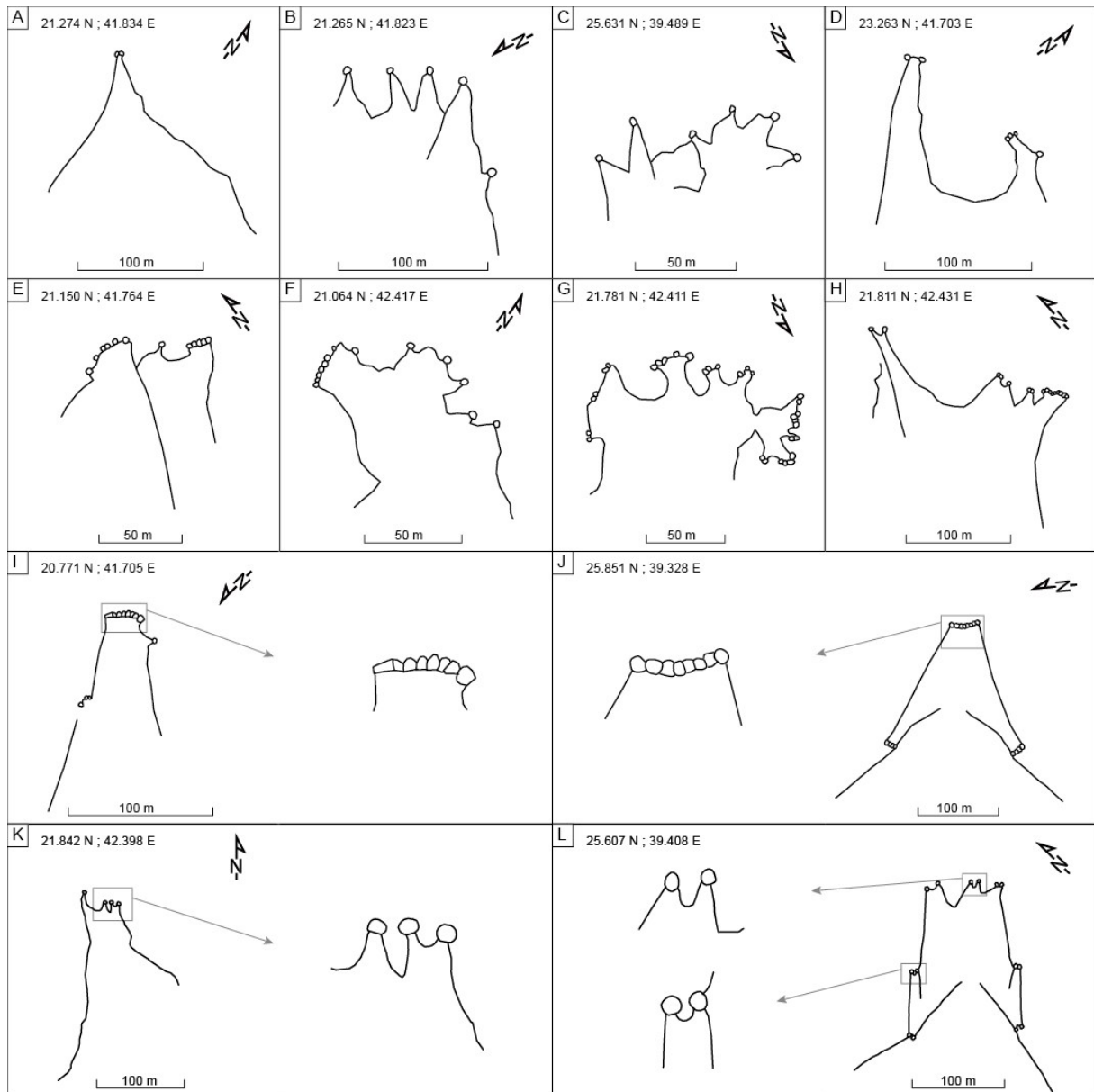


Figure 6: Morphological variability of Arabian open kites (A to H); Comparison of contiguous pit-traps (I and J) and pit-traps with micro-points (K and L) between Arabian open kites and desert kites stricto sensu.

The specificities and size of open kites can be assessed by the number of pit-traps and by the total length of the walls forming them (Fig. 7). The number of pit-traps varies greatly and can be very high in complex and unstandardized open kites: about 100 of these structures comprise at least 15 pit-traps and this number can reach 91. The total cumulative length of walls exceeds 500 m for the largest but there are also smaller structures. The length of simple V- or W-shaped walls is sometimes less than 100 metres. We observed that simple V-shaped kites often have more than one pit-trap, showing that contiguous pit-traps are very frequent. No distinct geographical distribution of these sub-types could be detected based on size or type (Fig. 5 and supplementary data, 2)

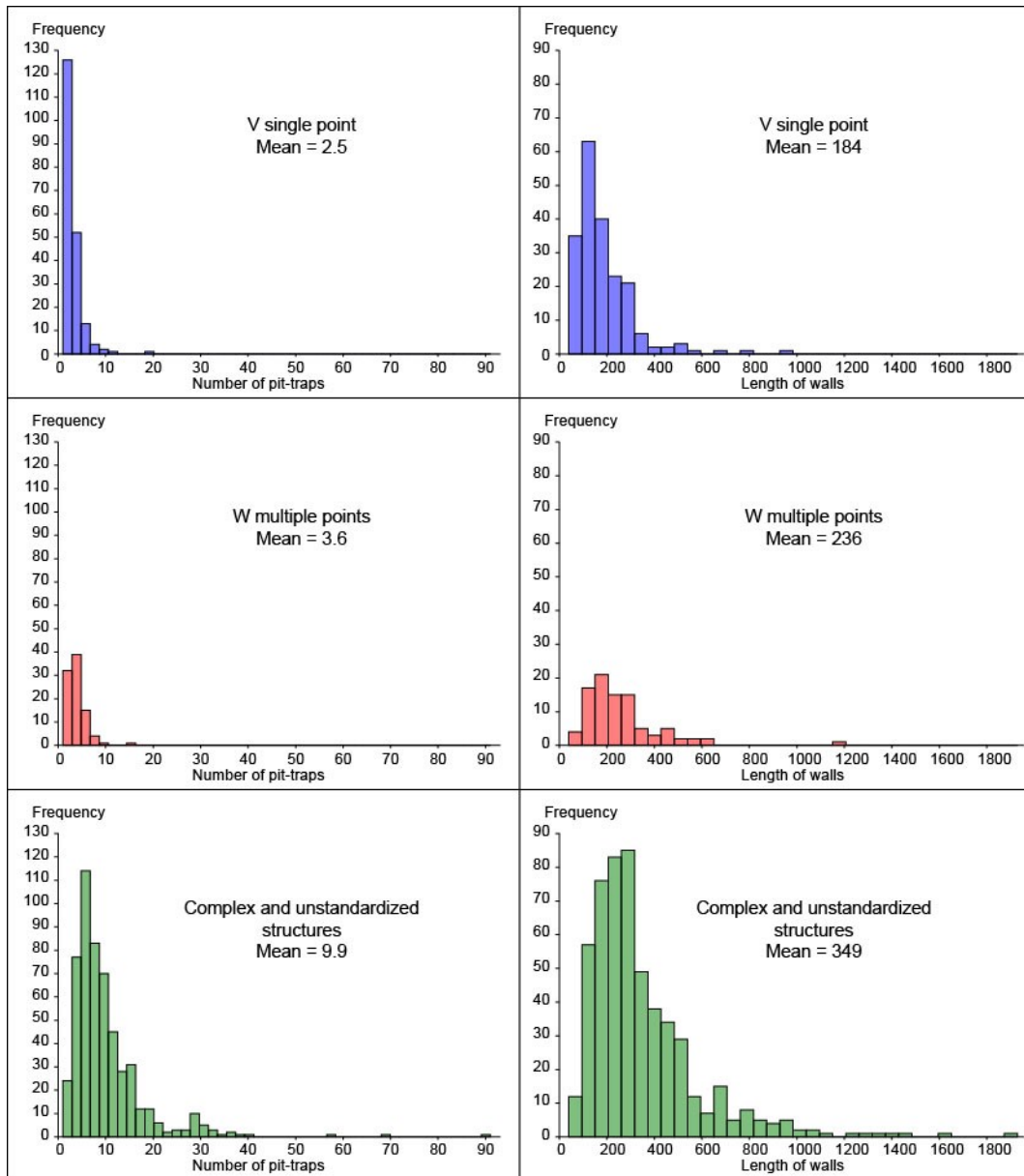
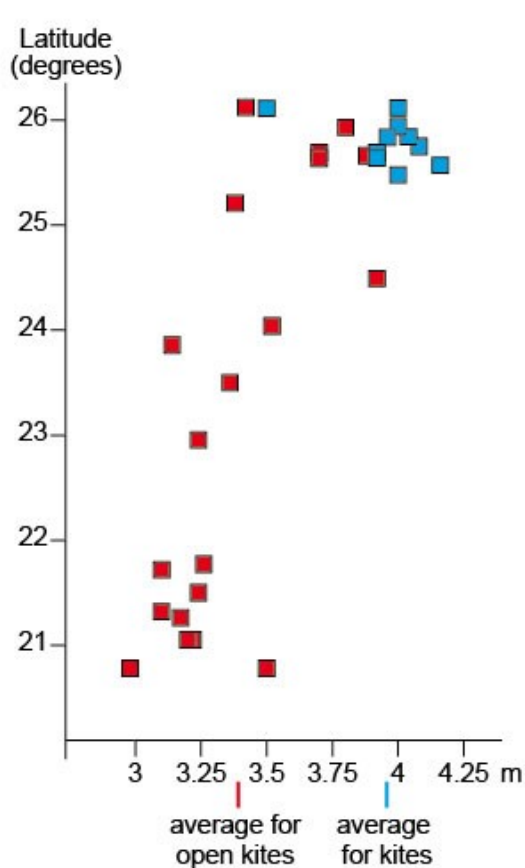


Figure 7: Histograms of the number of pit-traps and the total cumulative length of open kite walls, according to shape.

