Ancient agriculture in Southeast Arabia: A three thousand year record of runoff farming from central Oman (Rustaq)

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Abstract

Runoff farming is a key hydro-agricultural strategy that has proven efficient in arid areas. Research in Arabia on the function, development, maintenance, durability and abandonment of this technology is scarce. A multiproxy investigation (cartography, sedimentology, pedology, geochemistry, paleo-ecology and chronology) was conducted on a recently abandoned terraced area in Rustaq, Northern Oman. The aim was to characterize the formation, function and management of this runoff system and the driving factors behind its success. Cycles of cultivation were identified during the Iron Age II/III periods (specifically 750-450 BCE), the Early Pre-Islamic Period (PIR) (specifically 350-200 BCE), the Early and Middle Islamic periods (specifically 8-10th C CE, 13th-14th C CE) and the late Islamic period (specifically 17th C CE and later). This expansion and perenniality was possible thanks to: 1- available water (local to micro-regional orogenic precipitation despite a regional aridification during these periods); 2- suitable soils (weathered geological outcrops, probable aeolian /dust particles); 3- a system of production combining crops and husbandry; 4- a progressive increase in agricultural specialization (crops grown and techniques) in parallel with a diversification in hydraulic technology. These results are to some degree in accordance with known phases of settlement intensification and economic growth, but also reveal the persistence of small-scale rural livelihoods during periods of harsh conditions for which archaeological traces are very scarce.

Keywords

Land use, runoff, agriculture, geoarchaeology, paleoecology, Oman

1. Introduction

Agriculture has been practiced for millennia in numerous arid to semi-arid parts of the world, and has facilitated the exploitation of such environments thanks to the management of two scarce resources: soil and water. Runoff farming, floodwater farming, and oasis agriculture exploiting groundwater are the most common hydro-agricultural practices in these parts of the world. Runoff farming (also referred to as 'rainwater-harvesting agriculture'; Bruins, 1986) provides moisture by collecting surface or subsurface runoff from a catchment area using channels, dams and diversion systems.

Some of the oldest traces of runoff farming date from the Neolithic, and numerous systems have been identified and studied mainly in the Southern Levant (Israel: Evenari et al., 1971; Bruins et al., 1986; Ashkenazi et al., 2012; Jordan: Kirkbride 1966; Helms, 1981 ; Levy and Alon, 1983; Gilbertson, 1986; Barker et al., 1999; Meister et al., 2017 ; Lucke et al., 2019a), Yemen (Brunner and Haefner, 1986; Ghaleb, 1990; Wilkinson 1999, 2005, 2006; Harrower, 2009), as well as a North America (Nabhan, 1983; Doolittle, 2000; Sullivan, 2000; Sandor et al., 2007). Some of these systems have functioned for centuries and have allowed for the development and survival of semi-permanent settlements and regional exchanges of fruit trees, cereals and fodder crops (Beckers et al., 2013; Müller-Neuhof, 2014; Ashkenazi et al., 2015).

If well-constructed and managed, runoff farming has proved to be very important in sustaining rural livelihoods by increasing yields and crop diversification, reducing risk, improving pasture growth and supplying water to livestock, helping preserve soil and water, preventing erosion, limiting soil salinity, mitigating flood risks, increasing regional biodiversity and occasionally allowing for the recharge of local groundwater. The development of this agricultural system was - and remains - only possible if the infiltration rate is lower than the rainfall intensity, if soils are available and thick enough to retain water (Evenari et al., 1982; Bruins et al., 1986) and if structures are built to catch and store both soil and water (Bruins and Jongmans, 2012), such as dams, terraces, diverting channels and rock surface clearing.

Based on these assumptions, and sometimes with the objective of re-implementing runoff farming in arid areas (e.g. Avni et al., 2019), researchers have focused on understanding the physical aspect of small-scale and large scale runoff networks, including the hydrological and hydraulic properties of the catchment area (e.g. Evenari et al., 1968; Meister et al., 2018). In parallel, some researchers have also focused on understanding when these systems were built and abandoned, and the influence of technology, environment and socio-economy on their durability (Ashkenazi et al., 2012; Ashkenazi et al., 2020). It has been argued that the main drivers behind their construction could be better climate (Rubin, 1989; Bruins, 1994; Issar and Zohar, 2007; Rosen, 2007), soil geomorphology (Evenari et al., 1982; Yair, 1983; Lavee et al., 1997; Droppelman et al., 2000; Bruins and Ore, 2009; Sandor and Homburg, 2017; Lucke et al., 2019b), technological skills (Ashkenazi et al., 2020; Wieler et al., 2016), as well as political or economic systems such as the search for surplus production (Meister et al., 2017) or power (Shahack-Gross and Finkelstein, 2008). Studies suggest that these systems have been largely abandoned as a result of socio-economic and political changes (e.g. Donkin, 1979; Evenari et al., 1982; Johnson and Lewis, 1995; Avni et al., 2019), demographic growth (Blond et al., 2018), migrations (Barrow, 1999), or climatic shifts (Issar and Zohar, 2004; Issar and Zohar, 2007).

Nevertheless, independently of the driving factors behind their construction and abandonment, the agricultural purpose and chronology of runoff systems remains debated (Lucke et al., 2019b; Al Qudah et al., 2016; Avni et al., 2012; Bruins and van der Plicht, 2017). In the southern Levant, where most of the research on ancient runoff systems has been conducted, researchers suggest that these systems could also have been built for grazing (Al-Ayyash et al., 2012), for flood control to trap sediments and slow water flow, as well as for soil conservation and agriculture (Al Qudah et al., 2016), even if evidence for agricultural crops could just indicate nearby consumption or import of traded goods. Our understanding of runoff farming systems has been refined by integrated studies (e.g. Bruins, 2007; Shahack-Gross and Finkelstein, 2008; Shahack-Gross et al., 2014, Avni et al., 2019) which have built long-term models of agricultural traditions combining herding and crop farming, with large-scale constructions requiring steady maintenance and labor, often independent of long-term climatic change (Ashkenazi et al., 2020) or suitable soils (Avni et al., 2019). Moreover, the study of water availability through the hydrological modeling of runoff on ancient terraces (Al Qudah et al., 2016; Bruins et al., 2019) as well as the study of soil origin (Lucke et al., c) provide new references for further research on the agricultural purpose of runoff systems.

Unfortunately, in Southeast Arabia (United Arab Emirates and Oman), at the crossroads between Iran, Mesopotamia, India and Saudi Arabia, little is known about runoff systems. A recent publication (Charbonnier et al., 2017) provides the first detailed insights into runoff farming in the United Arab Emirates at Masafi during the Iron Age, around the 1st millennium BCE. Between 2013 and 2018, a large survey program (Kennet et al. 2016) has revealed the existence of numerous areas in Oman, mainly in the Hajar mountains, which cover most of the sultanate, where runoff farming has been practiced up until the 1960's. In order to provide new data, fill a regional gap and contribute to the ongoing debate, we developed a holistic approach to the study of these systems to reconstruct their socio-environmental history.

Three research questions were defined: 1) What are the processes and dynamics involved in the formation and evolution of agricultural runoff? 2) When areas were exploited, what was their function and how were soils, water and vegetation managed? 3) What might have been the long-term and short-term triggers for the development and abandonment of runoff agriculture? To answer these questions, we provide here the first study of a runoff farming system exploited for the last three millennia in southeast Arabia. The study is based on an integrated cartographic, sedimentological, pedological, geochemical, paleo-ecological and chronological study of one cultivated area close to the old capital city of Rustaq (Oman) (Fig 1.A).

2. Regional setting

2.1. Geological, climatic and hydrological background

The town of Rustaq (*UTM* 40Q 543558/2586943 E, circa 300m absl) is located in the South Batinah region, circa 45 km inland from the coast (Fig 1.A). Rustaq is a fluvial oasis located on the northern piedmont of the al Hajar mountains, which cover parts of Northern Oman and the United Arab Emirates. This mountain chain, 650 km long, 40 to 120 km wide, and 3000 m high in some areas, is composed of superimposed sheets of limestone and ophiolites as a result of subduction events during the Cretaceous and earlier uplift during the Oligocene. Rustaq lies at the contact between three geological formations (Fig 1.B): the Jabal Akhdar formation (Pre-Permian limestone and dolomite belonging to the "autochthonous" sequences of the Arabian platform), the Haylay'n block (Harburgite of the Samail ophiolithe nappe) and the Hawasina Nappe (Beurrier et al., 1986), a succession of sedimentary decollement nappes. The study area is located on a 13km long strip of land close to and just downstream of the confluence of Wadi Bani Auf and Wadi al-Sahatan (Fig 1.B). Both wadis are intermittent, braided and entrenched (Parton, 2015; Garnier and Purdue, 2018) and surrounded by ancient cemented alluvial terraces (Terrace 1 to 4) (Fig 1.C), deprived of fine sediment input.

The climate is arid (Böer, 1997), with current average annual temperatures reaching 26°C and annual average precipitation not exceeding 80 mm/year (http://worldweatheronline.com, 2009–2019 average in Rustaq) (Fig 2). Rainfall occurs in winter, mainly in February and March, and derives from the east coast of Africa, frontal storms from the Mediterranean, and the southward advance of the westerlies. In summer, Indian monsoon convective storms are responsible for localized rainfall events mainly in July and August.

Due to the local geology and topography, Rustaq has benefitted from multiple water sources: groundwater, springs and wadi flow. These multiple resources have allowed for the agricultural development of the oasis for at least the last four and a half millennia (Kennet et al., 2014). Channeled underground water (Da'udi falaj) and spring water ('Ayni falaj) appear to have supplied most of Rustaq's old oasis throughout history. More recent palm groves, located north of the old oasis, mainly exploit deep underground water through diesel pumps. While runoff farming has rarely been exploited to its full extent, the exploitation of wadi or surface flow (Ghayli falaj) is clearly attested in many areas throughout the valley by surface canals, fields, and terraces. Despite the recent abandonment of this type of irrigation for economic and climatic purposes, we suggest that it has been used and developed throughout the history of Rustaq. This is the case of our area of study, the site of "Manaqi Field South", in the northern part of the oasis (Fig 1.B and C).

2.2. Archaeological and environmental background of the site of Manaqi

There is a lack of archaeological data and surveys from parts of central Oman, particularly on the eastern piedmonts of the Hajar Mountains and the Batinah coastal plain. Recent projects, and mainly the *Rustaq Batinah Archaeological Survey*, have uncovered a long history of settlement in these areas (Kennet et al., 2016). One of the main features of settlement history in this region is that it is broken into periods of settlement expansion, for which archaeological evidence is widespread and common (e.g. Early Bronze Age (3200-2000 BCE), Iron Age II (1000-600 BCE), Late Islamic (c. 17-19th C CE), and periods of settlement reduction, for which very little evidence is present (e.g. Late Bronze/Early Iron (1650-1200 BCE), the late Pre-Islamic (PIR)/Sasanian (3rd -7th C CE)).

The archaeological area of Manaqi (RBAS Site 02/20) was discovered in 2013 during archaeological survey (Kennet et al., 2014). This area stands out for a number of reasons. Firstly, three major archaeological sites have been located in close proximity, dated from the 3mil BCE to the 4th c. BCE, whilst numerous smaller scattered settlements have been dated to the later Islamic period (17th to 20th century) (Fig 1.B). It is certain that the populations of each of these settlements would have been engaged in cultivation in the immediately surrounding area. Secondly, this area contains numerous abandoned agricultural structures visible on the surface, such as fields, channels, walls, terraces and clearance mounds, which are formed by stones being cleared from the surface to create fields and reduce the level of the land (Al-Jahwari and Kennet, 2008) (Fig 3.C). Buried walls and ancient deposits have been exposed 1 to 1.5 m below the surface by erosion, highlighting a long history of agricultural usage (Fig 3 and 4). This is confirmed by a scatter of sherds dating from the Iron Age II (c 1000-600 BCE) until the present day which were discovered on the surface.

All these structures are located in a small watershed covering an area of 54.6 ha (Fig 3.A). This watershed is located on an ancient alluvial terrace (T2 Pleistocene terrace), 3 to 5 meters above the current wadi bed (Fig. 1.C). This terrace is composed of large cobbles and boulders in a cemented carbonated matrix (Fig 4.D). To the west and overlooking the site, a small hill also composed of cemented cobbles and boulders in sandy matrix suggests the existence of a much older terrace, probably representing an ancient Pleistocene fluvial point bar (terrace T1) (Fig 4.A). Pockets of surface deposits were identified on this terrace. Interestingly, these deposits are blocked to the north by an outcrop of Cretaceous red radiolarian chert and micritic limestone from the Hawasina nappe. The runoff system takes advantage of this natural topography, with the diversion and channelling of runoff water and sediments from this ancient T1 terrace to the fields located on the T2 terrace.

Three sub-watersheds have been identified (Area 1, 2 and 3) (Fig 3). Area 1 (10.3 ha), on which we will focus in this manuscript, drains water from the western slope of Terrace 1 for a distance of 800m (Fig 3). Some diversion canals supplying water to the fields were noticed at different elevations, some of which presented traces of headgates. Probably as a result of steep slopes, no fine soils were discovered upstream of this sub-watershed (Fig 4.E) but an accumulation of two meters of deposits, currently exposed by erosion, was identified downstream of this area (Fig 4.F and G).

