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Mass-kill hunting and Late Quaternary ecology: New insights into the 'desert kite' phenomenon in Arabia

Huw S. Groucutt[a,b,c,*], W. Christopher Carleton[a]

[a] Extreme Events Research Groups, Max Planck Institutes for Chemical Ecology, the Science of Human History, and Biogeochemistry, Jena, Germany
[b] Department of Archaeology, Max Planck Institute for the Science of Human History, Jena, Germany
[c] Institute of Prehistoric Archaeology, University of Cologne, Cologne, Germany

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A B S T R A C T

Over 6,000 'desert kites'—mass-kill stone hunting traps constructed at various times over the last 10,000 years—have been identified from northern Arabia to western central Asia. It has been proposed that kites had a significant impact on animal demography, leading to changes in ecology and human societies. While there has been considerable discussion regarding the function and chronology of kites, their spatial distribution is poorly understood. Here we report over 300 desert kites from several areas of the Arabian Peninsula, including ~ 500 km further south than previously suggested. Using satellite imagery, we studied their super-imposition revealing an extended chronology of kite-construction, including multiple phases of rebuilding in some cases and kites built relatively recently. This shows that desert kites were significantly more spatially and temporally widespread than previously believed, suggesting that they played a role in transforming Late Quaternary ecosystems and offering insights into the behaviour of human societies in challenging environments.

1. Introduction

Desert kites are convergently shaped stone structures built by people (Fig. 1), often of a vast size, known to occur between at least northern Arabia and western Central Asia (e.g. Maitland, 1927; Reese, 1929; Helms and Betts, 1987; Betts, 1981; Holzer et al., 2010; Nadel et al., 2010; Kempe and Al-Malabeh, 2013; Zeder et al., 2013; Abu-Azizeh and Tarawneh, 2015; Arav et al., 2015; Betts and Burke, 2015; Barge et al., 2015a, 2015b, 2018; Brunner, 2015a, 2015b; Crassard et al., 2015; Kennedy et al., 2015; Malkinson et al., 2018; Hill et al., 2020). Around 6,000 of these structures have been reported (Barge et al., 2018; Malkinson et al., 2018). In the Harrat Al-Sham alone, it is estimated that kites collectively comprise nearly 4,000 km of stone walls (Kempe and Al-Malabeh, 2013). The desert kite phenomenon offers insights into a dramatic process of landscape modification, with cascading impacts on fauna, wider ecology, and human societies.

A broad definition of desert kites includes the presence of two converging walls (or 'antennae') which meet at a "circular enclosure at the apex" (Nadel et al., 2010, p.977), or "an enclosure or pit at the apex" (Holzer et al., 2010 p.806). An alternative, stricter, definition emphasises the presence of small subsidiary enclosures (or 'cells') around the main enclosed area at the end of the converging walls. Some have viewed the presence of these cells as a hallmark of true desert kites and representative of a unique and relatively localized cultural phenomenon specific to a region stretching from northern Arabia to Kazakhstan (Barge et al., 2015a, 2015b, 2018, 2020). For proponents of this strict definition, true kites should be distinguished from 'kite-like' structures in areas such as Yemen and the Negev/Sinai that feature convergent walls but do not have cells around a terminal enclosure (Fig. 2). Views somewhere between the tighter and looser definitions have also been offered (Crassard et al., 2015; Brunner, 2015b). Barge and colleagues (2015b), while emphasising the importance of subsidiary cells in defining desert kites, suggest that there can be exceptions, namely where structures lacking cells are found near those that do match the tighter definition. Barge and colleagues (2020) discuss some central Arabian structure as 'pseudo-kites', which they suggest do not fully meet the criteria of kites in the strict sense, but are clearly a related phenomenon.

The notion that there is a 'true' desert kite phenomenon, best known from areas such as the Harrat Al Sham and other nearby harrats (lava-fields), and that similar 'kite-like' structures from areas such as the Negev/Sinai and Yemen are independent phenomena, reflects a combined consideration of the morphology of structures and their spatial

* Corresponding author at: Extreme Events Research Groups, Max Planck Institutes for Chemical Ecology, the Science of Human History, and Biogeochemistry, Jena, Germany.

E-mail address: hgroucutt@ice.mpg.de (H.S. Groucutt).

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distribution. For instance, Barge and colleagues (2015b) argue that the 'south Arabian' form of kite/kite-like structure in Yemen (Brunner 2015b) are not really kites because they are too far from the next closest area containing desert kites that fit the stricter definition (northern Arabia). Such notions suppose a reliable understanding of the distribution of desert kites across space, which, as we shall explore in this paper, is actually lacking. Analogously, recent research has identified desert kites (or at least 'kite-like' structures), in several areas of Africa, such as Libya (Giannelli and Maestrucci, 2018; Gianelli and Maestrucci, 2019), the Nile Valley (Storemyr, 2011), and South Africa (Lombard et al., 2020). These findings again emphasise the need to re-evaluate the current consensus regarding the spatial distribution of desert kites. Spatial information is key to understanding the relationship between kites/kite-like structures in different regions, as well as the cumulative social and ecological impacts of their use.

Kites are highly regionalised in their morphology and other characteristics (Figs. 1, 2) (see e.g. Barge et al., 2015a, 2015b). While there is variation within particular regions, there are regionally specific dominant tendencies in morphology. In the Harrat al Sham, for instance, 'star-shaped' forms are ubiquitous (Betts, 1981; Barge et al., 2015a): with large kites, often occurring in connected chains, characterised by converging walls to star shaped chambers with cells around the margins. These kites also have a central wall between the two convergent guiding walls (Figs. 1, 2). In contrast, kites located in the Saudi Arabian lavafield of Harrat Khaybar are less characterised by distal enclosures and tend to feature various barbs that protrude from the converging walls (Kennedy et al., 2015). In the Negev/Sinai, kites tend to be small and isolated, characterised by walls that converge to a simple pit/enclosure (Holzer et al., 2010; Nadel et al., 2010). Other examples could be given, but this striking regional variability is important for understanding the desert kite phenomenon.