Pit-traps are a feature of kites and open kites. In the case of desert kites *stricto sensu*, our excavations in many parts of their global distribution area indicate that pit-traps are pits with a depth of several metres. The whole inner side of pits is stone-faced with rows of stones. They form the trapping element of the kite into which hunted animals fell (Crassard et al, 2021). Satellite images show characteristics shared by the pit-traps of the Harrat Khaybar kites and open kites. Outside Harrat Khaybar, the presence of desert kites with contiguous pit-traps is uncommon (15%). In Harrat Khaybar, this frequency increases to 72%. In particular, series of contiguous pit-traps (from three to more than a dozen, Fig. 6: J) are frequently observed. Open kites often share this characteristic too (Fig. 6: E, F, H and I): 41% of them comprise at least one series of more than three contiguous pit-traps. When they are not contiguous, it is also common in kites and open kites, for pit-traps to be connected, over a short distance, by a curvilinear wall delimiting a small indentation towards the outside, a micro-point (Fig. 6: K and L). In Harrat Khaybar, kite pit-traps are circular (which is not necessarily the case elsewhere), which is also the case for open kites. They are quite similar in size: 3.95 m in diameter on average for kites, 3.39 m for open kites. They are therefore slightly larger in kites, with more standardised dimensions (the standard deviation is 0.28 m for kites, 0.54 m for open



kites). We also observe that the size of open kite pit-traps tends to increase from south to north and is more similar to that of kites in the north (Fig. 8). Still unknown chrono-cultural factors may explain this north-south size gradient, with the gradual evolution of trap architecture as the hunting technique developed throughout the region.

Figure 8: Diameter of open kite pit-traps (red) and desert kite pit-traps (blue) according to latitude (supplementary data, 3)

4.3. Topographical implantation

The Harrat Khaybar kites clearly show that entrances predominantly open towards the west (animals coming from the west and going towards the east, Fig. 9: A). Open kites do not follow the same pattern as no particular orientation is discernible (Fig. 9: A). Our results contradict Groucutt and Carleton (2021), but this can be explained by the fact that we used continuous azimuth for this analysis and not simply the four single cardinal directions (N, E, S, W). When the orientation of each open kite

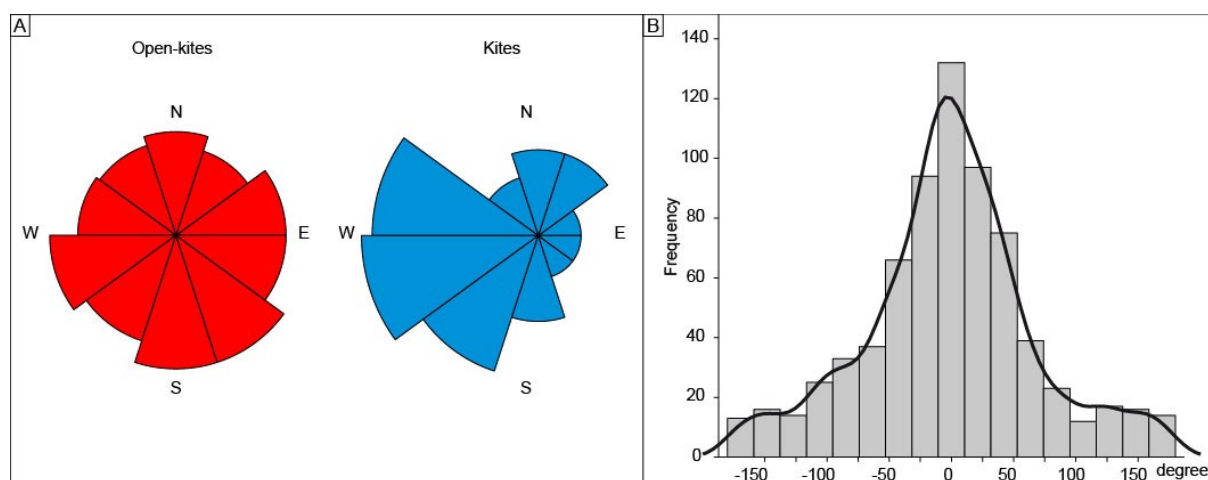


Figure 9: Orientation of kites and open kites (A); Histogram of the angular differences between the orientation of open kites and slope orientation (B), see supplementary data, 4

is compared with the orientation of the slope on which it is built, there is a clear tendency for open kites to conform to the local slope since 68% of them show an angular deviation from the slope of less than 60° (57% have an angular deviation of less than 45°). This trend can be clearly observed (Fig. 9: B) even if the method used for this comparison can be improved as the orientation of the slope was only determined by a single pixel (located approximately at the centre of the open kite) of the SRTM DTM with 30-metre resolution (Supplementary data, 4). This measurement from the open kite centre point is then less representative of the whole open kite surface area, while the measurement of an average slope surface area would yield more accurate results. In addition to these quantitative data, we also observed the relief on which open kites are built. Direct observations confirm that open kite orientations are adjusted to local slopes, as open kites are mainly positioned on a slope with a steeper gradient than the areas below, with the pit-traps located in the upper part of the structure. This can be the slope of a hillock overlooking a sub-horizontal area such as a mudflat (Fig. 10: A) or slopes delimiting the embankment of a wadi. In the latter case, we frequently observe that open kites are built on the opposite banks of the same wadi, with opposite orientations (Fig. 10: B). The fact that open kite pit-traps are predominantly located at the top of the structure may well be related to the fact that gazelles tend to flee upwards when frightened (Blank, 2020). In any case, open kites show opportunistic adaptation by builders to the natural topography, with for example the construction of pit-traps behind a convex break of slope.

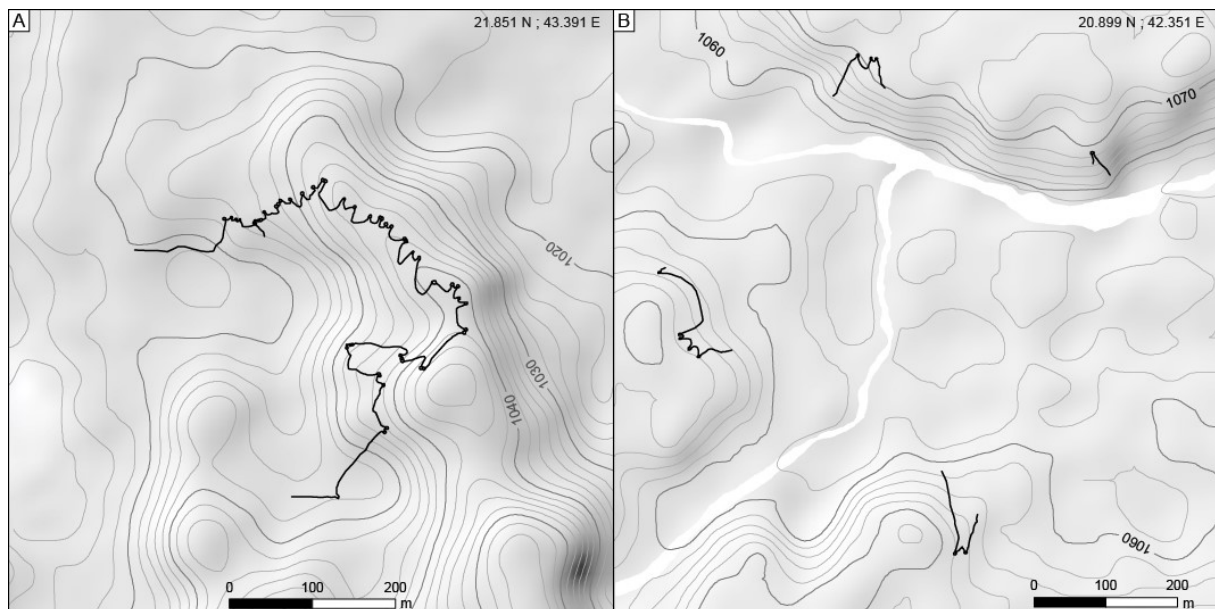


Figure 10: Two examples of the topographical layout of open kites.

