Beyond arrows on a map: the dynamics of Homo sapiens dispersal and occupation of Arabia during Marine Isotope Stage 5

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Beyond arrows on a map: the dynamics of *Homo sapiens* dispersal and occupation of Arabia during Marine Isotope Stage 5

Abstract

Arabia occupies a crucial central position between Africa and Eurasia. The northward expansion of the monsoonal rain-belt and the formation of grasslands during Marine Isotope Stage (MIS) 5 provided favourable conditions for *H. sapiens* to occupy and traverse now arid areas of Arabia. While "Green Arabia" may have been a crucial stepping-stone on the way to *H. sapiens* global settlement, the occupation of Arabia is an important area of study in itself and could offer vital perspectives into human-environment interactions. In particular, Green Arabia can offer a unique insight into processes of human dispersal, occupation and extirpation in an environmentally fluctuating landscape. Here we synthesise archaeological, palaeoclimate and ethnographic data to develop a holistic model for the occupation of Green Arabia and offer targets for future research. We suggest that, on broad timescales, the resource availability and carrying capacity of Green Arabia facilitated rapid population expansion and occupation across Arabia. On human time-scales, dispersal was probably a slow process due to the requirements of metapopulation structures, likely consisting of many "micro-dispersals" spanning numerous generations. Transitions to more arid conditions were probably echoed by local hominin extirpations, dispersals into surrounding regions and retraction to resource-retaining core areas.

1. Introduction

Homo sapiens occupation of Arabia during MIS 5 is becoming an important topic in the debate of human dispersals from Africa. Until recently, it was considered that MIS 5 *H. sapiens* dispersals were restricted to the East Mediterranean Levant; with "successful" expansions into broader Eurasia only occurring ~65-50 ka (Mellars, 2006; Shea, 2008; Klein, 2009; Mellars et al., 2013). However, mounting evidence shows that dispersals during MIS 5 may have had a longer-term impact on human distribution than previously considered (Petraglia et al., 2007; Liu et al., 2015; Rabett, 2018). These dispersals were probably facilitated by substantial increases of rainfall, abundant freshwater resources and grassland environments in Saharo-Arabia during MIS 5 warm substages (MIS 5e: 128-121 ka, 5c: 104-97 ka and 5a: ~82-77 ka) (Burns et al., 1998, 2001; Fleitmann et al., 2011; Rosenberg et al., 2011, 2012, 2013; Matter et al., 2015; Groucutt et al., 2018; Nicholson et al., 2020).

The role of Arabian environments is crucial for exploring dispersal models, given their position between sub-Saharan Africa and Eurasia (Fig. 1). Yet, owing to the early stages of research in the area, there has been a tendency to view Arabia as part of a network of prehistoric highways to the rest of Eurasia (Armitage et al., 2011; Rosenberg et al., 2011; Bae et al., 2017; Tierney et al., 2017). While useful when discussing broad changes in human distribution, this 'arrows on maps' approach obscures nuanced discussions of how *H. sapiens* dispersed (into Arabia and also back into Africa), traversed and occupied landscapes on "human" timescales. Such approaches can also obscure the specific local ecological and environmental characteristics that are critical in understanding introduction, occupation and extirpation.

To stimulate new discussions, we combine palaeoenvironmental, archaeological and ethnographic data to provide new insights into human-environment interactions within Green Arabia. The aim of this paper is to review the current state of knowledge and also, and more importantly, develop a more nuanced perspective and a new model for *H. sapiens* dispersal and occupation of Arabia. While the examples given are focussed towards Arabia, such discussions may be useful for understanding dispersal at broader geographical scales and in other landscape settings. In a similar fashion to White (2006) and Hosfield (2016), this paper is speculative and aims to stimulate new questions and targets for future research.

2. Arabian Climate and Palaeoclimate

2.1. Current climates and environments of Arabia

The current climate of Arabia is governed by two major weather systems: the Mediterranean frontal system in winter (December, January and February) and the African/Indian Summer Monsoon in summer (June, July and August). Precipitation over much of the peninsula averages <200 mm yr^{-1}, largely delivered in winter by the Winter Mediterranean Cyclonic system (WMCs). The African and Indian Summer Monsoons currently only penetrate the southernmost tips of Yemen and Oman, following the annual migration of the Inter-Tropical Convergence Zone (ITCZ) (Glennie and Singhvi, 2002; Weyhenmeyer et al., 2002). Annual precipitation is greatest in the highlands of Yemen, where rainfall may reach over 500 mm yr^{-1}. Temperatures across the Peninsula may reach well in excess of 40ºC during summer and can fall below freezing in winter. Evaporation over much of the peninsula is close to or greater than annual precipitation. The resultant low effective moisture (precipitation – evaporation) means that vegetation across most of the peninsula is sparsely distributed, which is also exaggerated by recent overgrazing. The densest and most diverse vegetation occurs within the highlands of Yemen, Hajar, Dhofar and Jebel Akhdar, focussed around streams, valleys and the south facing slopes prone to occasional mists (Miller and Cope, 1996). However, localised rains that penetrate deep into the soils are echoed by opportunistic vegetation blooms, even in the sandy deserts. Standing waterbodies and perennial rivers are not common and usually small in size. Localised rains and low carrying capacity of sands often allow the formation of interdunal ephemeral closed lakes and streams within the endoreic basins of Arabia. This means that, while indeed there are often water sources available, they are frequently scattered and spatiotemporally variable (e.g., Petraglia et al., 2020).

2.1 Palaeoclimate and environment of Arabia during MIS 5 wet periods

Substantial increases of precipitation across the Saharo-Arabian deserts occurred during MIS 5e (~128 to 121 ka BP), 5c (~104 to 97 ka BP) and 5a (~82 to 77 ka BP). Analysis of speleothem fluid inclusion $\delta^{18}O$ and δD from Yemen and Oman indicate that enhanced precipitation was delivered by the ASM and ISM (Fleitmann et al., 2003b; Nicholson et al., 2020). Substantial enhancements in the intensity and spatial extent of the monsoonal rain-belt were a result of increased summer insolation and reduced glacial-boundary conditions (Fleitmann et al., 2011; Rosenberg et al., 2013; Nicholson et al., 2020). Speleothem growth at Mukalla and Hoti Cave is coherent with the formation of Mediterranean sapropels S5 (128.3 – 121.5 ka BP), S4 (107.8 – 101.8 ka BP) and S3 (85.8 – 80.8 ka BP) and negative shifts in Soreq Cave $\delta^{18}O_{ca}$ (Bar-Matthews et al., 2003; Grant et al., 2012, 2016, 2017). These respond to increased precipitation in the Ethiopian Highlands and the “source effect”, caused by discharge of low-$\delta^{18}O$ monsoon-driven freshwater runoff from the Nile, respectively (Bar-Matthews et al., 2003; Grant et al., 2017). Further correspondence is observed with marine sediment cores from the Gulf of Aden (RC09-166: Tierney et al., 2017 and KL-15: Fleitmann, 1997), the Red Sea (KL-11: Fleitmann, 1997; Siddall et al., 2003) and the Mediterranean (ODP 967: Larrasoana et al., 2003; Williams et al., 2015; Grant et al., 2017); all records show substantial changes of Saharo-Arabian continental wetness (Fig. 2), recoding precipitation amount, surface runoff and soil humidity. While some palaeolake deposits and alluvial records do have ages that overlap with colder substages (e.g., Rosenberg et al., 2011, 2013; Parton et al., 2015a, 2018; Groucutt et al., 2018), the intervening periods of MIS 5d and 5b are generally characterised by a return to more arid conditions (Fleitmann et al., 2011; Grant et al., 2017; Nicholson et al., 2020).

The ASM and ISM increased annual precipitation to 600-300 mm yr^{-1} over much of Arabia (Otto-Bliesner, 2006; Fleitmann et al., 2011; Jennings et al., 2015; Fig. 2A). The ASM monsoon rain-belt reached as far north as the Nafud Desert, as determined by palaeolake activation and climatic modelling (Waldmann et al., 2010; Rosenberg et al., 2013; Jennings et al., 2015), and perhaps contributed to the catchment of palaeolake Mudawwara at 29°N during MIS 5e (Petit-Maire et al., 2010). Precipitation was lowest in the northern areas of Arabia, receiving annual rainfall of 300-200 mm yr^{-1} and in some places even less (Jennings et al., 2015). This resulted in meridional (more in the south) and zonal (more in the west) precipitation gradients across Arabia. The zonal precipitation gradient, for instance, was caused by the incursion of the ASM into western Arabia (Herold and Lohmann, 2009; Rosenberg et al., 2013; Gierz et al., 2017; Nicholson et al., 2020). In combination with speleothem fluid inclusion $\delta^{18}O$ and δD values, seasonal stalagmite $\delta^{18}O_{ca}$ and $\delta^{13}C_{ca}$ cycles (stalagmite H13 from Hoti Cave) indicate a shift to a summer-dominated precipitation regime. However, winter rains continued to deliver additional precipitation over Arabia (Gierz et al., 2017) and were enhanced in the Levant (Vaks et al., 2010; Orland et al., 2019). The dominance of summer rainfall across Arabia led to a distinct “wetter” summer and “drier” winter seasonality (Gierz et al., 2017; Nicholson et al., 2020). As well as increased summer precipitation, increased cloud cover of the monsoon system resulted in reduced evaporation (Herold and Lohmann, 2009) and led to increased effective moisture during the summer. The Dhofar region of Oman – which is prone to increased cloud cover, misting and vegetation blooms in the summer, despite rainfall remaining low – is frequently used as an analogue for periods of enhanced precipitation (e.g., Rose et al., 2019).

