remote sensing

Article

The Black Desert Drone Survey: New Perspectives on an Ancient Landscape

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Abstract: This paper presents the results of a large scale, drone-based aerial survey in northeastern Jordan. Drones have rapidly become one of the most cost-effective and efficient tools for collecting high-resolution landscape data, fitting between larger-scale, lower-resolution satellite data collection and the significantly more limited traditional terrestrial survey approaches. Drones are particularly effective in areas where anthropogenic features are visible on the surface but are too small to identify with commonly and economically available satellite data. Using imagery from fixed-wing and rotary-wing aircraft, along with photogrammetric processing, we surveyed an extensive archaeological landscape spanning 32 km^2 at the site of Wadi al-Qattafi in the eastern badia region of Jordan, the largest archaeological drone survey, to date, in Jordan. The resulting data allowed us to map a wide range of anthropogenic features, including hunting traps, domestic structures, and tombs, as well as modern alterations to the landscape including road construction and looting pits. We documented thousands of previously unrecorded and largely unknown prehistoric structures, providing an improved understanding of major shifts in the prehistoric use of this landscape.

Keywords: drones; archaeology; Jordan; Black Desert; desert kites; Neolithic

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1. Introduction

Unpiloted aerial vehicles (UAVs), or "drones", are transforming archaeological remote sensing by making increasingly large-scale and high-resolution landscape mapping feasible and affordable [1–12]. Drones can record the landscape at significantly higher levels of detail than was previously possible from terrestrial, aerial, or satellite mapping, and can do it more quickly and more cost-effectively. Combining that data with the advances in computer vision software, drone-based surveys can be particularly fruitful for mapping anthropogenic structures that tend to be small and difficult to identify from satellite data. They have become a regular part of archaeological research in the Mediterranean and Middle East [5,7,13–17]. For this research project, we undertook a large-scale archaeological remote-sensing survey of the extant archaeological features around the mesas of Wadi al-Qattafi, Jordan, part of the Eastern Badia Archaeological Project. The resulting data provides the best and most complete documentation, to date, of this remarkable prehistoric landscape along with the modern processes affecting it.

Brief Intro to Neolithic Badia

The eastern Jordanian badia (Figure 1) is a steppe/desert divided into two broad areas, the basaltic region (harra) and the open gravel plains of the eastern section (hamad). Oligocene to Quaternary basalts form the Black Desert [18,19], the largest volcanic field on the Arabian Plate (c. 50,000 sq. km); these lie above a series of Cenozoic limestones [20–22]. The harra, while closer to the settled agriculturally viable areas to the west, is very difficult to cross. Rainfall is low on average, with approximately 200 mm of mean annual rainfall to the north and less than 50 mm per year in the south, where only one or two events typically occur during a rainy season. Despite these currently arid conditions, the eastern badia environment contains archaeological sites spanning the late Quaternary period [23–28]. Presumably the environment was more amenable to human settlement during the early-to-mid-Holocene (c. 12–8 kya), with increased rainfall or increased surface water retention that could support animals and plants.

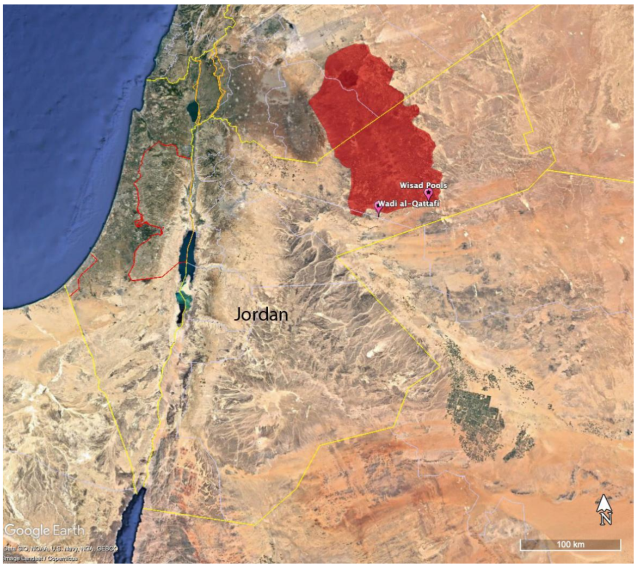

Figure 1. Location of Wadi al-Qattafi. The harra region is indicated in red.

Depositional basins in the region, known locally as qa′ (qe′an, plural), hold water for short periods of time after winter rains. These qe′an would not only attract people, but also the animals they hunted. Wadi al-Qattafi is a drainage system with three arms that merge about five km north of Qa′ al-Qattafi, an area of about 10 sq. km^2 in area. This drainage continues to the south approximately 10 km before emptying into a plain about 40 km southeast of Azraq. Directly to the north of the qa′, only a few isolated hunting or pastoral camps and burin sites are known [29].

Along this drainage system, 22 basalt-topped mesas rise above the desert floor by about 40–60 m (Figures 2 and 3). Surface artifacts indicate the presence of Late Acheulian and Mousterian hunters in the area, while several Middle and Late Pre-Pottery Neolithic B (PPNB) chipping stations are known around Mesas 3 and 4 [30]. Most mesas have at least one large tomb on top, all looted, while a few have many more structures atop the mesa and along the shoulders. A few have impressive numbers of structures, from small huts to tombs, and including animal enclosures and animal traps known as kites. Most of these features are not dated, although the tombs probably date to later periods (Early Bronze or Iron Age), with Safaitic inscriptions nearby that suggest visitors during the 2nd century BCE to 4th century CE. Most material culture collected on the surface appears to be late prehistoric, a timeframe further timeframe narrowed by the excavation of two structures, both Late Neolithic in date. On the southwest slope of M-4 (Maitland's Mesa), a structure dated to 5480–5320 cal BC [31], while another on the southern slope of M-7 dates to roughly 6455 to 6236 cal BC [32]. Evidence from these excavations documents a Late Neolithic subsistence economy that relied on hunting for meat and skins, particularly gazelle and smaller mammals (hare, fox). Grinding equipment was limited but not absent. Late Neolithic charcoal, from nearby Wisad Pools, included tabor oak, indicative of a climatic regime distinctly different to that of the present [33].

Figure 2. Wadi al-Qattafi aerial survey area with mesa numbering as established by the Aerial Photographic Archive for Archaeology in the Middle East (APAAME) project [32].

Figure 3. Oblique view of Wadi al-Qattafi with anthropogenic features visible. Looking north, M4 in the foreground.

Given the thousands of structures along Wadi al-Qattafi, ranging in size from the smallest at approximately 1–2 m diameter to others ranging for hundreds of meters, surveying and mapping these features with traditional equipment and methods proved a daunting prospect. No methodical survey of the features along Wadi al-Qattafi has been conducted previously. In the last few years, significant research on the largest of the structures in the region, the extensive animal traps known as "desert kites". This became possible even with the relatively low-resolution satellite imagery through services like Google Earth [34,35], but the majority of structures in the survey area are too small to map via satellite imagery alone (1–2 m in diameter). As a result, mapping of kites using sat data has continued, but tends to decontextualize them from the hundreds of nearby smaller features that may be associated. High-resolution, low-altitude drone mapping can allow for much more complete mapping of archaeological details. In 2016, we undertook a major drone-mapping project in the region. The goal was to record 32 km^2 around Wadi al-Qattafi, the largest drone survey in Jordan to date, in order to document all of the anthropogenic features visible on the surface in a way that would not have been possible even a few years ago. We also hoped to demonstrate that this sort of very large-scale drone-mapping project could be undertaken with low-cost, affordable technology that would be reproducible by other projects with limited funds for drone technology. Such DIY-style approaches make landscape mapping more accessible to researchers and the community.

2. Materials and Methods

Over the last decade, drones enabled a major revolution in approaches to landscape scale mapping for archaeologists [1,5,6,11,36–38]. Unpiloted aerial vehicles (UAVs) allow researchers to map landscapes at a scale and resolution that was impossible in the past. By flying lower than full-scale aircraft, and much lower than satellite cameras, drones can be used to produce georeferenced orthophotographs and digital elevation models (DEMs) that improve significantly on the resolution and cost-effectiveness of aerial surveys [1,3,6,7,38]. Drone-derived data can achieve resolutions of 1–2 cm/pixel compared to the 0.5 m/pixel that is commonly available for satellite data.