Area 2 is the largest sub-watershed (35.3 ha). The intermittent wadi, draining water from the eastern slopes of Terrace 1, flows on a gentle south-north slope (2%) for a distance of 2km before reaching the current wadi bed (Fig 4.A). The wadi is currently entrenched and has exposed the bedrock in its upstream section (Fig. 4.B), as well as buried walls at a depth of 1m (Fig 4.C). A diversion dam was discovered upstream of the sub-watershed and surface stone walls were identified transversal to the wadi. They were probably built to distribute flood water, prevent concentrated flow, and allow for water to percolate into the soil. Area 3 covers only 9ha (Fig 3). This small sub-watershed is directly connected to Area 2 and drains water on a very shallow slope. No hydraulic structures nor fine soils were discovered in this area apart from an irrigation canal that seems connected to it in its downstream section (Fig 3.B and C, blue dashed line). This channel originates from a large agricultural complex discovered in 2014 (Kennet et al., 2014) which diverted water from the main wadi during the Islamic Period, after the 12th century CE. This indicates that floodwater could have supplied water to Area 2 and 3 during that period.

In order to test if these areas could have received water from another source, surveys were conducted in 2017 in the vicinity. No traces of an underground water gallery or wells were discovered. Despite a lack of visible remains, manual watering could also have occurred in the area. It is also worth noting that no sources of fine sediment were identified nearby as most of the surrounding deposits are composed of cemented boulders, cobbles and gravels.

3. Material and methods

3.1. Mapping and field soil description

To map the site of Manaqi and its surroundings, geomatics data were compiled and processed with the softwares ESRI's ArcGIS10.8.1® and Clark University's TerrSet®, with a UTM geographic coordinate system (Universal Transverse Mercator) - Zone 40 North (WGS84). First, a high resolution (1mx1m) Digital Elevation Model (DEM) (Fig 3.A.) was created based on the elevation surveys of the semis or contour lines using a Trimble® Geo7XT differential global positioning system (DGPS), which allowed us to perform various mapping operations and create accurate 3D geographic information. With the differential correction, point coordinates were mapped to an accuracy of 1-2 cm. Second, a kite aerial survey of the area was conducted to properly record archaeological and hydro-agricultural structures. Pictures were assembled under the Agisoft Metashape 1.7.2 software (Fig 3.C.) and georectified using the DGPS. Last, regional and micro-regional maps were obtained using the 12.5 m resolution Digital Terrain Model (DTM) (ALOS PALSAR) and 50 cm resolution satellite images from QuickBird (source Google Earth) (Figure 3b).

Six test pits were excavated (TP1, TP2, TP3 and TP4 in Area 1, TP 5 and TP6 in Area 2) (Fig 3.C). The present study will focus only on TP1 in Area 1 which was systematically investigated (see Supplementary Material 1 for more details on TP2 to TP6). TP1 was excavated with a backhoe until reaching ancient cemented Pleistocene deposits (Terrace T2). The soil profile was described and classified based on the FAO and WRB (FAO, 2006; IUSS Working Group, 2015). Sedimentological units (SU), which correspond to sedimentary deposits not related to pedological processes (numbering from bottom to top), were assigned and complemented with soil horizons. As a remark, most of the soil horizons are very-weakly developed and they are many correspondences with sedimentological units. Deposits were described with common descriptors such as texture, coarse elements, color (Munsell Soil Color Charts), structure, stratigraphic boundaries, occurrence of anthropic and/or ecological inclusions, secondary features (accumulation of secondary carbonates, clay illuviation, oxidation features), *in situ* burning, etc.

Complete paleoenvironmental analysis was conducted in the profile. Bulk samples were collected from the middle of each sedimentological unit for physico-chemistry, geochemistry, particle size analysis, paleo-ecology (charcoal, shell and phytoliths studies), and chronology (radiocarbon). Thin section samples were carved in the profile, plastered and protected in bubble wrap.

3.2. Laboratory analyses

3.2.1. Physico-chemistry and particle size analysis

To describe and characterize the deposits, grain size analysis, Ph, electrical conductivity, $CaCO_3$ content and Loss on Ignition (LOI) were conducted in every sedimentological unit of TP1 (SU 1 to 16, 17 samples). Particle size distribution was conducted by sedimentation (PSDA procedure, AFNOR NF X31-107 standard) (AFNOR, 2004). Due to the calcaric composition of the deposits, we decided not to remove carbonates and considered that the content in secondary carbonates was too low to actually impact the measurements (see section 4.2.4). Five grams of sieved sediments (< 2mm) were mixed and agitated in an aqueous solution after destruction of organic matter by H_2O_2. Determination of the finest fractions (<50 µm) was conducted by means of 3 successive samplings (with a Robinson pipette) in the soil suspension. Sediments were dried and weighed. The sand fraction was then obtained after sieving, dried and weighed. Five textural fractions were determined: clays, fine silts (2-20µm), coarse silts (20-50 µm), fine sands (50-200 µm), and coarse sands (200µm-2mm). Ph and Redox potential were measured using a Eutech Instruments PC 450. Twenty grams of sieved sediments were mixed with 50ml of distilled water, agitated for two minutes, left to rest for 30 minutes (AFNOR, 1999 / n° X 31-117). An extra 50 ml was added to the mix, stabilized for 30 minutes, and centrifuged for 10 minutes at 2000 revolutions per minute in order to measure the electrical conductivity and total dissolved salts using the same Eutech Instruments PC 450 (AFNOR, 1999 / n° X 31-113).

The percentage of $CaCO_3$ was estimated using the Bernard Calcimeter. 0.25 grams of sediments were mixed with 10 ml of HCL and the volume of CO_2 released allows the percentage of $CaCO_3$ in the sediments to be measured (AFNOR, 1999 / X 31-105). For loss on ignition (LOI), each sampled (10g per SU) was dried for 3 days at 30°C (RosenMeier and Abbott, 2005), then 24 hours at 105 °C for residual humidity (Allen, 1974), burnt at 550°C for five hours to destroy the organic matter (Allen, 1974; Nelson and Sommers, 1996), and finally burnt for two hours at 950°C (Heiri, 2001) to remove the residual carbonates. The weight of the sample was measured after each passage through the stove and the oven. LOI550 is presented as a percentage of weight loss from the humidity free sample following combustion and is used a relative measure of organic carbon content (Santisteban et al. 2004)LOI950 was used as a proxi for carbonate content, obtained by multiplying the mass of CO_2 evolved in the combustion at 950 °C (LOI_{950}) by 1.36 (Heiry et al., 2001 based on Bengtsson and Enell, 1986).

3.2.2. Sediment geochemistry

The chemical composition and relative concentration of elements was measured on 12 samples from TP1. Strata 1, 3, 9, 10, and 16 were not processed due to their coarse texture and local origin. Measurements were conducted using an Olympus Vanta C Series XRF Analyzer fitted with a rhodium (Rh) anode 40 kV X-ray tube with a silicon drift detector (Kilbride et al., 2006). Five grams of sieved sediments (2mm) were dried at 40°C. To prevent contamination and to protect the detector window, a thin (<10 µm) plastic film was placed between the analyzer and samples. Eleven elements were selected Si, Al, P, Ti, Pb, Fe, Ca, Mn, Sr, Mg, K and their concentration measured in ppm. Ca/Ti (Calcium / Titanium) was used as a marker of silica versus local carbonate inputs, while K/Ti (Potassium / Titanium) was used as a proxy of irrigation and/or leaching processes.

3.2.3. *Magnetic susceptibility*

Magnetic susceptibility provides information on detritism (Arnaud et al., 2005; Sadiki et al., 2007), sediment sources such as aeolian particles (e.g. Thompson and Oldfield, 1986), and fire regime (e.g. Kletetschka and Banerjee, 1995; Peters et al., 2001). Magnetic susceptibility corresponds to the ability of a material to be magnetised in an external field. A surface-applied Bartington M2 instrument was used on flattened soil surfaces of the exposed TP1 to TP6 sequences and the magnetic susceptibility was measured every 5 cm. Due to the measurement conditions, the values measured correspond to the volume susceptibility (kappa) and are dimensionless (SI). Values on the MS2 however have a scale that corresponds to 10^{-5}. In order to understand the magnetic signal better, measurements were also taken on the cemented conglomerate (Terrace T1), on outcrops of ophiolithe and on fine surface deposits (five areas tested).

3.2.4. Micromorphology

Micromorphology is used in agricultural contexts to understand sedimentary processes, pedological and ecological dynamics, human activities (slash and burn, manuring, irrigation), and dynamics related to soil climate (e.g. Courty et al. 1989; Kapur et al. 2008; Stoops et al. 2010; Purdue and Berger, 2015). Six thin sections were sampled in TP1 and processed at the *Servizi per la Geologia* (Piombino, Italy). Thin sections were described using Bullock et al. (1985) and Stoops (2003) based on the selection of numerous markers. The latter were described qualitatively, by presence/absence or by frequency. Frequency refers to the proportionate area of the thin section occupied by the constituent or their total amount based on the use of charts (Stoops et al., 2003). The frequency classes defined depend on the marker selected and its usual presence. The markers selected were: mineral assemblage (presence/absence; frequency as proportion of other minerals), Maximum Grain Size (MGS), soil structure (qualitative), porosity (type of voids and frequency as proportion area of total area of the thin section), secondary carbonates and iron features (type and frequency as proportion of total area), pedofeatures (type and frequency as proportion of total area), traces of manuring or grazing (dung, bone fragments, plant ashes, burnt soil aggregates, and salt crystals in presence/absence) and charcoal (shape and frequency as proportion of total area).

3.2.5. Phytolith study

Phytoliths are microscopic opal particles that precipitate in cells and/or between living plant tissues and are naturally deposited in soils and sediments after plants die and decay (Piperno, 2006). They are useful in dry and anthropogenic environments due to their preservation (Vrydaghs et al., 2001; Ishida et al., 2003; Portillo et al., 2009, 2014) and because they allow Poaceae subfamilies to be differentiated (Twiss et al., 1969; Fredlund and Tiezsen, 1997, Madella et al., 2009, Jenkins et al., 2011) as well as other monocotyledons species such as Arecaceae, the date palm family (*Phoenix dactylifera*) (Kealhofer and Piperno, 1998, Vrydaghs et al. 2001, Piperno, 2006, Albert et al., 2015). Even if *in situ* decay is the dominant depositional pattern, several factors such as wind and water transport, fire, grazing herbivores, or organic material input may influence the dispersal of phytoliths and the interpretation of the vegetation cover (Fredlund and Tieszen, 1994; Pearsall, 2000; Kerns et al., 2001; Prebble et al., 2002; Piperno, 2006; Garnier et al., 2013). The combination of phytoliths analysis with other paleo-ecological and pedological studies is required to consider syn-sedimentary and post-depositional processes better in order to reconstruct vegetation cover in anthropogenic environments properly.

Nine samples from TP1 were selected based on their possible grazed or agricultural use (SU 4, 5, 8, 11, 12, 13 low, 13 high, 14, 15). Samples were prepared at the CEPAM-CNRS (Nice) according to Piperno (2006) and studied at the LGP-CNRS (Paris) following: (1) deflocculation of 15g of sediments in a sodium hexametaphosphate (Na_2CO_3) solution; (2) sieving at a 250 µm mesh and clay removal by decantation; (4) destruction of organic matter with a solution of H_2O_2 at 130%; (5) phytolith extraction by densimetric separation with a heavy liquid (sodium polytungstate Na_6) set at d = 2.30–2.35; and (6), mounting of samples on microscope slides using oil immersion to allow the observation of phytoliths in three dimensions.

All morphotypes were identified (as Strömberg, 2004; Neumann et al., 2009; Garnier et al., 2013) and described using the ICPN classification 2.0 (ICPT: Neumann et al., 2019). Three main classes of diagnostic phytoliths were differentiated (Fig 10): (1) morphotypes produced by woody and herbaceous dicotyledons : spheroid ornate phytoliths, which are ubiquitous , and polygonal to cylindrical facetate morphotype as well as two special phytoliths nodular/granulate, that have been mainly observed in African fossil and modern samples (Runge, 1999; Neumann et al., 2009; Garnier et al., 2013; 2018 ; Collura and Neumann, 2017) ; (2) Arecaceae (Palms) are characterized by a specific morphotype : spheroid echinate. However, because of the high occurrence and the morphological diversity of the spheroid ornate in our samples, we chose to differentiate three subtypes of spheroid echinate (Fig 10). Subtypes 1 and 2 correspond to the spheroidal phytolith with conical projections distributed over the entire surface. The size of subtype 1 ranges from 10 to 25µm while the subtype 2 morphotype is smaller with a size between 5 and 10µm. The shape of subtype 3 is similar but the surface is different. The conical projections are more spaced and the surface appears facetate. Consequently, this subtype has been called SPHEROID ECHINATE facetate. It is possible that these different morphotypes are produced by different species or subfamilies of Arecaceae and have to be distinguished but there is still no agreement on the diagnostic features. It appears necessary to conduct more research with morphometric data on modern reference material to improve the level of taxonomic resolution (ICPT: Neumann et al., 2019). (3) morphotypes produced by Poaceae. Grass silica short cells phytoliths (GSSCP) come exclusively from the epidermis of Poaceae while the morphotype bulliform flabellate may occur in the epidermal cells of both Poaceae or Cyperaceae (Esau, 1965). However, because the very specific Cyperaceae's morphotypes have not been observed in our samples, we can suppose that in our study, bulliform flabellate are mainly characteristic of Poaceae. The non- diagnostic morphotypes have been also observed and counted (Fig 10). The minimum count size of diagnostic phytoliths was set at 200 specimens whenever possible (Strömberg, 2009). Only one sample doesn't reach this minimal number whilst three were sterile or with degraded or a low number of diagnostic phytoliths (SU 13 high, 14 and 15).

