Prehistory and palaeoenvironments of the western Nefud Desert, Saudi Arabia

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Abstract

Mid-latitude dune fields offer significant records of human occupations in southwest Asia, reflecting human responses to past climate changes. Currently arid, but episodically wetter in the past, the Nefud desert of northern Saudi Arabia provides numerous examples of human-environment interactions and population movements in the desert belt. Here we describe results from interdisciplinary surveys in the western Nefud that targeted palaeolake deposits identified using satellite imagery. Surveys indicate the presence of thousands of discrete palaeolakes and palaeowetlands, providing valuable palaeoenvironmental records, and numerous archaeological and palaeontological assemblages. Geomorphological investigations suggest that many further deposits remain buried. Forty-six prehistoric archaeological sites have been identified in association with freshwater deposits, spanning the Lower Palaeolithic to the pre-Islamic Holocene. Lower Palaeolithic sites appear concentrated close to raw material sources near the Nefud fringe, despite the presence of freshwater and fauna deeper in the dune field. Middle Palaeolithic occupations extend more broadly, and by the early Holocene humans were at least periodically occupying areas deep in the desert. We present the first records of Neolithic sites in this dune field, including substantial hearth complexes distributed relatively deep within the dunes, potentially indicating increased mobility during this period. Later Holocene sites with stone structures are present around the dune fringes. Our results indicate that, during wet periods of the Pleistocene and Holocene, water in the western Nefud may have been more readily available than elsewhere in northern Arabia due to the high density of depressions where wetlands can form. The high frequency of lakes or marshes appears to have facilitated human occupations and dispersal through the region.

1. Introduction

The Nefud Desert is the northern-most of the major Arabian sand seas (Figure 1a). Covering ~58,500 km^2 between latitudes 27^{0}8′ and 29^{0}45′, the Nefud is dominated by densely-packed dunes that can reach 80 m or more in height (Figure 1b), a formidable barrier to overland movement. The Nefud is arid, receiving on average between 30-90 mm of rainfall a year (Edgell, 2006, pp. 144), although local flora is semi-arid in character (Schulz and Whitney, 1985) and rare heavy rainfall events can produce standing water that persists on playas for months.

Although currently semi to hyper-arid, palaeolake deposits in interdune depressions demonstrate that significant climatic changes during the past episodically resulted in the Nefud being considerably wetter than at present (Petraglia et al., 2011, 2012; Thomas et al., 1998; Schulz and Whitney, 1986; Garrard et al., 1981). Correlation of dates from these deposits with data from the wider Saharo-Arabian region initially suggested they related to wetter conditions during the Early Pleistocene (Thomas et al., 1998; Anton, 1984) and increased episodic moisture during the Late Pleistocene and Holocene (Schulz and Whitney, 1986; Hötzl et al., 1978). However, recent re-evaluations have indicated that Middle and Late Pleistocene humid phases were responsible for most of the palaeolake deposits in this region (Rosenberg et al., 2013; Stimpson et al., 2015).

The nature, scale, dynamics, and timing of Pleistocene and early Holocene climatic changes are important in discussions of past human occupations of Arabia, as they could have provided ameliorated conditions facilitating population dispersals and survival in the currently arid desert regions (Parton et al., 2015; Drake et al., 2013; Parker, 2009). This is supported by archaeological assemblages identified across the Arabian Peninsula dating to these humid intervals (Groucutt et al., 2015a, b; Petraglia et al., 2011, 2012, 2015; Groucutt and Petraglia, 2012; Armitage et al., 2011; Magee, 2014). Increased understanding of human-environment interactions in regions where extreme aridity alternated with humidity is a key objective for resolving debates concerning occupation in the middle latitudes. The Nefud, a sandy desert hosting numerous diachronic palaeoenvironmental archives, is an important region for evaluating such interactions.

The southern Nefud, particularly near Jubbah (Figure 1a), has long been known to host archaeological assemblages associated with palaeolake deposits (Groucutt et al., 2015a; Hilbert et al., 2014; Shipton et al., 2014; Jennings et al., 2013; Petraglia et al., 2012; Groucutt and Petraglia, 2012; Garrard et al., 1981). However, until recently the archaeology of the western Nefud remained largely unknown. To address this gap, since 2013, the Palaeodeserts project, the Saudi Commission for Tourism and National Heritage (SCTH), King Saud University and the Saudi Geological Survey (SGS) have performed collaborative surveys of the western Nefud combining palaeoenvironmental, palaeontological, and archaeological studies. Our research focuses upon an area of around 12,000 km^2, extending over ~100 km km E-W, and ~200 km N-S, and covering much of the south-western Nefud (Figure 1a). This study area was chosen due to the palaeoenvironmental potential indicated by prior research, and to cover a significant concentration of palaeolake deposits indicated by palaeohydrological analyses (Breeze et al., 2015). We specifically targeted palaeolake deposits for investigation, due to their importance as environmental proxies and the likelihood they may host fossils and archaeology, as demonstrated by prior studies (e.g. Jennings et al., 2016 ; Stimpson et al., 2016; Scerri et al., 2015; Petraglia et al., 2012; Rosenberg et al., 2013, Thomas et al., 1998; Garrard et al., 1981). The data from our surveys is reported here, and used to explore the changing distribution and character of prehistoric occupations in the western Nefud and discuss the environments present during these occupations.

2. Materials and methods

2.1. *Palaeolake target selection and geomorphological characterisation*

Recent palaeohydrological analyses (Breeze et al., 2015) provide a minimum estimate of the number and distribution of palaeolakes across the area. Initial target areas for survey, particularly those with notable densities of potential palaeolakes were chosen using Breeze et al.'s (2015) lake mapping dataset. A detailed examination of potential survey areas was also performed using high-resolution (~1m or less) satellite and aerial imagery (ESRI baselayer and Bing maps data) and local geological maps (Janjou et al., 1998; Vaslet et al., 1994). Since the extents, depths and areas of regional endorheic depressions larger than 1 km^2 in area had been calculated previously (Breeze et al., 2015), these data were also used in concert with Shuttle Radar Topography Mission (SRTM) elevation data to evaluate variations in the morphology of interdune basins across the Nefud.