It is important to note that there were variations in the duration and intensity of different wet periods. Speleothem $\delta^{18}O_{ca}$ (Mukalla and Hoti caves: Fleitmann et al., 2011; Nicholson et al., 2020), marine sediment core $\delta D_{leaf\text{-}wax}$ (RC09-166: Tierney et al., 2017) and grainsize data (KL-11 and KL-15: Fleitmann, 1997) indicate that MIS 5e experienced the longest and most intense increase in monsoonal precipitation. The ASM was intensified for ~6.8 kyrs as indicated by the deposition of sapropel S5 (Grant et al., 2017) and Nile outflow was ~8.8 times higher than today (Amies et al., 2019). While MIS 5c and 5a lasted for similar periods of ~6 and 5 kyrs respectively, they were characterized by more positive $\delta^{18}O_{ca}$ (Fleitmann et al., 2011; Nicholson et al., 2020) and $\delta D_{leaf\text{-}wax}$ (Tierney et al., 2017) compared to MIS 5e, indicating that rainfall was less intense than MIS 5e. To place these MIS 5 sub-stages in context, speleothem $\delta^{18}O_{ca}$ from all Late Pleistocene wet periods were more negative (increased rainfall) than the Holocene Humid Period (HHP), in which increased rainfall supported human occupation in the now arid interiors of the Sahara and Arabia (Kuper and Kropelin, 2015; Groucutt et al., 2020; Petraglia et al., 2020).

Extensive surveys and GIS analyses of the Arabian Peninsula have shown that increased precipitation activated widespread palaeolake and river systems (Breeze et al., 2015, 2016). In southern Arabia, this is exemplified by palaeolakes Mundafan, Khujaymah and Saiwan (Rosenberg et al., 2011, 2012; Groucutt et al., 2015c; Tab. 1), further lakes and sabkhas in the central Rub' al Khali (Matter et al., 2015) and alluvial/fluvial deposits in the UAE (Parton et al., 2015a). Southern Arabian palaeolakes typically contain the ostracod *Darwinula stevensoni* and the mollusc *Unio* sp., both require fresh and open running water conditions and diverse lacustrine flora and fauna communities (Rosenberg et al., 2011, 2012; Matter et al., 2015). In addition, the presence of *D. stevensoni* shows these lakes were perennial, retaining freshwater during dry seasons (Rosenberg et al., 2011, 2012). Phytolith data from Mundafan shows that grasslands, with some woody cover, were present in the nearby vicinity (Groucutt et al., 2015d).

In northern Arabia, extensive studies of the Jubbah basin have been crucial to characterising local environmental shifts in response to climate changes. Lake formation in the Jubbah basin occurred during MIS 5 (Parton et al., 2018; Tab. 2) with smaller interdunal lakes close by (Rosenberg et al., 2013). Despite a seasonal precipitation regime (Nicholson et al., 2020), rainfall was sufficient to sustain perennial freshwater lakes and riverine systems with diverse flora and fauna communities (Rosenberg et al., 2011, 2012; Breeze et al., 2015; Matter et al., 2015; Parton et al., 2018). Colder temperatures in winter months would have been echoed by reduced evaporation, perhaps aiding the perennial character of these waterbodies. Minor winter rainfall also likely contributed to maintaining year-round standing waterbodies, but most recharge would have occurred in the summer months by the ASM (Rosenberg et al., 2013). Additional deep lakes in northern Arabia include Al Wusta, B’r Hayzan and Khall Amayshan; their diatom and palaeontological records indicate environments and climates typically reflecting those of Jubbah (Rosenberg et al., 2013; M. Stewart et al., 2020b). GIS mapping has identified further large lake basins within 100 km of Jubbah (Breeze et al., 2015, 2017) and that wetlands and lakes were probably more numerous in the western Nafud than elsewhere in northern Arabia

(Breeze et al., 2017), and supported multiple phases of hominin occupation (Scerri et al., 2015).

While palaeolakes have been (and will continue to be) vital to characterising the environments of Green Arabia, improved dating must be a target for future research. OSL dating of palaeolake sediments is difficult, due to factors such as the challenge of estimating environmental dose rates in such dynamic environments (Clark-Balzan et al., 2017). Underlying sands are often dated as they consist of aeolian material theoretically good for OSL dating, and it can be argued that they would have become stabilised by the increased rainfall that led to lake formation shortly afterwards. While in some cases this is true (Groucutt et al., 2018), it is possible for lake deposition to occur on top of much older sands (M. Stewart et al., 2020a). Furthermore, compared to other records (such as speleothems), dating of palaeolakes suffers from considerable age uncertainties (often in excess of 10% of the absolute age) and are often “wiggle-matched” to speleothem ages (e.g., Rosenberg et al., 2013). Thus, unlike speleothem records (e.g., Nicholson et al., 2020), it is very difficult to construct precise palaeoclimate records from lake sequences. The challenges include identifying major hiatuses and seasonal differences in precipitation, assessing whether lakes were diachronic, or assigning lakes to specific MISs and their substages. While Bayesian approaches can be used to mitigate uncertainties (e.g., Groucutt et al., 2018), their applicability can be limited by small sample sizes with sometimes significant age reversals, which could provide artificial and misleading ages.

Nevertheless, the presence of perennial waterbodies supported large faunal communities across Arabia. Excavations at Al Wusta (late MIS 5) have yielded remains of *Hippopotamus*, *Kobus*, *Pelorovis* and *H. sapiens*, as well as ostrich eggshells (Groucutt et al., 2018). Large tooth marks on the fossils also indicate a diverse carnivore guild was present (Groucutt et al., 2018). Similar taxa have been identified at the nearby site of Khall Amayshan (117 ± 8 ka BP: Rosenberg et al., 2013) including, Elephantidae, Hippopotamidae, ostrich eggshell, Equidae, Bovidae and Hippotraginae (M. Stewart et al., 2020b). Three important points to take from the presence of *Hippopotamus* are 1) freshwater bodies were at least 2 m deep and likely perennial; 2) sufficient foraging and vegetation would have been present within 1-3 km of these lakes; and 3) the lakes would have included gently sloping banks and beaches (Jablonski, 2004), which would have made them easily accessible to other animals (including humans). Additionally, a mixture of juvenile and adult (interpreted to represent a herd) elephant prints (as well as fossils eroding from the sediments) were identified at the Alathar palaeolake (112 ± 10 to 121 ± 11 ka BP), suggesting that substantial biomass was located in the nearby vicinity (M. Stewart et al., 2020a).

The palaeontological records of southern Arabia seemingly match the pattern of northern Arabia: Alcelaphinae, Bovinae, *Arabitragus jayakari*, Cervidae and Equidae have been uncovered from Late Pleistocene deposits in the Rub’ Al Khali (McClure, 1984; Stewart et al., 2019). While many of these deposits were originally dated to MIS 3, they have since been re-dated to MIS 5 via the OSL and TT-OSL methods (Rosenberg et al., 2011, 2012). These taxa demonstrate that temperate to semi-arid grasslands were located near to perennial waterbodies, with sufficient vegetation resources to support communities of large herbivores.

Increased effective moisture and soil humidity suggest that vegetation density was enhanced across the Saharo-Arabian deserts during MIS 5 warm substages. In Arabia, grasslands were present both in close proximity to lakes (Rosenberg et al., 2013; Groucutt et al., 2015c, 2018) and elsewhere (Bretzke et al., 2013; Nicholson et al., 2020). Phytolith analysis of sediments recovered from MIS 5e archaeological contexts (assemblage C) of Jebal Faya, UAE, included Pooids, Panicoids, Chloridoids and long grasses. Cyperaceae, Asteraceae, Palmae and other grasses were also present in small quantities – evincing mixed C_3/C_4 grassland (Bretzke et al., 2013). Speleothem growth at both Mukalla and Hoti Cave indicate that effective moisture and soil humidity were much greater in MIS 5e, and soils had formed in the now desert areas of Yemen. Calcite carbon isotope ratios ($\delta^{13}C_{ca}$) at Mukalla Cave (-8 to -2‰) fall within C_3/C_4 grassland signatures (Nicholson et al., 2020). However, there remain three key uncertainties:

1) Speleothem $\delta^{13}C_{ca}$ and phytolith analyses cannot identify species-level floral compositions. Without species level assignments, it is not possible to establish plant based Mutual Climate Range estimates, or provide a detailed insight into the floral resources available to humans.