This survey was undertaken in 2016, at a time when reliable autonomous navigation was just becoming available for off-the-shelf multirotor drones, and flight times were still relatively short for existing systems, and costs remained relatively prohibitive for many projects (especially if trying to build in redundancy in case of failures in remote locations). Therefore, in order to survey the entire proposed 32 km^2 survey area, a combination of fixed-wing and rotary-wing aircraft were employed. Fixed-wing aircraft, although less commonly used than rotary wing due to the difficulties of launching and landing, fly more efficiently than rotary-wing aircraft, and so can generally stay aloft longer per battery, with flight times in excess of 1hr being feasible. This is particularly relevant where powering batteries and other devices is challenging [39]. Although off-the-shelf, ready-to fly fixed-wing systems are generally too expensive for archaeological survey budgets, much cheaper DIY-style systems can be constructed for under $2000, while providing the same functionality as high-priced systems [5,38]. In this case, the fixed-wing aircraft was a foam "Skywalker 1720" model (Figure 4), designed for hobbyists, utilizing an Ardupilot flight control computer, which enabled fully autonomous preprogrammed navigation for the efficient collection of photogrammetry image sets. Like modern rotary-wing aircraft, the Skywalker was set up to provide a live first person view (FPV) video from onboard the aircraft, for monitoring the flight as well as a whole range of telemetry data (GPS position, airspeed, ground speed, pitch angle, roll angle, etc.). The model can be programmed for complex autonomous mapping data collection via the open-source flight software "Mission Planner" [40].

Figure 4. The authors with the fixed-wing drone at Wadi al-Qattafi.

Although the Skywalker fixed-wing platform proved exceedingly useful in the field in 2016, it did have a number of limitations that made postprocessing and analysis of the resulting data more difficult. Many of these features could be improved now, several years later [38]. First, this fixed-wing drone was equipped with a Canon s100 camera as the primary mapping sensor. At the time of the fieldwork this was an ideal choice for cameras since it could be set up to run with an intervalometer; had significant manual controls, a relatively fast lens, and built-in GPS; is small and light (198 g with battery); and had sufficient resolution for photogrammetric recording at modest altitudes (12 mp, 1/1.7″ sensor). However, although full integration with the flight control computer was possible, so that the drone could be programmed to take photos at predefined locations optimized for photogrammetric processing, in practice it proved too complicated to use such a system in the field.I Instead, the camera would be run entirely independently from the drone, and programmed to continuously record photos throughout the entire course of the flight at the fastest speed possible. This creates two problems. First, the drone will record many more photos than necessary, including more photos along each transect and unnecessary photos during turns, before and after the survey portion of the mission, and during launching and landing. This overabundance of photos is helpful, on the one hand, since this DIY system also produces many more blurry photos than a modern integrated multirotor system, but on the other hand requires significantly more time during photogrammetric processing.

The fixed-wing "Skywalker" drone was supplemented by a DJI Phantom 3 (Figure 5). This off-the-shelf drone was more reliable than the Skywalker, but, at the time, autonomous navigation for DJI products was just becoming available via third party apps, to make photogrammetry data collection more efficient, and it was not yet implemented in our workflow. However, it could still be flown manually in order to collect photogrammetry sets and was invaluable for times when the fixed-wing drone was damaged (Figure 6). Because of the remote location, when the fixed-wing drone crashed, we flew the backup quadcopter until we returned to Amman and repaired the fixed-wing drone.

Figure 5. Phantom 3 at Wadi al-Qattafi, looking south with Mesa 3 in the background.

Figure 6. The results of a crash landing of the fixed-wing drone. Repaired by the pilot (Hill), the plane flew again several weeks later.

The survey described here builds upon earlier tests of drone mapping in the region with the Eastern Badia Archaeological Project. In 2012 and 2013, fixed-wing and rotary-wing drones captured high-resolution imagery around the main habitation sites at Wisad Pools as part of a survey to map the distribution of petroglyphs [41]. This confirmed the feasibility of attempting a larger drone survey in this austere environment.

In order to create real-world spatial data from drone-derived imagery, low-elevation images are processed in photogrammetry software to create undistorted orthophotographs and digital elevation models (DEMs) of the landscape. This has become a common practice in archaeology for recording spatial data from small scale to landscape scale [4,5,37,42,43]. All processing used Agisoft Photoscan Pro/Metashape. Initial processing in the field ensured sufficient coverage to construct a complete 3D model but final processing was done after the season, on a dedicated PC for 3D processing.

At Wadi al-Qattafi, the anthropogenic features densely clustered around the basalt mesas are practically nonexistent as distance to the mesas increases. This is almost certainly due to the difficulty of moving the large basalt stones that are favored for building construction, with the additional benefit of avoiding flooding areas during winter rains. In recognition of this, the limited field time, and flight time available for the survey, our approach centered on the mesas and the structures on and around them (Figures 7 and 8). Instead of flying over every square centimeter of the landscape, we focused on getting the highest resolution coverage of the areas surrounding, and on top of, each mesa. This allowed for a straightforward mapping process, where we could focus, serially, on one mesa at a time, planning flights that would ensure sufficient coverage of that mesa. Depending on the size of the mesas, typically this could be achieved in one to three flights, to ensure sufficient image overlap for photogrammetric processing.

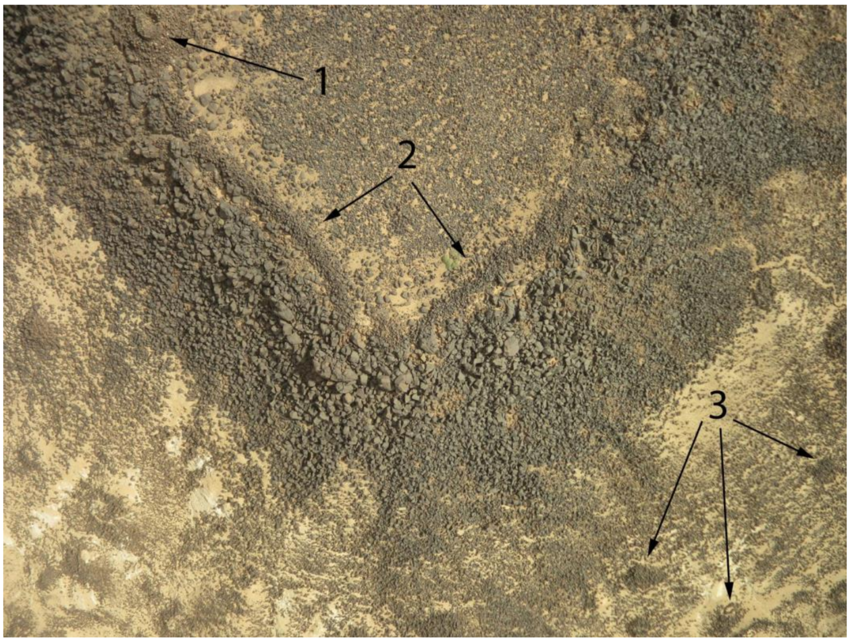

Figure 7. A single overhead image of Mesa 8 from the fixed-wing drone, showing a range of anthropogenic features visible from low-elevation, including (1) tomb, (2) walls, and (3) anthropogenic structures.

2.1. Limitations of Drone Survey in the Desert

The Black Desert is a difficult place to fly drones. The Eastern Badia Archaeological Project camps on site, as to reach the nearest town requires a few hours of rough, off-road driving. As a result, there is no power available for charging drone batteries, no supplies available for repair, and no replacement parts for drones if problems arise. As part of our logistical supplies, we brought a generator to charge the drone, camera, and laptop batteries, and copious spare parts and supplies to support moderate in-field repairs. This allowed us to fly multiple sessions each day, with breaks for charging batteries on the generator. We also planned to break up the survey into multiple visits to the site, in case of problems that required more extensive repair, with the first survey visit in April 2016, and the second, overlapping with the Eastern Badia Archaeological Project field season, in June 2016. This proved to be a good plan because of a catastrophic failure of the Skywalker fixed-wing drone in the second week of the April survey (Figure 6). Although flights continued during that phase with the manually flown Phantom, this was less efficient. Upon our return to Amman we found spare parts, repaired the fixed-wing, and flew again during the second session in June.