4.4. Study case in Harrat Khaybar: fieldwork in the Khaybar oasis area

The modern oasis of Khaybar, in western Saudi Arabia, is located in the central western side of Harrat Khaybar (Fig. 11). The region comprises a dense concentration of desert kites *stricto sensu*, characterised by a very specific type. Enclosures are often triangular, sometimes with a succession of several generally very regular and symmetrical giant triangles, and the driving lines leading to the enclosure are very straight and can be very long, up to more than several hundreds of metres (Fig. 12). In October 2020, a new archaeological research project was set up in the oasis area of Khaybar, with a comprehensive survey of a 56 sq. km area. The *Khaybar Longue Durée Archaeological Project* (KLDAP) documented a number of open kites in this area, the characteristics of some of which are presented here.

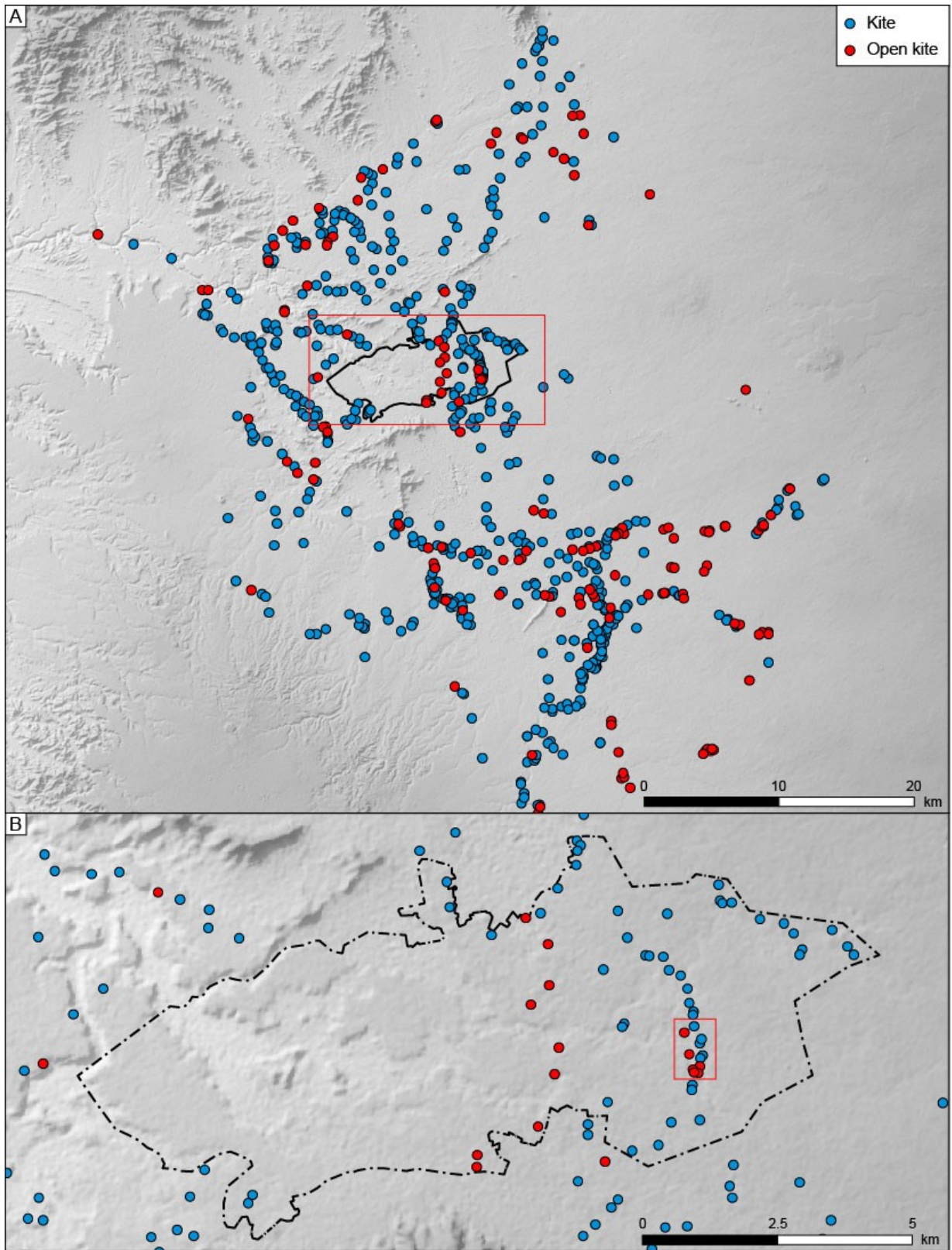


Figure 11: Overall map of the Khaybar Longue Durée Archaeological Project research area around the Khaybar oasis, and location of identified desert kites strictly speaking and open kites. The window in red (B) locates the study zone, enlarged in Fig. 16.

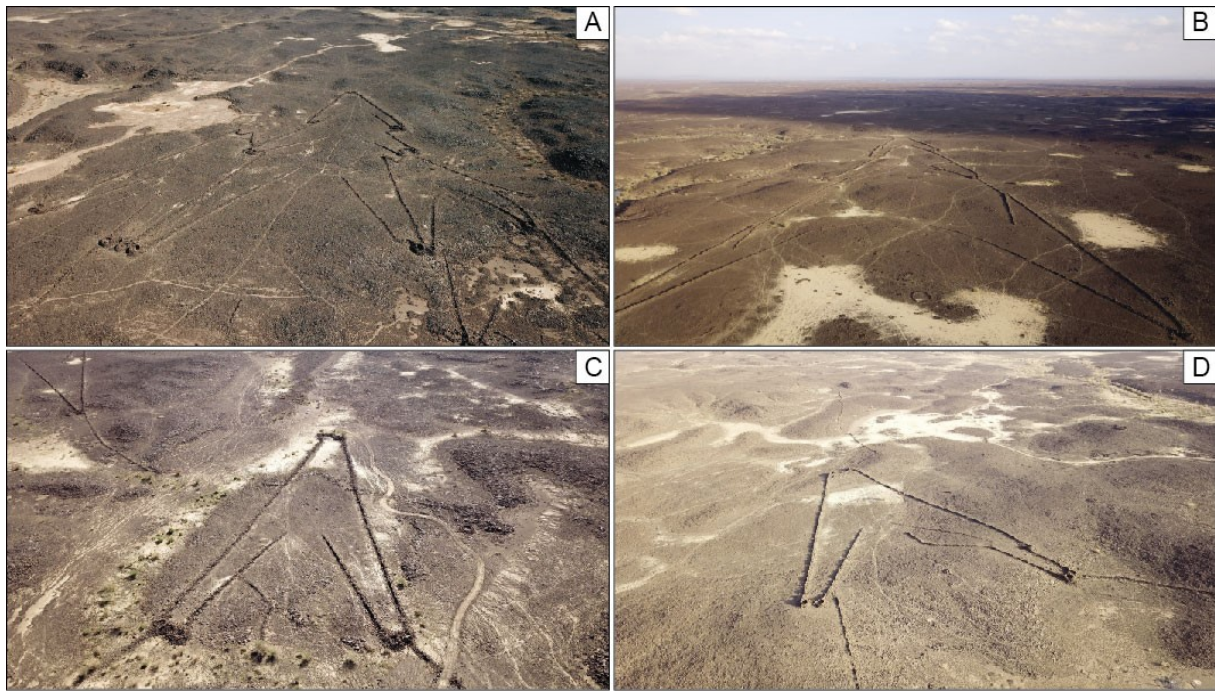


Figure 12: Oblique drone pictures of typical Khaybar desert kites with their generally triangular, regular and symmetrical shapes. Naming of the kites according to the Globalkites Project numbering system are: A: AB41; B: AB8; C: AB7; D: AB19. Photo credits: KLDAP.

Sixteen open kites have been identified so far in the research area (Table 1). Most of them are isolated structures in the landscape, and are rarely associated with other open kites. Indeed, they certainly do not operate in chains, as desert kites *stricto sensu* sometimes can. However, open kites can be positioned alongside a wadi, but at a considerable distance from it, and the two are never connected. The overall size of open kites in Khaybar is always smaller than desert kites.