2) Environmental records are sparsely distributed; meaning the majority of the "green" transformation of the Arabian landmass is based on interpolation or analogues with the Sahara (e.g., Larrasoaña et al., 2013). This interpretation is complicated by two factors; a recent Red Sea dust source record which demonstrates the Arabia-Nubian shield became the dominant dust source during MIS 5 warm substates, indicating some areas remained relatively dry (Hartman et al., 2020). Additionally, the archaeological and palaeontological records of northern Africa (where predicted precipitation matched northern Arabia) suggest a model of semi-isolated populations and show that some areas remained arid or semi-arid (Scerri et al., 2014b). It is therefore not self-evident that Arabia was completely "green".

And, 3) there is little knowledge of spatio-temporal environmental variability and seasonal differences in vegetation, which may have influenced seasonal survival strategies. Annual $\delta^{13}C_{ca}$ cycles of stalagmite H13 (Hoti Cave) indicate seasonal differences in drip-rate as a result of a drying of the aquifer and reduced soil moisture, which was likely echoed by a vegetation response. But there are no direct examples of seasonal vegetation variability. Understanding environmental responses to seasonal precipitation, both across space and time, must be a target for future research.

Another issue to consider is that our discussions of Arabian environments and their suitability for dispersal have typically been limited to climate and vegetation feedback (Erlandson and Braje, 2015; Nicholson et al., 2020). Groucutt (2020a) has recently stressed the importance of other factors – with an emphasis on volcanism – on shaping both the environment and topography of Arabia. For example, while eruptions can often have negative short-term effects (contamination of water, deterioration of patch quality), there are also long-term positives, such as creating particularly fertile areas. Eruptions were fairly common throughout MIS 5, with notably high frequencies during early (~130 ka BP) and late MIS 5 (~90-80 ka BP) (Groucutt, 2020a). While the impact of these on humans in Arabia is not understood, it certainly raises questions concerning the variable nature of environments, their impact on human populations within “green” phases, as well as human adaptation, resilience and/or localised exptirpations.

In summary, pronounced shifts of Arabian environments during MIS 5 were primarily influenced by expansions and contractions of the monsoon domain on orbital timescales . These resulted in the expansion of grassland environments and allowed *H. sapiens* to expand into the now arid interiors. However, there remain many uncertainties and key questions for the future. For example, were lakes diachronic, or, simlar to today, was there high variability in their availability? In the Arabian interior, what were environments like beyond riparian zones? How heterogenous was the landscape – both spatially and throughout the duration of these green periods – and what sort of microenvironments were present? What other topographic features played a role in shaping the environments available to humans? All-encompassing studies of environmental and topographic heterogeneity will be of key importance for moving beyond simplistic narratives of *H. sapiens* dispersals and occupations of Arabia.

2.2 Archaeology

Due to the scarcity of recovered hominin fossils, archaeological finds provide the main record of human activity in Arabia. Middle Palaeolithic (MP) assemblages characterise the early Late Pleistocene archaeological record of Arabia, found mostly in the now-arid interior (Fig. 3). While a large portion of these are surface finds, of those that have been excavated, most have been derived from palaeolake sediments, or deposits on the margins of palaeolakes (Petraglia et al., 2012; Groucutt et al., 2015b, 2015d, 2016), and close to fluvial channels (Breeze et al., 2015).

2.2.1 Northern Arabia

In northern Arabia, several Middle Palaeolithic assemblages have been described from the Jubbah Basin. The upper assemblage at the site of Jebel Qattar-1 (JQ-1) dates to ca. 75 ka BP, and features a focus on centripetal Levallois reduction, with both preferential and recurrent methods used (Petraglia et al., 2011; 2012). Other core reduction methods are present in small frequencies, such as discoidal. Retouched forms include side retouched flakes and a small retouched point. These characteristics are reminiscent of the African MSA and the Levantine MIS 5 Middle Palaeolithic (Groucutt et al., 2015b). Another site, Jebel Umm Sanman (JSM-1), consists of a surface scatter and small published excavations. Available OSL dates loosely constrain the assemblage to late MIS 5 or shortly after (Petraglia et al., 2012). The assemblage again features a focus on centripetal Levallois technology. A larger excavation was conducted at the site of JKF-1, but OSL dating the deposit again proved challenging, and resulted in an age range of 50-90 ka BP (Petraglia et al., 2012). While the core technology is rather amorphous, reflecting the frequent use of small quartz pebbles, the main reduction process involved the primarily unidirectional reduction of quartzite blocks to produce convergent Levallois flakes (Groucutt et al., 2015c). JKF-1 therefore demonstrates a rather different set of characteristics to JQ-1 and JSM-1, and reflects more similarities with MIS 3 sites from the region (e.g., Jennings et al., 2016). In addition to these sites, a variety of surface Middle Palaeolithic sites have been recovered, such as JKF-12 (e.g., Groucutt et al., 2017).

While research on the Middle Palaeolithic assemblages of Jubbah is ongoing, what can we say about the character and meaning of technological variability observed? Some aspects of this probably have a pragmatic basis. For instance, as mentioned the frequent use of small quartz pebbles at JKF-1 seems to have influenced reduction. Perhaps a wider impact, however, concerns differential reduction intensity. Groucutt et al. (2017) explored how reduction intensity (measured as the scar density index) varied with distance from raw material sources, and found a positive relationship. This explains why the JQ-1 assemblage is so small and reduced. Such factors, however, occur within an umbrella of centripetal Levallois technology.

Quantitative comparison of Jubbah lithic assemblages (JKF-1, JKF-12 and JSM-1) with assemblages from NE Africa highlighted that, while there were some similarities in core preparation techniques, high levels of technological variability mitigates against a simple interpretation (e.g. a single dispersal out of Africa echoed by a single techno-cultural complex). Instead, the variability was taken to reflect occupation by multiple populations at different times (Scerri et al., 2014a). However, given the nature of the burial contexts, current dating inaccuracies between these assemblages, as well as their temporal distribution, discussions of cultural hetero/homogeneity are not without uncertainty. Overall, while an MIS 5 occupation of the Jubbah area by hominin groups using centripetal Levallois technology is clear, further assessments are required to distinguish whether groups were present at other points, and indeed whether there were multiple occupations within MIS 5.

Similarities to Jubbah are apparent across northern Arabia. The Al Wusta archaeological assemblage (dated to late MIS 5 and the only assemblage discussed here with direct association to a *H. sapiens* fossil) again emphasises a focus on centripetal Levallois reduction, similar to those of east and NE Africa and the Levant (Groucutt et al., 2018). Interestingly, the assemblage was mostly comprised of chert artefacts (65%), showing that morphological similarities with the Jubbah assemblages transcend raw material choices. Elsewhere in northern Arabia, Middle Palaeolithic assemblages of the Najd appear more homogenous than in southern Arabia, although there are still differences between assemblages. For example, whereas cores from sites ABY-1 and SHW-11 were characterised by preferential centripetal Levallois reduction, AZA-2 was characterised by recurrent centripetal reduction. Additionally, QAN-1 possessed the only example of a Saudi Arabian assemblage dominated by discoidal reduction. The new sites presented by Groucutt et al. (2016) lack chronometric dating which, given that humans repeatedly occupied Arabia throughout the Pleistocene (Bailey et al., 2015; Scerri et al., 2018a), means addressing spatio-temporal variability from these assemblages is not straightforward. However, the variability does suggest that expectations of a single defining stone tool culture moving into Arabia are overly simplistic. Instead, it is apparent that different reduction strategies were employed within northern and central Arabia, likely reflecting differences in cultural traditions, mobility strategies or durations of individual occupations. Nevertheless, these findings present a clear indication that the Middle Palaeolithic record of northern Arabia is dominated by a focus on centripetal Levallois technology, as found with *Homo sapiens* in the Levant and northeast Africa (Groucutt et al., 2015b). This is likely influenced by dispersals from these regions into Arabia, as well as back into Africa and/or the Levant following returns to desert conditions.

An additional line of evidence for human activity comes from the identification of seven hominin footprints from a remnant of the Alathar palaeolake, dated between 112 ± 10 and 121 ± 11 ka BP (likely MIS 5e). M. Stewart et al. (2020a) suggest that these can be assigned to *H. sapiens* on the basis of the size of the prints, plus the spread of *H. sapiens* into Arabia and adjacent regions and absence of Neanderthals in the Levant during MIS 5. The recovery context, spatial distribution and orientation of the prints provide a snapshot of very high-resolution behavioural patterns from a rapidly forming site. The various orientation and scatter of the prints around the lake were interpreted to reflect non-directional activities, though these were mostly oriented in a southward direction. Combined with the absence of butchery practices on animal fossils and absence of stone tools, it was suggested that Alathar was, at this time, only briefly visited by humans. The absence of stone tools (while potentially related to poor surface preservation) contrasts other lake sites, which document more intensive usage of lake margin habitats, suggesting that the Alathar prints provides a unique record of human activity in Arabia.

2.2.2 Southern Arabia

The archaeology of southern Arabia is somewhat more variable than northern Arabia. Artefacts uncovered at the Mundafan palaeolake (~100-80 ka) included Levallois cores characterised by recurrent centripetal (30%) and preferential with centripetal preparation (22%) strategies (Groucutt et al., 2015d). Flakes were described as standardised and typically ovoid or rectangular in shape. Additionally, a high retouched component was present, which is typically uncommon in the Arabian Middle Palaeolithic. Further undated Middle Palaeolithic sites at Mundafan share a similar technology (Crassard et al., 2013), and lack other forms of technology such as the Nubian Levallois method.