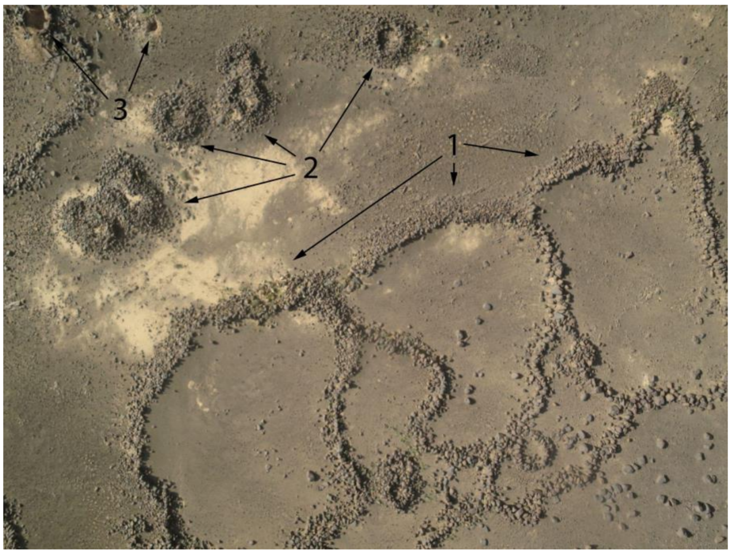

Figure 8. Example of images collected during the survey. This shot was taken by the fixed-wing drone over Mesa 4 (Maitland's Mesa) and shows (1) "garden walls", (2) ghura (local Arabic term for the mesas) huts, and (3) evidence of recent looting.

Due to the challenging field location, as well as the budget and time constraints, we did not attempt to place and record ground control points (GCPs) in the imagery we collected, nor did we have precision GNSS (real-time kinematic) geotags available for the imagery recorded onboard either drone. The large scale of the survey made it practically impossible to try to place targets across the landscape that we could record via total station or GNSS. Moreover, we had no access to GNSS equipment that would have made it possible to calculate accurate positions for targets on the ground or drones in the air [38,44]. Instead, we relied on the uncorrected GNSS geotags recorded for each photo. On the Phantom 3, images automatically include GNSS geotag positions from the onboard GNSS used for navigation. On the Skywalker plane, the GNSS flight track from the flight control computer can be downloaded after each mission, postprocessed, and then appended as geotags to the images. Photogrammetry software used basic positioning of the imagery for both alignment and rough georeferencing. Although the low-accuracy of the uncorrected GNSS data introduces significant error into the resulting orthophoto position, this could be improved later by adjusting the georeferencing of the orthophotos to satellite imagery in ArcGIS.

Both the technology and the laws pertaining to low-elevation aerial survey evolved rapidly over the last decade. Before 2012 and the beginning of the drone revolution in archaeology, the Eastern Badia Project relied on kite aerial photography (KAP) for collecting photogrammetry data sets to map parts of the survey region [30]. We began using UAVs in 2012, though initially budget and technological constraints limited the area that could be surveyed as it was only feasible to fly a manually piloted fixed-wing drone. Subsequent years allowed the adoption of onboard flight control computers capable of autonomous, preplanned mapping missions (as above) and the beginning of multirotor flights that take advantage of the convenience of vertical take-off and landing, and hovering [41,45].

These results represent the state of our workflow as of the summer of 2016. Even a few months after the present survey, our workflow could have been improved significantly for an easier/more efficient autonomous mapping process with the multirotor Phantom 3. Moreover, in the years following the collection of this data, the state-of-the-art workflows for drone mapping, and the drones themselves, have made it even easier to cover such a large area in terms of both efficiency and accuracy [38]. Smith [7], for example, provides a nice overview of the kind of workflow that is now possible in the region.

However, drone laws have also been evolving rapidly, around the globe, in response to the growing number of users of this technology and the potential dangers that they pose [46]. Jordan is no exception, and rules surrounding drone use have changed since this data was collected. After the summer of 2016, it became more difficult to obtain permission from the Jordanian government for drone flights. In subsequent seasons, we were forced to return to KAP technology to obtain limited aerial images for site photogrammetry [38]. However, the recent success of Smith et al. [7] in the badia suggests it is once again becoming possible to get permission to do this kind of work.

2.2. Online Collaboration

After recording the raw data in the field and postprocessing the images afterward, documenting all of the anthropogenic features in the resulting orthophotos and DEMs was the next, large task. Given our initial estimate that several thousand features are present on the landscape, this was no small endeavor. Initially, we planned to rely on crowd-sourcing to do the markup, led by the recent trend toward incorporating remote volunteers through online portals [47–49]. However, after some initial forays with volunteers, and on the basis of recent criticisms of this approach by scholars like Jesse Casana [50,51], we decided the number of features still fell within a total that could be handled by Casana's "Brute Force" method, utilizing systematic exploration by experts [51]. We set up a collaborative and accessible project in ArcGIS online to enable expert researchers to jointly access all of the processed orthophoto imagery, and edit a shared database of anthropogenic features in order to overcome the difficulty presented by managing traditional GIS approaches and large datasets. Given the difficulties inherent in identification of poorly understood ancient features, and the vicissitudes of imagery (e.g., shadows, blurry areas of imagery), this option seems the more reliable path for this project. Were this project a little bigger, it would have made sense to try to utilize a semiautomated classification system (e.g., [52–55]) however, given the scale of the survey, and the noise in the data, we opted for a manual analysis.

3. Results

Despite the difficulties operating drones in the badia, we were able to record around 40 flights worth of data, covering the majority of the mesas in the survey area. In terms of total flight time, this equates to only around 18–20 h, but with the difficulties of operating in the desert, the reliance on limited batteries and a generator, hardware problems, etc., it took two trips of approximately two weeks each to complete these 40 flights. The mix of autonomous and manual flights, the effect of significant wind, and the challenges of launching, landing, and operating the drones in such a difficult environment produced a challenging set of images for processing. Nevertheless, the images captured the landscape at a significantly greater resolution than was previously available, with the majority of images being sharp and at single-centimeter resolution (Figures 7 and 8). After processing and markup, we produced a database that records thousands of features (Figures 9 and 10), tabulated in Table 1.

Over the course of 40 flights, mixed between the fixed-wing and rotary-wing drones, we recorded approximately 12,500 aerial images. The majority of missions flew at around 100 m above the ground, with a goal of recording images with sufficient resolution for around 5 cm/pixel in the resulting orthophotographs. However, altitude was sometimes adjusted to account for the difference in elevation between the tops of the mesas and the lower elevation ground around them. The fixed-wing drone was capable of doing "terrain following" to keep a constant relative altitude when the elevation changed, but this also significantly impacted battery life, so we often opted to fly at an altitude that would ensure sufficient overlap of images at the tops of the mesas, and slightly lower ground resolution at the bottom of the mesas. A few flights were repeated due to problems with the camera (i.e., all images overexposed), the drone (i.e., drone crashed, problems with mission planning or coverage), and a few missions were done over additional features just outside of the core survey area published here.

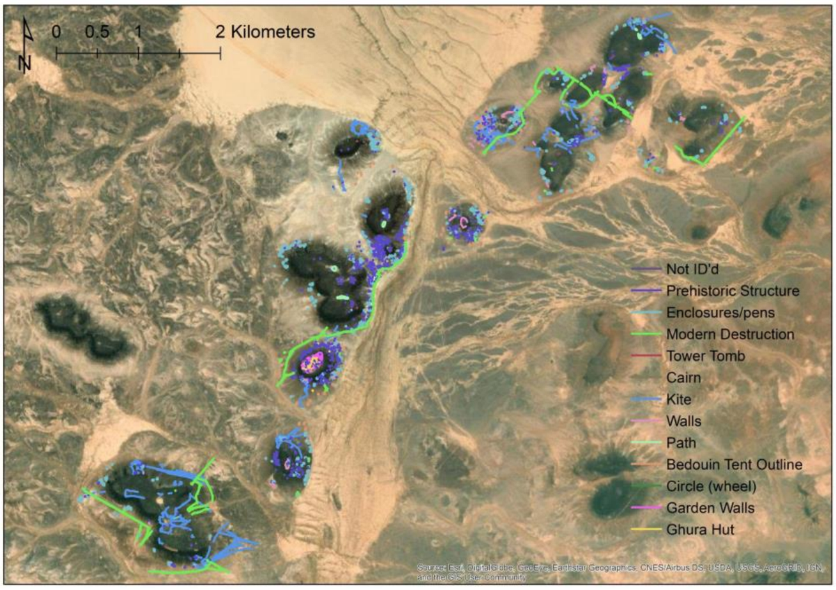

Figure 9. Overview of the Wadi al-Qattafi survey database displayed against an Esri World Imagery basemap. The basemap is used as a background because the orthophotos are not continuous for the entire area (see above). Basemap source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

