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Remote sensing and GIS techniques for reconstructing Arabian palaeohydrology and identifying archaeological sites

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Freshwater availability is critical for human survival, and in the Saharo-Arabian desert belt repeated fluctuations between aridity and humidity over the Quaternary mean the distribution of freshwater was likely a primary control upon routes and opportunities for hominin dispersals. However, our knowledge of the spatio-temporal distribution of palaeohydrological resources within Arabia during Mid–Late Pleistocene episodes of climatic amelioration remains limited. In this paper we outline a combined method for remotely mapping the location of palaeodrainage and palaeolakes in currently arid regions that were formerly subject to more humid conditions. We demonstrate the potential of this approach by mapping palaeochannels across the whole Arabian Peninsula, and palaeolakes and marshes for select regions covering c. 10% of its surface. Our palaeodrainage mapping is based upon quantitative thresholding of HydroSHEDs data, which applies flow routing to Digital Elevation Model (DEM) data, while our palaeolake mapping uses an innovative method where spectral classification of Landsat Thematic Mapper (TM) imagery is used to detect palaeolake deposits within endorheic (closed) basins, before modelling maximum lake extents by flooding the basin to the level of the elevation of the highest detected deposit. Field survey in the Nefud desert and the Dawadmi and Shuwaymis regions of Saudi Arabia indicates accuracies of 86% for palaeodrainage mapping, and 96% for identifying former palaeolake basins (73% accuracy of classification of individual deposits). The palaeolake mapping method has also demonstrated potential for identifying surface and stratified archaeological site locations, with 76% of the surveyed palaeolake basins containing archaeological material, including stratified Palaeolithic archaeology. Initial examination of palaeodrainage in relation to archaeological sites indicates a relationship between mapped features and previously recorded Palaeolithic sites. An example of the application of these data for period-specific regional palaeohydrological and archaeological reconstructions is presented for a region of Northern Saudi Arabia covering the southern Nefud desert and adjacent lava fields.

1. Palaeohydrology and hominin dispersals in the Arabian Peninsula

Palaeohydrology is key to understanding the dispersal of hominins into the Arabian Peninsula during the Quaternary, and for exploring hypotheses relating to the expansion and contraction of

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Palaeolithic populations both within Arabia and between regional refugia (Petraglia and Alsharekh, 2003; Field and Lahr, 2006; Rose and Petraglia, 2009; Armitage et al., 2011; Petraglia et al., 2011, 2012; Delagnes et al., 2012; Groucutt and Petraglia, 2012, 2014; Crassard et al., 2013a, 2013b; Scerri et al., 2014b). Surface freshwater availability, mediated by periodic incursions of increased rainfall, is likely to have been a critical control on the timing and routeways of hominin migrations across the mid-latitude Saharo-Arabian desert belt. Modern humans provide our only physiological analogue for other hominin species; adults require ~3 L of water daily, derived from both fluid and food intake, to counterbalance fluid loss (Sawka et al., 2005). Heat stress from physical activity in regions with higher temperatures (25–40 °C) elevates this value severely (Sawka et al., 2005), and in desert environments death can result after only a few days without water.

Numerous chronometrically dated palaeoenvironmental archives indicate that marked increases in continental precipitation occurred during 'wet' phases of the mid-late Pleistocene and the early Holocene (cf. Parker, 2009; Drake et al., 2013; Parton et al., this volume for reviews), potentially providing opportunities for human dispersal. In southern Arabia, additional moisture during these wetter episodes was produced by shifts in the northern limit of the Indian Ocean summer monsoon (Burns et al., 1998; Neff et al., 2001; Fleitmann et al., 2003, 2007). While any potential incursion of Mediterranean moisture into northern Arabia (Waldmann, 2010; Blome et al., 2012; Drake et al., 2013) was likely spatially limited (see Vaks, 2010, 2013; Parton et al., 2015), the enhancement of the East-African monsoon may have bought increased moisture to central and north-western Arabia (Herold and Lohmann, 2009; Rosenberg et al., 2013) broadly synchronously with the Indian Ocean Monsoon incursion into southern Arabia, and with a further potential contribution from low-level synoptic troughs along the Red Sea (Waldmann et al., 2010; Almazroui, 2011; de Vries et al., 2013). These climatic effects are linked to increased continental solar insolation with episodes of peak rainfall suggested to follow an eccentricity modulated precessional pattern (Blome et al., 2012; Drake et al., 2013; Parton et al., 2015). Key wet phases are documented during marine isotope stages (MIS) 11 and 9 (Rosenberg et al., 2013) and 6, 5, 3 and 1 (see Parker, 2009; Drake et al., 2013 for detailed reviews).

The extent, intensity, and synchronicity of these various humid episodes remain subjects of debate (Parton et al. 2015). During some of these periods large lakes formed in northwestern regions such as Mudawwara, Tayma and Jubbah, and in southern regions such as Mundafan and Khujaymah, and in eastern regions such as Saiwan (McClure, 1976, 1984; Garrard et al., 1981; Petit-Maire et al., 2002, 2010; Rosenberg et al., 2011, 2012; Engel et al., 2011; Petraglia et al., 2011, 2012; Crassard et al., 2013a). Numerous smaller interdunal and terminal alluvial fan lakes have been reported from the Rub' al-Khali, Nefud and Ramlat as-Sab'atayn (McClure, 1976, 1984; Schulz and Whitney, 1986; Lézine et al., 1998; Thomas et al., 1998; Rosenberg et al., 2011) and the western Hajar (Parton et al., 2013). The formation of large lakes suggests at least episodic activation of local fluvial systems. Evidence for this is provided by fluvial and alluvial fan deposits in southern Arabia dated to various humid phases (Blechschmidt et al., 2009; Mclaren et al., 2009; Parton et al., 2010; Rose et al., 2011; Atkinson et al., 2013; Parton et al., 2015a) and by incised relict drainage networks overlying Pliocene and Quaternary deposits across the peninsula (see Holm, 1960; Anton, 1984; Edgell, 2006; Blechschmidt et al., 2009).

Research in the Sahara has demonstrated that similar fluvial systems formed biogeographic corridors that permitted trans-Saharan dispersals during wetter phases of MIS 5 and the Holocene (Drake et al., 2011; Scerri et al., 2014a). Finlayson (2014, 2013) has hypothesised that spatio-temporal variations in freshwater availability may also have driven hominin movements throughout the wider mid-latitude belt. In Arabia the activation of palaeohydrological systems may have permitted hominin dispersal in the later Pleistocene (e.g. Armitage et al., 2011; Petraglia, 2011; Atkinson et al., 2013; Boivin et al., 2013). The archaeological record demonstrates a hominin presence evidenced by typo-technologically Middle Palaeolithic surface sites (Groucutt and Petraglia, 2012) across the peninsula, and by dated sites at around 211, 125, 107, 75, and 55,000 years ago (ka) (Armitage et al., 2011; Petraglia et al., 2011, 2012; Rose et al., 2011; Delagnes et al., 2012).

At present all of the stratified and dated Arabian Palaeolithic sites that have been published are associated with palaeohydrological features or at least seasonally wetted local environments indicated by lake-shore, palustrine, fluvial, or precipitation-influenced sediments (Petraglia et al., 2011, 2012; Rose et al., 2011; Sitzia et al., 2012; Bretzke et al., 2013). The dates for these sites coincide with potential 'humid' phases indicated by wider regional climatic records (Drake et al., 2013; Parton et al., 2015; Jennings et al., 2015a). It should be noted that this may in part be due to taphonomic effects, with an increased preservation potential of sediments consolidated during more humid periods. However, although stratified Arabian sites remain scarce, there has been in recent years a steady increase in new site discoveries which suggests they can be located through appropriately targeted survey; indeed, the consistent association of archaeological sites with fluvial, lacustrine or palustrine deposits highlights the possibility of targeting such landforms to identify further such sites.

Collectively, these data indicate that in order to investigate potential opportunities for Pleistocene hominin dispersals within the Saharo-Arabian belt, a detailed knowledge of the changing palaeohydrological conditions is required. Understanding the palaeohydrological setting at various times has the potential to improve models of the timing and routeways of hominin dispersals into the Arabian interior during humid phases, and of potential regional refugia. Such a refinement could be achieved by examining the palaeohydrology of Arabia and its relationship to the published archaeological record. Furthermore, such an approach may permit the identification of new archaeological sites by facilitating survey focused upon palaeohydrological features, and thereby expand our understanding of the demographic variability of early populations.

2. Requirements for paleohydrological mapping

The largest palaeodrainage systems in Arabia have long been recognised as the major trans-peninsula wadis of the Sabha, Dawasir and Batin, which were attributed in early geological summaries to Pleistocene pluvials (Holm, 1960; Powers et al., 1966). More detailed investigations were undertaken as part of the 'Quaternary Period in Saudi Arabia' (QPSA) research programme during the 1970s and 80s, which included geological assessments of wadi systems across Saudi Arabia and a synthesis of these results (Anton, 1984). This synthesis produced one of the first published maps reconstructing Arabian Quaternary palaeohydrology (Fig. 1). Further large-scale maps of the peninsula showing hypothesized drainage during Pleistocene humid phases were produced by Edgell (1989, 2006) and subsequent depictions of Arabian palaeodrainage have typically been based on Edgell or Anton's maps, or a combination of the two (e.g. Parker and Rose, 2008). However, although these maps provide a useful starting point, they are spatially and temporally imprecise and there are considerable inconsistencies between the different interpretations. Furthermore, these maps were necessarily produced only to depict selected drainage courses at an arbitrary scale, rather than using quantitative measurements to determine how drainage is displayed. Recent

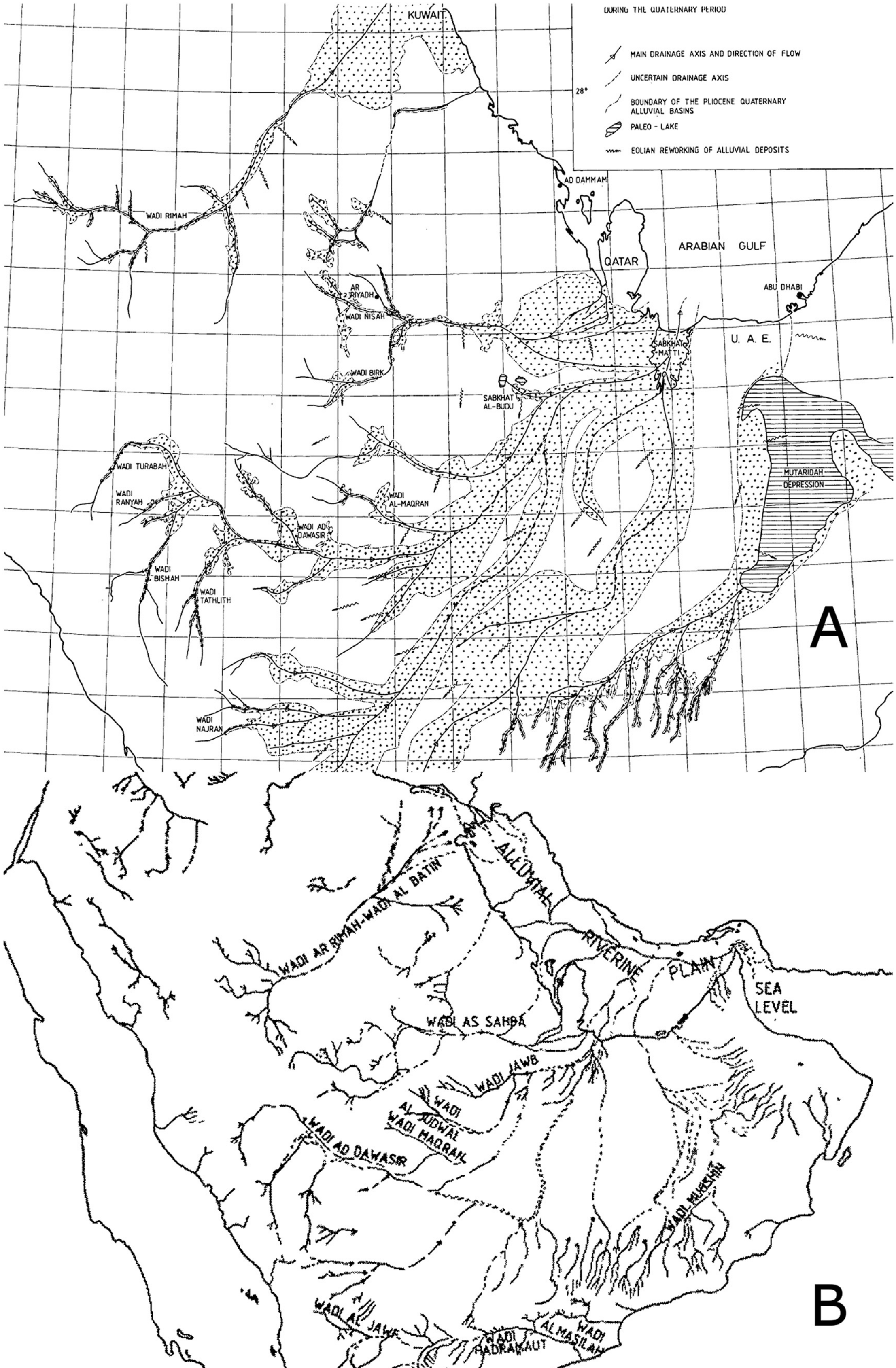

Fig. 1. Prior overview peninsula-scale maps of principal palaeodrainage systems for (A) the early Quaternary (Anton, 1984) and (B) the Late Pleistocene (Edgell, 2006). Both images reproduced with kind permission from Springer Science and Business Media.

research undertaken by the Palaeodeserts Project has begun to address this problem by displaying peninsula-scale drainage data generated using the methods discussed in this paper (Petraglia et al., 2012; Crassard et al., 2013a, 2013b). A higher level of spatial resolution has also been achieved by a number of palaeodrainage mapping studies at local and regional scales (e.g Cleuziou et al., 1992; Dabbagh et al., 1997, 1998; Petraglia et al., 2012; Crassard et al., 2013a, 2013b). However, the spatial coverage of palaeodrainage mapping of Arabia remains sparse, and there is a clear need to fill in the enormous gaps between these regions (and the scalar gaps between displaying local drainage and peninsula-scale drainage) in a consistent manner in order to enhance our understanding of the Quaternary evolution of palaeodrainage in the peninsula.