The index approach has also been developed for our samples. We applied the calculation of the D/P index to evaluate the tree cover density (Alexandre et al., 1997). The calculation is the ratio of spheroid ornate phytoliths (dicotyledons) versus total GSSCP (Poaceae). Values higher than 1 suggest a forest vegetation while values lower than 1 indicate an open environment. The calculation does not take into account the spheroid echinate which clearly dominate our samples. Thus, the index D/P provides information about the nature of vegetation associated with the palms.

3.2.6. Shell studies

Five samples were selected in the thickest units presenting a texture and structure favorable to shell development and preservation (SU 4, 5, 8, 11 and 13). Shells were identified using a binocular microscope (x2 to x4 magnification) after sieving and sorting (2mm, 1mm and 500 µm) of 10 L of sediments. Each identifiable species was counted and species were grouped into distinct ecological groups based on the ecology of current mollusks (Neubert, 1998; Amr et al., 2014; Feulner et al. 2005). This interpretation takes into account the limited evolution of the malacological fauna for the last millennia, but interspecific competition and taphonomical issues are also taken into account. The SU studied provided small quantities of preserved shells (n=861).

3.2.7. Charcoal studies

Charcoal was identified after sieving and sorting of 10 L of sediments from TP1 (SU 4, 5, 8, 11 and 13). Charcoal samples were identified under a reflected light microscope with a 50-500x magnification by comparing their anatomical structure with a modern collection of charred samples (CNRS Archéorient-Jalès France) and with identification literature (Schweingruber, 1990; Fahn et al., 1986). Only 55 samples were identified; others were not due to their small size or poor conservation. The small number of identified samples does not allow for a quantitative study. Thus, only the presence and the ecological data of taxa have been taken into account.

3.3. Chronology

Three AMS dates were processed at Poznan Radiocarbon Laboratory in Test Pit 1 (see Supplementary Material 1 for further data on chronology in the other test pits). The dated material derives from burnt wood and was obtained after the sieving and sorting of 10L of bulk sediment. Charcoal fragments were identified when possible prior to their dating in order to select suitable material and to avoid the 'old wood problem'. The protocol consists of a chemical pre-treatment (Brock et al., 2010), followed by the combustion and graphitisation of the sample (Czernik and Goslar, 2001). The ^{14}C content was measured by a 'Compact Carbon AMS' spectrometer (Goslar et al., 2004) and the ^{14}C age calculated (Stuiver and Polach, 1977) and calibrated using INTCAL 20-calibration curve (Reimer et al., 2020) on the OxCal ver. 4.2 software (Bronk Ramsey and Lee, 2013).

In parallel, we sampled all the visible ceramics in the profile. Their depth was measured and we attributed a soil horizon/sedimentological unit to all of them. A total of 61 ceramic fragments were recovered in TP1. They were visually dated on the basis of form (where present), fabric, surface treatment, and firing technique in relation to published stratigraphic sequences. Based on a macroscopic study and comparison with pottery from well-dated Iron Age sites in Rustaq, almost all of the material is dated to the Iron Age (1300-600 BCE).

4. Results

4.1. Field lithostratigraphy, chronology and pedostratigraphy (Test Pit 1)

Stratigraphic data, pedological characterization and chronology are presented Table 1, 2 and 3 as well as Fig 6.

4.1.1. Lithostratigraphy and chronology

Test Pit 1 is composed of 2 meters of deposits. The lithostratigraphy is comprised of sixteen Sedimentological Units (SU) numbered from the bottom to the top. The substratum is comprised of cobbles and boulders in a cemented carbonated matrix which corresponds to the Pleistocene alluvial terrace T2. Above, the weathered substratum is composed of coarse limestone gravels in a fine light reddish brown silt loam matrix (SU 1). A collapsed terrace wall, built into SU 1, was discovered during excavation (Fig 5.A and B, Fig 6). The presence of numerous Iron Age sherds in this stratum suggests that the landscape was partly modified at that time (Table 3 and Supplementary Material 2). Light yellowish brown loams (SU 2), rich in gravel, and greenish brown silt loams (SU 7, identified in the western corner of profile) cover SU 1. They could be associated with the first agricultural structuration of the area without corresponding to cultivated deposits themselves. Above, well-sorted pinkish grey to light brown loams were encountered and dated from 770-421 BCE (Table 2) (SU 4 and 5). These two SU, limited to the north by the above-mentioned wall, are directly packed against a small earthen butte composed of pinkish grey gravelly loams (SU3). SU 4 is locally sealed by a thin layer of ophiolitic gravels in a light brown loam matrix (SU 6) and buried again under loams (SU 8) containing a few ophiolitic gravels, dated from 758-416 BCE (Table 2). Above, nearly 50 cm of angular ophiolitic gravelly loams rich in sherds point towards collluvial deposition (SU 9 and 10) (Fig 5.A and C). They are buried under well-sorted light brown sandy clay loams (SU 11) dated from 368-173 BCE (Table 2), and massive brown sandy loams rich in fine limestone gravels (SU 12). Above, nearly 60 cm of well-sorted pinkish grey loams and silts loams were encountered (Fig 5.C) (SU 13). Clearly eroded in their upper part, they are buried under light brown to reddish loams, rich in fine and medium limestone gravels (SU 14 and 15). Whereas SU 15 lies at the surface, it has recently been laterally eroded by laminated grey gravelly sandy loams, rich in limestone gravels (SU 16).

4.1.2. Pedo-stratigraphy and soil classification

Deposits in TP1 are little affected by pedogenic properties. The profile is composed of alternating C and weakly developed A horizons. We defined C horizons as alluvio-colluvial or colluvial deposits without pedological signatures. They are composed of structureless loams to sandy loams, rich in limestone or ophiolitic gravels, and deprived of pedological features such as secondary carbonate accumulation. Most of the boundaries between the deposits are abrupt. Six C horizons have been defined and clearly resemble Sedimentological Units (SU): SU 16 (Hz C), SU 12 (Hz 5C), SU 10 and 9 (Hz 7C1 and 7C2), SU 6 (Hz 9C), SU 2, 3 and 7 (Hz 11 C1, 2 and 3) and the substratum (petrocalcic horizon, Hz Ckm).

In between these C horizons, we identified buried topsoils referred to as A(b) and A(p)b horizons. The latter are composed of silt loams, loams and sandy clay loams with a prismatic to polyhedral structure. They often contained inclusions such as gastropods, microcharcoal, artefacts (sherds), rare secondary carbonates (pseudomycelia and diffuse impregnations) and diffuse iron impregnations in the matrix. These inclusions are however too scattered to define a diagnostic horizon based on WRB classification. A(b) horizons, in which bedding structures were identified, were noticed at the base of the profile under the shape of 10-20 cm thick structured loams (Hz 10 Ab1, 10 Ab2 and 8 Ab). They are dated from the 8th-5th century BC. Ap(b) horizons, deprived of sedimentary signatures, probably correspond to ploughed deposits with an abrupt or gradual lower boundary. They also contain charcoal fragments, shells and occasional diffuse secondary carbonates (pseudomycelia). They were identified in the upper part of the profile as homogenized thick silt loams (Hz 2 Ap), loams (Hz 3 Apb, Hz 4Apb1 and 4Apb2) and sandy clay loams (Hz 6 Apb), dated from the 4th c. BCE up until today.

As a remark, only one layer was defined as a B horizon. Indeed, the weathered substratum presents traces of diffuse secondary carbonates and iron-manganese impregnation in the soils suggesting ancient pedological processes (SU 1, Hz 12Bk).

These field observations indicate the dominance of sedimentary processes with a weak vertical differentiation based on the diagnostic criteria defined by the WRB (IUSS Working Group, 2015). The loamy and unconsolidated nature of the deposits, their shallow thickness as well as the absence of diagnostic horizons apart for the presence of a petrocalcic horizon at the base of the profile, suggest these soils are regosols (IUSS Working Group, 2014). Parts of the profile present protocalcic properties as well as calcaric material, due to the presence of carbonates inherited from the parent material. Therefore we can consider that most of the deposits studied in Manaqi are Calcaric Regosols.

Soil Hz	SU	Depth[a]	Lower limit[b]	Munsell dry	Soil structure[c]	Soil texture[d]	clay (< 2µm)	fine silt (2-20 µm)	coarse silt (20-50 µm)	fine sand (50-200 µm)	coarse sand (200 µm-2 mm)	CSF[e] : Fine Gravel (2-6mm)	CSF[e] : Medium Gravel (0,6-2 cm)	CSF[e] : Coarse Gravel (2-6 cm)	pH	Ecé	LOI (550°C)	$CaCO_3$ LOI(950°C)[f]	$CaCO_3$ Bernard Calcimeter	Redox-properties[g]	Carbonate content[h]	Other[h]
		(cm)					[%]									µS	[%]	[%]	[%]			
C	16	0-35 (EP)	A	7.5YR 6/2	Massive	Sandy loam	9	13	11	31	36	M (L)	-	-	7.8	383	2,2	24,4	13	/	/	
2Ap	15	0-14 (SP)	G	7.5YR 6/4	Massive to platy	Silt loam	13	31	19	25	12	F (L)	-	-	7.7	630	2,5	26,2	33	/	PM	MC
3Apb	14	14-36 (SP)	A	7.5YR 6/6	Coarse polyhedral	Loam	17	27	19	27	9	-	M (L)	-	7.4	2580	3,4	23,7	30	/	PM	
4Apb1	13 high	36-60 (SP)	G	7.5YR 6/2 to 6/4	Weakly defined coarse polyhedral	Loam	19	28	17	25	11	-	-	-	7.4	1971	3,1	22,9	25	/	PM	S, SA
4Apb2	13 low	60-86 (SP)	A	7.5YR 6/2 to 6/4	Weakly defined coarse polyhedral	Silt loam	20	32	20	23	5	-	-	-	7.4	838	2,2	21,4	22	/	/	
5C	12	86-98 (SP)	A	7,5YR 5/4	Massive	Sandy loam	13	16	10	36	25	M (L,O)		-	7.4	638	2,4	24,8	20	/	/	
6Apb	11	98-110 (SP)	A	7.5YR 6/4	Weakly defined coarse polyhedral	Sandy clay loam	22	27	20	27	4	-	-	-	7.5	692	2,7	18	16	/	PM	C, A
7C1	10	110-124 (SP)	G	7.5YR N6/0 to 6/2	Granular to fine polyhedral	Loam	21	22	11	26	20	A(WO)		-	7.5	699	2,5	20,4	22	/	/	
7C2	9	124-144 (SP)	A	7.5YR N6/0 to 5/2	Granular to fine polyhedral	Loam	23	25	11	18	23	-	A (WO)	-	7.4	1333	2,7	20,5	24	/	/	
8Ab	8	144-152 (SP)	A (SU 6)	7.5YR 6/4	Fine polyhedral	Loam	21	25	18	29	7	-	F(O)	-	7.5	1161	2,4	20,4	20	/	PM, D	
9C	6	82-84 (EP)	A (SU 4)	7.5YR 6/4	Massive	Loam	20	22	13	19	28	-	A(O)	-	7.4	1366	1,7	29,8	17	/	/	
10Ab1	5	78-85 (EP)	A (SU 2)	7.5YR 5/2 to 6/4	Massive	Loam	18	19	14	41	7	-	-	-	7.4	1182	1,9	19,8	28	/	D	
10Ab2	4	84-92 (EP)	A (SU 1)	7.5YR 6/2	Coarse prismatic to fine polyhedral	Loam	20	27	17	34	3	-	-	-	7.6	771	1,8	22,6	21	D	PM, D	MC
11C1	3	72-86 (EP)	A (SU 2)	5YR 6/2	Massive	Loam	22	24	15	29	12	F (O)	-	-	7.4	1025	2,4	20,4	24		/	MC
11C3	7	125-156 (SP)	G (SU1)	7.5YR 5/2	Prismatic	Silt loam	26	34	21	16	3	-	-	-	7.5	1301	2,2	16,9	22		/	C
11C	2	90-96 (EP)	A (SU 1)	10YR 6/4	Fine polyhedral	Loam	23	28	11	11	27	-	C (O, I)	C (O, I)	7.3	410	2,1	27,3	27		/	S
12Bk	1	96-124 (EP) ; 156-200 (SP)	G	5YR 6/3	Fine polyhedral	Silt loam	29	31	8	7	26	-	C (WL)	C (WL)	7.6	734	2,4	21,8	30	D	PM, D	SA
12Ckm	Substratum	< 200 cm (SP)		10YR 8/2 to 6/2	Coarse polyhedral	Stones, cobbles	-	-	-	-	-	-	-	-	-	-	-	-	-		HL	-

Table 1. Stratigraphic description and physico-chemical data in Test Pit 1
a: EP - east profile, SP - south profile
b: A: abrupt, G: Gradual (FAO, 2006)
c: Based on FAO (2006)
d: Based on USDA (Schoeneberger et al., 2012)
e: Coarse surface fragments according to FAO, 2006 (F: 2-5%; C: 5-15 %; M : 15-40 % ; A: 40-80%) / L : limestone , O: ophiolithe; WO: weathered ophiolithe; WL: weathered limestone
f: Estimated % of carbonate calculated by multiplying (LOI_{950}) by 1.36 (Heiry et al., 2001 based on Bengtsson and Enell, 1986)
g: D: disperse Iron-manganese impregnation in the soil matrix
h: D: disperse powdery lime, PM: Pseudomycelia, HL: hard cemented layer or layers or carbonates (< 10 cm) (FAO, 2006)
i: MC : microcharcoal, C: charcoal, S: sherds, SA: soil aggregates, A: ash

Sites and excavation year	Test Pit	Soil Hz	SU	Material dated	Lb. Code	Age 14C BP	± 2 σ (95 %)	Calibrated Age BCE /CE (2 σ)	Cultural period	Status
RBAS 16	1	10 Ab2	4	Microcharcoal	Poz-90219	2475	35	770-421 BCE	Iron Age II	Accepted
RBAS 16	1	8 Ab	8	Charcoal (Acacia sp.)	Poz-90220	2460	35	758-416 BCE	Iron Age II	Accepted
RBAS 16	1	6Apb	11	Charcoal (Ziziphus sp.)	Poz-90221	2200	30	368-173 BCE	Late Pre-Islamic	Accepted

Table 2. Radiocarbon dates obtained in Test Pit 1. Dates were processed ad Poznan Radiocarbon Laboratory and were calibrated using INTCAL 20-calibration curve (Reimer et al., 2020) and Oxcal ver 4.2 software (Bronk and Lee, 2013).

