Journal of Archaeological Science: Reports 41 (2022) 103302

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Relict olive trees at runoff agriculture remains in Wadi Zetan, Negev Desert, Israel

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A R T I C L E I N F O

Keywords:
Negev region
Landrace olive trees
Sustainable dryland agriculture
Runoff agriculture
Byzantine
Early Islamic

A B S T R A C T

Olive (*Olea europaea*) trees in the arid Negev Desert of southern Israel are important relicts on the ancient agricultural landscape. Among them are a cluster of several trees located in Wadi Zetan, at the heart of the Shivta horticulture terroir, with its abundant agricultural runoff remains. Two isolated olive bearing trees stand in a sheltered beneath cliff in the upper part of the wadi. Radiocarbon dating of an internal part of the trunk of one of these living trees estimates its minimum age as the mid-16th – early 17th century CE (~500 years old). Archaeological excavations conducted beneath the trees and the adjacent dam revealed OSL samples of loess accumulation dated to the Early Islamic period (8th-9th centuries CE). The stratigraphy and chronology of this sediment deposition indicate its rapid and short accumulation. Palynological analysis of the same OSL dated samples indicates that grapevines and olive trees were cultivated in the immediate vicinity of the site during the Early Islamic period. The lack of pollen of cultivated taxa from the latter part of the sequence points to cessation of the agricultural activity, probably a few hundred years later. Leaf samples for DNA profiling of the trees in comparison to other local old olive trees around the country, indicate that the trees in Wadi Zetan are genetically close to a known cultivar common among ancient olive trees. The trees have survived for at least a few hundred years, in an arid area, due to the local conditions and enhanced drainage from the man-made upper runoff system. These old olive trees bear a powerful and symbolic significance, indicating the endurance and sustainability of ancient desert runoff agriculture. Moreover, the survival of their relicts in Wadi Zetan suggests their potential as cultivars greater resilience to the harsh growing conditions of arid environments.

1. Introduction

The remains of ancient surface runoff agriculture constitute a key component in the cultural landscape of the Negev Desert. These remains include dams, water-harvesting channels and agricultural installations that together provide evidence of complex and intensive farming in an arid environment. This typical runoff agriculture began in the vicinity of Shivta, one of the iconic farming villages of the period, already in the Roman period (second–fourth centuries CE), and was gradually abandoned during the Early Islamic period (seventh–ninth centuries CE). During the Byzantine period (fourth-seventh centuries CE) the area saw major settlement momentum and extensive development of its agricultural hinterland. Not far from Shivta village, in a small and hidden dry riverbed in the upstream of Wadi Zetan, several old olive trees (*Olea*

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https://doi.org/10.1016/j.jasrep.2021.103302
Received 1 July 2021; Received in revised form 17 November 2021; Accepted 29 November 2021

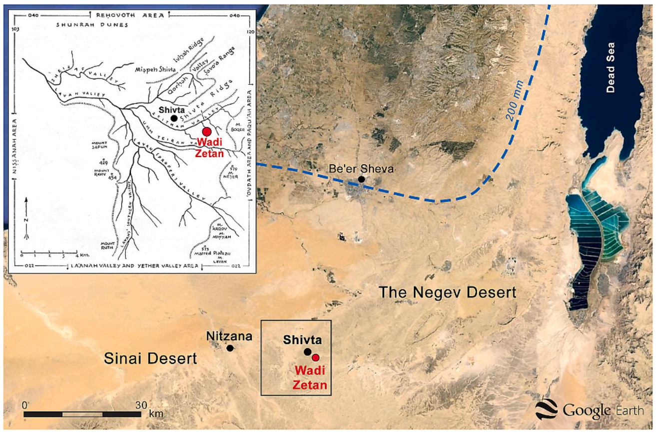

Fig. 1. Location map, the agricultural hinterland of Shivta and the Wadi Zetan site (after Kedar, 1957).

europaea) have survived to this day within the remnants of this ancient agricultural system (Fig. 1).

The olive trees in Wadi Zetan, which are among the last remnants of the ancient agricultural landscape in the region, continue to grow in this arid landscape and some of which are still bearing fruit, are the subject of the current research. These trees, which have survived outside the normal area of olive cultivation in the region, preserve a unique relict of the complex agricultural system that has allowed their endurance. The original centers of the trees are long-gone and they are estimated to be several centuries old. As such, they preserve a unique genetic fingerprint of heirloom olive cultivars adapted to a hot and arid environment.

In the framework of this research we studied the agricultural system in Wadi Zetan and the cultural history of the olive trees naturally thriving there, with the aim of determining their age and dating the agricultural system within which they have survived. To this end, we surveyed the system above the trees and excavated beneath them near the dam. We retrieved pollen samples from archaeological sections to assess the plant species that had presumably grown in the agricultural plots in the past. The age of the agricultural system was further determined optically stimulated luminescence (OSL) dating of the soil that had accumulated on both sides of the dam and under the roots of the trees. The minimal age of one of the trees was determined by radiocarbon dating of an internal part of the trunk. The results of our research provide important knowledge on the cultural history of these heirloom trees, and provide new insights into traditional and sustainable surface-runoff agriculture, with regard to the cultivation in arid regions of fruit trees in general and of olive trees in particular.

1.1. The culture of the olive in the Mediterranean basin and in arid regions

The wild olive tree, which originated in the Mediterranean region (Fig. 2), evolved over millennia along multiple historical pathways, as reflected in the numerous of varieties noted in both historical and modern-day records. It is an easily cultivated tree, well-adapted to harsh growing conditions (Fernández, 2014). Over the course of history, the olive became one of the most important crops in the Mediterranean basin, being both consumed as food and pressed for oil. Genetic analysis provides evidence of two scenarios: an initial, and primarily domestication, center in the northern Levant (Besnard et al., 2018): two independent domestication areas in the Mediterranean basin (Diez et al., 2015). The earliest archaeological, archaeobotanical and palynological evidence for the domestication of the olive in the Mediterranean Basin was found in the southern Levant and is dated to the fifth century BCE. Later, its cultivation spread westward to Greece, Italy and Spain, in a process that led to the development of a variety of cultivars with unique geographical affinities (Langgut et al., 2019).