Temporal data regarding the activation of Arabian palaeodrainage systems remains limited. Anton (1984), and the collective authors of the QPSA volumes (Al-Sayari and Zötl, 1978; Jado and Zötl, 1984), suggested that the major trans-Arabian wadi systems were incised in broadly their current configuration by between 3 and 1 million years ago, based upon relationships between basal Wadi ad Dawasir gravels and dated lava flows, and stratigraphic correlations posited between these and comparable gravels in the Sabha and Batin/Ar Rimah (hereon simply referred to as Wadi Batin). It has been suggested (Anton, 1984) that initial wadi incision and Wadi Batin fan deposition (Al-Sulaimi and Pitty, 1995), may have occurred during a Pliocene–Pleistocene boundary pluvial phase, and that fluvial reactivation of the major relict systems occurred during subsequent Pleistocene pluvial phases under semi-arid to semi-humid conditions (Holm, 1960; Anton, 1984; Edgell, 2006). The precise extent of this activation is unclear, as some sections of those systems are currently bisected by dunes, suggesting that they have been inactive for some time, although they may have been connected during Pleistocene humid phases (Holm, 1960; Brown et al., 1989; Edgell, 2006; Crassard et al., 2013a), and in some cases during the Holocene (Cleuziou et al., 1992; Edgell, 2006). Radiometric dating of the evolution of these major systems however, remains limited. Select radiocarbon dates were taken from lower wadi terraces in these systems during the QPSA studies (Al-Sayari and Zötl, 1978; Jado and Zötl, 1984). However, in light of the unreliability of some early radiocarbon dating highlighted by recent studies (Rosenberg et al., 2011, 2013), and the identification of Pleistocene terraces in more minor drainage elsewhere (Sitzia et al., 2012) re-evaluation of some of these dates may be needed, and further Pleistocene terraces, if identifiable, could provide valuable data. There are now a series of optically stimulated luminescence (OSL) and Uranium–Thorium (U/Th) dates indicating that varying levels of fluvial activity have occurred in south-central Arabia during wetter intervals of the mid–late Pleistocene (Maizels, 1987; Blechschmidt et al., 2009; Mclaren et al., 2009; Parton et al., 2010, 2013; Rose et al., 2011; Sitzia et al., 2012; Atkinson et al., 2013; Parton et al., 2015a), and these provide valuable data on local catchment activity. Information from northern Arabia however, remains limited, and only one of the studies mentioned above is situated in a major trans-Arabian wadi.

In contrast to rivers, lakes represent another element of Quaternary palaeohydrology that have provided improved temporal control. Numerous lakes have been identified and dated through localised field surveys (McClure, 1976, 1984; Garrard et al., 1981; Schulz and Whitney, 1986; Lézine et al., 1998; Thomas et al., 1998; Petit-Maire et al., 2002, 2010; Petraglia et al., 2011, 2012; Engel et al., 2011; Rosenberg et al., 2011, 2012; Parton et al., 2013; Crassard et al., 2013a). However, spatially comprehensive mapping of former lacustrine and palustrine features across large areas of the peninsula has not been undertaken (exceptions being analyses reported in Crassard et al., 2013a, 2013b; Petraglia et al., 2012, during the development of the method discussed here). This is largely due to the difficulties of identifying such features across wide expanses of terrain. There is a clear requirement for such mapping to be applied across the whole peninsula to refine our understanding of the spatial-temporal distribution of lake features during humid phases. Hydrological features in closed basins subject to climatic fluctuations exist along a palaeohydrographic continuum that can vary (sometimes cyclically) from perennial lake through to palaeomarsh and palaeoplaya (ephemeral lake) conditions (Bowler, 1986; Currey, 1990). A wide range of these conditions beyond purely lacustrine settings may provide freshwater and increased faunal and floral resources, potentially facilitating hominin habitation, and over time individual features may change their positions along this spectrum repeatedly in response to climatic and geomorphological change (Bowler, 1986). For this reason, lacustrine, palustrine and playa features all need to be considered in palaeohydrological mapping (the latter are typically referred to as Khabra/Khab'/Qa' in Arabia). For the sake of brevity and clarity we will refer to all features along this spectrum as 'palaeolakes' for the remainder of this paper. This term, however, is used as a catch-all description for the features above that represent former standing water and wetlands, and should not be considered a description of the individual character of palaeohydrological deposits being discussed here.

We note the need for refined temporal and spatial resolution mapping of palaeodrainage and palaeolake occurrence if we are to improve our current understanding of the extent and character of palaeohydrological activity during Pleistocene pluvials. This would ultimately help increase our understanding of the environments inhabited by past populations. Spatially refined datasets may provide targets for palaeoenvironmental and chronometric dating studies to further our understanding of the character and age of these features, and can be integrated with regional palaeoenvironmental data to attempt to map potential spatio-temporal variations in these hydrological features at the regional level. This temporal refinement is critical for any analyses of palaeohydrology in terms of their relationships to, and implications for, archaeological data. Such analyses also require palaeohydrological maps which are spatially comprehensive, and accurately map both palaeolakes and palaeodrainage at a range of scales. At the peninsula-scale, refined palaeohydrological maps may therefore permit more precise discussions of potential routes for hominin dispersals within the Arabian interior (or to/from adjacent regions) through quantitative spatial analyses of the relationship between archaeological sites and contemporary palaeohydrology. At the local scale, such refined maps may also provide palaeoenvironmental context to existing archaeological sites, and provide potential survey targets to help to identify new sites.

3. Refining present palaeohydrological maps

In order to begin to refine palaeohydrological data for Arabia to meet the abovementioned needs, we have developed a combined method for mapping palaeohydrology. This method permits relatively rapid regional-scale mapping, by using direct physical characteristics of former drainage and palaeolakes to automatically identify these features from remotely sensed data. Furthermore, these procedures produce maps of a high spatial resolution (capable of discriminating features of less than 100 m × 100 m scale), map the potential former extents of palaeolakes, and allow major palaeodrainage systems to be distinguished from streams and minor tributaries.

Previous papers of the Palaeodeserts project (e.g. Petraglia et al., 2012; Crassard et al., 2013a; Jennings et al., 2014) have included results based on this drainage mapping method and initial aspects of our palaeolake mapping method. This paper focusses directly upon these methods and provides a complete, revised and substantially automated version of our palaeolake mapping method which is quicker to apply over large areas and enhances removal of false positives through application of geomorphological rules. In the following sections, after outlining our methods (first for palaeodrainage, then for palaeolake mapping) we proceed to assess the outlined procedures. We assess the accuracy of these methods for identifying palaeohydrological features based upon field-testing, the advantages and limitations of the methods, and the effectiveness of using these data for locating archaeological sites. We also explore how these data may allow us to further our understanding of palaeohydrological controls on archaeological site distributions and hominin dispersals.

It should be noted that our remote sensing and GIS methods systematically identify the *locations* of former palaeolake and drainage features. However, from remotely sensed data alone we cannot define chronologies for these palaeolakes or hydrological characteristics such as salinity for specific points in time of their histories. To perform such analyses, extensive field investigation of the identified targets, and their underlying sequences, is required. Likewise, the temporal resolution of the present Arabian palaeoenvironmental record is insufficient to discriminate seasonal, decadal, or centennial cycles of precipitation variability and the effects these may have had upon the permanence, seasonality and temporal variability of the mapped hydrological features. Although high temporal resolution cannot therefore be achieved through mapping alone, we close this paper by presenting an example of how the data produced by these methods can be combined with available geochronological and palaeoenvironmental data to model regional palaeohydrology for a specific (though broad) period of time, while examining the archaeological implications of these data.

4. Methods and materials

Remote sensing analyses of freely available satellite data, when coupled with geospatial analyses of DEM's using GIS (Geographical Information System) methods, provide powerful tools for mapping vast areas in a semi-automated manner. The methods we have developed for using these techniques to perform palaeodrainage mapping (performed for the whole peninsula), and the mapping of closed basin palaeolake features (performed to date for a sample 10% of the peninsula) are detailed below.

4.1. Palaeodrainage mapping

Palaeochannel locations were derived from the HydroSHEDs dataset (Lehner et al., 2008), a global hydrologically conditioned dataset based upon Shuttle Radar Topography Mission (SRTM) DEM topographic data, using standard GIS hydrology procedures. Flow accumulation data was calculated from the 3 arc-second (90 m) HydroSHEDs D8 flow direction datasets (the highest resolution HydroSHEDs data available) to provide the maximum spatial precision. Locations where flow accumulated from upstream areas of greater than a chosen catchment area threshold were then extracted. In this manner, networks of palaeodrainage with catchment areas of >1000 km^2, >100 km^2, >10 km^2 and >1 km^2 can be defined, allowing major systems to be differentiated from lesser streams and headwaters (Fig. 2). In arid regions, such D8 drainage mapping using SRTM base data has been shown to be effective in the definition of surface and shallow-subsurface (due to the ability of SRTM to penetrate shallow sand cover- see Ghoneim and El-Baz, 2007a, 2007b) relict palaeodrainage courses preserved as incised channels. HydroSHEDS additionally preserves endorheic depressions in the original data (these are typically removed during GIS hydrology workflows), thereby producing fluvial networks which terminate in depressions and thus can be related to palaeolakes in these basins. Due to the likelihood of recent dune movement and accumulation producing flow lines not related to Pleistocene drainage, in our maps channels within the dune fields have been differentiated from those without, using geological map data (Pollastro et al., 1999). In addition, for maps intended to display Pleistocene rivers, the large drainage connections currently severed by dunes or by tectonics, but potentially active during the Pleistocene, were reinstated through DEM, Landsat TM image and geological map interpretation and are marked as interpreted in the maps we present (see SI for details).

4.2. Palaeolake mapping

To map the location and extent of closed basin palaeolakes we developed the workflow which is summarised visually in Fig. 3, and discussed below. This method has been heavily automated, using a sequence of custom ArcGIS automated tools we have developed for the bulk of the processing in Fig. 3. Select manual stages were run in separate remote sensing (ENVI) and GIS (SAGA) software. This workflow has been applied to four initial study areas within Saudi Arabia comprising 10% of the total area of the peninsula (Fig. 4). These were the southern Nefud region (encompassing the Nefud dunes and Harrat Ithnayn and Harrat Hutaymah) the Shuwaymis region of Harrat Khaybar and Ithnayn, the Dawadmi region of the central Arabian shield peneplain, and the Mundafan region of the western Rub' al-Khali and Wadi Dawasir. These were selected to test the method in regions of widely differing geomorphological and geological character.

4.2.1. Basin identification

Endorheic depressions are locations in arid regions where accumulation of direct precipitation, runoff and increased groundwater levels permit lake formation during humid periods. We first identified such basins within the study areas using a modified version of the workflow presented by Hesse (2008). SRTM version 4 DEM data (Reuter et al., 2007; Jarvis et al., 2008) were projected and a hydrology fill algorithm applied (Tarboton et al., 1991). HydroSHEDS DEM data was not used as the hydrological treatment necessary for flow mapping alters the initial (SRTM) DEM. For basin identification, and for volume and area calculations, it is therefore preferable to use the raw SRTM data. The original SRTM dataset was then subtracted from the filled data, producing a dataset outlining depression areas and depths.

4.2.2. Direct discrimination of palaeolake deposits

To determine whether there was evidence for palaeolake formation within these closed basins we then used multispectral classifications of Landsat satellite imagery to map potential palaeolake deposits within them. These classifications were performed using the Exelis Visual Information Solutions ENVI software package, using the following steps.