The dominant view is that kites were used primarily, if not exclusively, as hunting traps (e.g. Helms and Betts, 1987; Rosen and Perevolotsky, 1998; Bar-Oz et al., 2011; Zeder et al., 2013; Betts and Burke, 2015; Barge et al., 2018, 2020). Similar to the drive lines constructed by indigenous people of the North American Great Plains, kites appear to have served as hunting traps by allowing hunters to control the movements of herd animals. As the hunters pursued the herd, the animals would follow the stone walls of the kite, funnelling towards an enclosure. Other, less commonly invoked, explanations have ranged from kites being Roman defensive structures (Poidebard, 1934), religious sites (Eddy and Wendorf, 1999), or livestock corrals in pastoral societies (Echallier and Braemer, 1995). Independent categories of evidence regarding the function of kites – such as rock art – have proven ambiguous (Crassard et al., 2015; McDonald, 2005), and few kites have yet been excavated. For now, though, there seems to be no reason to doubt that the primary use of kites was for hunting. While gazelle – particularly *Gazella subgutturosa* – are often discussed in relation to kites, it is also possible that in Southwest Asia the Late Quaternary decline in various species such as ostrich, equid species, and hartebeest may reflect overhunting in part reflecting the use of kites. The propensity of *Gazella subgutturosa* to form dense groups, which run together and crucially, unlike other gazelles, do not jump (Kingswood and Blank, 1996), can be seen as behaviours facilitating the use of desert kites. It is, however, important to consider that taxa such as gazelles may have changed their behaviour considerably over time (Martin, 2000). It has been proposed by several researchers that mass-kill hunting using desert kites may have led to the virtual extinction of some species. For instance, at Tell Kuran in Syria a large and dense assemblage of *Gazella subgutturosa* was recovered dating to ~5.5–5.1 ka, close to a concentration of desert kites (Bar-Oz et al., 2011; Zeder et al., 2013). The density of bones is so great that the authors interpret it as indicating "unsustainable hunting practices" on a dramatic scale (Bar-Oz et al., 2011).

The chronology of desert kites has also been much discussed. A long-chronology suggests that desert kites were primarily a Neolithic phenomenon (Helms and Betts, 1987; Betts and Burke, 2015; Akkermans et al., 2014; Richter, 2004; Al Khasawneh et al., 2019a). Conversely, other researchers have argued that kites primarily date to the fourth and third millennia BC (Nadel et al., 2010; Zeder et al., 2013). Recent work in Armenia suggests that their use is more recent still, around 3.2–1.5 ka (Nadel et al., 2015). The accounts of western travellers in Southwest Asia describe the use of kites, or kite-like structures, into the last few hundred years (e.g., Burckhardt, 1831, see Crassard et al., 2015 for other examples). Several scenarios are consistent with these data; from a long-chronology across the range of desert kites, to their use at different times in different regions.

That desert kites may have had a significant ecological impact is implied by their high number, wide distribution, and long history. While a hunting use is the dominant interpretation, in the long run whether this was their exclusive use or whether they were also used for other

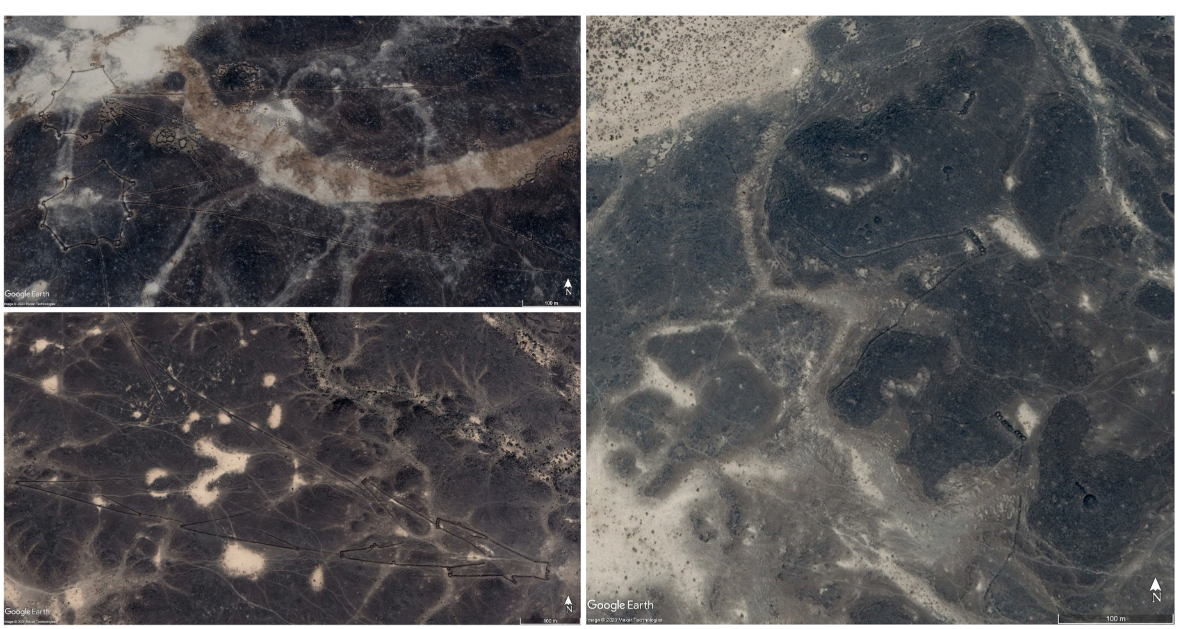

Fig. 1. Examples of desert kites in Southwest Asia. Top left: Harrat al Sham, eastern Jordan. Bottom Left: Harrat Khaybar, northwest Saudi Arabia. Right: newly discovered kites in Harrat Nawasif, western Saudi Arabia (images: Google Earth).

functions (such as some kind of role within pastoralism) does not undermine their ecological and social significance. Both large-scale hunting and extensive pastoralism are parts of interlinked processes where the biology and ecology of the region were transformed across the Holocene with the spread of domesticated animals and the reduction of wild fauna. In this sense kites played an important role in long-term human ecosystem modification and niche construction (see also Boivin et al., 2016). Some have suggested that caprine domestication developed due to the depletion of wild fauna, such as gazelle, as a result of excessive hunting (Martin, 2000; Legge and Rowley-Conwy, 1987). Alternatively, it may be that kites were used for seasonal hunting by otherwise pastoralist societies (Wasse et al., 2020). In fact, it may be that changes in wild animal behaviour driven by the development of pastoralism made the use of desert kites an effective approach (Henton et al., 2019). The function of kites may also have changed over time (Bar-Oz et al., 2011; Hill et al., 2020). They may, for instance, have initially had a subsistence focus, took on an increasingly social/cultural role over time (such as for feasting), and then in some cases they may have been re-used for pastoralism. These various possible scenarios reflect different historic trajectories for the depletion of wild fauna and an increasing emphasis on domestic fauna which emerged in the Holocene, with further widespread impacts including overgrazing (Henry et al., 2017). While the extinction of large animals is a frequent topic of discussion, in the context of global Late Quaternary megafauna extinctions (Galetti et al., 2018; Rowan and Faith, 2019; Stewart et al., 2021), studies from southwest Asia emphasise the additional importance of changes in medium size animals.