2.2. *Field survey*

Target locations were accessed using 4 x 4 vehicles, supplemented by helicopter survey, courtesy of the SGS helicopter (Figure 2). Helicopter survey into the east of the study area was subject to airspace restrictions and comparatively fewer sites were sampled in this area (see Figure 6). Target locations were selected to include a variety of geomorphological settings, and in particular to target a variety of palaeolake outcrops ranging from single small deposits to large, dense complexes. Additional areas were also investigated opportunistically. In addition to targets chosen from palaeohydrological analyses, published locations with fossil assemblages were explored, as were previously dated palaeolake deposits. The latter included sites reported by Thomas et al., (1998) and Rosenberg et al., (2013).

At each location, survey for archaeology and palaeontology took the form of an initial walkover to determine the presence or absence of artefacts or fossils on the surface and whether there was potential for buried assemblages. In interdune locations these initial group walkover surveys were performed across the extent of all palaeolake and palaeolandscape surfaces exposed within each interdune, and part-way up the current dunes flanking these. More detailed surveys were then undertaken in promising sites as appropriate. The density, characteristics, and GPS position of any archaeological or fossil assemblages were noted. In the case of stone tools, samples from each site were examined by specialists to determine their typo-technological characteristics. In the case of fossils, initial taxonomic assessments were conducted in the field where possible, and all surface specimens greater than ~1 cm in length were collected and GPS coordinates recorded, regardless of completeness of elements or taxonomic identity. If palaeolake deposits exhibited considerable potential for providing detailed environmental data through laboratory analyses, or for the recovery of stratified archaeological and palaeontological material, samples were recovered, with detailed results of these site-specific environmental and chronological analyses discussed in published (Scerri et al., 2015; Stimpson et al., 2016) and forthcoming articles.

3. Results

3.1. Palaeohydrological and geomorphological analyses

The palaeohydrological maps of Breeze et al. (2015) highlighted the presence of hundreds of palaeolake deposits in interdunes within the study area (n=730, see Figure 3). Examination of high resolution imagery for the targeted locations showed that numerous deposits are often present in the same basin, with Landsat recognising larger deposits and the high resolution imagery showing numerous further small ones. Detection of deposits with high levels of induration is problematic in multi-spectral data (see Breeze et al., 2015), but these could be readily percieved in the higher resolution imagery. These analyses suggest that thousands of palaeolake deposits are currently exposed across the western edge of the Nefud.

Palaeolake deposits in this region stratigraphically overlie bleached sands that define a former underlying palaeodune landscape, which is also exposed in some current interdunes (Stimpson et al., 2015, 2016; Rosenberg et al., 2013; Janjou et al., 1998; Thomas et al., 1998; Schulz and Whitney, 1986; Whitney et al., 1983). The timing of formation of this palaeodune landscape remains to be established; however, a minimum age of >500-600 ka may be suggested by absolute dating of fossils associated with palaeodune sands (Stimpson et al., 2016) and the oldest dates from OSL studies applied to the sands (Rosenberg et al., 2013). Multiple phases of palaeodune formation are evident, as lake deposits of different ages are stratigraphically bracketed by white palaeodune sands. This highlights that multiple periods of climatic amelioration and downturn since the early Middle Pleistocene have each been associated with local dune landscapes (Stimpson et al., 2016; Rosenberg et al., 2013).

Our basin analyses provide further important details concerning the geomorphological setting of the palaeolake deposits. The study area is populated by major transverse and transverse barchanoid mega-dunes with interdune depressions between them, relating to a dominant westerly palaeowind direction (Edgell, 2006; Janjou et al., 1998; Whitney et al., 1983). SRTM elevation data (masked to map only the dunes) demonstrates that the highest areas in the erg occur in the south-western Nefud, with the elevation dropping away to the north and east (Figure 4). On its own, this variation could simply reflect changes in the underlying bedrock topography. However, our analysis of relative depths of interdune basins across the Nefud derived from the SRTM data (Figure 5) confirm that the deepest interdune depressions (and correspondingly the relatively higher dunes) occur in the western Nefud, suggesting the dunes are larger and the erg thickest in this region, perhaps due to its close proximity to the source of the sands.

3.2. Field survey

3.2.1. Surveyed locations and identified materials

To date we have investigated a total of 67 locations, primarily distributed across the dune field of the Nefud, but also a few in the surrounding region (Figure 6). During survey within the dunes a 'location' was defined by the extent of the immediate interdune depression. Not all locations yielded archaeology, but amongst those which did a common pattern was for multiple archaeological sites of different ages to be identified in a single interdune along with multiple palaeolake deposits. Of the 53 locations visited in the dune field itself, 41 exhibited significant upstanding lake sediment outcrops, of varying potential as environmental archives, and the remaining 12 hosted ephemeral playa lakes/marshes or iron-pan deposits.

Table 1 lists those locations where prehistoric archaeology was identified and the materials associated with these locations (hereafter referred to as sites). In total 46 archaeological sites were identified, many exhibiting materials from multiple periods typically associated with different palaeolake deposits within the sites. Standard regional definitions of cultural phases were used to assign human occupations to particular periods (e.g. Groucutt and Petraglia, 2012). Lower Palaeolithic assemblages were identified by the presence of large cutting tools (particularly small handaxes). Middle Palaeolithic sites were defined by the dominance of prepared core technologies (particularly Levallois). Finally, Holocene (/Neolithic) assemblages were identified by the presence of minimally-weathered lithic assemblages, with high frequencies of exotic raw materials and featuring technologies such as the production of small arrowheads. In addition, Holocene sites feature abundant hearths and grindstones. Archaeological assemblages ranged from large-scale, relatively dense (>5 per m^2) scatters of material (termed "high significance" in Figures 10-12 and marked in Table 1 by +++), through moderate density and more constrained scatters (medium significance, ++), to relatively small, low-density (<1 per m^2) spot finds with relatively few associated finds (low significance, +). Our 'significance' category combines an estimation of artefactual density with a wider consideration of the site, such as total assemblage size and whether multiple categories of material (e.g. archaeological and palaeontological) are represented. Where only one or two finds occurred at a locality, these were considered to be off-sites or 'background noise' and are not included in Table 1 or discussed further. In this paper we provide an overview of the regional occurance of sites of different periods. More thorough quantitative analyses of assemblages at the site-specific level will be presented in future publications.