4.2.2.1. Selection of training sites using Landsat TM FCC data. Landsat Thematic Mapper (TM) false colour composites (FCC's) using bands 1, 4 and 7 have previously been demonstrated to maximise discrimination of lithological information in arid regions (Crippen, 1989). These band 7,4,1 or 7,4,2 RGB FCC's have been utilised for mapping arid environment palaeolake sediment outcrops, palaeochannel deposits and palaeolake shoreline features in several previous field-validated studies (Kusky and El-baz, 2000; Schuster et al., 2005; White et al., 2006; Drake et al., 2008). Information on the spectral properties of palaeolake/wetland deposits,

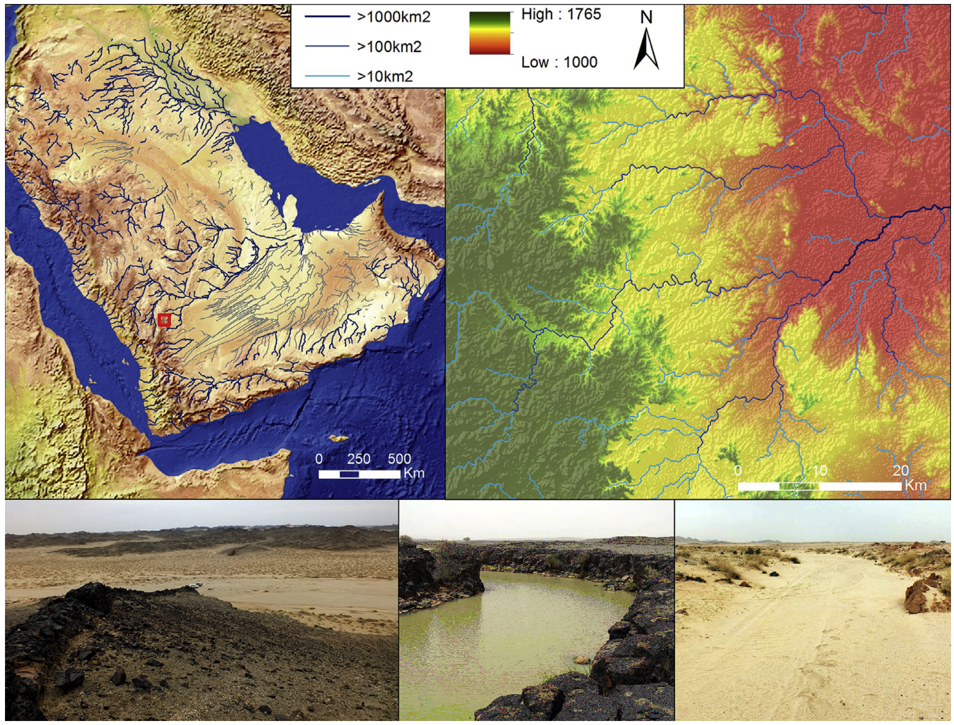

Fig. 2. Examples of scaling of drainage data, and of field validated drainage courses. Upper left, >1000 km^2 major drainage courses in dark blue (questionable drainage in dunes in grey, and no interpreted former connections displayed), with location of detail area (upper right) marked in red, overlying Natural Earth 2 basemap. Detail map (upper right) shows drainage data of varying catchment area scales, illustrating how as catchment area threshold is lowered, progressively smaller tributaries of drainage systems are plotted. Lower images show examples of field validated mapped drainage courses from the Dawadmi and Shuwaymas regions. Centre image is the location of the SH-11 site with ponded standing water (see text and Groucutt et al., 2015), whilst the lower right image shows minor headwaters (<10 km^2 catchment) with associated Acheulean archaeology near Safaqah (Jennings et al., 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which facilitate their identification in TM data, is provided in the Supporting information (SI 1). In our method 7,4,1 TM FCC interpretation was used to initially identify potential palaeolake outcrop or playa locations (bright blue FCC tones) visible in the mapped closed depressions (Fig. 5) in summer cloud-free early Landsat 5 TM images (minimising feature masking due to recent land cover change or ephemeral standing water). These locations were then used as training sites for classification algorithms, so as to automatically detect further such deposits across the Landsat scene. If published palaeolake deposits were present and visible in the data, these were also included in the training site selection.

4.2.2.2. Multispectral classification of potential palaeolake deposits. For each scene the training sites were then used as the input to two multi-spectral classifications, Matched Filtering (MF) and Spectral Angle Mapping (SAM). These were applied to all five non-thermal wavebands of the TM data, and a ratio image (MF/SAM) of the two classifications was then produced. This MF/SAM method was selected as the optimum classification method following initial tests of several different classifiers. MF (Boardman and Kruse, 2011) is a partial unmixing technique, defining relative sub-pixel abundance and occurrence of a target material, while SAM (Kruse et al., 1993) identifies the angular difference between the spectral vector of each pixel and the training sites, with lower angles representing closer matches (Yuhas et al., 1992; Kruse et al., 1993). As close matches will return higher MF values and lower SAM values, the ratio (MF/SAM) helps minimise the effect of potential false-positives generated by the MF classifier for rare materials (see Boardman and Kruse, 2011). Iterative thresholds were applied to identify the highest MF/SAM ratio value (closest match to the training spectra) preserving the locations and extents of known or interpreted lake deposits, while minimising false positive results. Any cells equal to or greater than this value were then classified as palaeolake deposits. Finally, results outside of endorheic depressions were removed and the dataset of deposits within depressions was 'cleaned' with a majority spatial filter (removing isolated single pixels, and aggregating groups of pixels) to produce a final dataset of potential palaeolake deposits in depressions. The accuracy of this deposit mapping analysis has been assessed in the field (Section 5.2.1).

4.2.3. Palaeolake extent mapping

We then used the deposit mapping results to determine potential lake extents. A lower threshold for basin size was required for this extent mapping phase of our method as it is computationally impractical to map basins at all scales when performing regional or peninsula-scale analyses, and because very small shallow basins could relate to small errors (pits) which can often occur in DEM's. Field testing sites (Section 5.2.1) included detected deposits in basins of all sizes, and it was observed that all confirmed palaeolake deposits other than small playa occurred in basins of greater than 1 km^2 in area. Across 4 study areas a total of only 13 confirmed deposits (all small Khabra) were present in basins below 1 km^2 in area, with the majority of these being in depressions along drainage courses in the Shuwaymis area; indicating that the shallow basins holding these features were in fact minor palustrine ponding locations, rather than true closed basins. Therefore, to meet the minimum threshold requirement, and to remove minor palustrine ponding features, any mapped deposits in minor depressions (smaller than 1 km^2 in area) were removed prior to modelling the former maximum extent of the lakes.

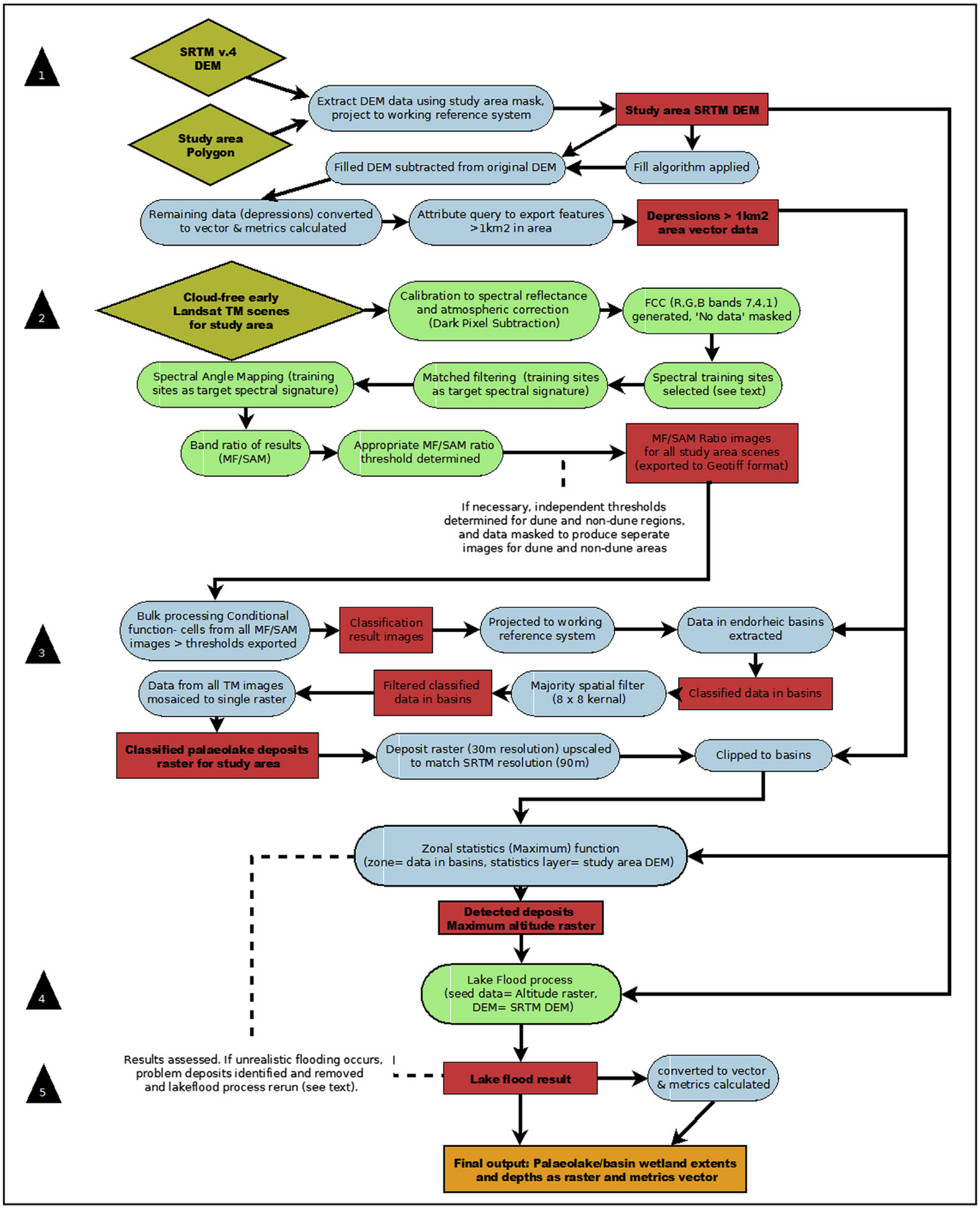

Fig. 3. Our palaeolake mapping GIS workflow (simplified schematic). Required initial input data is shown in diamonds. Processing steps are in rounded boxes. Output datasets resulting from processing are in red square boxes, with prominent outputs in bold. Stages 1, 3 & 5 (blue) are performed in ESRI ArcGIS and have been automated as custom tools. Stages 2 and 4 (green) are performed manually in ENVI and SAGA GIS, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The remaining data was then used as the input to a 'lake flood' procedure. This defines the former lake extent from the altitude of the deposits. A raster layer recording the maximum altitude of each detected deposit in each basin was created, using a maximum zonal statistics function applied to SRTMv4 data, applied to deposit data aggregated to the SRTM cell size. This raster (following addition of 0.001 m to each altitude value to ensure each deposit floods) was then used as the seed data for the 'lake flood' process in SAGA GIS. This 'floods' individual basins of the SRTM data by filling outwards from a seed pixel until reaching the altitude defined by that pixel. The output image therefore provides an estimate of the former extent of the palaeolake, and the changing depth values across it, as defined by the highest palaeolake deposit in each basin/sub-basin. This image was exported back to ArcGIS for integration with the other data and converted into a vector, following which lake number, depth, and area statistics could then be calculated using zonal information and standard GIS calculations.

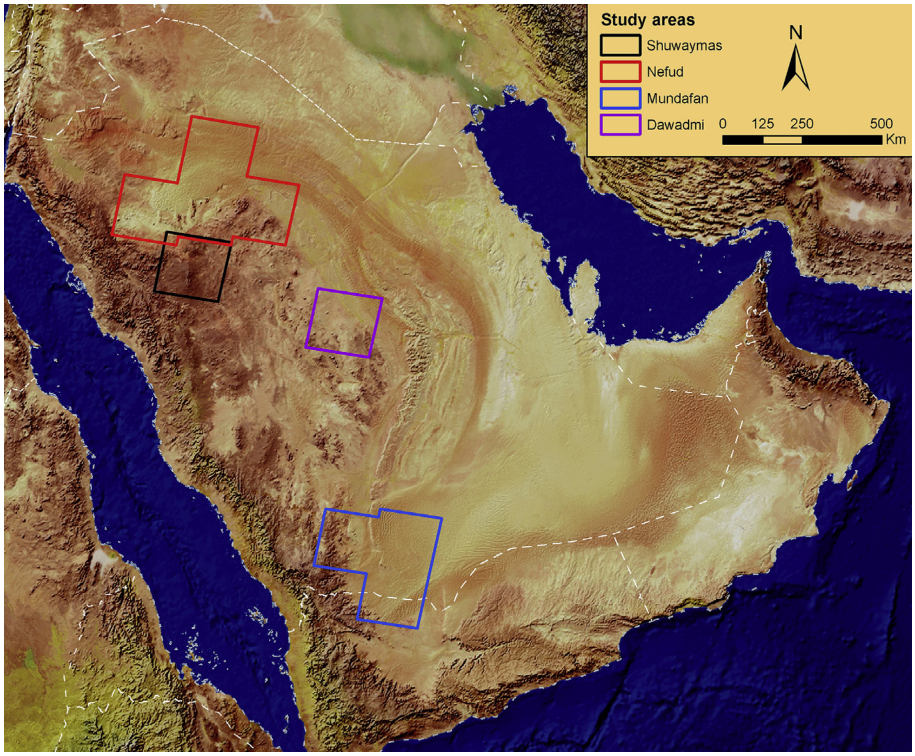

Fig. 4. Location of initial study regions discussed in this paper and used as test bed areas for the defined method, overlain on Natural Earth 2 basemap, with international borders marked. Note that the Shuwaymas and Nefud regions are treated collectively in Figs. 6, 11 and 12, due to their proximity.