During the first millennium CE increased demand for olive oil significantly influenced the commercial relationship between the East and the West. It is then when numerous olive presses are found throughout the Mediterranean Basin, many of which bear screw press, indicating the importance of oil production (Ayalon et al., 2009; Frankel, 2010). During that time a commercial hub for olive oil production peaked in Tripolitania in western Libya (Mattingly, 1988; Barker et al., 1996).

In the traditional agriculture of the Mediterranean basin, olive trees grow in marginal soils whose fertility is relatively low, usually on mountainous slopes that are unsuitable for other crops. In Israel, olive trees grow in all types of soil, wherever the multi-annual average rainfall is above 350 mm (Zohary et al., 2012). Drought is the main reason for a decline in olive tree growth and productivity (Ben-Gal et al., 2011).

In all the Mediterranean climate areas north of the Negev, archaeological research has documented numerous installations of oil production (Frankel et al., 1994), along with botanical remains (reviewed in Langgut et al., 2019) that demonstrate the production of olive oil over

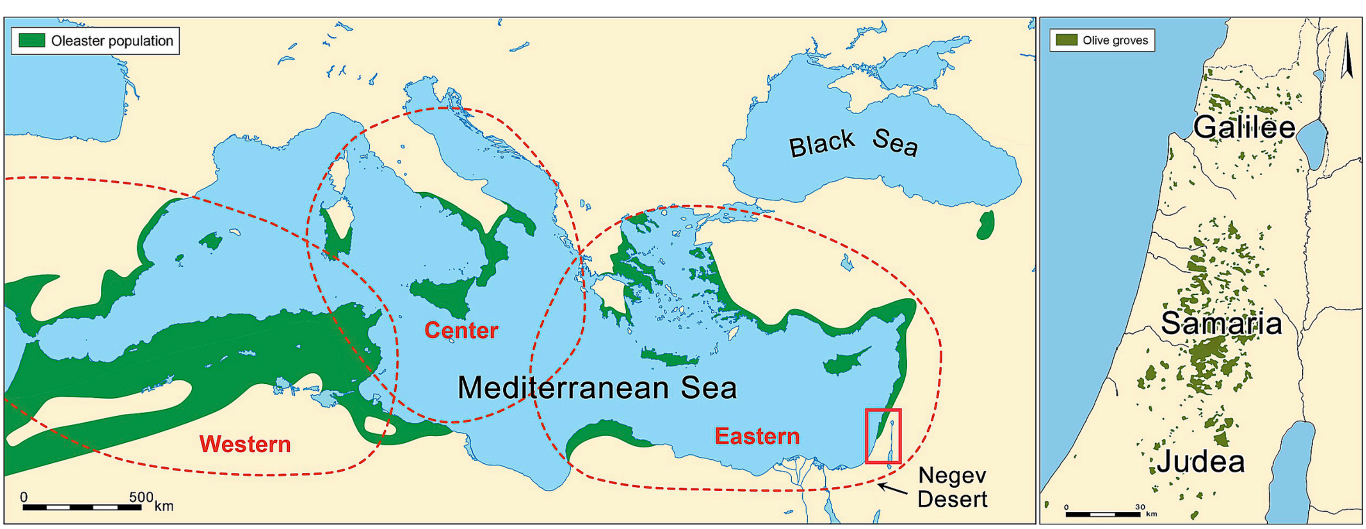

Fig. 2. A. Geographical distribution of genetically identifiable of *oleaster* around the eastern and western Mediterranean basin; the central circle indicates a high gene mixture of the two groups (Modified after: Lavee and Zohary, 2011); B. Distribution of traditional olive groves in the Land of Israel in 1935 (redrawn from: Frankel et al., 1994).