Test pit	Depth/SU	Quantity of sherds	Shape	Type	Dating	Cultural period	Calibrated Age BCE / CE , 2 σ (95.4%) obtained in the SU
1	Surface	7	S, Rim	Unstratified	1000-300 BCE	Iron Age II/III	
1	1	11	S, Rim	Coarse and semi-fine ware	1000-300 BCE	Iron Age II/III	
1	3	7	S	Coarse ware	1000-300 BCE	Iron Age II/III	
1	4	7	S, Rim	Coarse and fine ware	1000-300 BCE	Iron Age II/III	771-431 BCE
1	8	5	S	Coarse ware	1000-300 BCE	Iron Age II/III	759-416 BCE
1	9	18	S, Rim, Bases	Coarse, semi-fine and fine ware	1000-300 BCE	Iron Age II/III	
1	10	3	S	Coarse ware, same vessel	1000-300 BCE	Iron Age II/III	
1	11	1	S	Coarse ware	1000-300 BCE	Iron Age II/III	366-192 BCE
1	12	1	S	Coarse ware	1000-300 BCE	Iron Age II/III	
Close to TP1	equiv. 13	1	S	Turquish	8-10th c. CE	Early Islamic	

Table 3. Ceramics extracted from Test Pit 1 during its excavation and chronology

4.2. Soil properties (Test Pit 1)

4.2.1 Grain size analysis and physico-chemistry

In order to discuss better sedimentological and pedological processes, we will present results by Sedimentological Unit (SU) before comparing the results for C and A(p)(b) horizons.

Particle size analysis reveals that the sediments are mainly loams. Mean particle size content is 41 % sand, 40.4 % silt and 19.6 % clay (n=17) (Table 1). In general, the clay content decreases from the base to the top of the profile, while the silt content increases (SU 1 to 10, respectively 22 % and 39.5 %; SU 11 to 16, respectively 16 % and 44 %). Within the silt fraction, fine silt (20-200 µm) is dominant in SU 13 to 15, as well as in SU 1, 2 and 7 with values above 30%, while the sand content decreases in these same deposits (< 40 %). Coarse sand fraction content is highly variable but higher concentrations are recorded in SU 16, 12, 10, 9, 6 and 2 and fine sand content ranges from 10 to 18 %. When considering soil horizons, all the A(p)b horizons present an average of 19 % of clay, 27 % of fine silt, 18 % of coarse silts, 29 % of fine sand and 7 % of coarse sands. Their texture is finer than C horizons, which present an average content of 20 % of clay, 23 % of fine silt, 13 % of coarse silts, 23 % of fine sand and 22 % of coarse sands. The latter are also richer in local gravels.

Results from the chemical analysis show that pedological processes are weakly developed. All the deposits are neutral with an average pH value of 7.4. Higher values are recorded at the surface (pH=7.7 and 7.8 in SU 16 and 15) while lower values are recorded in SU 2 (7.2). No differences were noticed between C and A(p)b horizons. Ecé values are 1042 µS on average and the soils are considered as not salty. Higher values of conductivity were recorded in SU 14 (2580 µS), SU 13 high (1971 µS), closer to the surface, while the lowest values are recorded in SU 2 (410 µS) and SU 4 (771 µS). The $CaCO_3$ content, measured by the Bernard Calcimeter method, reaches an average of 23% versus 18% for LOI 950. We assessed the difference between these two measurement methods with a paired sample t-test. This test showed no significant differences between both methods (t (16) = -.51, p = .62). Peaks were noticed in SU 15 and 14, due to the presence of numerous limestone grains and occasional secondary carbonates in SU 15, and in SU 1 and 2, closer to the carbonated substratum. Neither the Ecé nor the $CaCO_3$ show differences between C and Ab horizons. LOI550 values reveal that soils are poor in carbon content with an average percentage of 2.3 %. Higher percentages are recorded in SU 13 to 15 (2.5 to 3 %), but the lowest ones are recorded in SU 4 and 5 (1.8-1.9 %), which, however, have been interpreted as Ab horizons in the field. While these values mainly correspond to a relative measure of organic carbon content, these variations could be explained by a sparse vegetation cover, temporary use or agricultural strategies (no residues left in the plot).

4.2.2 Geochemistry

Geochemical results provide information on both the origin of the sediments and soil formation (Fig 7 and Supplementary Material 3). Similarly, we will present results by Sedimentological Unit (SU) before comparing the results for C and A(p)(b) horizons. Al, P, Pb and high values of Fe and Ti were only identified in SU 2, 5, 6, 7, 12 and 15. SU 2, 6 and 12, in which local gravels were identified, present clear peaks in Mn, Pb and Fe. Deposits without gravels (SU 5, 7) present more or less higher P and/or Al values. All these SU correspond to C horizons. In parallel, the concentration in Si is higher in the upper part of the profile (SU 13 to 15) and lower in the other lower sedimentological units (SU 2, 7, 5, 6 and 11), suggesting an increasing silica content with time. On the other hand, concentration in Mg, Ca and Sr are higher in SU 5, 8, 13low and 15, which all correspond to A(p)b horizons. Some elements have an ambiguous signature, such as K. Indeed, its concentration peaks both in C horizons (SU 2, 7) and A(p)b horizons (SU 4, 8, 13) while K/Ti ratios are higher in A(p)b horizons (SU 4, 8, 11, SU 13 high) suggesting a possible sedimentological or geological significance more than a pedological one. Ca/Ti ratio is irregular in the lower part of the profile and more homogeneous in its upper part.

4.2.3 Magnetic susceptibility

In order to understand the signal, magnetic susceptibility measurements were made on the T1 terrace above the study area (cemented conglomerate and loose surface deposits) as well as on ophiolite outcrops (Table 5). As a reminder, the values measured are dimensionless (SI) and have a scale that corresponds to 10^{-5}.

These reference values show that magnetic susceptibility values are below 30 SI (10^{-5}) in the watershed, both on the conglomerate and the geological outcrop, which the conglomerate is packed against. Interestingly, high magnetic susceptibility values are recorded locally on specific cobbles or boulders, which maybe composed of serpentine (> 500 SI), but also on a loose pockets of sediment identified on the T1 terrace, which corresponds to easily erodible material. Values are homogeneous and span from 144 to 152 SI in average in Area 1 and 2. In TP1, magnetic susceptibility values (Fig 8) range from 30 to 100 SI. Average values reach 47 SI. Whereas values remain low in the bottom part of the profile (Magnetic susceptibility < 40 SI, SU 1 to 10), they clearly increase in SU 11 (80 SI), SU 12 (84 SI) and 13low (75 SI). Values of magnetic susceptibility decrease progressively up until the surface while remaining higher than the bottom part of the profile (circa 50 SI). An exception is surface deposits, for which values reach a peak of 86 SI.

Sub-watershed	Location, Terrace T1	Values of magnetic susceptibility per location (10-5 SI)					Averaged values (*10^{-5} SI)*
Area 1	Cemented conglomerate	20	46	31			**32**
	Random cobbles on the conglomerate	2	52	1	29	-1	**21**
	Possible serpentine cobbles ?	167	144	376	1573		**565**
	Surface pockets of loose sediment	95	165	178	139		**144**
Area 2	Cemented conglomerate	43	27	13	18		**25**
	Limestone cobbles	-1	0				**0**
	Outcrop reddish limestone	1	1	3	1		**2**
	Surface pockets of loose sediment	143	159	217	87		**152**
Area 1 / 2	Oucrop- Red radiolarian chert and micritic limestone	14	14	3	4	4	**8**

Table 5. Magnetic susceptibility (MS) measured in various areas of Area 1 and Area 2 sub-watersheds (unit in 10^{-5} SI)

4.2.4 Micromorphology

Micromorphological observations combine sedimentary and pedological observations. Results are synthetically presented in Fig 8, including semi-quantification methods, and Fig 9. Further details (general descriptive criteria and mineralogy) are provided in Supplementary Material 4.

The base of the profile (SU 1, Hz12Bk) is composed of silt loams, rich in local limestone grains and micritic disorthic nodules (Maximum Grain Size –MGS 4000 µm). Soil structure is massive with closed vughs (see Stoops, 2003 for terminology), iron nodules, and rare brown dusty coatings which suggest water percolation processes. No other features were encountered in this stratum.

Above, SU 7 (Hz 11C3) is composed of silt loam, rich in fine local limestone grains (MGS 176 µm). This stratum is the finest and better sorted stratum studied. Soil structure is massive, with a weakly developed porosity and dominant closed vughs. Some ferro-manganic hypocoatings were identified as well as numerous dusty brown clay coatings. Neither charcoal nor traces of organic matter were encountered.

SU 4 (Hz 10Ab2), 5 (Hz 10Ab1) and 8 (Hz 8Ab) correspond to loam deposits (average MGS 2015 µm, 2091 µm and 1000 µm). Micromorphological observations show that these deposits are in reality composed of nine microstrata, two of which have preserved traces of well-defined grading (SU 4b and 8) (Fig 8), circa 2-3mm thick. Mineralogy indicates that the sediments are generally composed of numerous aggregates of diversified and weathered schists, angular and rounded quartz, limestone, pyroxene and serpentine (Fig 9.A). The soil macrostructure is subrounded blocky with vughs and accommodated planes suggesting alternating wet and dry conditions. These pedoclimatic conditions are confirmed by the presence of occasional secondary carbonates and diffuse well impregnated iron features (Fig 9.B and C). Numerous dusty clay coatings have been noticed around the voids, as well as a soil crust in SU 8, suggesting both a discontinuous vegetation cover as well percolating processes followed by soil dryness. Numerous small particles of charcoal were identified in SU4 and 5 but could have been transported with the sediments. These have a more elongated shape and larger size in SU 8. Plants ashes and burnt soil aggregates were observed stratum 4b (Fig 9. D and E), and preserved (burnt) dung in strata 5a, 5c and 8.

These strata are buried under 60 cm of colluvial deposits (SU 9 and 10). Observations in SU 10 (Hz 7C1) indicate weakly sorted sediments, rich in large grains of local limestone, chert, serpentine and pyroxene (MGS 1200 µm).

SU 11 (Hz 6Apb) is composed of well sorted sandy clay loam (MGS 800 µm). Micromorphological observations reveal the existence of two microstrata composed of rounded to semi-rounded quartz, limestone, as well as some grains of chert, glauconite and micas, not identified below (Fig 9.F). Schists totally disappear from the mineral assemblage. Soil structure is subangular blocky to subrounded blocky, with voids mainly composed of channels and planes. Iron features, dusty clay coatings and salt crystals (Fig 9.F), reflect water percolation. Ashes, charcoal, bone fragments, dung and phosphatic coatings were identified (Fig 9.G).

SU 12 (Hz 5C) is composed of sandy loams, rich in semi-rounded and rounded quartz, limestone grains, schists and micas (MGS 600 µm). Soil structure is massive to vughy. No iron features, pedofeatures, bones or dung were observed. Salt crystals, similar to the ones observed in SU 11, and traces of plant ashes were observed, but this could result from post-depositional processes.

SU 13 (Hz 4Apb1 and 4Apb2) was divided into two soil horizons. SU 13low (Hz 4Apb2) is comprised of well-sorted silt loam, with rounded quartz grains, pyroxene, serpentine, glauconite, micas and limestone grains (MGS 600 µm). The crumbly soil structure and numerous pellets indicate active bioturbation processes. Dusty clay coatings and secondary carbonate coatings result from water percolation processes. Plant ashes as well as numerous rounded and semi-elongated charcoal were identified (Fig 9.H). SU 13high (Hz 4Apb1) is composed of average sorted loam (MGS 2480 µm). The mineral assemblage is slightly different, with the disappearance of glauconite and micas, and an increasing contribution in local limestone. The matrix is totally bioturbated, which could explain the absence of preserved pedo-features apart from a few dusty clay coatings, indicative of water percolation in the soil. Dung was noticed.

SU 14 (3 Apb) and SU 15 (Hz 2Ap) correspond to the upper part of the profile. Deposits are loamy (SU 14) and silty loamy (SU 15) and are average to weakly-sorted (MGS 3940 µm and 2790 µm). Two microstrata were identified in SU 15. All of deposits are composed of rounded and semi-angular quartz, quartz, limestone grains, chert and schists. Micas were observed on the surface. Structure is subangular to subrounded blocky, with channels, chambers and packing voids. SU 14 presents traces of weakly impregnated iron features. Above, SU 15 has preserved traces of light brown and dark brown dusty clay coating, as well as bone fragments, shell fragments and dung.