This process sometimes created very large former lake extents filling extremely large depressions, or overflowing into adjacent depressions. To ascertain their veracity, the largest mapped lakes were examined on a case-by case basis. If DEM data showed incised outflow channels where basins or sub-basins overflowed, if the highest detected deposits showed characteristics of mesas of old eroded palaeolake sediments, or if all data lay in the base of the depression where mapped drainage converged, the extent was considered valid. However, if this was not the case, then certain deposits were masked, before lake extents were run again. Such

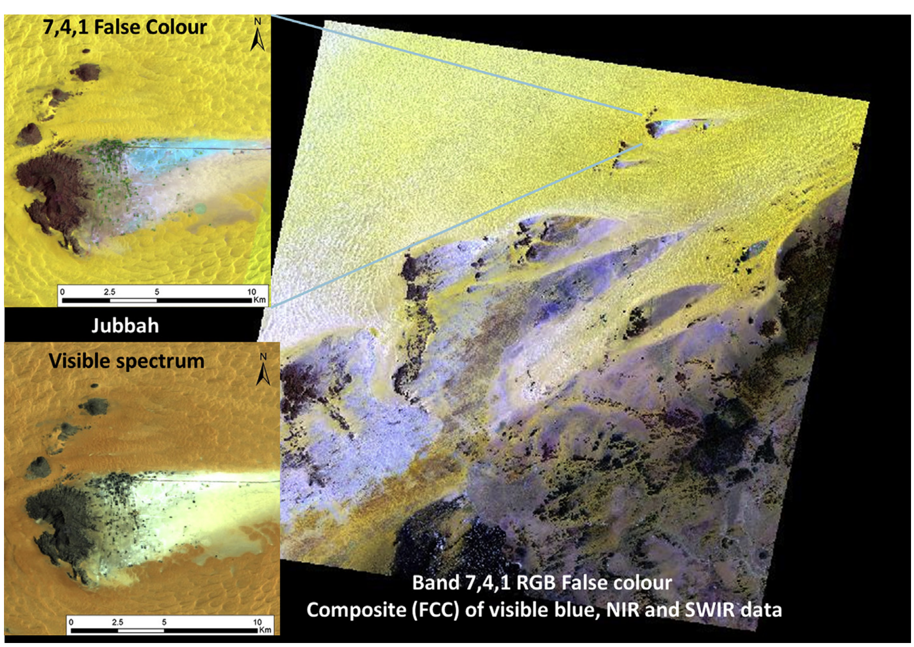

Fig. 5. Example of 7,4,1 TM FCC's for visual discrimination of initial palaeolake deposits for use as spectral training sites for the large known palaeolake basin of Jubbah. Note that although the basin appears uniformly white (high reflectance) across the visible spectrum, palaeolake deposits (primarily deflated gypsiferous deposits in this instance) can be readily differentiated in blue tones in the multispectral FCC data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deposits were those found lying on mapped drainage high on basin slopes (likely representing palustrine deposits along drainage),and those appearing to be perched playas, shallow ponds or springs in small sub-basins at the periphery of the main basin, or following clear ridge/scarp lines (suggesting they were geological 'false positives', such as exposed bedrock limestone deposits). The occlusion of data outside of topographically closed basins ensures groundwater discharge (GWD) deposits from valley slope springs and faulting are not included in the dataset, in keeping with guidelines for distinguishing GWD deposits from lacustrine and swamp episodes (Pigati et al., 2014). In the case of GWD deposits in basins, the removal of deposits forming isolated patterns oriented in a downslope direction from a point or line source ensured that these deposits were removed during lake extent estimates. These measures were required since, although representing basin humidity (and potentially of value as water sources to hominins), the deposit types discussed above are not indicative of an extensive horizontal water level, and so need to be removed to produce valid potential maximum lake/swamp area extents. In an ideal world every mapped deposit within a basin would be examined in the field sequentially in order to determine the valid former maximum lake extent. However the practicalities of regional scale mapping preclude this and hence rule-based editing is a necessary step during remote analyses.

It should also be noted that the mapped deposits may not necessarily represent the upper levels of any lacustrine or wetland sequence, merely its surviving deposits. Surface exposures of deeper water carbonates may represent lakes which had metres of former water column above the deposits, and will therefore be underestimated by extents generated by the deposit height, while conversely playa deflation often only stabilises at ground-water base level, and so present surface deposits could formerly have been basal regions of deep sub-lake bottom sequences. For these reasons, coupled with the potential effects of deflation at depression cores, the estimated lake depths should be treated with caution, and as merely indicative of the broad scale of the potential former accommodation space for the palaeohydrological features within a basin.

4.3. Field accuracy assessment and archaeological survey

To assess the validity of the deposit mapping method, we examined a series of the palaeolakes and drainage courses that we had mapped in the field across the Dawadmi, Shuwaymis and Nefud study areas (Fig. 6). In total 145 mapped drainage course locations (blue circles in Fig. 6), and 102 mapped palaeolake deposits (white circles in Fig. 6) in 48 closed basins, were examined in the field by palaeoenvironmental specialists and archaeologists. Features mapped as palaeolake deposits were examined and sampled for X-ray diffraction (XRD) bulk mineralogical analysis and, in select cases, for radiometric dating. Where possible, walk-over archaeological survey was also performed using transects walked from the basin cores towards the basin periphery.

4.4. Confusion matrix assessment

Remote sensing classification accuracy assessments should ideally be based upon sample locations that are widely spatially distributed, have minimal spatial autocorrelation, and are selected at random within their parent classes (Congalton and Green, 2009). However due to the logistical and financial necessities of large scale fieldwork (where proximity to the project base and to major roads, available time, environmental conditions and enclosure of land all govern the practicality of site access) these criteria cannot typically be fully met. While critical ground truth data was obtained from

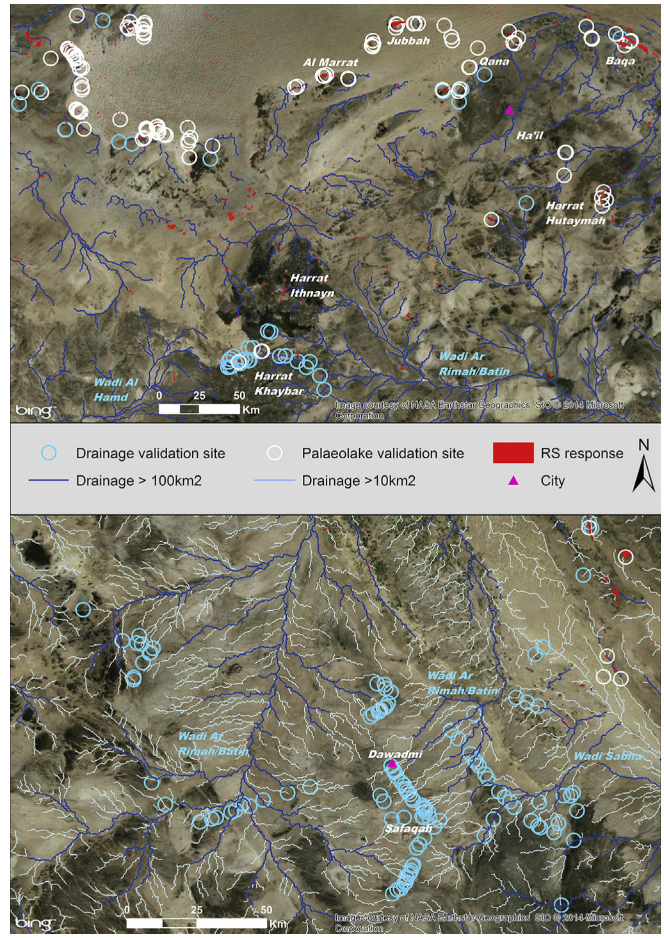

Fig. 6. Field validation locations in the Nefud & Shuwaymas (top) and Dawadmi (bottom) regions, for potential identified palaeolake deposits (final deposits from workflow displayed in red, exaggerated for visibility), and modelled drainage. Questionable drainage modelled in dunes not displayed for clarity (see text). Base imagery is Bing maps, with key geographic locations and features discussed in the text labelled. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

our field accuracy assessment, a semi-random distribution of sites was sampled (as classified sites were sampled on an ad-hoc basis within clusters around a region dependent upon time and accessibility). To examine whether these results were indicative of the accuracy of the method irrespective of the spatial bias these constraints introduce (and to produce the full set of standard measures of classification accuracy), it was necessary to also perform a standard remote sensing confusion matrix accuracy assessment. This was performed through stratified random sampling of the classifier results (after the minimum basin area threshold of 1 km^2 had been applied) for a single scene, and assessment of the accuracy of the classifier in the case of each of these random samples. This was performed through interpretation of high resolution satellite imagery (Bing Maps and Google Earth) informed by the results of the field survey (see SI 3 for full details).

5. Results

5.1. Drainage mapping results

We have produced palaeodrainage network data at a range of densities for the entire Arabian Peninsula. Generated data successfully delineates the known major palaeodrainage courses

(Fig. 2 compared with Fig. 1). As contributing area thresholds are lowered drainage networks can be generated at a substantially higher level of spatial precision and density than formerly available (Figs. 1 and 2), and scales of drainage differentiated based upon quantitative measures of contributing area. This precision allows detailed levels of regional and site-specific palaeohydrological research to be undertaken (Petraglia et al., 2012; Crassard et al., 2013a, 2013b).

5.1.1. Drainage accuracy assessment

The spatial accuracy of the mapped networks has been supported by both desk-based assessment of satellite imagery and field validation. Examination of 145 mapped drainage courses in the field in the Dawadmi and Shuwaymis regions showed that outside of dune areas incised drainage ranging from shallow sand-filled channels through to deeply incised valleys, was present in the mapped location and following the mapped course in 86% of cases (see Fig. 2 and Table 1). In the other 14% of cases mapped locations were found to be low angle floodplains and alluvial fan surfaces without any visible incised drainage, unless it was completely buried (see below). Low-angle regions can be areas of error for D8 analyses as the algorithm is forced to choose a single downstream flow direction in areas of low relief.

Examination of mapped drainage in the dunes in the field and in high-resolution satellite imagery showed that while channels are mapped by HydroSHEDS in interdune depressions, no fluvial landforms were visible and thus these should be regarded as likely erroneous. Long-distance overland flow in dunes during humid phases has not to date been evidenced in Arabia, though it has been in the dune fields of the Sahara (Drake et al., 2011). In some cases there are indications that in the Arabian data major flow accumulations exit the dunes in broadly correct locations (See Petraglia et al., 2012 SI), and occasionally reflect underlying topographic signatures from buried river valleys (Crassard et al., 2013a). Nonetheless, dune field data remains overall questionable, both in terms of its existence during humid periods, and its mapped position given the potential movement of dunes during subsequent arid episodes. Thus this dune field drainage has been marked as questionable in the resultant maps (Fig. 3). Comparison with SIR-C data published by Dabbagh et al. (1998, 1997) has demonstrated that in shallower sand sheets however, HydroSHEDS data successfully delineates shallow subsurface buried drainage (SI Fig. 2), as has previously been suggested for SRTM-based D8 data in the Sahara (Ghoneim and El-Baz, 2007a, 2007b).

5.2. Palaeolake mapping results

Our palaeolake mapping workflow has mapped a total of 8637 palaeolake deposit sites across the four study regions, with basin flood analyses indicating these may represent 1338 lakes with maximum surface areas ranging from <1 km to c.387 km^2 and potential depths ranging from 1 to 99 m (subject to the caveats discussed previously). Fig. 7 shows an example of the results of these palaeohydrological analyses, in this case for the southern Nefud region, and demonstrates how the method models regional drainage and numerous potential palaeolake features across the region, including features matching lakes which have formerly been identified through field survey, such as at Jubbah and Jebel Katefeh (Garrard et al., 1981; Petraglia et al., 2011, 2012), Tayma (Engel et al., 2011), and Ti's Al Ghadah (Thomas et al., 1998;

Table 1
Summary of results of field accuracy assessment for the palaeohydrological methods, and of archaeological survey targeted upon identified palaeolake basins.