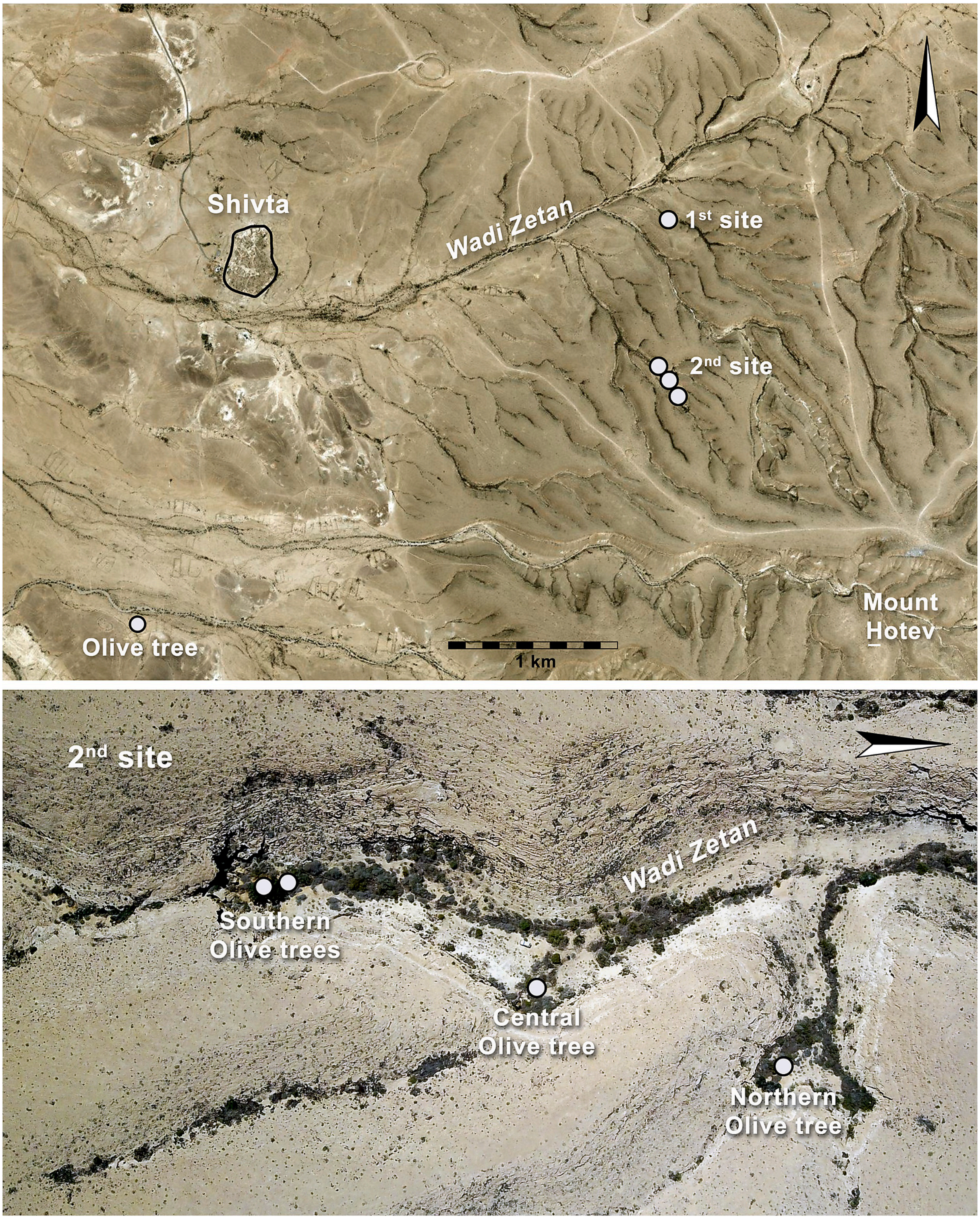

Fig. 3. Aerial photograph of the environs of the Shivta and Wadi Zetan olive tree sites (A). Drone photograph with location of olive trees at the 2nd site (B). (Photo: PZ).

long periods in these areas. In places where terroirs are optimal, olive trees may live for many years (Zohary et al., 2012:116). A mature olive tree has the unique ability to regenerate after traumatic conditions, such as abandonment, fire, deforestation, overgrazing and drought (Langgut et al., 2014). Determining the age of ancient olive trees, however, is complicated: dendrochronological tools cannot be used because the trees lack regular rings due to the irregular spread of the trunk or branches (Cherubini et al., 2013). The effective means of gauging the age of an olive tree is by radiocarbon dating of the root collar and inner parts of the hollow trunk. Using this approach, for example, revealed that the ancient olive trees in the Garden of Gethsemane in Jerusalem date from the Crusader period and are about 850 years old (Petruccelli et al., 2014).

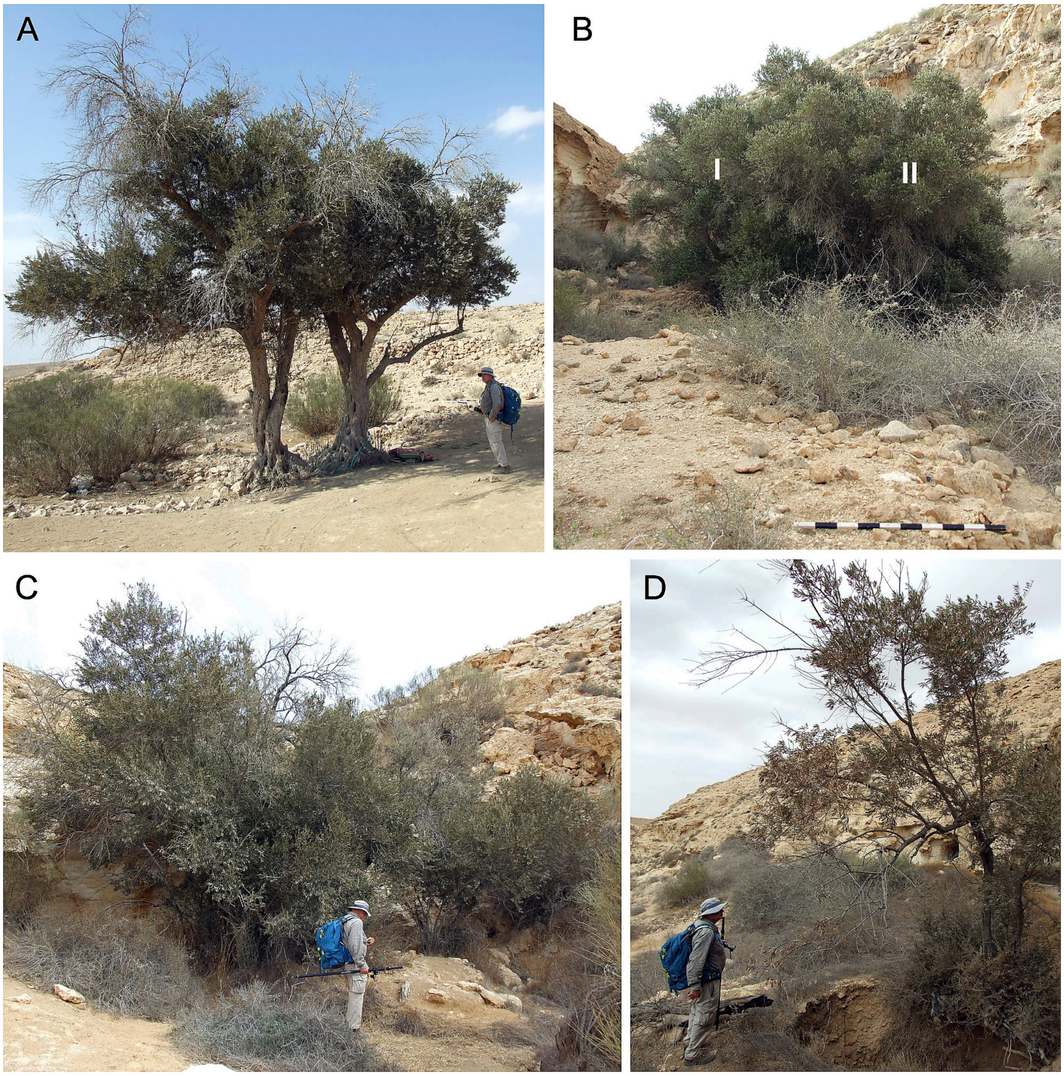

Fig. 4. The olive trees at Wadi Zetan: A- Tree at site 1. B-D- Trees at site 2: B. Southern olive trees (I and II). C. Northern olive tree. D. Central olive tree (photos: Yotam Tepper).