Structure No Globalkites	Structure No KLDAP	Observations	Type	Pit-trap number	Pit-trap mean diameter (m)	Cumulative wall length (m)
O-AB822	KH05000	Very eroded, cut by a more recent kite	V-shape	1	4.3	226
O-AB828	KH05001 KH05002	Triangular shape with one disconnected pit-trap	Complex shape	4	3.3	161
O-AB821	KH05003	Close to wadi cliff	W-shape	2	4.3	114
O-AB819	KH05004	Close to wadi cliff	Complex shape	10	3.9	313
O-AB820	KH05007	Close to wadi cliff	V-shape	1	5	106
O-AB824	KH05008 KH05009	Above natural gully with a slight slope, heavily collapsed, driving lines hard to see on the ground, good potential for excavation	Complex shape	2	3.5	130
O-AB823	KH05010	Open kite using natural round shape small depression	V-shape	1	3.9	141
O-AB46	KH05011 KH05012 KH05013 KH05014 KH05015 KH05016	Unclear pattern, Difficult to read in the field and heavily collapsed.	Complex shape	16	4.9	283

	KH05017					
O-AB829	KH05019	Curved entrance, general aspect heavily collapsed	Complex-shape	11	3.4	280
O-AB830	KH05020	Heavily destroyed	V-shape	1	3.3	47
O-AB831	KH05021	Single V-shape, very eroded	V-shape	1	6.1	263
O-AB832	KH05022	Eroded, cut by a more recent cairn on the left driving line	V-shape	1	2.8	114
O-AB172	KH05023 KH05024	Two parts, probably working together. South part heavily weathered for the driving lines and heavily collapsed for the cells	W-shape	3	3.6	215
O-AB833	KH05025	Very eroded, the cell is almost not visible, could be interesting to excavate	V-shape	1	3	78
O-AB834	KH05026	Star shape, short driving lines.	Complex-shape	4	4.2	256
O-AB835	KH05027	Triangular shape, cells heavily collapsed. Maybe superimposed with/by a pendant to the SW	Complex-shape	2	5.3	226

Table 1: List and preliminary description of open kites observed in the field in Khaybar; the description in the field sometimes requires the subdivision of constructions, which explains why the KLDAP digitization can include several numbers for the same open kite.

We can differentiate two main groups of open kites in the Khaybar oasis: simple forms, such as V- or W-shapes, and more complex forms. There are at least nine examples of simple forms with a simple plan consisting of two driving lines leading to a single pit-trap (Fig. 13: A), rarely to two coalescent pit-traps. When two of these V-shaped open kites are connected and conjoined at the extremity of one of their driving lines, they form a W-shaped open kite (Fig. 13: B). The topographical contexts of these simple forms are varied. Sometimes, the pit-trap is located on top of a plateau, with driving lines leading to it from a wadi bed. Driving lines can also be located on a flatter plateau surface sloping down slightly to a single pit-trap located at the edge of the same plateau. The pattern can also combine several of these features, with driving lines running upwards from a valley, to a hill or a narrow plateau area, and leading to a pit-trap located on the opposite slope.

The other examples of open kites in Khaybar are complex forms with very diversified sizes and layouts, as observed on satellite pictures elsewhere in western Arabia (Fig. 14). The Khaybar examples show rather small enclosure-like spaces, and short driving lines, when they exist. The latter are short and never straight, generally following natural topographical features such as cliff edges, and natural landforms.

The pit-traps in Khaybar open kites are generally located on a slope break at the edge of a natural escarpment. This configuration keeps the pit out of the animals' sight when they are following the driving lines, which generally run uphill. Open kite pit-traps show diversified sizes, ranging from a rather similar size to desert kite pit-traps of around 4 m in diameter (although always much more collapsed in open kites), to smaller modules less than 2 m in diameter (Fig. 15). Construction techniques are similar in both cases, with a rather organized piling of uncut basalt blocks available in the direct vicinity of structures. The remaining number of stone courses above present-day ground level is between one to five rows for open kites, while desert kite pit-traps are particularly well preserved in Khaybar with preserved elevations of sometimes up to 2 m above present-day ground levels.

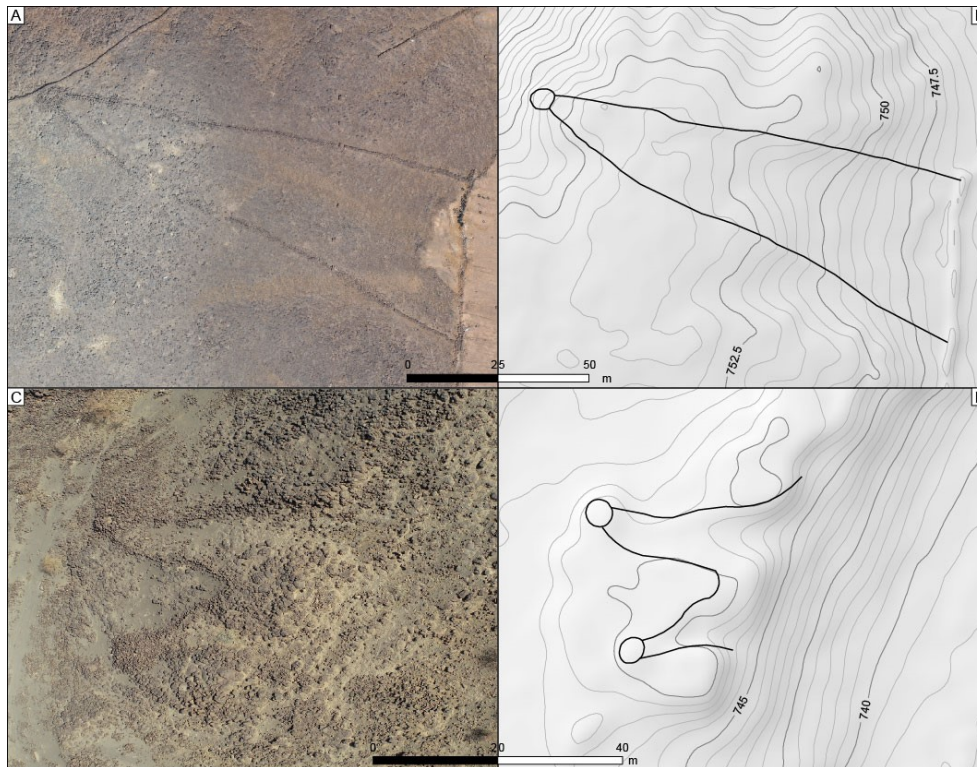


Figure 13: Aerial pictures of Khaybar simple open kites. A: V-shaped open kites (O-AB831 is approximately 130 m in length), driving line extremities were destroyed by bulldozer activities; B: W-shaped open kites (O-AB821 is approximately 22 m in length and 25 m in width). Photo credits: KLDAP.

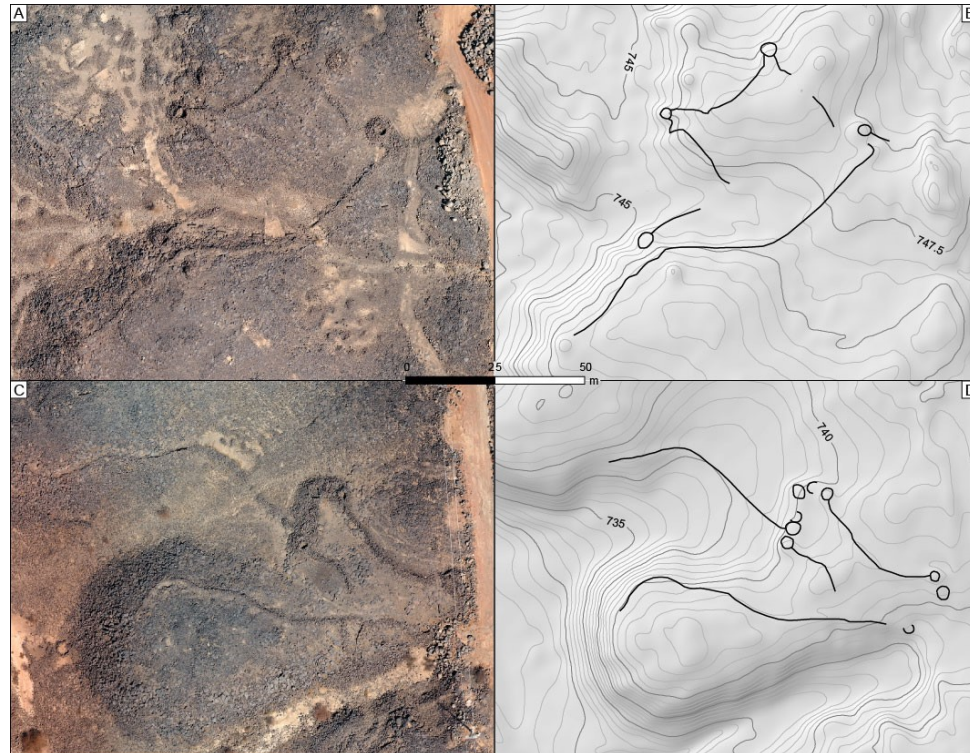


Figure 14: Aerial pictures of Khaybar complex open kites. A: vertical view of O-AB834 open kite with a difficult to follow layout, it may reflect consecutive uses of different structures; B: map of O-AB834; C: Aerial pictures of O-AB829 open kite, the funnel entrance and driving lines follow the edge of the thalweg escarpment, and the main trapping zone with at least six pit-traps is out of the axis alignment and follows the left driving line; D: map of O-AB829. Photo credits: KLDAP.



Figure 15: Pit-traps from Khaybar. A: set of six agglomerated and conjoined pit-traps at O-AB829 open kite, with different states of erosion and collapse; B: three pit-traps from AB40 desert kite strictly speaking, the preserved elevation of pit-trap walls is about 1.5 m above the present-day ground level; C: single pit-trap from O-AB831 V-shaped open kite, the wall running across the picture is modern; D: single pit-trap from O-AB820, heavily eroded and collapsed; E-F: pit-traps from O-AB834 open kite with remains of clear inner wall delimitations. Photo credits: KLDAP.