Fossil assemblages were recorded using a similar scheme. A total of 16 sites preserved fossils, ranging in abundance from single isolated specimens (+), to scattered remains likely representing several individuals (++), to a diverse faunal assemblage representative of the local biocoenosis (+++). The majority of fossils were recovered from the surface, with several sites exhibiting hundreds. While some sites (TAG, 16.3, KAM-4, and WNEF sites 16_1, 16_6, 16_9, 16_25 & 16_30) had fossils eroding out of primary depositional context (Figure 7 E and F), with the exception of sites such as TAG and KAM-4 these generally represent at most only one or two individuals and thus likely chance fossilisation events. Archaeology and fossils were often found in close proximity. Most surface fossils exhibited considerable weathering of their cortical surfaces from sandblasting and high rates of fragmentation. As such, identification to specific elements or taxonomic group was not possible for the majority of specimens recovered; nevertheless it is clear that most fossils recovered represent large-bodied mammals. All fossils are currently undergoing detailed taphonomic and taxonomic study, with these results to be reported elsewhere.

Environmental archives associated with the sites (palaeolake deposits) were also classified, with the highest class (+++) marking sites with multiple discrete palaeolake beds or a thickness of deposit indicating significant potential as geochronological and environmental archives, through to the lowest (+) denoting sites with only a single small palaeolake deposit and little vertical exposure of a sequence for analysis. Blanks in the table denote an absence of the materials in question at that site.

Figure 7 illustrates select examples of the types of materials recovered. To briefly catalogue the archaeological results, 19 locations yielded materials typo-technologically attributed to the Lower Palaeolithic (Table 1, examples in Figure 7 A and B), and in total, 31 sites hosted Middle Palaeolithic archaeology. Twenty-seven assemblages related to the Holocene/Neolithic were identified, evidenced by lithic materials, structural features (e.g. cairns), and particularly the presence of hearths (Figure 7 C and D).

3.2.2. Field observations concerning palaeolake deposits in the western Nefud

Palaeohydrological mapping indicates that palaeolake deposits are widespread across the western Nefud (Figure 3). Field surveys confirmed such deposits are present in very large numbers in the interdunes of the study area. Typically, exposed deposits are topographically elevated dark grey to pale white surfaces, surrounded by a deflation surface that slopes down to the interdune floor covered with a lag of comparable material (Figure 8a & b). These palaeolake/palaeowetland deposits range from diatomites to marls exhibiting varying levels of induration and diagenesis. Multiple exposures are often present in the same basin, in some cases existing at matching altitudes and possessing the same level of induration and attitude of surface, suggesting they were once contiguous and that erosion has produced the separation. In many basins, however, multiple deposits exhibit differing levels of induration or chemical weathering, different composition, and markedly different attitudes and altitudes, all indicating a palimpsest of palaeolakes of different ages are present in a single interdune. Our surveys indicate the occurrence of multiple, likely diachronic, deposits in a single basin are the norm rather than exception in the western Nefud.

Deposits show a wide variety of shapes when viewed in plan in aerial or satellite images (see Figure 2), in keeping with variable erosion and palaeogeographic settings. Although eroded, many planforms provide indications of the local palaeotopography, with deposit surfaces mirroring the basins they were originally emplaced within. Some surfaces are heavily inclined, suggesting where deposits were draped over the flanks of adjacent dunes, towards the shores of the lakes. In some cases (and as also noted by Rosenberg et al., 2013) remnant deposits preserve the inverse of a barchanoid planform, dipping towards their centre and curved around their edges, representing minimally-eroded footprints of lakes/wetlands that formed between former barchan dunes. Exposures also vary widely in scale. Some individual remnant deposits are only a few metres in diameter, some relatively complete barchanoids are <50 m in diameter, and some inclined ridges and single large exposed surfaces extend for a kilometre or more in length and hundreds of metres in breadth (Figure 2).

This variability continues in relation to the thickness of different deposits. Because the lacustrine/palustrine deposits armour the underlying friable palaeodunes (Stimpson et al., 2016), where they are eroded the latter have been deflated, undercutting the lake deposits and exposing them in section. Although an individual deposit can sometimes show variable lateral thickness (likely related to facies variations with distance from basin cores), substantial differences are seen in the overall thickness of different deposits. While many exhibit sections of between 0.1 – 0.5 m in thickness (Figure 8c), several much thicker sections of more than 2 m in thickness have also been observed (Figure 8d). This refers only to the surface capping marl or diatomaceous deposits, and in some cases clays and other deposits also underlie these and may provide a more complete palaeolake sequence and history. Some deposits have also experienced variable depositional and post-deposition chemical alteration, particularly iron-enrichment (Stimpson et al., 2016). Figure 8b shows a ferruginous marl deposit below and alongside another deposit in the same basin that has not been altered and remains white.

The variety discussed above emphasises the considerable complexity of the palaeogeography of the western Nefud. In this area palaeolake or palaeowetland formation during Quaternary humid periods was clearly frequent and widespread, likely associated with regional elevation of local groundwater. Regarding individual features, it is difficult from field observations to assess their longevity or fluctuating character over the course of these lacustrine episodes, and laboratory analyses of identified deposits are ongoing. Nonetheless, some initial observations are possible. Thinner deposits are potentially more likely to be short-lived lacustrine episodes, while the massive sequences may represent lakes being present over more prolonged periods. Furthermore, the occurrence (or preservation) of terminal evaporites as discrete crusts on palaeolake deposits appears extremely rare; only one halite crust was observed during four seasons of survey. Deposits dated to MIS 11-9 and MIS 5 by Rosenberg et al., (2013) demonstrated diatom assemblages consistent with fresh to brackish settings, with deeper freshwater conditions in MIS 11-9 lakes and more fluctuating lake levels in those relating to MIS 5. Coupled with the aforementioned paucity of evaporites, it appears likely that many of the lakes would have been relatively fresh and thus important for hominins and fauna, consistent with the presence of the associated archaeological and palaeontological assemblages.