2. Olive trees and remnants of ancient agriculture in Wadi Zetan

The dry bed of Wadi Zetan runs from south-east to west near the ancient agricultural settlement of Shivta (347 m asl). The summers there are hot and dry and the winters are cold with little rainfall (a multi-annual average of less than 100 mm a year). The geological setting of the hinterland of Shivta and its unique capabilities to collect runoff is described in Wieler et al. (2016). The few rainy days in winter (less than10 days per year) usually feature heavy rain events. These conditions produce several floods each year, which sweep water and loess soil into the wadis. The magnitude of flooding events is seen by the rapid accumulation of silt at wadi bed (Ruth Shahack-Gross and Yohav Avni Personal communication, 2019; see also Lucke et al., 2019a). Such conditions were essential for the development of surface runoff agriculture in the area, which was based on the construction of agricultural systems that harvested soil and water from the slopes to the wadis. The dams built across the wadis allowed the soil and water to accumulate downstream. Around Shivta and Wadi Zetan, more than 500 ha of plots in which orchards and grapes were grown were documented in the wadi beds. On the slopes above the channels stone heaps and rows of raking strips can be seen, which were built to increase the runoff of soil and water and direct them into the wadis (recently reviewed in Avriel-Avni et al., 2019).

The agricultural system in Wadi Zetan and the hinterland of Shivta reached its zenith during the Byzantine period, when pigeon-towers were constructed adjacent to the agricultural fields and were used to raise pigeons for their manure, which provided an optimal fertilizer to improve the nutrient-poor loess soil. The system reached full synchronization in the Byzantine period and was operated optimally until being completely abandoned in the seventh century CE (Tepper et al., 2020). These early systems could still constitute a good foundation for sustainable agriculture in the modern era (Avriel-Avni et al., 2019).

The bed of Wadi Zetan, which drains the slope of Shivta from the north (449 m asl) and the ridge of Mount Hotev in the south (545 m asl) with a basin of c. 16 km^2 near Shivta from the watershed to its east (412 m asl), is rocky and drains on a west–south-west axis. In the eastern part of the wadi bed, along c. 2.5 km and in the tributaries that drain into it from the south and north, dozens of archaeological field structure installations have been documented. They include stone heaps, towers and a network of walls and dams in the wadi beds, as well as a number of farmhouses, cisterns and animal pens. Pottery was also documented, dating the agricultural hinterland of Shivta to the Late Roman, Byzantine, Early Islamic and Ottoman periods. Upstream, where the wadi becomes narrow and cliff-like, similar archaeological complexes have been documented, although, dating the sherds retrieved here were dated to the Late Roman and Byzantine periods (Baumgarten, 2004). It is at the

Fig. 5. The southern olive trees (I and II). A. Looking east. B. Looking north. Note the location of the trees, beneath the cliff shade (photos: Yotam Tepper).

foot of these cliffs, in the upper part of the agricultural system that is relatively protected from wind and sun and with a large drainage basin above it, that the olive trees grow.

The first written description regarding the presence of several olive trees in Wadi Zetan was provided by Woolley and Lawrence (1914:97), about 100 years ago. They described these olive trees as “stunted trees”, probably due to their small size. About six decades later, Yehuda Feliks, who examined one of the olive tree in Wadi Zetan, pointed out its large size and good condition and estimated its age as about 1,600 years old (Rotem, 1971). Ashkenazi et al. (2011) describes two sites in Wadi Zetan where olive trees grow (Fig. 3). In our reconnaissance of the Wadi Zetan trees, at the first site we identified a single olive tree next to a dam across