Desert kites therefore offer a fascinating case study of interlinked human and ecological changes in the Holocene. While some major changes in animal demography may relate to climate change (e.g. Stewart et al., 2021), other aspects, seemingly including those relating to the kites discussed here, suggest a major human role in ecosystem modification. While the function and chronology of kites are important and continue to be key areas of research, the spatial distribution and geographical context of kites has been undervalued. Understanding their distribution is crucial for evaluating the ecological impacts, cultural context, and historical development of desert kites. Here we report a study of the distribution and character of desert kites in Arabia by examining previously unreported kites identified in satellite imagery.

2. Methods

To begin the investigation, we used Google Earth and (particularly) Bing Maps imagery to locate desert kites in the study area. The coordinates of sites were recorded, as well as the general orientation of the opening between the guiding walls (north, east, south, or west), the length of the kite (defined as a straight line between the central part of the distal end of the kite and the midpoint between the opening of the guiding walls, with the aim of producing a simple quantitative measure for kite size), and any additional observations (such as aspects of relative chronology).

We then selected two smaller areas within Harrat Nawasif that we identified as particularly informative. These two areas were chosen for their density of kites (Fig. 4) and the clear spatial relationships between kites observable in the lower-resolution Google/Bing imagery (Fig. 5). We purchased high-resolution panchromatic commercial satellite imagery of these areas, along with high-resolution digital surface models, from European Space Imaging (euspaceimaging.com). The images (black-and-white) were captured by DigitalGlobe's WorldView-02 satellite platform. They had a spatial resolution of 40 cm, while the two corresponding DSMs had resolutions of 1 m and 50 cm. The images and DSMs were orthorectified and all necessary pre-processing was handled by the seller – i.e., they were ready for use out-of-the-box. We then simply enhanced the contrast of the images by stretching the display values between +/− 2 standard deviations and manipulating image brightness. We used the DSM data to produce categorized colour maps to highlight elevation changes. Such high-resolution imagery revealed details not visible on freely available imagery: such as the nature of the

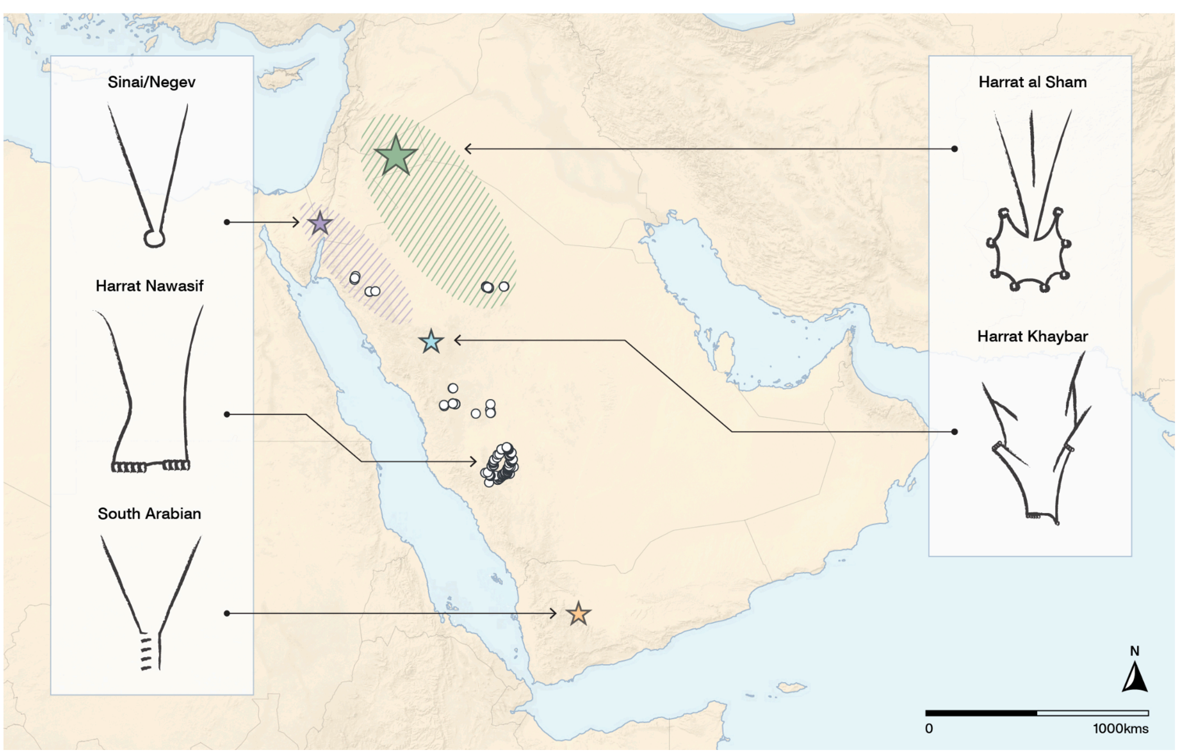

Fig. 2. The geography and variability of desert kites in the Levant and Arabia. Newly identified kites are shown by white dots. Coloured stars show simplified location of previous regional clusters. Insets show typical kite morphology in the different regions. Green and purple hashed area show hypothesised cultural spheres, where northern Arabian kites show close morphological parallels with kites to the north.

eastern guiding wall of the easternmost kite in Fig. 5. All of our analyses involving the imagery and DSMs were conducted in QGIS (https://www.qgis.org/en/site/).

3. Results

3.1. The distribution and regionalisation of desert kites

Our analysis of satellite imagery (see methods) revealed 306 desert kites (Fig. 2; supplementary table). We systematically evaluated a region within the Harrat Nawasif/Al Buqum area (hereafter simply referred to Harrat Nawsif), where 258 kites were identified. To help contextualise these findings we carried out more cursory survey of other parts of Saudi Arabia, revealing 13 kites in Northwest Arabia (near Tabuk), 15 kites near Ha'il in central northern Arabia, and 20 kites in central western Arabia, south of Medina and in the Harrat Kishb area. We have no doubt that future systematic surveys of these and other areas will reveal many more desert kites, and we note that during the time our paper was being reviewed, Barge and colleagues (2020) also observed some of the kites we report here.

3.2. New desert kites in central and northern Arabia

The 13 kites discovered in northwest Arabia (e.g. Supplementary Figs. 1 and 2) are a small but significant corpus of structures. They mostly consist of kites with a very similar morphology to the previously identified Negev/Sinai form, with simple usually singular structures leading to a pit/enclosure lacking cells. They are small in size (typically less than 100 m long). A similar kite was also recently reported from southern Jordan (Barge et al., 2018). These new northern Arabia kites occur in areas of basalt geology. These findings suggest a Sinai to northwest Arabian form of kite, with a wider distribution than previously known. As discussed in the introduction, where dated these structures have been assigned to the fourth and third millennia BC, though it should also be noted that in some cases these are minimum age estimates. Among the newly identified northwest Arabian structures, an exception to the 'Negev/Sinai' morphology is found around in one area (see e.g. 27.597 N, 36.835 E) where a few kites which are larger and have a different morphology are found.