Playas are frequently found in low points in the interdunes, and today episodically hold water after rare extreme rainfall events. This is illustrated by Normalised Difference Water Index (NDWI) data (a remote sensing procedure identifying surface water occurrence from multispectral satellite data) from January 1986, after a particularly strong storm that resulted in brief ponding of water on playas surrounding the Nefud, and to a much more limited extent within the dune field itself (Figure 9). These basin core playas were likely also the location of ephemeral pools/marshes during the Holocene. In the dunes they are typically composed of clays and silts with minor surface fine white sands. The latter are clearly redeposited from up-slope bleached palaeodune exposures, but the source of silt and clay fractions is less clear. Some may be derived from dust or interstitial fines blown into and washed off the dunes, however, the visible washing of interdune palaeo-lacustrine sediments into playas suggests they may be primarily redeposited from erosion of these upslope deposits. Thus playa formation in the dunes may be geomorphologically linked to the presence of the raised palaeolake deposits and to the deflation of hollows between these robust bounding features into which washes can accumulate. Playa erode until they reach groundwater level, which today does not lie close to the surface in the western Nefud. Thus it is likely deflation has been ongoing since playa formation, and that any near-surface deposits from recent episodic floods disconformably overlie deposits from earlier events. However, coring of the playas is required to confirm this and examine their character. In the western Nefud, Holocene archaeological sites are frequently positioned in locations overlooking these playas.

3.2.3. The distribution and character of fossils across the western Nefud

At present, all identified fossil localities are distributed primarily around the fringes of the western Nefud (Figure 10). While sites with limited to moderate numbers of fossils lie in the south-western and south-central study area, those with the most substantial assemblages seem focused upon the central western edge of the Nefud, along with a few south-eastern sites. The latter (such as TAG) are interesting, returning significant fossil assemblages but little associated archaeology, perhaps due to local raw material limitations. The chances of recovery of fossils at any given palaeolake deposit are probably largely determined by stochastic factors rather than the specific topographic or depositional attributes of the central western edges of the Nefud. However, they also appear to have some level of spatial association with Pleistocene archaeological assemblages, hinting the two may be linked in some way. Testing the nature of this association, however, awaits more detailed taphonomic data currently being generated as well as additional survey efforts.

4. Discussion: Archaeology and palaeoenvironments of the western Nefud

4.1. The late Quaternary geomorphology and palaeogeographic setting of the western Nefud

Our remote sensing and GIS analyses indicate that the western Nefud is characterised by deep interdune depressions between the stabilised mega-dunes. Field observations confirm that interdune floors here are generally bounded by very high dunes (Figure 1b & 2), and frequently include large exposures of underlying bedrock or palaeodunes (Figure 2). Further north and east, exposure of palaeolake deposits in interdunes ceases, with basins floored by mobile sand rather than the underlying palaeolandscape (Figure 5). The sediment source for the Nefud lies to the west (Garzanti et al., 2013) and it is possible that dunes are higher in the western Nefud due to increased sediment availability, with sand more dispersed downwind. Dunes may also have been present, and accumulating, for a longer duration close to this source, thus experiencing a greater number of arid-humid cycles which could have vegetated and stabilised local dunes, facilitating superimposition. Deeper interdunes may also have facilitated erosion and the exposure of the underlying surfaces between the superimposed dunes.

The precise evolution, spatio-temporal dynamics, and chronology of the major dunes of the western Nefud remains little understood, and there is a clear need for a programme of deep dune coring and dating. Some (notably Edgell, 2006) have suggested that the presence of palaeolake deposits between the major dunes indicated the latter stabilised prior to lake formation, implying a considerable antiquity for the present pattern. However, many deposits emerge from dune flanks, indicating some level of movement of dunes has occurred after lakes formed. Vegetation and a thick surface lag of coarse sand results in the major dunes being relatively protected from deflation (Janjou et al., 1998), and they may have comparatively low mobility, despite the current arid regime, explaining their classification in many studies as inactive (e.g. Janjou et al., 1998, Schulz & Whitney 1986, Edgell, 2006). Although all observed palaeolakes appear to have formed in a dune landscape, just how closely the positions of present dunes relate to those contemporaneous with different periods of lake formation therefore remains to be resolved.

The large numbers of lake deposits observed between these dunes across the western Nefud, many of which are partially buried, implies correspondingly larger numbers may remain hidden beneath the dunes. This illustrates the scale of the successive climatic fluctuations in the area, as thousands of additional deposits may remain buried. A suggestion that most of the south-western Nefud could be floored by a continuous lacustrine sequence relating to MIS 11 then topped by later lakes (Rosenberg et al. 2013) provides an alternative explanation for the deposit frequency. However, we are sceptical of a single MIS 11 large lake across the south-western Nefud, as deposits dated to MIS 11 occur at different altitudes, with the hypothesised nearshore deposits being 40 m lower than those considered to be at the basin centre, a topographic situation that is clearly impossible for a large lake. Furthermore, SRTM data (Figure 1a) highlights that, rather than providing a basin in which such deposits might form, regional topography dips consistently from south-west to north-east (see also Edgell, 2006).

4.2 Local lithic raw material availability

Underlying bedrock in the area consists of sandstone, containing ferruginized 'quartzitic' beds that were the main raw material used by hominins locally. Our survey found that large exposures of relatively high quality quartzitic sandstone are located around the mid-western part of the survey area, in contrast to the southern margins of the Nefud. At localities such as WNEF16_12, for instance, large and prominent exposures of quartzitic sandstone were identified. The sandstone beds of the area also contain abundant small round quartz pebbles. These were used more frequently during the Holocene than in earlier periods. Various forms of chert were identified, particularly at Holocene sites, and our surveys located several lakebeds where 'lacustrine chert' had formed and was clearly knapped on site (WNEF16_4 is a notable example). Chert from such sources is generally of low quality. While there was probably some variation in access to particular raw materials between periods, such as exposures of sources in interdunal low points which were subsequently covered by sand, on the whole the raw materials available for hominins through time were broadly similar. Changing patterns in raw material use therefore primarily reflect hominin choices and technological changes potentially influenced by different mobility patterns.