In Dhofar, in the southwest of Oman, a rather different kind of Middle Palaeolithic technology dominates. Here numerous assemblages, particularly in western Dhofar near the spring at Mudayy, demonstrate a focus on the Nubian Levallois reduction method (Rose et al., 2011; Usik et al., 2013). The findings are virtually all surface scatters, except at the site of Aybut al Auwal where a single Nubian Levallois core and a few other lithics were found redeposited in a fluvial channel (Rose et al., 2011). To the discoverers these sites, as well as occasional hints of Nubian Levallois technology in Saudi Arabia (e.g., Crassard and Hilbert, 2013), provide evidence for long distance movement between the Nile Valley and southern Arabia. Groucutt (2020b) has suggested an alternative explanation, that the Dhofar Middle Palaeolithic possibly represents convergent evolution of Nubian Levallois technology, which is found from South Africa to India and over a ca. 200,000 year period. Given the minimum age of ca. 107 ka from Aybut al Auwal, it may be that MIS 5e or earlier dispersals retracted to reliable water sources in southern Arabia and developed distinctive local cultural trajectories. While currently poorly chronologically constrained, the varied Palaeolithic assemblages from southern Arabia certainly indicate a complex demographic history (e.g., Jagher, 2009; Delagnes et al., 2012; Bailey et al., 2015).

Further regional artefact variability is confirmed at Jebal Faya, UAE. This site is a notable exception to the general Arabian record, with artefacts recovered from rock shelter sediments and an occupation history spanning from MIS 5e to MIS 3 (Armitage et al., 2011; Bretzke et al., 2014). Assemblage C, dated to 127 ± 16 and 123 ± 10 ka (MIS 5e), contained artefacts with a variety of reduction strategies including the production of volumetric blades and Levallois debitage, bifaces, and retouched forms. Qualitative characteristics of this assemblage were considered similar to artefacts recovered from sites such as Muguruk, Kenya (Armitage et al., 2011). Indeed, while apparently diverse in its characteristics, the dominant characteristic of Assemblage C seems to be the focus on bifacial reduction, which is unusual for the Arabian Middle Palaeolithic. Assemblage B, however, contained little evidence of bifacial and Levallois reduction, with the exception of a few convergent flakes which are similar to Levallois points (Armitage et al., 2011). Further variability was observed in assemblage A dated to 40.2 ± 3.0 and 38.6 ± 3.1 ka (MIS 3); assemblage A contained a diverse range of reduction strategies and retouched morphologies including the production of denticulates, side scrapers, end scrapers, and burins. Flakes were produced from platform cores, which contrasts the apparent absence of prepared platforms from Assemblage C (Armitage et al., 2011). The difference between artefact types, as well as densities, have been interpreted to relate to differences in techno-cultures (Armitage et al., 2011) and “distinct traditions in spatial behaviour” (Bretzke and Conard, 2017) between occupation phases. In summary, the assemblages of Jebel Faya are not only different from each other, but also seemingly differ from other Arabian assemblages.

2.2.3 Summary

Overall, there is a high degree of spatial variability in stone tool assemblages across Arabia (e.g., Fig. 4). Ongoing analysis of the archaeological record of Arabia suggests that sites in northern Arabia are repeatedly similar to those from NE Africa and the Levant (Petraglia et al., 2012; Scerri et al., 2014b; Groucutt et al., 2019), whereas those in the south repeatedly feature localised characteristics (Armitage et al., 2011; Delagnes et al., 2012). We posit three, not necessarily mutually exclusive, potential explanations for this:

1) multiple populations, with entirely different techno-cultures, entered Arabia during various MIS 5 substages, perhaps from different routes (via the Sinai Peninsula or the Bab al Mandab strait).

2) *H. sapiens* populations entered southern Arabia by crossing the Bab al Mandeb strait on to an exposed continental shelf during periods of low sea-levels (Parker and Rose, 2008; Bailey et al., 2015). Low sea-levels, however, are typically related to drier periods (Rosenberg et al., 2011) and thus initial dispersals would take place prior to the onset of MIS 5e, 5c and 5a (e.g., Rohling et al., 2013). In this instance, widespread population expansions into the Arabian interiors would occur with the onset of wetter conditions (Armitage et al., 2011).

3) Arabian assemblages, particularly those in the south, represent a high degree of localisation following an initial dispersal into northern Arabia.

In terms of entry points into Arabia, it is important to consider that Arabian wet phases in the warm substages of MIS 5 (Fleitmann et al., 2011; Nicholson et al., 2020) occurred when sea-levels were higher than the intervening periods (Rosenberg et al., 2012; Grant et al., 2014). During the intervening stadials, an expansion of the desert likely inhibited widespread dispersals into Arabia. There is also currently no evidence from Arabia or NE Africa for relevant sea-faring technologies. We take this pattern to suggest a northern dispersal route into Arabia, followed by southward movements into Arabia following green palaeohydrological corridors (e.g., Breeze et al., 2016). We interpret the archaeological signature of the north to represent initial dispersed populations, which quickly diversified and adapted to local environments. As populations expanded southwards into Arabia, local techno-cultural characteristics developed in response to increasing distance from initial populations and local environmental and cultural factors. This pattern was likely repeated during each MIS 5 wet period, as each substage was likely represented by a new wave of settlement. However, only a handful of dated sites are currently available for analysis and few are temporally aligned. It is therefore vital to increase the spatio-temporal resolution and variability of the Arabian archaeological record to test this. The current available methods and the nature of preservation in these environments means that producing such a database will be challenging. Furthermore, many reports from Arabian archaeological sites classify assemblages based on qualitative morphological features; there is currently only one example of inter-site quantitative morphological comparison (e.g., Scerri et al., 2014b). Further analysis comparing many assemblages are needed to generate key information on inter-assemblage morphological variability across Arabia.

Analysis and interpretation of the Arabian and Levantine records is also complicated by survey biases and taphonomic issues. One is geography – the Levant is less than one-tenth the size of Arabia. Another consideration is that the history and intensity of extensive Palaeolithic archaeological survey in Arabia is much younger than that of the Levant. Simply put, we may have much fewer pieces of the puzzle in Arabia. Assemblages that actually or potentially display similarities to other regions (i.e., the Levant and NE Africa [Groucutt et al., 2019], or East Africa [Armitage et al., 2011]) may be the only pieces yet identified in a much more complicated puzzle. What of population links between Mesopotamia and NE Arabia? Did these exist and did the Euphrates and Tigris rivers act as population corridors between these regions (e.g., Breeze et al., 2016; Bretzke and Conard, 2017)? If so, to what extent did these demographic links shape stone tool assemblages and morphologies? Another pertinent consideration is the recovery context and the impact on geomorphic, hydrological and physiographic factors. Most of the dated and stratified archaeological assemblages from Arabia were found in alluvial, fluvial and lacustrine sediments (apart from Jebel Faya). However, surface sites have been located across Arabia (Rose et al., 2011; Groucutt et al., 2016). These, and areas comprised of drift sands, would have experienced greater reworking than stratified alluvial, fluvial and lacustrine sediments. The resulting variations in assemblage formation and composition are partially shaping our understanding of the prehistoric settlement of Arabia.

It is important to note that many objects (e.g. bone tools, wood tools, eggshells) do not readily preserve but could have been crucial to surviving Green Arabia. For example, Ostrich eggs could have been used as water containers, and facilitated temporary movement away from waterbodies. While ostrich eggshell fragments were uncovered at Mundafan (Groucutt et al., 2015d), it cannot be discerned whether these were used by humans. Also, animal skins and bladders could have been used to carry water and are commonly used today. Again, these do not readily preserve in the archaeological record. Additionally, the archaeological record of Arabia does not provide evidence of symbolic practices, which are commonly associated with rock shelters and caves in regions with dense *H. sapiens* occupation histories. Across Africa, it is clear that the MSA included specialised hunting tools, use of aquatic resources, bone tools, microlithic technologies, long distance trade, art and decoration, use of pigment, specialised hunting, structure building, social organisation and systematic processing (Mcbrearty and Brooks, 2000; Blegen, 2017; Scerri, 2017; Brooks et al., 2018). While evidence of all of these are not available from Arabia, hints of long-distance sourcing/transfer comes from occasional examples of putatively exotic raw materials in available assemblages (Petraglia et al., 2012). However, further research needs to be done on characterising raw material source, and distinguishing primary and secondary (e.g. fluvial) raw material sources. Given that *H. sapiens* dispersed from NE Africa, it is likely that many behaviours present in Middle to Late Pleistocene Africa were key components of their behavioural repertoire. Conversely, our interpretation that *H. sapiens* were highly mobile (see below) could suggest that costly symbolising practices were not effective in these settings. Nevertheless, finding specific examples from Arabia is necessary for understanding the range of *H. sapiens* behavioural variability. This must be a target of future research.

3. *H. sapiens* in Green Arabia

In order to understand how humans became established, survived and retracted in Arabia, it is necessary to synthesise the environmental and archaeological records with reference to ecological, anthropological and biological datasets. Here, we address the processes of dispersal into Arabia, the dynamics of long-term survival, and population decline in the face of fluctuating climates.