In another region, near Ha'il (shown by white dots at base of green hashed area on Fig. 2), we identified 15 desert kites, including relocating one described several decades ago by Parr and colleagues (1978) which has been overlooked in most subsequent studies. Most of the kites we identified occur in a sandstone area northwest of Ha'il, between the city and the Nefud Desert, with an additional group around 50 km east. All of the Ha'il group kites have a star shaped morphology very similar to those known from Harrat Al Sham, with both the distinctive star shaped enclosure and peripheral cells, as well as the central guiding wall between the two convergent entrance-way walls (e.g. Supplementary Fig. 3). The Ha'il kites vary in size, but are typically somewhat larger than those described above from further west. The eastern group of kites in the Ha'il group show an interesting use of the landscape. A north to south ridge occurs between two low-lying areas on either side, characterized by playas and agricultural land, between which the ridge provides a convenient route to move through the landscape. A kite with an enclosure at 27.7754 N, 42.2520 E features a central wall which extends eastwards for nearly three kilometres, extending across the entire ridge. Additional kites are found just south of this kite in both the east (Supplementary Fig. 3) and the west. Not only is the morphology of these kites similar to that from Harrat al Sham, but the coordination of kites into groups can also be seen as similar.

Further south, we identified 20 kites between Medina and Harrat Kishb. They differ from the above described forms and forms known from Harrat Khaybar (Kennedy et al., 2015). This Medina/Kishb group are morphologically varied, but are often characterized by a shallow angle to the guiding walls. An interesting feature of this group is the use of the landscape to amplify the impacts of the kites. Examining the landscape between approximately 23.512 N, 40.060 E and 23.314 N, 40.578 E, we see an east–west expanse approximately 50 km wide where the landscape imposes several restrictions on movement. The western half is characterised by recent lavaflows, which are often very steep sided and challenging to cross, while the eastern half is a low-lying playa that would have been a wetland during humid periods during the Holocene. Several desert kites were situated in the small gap between lava and playa, making full use of the challenging terrain to both the west and east (23.4724 N, 40.3002 E). Nearby, kites are situated against the steep-sided edges of recent lava flows; perhaps to trap animals which had escaped the kites just described. These kites and lava flows can be seen at 23.4869 N, 40.2947 E and 23.4968 N, 40.1944 E. Likewise, a little further west, several kites were constructed in a valley flanked by highland areas (e.g. 23.399 N, 39.8496 E). In all of these cases, kite-builders took advantage of the natural landscape to carefully position the traps for maximum effect. Most of the sites just discussed show evidence for multiple phases of construction, attesting to long use and gradual improvement. Thus, while their chronology is imprecisely known, the kites were in use over an extended period, which implies a long-lived hunting tradition and process of landscape modification.

In the Medina/Kishb region, we also identified 'meandering walls'. In Jordan these have been regarded as the earliest kinds of kite-like structure (Helms and Betts, 1987). Examples include around 23.1005 N, 40.4156 E. Currently all that can said on the chronology of these central Arabian 'meandering walls' is that they are older than pendant tombs (e.g. 23.0048 N, 40.3973 E). We will return to chronological aspects later in this paper.

3.3. The desert kites of Harrat Nawasif

The densest distribution of desert kites we identified are located in the Harrat Nawasif area, 200 to 300 km east of Makkah. Given the significant concentration, we selected this area for detailed systematic visual survey. Kites are an abundant feature in this landscape, with the 258 examples we identified composed of more than 40,000 m of stone walls in total (Fig. 3, Fig. 4, Fig. 5, Fig. 6; Supplementary Figs. 4–15). While these structures will have been observed by local people, they have not been the subject of systematic evaluation. Kennedy (2012) noted two kites in the area, and during the review process for this paper Barge and colleagues (2020) reported some 'kite-like' structures around Harrat Nawasif.

Harrat Nawasif is the southernmost of the major harrats (lavafields) of Saudi Arabia (Al-Muallem and Smith, 1998). It sits in a geographically significant area on the edge of the highland spine of western Arabia, a region characterised by relatively high rainfall, and at the source of west-to-east flowing fluvial systems (Breeze et al., 2015, 2016). The kites are concentrated around the edges of the lavafield (Supplementary Fig. 4), and where small valleys extend back into the lavafield (Fig. 3). This pattern is particularly visible in the southeastern part of the study area, where numerous kites are located along Wadi Ranyah and its tributaries. In the northern part of Harrat Nawasif kites occur in considerable numbers in proximity with playas identified as probable palaeolakes (Fig. 3).

Kites were built in diverse landscape settings, but with some consistent patterns regarding the juxtaposition of kites and topography. One common pattern is for the terminal area of the kite to be constructed on the edge of the lavafield, with walls extending into neighbouring lower lying land. Likewise, frequent use of the rise and fall of a hillside was made to conceal the end of the kite (Figs. 4, 5). Another common pattern, significant in the absence of the kind of constructed distal enclosures typical of areas such as Harrat al Sham, is the use of cliffs and other steep slopes to create an enclosure-like effect using the natural surface (e.g. 20.8371 N, 42.3376 E; 20.8107 N, 42.2567 E; 20.7939 N, 42.2260 E). A third pattern involves the use of cliffs to form one axis of the kite, meaning only one long wall had to be constructed (as at