4.3 Paleoecology (Test Pit 1)

4.3.1 Phytolith study

The phytolith assemblages of the six stratigraphic units analyzed show a relatively low diversity (Fig 10, Supplementary Material 5). In general, the phytoliths are not broken and the number of unidentified ones is correct (11-30 %), suggesting that the phytolith were probably not fluvially transported. The absence of hairs, papillae and long cells with decoration can however question the possible dissolution of weaker morphotypes such as GSSCP and long cells, with a better preservation of more robust morphotypes, such as spheroid phytoliths. Based on the significant amount of phytoliths counted in every SU, we considered them as indicators of a local or extra-local vegetation. In the samples studied, the high values reached by spheroid echinate phytoliths produced by Arecaceae (53-85%) reflect a strong representation of palms in the vegetation cover.

SU 4 (Hz 10Ab2) recorded the weakest percentage of spheroid echinate (53%, subtype 1: 32%). This horizon also records a significant proportion of phytoliths produced by woody dicotyledons (31%) while Poaceae phytoliths reach 6.5%. These results and the high D/P value (3.5) reflect a relatively closed environment with an upper layer composed mainly of Arecaceae and trees and a sparse grass layer cover. Interestingly, the phytolith assemblage in SU5 (Hz 10Ab1) contains higher spheroid echinate (70%), lower dicotyledons morphotypes (23%), and a stable weak percentage of Poaceae (4%). However, the very low amount of polyhedral to cylindrical facetate morphotypes (4%) indicates a different tree cover. Above (SU 8, Hz 8Ab) an increase in Poaceae morphotypes (16%) and a decline in those produced by trees and shrubs (12%) and Arecaceae (64%) reflect a more open landscape. Indeed, the D/P index has a value lower than 1 (0.9) suggesting an open environment. The GSSCP are diversified suggesting the presence of different Poaceae subfamilies. Especially we observe the presence of the morphotype crenate GSSCP. This GSSCP is typical for the subfamily Pooideae to which belongs wheat (*Triticum* sp.) and barley (*Hordeum vulgare*). This result may be indicative as evidence of crop cultivation. Unlike other strata, the Palm morphotype Subtype 3, spheroid echinate facetate, is over-represented reaching 47%. This could indicate another Arecaceae species in the upper tree layer, but we lack further precision in to the available data.

In SU11 (Hz 6Apb) and 12 (Hz 5C), spheroid echinate morphotypes reach 75 and 79%, whereas values from those produced by woody dicotyledons are of 18 and 13% and Poaceae phytoliths only represent 4% for both assemblages. However, the presence of crenate GSSCP in the SU11 can be a signature of cereal cultivation. The D/P index shows high values (3.8 and 3). This trend towards a denser vegetation cover is confirmed in the phytolith assemblage of SU 13 low (Hz 4Apb2) with dominant palm morphotypes (85%, subtype 1: 65 %), some ligneous tree phytoliths (11%) and nearly no grasses (2%). Crenate GSSCP is not observed.

No preserved phytoliths were identified in Strata 13b (Hz 4 Apb2), 14 (3 Apb) and 15 (Hz 2Ap).

4.3.2 Charcoal study

Of the 55 charcoal fragments sampled in TP1, only four taxa were identified: (1) Christ's thorn jujube (*Ziziphus* cf. *spina-christi*) is the most represented species. Ziziphus is a nubi-sindienne specie dominant in Arabian pseudo-savannas. It is used for its wood and the fruits can be also consumed. It can grow naturally but can also be cultivated in oases; (2) Acacia (*Acacia* sp.) is also typical of Arabian pseudo-savannas; (3) Chenopodiaceae; and (4) Date palm (*Phoenix dactylifera*). Charcoal fragments were only identified in SU4 (Hz 10Ab2), 5 (Hz 10Ab1), 8 (Hz 8Ab) and 11 (Hz 6Apb). Two charcoal fragments of Ziziphus sp. were identified in SU4 (Hz 10Ab), two of chenopodiaceae in SU5 (Hz 10Ab1), and six fragments of Acacia were identified in SU8, which could suggest a progressive evolution in the vegetation cover. The charcoal assemblage is the richest in SU 11 (Hz 6Apb) in which 42 fragments of ziziphus sp. and one of palm tree were identified.

4.3.3 Shell studies

A total of 831 shells were identified, represented by nine different taxa (Fig 11, Supplementary Material 6): (1) Zootecus *insularis* (adult and juvenile) (Ehrenberg, 1831)*,* typical of a dry and xerophile station; (2) Pupoides *coenopictus,* which traditionally lives under a dry but existent vegetation cover (Hutton, 1834 in Nasser, 2010); (3) Allopeas *gracilis* (adult and juvenile), typical of wetter soils with a vegetation cover. Initially considered as introduced from the Neotropics (eg. Pilsbry, 1946, Neubert, 1998), they seem to originate in the Old World Tropics (Christensen and Kirch, 1981) and their presence is actually attested in archaeological contexts in many areas, including the Middle East (eg. Glover, 1995; Feulner and Green, 2003) ; (4) Melanoides *tuberculata* (adult and juvenile) is an ubiquitous euryhaline and eurythermal species usually encountered in water and/or very wet soil conditions (Müller, 1774); (5) Quickia *consica* is encountered in woody and bushy vegetation (Morelet, 1848); (6) (7) (8) Coilostele *isseli*, Cecilloides *acicula* and Cecilloides sp. are burrowers under vegetated soils; and (9) Protoconh, which does not provide any ecological information.

Shells were only present in SU 4 (Hz 10Ab2), 8 (Hz 8Ab), 11 (Hz 6Apb) and 13 (Hz 4Apb1 and 4Apb2). In SU4 (Hz 10Ab), only 10 *Melanoides tuberculata* were identified, while only one fragment of juvenile *Melanoides tuberculata* was counted in SU8 (Hz 8Ab). This very low amount of shell fragments prevents us from reconstructing full environmental conditions. However, this may reflect a weakly anthropized environment with possibly wetter conditions, but unsuitable conditions for faunal development. The malacological assemblage evolves and increases in SU 11 (Hz 6Apb) represented by 19 individuals (juvenile *Zootecus insularis,* P*upoides coenopictus, Allopeas gracilis,* juvenile *Melanoides tuberculata*. This suggests that, despite probable constraining conditions, which could explain the low amount of shells, local vegetation has developed in alternating dry and wet conditions. This is much clearer in SU13 (Hz 4Apb1 and 4Apb2), in which 831 individuals were counted, amongst which 8 different species and 1 individual identified all the way to the genus with respect to the *Ceciloides* sp.. *Melanoides tuberculata* and *Quickia consica* individuals reflect significant hydric conditions (probable irrigation) and more developed soils. C*oilostele issili* an*d Allopeas gracilis* individuals indicate vegetated soils but they can also have been encountered in secondary position, after burrowing. Last, the presence of *Zootecus insularis* and *Pupoides cenopictus* point towards dry and contrasting conditions, even if the total amount of individual and its exponential increase in this stratum indicate favorable conditions to the development of these species.

5. Interpretation and discussion

5.1. Sediment sources and site formation processes

5.1.1. Characterization of the depositional system based on sedimentary signatures, micromorphology and magnetic susceptibility

Sedimentary data, micromorphological observations (grading, inclusions, mineralogy, maximum grain size), (grain size analysis), and magnetic susceptibility values reveal that: (1) Nearly all the deposits contain material from local sources with particles larger than 200 µm. Moreover, many of them present traces of grading. Therefore, the stratigraphy at Manaqi is composed of fluvially re-deposited material. (2) Two mineralogical facies were identified. The first one is composed of schists, limestone grains, quartz (semi-angular, angular, rounded), pyroxene and serpentine, whereas the second is dominated by quartz (rounded, semi-rounded), limestone grains, with inclusions of cherts, glauconite, epidote and micas (Fig 8 and Supplementary Material 4). (3) All the deposits have a loamy texture but a higher content in coarse silt (20-50 µm) was noticed in the upper part of the profile (SU 11 and above). (4) Magnetic Susceptibility values on reference samples show two clear trends with values below 40 (10^{-5}SI) (cemented conglomerate, limestone cobbles) and values above 40 (10^{-5}SI) (surface pockets of sand/loam, possible serpentine cobble) (Table 5). In TP1, low values of magnetic susceptibility are linked to the first mineralogical facies, whereas higher values are connected to the second one (Fig 8). Moreover, these higher values of magnetic susceptibility are linked with a higher content in coarse silt (20-50 µm). Based on these results, as well as the weak soil development in TP1 and the absence of in situ burning which could explain high magnetic susceptibility values, magnetic susceptibility was considered as a marker of detritism and sediment origin.

Based on these observations, three types of site formation processes were defined and are presented Table 7.
TYPE 1- fluvial remobilization of loam composed of schists, angular to rounded quartz and limestone from Terrace T1. Based on the mineralogical assemblage and low Magnetic Susceptibility values, these deposits mainly originate from the weathered Terrace T1 and geological outcrops.
TYPE 2- Fluvial remobilization of silt, sandy and sandy clay loam, composed of rounded and semi-rounded quartz, limestone, occasional micas and glaucony and rare schists, from Terrace T1. The siltier texture of the deposits, the decreasing amount of material supplied by erosion of local sources and higher magnetic susceptibility values, very different from the local geological material (Terrace T1 and outcrops), raises the question of a new sediment input. The first hypothesis is that this input could originate from a localized area on the ancient Pleistocene conglomerate (Terrace T1), which, as a reminder, corresponds to an ancient fluvial point bar. For instance, the finer texture of the deposits could correspond to the "recycling" of cemented loess or finer alluvial deposits. However, if that was the case, we would expect to encounter cemented and

carbonated soil aggregates in the deposits, as well as other particles which could explain the higher magnetic susceptibility values, such as serpentine, which is not the case.

The second hypothesis is that these deposits correspond to voluntarily removed sediments for agricultural purposes. In Rustaq however, there are no easily accessible sources of fine sediment which could have been removed by people for agricultural purposes, as most superficial landforms are composed of weathered bedrock or cemented conglomerates with a carbonated matrix.

The third hypothesis is that these deposits have an exogenous origin and were deposited on Terrace T1 at a later period of time, similarly to the loose pockets of sediments identified in many places on the ridge. Based on the texture of the deposits and because they can't have a fluvial origin, we put forward the hypothesis that they correspond to wind transported dust, even if we are aware that further analyses should be conducted on dust transportation and deposition in the area (eg. Lucke et al., 2019 c). This hypothesis is also supported by the fact that the thickness and spatial distribution of the fine deposits in Manaqi can hardly be explained by the only erosion of the hard cemented conglomerate composing T1 and the weathered outcrops. Because the mineral assemblage we identified could have a local to micro-regional origin (at the scale of the watershed), we suggest an important remobilization of wadi material by winds. The T1 topography, terrace walls as well as a denser vegetation cover could have locally reduced wind intensity and created a trap for these particles (Lucke et al., 2019c).

TYPE 3- scree deposits composed of weathered ophiolite. The latter clearly separate the upper part of the profile (SU 11 to 16) from the lower one (SU 1 to 8).

TYPE	Texture	Grading	Inclusions	Magnetic susceptibility (10^{-5} SI)	Mineralogical assemblage -dominant	Depositional process	Interpretation	Status of the runoff-collection system	SU
1	Loam	Yes	None	< 40 SI	Schists	Fluvial	Material supplied by erosion of local sources : weathered Terrace T1 and geological outcrop	Well-functioning with controlled flood / uncontrolled low-energy fluvial process	4,5, 8
	Loam	No	Medium to coarse gravel	< 40 SI	Schists	Fluvial	Material supplied by erosion of local sources : weathered Terrace T1 and geological outcrop	Well-functioning with uncontrolled flood / abandoned system	2, 6, 16
	Silt loam	No	None	< 40 SI	Limestone	Fluvial	Material supplied by erosion of geological outcrop	Well-functioning / uncontrolled very low-energy fluvial process and water stagnation	7
2	Sandy loam to silt loam	No	Fine to medium gravel	[50-90 SI]	Limestone, occasional schists	Fluvial	Material supplied by erosion of local sources and aeolian/dust particles deposited in the catchment	Well-functioning with bioturbation or ploughing / well-functioning with uncontrolled flood / abandoned system	12, 13 high, 14, 15
	Sandy clay loam	No	None	[70-90 SI]	Glaucony / micas, limestone	Fluvial/aeolian	Material supplied by erosion of aeolian/dust particles deposited in the catchment and/or *in situ* deposition	Well-functioning with controlled flood or stone removal / uncontrolled low-energy fluvial process	11, 13low
3	Loam	No	Fine and medium gravel	< 40 SI	Local ophiolithe	Colluvium	Material supplied by erosion of local sources => Scree deposition	Abandonment	9, 10

Table 7. Classification of sediment origin and depositional processes based on sedimentary signatures, mineralogy and magnetic susceptibility

5.1.2. Diachronic evolution of sediment sources and site formation processes

Based on this typology, we propose a diachronic and local model of site formation processes (Table 7, Fig 12). The model combines phases of remobilization and deposition of pockets of loam interspersed with phases of weak soil development.