Dispersal

Dispersal differs from migration, being defined as “a strategy to increase fitness in a heterogeneous landscape by changing the environment in which an organism lives” (Bowler and Benton, 2005: 218). One of the most crucial factors when discussing the distribution of organisms and their introduction into new areas is the resources available to enhance their reproductive fitness. Both periods of increased rainfall (Shultz and Maslin, 2013; Maslin et al., 2014) and aridity (deMenocal, 1995) have been considered to influence hominin adaptation and dispersal on long time-scales through their impacts on changing resources and population dynamics. Whereas transitions to aridity promote dispersal or extirpation due to reduced resources – namely, water, flora and fauna (deMenocal, 1995) – periods of increased rainfall (and vegetation) promote population expansions within the hominin food chain, resulting in hominin population increases and, ultimately, dispersal/adaptation/extinction due to competition pressure (Shultz and Maslin, 2013; Maslin et al., 2014). The palaeoenvironmental record of Arabia clearly highlights that increased resources (water, vegetation and other animals) meant carrying capacity was greatly enhanced and offered new habitats for dispersal during wet periods. On the other hand, returns to aridity may have had a push and/or extirpating effect on resident populations. Another consideration is that shorter events within both ‘wetter’ and ‘drier’ phases, and how these might have stimulated potentially short-lived and rapid dispersals and declines.

This is consistent with recent considerations of *source* and *sink* population dynamics (Dennell et al., 2011; Dennell, 2017). A population sink is described as a region in which reproduction is too low to replace individuals. These are typically located in areas in which resource availability is either scarce or highly variable. On the other hand, source areas are regions in which reproduction outweighs the replacement of individuals, due to resource abundance or stability. Dennell (2017: 5390) explains that "Demographic expansion thus depends greatly upon (i) extinction rates in sink populations at the edge of the inhabited range and (ii) the ability of the main source populations to support sink populations, especially those at the edge of the range. This becomes difficult when population densities are low and intergroup distances are high". With regards to Arabia, we may infer that rates of extinction were severely lowered at the edge of original habitats (such as sub-Saharan Africa and NE Africa) in green phases such as early MIS 5e, due to increased resources promoted by monsoonal rainfall. This facilitated former sink populations to become new source populations and allowed expansion into newly habitable areas.

It must also be considered that human populations typically form metapopulations, which can be defined as "a group of spatially separated populations occupying a nexus of favourable patches" (Smith, 2013: 75). Humans can be characterised by "tight" metapopulations, which maintain cohesion through kinship, ideology, culture and additional forms of identity over large distances (Dennell, 2017; Scerri et al., 2018b, 2019). The examples given above of long-distance cultural exchange throughout the MSA suggest that human metapopulations were maintained over >100s of kms (Blegen, 2017; B. A. Stewart et al., 2020). Dennell (2017) highlights two main benefits of species that settle areas as part of a broader metapopulation. Firstly, resilience to stochastic events and environmental/resource variability at the metapopulation level. Whereby groups comprising a metapopulation are more widely distributed in a landscape, mitigating against a metapopulation extinction. Secondly, a trial-and-error basis of settling new habitats in which a "failing" group can be replaced or repopulated by groups from the broader metapopulation. Smith (2013) and Dennell (2017) highlight that this trial-and-error basis allows multiple groups to settle new habitats in a short period of time, where sufficient inter-group connectivity mitigates against local extinctions. If this model was relevant to Green Arabia dispersals then we should expect to see evidence that Arabian populations with cultural similarities likely maintained some contact over considerable distances. There is currently a suggestion for imported material into the Jubbah basin; however, further examples of long-distance exchange are required to understand the specific inter-connectivity of Arabian populations.

In summary, it is likely that dispersal and settlement of Arabia was a response to feedback effects between resource availability, patch carrying capacity and population pressure. Increasing rainfall across the southern limits of Saharo-Arabia, in which *H. sapiens* were likely already present, meant populations gradually expanded, resulting in increased pressure for dispersal into the new surrounding areas. We may describe this almost as a continuous dispersal, whereby populations expanded gradually into new areas with higher carrying capacities, which facilitated local population growth. Over time, local competition pressure forced expansion into additional new habitats. As rains were predominantly derived from the ASM and ISM monsoons, one likely aspect is that, as populations likely entered northern Arabia, the easiest expansion route was southwards towards greater water availability and food resources. Although the specifics of mobility were likely structured by lakes, rivers and other waterbodies (such as the Wadi Al-Batin) could have provided corridors towards the eastern coast of Arabia (Breeze et al., 2016; Petraglia et al., 2020). As populations moved southwards, increasing differentiation due to separation from a metapopulation and autochthonous development may explain the localisation of stone tool assemblages in these regions. Additionally, northward dispersals into the Levant were likely aided by increased winter (Vaks et al., 2010) and (particularly during MIS 5e) summer (Petit-

Maire et al., 2010; Torfstein et al., 2015; Orland et al., 2019) precipitation across the southern Levant. This dual source of rainfall could mean that human mobility patterns differed, though, more information on the specific duration and impact of summer rainfall is required from the Levant.

Another important factor concerns whether Arabia was already occupied when humans dispersed into the area in MIS 5. Whether other human populations (or species) were already present could have had a dramatic impact on how *H. sapiens* settled Arabia (e.g., Dennell 2017). Evidence of Oldowan and Acheulean artefacts across Arabia likely suggest that pre-MIS 5 occupations had occurred (Groucutt and Petraglia, 2012). Recent dating of the Saffaqah archaeological deposits conform to this, placing an Acheulean occupation during late MIS 7 and possibly extending into MIS 6 (Scerri et al., 2018a). Identification of *H. sapiens* at Apidima (Greece: Harvati et al., 2019) and Misliya (Israel: Hershkovitz et al., 2018, but see Sharp and Paces, 2018) caves, argued to date to MIS 7 and MIS 6 respectively, suggest that *H. sapiens* had dispersed from Africa prior to MIS 5, and Arabia would have been along this dispersal pathway. If these fossils and dates are accepted then, it is possible that *H. sapiens* occupied Arabia during MIS 7 or 6.

Yet, debates on whether there were long-term refugia in Arabia have not produced clear results (e.g., Rose, 2010; Bretzke and Conard, 2017). It must be considered that the majority of dated sites from Arabia have been excavated from palaeolake sediments, which are strongly aligned to interglacial periods. In other words, a failure to identify archaeological material from glacial periods is to be expected if lakes were less frequent. While indeed alluvial aggradation in Oman suggests MIS 6 was characterised by perhaps long-term, albeit less intense precipitation ~160-150 ka BP (Parton et al., 2015a), absence of stalagmite growth in both the Negev (with exemption of one sample dated to 157.2 ± 3.8 ka BP; Vaks et al., 2010) and southern Arabia (Nicholson et al., 2020) highlight that precipitation was generally lower between during MIS 6. In this case, Arabia may have been particularly challenging for hominin occupation prior to 130 ka BP, or perhaps characterised by a low intensity occupation in isolated areas such as the Yemeni highlands. For now, our working model is that Arabia was frequently occupied during Arabian green phases throughout the Middle Pleistocene (Scerri et al., 2018a; Nicholson et al., 2020); whereas returns to aridity saw depopulations (see below). Therefore, it is very likely that Arabia was devoid of other humans when *H. sapiens* first entered during MIS 5e. In this case, if settlement and occupation across Green Arabia was uncontested, it was perhaps more rapid than it might have otherwise been.

<u>Occupation</u>

But what can we say about the more intricate processes of occupying Green Arabia? We have discussed the broad environmental outlines of Arabia, yet many fundamental aspects are currently not known. For example, while some areas would have become grassland environments with water sources, the attractiveness and stability of these landscapes is currently poorly constrained. Many Arabian Palaeolithic archaeological sites are located close to palaeolakes (Petraglia et al., 2012; Groucutt et al., 2015c, 2018; Scerri et al., 2015); although Jebel Faya is a notable exception, wadis and lakes have been identified within 5 km of the site (Armitage et al., 2011; Bretzke et al., 2013). The perennial nature of the palaeolakes made these attractive habitats, which included the provision of freshwater during the drier winter months. These could have also provided rich opportunities for hunters (human and non-human) to ambush prey that are drawn to the water (Hitchcock et al., 2019). Yet, the discovery of hippo fossils – arguably one of the most dangerous land mammals, killing ca. 500 people a year –

and evidence of a diverse carnivore guild during late MIS 5 and other Pleistocene sites (Groucutt et al., 2018; Stewart et al., 2019) indicate that small lakes in Arabia also came with challenges.

A further complicating factor is that we currently have little information on the character of edible plant resources for *H. sapiens* in Arabia. For example, bushed or wooded lake shores and river margins of East Africa tend to host mesophilic plants and other plants producing berries, nuts and seeds (Lind and Morrison, 1974; Sept, 1994; Marean, 1997). Drier soils, escarpments and inselbergs contain a plethora of carbohydrate rich plants with underground storage organs (USOs – including rhizomes, tubers, corns and bulbs; Vincent 1985); these are generally nutritious, palatable and visible year-round, requiring little to no processing (Gott and Murray, 1982; Vincent, 1985). As such, these are staple constituents of the year-round diet of traditional societies across Africa (Vincent, 1985; Marean, 1997). Their wide usage by traditional societies and identification of charred rhizomes (*Hypoxis*) at Border Cave (Wadley et al., 2020) may suggest these were a crucial source of year-round nutrition in the past. These could have been extremely useful resources during the drier seasons of Green Arabia, when other vegetation resources declined. However, the specific characteristics of the flora of Green Arabia must be a target for future research.