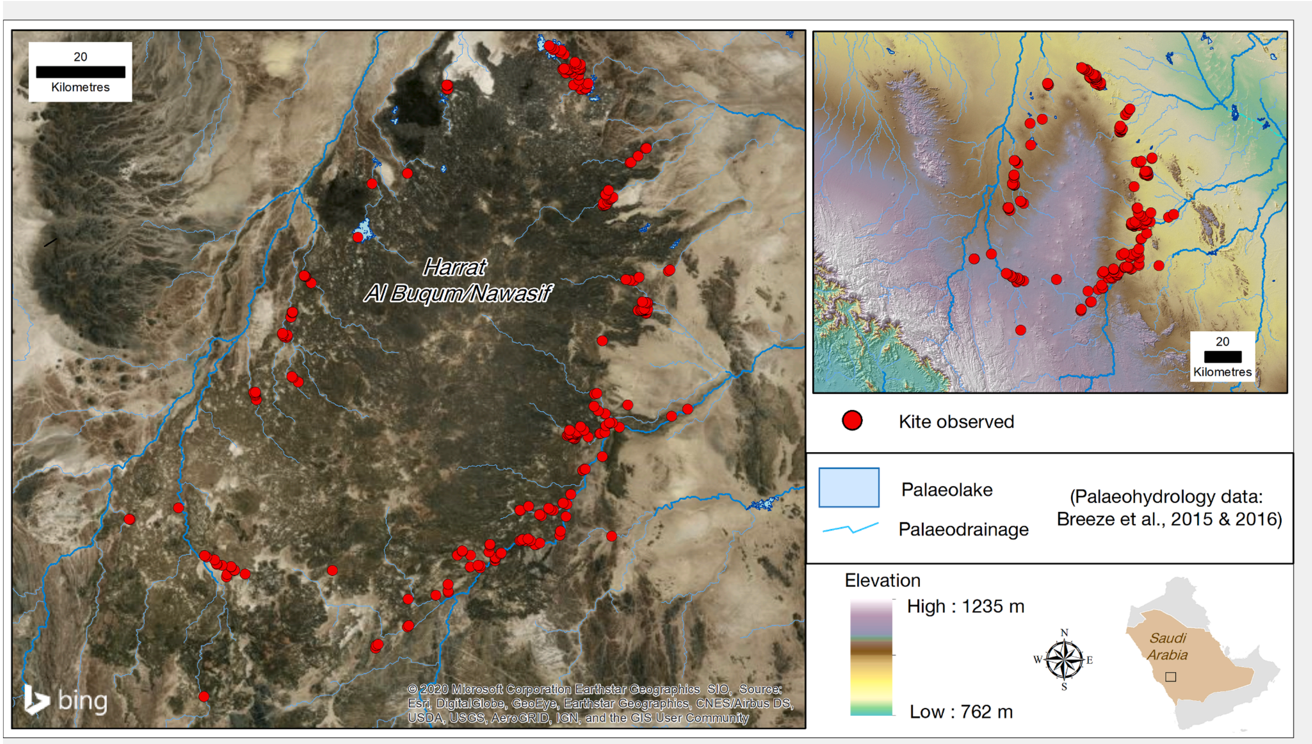

Fig. 3. Desert kites of Harrat Nawasif. The sites are showing in relation to regional palaeohydrology and altitude (right).

20.7947 N, 42.2218 E). Together, these repeated patterns imply there were a set of common strategies used to determine the optimal location and form of kites given the features of the landscape in which kite-construction was embedded.

It is important to emphasise how processes of landscape change have impacted kites themselves, which must be kept in mind when we interpret these structures. In some cases, it seems that erosion has removed the walls, as can be seen at examples between 21.5441 N, 42.4902 E and 21.5495 N, 42.4987 E, while in other cases in seems that walls have been partly buried by sediments. As shown in Supplementary Fig. 12, much of one of the largest kites identified was underwater as a lake formed following rainfall shortly before the imagery available on Google Earth in 2020 was taken.

The kites of Harrat Nawasif are morphologically varied (Figs. 4 and 5, Supplementary Figs. 5 to 14), but we can describe some typical characteristics. The main feature is a simplicity in morphology, with two gently converging walls and cells only occurring on the far distal end of the structure. They typically lack elaborate distal (i.e. the terminal end) enclosures, or features such as barbs (ancillary walls that jut away from the main convergent walls of a kite toward the open end like the tangs or barbs of an arrowhead). In many cases the distal ends of these kites converge to straight walls with small cells, but a common feature is for the end to split into two sections of wall featuring cells slightly offset to each other (as at 20.8226 N, 42.1887 E, for instance). In rare cases, the distal end does have enclosure-like walls and multiple cells around much of this enclosure (e.g. Supplementary Fig. 10). Given these observations, we think that the characterisation by Barge and colleagues (2020) of some of these structures as 'pseudo-kites' is incorrect. Part of this comes down to a conceptual ambiguity about what constitutes a distal 'enclosure', but in our view the Harrat Nawasif certainly demonstrate a distal enclosure created by a mixture of wall construction and natural topography.

The kites of Harrat Nawasif vary considerably in size, challenging the notion of kites as always being very large structures. Many are very small, but in one case (Supplementary Fig. 13) with the terminal enclosure at 21.1055 N 42.4831 E, the kite is vast, with a length of around 1400 m. Featuring around 3000 m of walls and enclosing an area of over 500,000 m^2, this is a very large structure. It also reveals the kind of landscape processes reshaping the area, as the distal enclosure appears to have been heavily damaged by fluvial activity. Using length (from the central point of the distal end to the midpoint between the start of the two converging walls) we are able to offer a quantitative perspective on the size of the structures. We were able to record this measurement in 76% of cases – in the remaining examples we were not confident in recording the measurement due to erosion or burial of the walls. The mean and median values for length are 107 and 90 m (with 50% falling between 67 and 130 m). Most of the kites are therefore relatively small compared to the large forms of the Harrat al Sham and Harrat Khaybar. With the one very large outlier removed, the median value only changes slightly, to 89 m, but the mean average reduces to 100.5 m. The sizes of kites are shown in a mapped form in Supplementary Fig. 15.

Kites are spatially related to each other in various ways. Some are isolated individual structures (e.g. Supplementary Fig. 11), others are situated in close proximity to several neighbouring kites (e.g. Supplementary Figs. 8 to 10), and still others link up to form dense groups of connected kites. In the area shown in Fig. 4, for instance, multiple kites are arranged in close proximity over a 1.5 km stretch. This involves kilometres of walls and hundreds of cells in a virtually continuous line of kites along a ridge. This variability in grouping in Harrat Nawasif contrasts with the individual kites of the Sinai-NW Arabia group and the typically grouped character of the Harrat al Sham kites.

While the major axis of the opening of the kites varies in orientation, the kites of Harrat Nawasif open to the south more frequently than any other cardinal direction (48.2%) (Supplementary Fig. 16). This contrasts with the westward orientation dominant in Harrat Khaybar (Kennedy et al., 2015), and eastward orientation typical in the Harrat al Sham (e.g. Hill et al., 2020).