In terms of understanding how these open kites functioned, and the possibility that they may have functioned simultaneously, it is interesting to note that in the Khaybar study zone (Fig. 16), there are two to four V- and W-shaped open kites along the western bank of the wadi, and a more complex open kite along the eastern bank. The rest of the landscape along this same bank is covered by five gigantic Khaybar-type desert kites. Two additional open kites, that may have functioned together, and that bear witness to two chronological phases of use, complete the inventory. The whole landscape is quite difficult to interpret as no dating elements are yet available. However, the general pattern of open kites on the opposite banks of the same wadi, with opposite orientations, has also been regularly observed in other regions south of Khaybar (e.g.: Fig. 10: B).

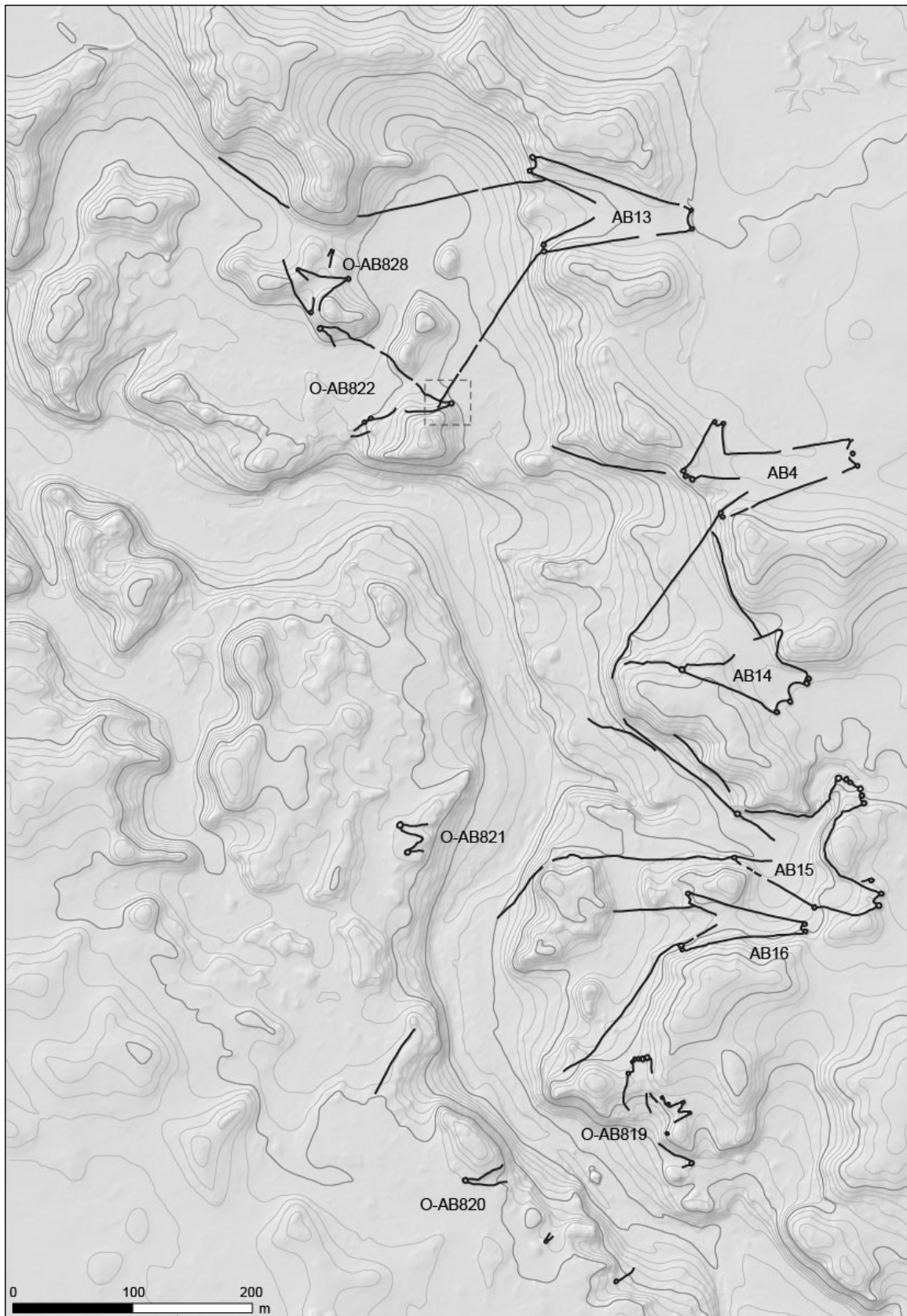


Figure 16: Eastern case study zone; the rectangle illustrates where kite AB13 covers the open kite O-AB822.

4.5. Relative chronology of open kites and desert kites: erosion and superimposition

On satellite imagery, open kites are more difficult to detect than desert kites, as they were regularly adapted to the natural topography. When driving lines, for example, strictly follow the edge of a cliff, it is difficult to recognize an anthropogenic construction, unless a detailed observation can be made on the ground. Also, open kites are often made of smaller blocks, and they are systematically more collapsed and eroded than nearby desert kites. This is clearly observable on the ground too, and the surface state of the rocks used in the construction of open kites seems to have endured more weathering. At first sight, these observations may have chronological implications for the interpretation of the two types of structures. It seems obvious that open kites might be an older form of desert kites, possibly a more primitive or simpler construction. Future excavations and dating of kite-like and kite structures will confirm whether or not they were synchronous.

One example of superimposition is directly observable in the field in the Khaybar oasis area, confirmed by the high-resolution (2 pixels per cm) drone pictures made on site. In the window of study (Fig. 16), a series of desert kites are clearly observable. One of them (AB13) shows a southern driving line overlapping an open kite driving line (O-AB822). This relative chronological evidence is clear on the ground (Fig. 17), as well as on the aerial picture (Fig. 18).

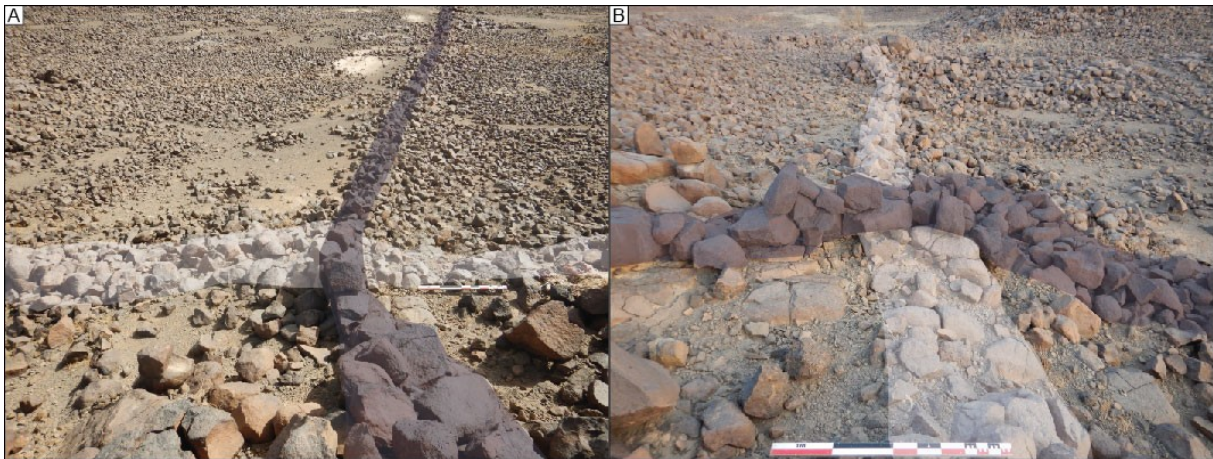


Figure 17: Relative chronology: the driving line from the AB13 kite (in dark colour) overlaps the driving line of the O-AB822 V-shaped open kite (in light colour). A: view from the southwest; B: view from the southeast.

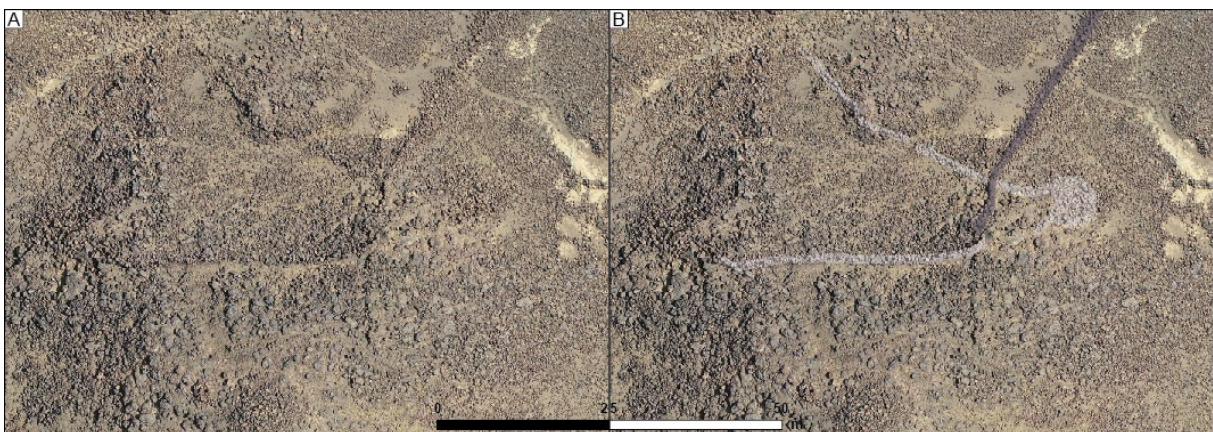


Figure 18: Orthophotograph of the superimposition of AB13 kite on O-AB822 open kite. A: raw image; B: interpreted image with AB13 kite (in dark colour) overlapping the driving line of the O-AB822 V-shaped open kite (in light colour). Photo credits: KLDAP.