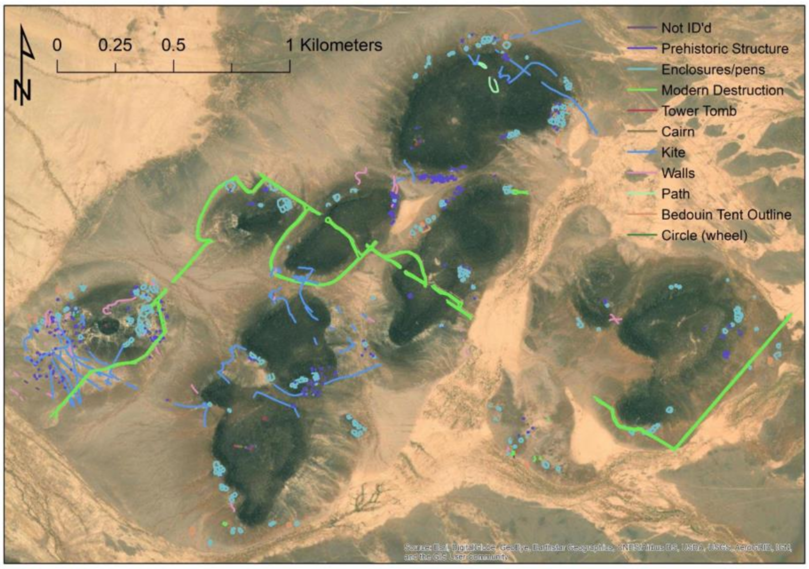

Figure 10. Closeup of all identified features in the northern end of the survey region. Basemap source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Table 1. Total count of various types of features recorded in the survey database.

Mesa #	1/Anthropogenic Structures	2/Enclosure/ Pen	3/Modern Destruction/ Building	4/Tower Tomb	5/Cairn/ Tail	6/Kite	7/Wall	8/Path	9/Bedouin Tent Outline	10/Circle (Wheel)	11/Garden Wall	12/Ghura Hut	Total
2	57	45	3	2	48	3	3	0	0	0	0	0	**161**
3	97	40	2	1	0	1	4	0	4	0	0	0	**149**
4	318	24	2	1	42	0	2	0	10	0	54	63	**516**
5	80	74	1	6	0	0	1	2	0	0	0	0	**164**
6	91	37	0	0	0	0	1	1	1	0	0	0	**131**
7	66	31	1	1	0	0	3	0	1	1	0	1	**105**
8	84	44	3	2	0	0	3	0	11	0	0	0	**147**
9	11	33	0	1	0	1	0	0	9	0	0	0	**55**
10	95	61	1	1	0	1	12	0	7	0	0	0	**178**
11	4	39	3	3	12	0	2	0	2	0	0	0	**65**
12	30	20	0	0	0	1	2	0	0	0	0	0	**53**
13	29	3	1	0	0	1	4	0	0	0	0	0	**38**
14	28	29	1	0	0	0	1	0	3	0	0	0	**62**
15	100	52	0	2		1	0	2	3	0	0	0	**160**
16	8	36	1	0	0	0	2	0	1	0	0	0	**48**
17	10	9	1	0	0	0	0	0	0	0	0	0	**20**
Total	**1108**	**577**	**20**	**20**	**102**	**9**	**40**	**5**	**52**	**1**	**54**	**64**	**2052**

As discussed above, the use of the s100 camera in "intervalometer" mode, combined with the limitations of the shutter speed, aperture of the camera, and the relatively heavy vibrations from the Skywalker motor created a significant number of "blurry" photos in the resulting image sets. One benefit of taking more photos than necessary was, then, also the possibility of removing some blurry photos from the image processing, while still retaining sufficient overlap for a complete orthophoto. However, the photos from the s100 did not just produce images that were "blurry" or "not blurry", but, rather, a range of sharpness that overlaps some critical threshold of utility. Thankfully, Agisoft Metashape includes a tool to "estimate image quality", an imperfect way to quantify sharpness and useability of the individual photos in each photo set. For each set of photos, we quantified image quality, and then removed all of the lowest-value images (usually photos with egregious motion blurring during sharp turns) from processing. In some cases, the quality estimate is high even for images with very bad motion blur, so in addition to relying on calculated quality values, we also manually removed individual frames that were obviously useless for processing. However, choosing a quality threshold to remove images from processing is not straightforward in this case, as removing too many photos would often result in holes in the resulting orthophotos. So, for each image set, depending on the relative proportion and distribution of sharp images, some "blurrier" images would be manually retained to ensure a complete orthophoto resulting in some areas in a final orthophoto that would be visibly less sharp. As a result, it is difficult to quantify the total number of "blurry" vs. "sharp" images. However, the missions over Mesa 2 provide a good example. This is the largest mesa and required three fixed-wing flights to cover. This was supplemented by two manual flights with the rotary wing. In total, there were 1430 images recorded of the mesa. This includes blurry images, and images on the ground and during the launch and landing sequence. Of the 1430 images, only 754 were used in the final orthophoto, which has a ground resolution of 8.4 cm/pixel. A summary of the total number of photos recorded in relationship to each of the orthophotos and the resulting ground resolution of each is provided in Table 2.

In our original plan, we hoped to produce a single continuous orthophoto for the entire survey area. However, due to the limitations of fieldwork in the Black Desert, problems encountered with the drones, and constraints of batteries and hardware, we decided early on to prioritize recording all of the anthropogenic features, which cluster close to the individual mesas. In practice, this meant that we did not record sufficient data to produce orthophotos that overlap where the mesas are far apart, since there are no anthropogenic features to record in much of the large areas between the mesas. In the northern half of the survey area, the mesas are naturally close enough together that all of the missions from these mesas (mesas 10–16) could be processed together to produce a single continuous orthophoto, but for the mesas to the south (mesas 2–9) the photos from missions over each mesa were processed separately. So, the final result of the processing was eight orthophotos. Because these were produced without ground control points, they have significant error (up to several meters) though the georeferencing was later updated, in ArcGIS, using lower-resolution satellite imagery.

Table 2. Details of the orthophotos used in the analysis.

Orthophoto of Mesa #	Total Images	Number of Images Used in Orthophoto	Cm/Pixel of Orthophoto
2	1430	754	8.4
3	460	227	5.7
4	1017	363	2.4
5	786	471	9
6 + 7	801	462	3.4
8	368	282	4.1
9	479	325	3.9
10–17	3600	3234	7.5

In total, the drone survey allowed us to record over 2000 discrete anthropogenic features (Table 1). The majority of these (1108, 54%) are categorized as "prehistoric structures" and include a range of (likely) Neolithic structures similar to the buildings excavated at Mesa 4 and 7 over the last several years (Figure 11) by the Eastern Badia Archaeological Project [30–32,56–58]. In addition to the general category of "prehistoric features", we tracked additional, more specific categories of prehistoric structures such as kites, circles, and ghura huts. Some, such as tower tombs and cairns, may date to later, historic periods, although this is by no means certain. So-called tower tombs are well-distributed across the mesas, likely because they are large well-constructed monuments meant to commemorate individuals and were likely placed intentionally away from other tower tombs as prominent and visible markers on the landscape [59]. Some features cannot be assigned a probable date or function and so are only identified as walls. Modern and historic features are also tracked, including Bedouin tent outlines and modern destruction such as roads (see below).

Figure 11. Orthophotograph of Structure SS1, a Late Neolithic building on the slope of Mesa 7.

The database of anthropogenic features documents a few key features of the Neolithic use of the landscape that we documented previously but struggled to effectively visualize. Across the whole survey region, Neolithic structures cluster on and immediately adjacent to the basalt mesas. Instead, it is far easier to create level ground on the slopes and construct buildings as close to the source of the raw material as possible [30]. This is evident by looking at the location of features in the digital elevation models, which clearly show the clustering on the slopes of the mesas.