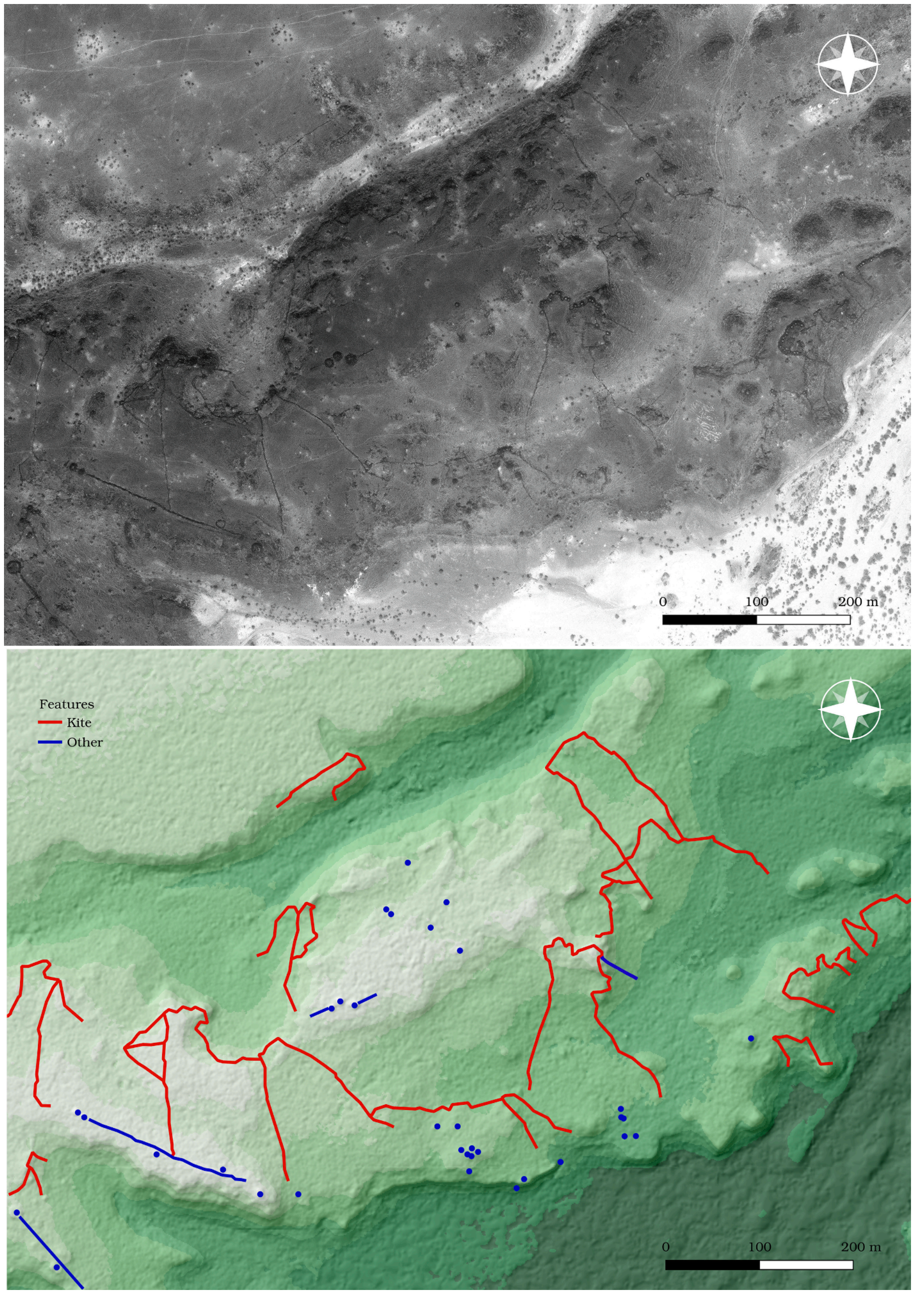

Fig. 4. Satellite image and elevation model of a dense group of kites in Harrat Nawasif (21.319 N, 42.562 E). For clarity, the lower images shows a simplified vector layer of kites and other structures (mostly cairns and pendants). Higher areas are lighter colours. The careful use of topography in locating kites is clear, as is the frequent rebuilding of kites.

3.4. The context and chronology of Harrat Nawasif kites and other stone structures

As well as the abundant kites that we have described above, Harrat Nawasif features various other forms of stone structure (Figs. 4–6; Supplementary Figs. 17–20), showing recurrent human use of the area. The study of these, particularly the relative superimposition of different structural types, provides both physical and temporal context to the desert kites and allows us to more fully document the changing character of human societies in the area. Harrat Nawasif receives relatively high rainfall compared to much of Arabia (Subyani and Al Ahmadi, 2010), and there are significant aquifers in the area. Indeed, Wadi Ranyah has been described as the “most important water resources” in western Arabia (Subyani and Al Ahmadi, 2010). The relatively high rainfall of this region also interacts with the geology to aid water retention. As recently emphasised by Groucutt (2020), the complex local topography caused by volcanic activity, combined with the impermeable nature of much of the local geology, means that after rainfall episodes there are numerous and sometimes large bodies of water in the landscape (Supplementary Fig. 21), and good pasture in many areas. The character of human societies in this landscape was therefore influenced by a particular combination of geological and hydrological factors.

We will return to the absolute chronology and interregional aspects in the discussion, for now our focus is on establishing a relative chronology of stone structure forms in Harrat Nawasif, with a focus on how this offers insights into the desert kite phenomenon. Pendants—cairns with a long stone ‘tail’—are abundant in Harrat Nawasif (e.g. Figs. 4, 5; Supplementary Figs. 9, 17–20), as they are across the wider region (Kennedy, 2011, 2012). Sometimes the pendants are kilometres long (e.g. 21.146 N, 42.149 E). Linear structures with more segmented walls