4.3 The Early and Middle Pleistocene and the Lower Palaeolithic (~1.8 Ma to 250 ka)

Palaeolake deposits have been broadly dated to the Middle Pleistocene (Stimpson et al., 2016; Rosenberg et al., 2013) in various locations around the western Nefud (Figure 11). Rosenberg et al. (2013) highlighted significant lake formation episodes associated with humid phases of MIS 9 and 11 (Figure 11). The spatial distribution of dated and detected lakes across the Nefud, with dated examples from each interglacial (and some interstadials) from the present back to MIS 11 (with the potential exception of the Holocene) suggests that lake formation was ubiquitous across the area during some of these periods (Breeze et al., 2015; Shipton et al., 2014). Lower Palaeolithic hominins in particular could at times have experienced widespread favourable environmental conditions. Stimpson et al. (2015, 2016) reported fossil faunal assemblages from the site of T'is Al Ghadah (TAG, Figure 11 and Table 1) dating to ~500 ka. These fauna included a mixture of Eurasian (*Panthera gombaszogensis*), African (*Palaeoloxodon* cf. *recki, Canis anthus*), Arabian (*Oryx* cf. *leucoryx*), Asian and Levantine (*Equus hemionus*) taxa, as well as more widespread mammals such as the hyena (cf. *Crocuta*) and fox (*Vulpes* sp.). The presence of animals associated with grasslands, carnivores dependent on large vertebrate prey, aquatic birds, and megafauna such as elephants, coupled with deep perennial palaeolakes (Rosenberg et al., 2013) illustrates the kind of environments present during periods of potential hominin dispersal.

Several key sites demonstrating a Lower Palaeolithic presence in the western Nefud region were previously outlined by Scerri et al., (2015), and our data now expands upon this spatially. All such sites in the dune field are tightly associated with palaeolake deposits, generally occurring atop their surface. This close association may not simply be taphonomic, as recent studies suggest a preferential utilisation of lake-shore environments by Lower Palaeolithic populations, even accounting for preservation bias (Roach et al., 2016). Interestingly, however, and despite a widespread distribution of Middle Pleistocene lakes across the area and the likelihood that much of the region episodically experienced an ameliorated climate, our surveys suggest the densest concentrations of Lower Palaeolithic finds are broadly focused around the western flank of the dune field (Figure 11). The southwestern fringe of the western Nefud shows a particular dearth of sites, for example, no lower Palaeolithic material has yet been recovered from excavations at TAG, despite the rich faunal assemblage. These patterns do not appear related to survey bias, or even to the presence of multiple taphonomically favourable palaeolake sequences, as comparable sites were surveyed across the wider region and did not exhibit such assemblages.

The presence of multiple sites along the dune margins suggests raw material availability (outcropping bedrock) may be a driver of distribution of archaeological material. This is also the case for a single significant site slightly deeper into the desert towards the north of the study area (Figure 11), in a region notable for the local presence of multiple large exposures of bedrock within the interdune depressions. This may suggest that the densest sites (potentially primary reduction sites) were constrained to regions proximal to bedrock. Our data do not suggest deep penetration into the western Nefud by hominins during the Lower Palaeolithic, the sites furthest from the dune edge being only 20 km into the dune field (based on the current dune extent). Further east, near Jubbah, hominins reached slightly further into the dunes, although, (apart from a single handaxe) only in areas defined by large basins bounded by bedrock, rather than aeolian, basins (Shipton et al., 2014).

Data presented here and in Scerri et al. (2015) provide perspective on the Lower Palaeolithic of the western Nefud, complimenting that from the south-eastern Nefud, where a series of Lower Palaeolithic sites were identified, again predominantly associated with palaeolacustrine (and near Al Qana, alluvial) settings (Shipton et al., 2014). Shipton and colleagues (2014) emphasised that these follow the general Acheulean pattern of preferential curation of artefacts produced at workshop sites and transport of these to water sources; our data from the western Nefud also appears to follow this trend. Nonetheless, despite their high visibility, overall Lower Palaeolithic materials remain relatively scarce in the western Nefud compared to other periods. The only locations exhibiting substantial assemblages are those where palaeolake sediments facilitating assemblage preservation appear to be close to good raw material sources. Specifically, handaxes appear most abundantly concentrated at sites along the central western edge of the Nefud, possibly due to proximity to raw material sources, though this needs to be confirmed by identification of the raw material procurement localities.

4.4 The later Middle and Late Pleistocene (~250 ka-12 ka)

Several palaeolakes in the area have been dated to MIS 5 (and potentially MIS 7), interpreted as reflecting more fluctuating conditions compared to perennial lakes of the earlier Middle Pleistocene, as deposits exhibit evidence for deeper freshwater interspersed with, or grading into, more alkaline and shallow waterbodies (Rosenberg et al., 2013). Palaeohydrological analyses have suggested that during sub-stages MIS 5e and possibly 5a, the western Nefud was relatively ameliorated and dispersals into the area from the Levant could have occurred via the Tabuk corridor (Breeze et al., 2016), with the additional possibility of an as yet unconfirmed connection along the Sirhan depression (Ames and Cordova, 2015; Cordova et al., 2013). Climate models suggest that at this time access to the southern Nefud from southern areas of Arabia may also have been possible (Jennings et al., 2015; Parton et al., 2015, Breeze et al., 2016). The western Nefud was therefore likely an important nexus for populations with diverse (including exogenic) origins during at least some sub-stages of MIS 5 (and likely during other Pleistocene humid episodes). This is supported by the local fauna during MIS 5 (i.e. Khall Amayshan 1 of Thomas et al. 1998), which included African (*Pelorovis* cf. *oldowayensis*), Asian (cf. *Hexaprotodon*), and other widespread taxa (*Equus*). Given this pivotal position at the end of a potential MIS 5 dispersal route, the Middle Palaeolithic archaeology of the Nefud has an important role to play in revising our understanding of hominin demography and population movements during these periods.