In any case, given the predominantly grassland character of Green Arabia during pluvial periods and the palaeontological record (e.g., Groucutt et al., 2018; Stewart et al., 2019), it is likely that meat was also a significant component of the hominin diet. As well as the spread of animals from places such as Africa using the same semi-arid landscapes followed by humans, i.e. the ‘fellow travellers’, there could also have been rich animal resources already present within Arabia. As Foley (1987) noted, in important ways plants vary more than animals, and so rapid spread without significant adaptation could have occurred. Foley (1987: 263) commented that a “deer is very much like an antelope”, and so for human groups moving into Arabia they would have encountered grasslands rich in bovids at least broadly similar to those with which they were familiar. As described above, it is quite possible that humans arriving during MIS 5 entered a region in which other human were absent for tens of thousands of years due to the prevailing harsh environmental conditions of MIS 6. In such a situation, humans may have faced a ‘naïve fauna’ (e.g., Dennell, 2018), and as a result been able to expand rapidly before animals changed their behaviour.

Data compiled by Binford (2001) and Kelly (2013) illustrates clear relationships between productivity and aspects of human demography and behaviour. Ethnographic studies indicate that arid and semi-arid environments are associated with highly mobile populations living in large ranges, with low population densities. Most hunter gatherer groups – i.e. excluding rare examples such as the sedentary groups of the north American coast – live at densities of 0.1 to 1 person per km^2 (Kelly, 2013), and sometimes at less than a tenth of this. Likewise, societies with a high reliance on meat tend to be highly mobile and live at low population densities (Grove, 2009). There are however caveats to the kinds of datasets presented in sources such as Binford (2001) and Kelly (2013). For example, most studied societies are from the Americas, with very few samples from Asia, and none from northern Africa and the Middle East. But even accounting for regional specifics, the broad pattern of how demographic and behavioural dynamics relate to the environments offers us an approximation of past patterns. It is clear from the data presented by Kelly (2013: 80-84) that low primary biomass is associated with large total areas for hunter gatherer groups and large total distances covered annually. In the more marginal areas of northern Arabia – which were at the limits of the monsoonal rains during periods such as MIS 5 – we can expect pioneering human groups to have been highly mobile and with large ranges.

Another consideration is that, while virtually all studied human groups have been expanding in population size at a relatively rapid rate (i.e. often more than 1% a year; Gurven and Davison, 2019), it is clear that hunter-gatherer populations remained relatively small in the long run. There must, therefore, have been periodic phases of catastrophic mortality (Gurven and Davison, 2019). Arabia probably exemplifies such processes, as the opening of a window of opportunity in northern Arabia could have led to rapid population expansion south- and eastwards (as above), but also environmental fluctuations (e.g., brief arid periods) were likely reflected by sudden population declines. For example, climate records from the Holocene Humid Period demonstrate that Green Arabia was prone to sudden and brief periods of aridity (such as the 8.2 kyr event; Fleitmann et al., 2003a), which were likely echoed by population declines (Petraglia et al., 2020). While current palaeoclimate records from MIS 5e, 5c and 5a are not of sufficient resolution to detect brief periods of aridity, it is probable that variable climatic factors continued to exert control on population.

The specific geological and environmental aspects of Arabia are also significant for human occupations. The deserts of Arabia are typically characterised by either rocky surfaces or deep sand (Miller and Cope, 1996). This contrasts with somewhere like Australia, where a thin sand cover means small water holes are abundant, allowing widespread occupation as long as populations are at low density and are highly mobile (e.g., Smith, 2013). Current evidence suggests that in some areas of Arabia there was little occupation for broad periods of the past, due to a lack of water. Examples of this include areas in northern Arabia which were not proximal to palaeolakes and feature a very sparse archaeological record (Breeze et al., 2017), and a paucity of evidence for post-Acheulean occupation in the Dawadmi area of central Arabia (Jennings et al., 2015; Groucutt et al., 2016; Shipton et al., 2018). It is our impression that populations in Pleistocene Arabia were relatively tethered to water sources, such as lakes and rivers. These would have occurred at varying scales. It is the deep basins that contained palaeolakes, such as Jubbah in the Nafud Desert, which have produced archaeological findings covering every major period of human prehistory from the Acheulean onwards (Scerri et al., 2015, 2018a). Middle Palaeolithic sites, which mostly date to MIS 5, are significantly closer to palaeorivers than would be expected by a random distribution (Breeze et al., 2015). The connection between human demography/behaviour and the palaeohydrological structure of Arabia is therefore clear at a broad scale. The fact that Arabia is a tilted plateau – rising steeply along the entire western margin, dropping away gradually to the east – means that during Pleistocene humid periods an extensive network of rivers formed across the peninsula (Breeze et al., 2015, 2016). What is unclear is the finer scale mechanics of this process, such as the mobility patterns which allowed survival in highly seasonal environments. This must on some level have meant retraction to perennial water sources, yet as discussed above there would have been competition for these and so the specific mobility and social strategies employed are currently unclear.

Decline

An important aspect for understanding *H. sapiens* occupation in Arabia is what happened following climatic optima. As climates deteriorated during MISs 5e-5d and 5c-5b and 5a-4, reduced resources and lowered habitat carrying capacity would have increased competition pressure, resulting in population declines via dispersals, retractions and local extirpations (Bretzke and Conard, 2017). This may have included “back to Africa” dispersals, for which analogues may be drawn from MIS 4-3 genetic data (Soares et al., 2012; Hervella et al., 2016). Additionally, absence of clean genetic splits throughout the Pleistocene suggest ongoing gene flow for tens of thousands of years (Groucutt et al., 2015a; Bergström et al., 2020). For the most part, however, we expect that depopulations were complex processes with varying human responses.

Depopulations during drier periods are supported by a lack of continuity in the archaeological record at sites in the north (Groucutt et al., 2015b) and also large occupation gaps at Jebel Faya (Armitage et al., 2011; Bretzke and Conard, 2017). While lack of continuity in northern Arabia lake sites may partly be a result of taphonomic processes and the favourable preservation biases of wet periods, punctuated archaeological phases at Jebel Faya provides additional evidence for a reduced human presence on the Arabian Peninsula during drier periods. However, evidence of occupation during MIS 3 complicates the rather simplistic picture that humans could not survive drier periods (Armitage et al., 2011; Delagnes et al., 2012; Jennings et al., 2016), suggesting either: 1) humans re-entered Arabia during MIS 4-3 (Mellars, 2006); or 2) some populations survived following the return to arid conditions during the MIS 5a-4 transition (e.g., Armitage et al., 2011). Absence of prolonged, wide-spread and intense climatic amelioration across Saharo-Arabia during MIS 4-3 (Fleitmann et al., 2011; Rosenberg et al., 2013; Grant et al., 2017; Tierney et al., 2017; Nicholson et al., 2020) means a large-scale dispersal and sustained occupation would be surprising from a palaeoclimatic perspective. Perhaps the MIS 3 evidence represents small-scale 'pulse' dispersals and short-lived occupations associated with brief wetter events? In the latter case, the low resource availability across much of the peninsula implies that these were probably outliers, which survived in temporary green spots and/or in the higher productivity areas of the southern Arabian highlands (Delagnes et al., 2012, 2013). Previous hints of different land-use patterns between occupation phases have been witnessed in the Jebel Faya artefact assemblages (C: MIS 5e; B: late MIS 5 or MIS 3; and C: MIS 3), suggesting localised adaptations to changing environmental conditions (Armitage et al., 2011; Bretzke and Conard, 2017).

As outlined above, the debate on whether long-term refugia existed across Arabia have not produced clear results. So, whether or not *H. sapiens* populations survived within Arabia at varying scales and repopulated Arabia during the MIS 4-3 transition or were completely extirpated during returns to aridity (and the implications that might have for MIS 5d-5c and 5b-5a) is not clear. Others have considered that coastal regions may have provided suitable habitats for occupation following returns to aridity (e.g., Bailey et al., 2015; Erlandson and Braje, 2015). The expulsion of groundwater aquifers may have transformed exposed continental shelves into high resource areas (Faure et al., 2002; Rose, 2010; Erlandson and Braje, 2015). Yet there is currently insufficient data from Arabia to understand both their specific environmental character, spatio-temporal distribution and suitability to provide long-term habitats. Another potential issue is that where hominins have been present in coastal environments, productive inland environments were also available and exploited (e.g., Rector & Reed, 2010; Reynard & Henshilwood, 2019; Roberts et al., 2020). So, whether a long-term population could flourish whilst pinned to a narrow coastal strip in an otherwise barren landscape is not without uncertainty. Until further evidence for sustained coastal occupation and relevant sea-faring technologies becomes available, we suggest that populations dispersed primarily into inland habitats and occasionally exploited coastal environments. Further evidence of specific micro-environments, potential dispersal pathways and their suitability for occupation between wetter phases are required to understand the resilience of human populations following transitions to aridity.