Field Accuracy Assessments			
	Closed basin palaeolake mapping		
Depressions classified as palaeolake basins (48 investigated)	# correct (held lake/marsh deposits)		**46 (96%)**
	# incorrect		**2 (4%)**
	# surveyed for archaeology		25
	# with archaeology		**19 (76%)**
	# Identified sites, by period	Lower Palaeolithic	5
		Middle Palaeolithic	15
		Undiagnostic Palaeolithic	3
		Neolithic	8
		post-neolithic	1
			32 *(total #)*
Individual identified deposits (102 investigated)	# correct (lake/marsh deposit)†		**74 (73%)**
	# incorrect		**28 (27%)**
† Features considered as correct (indicative of former palaeolake/marsh locations) were deposits interpreted in the field as gypcrete, marl, calcrete, playa deposits, and deflated carbonate/gypsiferous deposits (see Figure 8 for examples).			
	Palaeodrainage mapping		
Mapped drainage locations outside dunes (145 observed)	# correct (channel present)		**(86%)**
	# incorrect		**(14%)**

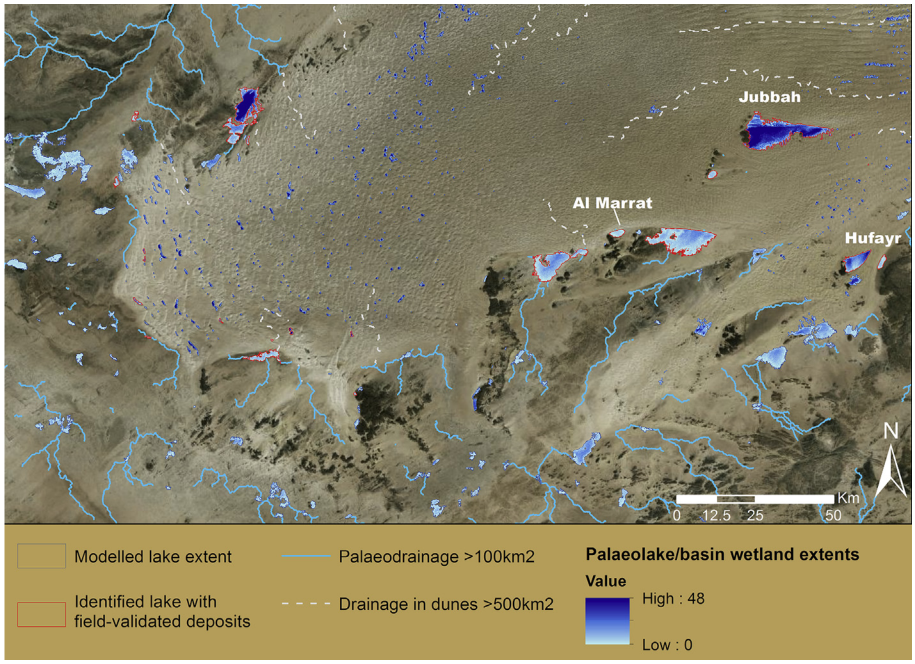

Fig. 7. Results of our palaeohydrological analyses focussed upon the southern Nefud region, showing mapped drainage (questionable drainage in dunes marked in grey), and modelled palaeolake extents.

Stimpson et al., 2015). The implications of our modelled data for the whole Nefud region in the context of palaeoenvironmental and archaeological data are explored later in this paper.

Based upon the analyses across all study areas, palaeohydrological features may have covered up to 3597 km^2 of the ~10% of Arabia (266,622 km^2) surveyed. To begin to determine chronologies, and therefore the extent to which these may have been synchronous, requires the integration of this regional palaeohydrological data with dated palaeoenvironmental datasets, and ideally, intensive field survey to directly date the identified features.

5.2.1. Palaeolake field accuracy assessment

A total of 104 mapped potential palaeolake deposits (the output of the Multispectral classification prior to extent calculations and editing) in 48 identified closed basins were examined during fieldwork in the Nefud, Shuwaymis and Dawadmi regions. These included classifier training sites (all field-confirmed as palaeolake surfaces) and random sample locations used in the confusion matrix accuracy assessment. Overall accuracies of the classification based on field survey are given in Table 1. This indicates both the accuracy of detecting basins containing palaeolakes, and the per-deposit accuracy that considers the different deposits investigated within each basin.

At the basin level, 96% of the examined basins contained palaeohydrological deposits. The other 4% were basins containing bleached sand or distal fan deposits (see below). At the per-deposit level (Table 2), materials interpreted as palaeolake deposits formed the majority of the field-assessed responses (73%) and consisted of marl, gypcrete, calcrete, or Khabra' (silty/clay lake bed, Holm, 1960) deposits (Fig. 8A–F, and Table 1). These represent a range of palaeohydrological conditions from deep-water lacustrine (marl) to shallow ephemeral (Khabra') lakes and wetlands. In the case of features interpreted as gypcretes, calcretes and marls in the field, XRD analyses of surface sediment samples suggest that the detected palaeolake features commonly contained calcite, quartz, kaolinite and gypsum. Khabra playa deposits shared clay minerals such as palygorskite and kaolinite, calcite, quartz and occasionally gypsum. When in proximity to volcanic terrains the latter also contained igneous minerals such as hornblende and anorthite. Erroneous detections (27% of assessed deposits) were largely within the dune fields and consisted of either bleached white sands, often associated with palaeodune systems (particularly in the western Nefud-see Rosenberg et al., 2013) or weakly-incipient palaeosols with rhyzoliths (Fig. 8; G and H). XRD analyses of these deposits suggest kaolinite and dolomite components that may be producing the high visible reflectance, thus producing spectral similarity to the lacustrine features at the Landsat TM spectral resolution. While the palaeosols are erroneous (i.e. not lake sediment) classifications, they nonetheless represent episodes of increased humidity within the parent basins that were sufficient for vegetation to develop, and thus are of interest in palaeoenvironmental analyses.

The identified deposits are only the surviving post-deflation surface exposures of the identified lakes, and therefore are snapshots in time from features which may have shown repeated fluctuations in depth and hydrological characteristics such as salinity (Bowler, 1986; Currey, 1990) over time in response to climatic change and local geomorphology. Consequently, any sequences present below these deposits may show considerable vertical variation and high value as palaeoenvironmental archives. Within the Nefud, rapid excavations exposed palaeohydrological sequences of several metres depth below some surface gypcrete and marl exposures which will be the subjects of future publications. Khabra' playa may also have considerable value as palaeoenvironmental archives (Shaw and Bryant, 2011), but are more difficult to access. Playa may still receive limited surface input from modern rainfall, however in the case of Jordanian Khabra' Davies (2005) noted that surface exposure of archaeological deposits suggests net deflation in playa basins, which, coupled with low levels of present rainfall and the large areas of the present arid region covered by these deposits, demonstrates their antiquity. These observations also hold true for the Saudi Arabian examples observed in the field in our study. Coring of Khabra in large basins, particularly in southern Jordan, has demonstrated that present

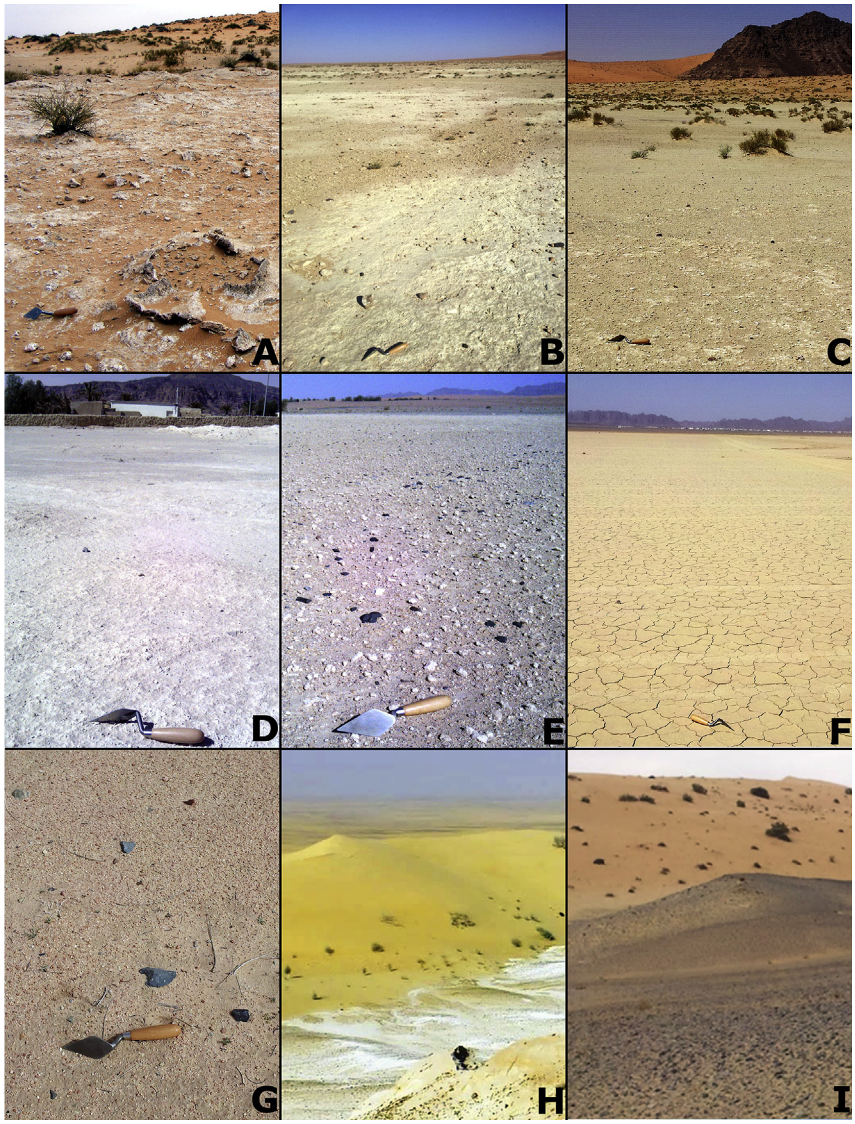

Fig. 8. Typical examples of surface characteristics of field tested sites from the Nefud study area. A: Interdunal gypcrete with dessication curls capping lacustrine silts, Jubbah basin. B: Marl, Khabb Araf basin. C: Gypcrete, Khabb Araf basin D: Reworked gypsiferous and carbonate rich sediments, Jubbah basin. E: Calcrete, Hufayr basin. F: Khabra' playa pan, Harrat Hutaymah. G: Incipient palaeosol with Middle Palaeolithic tools, (QAN-1 site) H: Bleached palaeodune (fore and mid-ground) western Nefud. I: Heavily indurated gypcrete/marl (western Nefud).

exposed playa surfaces can sometimes cap lengthy alternating lacustrine/aeolian/alluvial sequences (Davies, 2000, 2005). In the case of Khab' al Jafr, a core in excess of 31 m depth was recovered (Davies, 2005). In this core near surface Aeolian/alluvial deposits were dated to 16 ka, while lacustrine deposits at the base were capped by groundwater alteration sequences (separated from the upper sequence by an disconformity) which were suggested to potentially have required up to hundreds of thousands of years to form (Davies, 2005), although these lower levels were not dated. Surficial lacustrine limestones elsewhere in the same basin were however dated to 83 ka (Macumber, 2008). Other characteristics of the core were the aforementioned discontinuity at 11 m depth, and potentially no preservation of any Holocene sequence. The latter feature was also suggested for a 50 m + core from Azraq (Davies, 2000). Comparable longevity of deposition and variability may also be present in larger Arabian playa, and future coring exercises may yield high dividends.

These caveats notwithstanding, XRD results and field observations of the surface exposures may give very limited indications of salinity of the features at the time of deposition. The surfaces of identified playa typically showed little surface salt formation. However it should be noted that playa are complex environments where surface and shallow subsurface deposition of evaporites only occurs when shallow interstitial water in the underlying sediments reaches saturation levels for those salts (Bowler, 1986). While the gypcrete deposits may represent increased salinity at the time of deposition, the absence of halite formation in these sequences may suggest that evaporating water bodies and shallow subsurface waters were not hypersaline prior to evaporation. Contrastingly, carbonate precipitation features such as calcretes and marls lacking salt components may indicate comparatively fresher standing or infiltrated water.

5.2.2. Confusion matrix accuracy assessment

The spatially unbiased confusion matrix accuracy assessment of a representative scene (see SI 3) suggested an overall accuracy of 81.3% for the MF/SAM classifier when individual deposits are considered and data was masked to >1 km^2 basins. This provided a

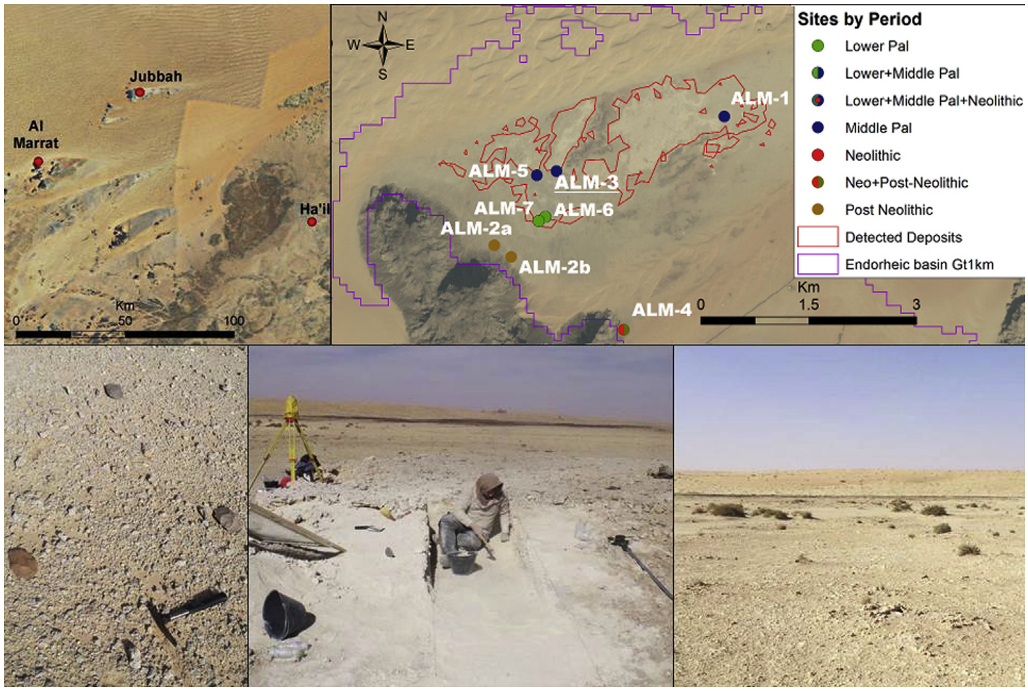

Fig. 9. The Al Marrat basin and materials identified by the classifier. Clockwise from top left; regional location; deposits identified by the classifier within the basin and archaeological site locations; detected gypcrete mesas; Excavation at the ALM-3 stratified site (see Jennings et al. forthcoming); and Acheulean surface scatter.