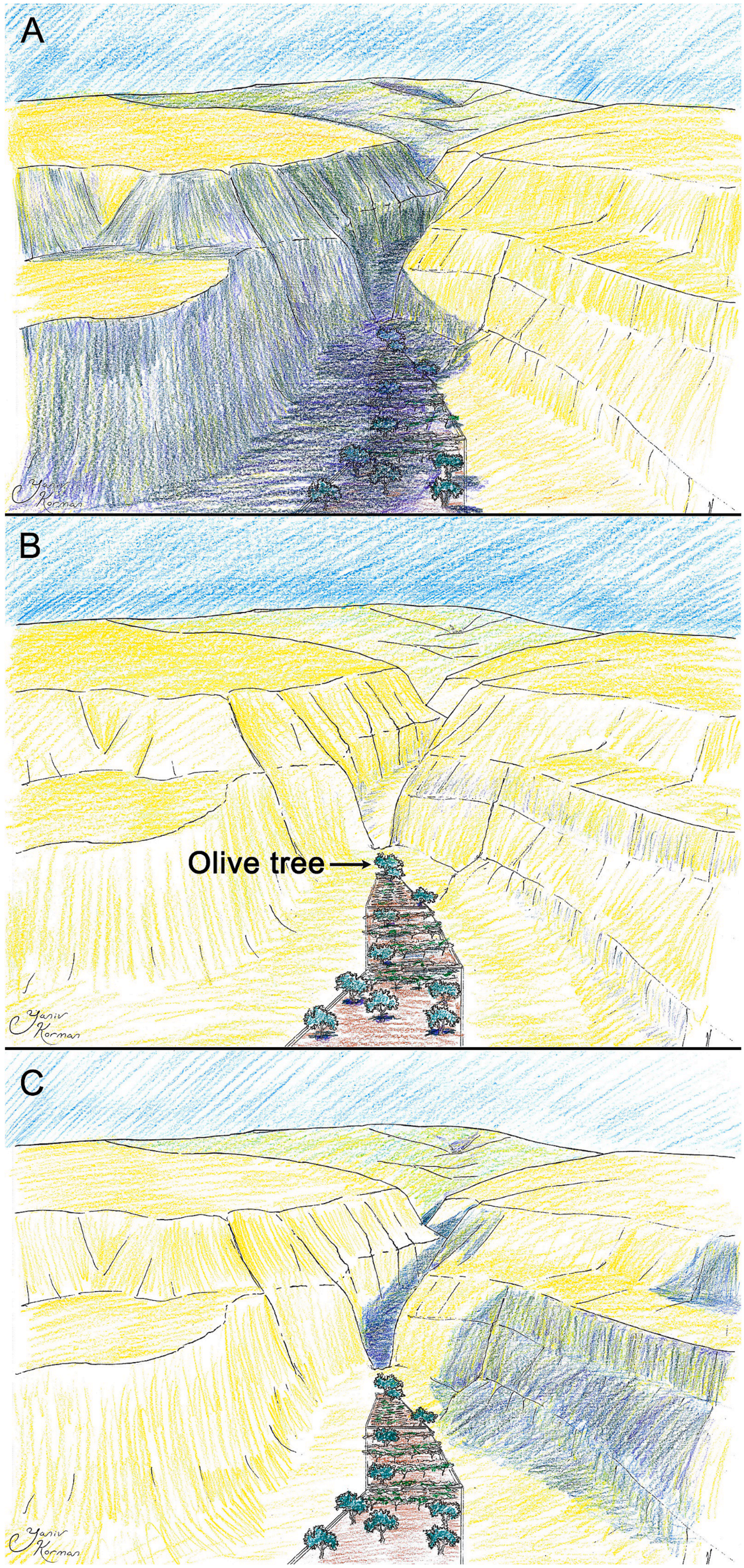

Fig. 6. Artisan reconstruction of the Wadi Zetan site, summer season- sunlight and shadow during the day: at 7 AM (A); at 12 PM (B); at 4 PM (C). See the black arrow pointing to the location of the two relic olive trees (drawing: Yaniv Korman).

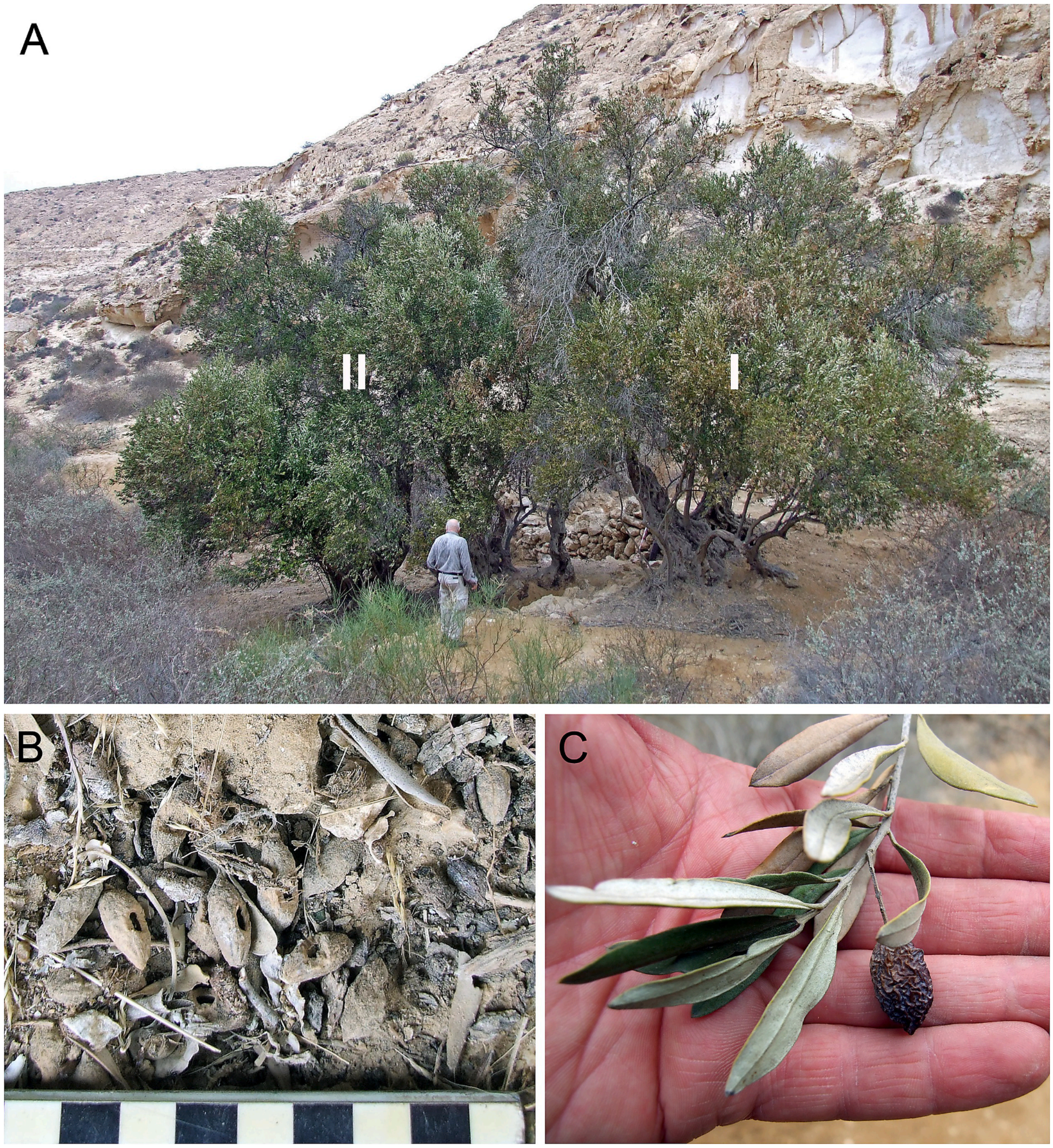

Fig. 7. Southern olive trees at Wadi Zetan. A. General view: the southern tree (I). The northern tree (II). B. Olive kernels under tree 2. C. Olive fruit from tree 1 (photo: Yotam Tepper).