For now, our working model is that the Late Pleistocene saw repeated population expansions into Arabia, with the largest and most sustained dispersals occurring during warm substages. This was followed by regional extirpations and population retractions during returns to aridity (e.g., MIS 5d, 5b and 4) (Bretzke and Conard, 2017). This perhaps included retractions to retaining high-resource areas, as well as “pumped” dispersals out of Arabia and into the Levant and back into Africa (e.g., Groucutt et al., 2015a).

5. Summary and conclusion

Overall, we highlight that dispersal likely occurred on different rates and scales. In the first instance, we stress that dispersal could have been a rather slow process on human and ecological timescales as a) populations need time to grow, and b) it is unlikely that there was specific directionality to dispersal. As precipitation and primary productivity rose in Saharo-Arabia, populations inflated, and competition pressure forced expansion into new patches with higher carrying capacities. In order to maintain successful populations, it is highly unlikely that societies were rapidly moving across these landscapes, with a single population traversing from Africa into Eurasia. Instead, multiple semi-connected mobile metapopulations (Scerri et al., 2019) were linked across semi-arid Arabia by palaeohydrological corridors (e.g., Scerri et al., 2014a; Breeze et al., 2016). Over time, this would have included expansion towards areas of higher primary productivity and following water courses into southern Arabia (Groucutt and Petraglia, 2012; Breeze et al., 2017) and also the Levant (Shea, 2008). As populations moved into southern Arabia, it is expected that, due to both distance and ultimately due to separation, distinctive regional populations developed and came to vary from their parent populations (Fig. 5). This is potentially reflected by the localised characteristics of Middle Palaeolithic southern Arabian archaeological assemblages and autochthonous development of stone tool techno-cultures following green periods (Armitage et al., 2011; Delagnes et al., 2012). As precipitation declined and "green" environments retracted and dilapidated, reduced resources caused increased competition pressure, local extirpations (Bretzke and Conard, 2017), fragmentation, dispersal into remaining higher-resource areas (Delagnes et al., 2012), and group home-range size expansions. We relate these longer-term dispersals to the warm substages of MIS 5e, 5c and 5a, and perhaps MIS 3.

However, dispersal could have, at times, been rather rapid. Stochastic increases of precipitation and environmental amelioration could have facilitated very brief expansions into the now arid interiors of Arabia. These dispersals were perhaps more ephemeral and mobile in nature and perhaps subjected to local extirpations. Our current interpretation of these more ephemeral dispersals is that these were likely related to colder substages, such as MIS 5d and 5b, and perhaps MIS 4, 3 and 2. However, we emphasise that understanding these differences in environments, dispersal rates and dynamics will be key for moving away from simplistic narratives of *H. sapiens* dispersals.

6. Targets for future research

The conclusions drawn from this paper are based on current and limited evidences which are partly linked to theoretical expectations. We acknowledge that substantial gaps remain in both archaeological and environmental datasets, which obscure our understanding of human-environment interactions in the past. Throughout this paper we have identified challenges and targets for new research. Here, we briefly provide a few suggestions as to how these may be achieved:

1. Linking theoretical models with archaeological data can allow us to overcome simplistic narratives of how humans occupied and moved through Arabia. This includes considering macro-scale causes of dispersal, but also more micro-scale and immediate influences on human "lived" timescales. Yet, we must be cautious of interpreting archaeological data to fit our theoretical expectations: further analysis must also test expectations. For example:
    a. It is not necessarily the case that past animal migration patterns matched the present (e.g., Henton et al., 2018). If past migration patterns of prey species altered from the present, this could alter our expectations of hominin migration and dispersal patterns. Detailed isotope (O, C and Sr) analysis of both animal and human remains could prove useful in discussions of home-range sizes and seasonal migration patterns (Pike et al., 2016; Henton et al., 2018).
    b. Chemical analyses (X-Ray Fluorescence/electron probe microanalysis) of stone tool assemblages and local and distant raw material outcrops could provide information on the distance of raw material transfer (local sourcing versus imported material) (Blegen, 2017; Brooks et al., 2018). This could be used to determine how "connected" past populations may have been, and how far groups were moving.
    c. Linking climate records, environmental parameters and population dynamics through numerical models (e.g., Beyer et al., 2020) could

provide an additional method to visualise and test dispersal models across the Arabian Peninsula.

2. Identification and mitigation of biases within both archaeological and environmental records must be achieved to understand the full suite of *H. sapiens* behaviours and human-environment interactions in Green Arabia. For example:
    a. There are very few examples of material culture beyond stone artefacts in Arabia. Further surveys of caves and open-air sites, which are not raw material procurement localities, on the Arabian Peninsula should be conducted to identify evidence of more permanent residency and material culture beyond stone artefacts.
    b. Although it is not currently certain if a-DNA could preserve in Arabian speleothems, efforts to extract and analyse a-DNA could provide species level identification flora and fauna (e.g., Stahlschmidt et al., 2019) and improve the current environmental record of Arabia. Additionally, more detailed considerations of the Mutual Climatic Range (MCR) of fossil fauna, diatoms, ostracods and phytolith taxa could prove useful in characterising past environments.
3. Improved dating of archaeological contexts is crucial for linking these to other palaeoclimate datasets and understanding the dynamics of *H. sapiens* occupation and dispersal. Current methods favour Bayesian statistical modelling (e.g., Groucutt et al., 2018) or “wiggle-matching” with precisely dated records (such as stalagmites, e.g., Rosenberg et al., 2013). New methods must be developed, as well as development of current methods

(e.g., OSL and single amino acids for ^{14}C dating), to provide robust and independently dated archaeological records.

Here, we have synthesised palaeoclimate, environmental, archaeological and anthropological data – and combined these with theoretical models – to understand human-environment interactions and dispersal mechanism in Arabia during MIS 5. Current evidence has allowed us to create a working model that moves beyond an “arrows on a map linking Africa to Eurasia” approach to dispersal. We emphasise that macroscale as well as microscale population dynamics must be considered when explaining human dispersal across landscapes.

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Fig. 1. (A) modern annual precipitation (1970-2000; Fick and Hijmans 2017) map of Arabia showing permanent lakes (>10 ha; black circles: HYRDOlakes dataset), permanent rivers (HYDROlakes dataset), endoreic basins (HYDROsheds) and major weather systems (Parton et al., 2015b). Hydrological data available at AQUASTAT. (B) map of terrestrial biomes (data available from WWF. Adapted using Miller and Cope, 1996), including rivers, lakes and endoreic basins.

Lake basin	***Site/core***	***Method***	***Age***	***MIS***	***Note***	***Ref***

Mundafan (Saudi Arabia)	C	TT-OSL (sands underlying lake marls)	101 ± 6 ka	MIS 5c		Rosenberg et al. (2011)
Mundafan (Saudi Arabia)	MDF-61	OSL and TT-OSL	A Bayesian statistical model of multi-grain OSL and TT-OSL dates places site formation between 97-77 ka BP.	MIS 5c		Groucutt et al. (2015d)
Khujaymah (Saudi Arabia)	B	TT-OSL (sands underlying lake marl)	Top: 136 ± 14 ka Bottom: 120 ± 10 ka	MIS 5e	Punctuated lake/sand deposits between ages	Rosenberg et al. (2011)
Khujaymah (Saudi Arabia)	D	TT-OSL (sands underlying lake marl)	99 ± 11, 96 ± 8 and 88 ± 6 ka	MIS 5c/a		Rosenberg et al. (2011)
Saiwan (Oman)	11.2	TT-OSL	108 ± 8 ka	MIS 5c		Rosenberg et al. (2012)
Saiwan (Oman)	13.6	TT-OSL	125 ± 9 ka	MIS 5e		Rosenberg et al. (2012)
Saiwan (Oman)	11.3	TT-OSL	102 ± 9 ka	MIS 5c		Rosenberg et al. (2012)
Saiwan (Oman)	11.4	TT-OSL	119 ± 14 ka	MIS 5e		Rosenberg et al. (2012)
Saiwan (Oman)	12.1	TT-OSL	Top: 102 ± 8 ka	MIS 5c		Rosenberg et al. (2012)

			Bottom: 114 ± 9 ka			
Saiwan (Oman)	12.8	TT-OSL	97 ± 12 ka	MIS 5c		Rosenberg et al. (2012)
Rub' al Khali (Saudi Arabia)	14.3	OSL	122 ± 6, 111 ± 9 and 118 ± 10 ka	MIS 5e		Matter et al. (2015)
Rub' al Khali (Saudi Arabia)	15.1	OSL (aeolian sands underlying limestone)	107 ± 13 ka	MIS 5c		Matter et al. (2015)
Rub' al Khali (Saudi Arabia)	15.3	OSL (aeolian sands underlying gypsums)	96 ± 6 ka	MIS 5c/a		Matter et al. (2015)
Rub' al Khali (Oman)	b18.1	TT-OSL	Top: 115 ± 5 ka Bottom: 82 ± 4 ka	MIS 5c/a	Sabkha	Matter et al. (2015)
Al Sibetah (UAE)		OSL	Phase IX: 88 ± 7.8 ka Phase VII: 130 ± 6.4 ka	MIS 5e, 5c and 5a	Three phases of stream activation + grassland development between 130-88 ka considered to represent MIS 5e, 5c and 5a	Parton et al. (2015)

Tab. 1. Ages of palaeolake formations in southern Arabia.