This example of the relative chronology of both types of structure tends to reinforce the hypothesis that open kites are older forms of hunting-traps than desert kites, the latter being much larger, more regular in shape, and comprising bigger pit-traps. The different erosive states, and preservation states, of open kites and desert kites seems to be a reliable chronological indicator, that will need to be confirmed by future excavations of both kite-like structures and kites with absolute dating elements. Other indications of relative chronology, such as superimpositions, or reuse of kite stones in later, and better dated, constructions, will be given particular attention in forthcoming fieldwork seasons in Khaybar.

5. Modifications of the distribution area of kites in Saudi Arabia

5.1. Morphological characterisation

Among the recent discoveries, apart from the numerous open kites, the number of kites *stricto sensu* in the Tabuk region and the Ha'il region is relatively low (respectively 30 and 20 kites). They nonetheless present interesting morphological characteristics as they are comparable to kites located further north.

The kites in the Tabuk area consist of two or three driving lines of 70 to 440 metres in length. They end in a very small enclosure (between 0.1 and 0.5 ha), usually with a single pit-trap, many of which are point-shaped. Kites in the Ha'il region have two to four driving lines. Their length is generally limited to a few hundred metres, but it is not easy to observe them on the images and some of them may have been much longer (there is one observed case of a driving line of almost 3 km). Enclosure size is moderate, but nevertheless larger than kites in the Tabuk area. Their shape is characterised by a star shape made up of points ending in five to seven pit-traps.

In order to establish a comparison between these two groups of kites and other kites from the southern part of the distribution range, we first calculated the central values of morphological variables observed or measured on satellite images for these two groups, as well as for four other groups made up of morphologically homogeneous kites distributed to the north and south of these two groups (Table 2, supplementary data, 1). Group 1 includes kites found west of Harrat al-Shamm and as far as the Damascus region. Group 2 corresponds to kites found mainly east of Harrat al-Shaam. Group 3 consists of relatively scattered kites north of the Nefud and west of Harrat al-Shaam. Groups 4 and 5 correspond to the stereotypical kites of Harrat Khaybar, the former consisting of a single triangular base while the latter combine several.

	A	B	C	D	E	F	G	H	I	J
Tabuk	2.27	190	0.19	0	11.5	1.2	18	14	68	0
Ha'il	3.1	248	0.43	83	12	5.7	0	0	97	3
Group 1	2.8	478	0.33	1.5	9	3.9	22.2	19.6	31.2	27
Group 2	3.7	1562	1.19	77.7	19	10.7	8	5	37	50
Group 3	2.6	426	0.49	100	10	5.8	8	8	70	14
Group 4	1.9	222	0.43	100	21	6.3	14	8	66	11
Group 5	2.2	312	1.02	100	24	14	39	1	52	7

Table 2: Central values (mean, median or frequency) of morphological variables used to compare kites in the regions of Ha'il et Tabuk with kites in clusters to the south of the general distribution zone of kites: A- Number of driving lines (mean); B- Mean length of driving lines (median); C- Surface of enclosures (median); D- Frequency of proximal indentations; E- Width of entrance (median); F- Number of pit-traps (mean); G- % of straight pit-traps; H- % of angle pit-traps; I- % of pointed pit-traps; J- % of incipient pointed pit-traps

The values of the small kites in the Tabuk area are close to those of group 1. They have no funnel entrance, no proximal indentations, reduced entry width and few pit-traps. In fact, size values (length of driving lines, enclosure area, number of pit traps) are always smaller than those of group 1, which has the lowest values of all the comparison groups. In summary, the kites of group 1 and those of the

Tabuk region have very similar morphological characteristics, the former can be described as small, the latter as very small.

Kites in the Ha'il region are morphologically close to those of group 3. Like them, they do not have funnel-shaped entrances, almost systematically have proximal indentations, the same number of pit-traps (with a large majority of pointed pit-traps), and equivalent enclosure size. Only the length of driving lines is shorter, but we know that this may have been underestimated for the Ha'il kites.

This comparison can be represented graphically using the central values of the variables proposed in figure 19. Enclosure size is represented by a square with an opening at the top proportional to the width of the kite entrance. This opening can be accompanied by graphic signs corresponding to specific features (funnel entrance and proximal indentation) when these are significantly present. The size and number of driving lines are represented by a red rectangle at the top and the number of cells of each type by a circle in the centre. Similarities between the profiles of group 1 and the kites from the Tabuk area are clearly visible: the latter are merely smaller and more frequently feature pointed pit-traps. The similarity is even more obvious for group 3 kites and those from the Ha'il area. Conversely, the kites from these two new regions do not show any similarities with kites from the eastern Harrat al-Shaam (group 2) or the Khaybar region (groups 4 and 5).

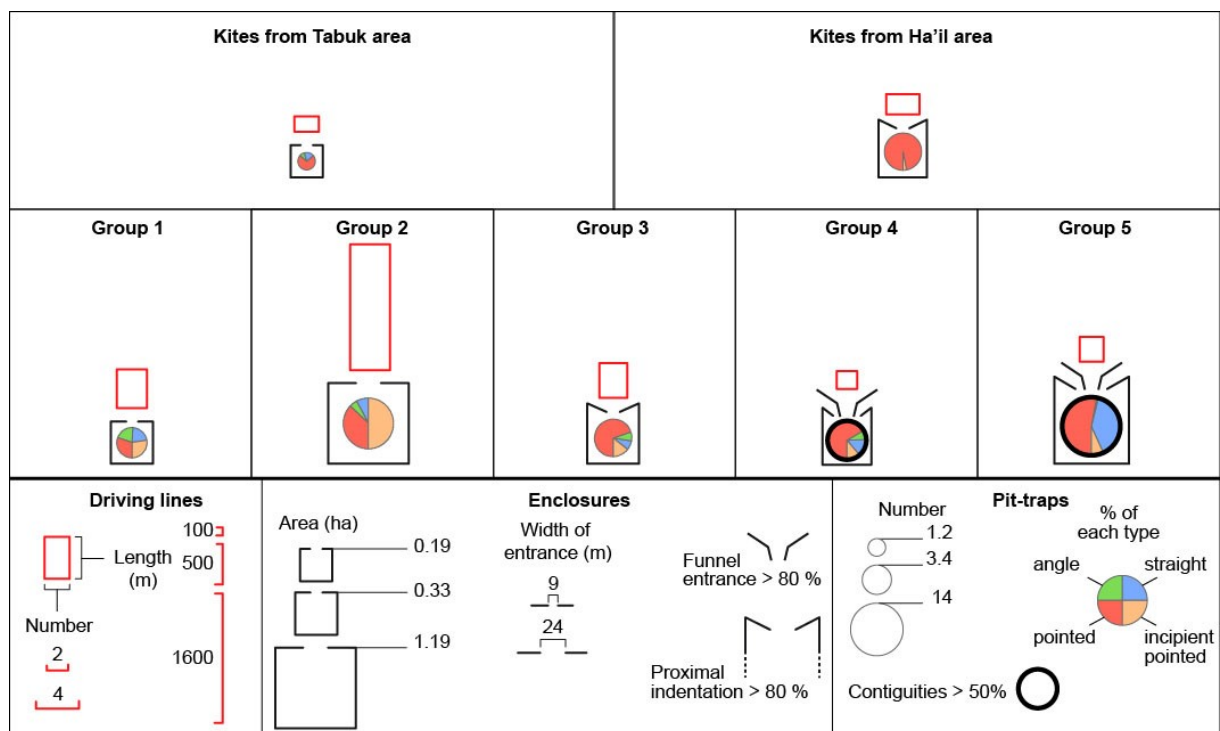


Figure 19: Graphic representation of the central values of morphological variables of the kite groups; for each group, the red rectangle represents driving lines, the black figure enclosure size and the characteristics of the entrances and the central circle the number and proportions of each type of pit-traps (see legend below).