a tributary in an early agricultural system that collects the surface runoff from about ca. 12 ha (Fig. 3: site 1; Fig. 4A). The size and shape of the tree indicate it has been relatively well preserved and it is an estimated as 4–5 m tall. At the second site (Fig. 3: site 2) four olive trees are known: two in the south (Fig. 4B), one in the north (Fig. 4C) and one in the center (Fig. 4D). All four trees are preserved and in good condition reach ca. 4–8 m in height, and growing above the walls of dams at the foot of a steep, rocky cliff. The two southern trees, on which our research focuses, are ca. 1 m apart (Fig. 4B, I-II). The trunk of the upper tree (no. I), has divided into two (total diameter 4 m): the eastern trunk is 1.7 m in diameter and the western trunk, 1.5 m in diameter. The lower tree (no. II), is divided into three trunks (total diameter 4.5 m): the diameter of the upper one is 1.7 m and the middle and lower ones are each 2 m.

The two olive trees in the southern group grow at the foot of a natural cliff in the upper part of the agricultural system (Fig. 5). A wall, 1.2 m wide, documented parallel to the wadi bed, delimits the trees on the north. Between the two trees is another wall, 1.5 m wide, built across the wadi. The two walls are constructed of large and medium-size fieldstones interspersed with a fill of small stones. These walls are part of the complex system of boundary walls and dams built downstream in the wadi and north of the trees. The dam walls of the system in within which the trees are growing are 10–20 m long and comprise of 8–10 courses, with 1–2 m of loess soil accumulating behind them. The downstream dams are surrounded by boundary walls that directed the soil and water into the agricultural plots, and also prevented people and animals from entering the plots. Additional, low lines of small size stones, seen on the spurs, divide the slopes and directed the soil and water runoff into several different lower plots, downstream.

Upstream, above the rocky cliff south of the trees, the topography is less steep and in this part of Wadi Zetan a relatively few, isolated, dams were found. These dams, which were built across the wadi bed without boundary walls between them, were all short (up to 7 m long, height 1–3 courses) with little accumulation of loess behind them (<than 0.5–1 m depth). Near the cliff, upstream and south of the trees, a square animal pen was also documented, built in the wadi bed. Along the slopes south of the cliff, a long wall (hundreds of meters long) was found that delimited the drainage basin of the trees. The wall was constructed of fieldstones laid along the watershed that bounds the drainage basin. In this area, soil and water were harvested during floods and directed toward the plots in which the olive trees are growing. The investment in