There are a few areas with particular concentrations of prehistoric structures, many of which may date to the Late Neolithic period. The greatest concentrations occur around M4 (Maitland's Mesa), with more than twice as many structures located here as on any other mesa (Table 1, Figure 12). Additional concentrations on the eastern slopes of M5, and between the slopes of M6 and M7 form a second significant cluster. There is apparently a tendency for these to be located along the eastern slopes, perhaps because the main channel of Wadi al-Qattafi runs immediately to the east. This is, of course, the side where kites are also generally located, and which open to the east. Nonetheless, there is not an obvious correlation between the location of the kites and the prehistoric structures, though they are close. This possible correlation will be the focus of future investigations that build upon this study.

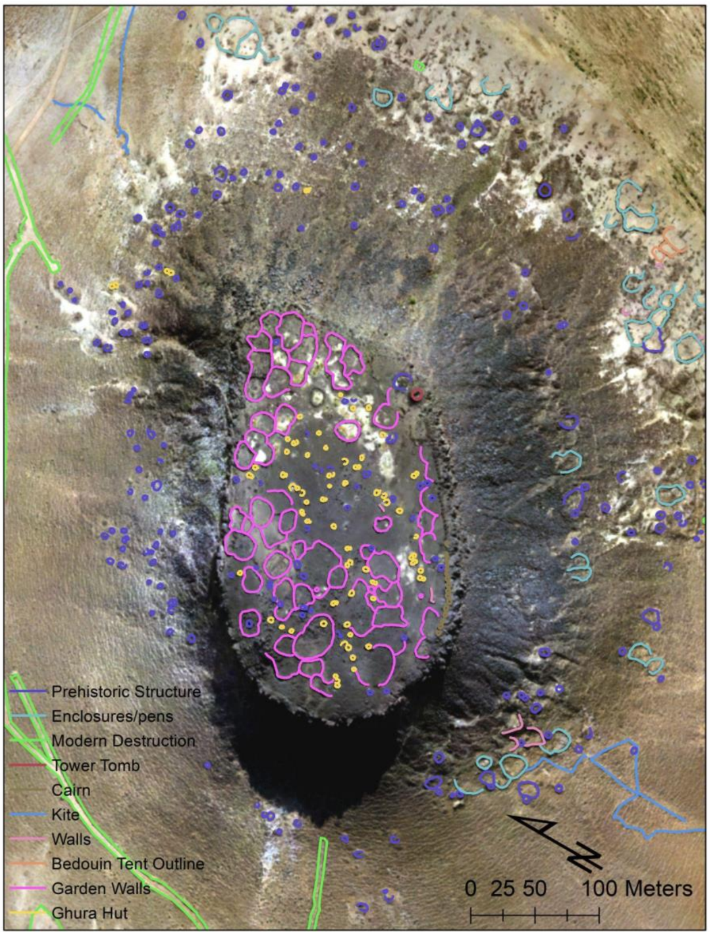

Figure 12. Closeup of M4, with orthophoto basemap, showing clustering of structures on the lower slopes, and ghura huts and garden walls on the top.

In addition to the largest concentration of structures, M4 also contains structures found almost nowhere else in the survey area. Ghura huts are concentrated on top of M4, and may suggest a chronological shift. Similar constructions at Tulul al-Ghusayn in the northeastern badia date to the mid-fourth millennium cal BCE, providing a possible date for these on M4 (Ref. [60] and Figure 4). Also concentrated on the top of M4 are the enigmatic enclosures.

These are similar to structures identified as gardens at Tulul al-Ghusayn, where they are located on the slopes of the crater [61,62]. The slight slope of the western side of M4 towards the east was perhaps the reason this mesa was chosen, while others were not.

The database also tracks the presence of desert kites. Kites are, of course, present throughout the region and are increasingly well-mapped using satellite and historical imagery [34,41,63]. However, the kites in the survey region overlooked in some of the satellite-mapping studies [35], are located well away from the well-documented kite "chains" in the heart of the harra. We were aware of most of the kites in the survey area before we began this project from careful study of the available satellite imagery, but the drone data provided several new insights into the kites in the region. First, the elevation data provides clear evidence for some of the crucial decisions about building kites. As we documented before [45], and others have noted [34,64,65] the kites were often built utilizing the topography in order to make more effective traps. This is clear when visualizing the location of kites with the digital elevation models. Kites are frequently built so that the enclosure, the business end of the trap where gazelle were guided so that they could be killed and harvested, is hidden by the slopes of the mesas. The kites on Tell A (mesa #2), for instance, have one enclosure placed on top of the mesa in a very shallow depression (Figure 13), while the traps on the sides have the enclosures wrapped around the base of the mesa. This sort of visualization is not possible with satellite imagery because it lacks elevation data. A more exciting discovery was the realization that the kites in the survey area are, in fact, all linked together like the more well-known "chains" of traps to the north via a series of short wall sections and the natural barriers presented by the mesas themselves (Figure 14 and Ref. [45]). There are nine kites in the survey area, and they probably connected to at least two additional kites to the north.

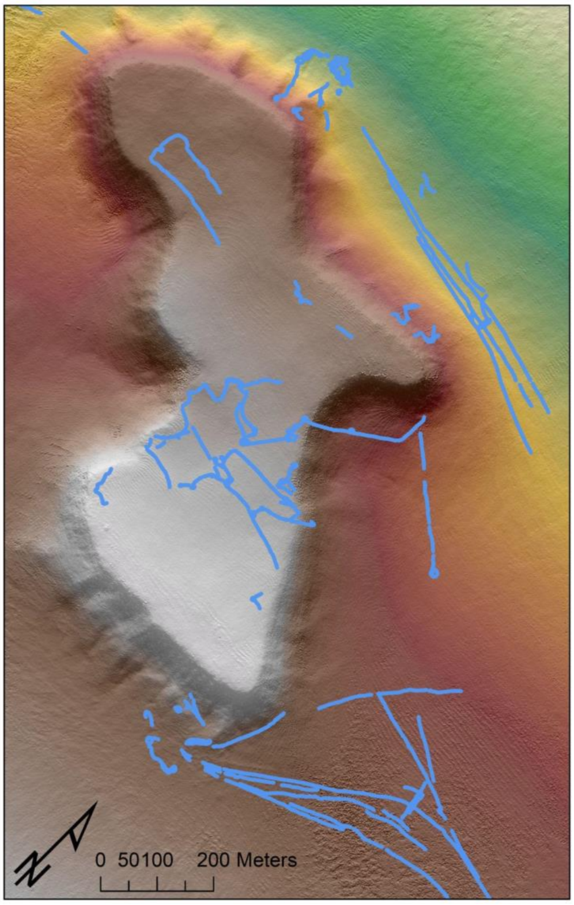

Figure 13. Three kites clustered on Mesa #2 ("Tell A"). One enclosure utilizes the top of the mesa, while the other two wrap around the northern and southern sides.

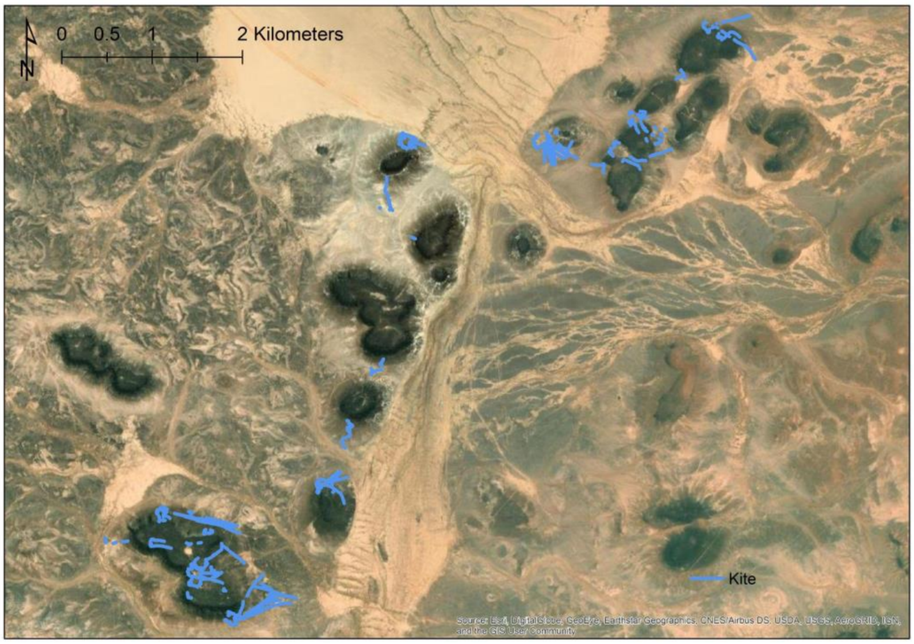

Figure 14. Overview of kites in the survey region. Kites spread along the mesas, and connect by walls or the natural topography of the mesas themselves. Basemap source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