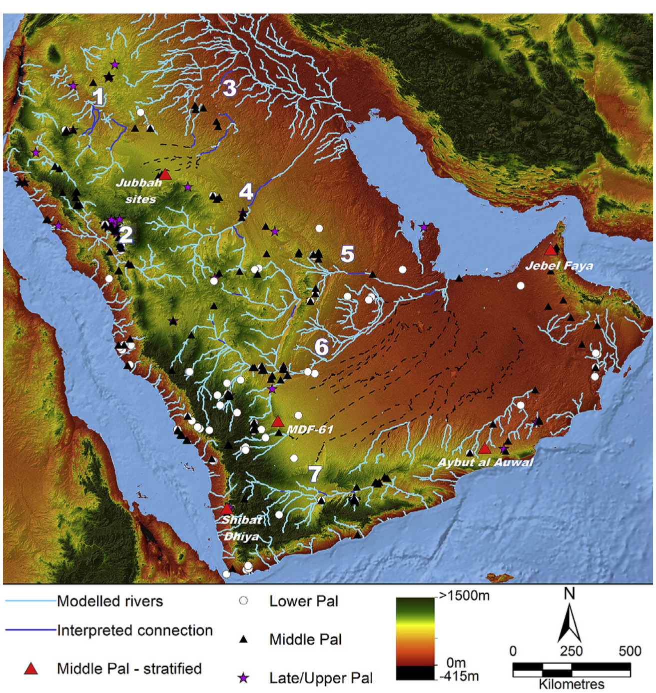

Fig. 10. Principal modelled palaeodrainage of the peninsula (>1000 km^2 contributing area, strahler stream order 2 and above, pruned for clarity-see Fig. 2 for unpruned data), with interpreted Pleistocene connections (early and late) reinstated and published archaeological site locations. Stratified dated sites are labelled. Major drainage systems: 1; Wadi Sirhan trough, 2; Wadi al Hamd, 3; Euphrates (note that due to this region still receiving runoff drainage in the central Euphrates-Tigris depression may reflect recent activity, and should be considered indicative only), 4; Wadi ar Rimah/Batin, 5; Wadi Sabha, 6; Wadi ad Dawasir, 7; Wadi Hadramawt. Drainage in dunes differentiated (dashed lines).

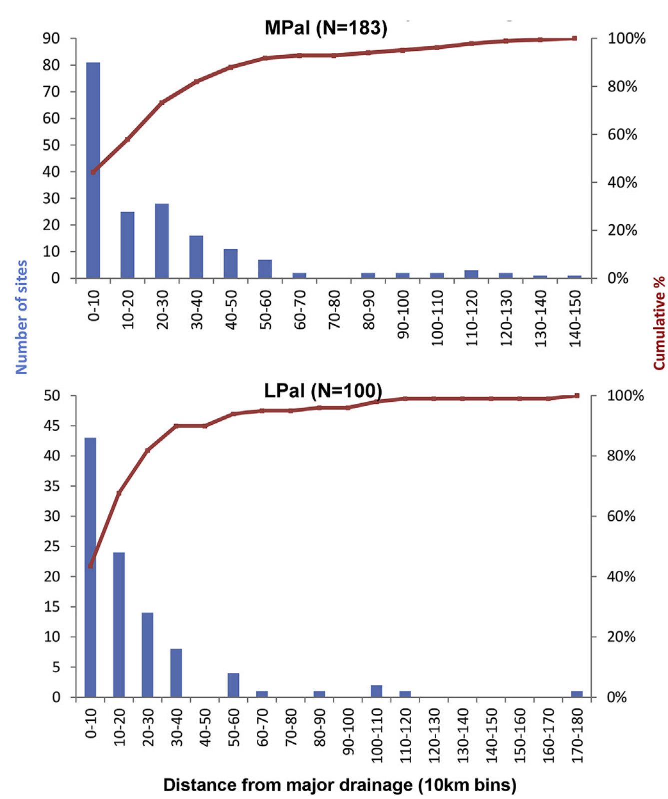

Fig. 11. Histograms of distance from the principal modelled palaeodrainage displayed in Fig. 10, for Middle and Lower Palaeolithic sites from Groucutt and Petraglia (2012). Only distance to the largest major drainage systems has been assessed, to provide a conservative assessment.

Table 2
Summary of results of field accuracy assessment showing deposits by type, and percentage of those sites surveyed of each deposit type which had Palaeolithic archaeology directly upon their surface (see Table 1 for results by basin), and number of archaeological sites of every period associated with each deposit type. For classes marked by † the majority of the surveyed sites were in basins which also held valid lake deposits.

Field-assessed deposits by type		Number	% of total	% of sites surveyed with archaeology	Lpal sites	Mpal sites	Holo sites
Lake deposits	Marl	6	5.9	33		2	
	Gypcrete	14	13.7	64	1	6	4
	Khabra playa	53	52.0	23		6	7
	Calcrete	1	1.0	100		1	
Errors- not lake deposits	Ephemeral muds	3	2.9	0			
	Bleached sand/incipient palaeosol	18	17.6	57	2	7†	
	Sandstone (bleached sand source)	7	6.9	100†		2†	
		102	Total				

kappa coefficient indicating 61% higher accuracy than that to be expected for chance alone. Values of 18% for errors of commission and 26% for errors of omission were reported. Despite the likelihood of spatial bias in the field-sampled data, it was found that percentages of lake classifications found to be lakes (73%), and found not to be lakes (27%) from the randomly sampled confusion matrix assessment closely matched those of the field sampled accuracy assessment (Table 1).

5.3. Archaeological results

The potential for using the palaeolake reconstructions described above as a tool for archaeological prospection was explored by targeting archaeological survey upon those closed basins indicated by the classifier to contain palaeohydrological deposits. Rapid archaeological survey (often less than 6 surveyor hours per basin) was performed in 48 identified basins within the Dawadmi, Shuwaymis and Nefud regions. Survey took the form of transects walked from basin cores towards the basin peripheries, and targeting of exposed palaeolake deposits within the basins. Despite the rapid nature of the survey, 76% of the examined basins were found to contain archaeological sites (73% if the count excludes sites previously identified by the Palaeodeserts team near Jubbah prior to January 2013 when our palaeohydrological model targeted surveys began). A total of 32 new archaeological sites were identified within these basins (see Fig. 12 for sites in the Nefud/Shuwaymis region), ranging in period from the Lower Palaeolithic through to post-Neolithic funerary complexes and rock art (see Jennings et al., 2013) (Table 1). The majority of the sites identified within the detected basins were Palaeolithic surface scatters, with typo-technologically Middle Palaeolithic assemblages the most prevalent, often directly associated with the surface of gypcrete deposits detected by the classifier.

Some erroneously detected basins also contained sites. Indeed, 57% of the palaeosol deposits were associated with archaeology, including the significant site of QAN-1 (Fig. 13) — a Middle and Lower Palaeolithic site in the Hail region (Shipton et al., 2014; Groucutt et al., in review) identified within a basin erroneously identified as holding lake deposits by the classifier. The archaeological implications of the identified sites are discussed elsewhere (Jennings et al., 2015b; Groucutt et al., in review; Scerri et al., 2015).

The great potential of this approach was illustrated by the survey of a basin identified by the method at Al-Marrat, also in the Hail region (Figs. 9 and 13). Here, during investigation of large areas of gypcrete deposits detected by the classifier, stratified Middle Palaeolithic archaeology was identified in indurated carbonates immediately adjacent to the detected gypcretes (Fig. 9, Jennings et al., forthcoming). In addition to guiding us to this new basin with stratified archaeology, the palaeohydrological data also identified other palaeolake basins associated with known stratified sites around Jubbah, Jebel Katefeh and Mundafan that have previously been excavated by the Palaeodeserts Project (Petraglia et al., 2011, 2012; Groucutt et al., forthcoming), retrospectively confirming its potential as a method for locating further such sites.

In order to determine whether mapped drainage systems may also host archaeological sites, select survey was also targeted upon palaeodrainage data in the Dawadmi and Shuwaymis regions. Here, we specifically surveyed in the vicinity of 37 field-validated drainage locations of >10 km^2 catchment area. During these surveys a site was classed as 'associated' with the validated drainage if it lay within 1 km of the confirmed mapped course, however it should be remembered that drainage chronologies within the study areas were (with minor exceptions) relatively indeterminate and hence this is a spatial, rather than temporal association. The low distance threshold, coupled with a larger catchment threshold, was chosen to provide a conservative measure, as drainage density increases significantly with lower thresholds, maximising the likelihood of a site being in proximity to a mapped drainage course by chance alone.

A total of 16 new sites (31 including existing sites) were identified from 11 of these locations. Differential patterning of site types was observed across the study areas, with the Shuwaymis sites being predominantly Holocene surface lithic, rock art and structural sites, while in Dawadmi the bulk of the assemblages were Acheulean. Few Middle Palaeolithic assemblages were recovered in either region. These patterns likely relate to factors such as raw material availability, particularly in the case of the Dawadmi region (see Groucutt et al., in review; Jennings et al., 2015). In the Dawadmi region additional systematic survey was also focussed on a specific constrained study area, including mapped drainage courses down to >1 km^2 catchment area, and revealed numerous archaeological assemblages and sites which are detailed in Jennings et al. (2015).

Examples of prominent results from these surveys were the identification of high densities of Acheulean artefacts concentrated along now relict incised channels in proximity to the known Acheulean site of Safaqah near Dawadmi, and the discovery of the Middle Palaeolithic site of SH-11 near Shuwaymis. At Safaqah, artefacts were found along the minor headwaters (~1 km^2 catchment area) of rivers that straddle the drainage divide between the major trans-Arabian drainage systems of Wadi Sabha and Batin (Fig. 6), with Acheulean materials appearing potentially distributed along their course through anthropogenic rather than fluvial taphonomic processes (Jennings et al., 2015b). In the case of the Shuwaymis area, the site of SH-11 (Groucutt et al., in review) is a Middle Palaeolithic lithic assemblage positioned on a ~10 m wide meander bend of an upper reach of Wadi Batin which is incised to a depth of ~4 m through basalts mapped (Roobol and Camp, 1991) as Early-Middle Pleistocene in age (Figs. 2 and 13). SH-11 is the first