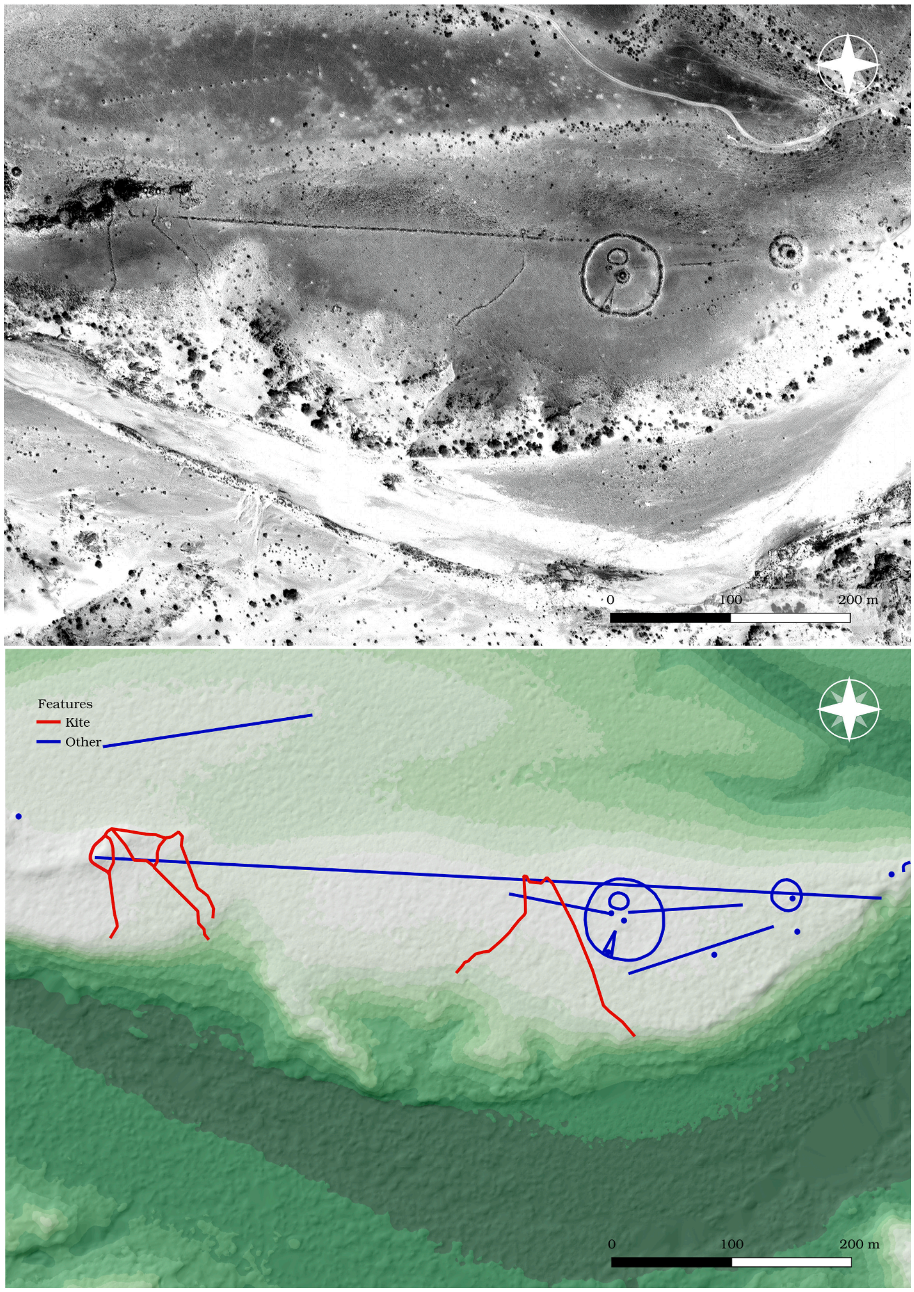

Fig. 5. Satellite image and elevation model of kites and other stone structures in Harrat Nawasif (20.837 N, 42.341 E). A raised area beside the Wadi Ranyah channel shows both interesting examples of desert kites and provides a relative chronology as different types of structures overlap (see Fig. 6).

also occur, as shown in the northwestern part of the area shown in Fig. 5. 'Keyholes' are another common kind of structure in the area, as previously discussed in northern Arabia, which feature elongated triangular shaped walls extending from a circular base (Kennedy, 2011, 2012). Much of this terminology is arguably in need of revision, but that is beyond the remit of the current paper. Various kinds of circular structures also occur in Harrat Nawasif (Fig. 5). These range from 'bullseye' structure which are a cairn surrounded by a relatively small circular structure, up to vast stone circles which can be several hundred metres across (e.g. Supplementary Fig. 18).

While different kinds of structures are often built in slightly different parts of the landscape—unsurprising given their different functions—in many cases it is possible to determine a relative chronology of structures. This is possible because the builders often used stone from older structures, creating clear superimposition. In a less clear, but still noteworthy way, relative chronology is also implied when the presence of one structure interferes with the sensible use of another, which suggests that the former postdates the latter. We can divide the relative chronological information visible in the satellite imagery into three categories. The first concerns the modification and rebuilding of kites themselves. The second concerns the overlap between kites and other kinds of structures. The final category concerns the relationships between these other kinds of structures, which provide indirect temporal context for kites.

Many examples of kites show rebuilding, sometimes minor, sometimes major. For instance, the kites in Figs. 4–6 show multiple examples of rebuilding. This is significant, as it shows that kites were used over an extended period of time. An example can be seen in the western part of the area shown in Fig. 5. Here three generations of kites were built, with slight modifications each time (Fig. 6). Many other examples could be given from Harrat Nawasif. For instance, an informative example is found at 20.837 N, 42.246 E. Here there was at least one small kite. This

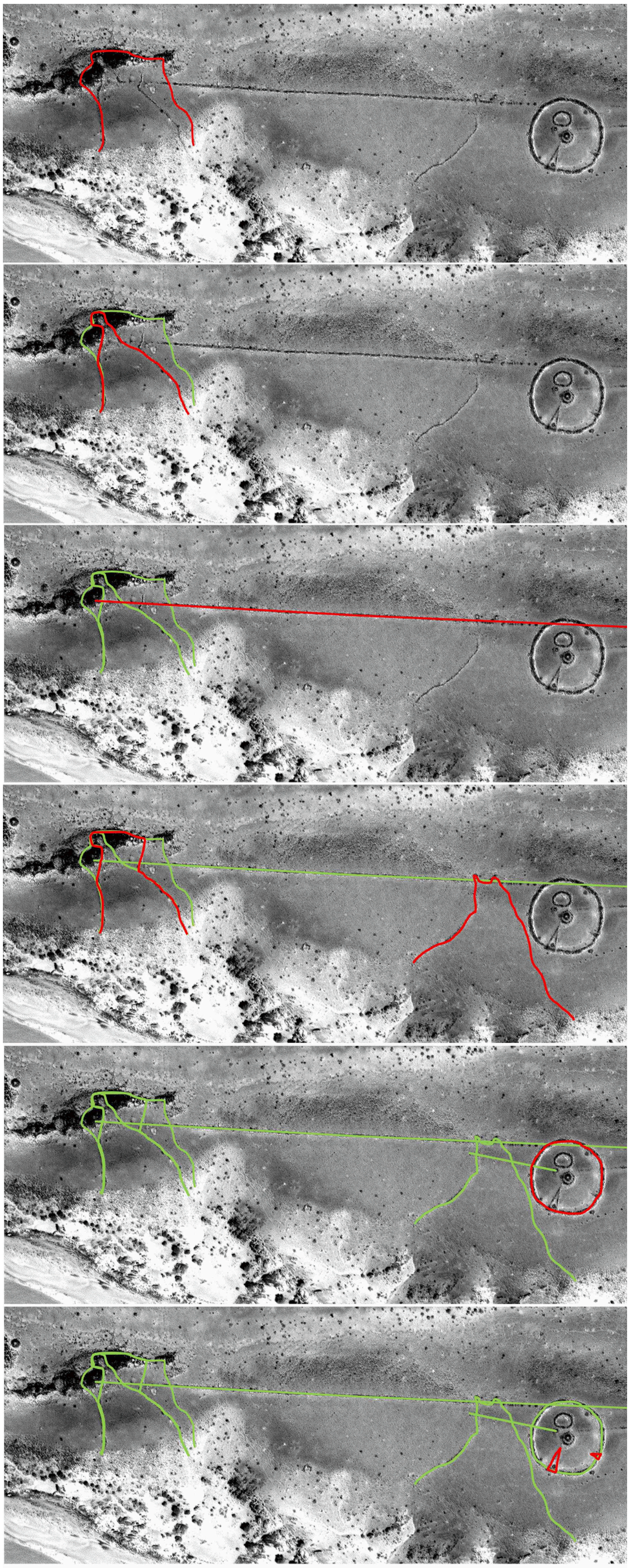

Fig. 6. An example of the relative chronology of stone structures in Harrat Nawasif. This shows the sequence of construction from oldest (top) to youngest (bottom), with the structure for each phase highlighted in red and then pre-existing structures shown in green.

original small kite had been modified, by widening the guiding walls into the structure as it was originally a narrow opening. Then this kite was abandoned and a whole new much bigger one built on top. The orientation of the kite was changed by this rebuilding and the new distal enclosure itself was modified, as was the eastern guiding wall, which was extended further south. This kind of modification and rebuilding, at a scale clearly visible from satellite imagery, is relatively common in the area.