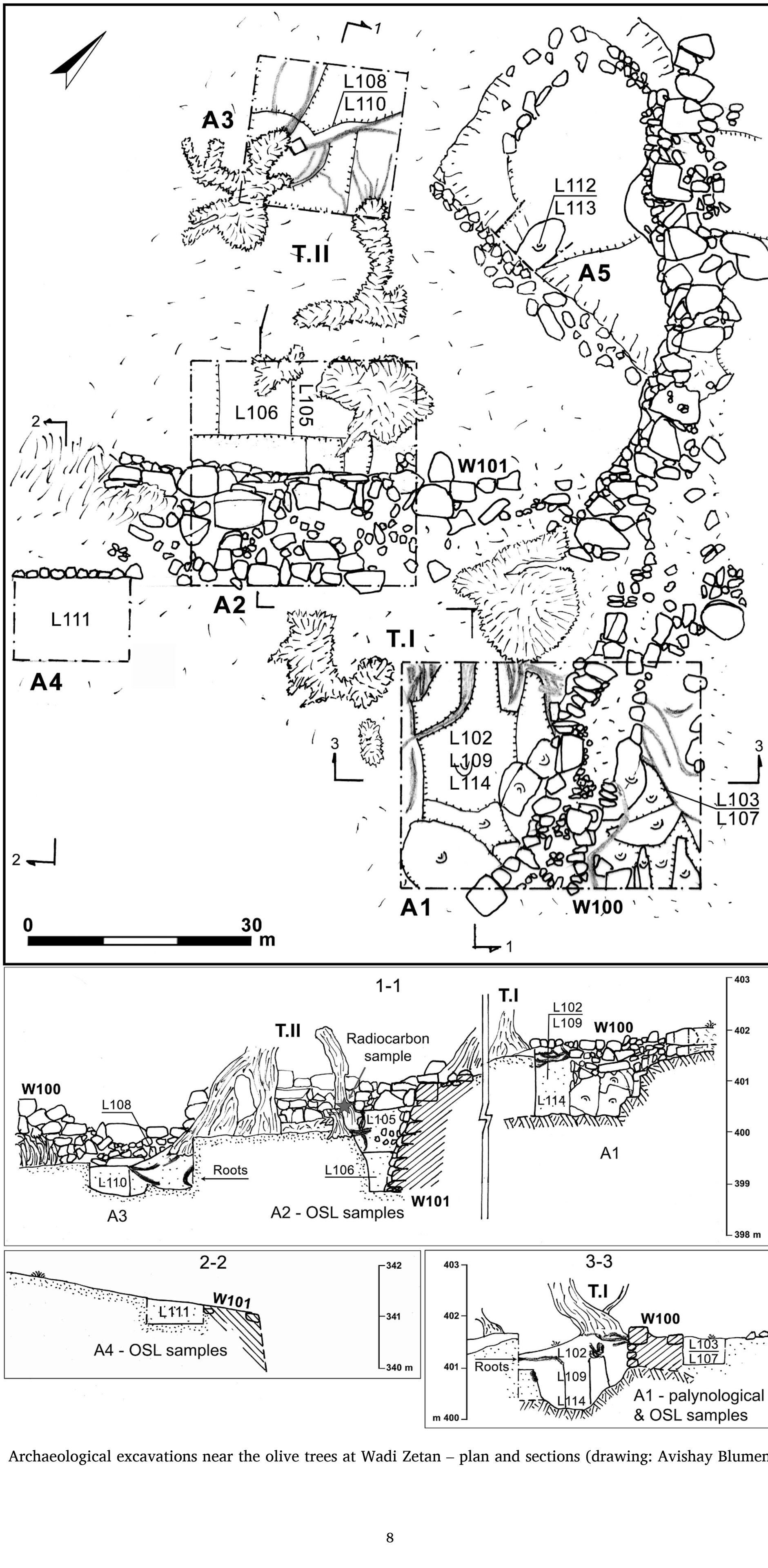

Fig. 8. Archaeological excavations near the olive trees at Wadi Zetan – plan and sections (drawing: Avishay Blumenkrantz).

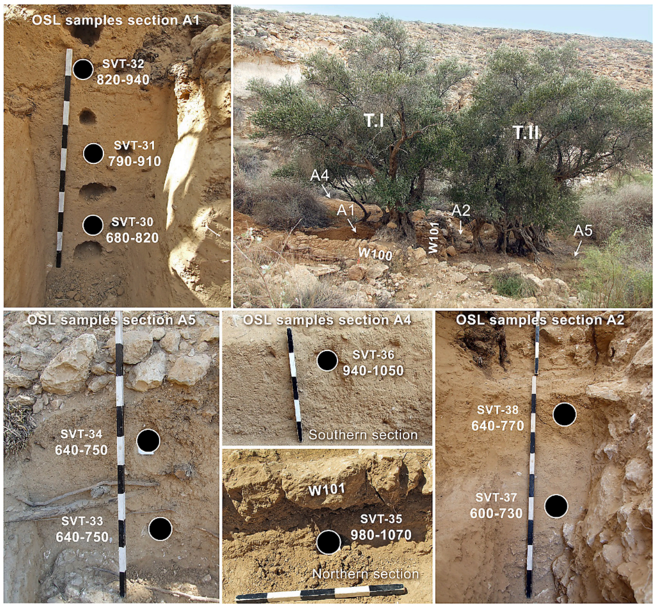

Fig. 9. Wedi Zetan: OSL samples from sections A1-A2; A4-A5 (note: samples for palynological analysis were taken from section A1; Photo: Yotam Tepper).

labor on the slopes and the construction of dams in the wadi bed are what have allowed the olive trees to survive under these arid conditions to this day. Of importance, however, is the specific location of these trees, in the cliff's shade, which provide them with unique environmental conditions compared to their immediately surroundings: during the hot summer season they are relatively protected, and due to their location they receive fewer hours of direct solar radiation (Fig. 6).

3. Materials and methods

The two olive trees that were studied in our project are numbered I and II for the southern and northern trees, respectively, and the dam (Wall 101) is situated between them (Fig. 7A). Several olive fruit kernels were found near tree No. 2. (Fig. 7B) and a few whole olives on both trees (Fig. 7C), Five archaeological trenches (A1-6) were dug alongside each tree and along the dam wall, between the trees and across the wadi bed: two trenches above the dam and alongside the southern tree (I) and three at the foot of and alongside the northern tree (II), which was the more developed of the two trees (Fig. 8). All the excavated sediments were dry-sieved (with a 5 mm sieve). Datable archaeological material was retrieved and samples were taken from the soil for pollen testing and OSL dating of the soil's age. Roots were uncovered in the excavation near the root collar of tree II: the distal parts of these roots were sawed off determine the minimum age of the tree by radiocarbon dating. In addition, leaf samples were taken from the canopy and from the suckers that had developed at the base of the trunk (as a proxy of rootstock), for genetic analysis. The trunk perimeter of each tree was determined.

Samples for OSL dating were collected from the sediment sections exposed during the excavation, by drilling horizontally into the sediment using a hand-held auger with a diameter of 5 cm, at depths of 0.3 m to 1.6 m. The samples were collected under an opaque cover to prevent any exposure to sunlight. An additional sample from each spot was collected in order to evaluate the dose rates. Nine samples were collected from four different pits and depths in the sections, to cover both the initial and final phases of dam construction and use (Fig. 9). The samples were processed using routine laboratory procedures (Faershtein et al., 2016). To determine the most suitable measurement conditions, dose recovery tests over a range of preheat temperatures were carried out for a sample taken from the main Shivta site (SVT-2), as the sediment at both sites is very similar and the source of quartz is