In a second stage, the comparison of enclosure shapes confirms these similarities (Fig. 20). The comparison of enclosure shapes entails the comparison of specific cases of kites (with the question of representativeness). However, statistical variables only indirectly take into account enclosure shape. The comparison of shapes, which is qualitative and less abstract than the comparison of statistical variables, therefore provides additional information. In the case of the Tabuk region and Group 1 kites, the circular or geometrically simple shape, the connection to the driving lines and the distribution of a small number of pit-traps are obvious common features. In the case of the kites from the Ha'il region and group 3, the layout of pit-traps in a point determines in each case a different star shape, but the eight presented cases clearly belong to the same set. The difference with kites from Harrat al-Shaam (group 2), to which the kites from the Ha'il region could have been hastily associated, is clear. In

Harrat al-Shaam, the star shape is less regular because the points are only really proximally marked, and the pit-traps in the distal position are actually incipient pointed pit-traps. Pit-traps are also more numerous and enclosures are larger. Kites from the Khaybar region (groups 4 and 5) stand out from all the others, with very pronounced proximal indentations, frequent contiguous pit-traps and a very high proportion of straight enclosure walls.

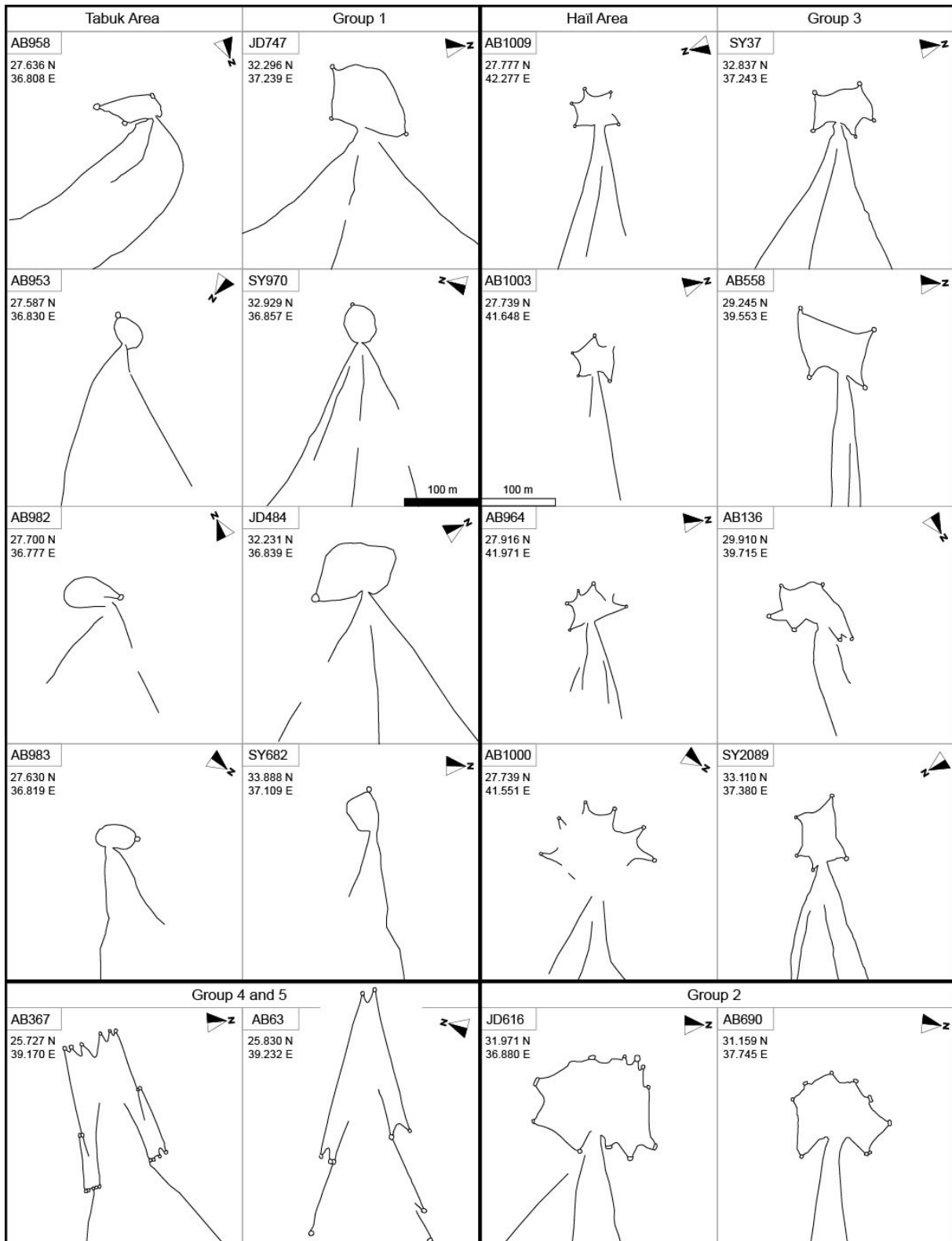


Figure 20: Comparison of enclosure shapes of kites from the regions of Ha'il et Tabuk with kites from clusters to the south of the overall kite distribution area.

The two methods of comparison thus yield identical results. After comparison with the five groups, kites in the Tabuk and Ha'il regions can be associated with two groups of kites, while they are clearly distinguished from the other three groups.

5.2 General cartography of the southern part of the global kite distribution area

Once these morphological relationships have been established, we can map out the different kite families (Fig. 21). These consist of V-shaped kites, Arabian open kites and kites *stricto sensu* from the Tabuk and Ha'il regions discussed in this study. In addition, a sample of other kites north of the 28th parallel and in Harrat Khaybar is represented based on their affiliation to the groups used for comparison (groups 1 to 5). The sample represents about 10% of kites, the others are considered as indeterminate (Fig. 21: grey circles).

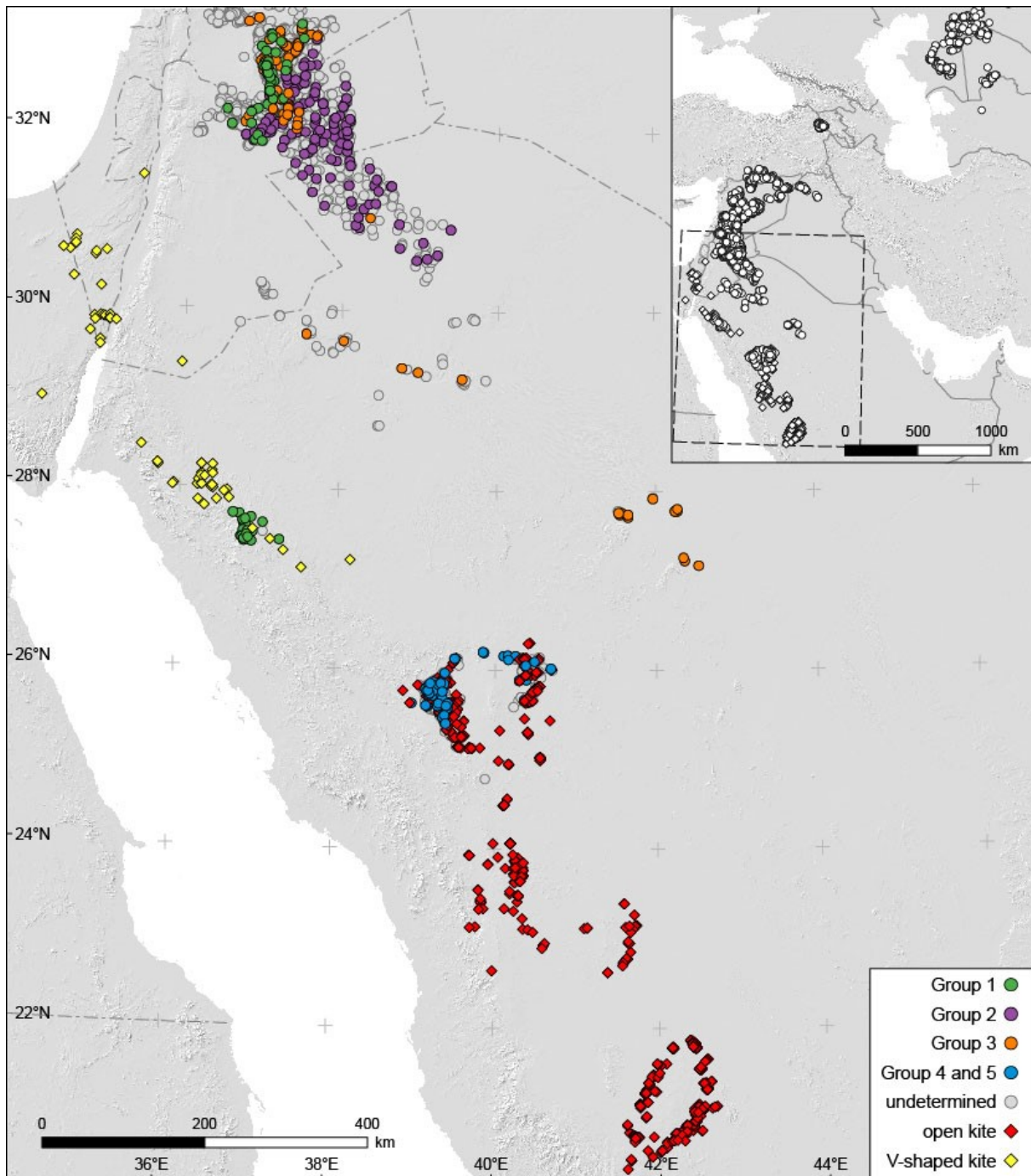


Figure 21: Distribution of families of kites and kite-like structures in the south of the overall distribution area.