The survey also documented significant damage to the landscape, despite the relatively remote area visited by only a few Bedouin annually. There is significant evidence of recent alterations to the prehistoric landscape. The greatest damage is the result of tracks cut across the mesas with bulldozer or road-grader blades. This damage is the most conspicuous feature in the aerial imagery and clearly visible in Figures 9 and 10 as straight lines cutting across the landscape and through Neolithic features such as the kites on Mesa 10. Smaller-scale modification to the landscape is visible in recent Bedouin tent outlines and newly rebuilt animal pens, which are tracked in the GIS database. Finally, the imagery also picks up damage from recent looting events. Many of the structures on and around the mesas have been disturbed by looting, particularly the apparent tower tombs. This is discernible in many of the images (e.g., Figure 8) and tracked by us on the ground (Figure 15). This is a common problem for archaeological sites around the world, but it is nevertheless disappointing to find significant damage at such remote sites. Although there is less damage here than in many of the well-documented and more easily visited sites in Jordan (see, for instance, [66,67]), the level of destruction in this relatively inaccessible area is concerning, continuous, and particularly devastating to the more easily destroyed prehistoric remains.

Tracking looting is critical for archaeologists and remote-sensing experts concerned about the preservation of cultural heritage [47,66,68–73], and this work increasingly focuses on large-scale looting across large regions [69] with automated or semiautomated detection of looting events [72] based on satellite imagery. Drone-based looting detection provides a significantly higher resolution for identifying smaller levels of site and feature damage, such as the relatively small-scale and haphazard looting found across the Wadi al-Qattafi survey region. The damage here is not as extensive and dramatic as at many other sites around the world, but prehistoric structures are also more easily destroyed. This destructive and illegal digging would be difficult to detect using satellite-based means alone, and even at this smaller scale should be cause for concern. As the feasibility of large-scale drone-based regional surveys increases (as evidenced by surveys such as this one), drones become a greater tool for heritage site monitoring.

Figure 15. Oblique terrestrial documentation of recent looting near M9, recorded with a pole aerial photography (PAP) setup.

4. Conclusions

Archaeological remote sensing of the mesas along Wadi al-Qattafi using drones provides a dramatically improved level of mapping in this area. By creating georeferenced orthophotographs and DEMs, the resulting superior resolution improves the cost-effectiveness of survey beyond anything that could be obtained a mere decade ago without extremely large budgets. Drone-derived remote sensing can achieve resolutions of 1–2 cm per pixel in contrast to the average 40–50 cm/pixel typically available with satellite data; while the latter is acceptable for larger landscape features, it is ineffective for mapping many prehistoric features. In the landscape along Wadi al-Qattafi, and other regions of the Black Desert, prehistoric buildings would remain largely unmapped at the broader scale if we relied solely on satellite imagery. Like the kites, many of the prehistoric structures are barely perceptible on the ground (in part the reason that these were essentially unknown before recent field projects were initiated). This sort of mapping project helps us to understand how the individual prehistoric structures in the badia represent a large-scale, intensive, and interrelated use of the landscape. Excavations provide critical details about how people lived during this period, but this sort of mapping project helps to place those results into a regional context.

At times intensively visited and exploited, this region apparently witnessed intensive occupation and building during the Late Neolithic period. Similar evidence is becoming apparent from the Jebel Qurma project to the southwest of Wadi al-Qattafi [74,75] and the Jawa Hinterland project to the north [60,61]. Whether the result of increased gazelle hunting or herding of domesticates, or both, the significant increase in building a variety of structures along Wadi al-Qattafi underscores the presence of small groups spending extended periods of time there. This evidence contradicts earlier assumptions that the region was only rarely populated by occasional, short-term hunter–herders, fundamentally changing our understanding of how and when the region was populated. Rather than a marginal environment of limited utility, this region was populated and repeatedly visited. This further contextualizes the kites along Wadi al-Qattafi, which form a chain by incorporating walls and mesas. Could these kites relate to the hundreds of similar structures that apparently date to the Late Neolithic? The addition of this fine-grained data would support the coeval nature of kite infrastructure and the many small Late Neolithic structures clustered around the slopes of the mesas.

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References

1. Campana, S. Drones in Archaeology. State-of-the-Art and Future Perspectives: Drones in Archaeology. *Archaeol. Prospect.* **2017**, *24*, 275–296. [CrossRef]
2. Agudo, P.; Pajas, J.; Pérez-Cabello, F.; Redón, J.; Lebrón, B. The Potential of Drones and Sensors to Enhance Detection of Archaeological Cropmarks: A Comparative Study Between Multi-Spectral and Thermal Imagery. *Drones* **2018**, *2*, 29. [CrossRef]
3. Olson, K.G.; Rouse, L.M. A Beginner's Guide to Mesoscale Survey with Quadrotor-UAV Systems—CORRIGENDUM. *Adv. Archaeol. Pract.* **2019**, *7*, 215. [CrossRef]
4. Chiabrando, F.; D'Andria, F.; Sammartano, G.; Spanò, A. UAV Photogrammetry for Archaeological Site Survey. 3D Models at the Hierapolis in Phrygia (Turkey). *Virtual Archaeol. Rev.* **2018**, *9*, 28–43. [CrossRef]
5. Hill, A.C. UAVs at Marj Rabba, Israel: Low-Cost High-Tech Tools for Aerial Photography and Photogrammetry. *SAA Archaeol. Rec.* **2013**, *13*, 25–29.
6. Gutiérrez, G.; Searcy, M.T. Introduction to the UAV Special Edition. *SAA Archaeol. Rec. Spec. Issue Drones Archaeol.* **2016**, *16*, 6–9.
7. Smith, S.L. Drones over the "Black Desert": The Advantages of Rotary-Wing UAVs for Complementing Archaeological Fieldwork in the Hard-to-Access Landscapes of Preservation of North-Eastern Jordan. *Geosciences* **2020**, *10*, 426. [CrossRef]
8. Bendea, H.; Chiabrando, F.; Tonolo, F.G.; Marenchino, D. Mapping of Archaeological Areas Using a Low-Cost UAV. The Augusta Bagiennorum Test Site. In Proceedings of the XXI International CIPA Symposium, Athens, Greece, 1–6 October 2007; Volume 1.
9. Risbøl, O.; Gustavsen, L. LiDAR from Drones Employed for Mapping Archaeology—Potential, Benefits and Challenges. *Archaeol. Prospect.* **2018**, *25*, 329–338. [CrossRef]
10. VanValkenburgh, P.; Cushman, K.C.; Butters, L.J.C.; Vega, C.R.; Roberts, C.B.; Kepler, C.; Kellner, J. Lasers Without Lost Cities: Using Drone Lidar to Capture Architectural Complexity at Kuelap, Amazonas, Peru. *J. Field Archaeol.* **2020**, *45*, S75–S88. [CrossRef]
11. Verhoeven, G.J.J. Providing an Archaeological Bird's-Eye View—An Overall Picture of Ground-Based Means to Execute Low-Altitude Aerial Photography (LAAP) in Archaeology. *Archaeol. Prospect.* **2009**, *16*, 233–249. [CrossRef]
12. Lehmann, J.R.K.; Smithson, K.Z.; Prinz, T. Making the Invisible Visible: Using UAS-Based High-Resolution Color-Infrared Imagery to Identify Buried Medieval Monastery Walls. *J. Unmanned Veh. Syst.* **2015**, *3*, 58–67. [CrossRef]
13. Herrmann, J.T.; Glissmann, B.; Sconzo, P.; Pfälzner, P. Unmanned Aerial Vehicle (UAV) Survey with Commercial-Grade Instruments: A Case Study from the Eastern Ḫabur Archaeological Survey, Iraq. *J. Field Archaeol.* **2018**, *43*, 269–283. [CrossRef]
14. Lech, P.; Zakrzewski, P. Depopulation and Devastation: Using GIS for Tracing Changes in the Archaeological Landscape of Kharaib Al-Dasht, a Late Islamic Fishing Village (Kuwait). *Archaeol. Prospect.* **2021**, *28*, 17–24. [CrossRef]
15. Stek, T.D. Drones over Mediterranean Landscapes. The Potential of Small UAV's (Drones) for Site Detection and Heritage Management in Archaeological Survey Projects: A Case Study from Le Pianelle in the Tappino Valley, Molise (Italy). *J. Cult. Herit.* **2016**, *22*, 1066–1071. [CrossRef]
16. Yasur-Landau, A.; Shtienberg, G.; Gambash, G.; Spada, G.; Melini, D.; Arkin-Shalev, E.; Tamberino, A.; Reese, J.; Levy, T.E.; Sivan, D. New Relative Sea-Level (RSL) Indications from the Eastern Mediterranean: Middle Bronze Age to the Roman Period (~3800–1800 y BP) Archaeological Constructions at Dor, the Carmel Coast, Israel. *PLoS ONE* **2021**, *16*, e0251870. [CrossRef]
17. Hill, A.; Rowan, Y.; Kersel, M.M. Mapping with Aerial Photographs: Recording the Past, the Present, and the Invisible at Marj Rabba, Israel. *Near East. Archaeol.* **2014**, *77*, 182–186. [CrossRef]