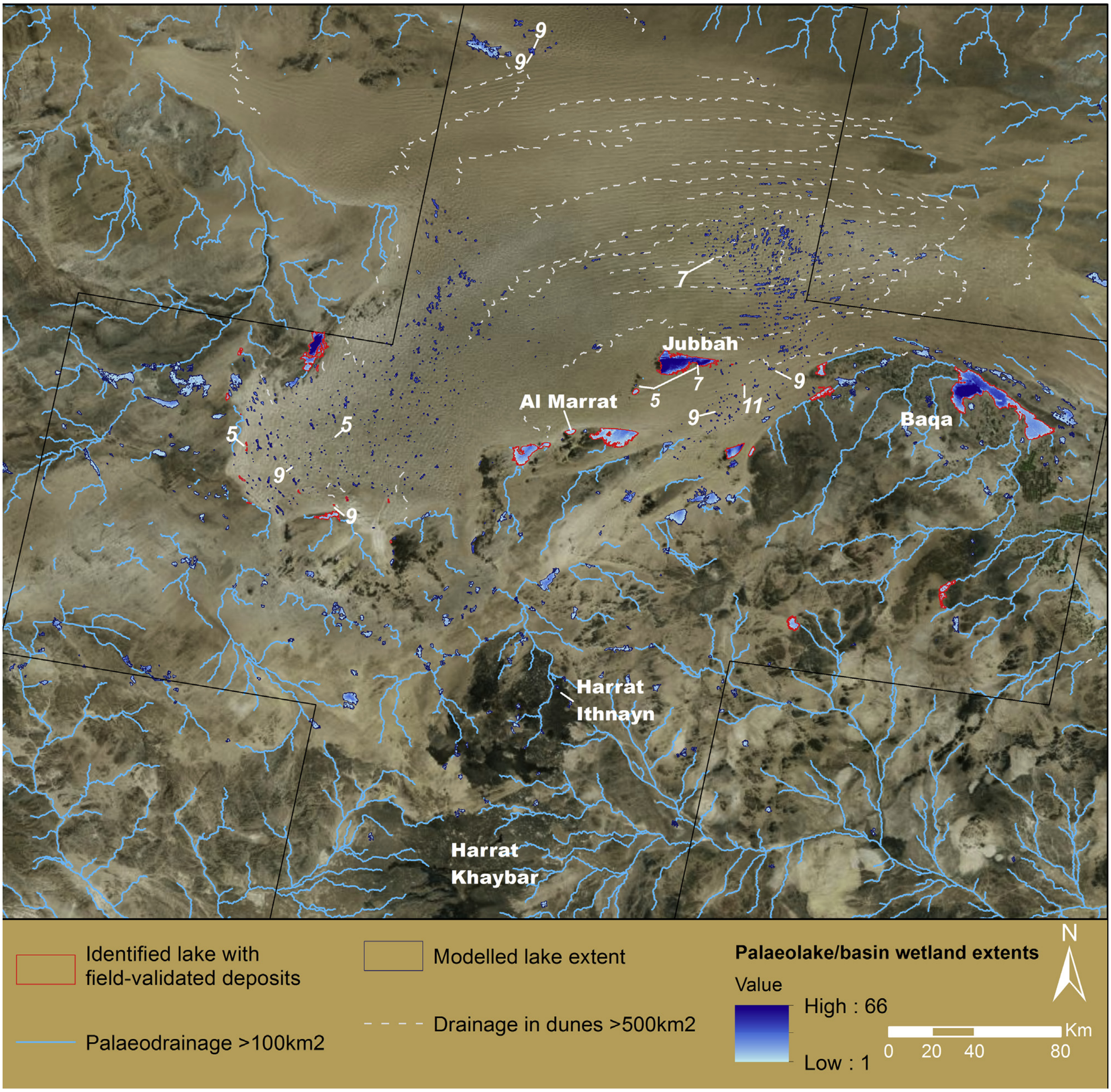

Fig. 12. Modelled palaeohydrology for the Nefud and Shuwaymas study areas displayed over Bing Maps imagery. Locations discussed in the text are labelled, and modelled lakes containing deposits that have been field validated as lake deposits are marked in red. Numbers show the MIS phase of formerly dated lake locations (Petraglia et al., 2011, 2012; Rosenberg et al., 2013) also mapped by our method. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Middle Palaeolithic site known from the Shuwaymis region, across which the HydroSHEDS data successfully mapped meandering drainage incised through Quaternary lava flows that ranged from minor >10 km^2 catchment area headwaters through to major incised valleys.

5.4. Limitations

Although these results show significant success for our automated method, there remain some limitations. The most obvious is that remotely sensed data can only record the present surface and very shallow subsurface topography. Therefore, in regions subjected to substantial topographic changes during the Quaternary (such as tectonics or aeolian erosion and deposition) the data must be manually interpreted for different periods. As discussed above, Quaternary dune fields represent an environment subject to considerable topographic alteration with a strong impact on palaeodrainage. Similarly, alterations in dune field morphology since the formation of interdunal lakes may also impact drainage basin morphology and calculated palaeolake extents. For northern Arabia, dates from interdune lacustrine and palustrine carbonates in the Nefud (JQ1, Petraglia et al., 2012) could potentially support relative stability of dune cores in these areas since c. MIS 7. Previous investigations (Rosenberg et al., 2013) identified a series of interdunal lakes across the Nefud dated to MIS 5, indicating that the main dune fields were in place before this period and likely played an important role in determining subsequent lake basin morphology. However, substantially refined Quaternary dune field

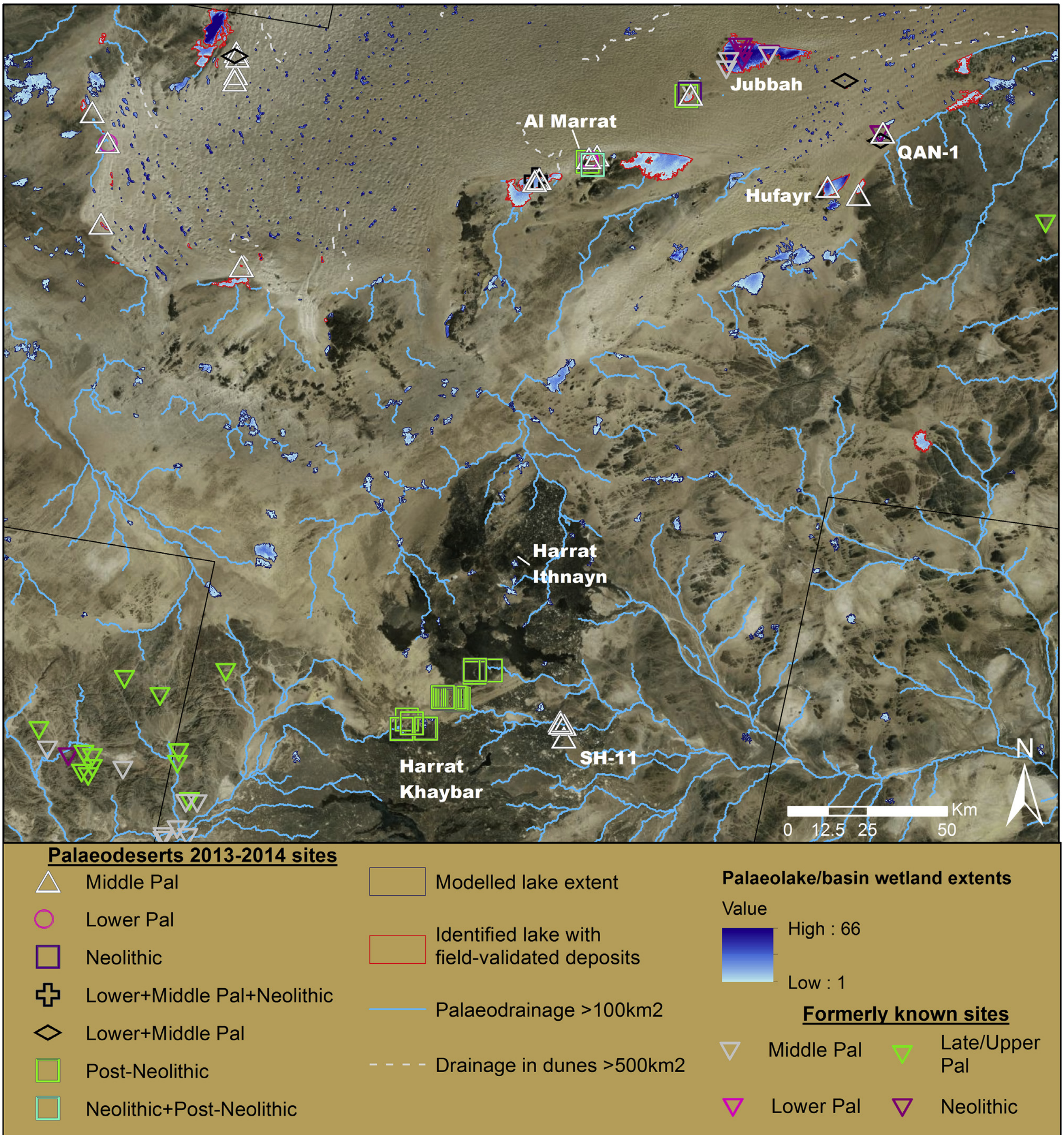

Fig. 13. Archaeological sites identified during palaeohydrologically targeted survey within the Nefud and Shuwaymas study areas, differentiated by period and displayed over Bing Maps imagery and palaeohydrological data. Sites and locations discussed in the text are labelled.

chronologies for the study areas are required before detailed spatio-temporal discussion of dune field paleohydrological evolution can be performed. Given the relevance of this period to early human demographic variability, such chronologies may be critical in elucidating potential routes into and through large sand seas following climatic amelioration.

Erroneous detections by the classifier have already been discussed above, and in Table 2. However, in terms of classifier omissions, during field survey it was also observed that the classifier did not directly identify several heavily indurated calcretes/gypcretes potentially associated with earlier Pleistocene humid episodes (Fig. 8; I). These were often detected by proxy however, as other less indurated shallow lacustrine/palustrine materials were identified within the same basins, demonstrating recurrent hydrological episodes. Notwithstanding this proxy identification, direct identification would be preferable as in several cases they were shown to be associated with archaeology and the preservation of stratified Palaeolithic sites (Jennings et al., forthcoming).

Finally, while our data provides an overall model of the location of past water sources within a given region, discrimination between different palaeohydrological feature types (lacustrine vs. shallow marsh), perennial or seasonal activation, and levels of potability cannot be achieved from the remotely sensed data alone. Additionally, our lake extents present simply a time-averaged model of the potential maximum former lake sizes based upon the detected data. Real-world lake shorelines cannot be remotely detected by our method at present. In particular, shorelines observed during fieldwork have typically been defined by the internal character of preserved remnant lake deposits, rather than by upstanding geomorphological features such as preserved strandlines. Therefore, to attempt to accurately determine the nature of the water body represented by these deposits, targeted field survey and palaeoenvironmental sampling are required.

6. Discussion

Having demonstrated the accuracy of the method we have developed for mapping the location of palaeohydrological features in Arabia, and its utility for locating archaeological sites, we illustrate how the data produced by these analyses can be employed to start to address large scale archaeological questions.

6.1. Arabian Peninsula palaeohydrology and archaeology

Our mapped major palaeodrainage data, when visually overlain with previously identified archaeological sites for the Arabian Peninsula (Groucutt and Petraglia, 2012, updated with recent literature) highlights an apparent spatial association between major palaeohydrological features and sites of Middle Palaeolithic (Mpal) and Lower Palaeolithic (Lpal) technology (Fig. 10). We cannot account for any unknown potential historical bias of archaeological survey towards wadi courses, however to avoid known bias, archaeological sites that were identified during our explicitly palaeohydrologically targeted surveys are not included in Fig. 10. To examine this visual association, initial simple distance analyses were then performed, examining the distribution of these 183 known MPal, and 100 LPal sites (or clusters of sites) in relation to the major drainage features. For this purpose, major drainage systems were defined as those of greater than 1000 km^2 catchment area and of strahler stream order higher than 2 (excluding drainage mapped within dune fields and minor disconnected systems, but including interpreted major former Pleistocene connections-see SI 2 for details). This is a deliberately conservative choice of threshold and criteria, as large rivers can occur can also at the 100 km^2 level and smaller stream orders.

The average distance from drainage across the areas covered by the archaeological databases was first calculated (so as to determine whether archaeological sites were typically closer, or further from drainage than this value). To do this Euclidean distance from drainage across the areas covered by the archaeological databases was calculated as a raster at 90 m resolution. This calculated the distance to drainage for every location (i.e. every 90 m cell) across Saudi Arabia, Yemen, the UAE, Qatar & Oman. The median distance to drainage was 25.45 km (median is reported as distances from drainage are skewed distributions) with an interquartile range of 56 km (11 km–67 km), while maximum distance from drainage for any single cell was 260 km.

When the distance from drainage of the archaeological sites was assessed however, the median distance from drainage for Middle Palaeolithic sites was only 13.18 km (interquartile range of 30 km; 3 km–33 km), and for Lower Palaeolithic sites was 13.26 km (Interquartile range of 24 km; 3 km–27 km); values substantially smaller than the median distance from drainage for all locations. Furthermore, there is a progressive drop in the number of recorded archaeological sites as distance from major drainage features increases (Fig. 11), with 44% and 43% of MPal and LPal sites respectively within 10 km of drainage, and 58% and 68% respectively within 20 km of drainage.

These initial broad observations of known sites being in closer than average proximity to major drainage, and decreasing in number with increased distance from this, may begin to support hypotheses that hominin dispersals followed continental riparian routes during past humid periods with greater freshwater availability and associated flora and fauna along stream courses, as suggested by several studies in Arabia during the past years (e.g. Rose and Petraglia, 2009; Petraglia, 2011; Rose et al., 2011; Groucutt and Petraglia, 2012; Crassard and Hilbert, 2013). However, it is important to note that the mapped palaeohydrological features are time-averaged data, formed during repeated hydrological activity across multiple humid phases. Even within humid phases there was likely substantial spatio-temporal variation in the activation of hydrology across different areas of the peninsula. Therefore, to discuss palaeohydrology or quantitative relationships between archaeology and palaeohydrology more effectively for specific periods, it is critical to incorporate both rivers and lakes in these assessments, and to evaluate which palaeohydrological features may have been contemporaneously active, and their potential level of activation (perennial/seasonal). The latter information cannot be derived from remotely sensed data alone. However, we show here that the remotely sensed data allows us to begin to address freshwater availability and hominin dispersals over large temporal and spatial scales.

6.2. Example of regional palaeohydrological reconstruction for specific periods

To examine the relationship between palaeohydrology and archaeology in more temporal detail, integration of palaeoenvironmental and archaeological databases with the lake mapping needs to be performed. An example of how this can be achieved at a regional scale, and the information it can provide, is presented for the Nefud and Shuwaymis regions (Fig. 12). Published palaeoenvironmental evidence from previous studies has been collated and is presented in Fig. 12 alongside our lake data. These data only allow broad temporal reconstructions, due to the large error ranges associated with radiometric dating, and decadal, centennial, and even millennial-scale variations in precipitation cannot be determined. Analyses capable of exploring these higher temporal resolutions could potentially become possible in the future however, through integration with emerging palaeoclimate modelling, where these high-temporal resolution data are well-validated (see Jennings et al., 2015b.