Phase 1 corresponds to the Pleistocene substratum (SU 1). No sediments are preserved between this period and the 8^{th} c. BCE. *Phase 2* corresponds to the fluvial deposition of loam eroded from Terrace T1 and the geological outcrops between the 8^{th} and 4^{th} c. BCE (SU 2 to 8, Type 1). This phase is initially characterized by a very low energy fluvial sedimentation maybe even associated with localized and temporary water stagnation as suggested by the prismatic structure, closed vughs and iron features of some deposits (SU 7). Laterally, the occurrence of massive loam indicates possible uncontrolled flow (SU 2). This is followed by a well-functioning runoff-collection system (SU 4, 5, 8,) alternating with periods of temporary abandonment (SU 6). *Phase 3* corresponds to the deposition of scree deposits (SU 9 and 10, Type 3). The localized sediments probably protected the underlying sediments from gullying processes and clearly indicate that the system was not in use.

Phase 4 and 5 are mainly characterized by an evolution in the mineralogical assemblage (SU 11, 12 and 13 low, Type 2), chronologically framed between the 4-2^{nd} c. BCE and the 8-10^{th} century CE. It is highly probable that the local sediment source (loam and schists) identified at the bottom of the profile had probably dried up or that thick pockets of sandy loam were available and erodible in the watershed. Indeed, well-sorted sandy clay loam rich in glauconite and micas, lighter in color, and with a high magnetic susceptibility, probably indicate an increasing aeolian- dust input, fluvially re-deposited from the catchment and/or deposited *in situ*. Controlled flooding, stone removals or the adding of ashes could also explain the fine texture of the sediments. During this time span, periods of agricultural activity are recorded (SU 11 and 13 low) as well as period of uncontrolled flooding (SU 12). Erosion probably occurred and would explain the total absence of deposits dated from the PreIslamic and Sassanian period (Fig 12, Phase 5).

Phase 6, 7 and 8 are characterized by deposits with lower magnetic susceptibility values and a higher input in local material (limestone particles) (SU 13 high, 14 and 15, Type 2). This could indicate a progressive drying up of the aeolian-dust sedimentary input and an increasing contribution of local weathered sediments after the

8th-10th c. CE. The recurrent inclusion of gravel in the deposits probably results from ploughing and bioturbation processes but raises the question of uncontrolled flooding events and gullying in between episodes of agricultural development. The abrupt sedimentary boundary between SU 13high and SU 14, dated from the 17-18th c. CE (Phase 7), comforts this idea of flash flooding and soil removal as a result of the abandonment of terracing. Soils were abandoned in the middle of the 20th century. Deflation, gullying and local aeolian/dust sedimentation are ongoing.

5.2. Function and management of the Manaqi runoff system

The results obtained in TP1 reveal a detailed history of local land use and environmental conditions structured around 8 phases (Fig 12). Five phases of land use (Phase 2, 4, 6 and 8), presented below, alternate with episodes for which we have no data, due to erosion or abandonment (Phase 1, 3, 5 and 7).

5.2.1. Runoff farming/grazing, humid conditions, and three-level vegetation cover (750-450 BCE, Iron Age II, Phase 2)

The first traces of runoff farming date from the Iron Age II/III, between 750-450 BCE. Two very different, temporary uses of the area are recorded. First, two plots of land (SU 4 and 5, Horizon 10 Ab1 and Ab2) delimitated to the north by a wall and separated by a small ridge (SU3, Hz 11C1), seem to have been in use at the same time. Partially preserved grading reflects regular sedimentation but a weakly developed or temporary land use. Soil pedoclimate indicates wet conditions. The close contact with the cemented T2 substratum could have favored the existence of ephemeral groundwater. The vegetation cover seems composed of an upper layer incorporating both Arecaceae and ligneous species, and a grassy layer, implying sufficient sunlight reached the ground. Interestingly, more Poaceae, ligneous and *Melanoides tuberculata* species were recorded in SU4 than 5. This indicates that the area was probably used for agricultural purposes more than for grazing. Charcoal, dung, burnt dung and burnt soil aggregates indicate crop-livestock interaction strategies probably combining herding and food crops. The second phase of runoff farming dated from the same period suggests a rapid shift in agricultural practices (SU 8, Hz 8Ab). Indeed, the levelling of the small ridge (SU 3) separating the two previous distinct plots (SU 4 and 5), suggests a process of land reorganization. The vegetation cover evolved rapidly. The grass silica short cells phytoliths (GSSCP) are more abundant (12%) and diversified, indicating a denser grass layer. The crenate GSSCP identified in SU8 and produced by the Pooideae subfamily, may be the signal of cultivation crops such as barley or wheat. Charcoal of *Acacia* sp. and *Ziziphus spina-christi* charcoal, support the idea of more open vegetation cover. The presence of slaking crusts and numerous juvenile *Melania Tuberculata* reflect a shift towards drier pedoclimatic conditions. The presence of dung also suggests husbandry and raises the hypothesis of local grazing.

5.2.2. Runoff farming, dry conditions, fruit tree production (350-200 BCE, Late Pre-Islamic Period, Phase 4)

The cultivated deposits (SU 11, Hz 6Apb) are bioturbated and present pedofeatures which indicate leaching processes. The evolution in their composition, with a probable increase in aeolian-dust input, probably provided new nutrients to the soils. Numerous jujube and one fragment of palm tree charcoal, as well as phytoliths of Arecaceae and dicotyledons, suggest the possible exploitation or cultivation of fruit trees for nutritional purposes, as is shown at several sites in the region on both coastal and hinterland sites (Tengberg and Lombard, 2001; Tengberg, 2002; Bellini et al., 2011; Kimiaie and Mc Corriston, 2014). It seems that farmers added plant ash and charcoal to the soil resulting from the possibly burnt trees and palm fronds. The presence of bone fragments and dung suggest the adding of animal manure, and the persistence of animal husbandry. Interestingly, the area appears to be more 'managed'. The crops grown suggest a possible early agricultural specialization, while the agricultural practices seem to evolve (i.e. ash dispersal in the fields, possibly as a fertilizer), even if they suggest the continued importance of herding in the agrosystem.

5.2.3. Runoff and floodwater farming, technological shifts and palm tree specialization (8^{th}-14^{th} C CE, Early-Middle Islamic period, Phase 6)

From a pedological and agricultural standpoint, we include both SU13low and 13high in this phase (Hz 4Apb1, Hz 4Apb2). SU 13low, composed of fluvially re-deposited local and probable aeolian-dust particles, was probably exploited between the 8^{th} and 10^{th} C CE, while SU 13 high seems to have been in use between the 13-14^{th} C CE. In these deposits palm morphotypes are dominant, while the absence of Poaceae suggests densified vegetation cover as early as the 8^{th} C CE, which is confirmed by the malacological corpus. The totally mixed matrix, numerous pellets and pedofeatures indicate well-developed soil bioturbation under wetter conditions, which may be due to irrigation or additional water supply. Numerous rounded particles of charcoal and plant ashes reflect the persistence of burning practices, likely utilizing palm leaves. Dung was identified, and this is probably due to the need to increase the organic content of the soil.

This phase of farming reveals an increasing management of the area towards a potential focus on palm tree production. However, it is necessary to mention that palm trees require a high amount of water. This implies increasing rainfall locally favoring runoff events and/or water input from a different source. An open air canal identified south of our area of study (Fig 3. B and C), which diverts water from the main wadi and channels it circa 1km towards the north, could have supplied Area 2 with the required additional water but not Area 1. Cisterns or wells could have been used. While this investment would have increased the agricultural potential of the area, its construction and management also involved cooperation between agricultural communities. It also infers that small-scale farming outside of core cultivated areas (here the central oasis of Rustaq) could have contributed to the socio-economic development of the town.

5.2.4. Later agriculture (> 17th c. CE, Late Islamic Period, Phase 8)

Unfortunately we were not able to securely date the final phase of the site occupation (Strata 14 and 15, Hz 3 Abp and 2Ap). Based on archaeological surveys, which revealed the existence of numerous smaller settlements dated from the 17th to 20th century and scattered within close proximity (Kennet et al., 2014), the last phase of agriculture is most likely to date to the Late Islamic Period. No paleoecological data were available for this phase but, despite the apparent sterility of the deposits, we know from local informants that the fields were cultivated during the 20th century CE. Physico-chemical data and soil micromorphology suggest leaching processes. Dung, plant ashes, bone and shell fragments represent well-developed manuring practices, with the persistence of animal and crop farming. While it remains unclear as to how the area was supplied with water during this time, alongside runoff water management and possible well extraction, we believe floodwater could still have supplied Area 2 of Manaqi.

Despite being a generally arid area, traces of runoff farming have been identified over the last three millennia at Manaqi (RBAS Site 02/20). We observe the evolution from a flexible opportunistic system, possibly combining agriculture and grazing, to a highly managed and anthropogenic one, possibly specializing in date palm production, which could have decreased the adaptability of farmers to external/internal constraints.

5.3. Insights into the socio-environmental significance and implications of runoff agriculture

The site of Manaqi provides a new dated record of runoff agriculture for the last three millennia in Oman. This natural landscape has been transformed into a highly anthropogenic one, continuously transformed by agricultural activity, during a harsh and unfavourable period for agricultural development outside localized oases supplied with underground water. In the Hajar mountains in Oman, sedimentary archives are extremely scarce and the only available ones often result from agricultural activity. The discovery of this long-term sedimentary and paleoenvironmental record raises a larger and challenging question on the equifinality of agricultural landscapes and mainly the diversity and scale of the triggering socio-environmental factors responsible for the development, intensification or abandonment of this practice.

Agricultural activity occurred in Manaqi during a well-attested period of macro-regional aridification (Lückge et al., 2001). Climate reconstructions, and mainly the study of speleothems, provide means regional paleoclimatic trends which are difficult to correlate with archaeological data. The study of terrestrial archives can provide the missing link between climate change and human occupation, however caution should be taken when studying agricultural areas, which are localized and anthropogenic landscapes. Indeed, more than on mean climatic trends, the development of runoff agriculture is highly dependent on the local distribution, timing, amount and intensity of rainfall (Russel, 1995; Bruins, 1986), as well as the frequency of droughts (Bruins, 1986). For instance, without any average increase in rainfall, topography can allow for the concentration and channeling of water and sediments. Ethnographic studies (Avner, 2007) and experimental archaeology conducted in the Negev (eg. Evenari et al., 1982) indicate that opportunistic runoff agriculture, following significant rainfall, can provide food and grains to large agricultural communities for a couple of years in hyper arid areas that receive less than 85mm of precipitation per year. Even during periods of droughts, more runoff can be produced due to the variable intensity and duration of precipitation (Bruins, 1986) and small watersheds can even produce more runoff water than large ones (Shanan, 2000). Furthermore, recent research has revealed that signatures of increased sedimentation rates or sediment coarsening in agricultural deposits cannot be directly related to wetter hydro-climatic conditions but mainly to available sediment sources (Lucke et al., 2019c). Therefore, the development of runoff agriculture in Manaqi could just result from a combination of technological skills, topographic control and maximised orogenically-driven precipitation, with short-lived and fast-breaking storm cells providing temporary and easily exploitable water. The presence of aeolian dust in the agricultural deposits dated between the 4th C BCE to the 8th C CE could point toward increasingly dry regional conditions. Nonetheless, this could also indicate that agricultural communities were flexible and resilient, and adopted riskier strategies in areas where moister sources remained. To better assess the connection between runoff agriculture and climate change, diachronic hydrological modelling and further research on soil origin should definitely be pursued in agricultural areas and confronted, when possible, with off-site paleoenvironmental and paleoclimatic terrestrial records.

The development of agricultural strategies is also embedded in a cultural, socio-economic and external political framework, which includes regional trade and settlement pattern strategies (Bruins, 1986, 2012; Marston, 2012). Identifying the large-scale factors behind the local development of runoff farming is challenging. To date, the development and abandonment of this practice in Manaqi seems largely related to population growth/retraction and socio-economic systems. Between 750-450 BCE (Phase 2), the growth of crops, combining herding and possible grazing, is in accordance with local and regional archaeological data indicating settlement intensification in different ecotones, shortly after 1000 BCE (Benoist, 2000; Magee, 2007; Cremaschi et al., 2018 ; Kennet et al., 2016). The availability of labour and the increased demand for food created by a larger population could explain the development of this practice. During the Early Islamic Period, between the 8-14thC CE (Phase 6), the agricultural expansion, intensification and specialization in Manaqi is recorded with the exclusive production of dates and a widespread use of ash, probably from burning palm leafs. The development of a substantial settlement and agricultural area just south of our area of study (Fig 1.B), diverting wadi flow and connected to Area 2, would have allowed farmers to increase crop production and water supply for palm trees. After the 17thC CE (Phase 8), traces of occupation increase exponentially around Rustaq and at the regional scale (Kennet et al., 2016) with the establishment of large agricultural estates (Mershen, 2001) which produced and exported dates to India (Power and Sheehan, 2012). In Manaqi, information regarding the agrosystem is lacking, however, we know that farmers had fields and herds during this time.

In contrast and clearly underlining the issue of equifinality, traces of runoff agriculture are also recorded during periods of reduced regional occupation. Between 350-200 BCE (Phase 4), local cultivators in Manaqi were probably growing fruit trees and manured their fields. This new record of occupation during the Late Pre-Islamic period is important, since archaeological data at Rustaq (and elsewhere in the region) indicate only low levels of occupation between c. 300 BCE and 300 CE (Kennet et al., 2016). Manaqi could have sustained small-scale rural livelihoods (not easily visible in the traditional archaeological record) during gradually harsher conditions and socio-economic unbalance. Farmer could have taken advantage of an already existing agricultural landscape, exploiting available sediments trapped behind ancient agricultural structures (eg. Mayerson, 1960).