Pendants are the key type of other stone structure which intersect with kites relatively often. Pendants often appear to be younger than kites, but typically this is somewhat ambiguous (although in some cases it seems clear: e.g. 21.063967 N, 42.4237630 E). In other cases, while there is no direct stratigraphic relationship, the construction of a pendant across the opening of a kite suggests that the kite is older (e.g. 20.992 N, 42.441 E). The area shown in Fig. 5 shows a particularly significant example of relative stratigraphy, showing both extensive rebuilding of kites, but also demonstrating that some kites are older than a 650-metre-long pendant, but also that some are younger (as shown by gaps in the pendant) (Fig. 6). In this case two generations of kite were built before a pendant, and two kites after. This is an important observation as it indicates that kites were being both before and after the construction of a pendant, and therefore offers a relative chronological anchor. A segmented linear structure was then built across the opening of the eastern kite. Then circular structures were built at the eastern end of the area. Finally, a keyhole was added to the southern area of the largest circular structure.

That kites can be younger than pendants in the Harrat Nawasif area has so far only clearly been seen at this one site. The other aspects of the relative chronology are, however, repeated at numerous sites across Harrat Nawasif. For instance, circular structures are repeatedly younger than pendants, and keyholes are younger again (e.g. Supplementary Figs. 19, 20). This sequence is demonstrated at numerous sites in the study area.

4. Discussion

The discovery of over three hundred new desert kites in Arabia—particularly in Harrat Nawasif around 500 km south of their previous range—extends the previously known limits of the desert kite phenomenon and its impacts. Despite possible hints of a more widespread distribution, such as an engraving in western Arabia seemingly depicting a kite (Zarins et al., 1981), and suggestions that structures in central Arabia were 'pseudo-kites' (Barge et al., 2020) previous major studies on desert kites suggested that the southernmost examples were located around Harrat Khaybar, with Crassard and colleagues (2015) only depicting a single kite below 25 degrees north. While much remains to be learned, the greater the number, spatial distribution, and temporal span of kites the greater their impacts should have been.

This more widespread presence of kites further emphasises the striking regionalisation of kite forms, with the Harrat Nawasif kites presenting a previously unknown morphology (Fig. 2). Distinguishing between cultural transmission and convergent evolution will require detailed comparative studies of kite morphology, distribution, and chronology. Given the broad distribution of kites we imagine that convergent evolution has sometimes occurred, which is unsurprising given the presence of conceptually similar structures and approaches across the world, often of organic materials (Ingold, 1980).

Our findings also suggest a previously unrecognised developmental sequence within Southwest Asia, constituting an important addition to discussions about the prehistory of the region (Groucutt et al., 2020; Petraglia et al., 2020). The archaeological record of southern Arabia often indicates autochthonous characteristics, compared to greater evidence for connections with the Fertile Crescent in northern Arabia. Kites arguably provide a striking example of this. Firstly, two independent kite groupings suggest cultural connections between northern Arabia and areas to the north (Fig. 2). Secondly, there is seemingly a consistent pattern of change in kite morphology from north to south, which can be summarised as an increasing emphasis on the distal area of the structure, as opposed to a constructed enclosure. In the north, the Harrat al Sham kites have elaborate distal enclosures, but to the south the Harrat Khaybar kites have no such elaboration tending instead to comprise converging walls to a simpler distal area, albeit with barbs along the way. This trend continues in Harrat Nawasif, and then even more so in Yemen where kite design is spartan and the distal end opens at a single point rather than the structures having a fully enclosed space. In our opinion this not only suggests a possibly fascinating example of a cultural development, but implies that a broad definition of kites is more useful than one based on the characteristics of kites in only certain areas, particularly Jordan and Armenia which have been the focus of recent studies (e.g. Crassard et al., 2015; Barge et al., 2020). To test such models, and explore the character and impacts of kites more broadly, requires detailed comparative studies of broadly defined kites.

We have shown that kites chronologically weave into the spatio-temporal patterning of human occupation in the area, often being seemingly the oldest structures in the landscape, but also seemingly overlapping with pendants, which have previously been attributed to the Bronze or Iron Age (Braemer et al., 2001; De Maigret, 2009; Kennedy, 2011, 2012). In the final centuries BC and early centuries AD, other linear structures are known from the wider region (McCorriston et al., 2011; Al Khasawneh et al., 2019b). In Harrat Nawasif pendants are followed by widespread circular structures. Keyholes had previously been speculated to represent an "elaborated form of pendant" (Kennedy et al., 2015, p.185), but no chronometric or relative dating was available to explore this possibility. In Harrat Nawasif keyholes follow both pendants and circular structures, and are therefore clearly late in the prehistoric sequence. In fact, with this insight we briefly looked at the areas of northwest Arabia where pendants and keyholes occur in profusion, but rarely overlap each other, and noticed clear examples supporting this demonstration that keyholes are younger than pendants (e.g. 25.9906 N, 40.5081E; 26.0117 N, 40.4991 E). Conversely, however, that keyholes and pendants do seemingly only rarely overlap in northern Arabia, such as around Al Hait, despite commonly occurring in close proximity, may imply that they date to a similar chronological period to each other.

We have shown that kites both occur across a larger spatial range than previously known, and that they occur both relatively early and relatively late (i.e. both before and after Bronze/Iron-age pendants). Along with the widespread evidence for kite modification in multiple phases, these findings suggest an extended span for kite construction and use in Harrat Nawasif. This fits with recent evidence for an extended chronology for the kite phenomenon in neighbouring regions (Nadel et al., 2015; Al Khasawneh et al., 2019a), Kites offer insights into the changes in subsistence and societies that occurred across the Holocene. These changes, with impacts on aspects such as biodiversity and overgrazing, led to major ecological changes in the region. Exploring and quantifying the nature of these ecological impacts should be a target for future research. The late Quaternary saw major changes in global ecosystems, such as population declines and extinctions of various species of large animals (megafauna). While some of these may have been driven by natural climate change, the desert kite phenomenon indicates that at least in some regions, humans played a major role. Our study highlights the importance of clarifying the spatial distribution of kites. Ground survey and excavation of these structures should be a priority for future research.

5. Author statement

We declare there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2021.102995.

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