A number of sites have produced significant Middle Palaeolithic assemblages in the Nefud (Groucutt et al., 2015a, 2016; Petraglia et al., 2011, 2012, Scerri et al., 2015). This research is complemented by 31 additional sites revealed by our subsequent surveys. While in many cases Middle Palaeolithic assemblages are small, they add to regional-scale site distribution patterns (e.g. WNEF16_3, 14, 18, 22, 23, and 28).

There are a greater number of Middle Palaeolithic sites than those of any other period, and these appear slightly more widely distributed than in the Lower Palaeolithic, potentially indicating occupations were less tightly constrained to desert edges and raw material locations. Key sites for understanding the Middle Palaeolithic are those where lithics are associated with fossils and dateable sediments. Such sites are generally rare in Arabia; however several have been identified in the area (Table 1). In virtually all the sites identified, lithic technology is similar – emphasising centripetal Levallois technology – and the on-going detailed analysis of lithics in the region offers considerable potential for understanding the Middle Palaeolithic.

4.5 The Holocene, from the Neolithic to the pre-Islamic periods

The final archaeological period we assessed is the pre-Islamic Holocene. This broad classification is used as some sites clearly include Neolithic components, such as large grinding stones and ground stone axes. For features such as hearths, however, without detailed study and chronometric dating attribution to a specific period within the Holocene is problematic.

Given research interest in the process of 'Neolithisation' in Arabia – i.e. migration of Levantine pastoralists vs. indigenous development with the Peninsula - Neolithic findings are highly significant. No Neolithic sites had formerly been reported from the western Nefud itself, although prehistoric rock art is known from areas surrounding, and further south of, the dune field (Jennings et al., 2014; Engel et al., 2011). In the south-eastern Nefud however, an important site exhibiting possible Levantine Pre-Pottery Neolithic affiliations lies in proximity to a Holocene palaeolake at Jubbah (Crassard et al., 2013b) along with rock art ranging from the early Holocene through to recent periods (Jennings et al., 2013).

Regarding the Neolithic/Holocene, our survey revealed multiple sites hosting lithics, grindstone fragments, hearths and, more rarely, small numbers of fossils and ostrich eggshell fragments. At some localities, occasional arrowheads or endscrapers can be seen as 'background noise'. Eleven sites (WNEF16_2, 4, 11, 12, 13, 14, 16, 20, 21, 24, 29- Table 1) produced richer evidence: moderate numbers of lithics, several grinding stones and multiple hearths. For example, at WNEF16_2 more than nine hearths were located in one small area. At many of these sites lithics are dominated by more exotic raw materials (particularly chert) relative to earlier periods. The two key new sites for the Neolithic/Holocene are WNEF16_6 (in particular) and WNEF16_22. In both cases large number of lithics and dozens of hearths were recorded. These sites were typically positioned atop the prominent inverted relief features of the older (Pleistocene) lakebeds, which due to subsequent erosion stand above the Holocene playas (e.g. WNEF16_6). For the (probably) more recent part of the Holocene, several sites on the desert margins also revealed structural remains, and are discussed in detail later in this section. The key site in this regard is WNEF16_12. Pottery was discovered at two sites (WNEF16_6 and 17).

While our data highlights that the western Nefud holds a relatively rich Holocene record, it should be noted that Upper and Epi-Palaeolithic assemblages still remain unknown. Although an important Epi-Palaeolithic assemblage has been reported near Jubbah (Hilbert et al., 2014), comparable material has yet to be identified in the western Nefud. This paucity of archaeological material and dated sediments for the period between MIS 3 and 1 is consistent with a lack of human occupation broadly around the Last Glacial Maximum.

Some of the Holocene occupations in the Nefud likely occurred under different environmental conditions than earlier periods. In Arabia a period of increased humidity occurred during the early Holocene, broadly between ~10-6 ka, with available evidence indicating latitudinal variations in the timing of the onset and decline of this monsoonal humidity (Parker 2009). At present the only dated evidence in the Nefud for lake formation during this amelioration event comes from Tayma and Jubbah. At Tayma a perennial >13 m deep palaeolake formed during the early Holocene wet phase ~10 ka, contracting after around 8.5 ka (Engel et al., 2011). At Jubbah, palaeolakes formed around 12-11 ka (Hilbert et al., 2014), between 9-6 ka (Crassard et al., 2013b), and at ~6.6 ka (Hilbert et al., 2014; Garrard et al., 1981). These lakes at Jubbah and Tayma both occurred in bedrock basins, contrasting with the interdune depression palaeolake sites we have recorded. Schulz and Whitney (1986) reported Holocene lakes from north-central Saudi Arabia dated to 8.4 - 5.4 ka, however from the Nefud they list only a single pan east of Tayma with a formation age of ~6 ka.

Given the rich, diachronic complex of carbonate and diatomaceous deposits in the western Nefud, the absence of any deposits dating to this Holocene wet phase is notable. To date none of our analyses contradict Rosenberg et al.'s (2013) interpretation that this indicates an absence of perrenial interdune lakes during the Holocene. However, the presence of playas suggests that short-term shallow ephemeral lakes or marshes may have existed seasonally in the dunes and provided important, though transitory, resources. On the dune fringe, water accumulates and lingers upon these playa following major storms (Figure 9), and during the

Holocene wet phase, when Engel et al. (2011) suggest regional rainfall reached levels 300% higher than present, a similar pattern would likely have occurred deeper in the dunes.

Later in the Holocene, Tayma remained an important oasis, being a focal point for Bronze Age occupation, and subsequently a nexus on caravan trading routes (Engel et al., 2011), as was Jubbah (Jennings et al., 2013). Away from these oases however, the dune field likely remained arid during the later Holocene, with an absence of perennial surface water. Wells recorded on local geological maps show that in a few places groundwater is relatively near the surface at ~10-30m depth (Janjou et al., 1998), however, how far back in antiquity the use of wells within the Nefud dunes stretches remains unclear. Episodically, water would have ponded on regional playas, as illustrated by Figure 9. However, even during the extreme rainfall event of January 1986 only a few areas of standing water (~140 out of 2915) occurred within the dunes, all close to the periphery (within 12 km of the dune edge). Examination of archived Landsat data for the area suggests such events are infrequent, with only a few occurring since 1984, when the archive begins.