18. Al Kwatli, M.A.; Gillot, P.Y.; Zeyen, H.; Hildenbrand, A.; Al Gharib, I. Volcano-Tectonic Evolution of the Northern Part of the Arabian Plate in the Light of New K–Ar Ages and Remote Sensing: Harrat Ash Shaam Volcanic Province (Syria). *Tectonophysics* **2012**, *580*, 192–207. [CrossRef]
19. Ilani, S.; Harlavan, Y.; Tarawneh, K.; Rabba, I.; Weinberger, R.; Ibrahim, K.; Peltz, S.; Steinitz, G. New K-Ar Ages of Basalts from the Harrat Ash Shaam Volcanic Field in Jordan: Implications for the Span and Duration of the Upper-Mantle Upwelling beneath the Western Arabian Plate. *Geology* **2001**, *29*, 171–174. [CrossRef]
20. Bender, F. *Geologie von Jordanien*; Regionlae Geologie Erde; Gebrueder Borntraeger: Stuttgart, Germany, 1968; Volume 7.
21. Ibrahim, K. *The Geological Framework for the Harrat Ash-Shaam Basaltic Super-Group and Its Volcanotectonic Evolution*; 1:50,000 Geological Mapping Series Geological Bulletin; Natural Resources Authority, Geological Directorate Geological Mapping Division: Amman, Jordan, 1993.
22. Rabaa', I. *The Geology of Umm Nukhayla and Wadi al Qattafi Areas Map Sheets No. 3453-II and 3453-I*; 1:50,000 Geo-logical Mapping Series Geological Bulletin; Natural Resources Authority, Geological Directorate Geological Mapping Division: Amman, Jordan, 2005.
23. Betts, A.V.; Colledge, S.; Martin, L.; McCartney, C.; Wright, K.; Yagodin, V. *The Harra and the Hamad: Excavations and Surveys in Eastern Jordan, Volume 1*; Sheffield Archaeological Monographs; Sheffield Academic Press: Sheffield, UK, 1998; Volume 9.
24. Garrard, A.; Baird, D.; Colledge, S.; Martin, L.; Wright, K. Prehistoric Environment and Settlement in the Azraq Basin: An Interim Report on the 1987 and 1988 Excavation Seasons. *Levant* **1994**, *26*, 73–109. [CrossRef]
25. Maher, L.A.; Macdonald, D.A. Communities of Interaction: Tradition and Learning in Stone Tool Production Through the Lens of the Epipaleolithic of Kharaneh IV, Jordan. In *Culture History and Convergent Evolution*; Groucutt, H.S., Ed.; Vertebrate Paleobiology and Paleoanthropology; Springer International Publishing: Cham, Switzerland, 2020; pp. 213–243; ISBN 978-3-030-46125-6.
26. Meister, J.; Krause, J.; Müller-Neuhof, B.; Portillo, M.; Reimann, T.; Schütt, B. Desert Agricultural Systems at EBA Jawa (Jordan): Integrating Archaeological and Paleoenvironmental Records. *Quat. Int.* **2017**, *434*, 33–50. [CrossRef]
27. Nowell, A.; Walker, C.; Cordova, C.E.; Ames, C.J.H.; Pokines, J.T.; Stueber, D.; DeWitt, R.; al-Souliman, A.S.A. Middle Pleistocene Subsistence in the Azraq Oasis, Jordan: Protein Residue and Other Proxies. *J. Archaeol. Sci.* **2016**, *73*, 36–44. [CrossRef]
28. Richter, T. Natufian and Early Neolithic in the Black Desert, Eastern Jordan. In *Quaternary of the Levant*; Enzel, Y., Bar-Yosef, O., Eds.; Cambridge University Press: Cambridge, UK, 2017; pp. 715–722; ISBN 978-1-316-10675-4.
29. Jones, M.D.; Richter, T.; Rollefson, G.; Rowan, Y.; Roe, J.; Toms, P.; Wood, J.; Wasse, A.; Ikram, H.; Williams, M.; et al. The Palaeoenvironmental Potential of the Eastern Jordanian Desert Basins (Qe'an). *Quat. Int.* **2021**, S1040618221003724. [CrossRef]
30. Rowan, Y.M.; Rollefson, G.O.; Wasse, A.; Abu-Azizeh, W.; Hill, A.C.; Kersel, M.M. The "Land of Conjecture:" New Late Prehistoric Discoveries at Maitland's Mesa and Wisad Pools, Jordan. *J. Field Archaeol.* **2015**, *40*, 176–189. [CrossRef]
31. Wasse, A.; Rowan, Y.; Rollefson, G.O. A 7th Millennium BC Late Neolithic Village at Mesa 4 in Wadi Al-Qattafi, Eastern Jordan. *Neo-Lithics* **2012**, *1*, 15–24.
32. Rollefson, G.O.; Wasse, A.; Rowan, Y.; Kersel, M.; Jones, M.; Lorentzen, B.; Hill, A.C.; Ramsay, J. The 2016 Excavation Season at the Late Neolithic Structure SS-1 on Mesa 7, Black Desert. *Neo-Lithics* **2017**, *2*, 19–29.
33. Rollefson, G.O.; Athanassas, C.D.; Rowan, Y.M.; Wasse, A.M. First Chronometric Results for 'Works of the Old Men': Late Prehistoric 'Wheels' near Wisad Pools, Black Desert, Jordan. *Antiquity* **2016**, *90*, 939–952. [CrossRef]
34. Crassard, R.; Barge, O.; Bichot, C.-E.; Brochier, J.É.; Chahoud, J.; Chambrade, M.-L.; Chataigner, C.; Madi, K.; Régagnon, E.; Seba, H. Addressing the Desert Kites Phenomenon and Its Global Range through a Multi-Proxy Approach. *J. Archaeol. Method Theory* **2015**, *22*, 1093–1121. [CrossRef]
35. Kempe, S.; Al-Malabeh, A. Hunting Kites ('Desert Kites') and Associated Structures along the Eastern Rim of the Jordanian Harrat: A Geo-Archaeological Google Earth Images Survey. *Z. Orient-Archäol.* **2010**, *10*, 46–86.
36. Eisenbeiss, H.; Sauerbier, M. Investigation of Uav Systems and Flight Modes for Photogrammetric Applications: Investigation of UAV Systems and Flight Modes. *Photogramm. Rec.* **2011**, *26*, 400–421. [CrossRef]
37. Roosevelt, C.H. Mapping Site-Level Microtopography with Real-Time Kinematic Global Navigation Satellite Systems (RTK GNSS) and Unmanned Aerial Vehicle Photogrammetry (UAVP). *Open Archaeol.* **2014**, *1*. [CrossRef]
38. Hill, A.C. Economical Drone Mapping for Archaeology: Comparisons of Efficiency and Accuracy. *J. Archaeol. Sci. Rep.* **2019**, *24*, 80–91. [CrossRef]
39. Dibble, H.; McPherron, S.J.P.; McPherron, T. 12V. *SAA Archaeol. Rec.* **2007**, *7*, 35–41.
40. Osborne, M. Mission Planner. 2021. Available online: https://ardupilot.org/planner/ (accessed on 1 January 2022).
41. Hill, A.C.; Rowan, Y.M.; Wasse, A.; Rollefson, G.O. Inscribed Landscapes in the Black Desert: Petroglyphs and Kites at Wisad Pools, Jordan. *Arab. Archaeol. Epigr.* **2020**, *31*, 245–262. [CrossRef]
42. Douglass, M.; Lin, S.; Chodoronek, M. The Application of 3D Photogrammetry for In-Field Documentation of Archaeological Features. *Adv. Archaeol. Pract.* **2015**, *3*, 136–152. [CrossRef]
43. Olson, B.R.; Placchetti, R.A.; Quartermaine, J.; Killebrew, A.E. The Tel Akko Total Archaeology Project (Akko, Israel): Assessing the Suitability of Multi-Scale 3D Field Recording in Archaeology. *J. Field Archaeol.* **2013**, *38*, 244–262. [CrossRef]
44. Hill, A.C.; Limp, F.; Casana, J.; Laugier, E.J.; Williamson, M. A New Era in Spatial Data Recording: Low-Cost GNSS. *Adv. Archaeol. Pract.* **2019**, *7*, 169–177. [CrossRef]
45. Hill, A.C.; Rowan, Y. Droning on in the Badia: UAVs and Site Documentation at Wadi al-Qattafi. *Near East. Archaeol.* **2017**, *80*, 114–123. [CrossRef]