The presence of lakes in these Nefud basins is confirmed for numerous past humid periods, with lakes dated to the Holocene at Tayma and Jubbah (Engel et al., 2011; Crassard et al., 2013b), MIS 7 and 5 at Jubbah (Petraglia et al., 2011, 2012) and interdune locations scattered across the southern Nefud (Rosenberg et al., 2013), and to MIS 11 and MIS 9 in both the southern and northern Nefud (Rosenberg et al., 2013). This demonstrates that during interglacial wet phases enhanced precipitation resulted in lake formation across the Nefud, which would have resulted in some level of drainage system reactivation in catchments such as those of the Nayyal, Batin and al Hamd.

Combining the data from these proxies to our modelled data suggests that during past humid phases large palaeolakes, with maximum extents of up to 387 km^2 in area and potentially up to 16–72 m in depth (see discussion in Section 4.2.3 of depth caveats), formed in large topographic depressions along the southern and western edges of the Nefud dune field. Our lake modelling produces lakes at the known palaeolake sites of Tayma (Engel et al., 2011) and Jubbah (Petraglia et al., 2012), and at 11 of the 19 different Nefud lake sediment sites dated by Rosenberg et al. (2013). In our data the Tayma lake is suggested as having a former maximum extent of c.13 km^2, slightly smaller than its suggested Holocene extent (Engel et al., 2011), while water extent in the Jubbah basin is similar to previous studies (Petraglia et al., 2012) and lake depth may potentially have reached 48 m.

During the regional humid periods discussed above it is likely that lake formation also occurred in the undated lake basins which we have identified within the study area, given the regional nature of the enhanced monsoon rainfall that has been suggested to have provided the necessary water at these times (Rosenberg et al., 2013; see Parton et al., this volume for further review). For example, monsoon activated overland flow would have resulted in drainage flowing in a north-easterly direction, forming a large palaeolake (up to 387 km^2) south of the Ad Dhana in the region around Baqa (an extensive Khabra' playa). Other depressions holding large lakes are found on the southern and northern margins of the Nefud (Fig. 12), including the lake at Al Marrat. In the smaller interdune depressions in the western Nefud, palaeolakes ranging from 1 to 99 m in depth may have formed. Rosenberg et al. (2013) dated some of these interdune Nefud lakes to MIS 11-9 and MIS 5. However, reconstructing the previous extent and depth of interdunal lakes from the modelled data is problematic, as the higher depth values may reflect data from classified cells overlapping onto dune slopes, and in all cases erosion and deposition during dry periods may have led to substantial topographic change. Thus, identified deposits could represent either MIS 11-9 carbonates from lakes originally present in a different topographic setting, or MIS 5 carbonates or Holocene playa in an interdunal setting, potentially closely mirroring that of the present. Whether any interdune carbonate deposits in the Nefud date to the Holocene, remains unclear at present (Rosenberg et al., 2013). However, the presence of small playa deposits in interdune depressions (some radiocarbon dated to between 8.4 and 5.2 ka BP, see Whitney et al., 1983) suggests that periods of increased moisture availability during the Holocene may also have resulted in some level of (ephemeral) water availability in the dunes themselves, particularly in areas with shallow groundwater. Indeed, Holocene lakes at Tayma and Jubbah (Garrard et al., 1981; Engel et al., 2011; Crassard et al., 2013b; Hilbert et al., 2014) confirm the presence of increased rainfall in the Nefud between c. 10 and 6 ka.

To the south, in the Shuwaymis region, reactivation of drainage on the basalt flows associated with the upper Wadi Ar Rimah/Batin would have led to ponding in minor depressions along the drainage courses on the Harrats Ithnayn and Khaybar, forming palustrine areas (this phenomenon was visible on a reduced level immediately after heavy rainfall during fieldwork). However, larger depressions bordering the basalt flows, and a small number of fully enclosed basins within the basalt fields may also have held palaeolakes (89 features in total). The through-flowing palustrine basins would likely have supported increased vegetation, and encouraged local biodiversity. Furthermore, this region of wetlands along drainage courses through the basalts may have provided freshwater sources in an otherwise inhospitable region and further facilitated regional hominin movements, as these networks extend spatially from the headwaters of the Wadi's Rimah/Batin and Hamd, all the way to the southern Nefud, feeding palaeolakes in this region (Fig. 12) and facilitating demographic connectivity. During the Holocene, Neolithic rock art across the region (e.g. Jennings et al., 2014) testifies to the presence of humans during wet phases. Furthermore, fluvial ponding locations along mapped drainage appear to have been of significance during the Neolithic and potentially Iron Age periods, forming focal points for structural and funerary activity within the region (Fig. 13). In addition to these Holocene associations, the SH-11 site suggests that Pleistocene humid periods also hosted palaeodrainage sufficient to provide freshwater and faunal resources to support hominins within the otherwise barren Harrats.

In total, across the Nefud and Shuwaymis study area we find that 1162 lakes may have existed in regional endorheic depressions. A discussion of the palaeohydrological connections of the Nefud region and their implications in regards to hominin dispersals based upon our drainage data was performed previously in Petraglia et al. (2012). The refined palaeolake data presented here (Fig. 12) expands upon our previous findings, and further complements the suggestions we made there, that palaeohydrology within the region may have facilitated hominin dispersals. Middle Palaeolithic and Neolithic archaeology within the Nefud dunes at Jubbah during MIS 7, 5, and the Holocene (Petraglia et al., 2011, 2012; Jennings et al., 2013; Crassard et al., 2013b) previously provided striking evidence for the accessibility of the area under humid conditions that has now been further complemented by the sites identified during this study associated with southern Nefud palaeolakes (Fig. 13. See also Groucutt et al., in review; Scerri et al., 2015; Jennings et al., forthcoming). The importance of these lakes as a focus for Palaeolithic activity is discussed by Scerri et al. (2015) and is clearly highlighted by Fig. 13. Numerous Middle Palaeolithic sites have been identified across the region during palaeohydrologically targeted survey in 2013–2014 Palaeodeserts Project survey seasons.

When these data are compared with the few known sites for the study region prior to our surveys (also shown on Fig. 13) the potential for surveys targeted on mapped palaeohydrology to enhance the archaeological record over relatively short periods becomes readily apparent. Middle Palaeolithic sites for the region were formerly limited to the upper reaches of Wadi al Hamd (bottom left, Fig. 13) and the Jubbah basin (Petraglia et al., 2011, 2012). Our surveys have demonstrated that these occurrences are not isolated events, with Middle Palaeolithic occupations now shown to have occurred in both Wadi Batin and Wadi al Hamd in this region, and along the whole southern edge of the Nefud in association with large palaeolakes.

The presence of extensive palaeolakes and wetlands around the southern fringe of the Nefud would have provided favourable environments of faunal and freshwater availability during the humid phases mentioned above. Given this prevalence of lakes and wetlands across the southern Nefud, 'lake-hopping' between fluctuating freshwater sources within the seasonal or annual ranges of hominin groups may have provided a valuable survival strategy, and facilitated dispersals (sensu Finlayson, 2014). In this manner, the numerous palaeolakes may also have facilitated movements to and from the major palaeodrainage of the Wadi's Nayyal, Batin/Ar Rimah, and Al Hamd via their tributaries, over larger temporal scales potentially allowing dispersal across a region stretching from the Arabian Gulf to the Red sea via the Nefud and Shuwaymis regions.

These data also have implications at the peninsula level. Palaeoprecipitation models suggest the extent of increased rainfall during interglacials such as MIS 5e (Jennings et al., 2015b), and an increasing body of palaeoenvironmental records, coupled with our palaeohydrological reconstruction and modelling indicates that during humid episodes potentially thousands of water bodies may have existed across areas of the Arabian interior, expanding favourable biogeographic zones and facilitating the expansion of mammalian populations. This confirms early work by researchers such as McClure, who hypothesised that several thousand water bodies, ranging from ephemeral ponds to large freshwater lakes were scattered across Arabia. The frequency of archaeological sites associated with lakes in the Nefud desert suggests that they are likely to be as important as rivers in influencing hominin dispersals into the interior of Arabia, and indicates that lakes need to be mapped across the entire peninsula to evaluate the relative importance of these two aspects of the palaeohydrology, and wherever possible, dated. This is the subject of on-going research.

7. Conclusions

The remote sensing and GIS methods presented here provide a rapid, effective, spatially comprehensive and multi-scalar technique for mapping the location of Quaternary palaeohydrological features in arid regions. We have applied drainage mapping across the whole Arabian Peninsula, and initial palaeolake mapping to a sizeable (10%) subset of the peninsula. This mapping has been demonstrated to provide a high level of accuracy in identifying former palaeohydrological features, facilitating regional modelling of palaeohydrology in relation to existing archives and new field investigations of archaeology and palaeoenvironments. These datasets begin to provide a framework for examining spatial and temporal variations in surface freshwater occurrence during humid periods, crucial to refining existing discussions of hominin demography and dispersals throughout the Arabian Peninsula and provide precise spatial data that allows integration with archaeological records.

Initial examinations of distance of known archaeological sites from major rivers suggests a relationship between mapped palaeodrainage and Palaeolithic archaeology, although more precise temporal assessments are required to examine these relationships in detail. Our regional analyses of the Nefud and Shuwaymis regions demonstrate how palaeohydrological mapping can enhance the existing records, and suggest environments during Pleistocene humid phases could have provided plentiful freshwater, been rich in faunal resources, and may have been hydrologically well-connected to wider regions, facilitating hominin dispersals along drainage courses and through ‘lake-hopping’.

The potential for enhancing the Arabian archaeological record by using the mapped data to target archaeological survey has also been amply demonstrated, further highlighting the importance of water bodies to populations in the Arabian Peninsula. Our field survey results suggest that targeting lakes may provide relatively higher potential for locating archaeological sites than targeting drainage. However, this likely relates primarily to lakes basins being constrained areas for survey, which combine locations for favourable preservation of stratified sites with wide deflated areas that enhance surface site visibility. This contrasts with drainage systems, which occupy extensive areas of the landscape and often have significant cover of recent alluvium. These observations highlight however, that it is important to include lakes within regional and peninsula-scale archaeological assessments and landscape reconstructions as well as rivers. Our lake mapping method provides a rapid and relatively effective method for facilitating such survey, and mapping lakes across the whole of Arabia is a priority for future research.

A key priority for studies of Arabian prehistory is locating further stratified dateable Palaeolithic sites, given the relative paucity of such sites within the peninsula. With five of the eight currently dated Arabian Middle Palaeolithic sites (Armitage et al., 2011; Petraglia et al., 2011, 2012; Rose et al., 2011; Delagnes et al., 2012; Jennings et al., forthcoming; Groucutt et al., forthcoming) located in lake basins which are (retrospectively) identified by the palaeolake classification method presented here, our data has shown high potential as a method for locating these valuable archaeological assemblages.

As a final note, although in this paper we have highlighted the significance of palaeohydrology, it is important to realize that freshwater availability, although being a critical primary control upon the potential for hominins to survive and disperse in an arid to semi-arid region like Arabia, would not be the sole determining factor in either dispersals or site location choice. A variety of further factors, such as demographic pressure, lithic raw material availability and the distribution of floral and faunal resources would all have played key and dynamically varying roles in these processes throughout the Pleistocene. The severity of the spatial control freshwater distribution exerted upon hominin populations would also have varied with fluctuations in the level of environmental amelioration, with populations likely tied more closely to these resources during more arid conditions when lakes and drainage were more ephemeral and spatially dispersed, than during periods when widespread availability of surface freshwater was prevalent. Unfortunately, at present our understanding of the precise levels of climatic amelioration experienced during different periods of the Pleistocene remains in its infancy, and of relatively low spatial and temporal precision, although it is an area of considerable evolving research (see Parton et al., this volume for a detailed review). This renders addressing this dynamism and the various factors discussed above with any precision problematic. Furthermore, over the course of the Pleistocene hominin evolutionary, behavioural and technological responses to limited freshwater availability (such as larger, dynamic or seasonal home ranges, “rain-chasing” sensu Finlayson, 2014; or the use of water containers) may also have influenced the level of spatial constraint imposed by freshwater distribution, although defining such responses in the archaeological record is not yet possible. Discussions of the potential characteristics of hominin life ways during the Pleistocene in light of all of these dynamic factors is beyond the remit of this paper, and forms the crux of many of the current key debates in Arabian (and wider desert) palaeoanthropology.

In summary, therefore, while it is not the sole predictor or determinant of the location of hominin sites, we feel that the apparent high frequency of archaeological association with palaeohydrological features highlights their significance to contemporary populations and their utility as targets for archaeological survey. Furthermore, we view the data we have presented here as a useful step in attempting to approach the question of how hominins were able to disperse into this comparatively arid region by providing a broad baseline of where water may have been, and (for the Nefud region) when it may have been extant. Further work and high resolution palaeoenvironmental archives are required however to provide precision to refine this picture, in particular on the ground research to determine dates, salinity and micro and macro faunal associations of individual features. We are hopeful that the expanding level of Quaternary research in Arabia evident over recent years will continue, and may help to provide the increased spatio-temporal precision which is critical to Palaeolithic research in the Peninsula.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2015.01.022.

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