Lake basin	***Site/core***	***Method***	***Age***	***MIS***	***Note***	***Ref***
Jubbah (Saudi Arabia)	JB1 (zone III and IV)	OSL	<135.8 ± 23.9 and >73.4 ± 6.8 ka	MIS 5e (zone III) and MIS 5a (zone IV)		Parton et al. (2018)
Jubbah (Saudi Arabia)	JB3 (zone III)	OSL	75.3 ± 8.1 ka	MIS 5a	Age reversal (100.5 ± 20.5 ka) above considered to fall within MIS 5a.	Parton et al. (2018)
Jubbah (Saudi Arabia)	JQ1	OSL	Calcrete: 75 ± 5 ka Palaeosol: 95 ± 7 ka	MIS 5a and MIS 5c		Petraglia et al. (2011)
Khall Amayshan (Saudi Arabia)	16.4	TT-OSL (sands overlying and underlying lake diatomites)	Top: 117 ± 8 ka Bottom: 99 ± 7 ka	MIS 5e-c		Rosenberg et al. (2013)
Nafud (interdunal). Close to Khall Amayshan. (Saudi Arabia)	16.3	TT-OSL (sands underlying lake diatomites).	99 ± 7 ka	MIS 5c-a	Interdunal palaeolake	Rosenberg et al. (2013)
Nafud (interdunal). Close to B'r al Hayzan. (Saudi Arabia)	16.5	TT-OSL (sands overlying and underlying lake diatomites).	Top: 128 ± 9 ka Bottom: 125 ± 10 ka	MIS 5e	Interdunal palaeolake	Rosenberg et al. (2013)

Nafud (interdunal). Close to B'r al Hayzan. (Saudi Arabia)	17.3	TT-OSL (sands underlying lake diatomites).	99 ± 7 ka	MIS 5c-a	Interdunal palaeolake	Rosenberg et al. (2013)
Nafud (interdunal). *Close to Jubbah. (Saudi Arabia)*	14.3	TT-OSL (sands overlying and underlying lake diatomites).	Top: 19 ± 1 ka Bottom: 122 ± 10 ka	MIS 5e	Interdunal palaeolake	Rosenberg et al. (2013)
Nafud (interdunal). *Close to Jubbah. (Saudi Arabia)*	13.2	TT-OSL (sands underlying lake diatomites).	109 ± 8 ka	MIS 5c	Interdunal palaeolake.	Rosenberg et al. (2013)
Al Wusta (Saudi Arabia).		OSL (sands overlying and underlying lake diatomite). U-Series/ESR (palaeontological remains).	Top: 98.6 ± 7 ka Bottom: 85.3 ± 5.6, 92.0 ± 6.3 and 92.2 ± 6.8 ka AW1 (U-series): 87.6 ± 2.5 ka WU1601 (enamel U-series): 83.5 ± 8.1 ka WU1601 (combined U-series	MIS late 5c/early 5a.	Baysian model assigned suggests underlying sands (unit 1) were stabilised at 93.1 ± 2.6ka and unit 2 and 3 were deposited between 92.2 ± 2.6 ka and 90.4 ± 3.9 ka.	Groucutt et al. (2018)

		ESR): 103 +10/-9 ka		
Alathar (Saudi Arabia)	OSL of diatomites overlying and underlying hominin footprints	112 ± 10 ka BP (PD62; unit 5) and 121 ± 11 ka BP (PD61; unit 2)	Early MIS 5, likely MIS 5e	M. Stewart et al. (2020a)
Mudawwara (Jordan).	U-series (mollusc carbonate)	125 ± 5 121 ± 9 124 +10/-9 116 +5.5/-5.2 95.4 +3.2/-3/1 91.1 +3.4/-3.3 135 ± 6 88 ± 5 77 ± 8	MIS 5e and 5c/a	Petit-Maire et al. (2010)

Tab. 2. Ages of palaeolake activation in northern Arabia.

Fig. 2. (A) Precipitation map of Arabia showing locations of palaeolakes (light blue circles), speleothem cave sites (white circles), marine sediment (green circles) and fluvial/alluvial (dark blue circles). (B) Late Pleistocene climate records from Arabia. (a)

ODP 967 sapropels (black rectangles) and wet/dry (blue/red line) index (Grant et al., 2017) *vs. Soreq Cave stalagmite* $\delta^{18}O_{ca}$ *(black line)* (Bar-Matthews et al., 2003; Grant et al., 2014) *and Negev desert stalagmite formation (black circles)* (Vaks et al., 2010)*. (b) Lake activation (TT-)OSL ages in Northern Arabia vs. Southern Arabia* (Rosenberg et al., 2011, 2012, 2013; Petraglia et al., 2012; Jennings et al., 2016; Parton et al., 2018)*. (c) Red Sea grain sizes (KL-11)* (Fleitmann, 1997)*. (d) Stalagmite determined SAHPs (green bars) vs. Hoti Cave* $\delta^{18}O_{ca}$ *values and Mukalla Cave* $\delta^{18}O_{ca}$ *(box-whisker plot) and* $\delta^{13}C_{ca}$ *(black circles) values* (Nicholson et al., 2020)*. (e) Gulf of Aden grainsize data (KL-15) vs.* $\delta D_{leaf\text{-}wax}$ *values (RC09-166)* (Fleitmann, 1997; Tierney et al., 2017)*. (f) insolation at 15°N (W* m^2*) vs. global ice-volume (LR04* $\delta^{18}O_{benthic}$*) and Marine Isotope Stages* (Berger and Loutre, 1991; Lisiecki and Raymo, 2005)*.*

Fig. 3. (A) map showing locations of key (dated to MIS 5: white circles; undated: black circles) Arabian Middle Palaeolithic archaeological sites and annual precipitation during MIS 5e. (B) Ages of key dated Arabian archaeological sites (Armitage et al., 2011; Petraglia et al., 2011, 2012; Rose et al., 2011; Delagnes et al., 2012; Groucutt et al., 2015d, 2018) *compared to global ice-volume (LR04; Lisiecki and Raymo, 2005) and Marine Isotope Stages. Different methods of age calculation are represented by circles (OSL), triangles (TT-OSL) and U-Th/combined U-Th-ESR (squares). Arrows denote maximum or minimum ages. Assemblage/unit identifiers are given for Jebel Faya. The blue bar denotes tentative age assignment for Jebel Faya assemblage B.*

Location and Site	***Assemblage***	***Age***	***Method***	***(Ref.)***
Al Wusta (Nafud Desert, Saudi Arabia)		Insolation peak at ~84 ka	Combined UTh-ESR, OSL and Bayesian age modelling	Groucutt et al. (2018)
Jebel Katafah (Nafud Desert, Saudi Arabia)	JKF-1; Unit H.	~90-50 ka	OSL	Petraglia et al. (2012)
Jebel Qattar (Nafud desert, Saudi Arabia(	JQ-1	75 ± 5 ka	OSL	Petraglia et al. (2011)
Khall Amayshan	KAM-1	~120 ka	OSL	Scerri et al. (2015)
Mundafan (Rub' al Khali, Saudi Arabia)	MDF-61	~100-80 ka	OSL and TT-OSL and Bayesian statistical modelling	Groucutt, White, et al. (2015)
Jebel Faya (UAE)	C	127 ± 16 123 ± 10 ka (± = 1σ).	OSL	Armitage et al. (2011)
	B	Relatively assigned to ~50-1000 ka based on stratigraphic position.		
	C	40.2 ± 3.0 to 38.6 ± 3.1 ka (± 1σ)		
Aybut al Auwal (Dhofar, Oman)		106 ± 9 ka (minimum age)	OSL	Rose et al. (2011)

Tab. 3. Ages of key MIS 5 archaeological sites in Arabia.

Fig. 4. Cores, retouched tools and flakes from (A) Jebel Faya assemblage C, UAE, ~125 ka, (B) Aybut Al Auwal and Mudayy As Sodh, Oman, early MIS 5, (C) Mundafan, southwest Saudi Arabia, MIS 5, (D) Jebel-Qattar 1, Nefud Desert, ~75 ka (Illustrations modified from Armitage et al., 2011; Petraglia et al., 2011; Rose et al., 2011; Crassard et al., 2013).

Fig. 5. Conceptual model for the dispersal of H. sapiens into Arabia and Eurasia using MIS 5e as an example. Circles denote hypothetical metapopulations, which are comprised of numerous inter-connected populations. Metapopulations are also semi-connected to other metapopulations at a much broader scale, with connectivity denoted by colour. As populations expand, they begin to differ from initial metapopulations as they adapt to new environments and develop new cultures. Rainfall maps include simulations for 140-120 ka BP (wetter period: Otto-Bliesner, 2006) and modern day (drier periods: Fick and Hijmans, 2017) and tuned to the chronology of sapropel S5.