We observe a regionalisation of kite families on the basis of morphological similarities, particularly in the southern part of the overall distribution zone. The numerous open kites significantly extend the scope of kite distribution southwards, along the lava fields of western Saudi Arabia. They only share the north of the area where they are present with the large concentration of kites in the Khaybar and Al-Hait region. Further north and up to Harrat al-Shaam, kite distribution is more diffuse but the morphological families are nevertheless regionalised. The well-known V-shaped kites of the Negev extend to the south and occupy an elongated area about 500 km long running north-northwest (Negev) south-southeast (Tabuk region). In this latter area, a small group of small kites can be related to the numerous kites found west of Harrat al-Shaam to Damascus (Group 1). Groups of star-shaped kites (including those in the vicinity of Ha'il), scattered to the east between 27 and 30 degrees latitude, fill the space between the two large concentrations of Harrat al-Shaam and Harrat Khaybar, but are nonetheless morphologically distinct from them. Examples of this group of kites (Group 3) are also found in the western half of Harrat al-Shaam.

6. Discussion

The need for hunting and the reasoning behind it shifted during the Neolithic from a survival practice to a more complex tradition infused with various meanings. The economic and social values of hunting activities can be defined by food and raw material procurement, territorial demarcation of areas with different functions, ritual or social use (offering, sacrifice, feasting), prestige, elite or cultural practice (trophy, royal hunts). The degree of dependency on these values, the selection of specific prey, the knowledge of animal ethology (where they occur and how they can be captured) are the main factors that might have led to the adoption of a specific hunting technique and mobility patterns by Holocene hunters. Furthermore, the outcome of a hunt has two facets: single prey or mass-killing of herds, involving choices in the pre-selection of the outcome, or how to use, process and transport animal products. The economic costs and benefits associated with communal hunting are plausibly related to meat provisioning and ensuring a tradable resource. The costs of a hunting technique encompass effort during hunting, the making and maintenance of tools and structures, efficiency and reliability of capture (productivity) (Smith 1983). The choice of a meat surplus could be a reason behind the choice of communal mega-trap hunting, while communal hunting is also considered as a large-scale socio-cultural event (Kornfeld et al. 2010).

Almost nothing is known about mega-traps users in the kite distribution area. More dating is required as well as the excavation of related sites in order to clearly associate them with a cultural facies. Were hunting excursions organized by specialized hunters from a local authority? Were tribes specialised in hunting activities and trade? Most ethnographic accounts consider hunting systems of driving and trapping animals as low-rank activities in societies (e.g., Solubba, Arabian Bedouin societies; Betts 1989), where closed groups exchange and trade their skills and the products of the hunt. In addition, the development of such large structures would involve some notion of property rights, since a community would not invest its time in building mega-traps if the captured prey could be claimed by outsiders.

Hunting activities vary depending on capture techniques (trapping, pinning down, etc.), community investment (planning, time, number of hunters), the outcome and purpose of the hunt (number of prey, selected animals, a single or several captures) and the tools used to kill (trap, arrow, spear, etc.). How did they operate and how were they organized? In the case of mega-traps, and according to most ethnographical data, the hunt was more active and even cooperative (Legge & Rowley-Conwy 2000) than regular 'passive' traps (e.g., wheel traps, snares, nets), most probably requiring the involvement and presence of hunters throughout the process. But exactly how these prehistoric mega-traps worked remains unknown.

Kites and open kites are two distinct types of traps, but with a number of shared characteristics, which establishes a certain kinship between them. This raises the question of the similarities and differences between these two types of traps from the point of view of how the hunt operated. It is difficult to grasp how hunting was carried out with kites and open kites. The active participation of hunters seems to be vital for these traps to work, but data are lacking to establish hunting methods (number, location,

and behaviour of hunters/trappers, possible use of dogs) and temporality (duration of the hunting action, succession of the different trapping phases, seasonal or continuous use). However, it is worth noting that the layout of both types of traps opportunely takes advantage of local topography, making use of slopes and counter-slopes probably to limit the animals' visual range. We know above all that pit-traps mark the final phase of the hunt. In both cases, animals were trapped and were probably killed as they fell into these pits. However, the morphology and orientation of constructions show that the phase(s) prior to trapping as such, during which animals were forced to move towards the pits, were different. The overwhelming westerly orientation of kites *stricto sensu* suggests that kite builders had excellent knowledge of the temporality, rhythms and routes of seasonal migrations and other wild animal movements. The systematic layout of driving lines opening onto a vast space and converging on an enclosure with a narrow entrance shows sophisticated overall architecture, suggesting a standardised hunting technique and a search for efficiency. The morphology of open kites appears less elaborate. Some of them attain considerable sizes, but they are more often smaller constructions than their counterparts. Their layouts are very varied and not systematised in the same way as kites. The orientation of these structures is independent of cardinal orientation and is directed more towards the top of the slopes, suggest a more localized driving area. It is thus possible to affirm that the hunting techniques used with these two types of traps were related, but different and probably more formalised in the case of kites. The on-site observation of the superimposition of a kite driving line on the terminal part of an open kite at Khaybar establishes the anteriority of open kites (Fig. 18 and Fig. 19). This precedence can also be observed in the field at Khaybar by the better state of preservation of kites, both in terms of their preserved elevation and the state of the weathered surface of the basaltic blocks used in their construction. The construction technique of open kites also appears to be more rustic. Thus, it would seem that an early hunting technique was developed using open kites, from Harrat Khaybar to Harrat Nawasif. Later, another more sophisticated hunting technique was implemented in the north of this region using only kites. We therefore suggest that open kites should be considered as 'proto-kites'. Further north, in Harrat al-Shaam, long undulating walls, called meander walls, have also been recognized as hunting constructions prior to kites (Kempe & Al-Malabeh 2013). Some include pit-traps in their layout and it seems that these constructions evolved over time (bag-shaped kites) before the appearance of kites with a clearly closed enclosure (Betts & Burke 2021). Other 'proto-kites' therefore probably exist, but, in the absence of absolute dating, it is still impossible to design a chronology of these different constructions.

The number of known kites and kite-like structures, including V-shaped and open kites, currently amounts to 7151. In this southern part of the overall kite distribution area, the clear identification and mapping of morphologically different groups offers a spatialized image of the different types of kites (Fig. 22). This image probably carries chronological connotations (Barge et al, 2020). Each group of kites can be considered as material evidence of a singular kite hunting technique in a given region and period. These data provide a basis for recording the spatial and temporal spread of the kite-hunting technique, once absolute chronological data become available. Within this complex web, the identification of a proto-kite form to the south of the extension area is an important piece of information. However, it would be premature to deem that open kites are the only early form of kites from which Khaybar kites originated, a model from which the hunting technique spread further north to Kazakhstan. On the one hand, there are other potential forms of proto-kites; the meandering walls of the Harrat al-Shaam, which largely overlap kite structures, also have pit-traps, at least in some of their extensions. On the other hand, if open kites are primitive kites, the technical innovations that led to kites may have been developed in another region further north, before spreading southwards again to give rise to the Khaybar kites.

7. Conclusion

In western Arabia, kites and open kites show many morphological similarities: the presence of pit-traps, with the same layout, shows that these constructions are related. Hunting techniques, at least for some hunting phases, on the other hand, must have been different. The examination of topographical layouts shows that kites and open kites do not follow the same logic and that their general architecture

is different. Kites appear to be more sophisticated, with the recurrent layout of standardised elements (driving lines, enclosures, pit-traps), whereas open kites show very diversified layouts. However, the partial overlapping, in Harrat Khaybar, of the geographical distribution areas of the two types of constructions suggests that they derive from each other. Kites and open kites may have been in operation at the same time, defining related but different hunting techniques. They may also have followed each other in time, with one technique leading to the emergence of the other, forms of ‘proto-kites’ predeveloping the sophisticated and standardized forms of desert kites. The more general question of the phenomenon of the diffusion of the kite hunting technique, and its documentation, is a current issue in research on these constructions. The discovery and characterisation of open kites through the examination of satellite images and the overall mapping of the region undoubtedly provide new elements in this respect. However, the understanding of open kites (age, coveted species, groups behind their constructions), like that of the Harrat Khaybar kites, is totally dependent on fieldwork. Forthcoming research in the field, involving excavations and dating, will undoubtedly enhance our knowledge of these structures, their evolution, diffusion, and operational methods.

Acknowledgements

Fieldwork in Khaybar was carried out as part of the Khaybar Longue Durée Archaeological Project (codirection: Guillaume Charloux, Rémy Crassard, Munirah AlMushawh). We thank the French Agency for the development of AIUla (AFALULA) and the Royal Commission for AIUla (RCU) for their support and fieldwork permit. This research is also part of the Globalkites Project, supported by the French National Research Agency (2013-2018) and the CNRS team Archéorient.

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Supplementary data

Open kites and kites feature classes (1), Regional mapping of open kites (2), Use of regular grid of 10 km x 10 km (3), Angular differences between the orientation, of open kites and slope orientation (4).