The four periods of abandonment recorded in Manaqi between 450-350 BCE (Phase 3), the 2^{nd} – 8^{th} C BCE (Phase 5), the 14^{th}-16^{th}C CE (Phase 7) and after the 1960’s are clearly related to periods of settlement shifts and decline, as well as socio-economic changes. This is the case at the end of Iron Age II (after 600 BCE), with the decline in settlement intensity over much of southeast Arabia (including Rustaq) possibly as a result of regional decreasing resources (eg. Córdoba, 2013) and/or conflicts between groups (eg. Benoist, 2000). Similarly, the almost millennia-long abandonment of Manaqi between the 2^{nd} C BCE- 8^{th} C CE is in accordance with relatively little evidence for local and regional settlement (Kennet et al., 2016) while the abandonment of runoff agriculture between the 14^{th}-16^{th}C CE occurs during a shift in the political power with the economic development of the Omani coasts at the expense of mountainous areas. Last, the abandonment of Manaqi after the 1960’s probably results from an economic shift linked to the introduction of pumps and a technological change towards groundwater extraction nearer the coast.

6- Conclusions

The study of the agricultural area of Manaqi (RBAS Site 02/20) in Oman is one of the first to provide information on the formation and function of a runoff system in southeast Arabia. Information on cycles of land use, erosion and abandonment are provided from the Iron Age until the present day, i.e. the last three millennia, based on the integrated study of one pedo-sedimentary archive. Five phases of soil use are recorded between the 750-450 BCE (Iron Age II), 350-200 BCE (Early Pre-Islamic Period), the 8-10^{th}C CE and 13^{th}-14^{th}C CE (Early/Middle Islamic period) and after the 17^{th} C CE (late Islamic period). Four phases of abandonment and/or erosion, characterized by scree deposition or gullying, are recorded between 450-350 CE (Iron Age III), the 2^{nd}C BCE to the 8^{th}C CE (Late Pre-Islamic, Sasanian Period), discretely between the 11-12^{th}C CE (Middle Islamic Period), and the 14-16^{th}C CE (Middle Islamic Period). How typical this development is of the region or even of the Rustaq area itself is still to be determined. While this paper provides new data on water, crops and soil management, it also provides new data on the durability of runoff farming. We can highlight the following key points:

1- Runoff farming in Manaqi (Rustaq, Oman) has relied, for the last three millennia, on the persistence of a system of production combining crops and husbandry. Some evidence is provided for the existence of grazing during the Iron Age.

2- Soil weathering on the slopes of the catchment combined with probable aeolian-dust deposition, as well as maximized origenically-driven precipitation, have allowed for the successful long-term use of this agricultural practice, independently from regional climatic trends. While off-site terrestrial archives are definitely needed to contextualize archaeological and agricultural records, diachronic hydrological modelling and further research should be conducted on soil origin which might be the key to better discuss climate as a driving factor of agricultural durability.

3- Locally, diversification has decreased through time. While early agricultural practices were diversified and temporary in Manaqi (Iron Age with three levels of vegetation and the Late Pre-Islamic period with fruit tree production), we witness a progressive specialization starting around the 9thC CE (Islamic Period) (i.e. date palm production with ash dispersal). The investment in larger hydraulic systems allowed for higher yields but probably reduced the flexibility of farmers while increasing their vulnerability to hydro-climatic and socio-economic changes. At the same time, it needs to be remembered that these data come from one (relatively) small and specific area and may not reflect broader trends.

4- In many cases the development of farming as mapped out here follows established regional patterns of settlement intensification and decline, suggesting that the exploitation of areas for runoff farming is something that occurs in periods of economic growth.

5- As such, evidence of runoff farming under dry (i.e. contemporary) conditions highlights the potential of the region to sustain small-scale farming near the mountain front. At a wider regional scale, the evidence presented here suggests that the sustainable management of field terraces has the potential to provide a range of benefits to the landscape through increased land stability and rainwater retention. These may, in turn, help to increase regional biodiversity and mitigate flooding through a reduction in overland flow. Given current concerns over biodiversity losses and extreme weather events, these issues should be focused upon in future investigations.

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L. Purdue et al. : Ancient agriculture in Southeast Arabia: A three thousand year record of runoff farming from central Oman (Rustaq)

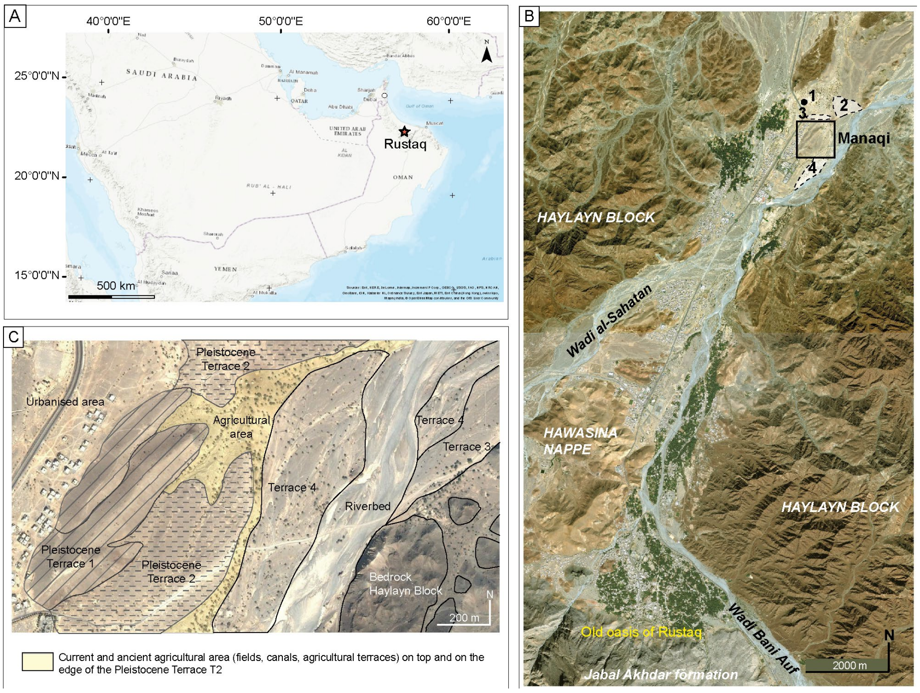

Fig. 1. A. Location of Rustaq, Oman; B. Geological background, location of the field system of Manaqi (RBAS Site 02/20) and close-by archaeological sites: 1- Umm al-Nar tower, cemetery and settlement (3rd Mil BCE); 2- Iron Age settlement (1000-300 BCE) composed of a circa 54 ha surface scatter of pottery and stone buildings; 3- Early and Middle Islamic cemeteries, structures and scattered remains (1000-300 BCE); 4- Early and Middle Islamic agricultural complex (9-12th C CE). C. Geomorphic context.

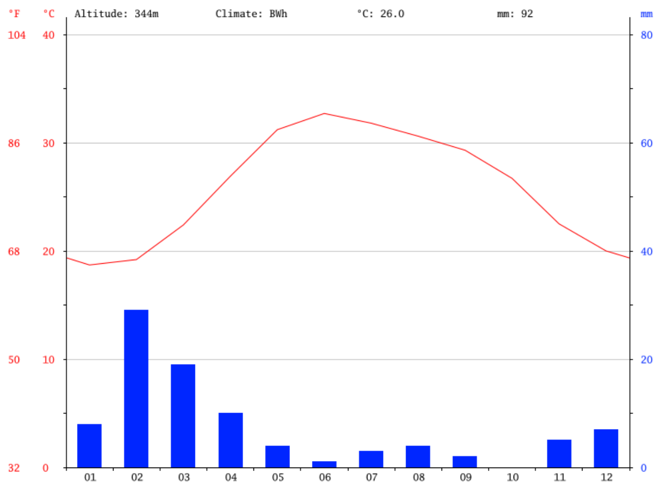

Fig. 2. Precipitation and temperature in Rustaq (Climate-data.org, between 1982-2012).

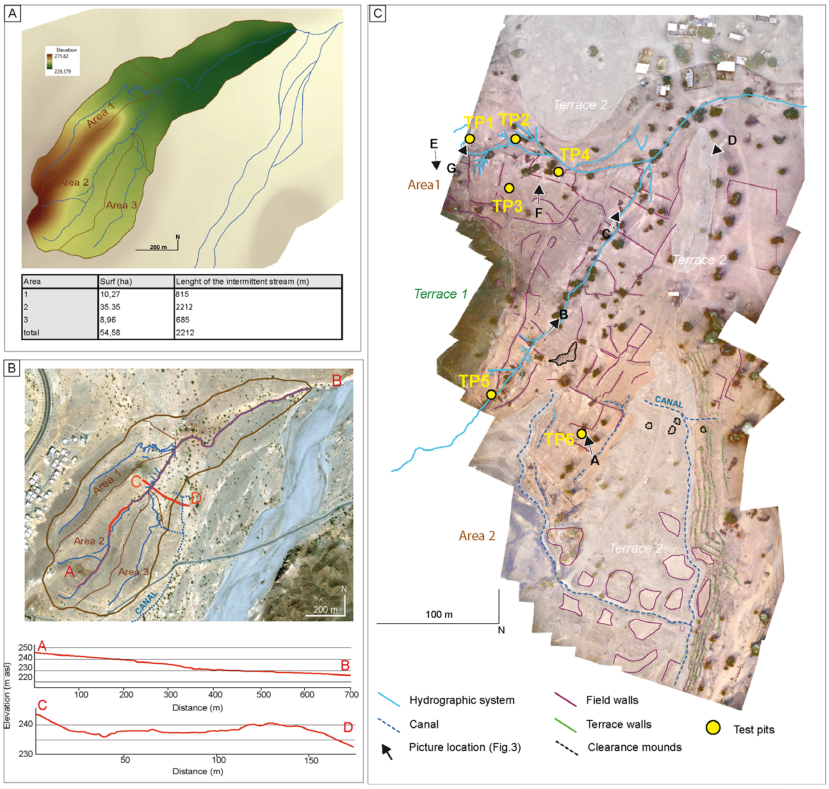

Fig. 3. A. DEM of Manaqi (RBAS Site 02/20) and properties of the 3 sub-catchment areas. B. Topographical profiles. C. Kite view of the runoff farming system of Manaqi with location of the abandoned structures and test pit studied.

Fig. 4. A. View from the South of Area 2 and geomorphic units (Terrace 1 and 2); B. View from the South of the exposed ophiolithic bedrock, C.View from the South of the erosion in Area 2, and the natural exposure of buried walls; D. Zoom on the cemented T2 terrace, E. View from the North West of Area 1 and shallow terraces; F. View from the south of the downstream section of Area 1 subject to active gullying. Location of TP1 and TP4; G. View from the south of the natural exposure of TP1 prior to its excavation with a backhoe.

Fig. 5. A. View from West of the base of the TP1 and lower fields; B. View from the North West of the wall dug into Terrace T2 and lower fields; C. View from the South of the upper part of TP1. Note the clear color and textural shift between SU 9/10 and SU11.

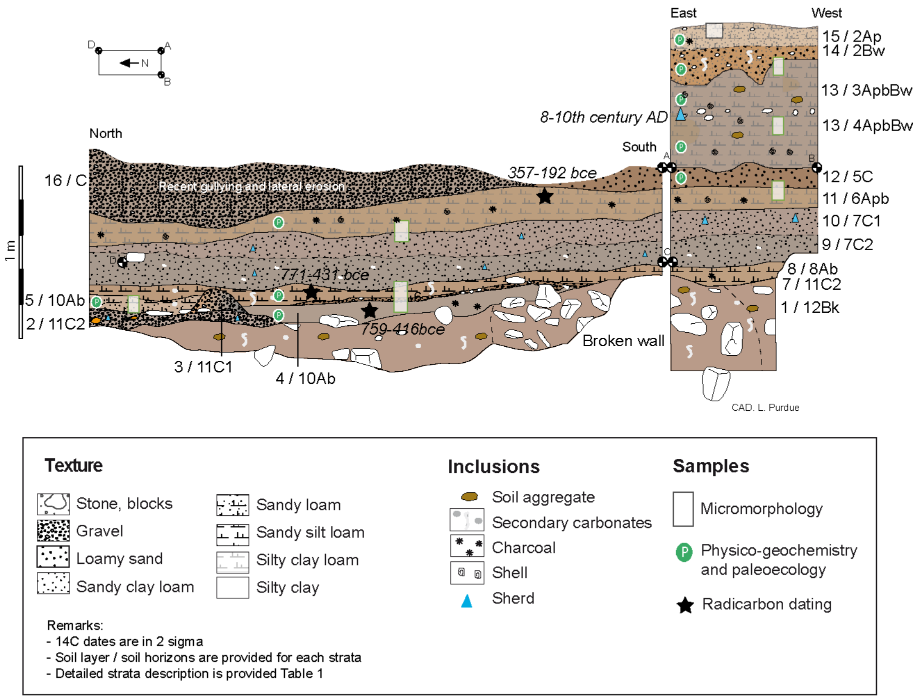

Fig. 6. Lithostratigraphy of TP1 including sedimentological units and soil profiles, with chronology and location of the samples studied