Given the paucity of surface water for much of the Holocene, it is notable that the distribution of Neolithic/Holocene sites extends somewhat deeper into the dune field than that of earlier periods. Several factors could potentially explain this. The first would be if all such sites relate to the Holocene wet period, when ponding of water could have been more frequent within the dune field (given the evidence for substantially enhanced moisture at Tayma) and many of the ephemeral lakes in the base of the interdune depressions may have formed. However, this pattern may instead reflect Holocene populations in and around the Nefud being more mobile than during earlier periods. The adoption of nomadic domesticate pastoralism from the middle Neolithic onwards in Arabia (Magee, 2014), locally indicated by rock art to the south (Guagnin et al., 2016), could have provided a buffer against aridity, and encouraged seasonal exploitation of the Nefud for grazing. Even today the Nefud is relatively more vegetated than the surrounding areas, maintaining a semi-arid floral assemblage, and is used for seasonal grazing by the now settled Bedouin groups on its fringes. It is thus likely that during the early Holocene when it was much wetter than present, the vegetated dunes would have provided correspondingly increased grazing opportunities. Furthermore, by around 3 ka, desert mobility and nomadism would have been substantially facilitated by domestication and pastoralism of the dromedary camel (Guagnin et al., 2016; Magee, 2014).

Structures, presumably later Holocene, were also observed in the region. Numerous complexes of structural outlines delineated by low walls were discerned during helicopter survey (Figure 14b) particularly distributed across the bedrock areas west of the dunes (Figure 13), and also to the north on bedrock exposures within the dunes themselves. The only site examined in the field was WNEF16_12 (Figure 13 & 14a). Here seven circular/ovate structures and 2 large cairns were recorded, varying in scale, planform and the number of apparent former internal partitions, with further structure groups visible on the horizon a short distance away. Walls delineating the structures were generally a single course in height and ~2/3 in thickness, composed of irregular large stones (Figure 14a). Given the absence of sufficient collapse to indicate formerly higher stone walls, the upper levels of the walls may have been composed of perishable materials such as adobe. A set of irregularly placed standing stones was observed inside one structure, and a basal stone door frame in another. It is unclear how much time is represented by the site. In our visit, neither stone artefacts nor other materials (e.g. metal) were identified, and sediment at the site is likely highly acidic owing to the character of the bedrock. The lack of lithics typical of the earlier Holocene would suggest that the structures belong to the later part of the Holocene.

These substantial features are distinct from recent Bedouin tent outlines (Figure 14c), which are typically smaller in scale, and defined by clearance of the underlying surface of stones which are used to weigh the tent fringe. Many such outlines were also observed immediately west of the Nefud. While the structural features were visible due to the outlines of their walls, tent outlines are prominent due to the stark contrast between the cleared area within the outlines and the surrounding area (Figure 14c).

5 Conclusions

Our analyses and surveys indicate that an exceptionally large number of palaeolake deposits (n>730) occur across the western Nefud, often associated with archaeological and fossil assemblages. The intimate spatial association between palaeolakes, archaeology, and fossils observed in the dune field (Table 1) is a product of prehistoric behaviour, preservation conditions, and our survey strategy. From a behavioural perspective, it is likely hominins and fauna would be closely tied to available water sources in the semi-arid environs characterising the northern Arabian humid episodes. These were probably the only periods when permanent occupation of the Nefud was possible. With respect to taphonomic conditions and visibility, only exposed basins possessing surfaces pre-dating major dunes, which protect and preserve archaeology and palaeolake deposits, were observed. With respect to survey strategy, we specifically targeted dateable palaeolakes for intensive examination at the expense of dune and bedrock landscapes. While topographic features such as dunes were briefly inspected at numerous points during the surveys, they never exhibited any archaeological records other than downslope of palaeolandscape deposits. Although low-density and occasional single finds were observed on bedrock surfaces in some areas outside the dunes, the densest archaeological assemblages observed were directly on top of or immediately down-slope of palaeolake deposits, suggesting that these were focal points for hominin activity. Nevertheless, further investigations of bedrock exposures should be a priority for future work.

Archaeological finds relating to all temporal periods other than the Oldowan and the final Palaeolithic (e.g. Epi-Palaeolithic) were identified in the western Nefud, indicating a repeated hominin presence in the late Quaternary. Prior to the Holocene, it is likely that such occupations were limited to more humid episodes. During the Lower Palaeolithic, lithics are concentrated in their greatest density close to potential raw material sources on the western fringe, and potential exploitation of the deeper dune field remains largely undemonstrated. Middle Palaeolithic occupations appear to have extended somewhat more broadly than in the Lower Palaeolithic. By the Neolithic humans were at least periodically occupying areas deep into the desert, potentially indicating increased mobility facilitated by the introduction of domesticates. Multiple periods of material culture in the same basin appear to be most common where there appear to be multiple different lake deposits and/or playa exposed in the same interdune.

At this early stage in research we have focused upon water sources since, as a critical requirement for human survival in semi-arid environments, they are key to demonstrating when dispersals (which would also have been influenced by a wide variety of additional variables for different hominins at different times) into, and occupations of, the Nefud were broadly possible. A striking observation from our studies is that, on the basis of the very high density of apparently diachronic palaeolake deposits observed, the western Nefud may actually have been one of the better-watered areas of northern Arabia, rather than a marginal environment, and during wetter periods its dune belts, or at least their fringes, would have provided suitable resources for hominin habitation. Geomorphological processes have facilitated both the formation and present visibility of palaeolake deposits in this region, and the extent to which these features also continue beneath the dunes further east remains unclear. However, our observations suggest the exposed archaeological finds may be only a fraction of what lays buried beneath extant dunes. Our surveys to date have provided significant new insights into the palaeogeography, palaeoecology, and archaeology of the Nefud, even though we have only scratched the surface of this natural and cultural archive, highlighting the enormous potential of the Nefud desert for examining climatic, faunal, and human interactions during the Quaternary.