46. Ravich, T. A Comparative Global Analysis of Drone Laws: Best Practices and Policies. In *The Future of Drone Use*; Custers, B., Ed.; Information Technology and Law Series; T.M.C. Asser Press: The Hague, The Netherlands, 2016; Volume 27, pp. 301–322; ISBN 978-94-6265-131-9.
47. Stone, E.C. Patterns of Looting in Southern Iraq. *Antiquity* **2008**, *82*, 125–138. [CrossRef]
48. Danti, M.; Branting, S.; Penacho, S. The American Schools of Oriental Research Cultural Heritage Initiatives: Monitoring Cultural Heritage in Syria and Northern Iraq by Geospatial Imagery. *Geosciences* **2017**, *7*, 95. [CrossRef]
49. Smith, M.L. Citizen Science in Archaeology. *Am. Antiq.* **2014**, *79*, 749–762. [CrossRef]
50. Casana, J. Global-Scale Archaeological Prospection Using CORONA Satellite Imagery: Automated, Crowd-Sourced, and Expert-Led Approaches. *J. Field Archaeol.* **2020**, *45*, S89–S100. [CrossRef]
51. Casana, J. Regional-Scale Archaeological Remote Sensing in the Age of Big Data: Automated Site Discovery vs. Brute Force Methods. *Adv. Archaeol. Pract.* **2014**, *2*, 222–233. [CrossRef]
52. Masini, N.; Lasaponara, R. Remote and Close Range Sensing for the Automatic Identification and Characterization of Archaeological Looting. The Case of Peru. *J. Comput. Appl. Archaeol.* **2021**, *4*, 126–144. [CrossRef]
53. Davis, D.S. Object-based Image Analysis: A Review of Developments and Future Directions of Automated Feature Detection in Landscape Archaeology. *Archaeol. Prospect.* **2019**, *26*, 155–163. [CrossRef]
54. Trier, Ø.D.; Zortea, M.; Tonning, C. Automatic Detection of Mound Structures in Airborne Laser Scanning Data. *J. Archaeol. Sci. Rep.* **2015**, *2*, 69–79. [CrossRef]
55. Verschoof-van der Vaart, W.B.; Lambers, K. Learning to Look at LiDAR: The Use of R-CNN in the Automated Detection of Archaeological Objects in LiDAR Data from the Netherlands. *J. Comput. Appl. Archaeol.* **2019**, *2*, 31–40. [CrossRef]
56. Rowan, Y.M.; Rollefson, G.O.; Wasse, A. Populating the Black Desert. The Late Neolithic Presence. In *Landscapes of Survival: The Archaeology and Epigraphy of Jordan's North-Eastern Desert and Beyond*; Akkermans, P.M., Ed.; Sidestone Press: Leiden, The Netherlands, 2020.
57. Rollefson, G.; Rowan, Y.; Wasse, A. The Late Neolithic Colonization of the Eastern Badia of Jordan. *Levant* **2014**, *46*, 285–301. [CrossRef]
58. Wasse, A.; Rowan, Y.M.; Rollefson, G.O. Flamingos in the Desert. In *Landscapes of Survival: The Archaeology and Epigraphy of Jordan's North-Eastern Desert and Beyond*; Akkermans, P.M., Ed.; Sidestone Press: Leiden, The Netherlands, 2020.
59. Akkermans, P.M.M.G.; Brüning, M.L. Nothing but Cold Ashes? The Cairn Burials of Jebel Qurma, Northeastern Jordan. *Near East. Archaeol.* **2017**, *80*, 132–139. [CrossRef]
60. Müller-Neuhof, B.; Abu-Azizeh, W. Milestones for a Tentative Chronological Framework for the Late Prehistoric Colonization of the Basalt Desert (North-Eastern Jordan). *Levant* **2016**, *48*, 220–235. [CrossRef]
61. Müller-Neuhof, B. A 'Marginal' Region with Many Options: The Diversity of Chalcolithic/Early Bronze Age Socio-Economic Activities in the Hinterland of Jawa. *Levant* **2014**, *46*, 230–248. [CrossRef]
62. Müller-Neuhof, B.; Abu Azizeh, W. Insights into the Chalcolithic / Early Bronze Age Colonization of the Harra (NE-Jordan)—Part I: Tūlūl al-Ghuṣayn. *Annu. Dep. Antiq. Jordan* **2018**, *59*, 411–424.
63. Hammer, E.; Lauricella, A. Historical Imagery of Desert Kites in Eastern Jordan. *Near East. Archaeol.* **2017**, *80*, 74–83. [CrossRef]
64. Helms, S.; Betts, A. The Desert "Kites" of the Badiyat Esh-Sham and North Arabia. *Paléorient* **1987**, *13*, 41–67. [CrossRef]
65. Abu-Azizeh, W.; Tarawneh, M.B. Out of the Harra: Desert Kites in South-Eastern Jordan. New Results from the South Eastern Badia Archaeological Project. *Arab. Archaeol. Epigr.* **2015**, *26*, 95–119. [CrossRef]
66. Contreras, D.A.; Brodie, N. The Utility of Publicly-Available Satellite Imagery for Investigating Looting of Archaeological Sites in Jordan. *J. Field Archaeol.* **2010**, *35*, 101–114. [CrossRef]
67. Kersel, M.M.; Hill, A. The (W)Hole Picture: Responses to a Looted Landscape. *Int. J. Cult. Prop.* **2019**, *26*, 305–329. [CrossRef]
68. Casana, J. Satellite Imagery-Based Analysis of Archaeological Looting in Syria. *Near East. Archaeol.* **2015**, *78*, 142–152. [CrossRef]
69. Casana, J.; Laugier, E.J. Satellite Imagery-Based Monitoring of Archaeological Site Damage in the Syrian Civil War. *PLoS ONE* **2017**, *12*, e0188589. [CrossRef]
70. Stone, E.C. An Update on the Looting of Archaeological Sites in Iraq. *Near East. Archaeol.* **2015**, *78*, 178–186. [CrossRef]
71. Contreras, D.A. Huaqueros and Remote Sensing Imagery: Assessing Looting Damage in the Virú Valley, Peru. *Antiquity* **2010**, *84*, 544–555. [CrossRef]
72. Tapete, D.; Cigna, F. Detection of Archaeological Looting from Space: Methods, Achievements and Challenges. *Remote Sens.* **2019**, *11*, 2389. [CrossRef]
73. Lauricella, A.; Cannon, J.; Branting, S.; Hammer, E. Semi-Automated Detection of Looting in Afghanistan Using Multispectral Imagery and Principal Component Analysis. *Antiquity* **2017**, *91*, 1344–1355. [CrossRef]
74. Akkermans, P.M.; Huigens, H.O.; Brüning, M.L. A Landscape of Preservation: Late Prehistoric Settlement and Sequence in the Jebel Qurma Region, North-Eastern Jordan. *Levant* **2014**, *46*, 186–205. [CrossRef]
75. Akkermans, P.M.M.G.; Bruning, M.L. East of Azraq: Settlement, Burial and Chronology from the Chalcolithic to the Bronze Age and Iron Age in the Jebel Qurma Region, Black Desert, North-East Jordan. In *Landscapes of Survival*; Akkermans, P.M.M.G., Ed.; Sidestone Press: Leiden, The Netherlands, 2020; pp. 185–215.