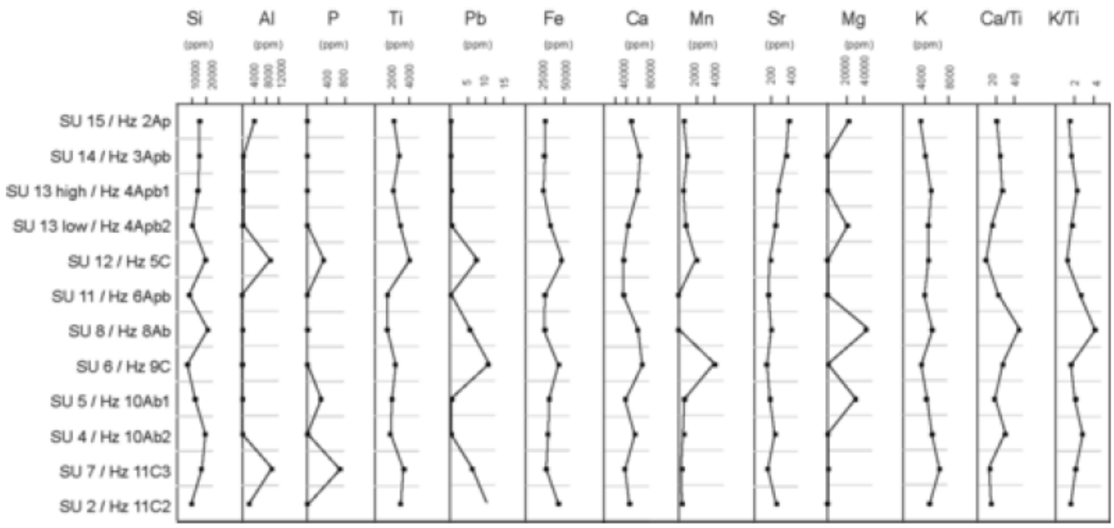

Fig.7. Results of the geochemical study in TP1

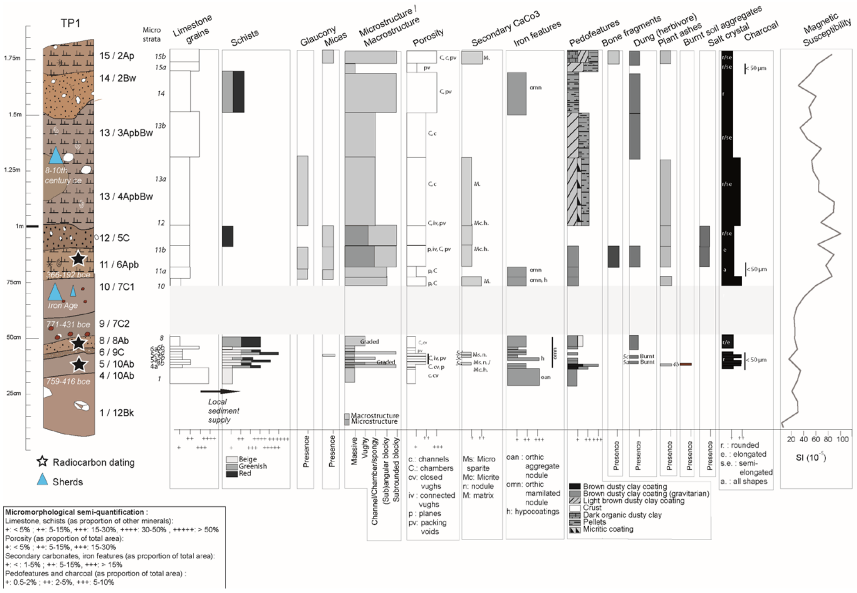

Fig.8. Results of the micromorphological study in TP1

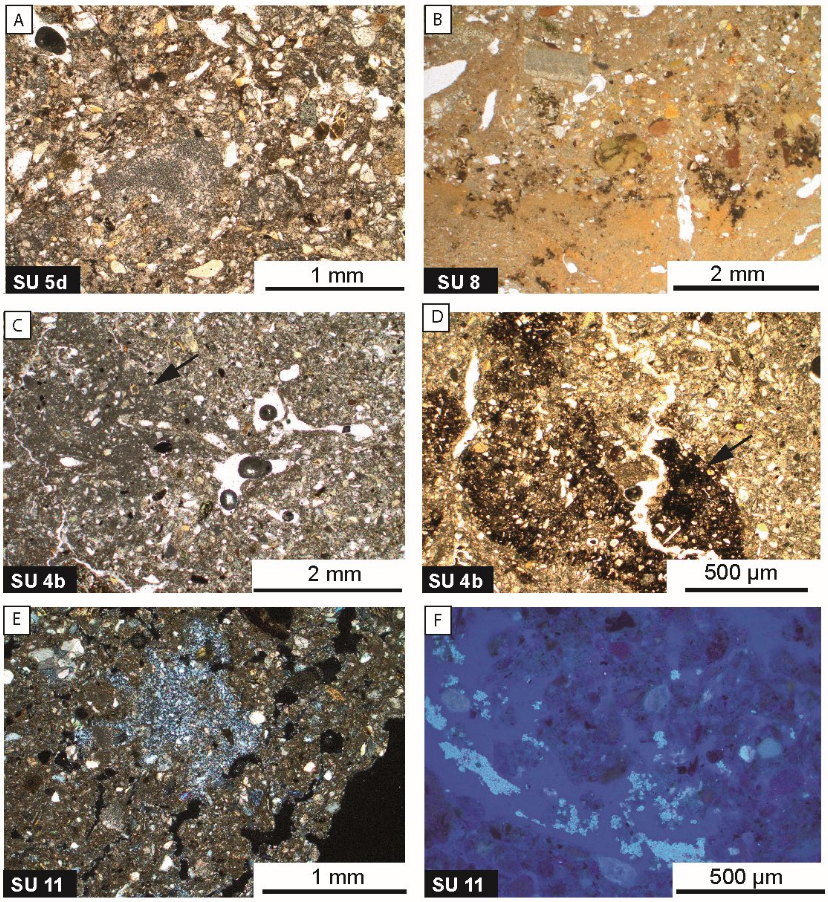

Fig. 9. Microphotographs of selected features in TP1. PPL : Plane polarized light, XPL: Cross polarized light, IL: Incident light, FL : Fluorescent light. A – General observation of the petrographic assemblage typical of the lower sedimentological units schists, quartz, and limestone (XPL), B- Micritic to microsparitic infilling in the porosity (PPL); C- Traces of preserved grading and Femn impregnation in the suspension deposits (IL) ; D- Mixed carbonated (see arrow) and soil matrix, probably as a results of ash mixing in the soil (PPL); E- Burnt soil aggregate (see arrow) (PPL); F- Salt crystals in the porosity (XPL). Note the mineralogical facies with the absence of schists and increased content in rounded quartz grains; G- Phosphate infill in the porosity (FL); H – Charcoal particles and burnt organic matter (IL).

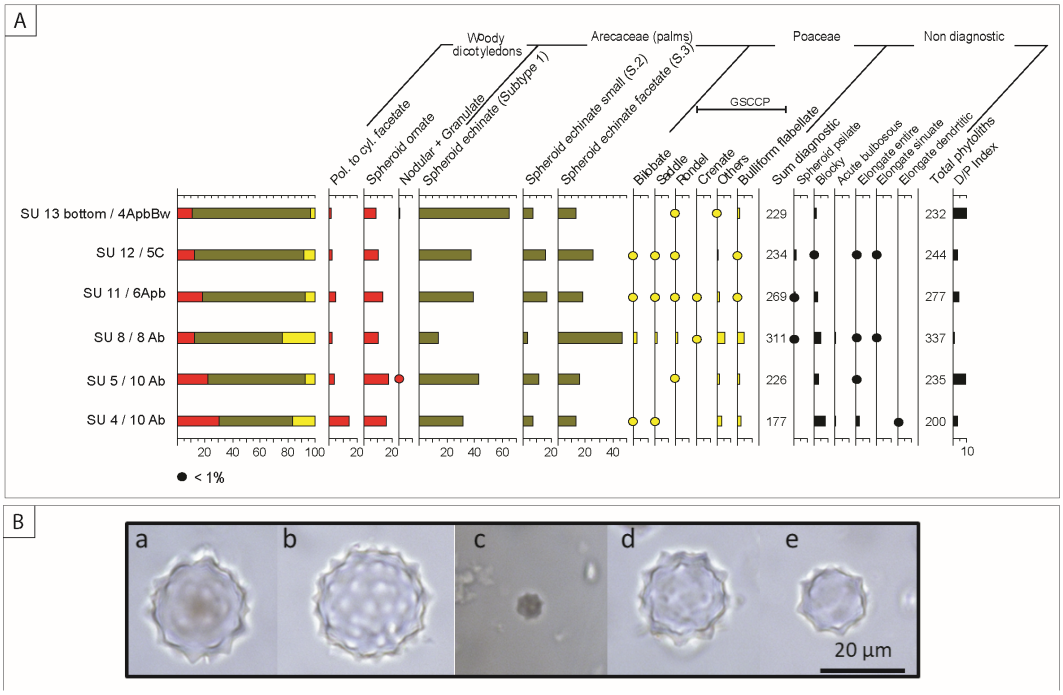

Fig. 10. A. Results of the phytolith study in TP1; B. Morphotypes produced by the Arecaceae family and identified in the samples, a-b: Spheroid echinate; c: Spheroid echinate small ; d-e: Spheroid echinate facetate.

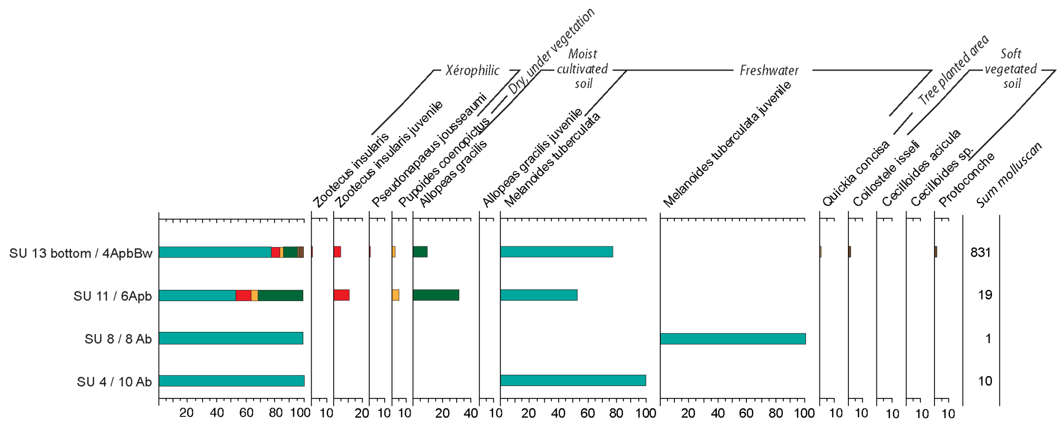

Fig. 11. Results of the shell study in TP1

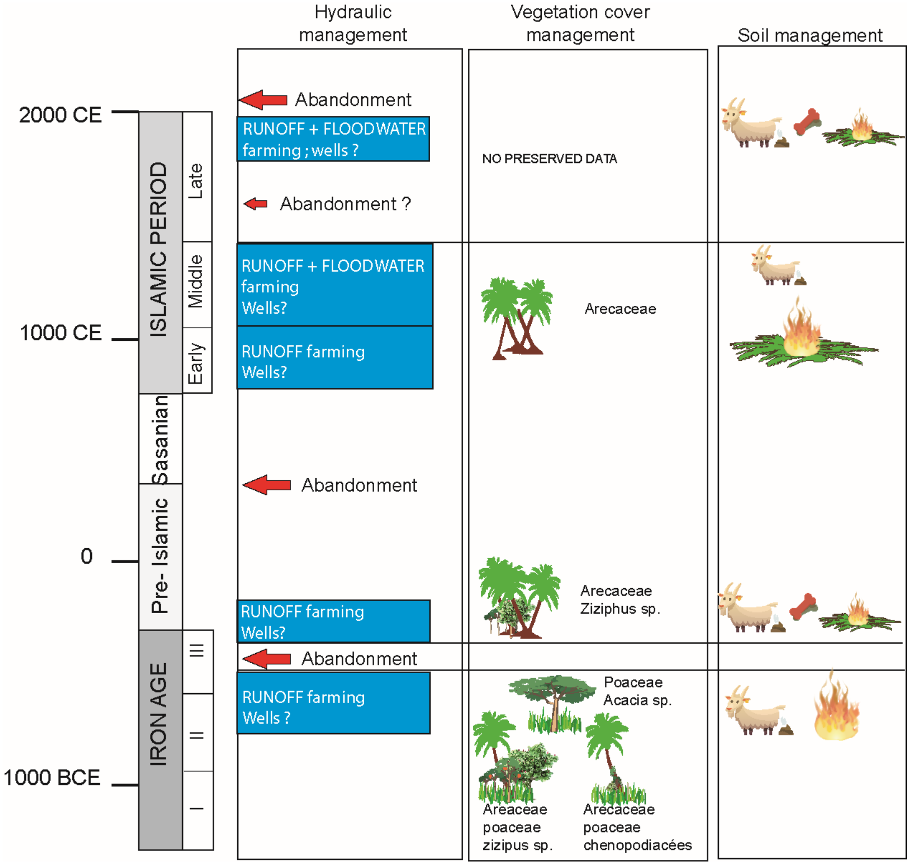

Fig. 12. Proposal of a synthetic hydro-agricultural evolution of Area 1 in Manaqi (RBAS Site 02/20)