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Figure and Table Captions:

Figure 1. The western Nefud desert in northern Saudi Arabia. A; Map showing the Nefud desert, study area, key locations and geomorphic features discussed in the text, and the extent of present dune cover. Inset shows the location of this map in relation to the wider Arabian Peninsula, with national borders and the extents of Arabian dune fields shown (Pollastro et al., 1999). B; Aerial photograph showing the present landscape of the western Nefud dune field.

Figure 2. Palaeolake deposits and survey in the western Nefud. Counter-clockwise from top left: A) Image taken during aerial survey, showing multiple discrete moderate-sized exposures of palaeolake deposits in interdune hollows between stabilised dunes running from the foreground into the distance. B) Very large continuous expanse of palaeolake deposits (grey, marked by arrow) covering an interdune floor. C) Interdisciplinary field survey of a palaeolake deposit (cream/white material) in progress. D) Profile through exposed palaeolake marls (c.1.5m thick) in the foreground, with further deposits (marked by arrow) visible in the background beneath the survey helicopter.

Figure 3. The distribution of palaeolake deposits within the western Nefud dunes, as indicated by multi-spectral classifications and GIS analysis (Breeze et al., 2015). This was suggested to be a minimum estimate, with field observations confirming that this data underestimates the overall number of deposits. Local towns, villages and places of interest marked in white.

Figure 4. Hillshaded SRTM DEM of the Nefud dunes. Bedrock and mountains on the Nefud fringe and near Jubbah are masked so that only dune heights are shown.

Figure 5. Interdune basin depths across the Nefud, in relation to the western edge of the dune field (the primary source of dune sands; Garzanti et al., 2013). The western Nefud is characterised by the densest concentration of the deepest aeolian depressions (structural depressions near Jubbah, and shallow interdunes on the Nefud edge that basin analyses amalgamate with structural depressions outside the dunes are excluded).

Figure 6. Locations surveyed across the western Nefud 2013-2016. Points mark all locations where on-the-ground survey was performed by the interdisciplinary teams; dashed paths link those locations that were reached by helicopter. Sites listed in Table 1 are marked by numbers. While the south-western most Nefud was surveyed across much of its area, including deeper in the dune field, the presence of prohibited airspace inhibited widespread survey deeper inside the dunes to the east.

Figure 7. Archaeological and fossil finds from the Western Nefud. A) Handaxes and cores (top left) from WNEF16_26, all composed of ferruginous quartzite/sandstone, note range in colour and weathering (the longest handaxe is 20 cm in length). B) An example of a handaxe found on a surface consisting of weathered lacustrine sediment and aeolian sand at site 17.2, 12 cm in length and composed of quartzite. C) A hearth from WNEF16_7, approximately 100 cm in radius. D) A hearth from WNEF16_22, note the vertical sides made from weathered slabs of lacustrine sediment. E) Dense and well preserved fossil assemblage, including several in situ vertebra (*Oryx* sp.) shown here at Ti's al Ghadah. F) An isolated fossil mandible (cf. *Oryx*) found eroding out at WNEF16_9; note the rapid fragmentation following surface exposure.

Figure 8. Variations in palaeolake deposits across the western Nefud. A; a view of the massive diatomite deposit at Bi'r Hayzan, looking downslope from the deposit surface in the foreground, past a member of the survey team, to the base of the depression far below the level of the deposit. The SGS helicopter sits on top of a playa at the basin core, and provides scale. B; Large marl deposits (one iron-stained, one not) around 100 m in diameter, (surveyed location immediately north of site 12 and east of site 24 in Figure 6). C; Thin deposits, shown in close up, but only around 50 cm thick at site WNEF16_30. D; thick deposits (a minimum of ~2 m – sequence is not bottomed) at TREC-3.

Figure 9. NDWI results showing standing water (red) from a particularly heavy rainfall event during January 1986, overlain for display onto band 1 of the processed Landsat scene. Produced using an NDWI calculation applied to TM scene P171 R41 following procedures and thresholds (L2,5; fw=100%) outlined by Ji et al. (2009) for mapping pure water pixels.

Figure 10. Later Quaternary fossil sites from the western Nefud

Figure 11. The distribution of Lower Palaeolithic material across the study area. Lower Palaeolithic sites are ranked by density/significance. Dated and suggested Middle Pleistocene palaeolake locations (MIS 11-9; Rosenberg et al., 2013, Stimpson et al., 2016) marked. Surveyed locations without Lower Palaeolithic materials are also displayed to highlight where absence is confirmed rather than undetermined.

Figure 12. The distribution of Middle Palaeolithic material across the study area. Middle Palaeolithic sites are ranked by density/significance. Dated and suggested later Middle to early Late Pleistocene palaeolake locations (MIS 7-5; Rosenberg et al., 2013, Stimpson et al., 2016) marked. Surveyed locations without Middle Palaeolithic materials are also displayed to highlight where absence is confirmed rather than undetermined.

Figure 13. The distribution of Neolithic/Holocene material across the study area. Sites are ranked by density/significance. Surveyed locations without Holocene materials are also displayed to highlight where absence is confirmed rather than undetermined. Palaeolake occurrence at Tayma (Engel et al., 2011- see text) displayed, as is pan formation around the western Nefud ~6ka (Whitney et al 1983). SC denotes the rough areas where numerous complexes of Holocene structural features observed from the air during helicopter survey.

Figure 14. Holocene structural features. A; Circular structure (c. 7 m diameter) from WNEF16_12 (see text and Table 1). B; comparable features (marked by arrows) observed from the air during helicopter survey- some of the numerous structures observed in the area marked SC on Figure 13. C; Former Bedouin tent outlines observed from the air (two of the many examples in the figure are marked by arrows for scale, car tracks are ~1. 5m in width).

Table 1. Sites identified during survey across the western Nefud, and the materials present at each site (see text). Site names are used in the text, and location ID codes used on map figures.