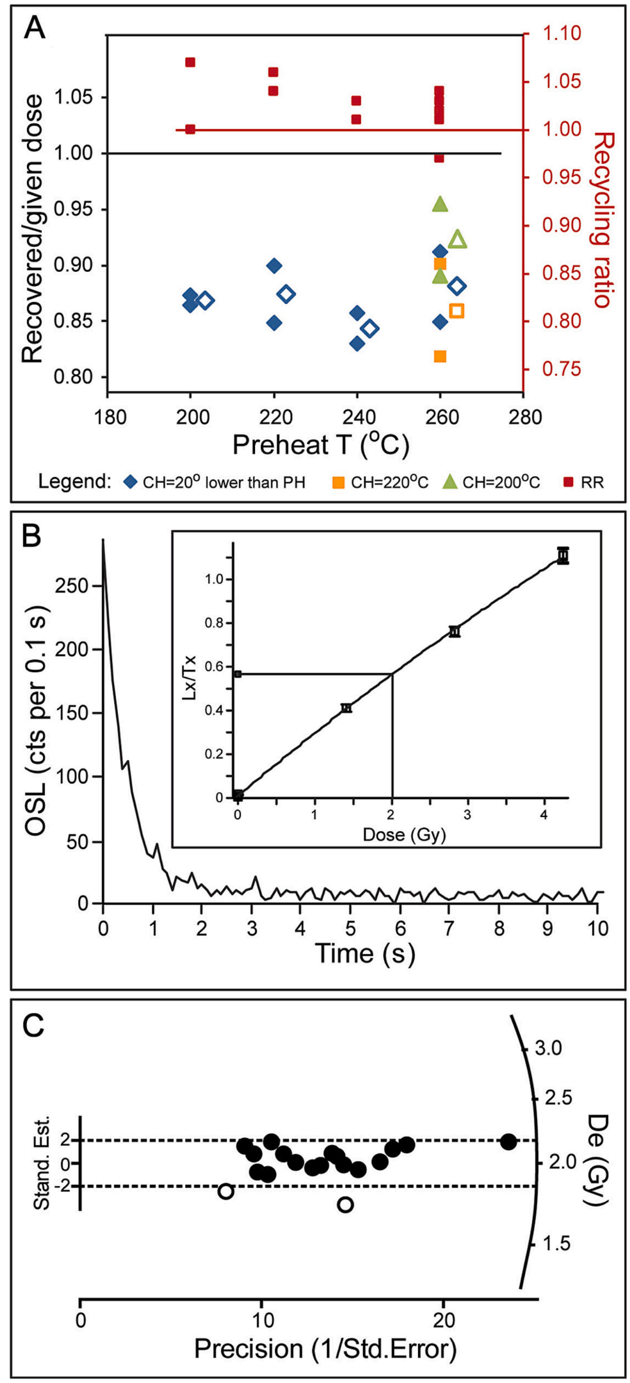

Fig. 10. OSL results. a. Dose-recovery pre heat-plateau test for sample SVT-2 from the nearby main Shivta site. Twelve aliquots were bleached under the sun for several hours and given a dose of 9 Gy. Apparent De was measured under varying pre-heat (PH) and cut-heat (CH) conditions. PH temperature for each aliquot is shown on the x-axis and the recovery ratio on the y-axis; CH temperatures are given in the legend; and averages are in open symbols. Right-hand axis (red) shows recycling ratios (RR) for the same set of measurements. The best recovery, 0.92, was obtained for pre-heat and cut-heat temperatures of 260 °C and 200 °C, respectively (green triangles). b. Natural OSL signal for a 2 mm aliquot of sample SVT-33. The first 10 s (out of 40 s) show a rapid depletion of the signal to background levels within 2–3 s. Inset: Dose response curve for the same aliquot. Recycling ratio (at 4.2 Gy) is 1.01, recuperation is 2.8%, and De = 2.0 ± 0.1 Gy. c. Radial plot of all measured aliquots for SVT-33 (N = 19); De = 2.01 ± 0.05 Gy (calculated using the Central Age Model). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

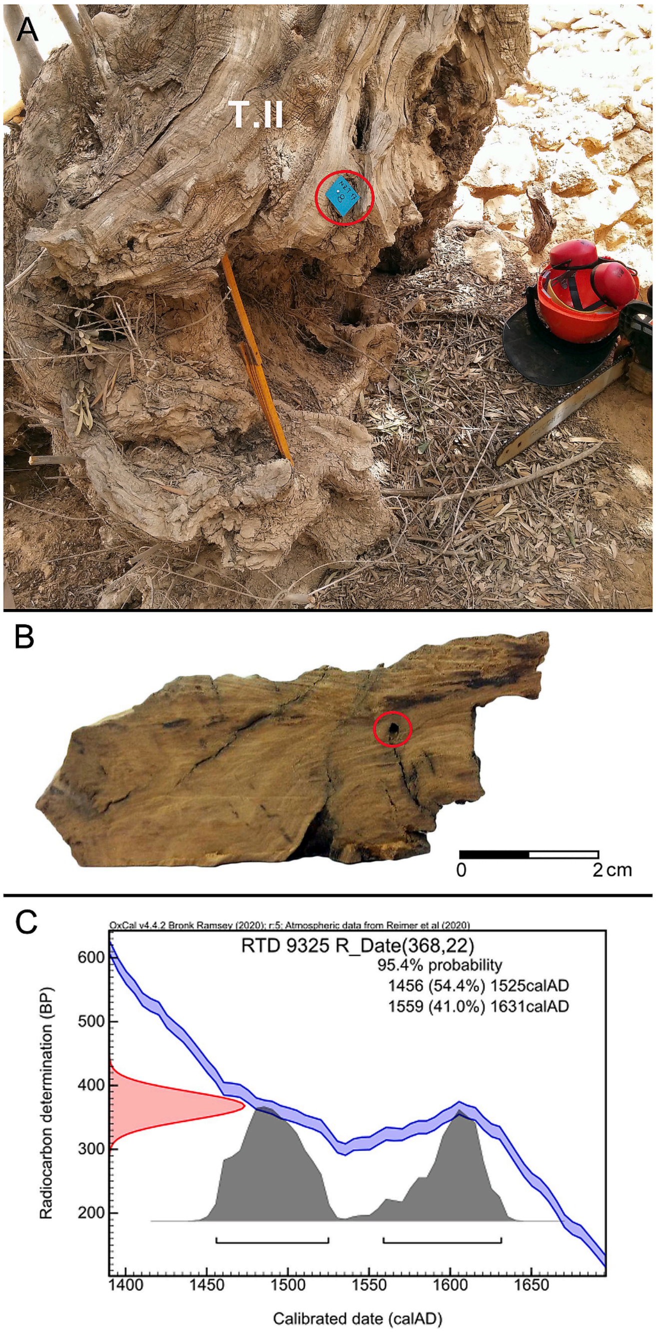

Fig. 11. A. NZT-17 8 - Sampling for radiocarbon dating of tree No. II., red circle indicates sampling area. B. Wood after rough polishing, the location of the sampled material is indicated with the red circle. C. RTD 9325 - the obtained calibrated date, between 1465 and 1620 CE (i.e., 570–390 years old; for ± 1σ probability distribution). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

identical (Lucke et al., 2019b).

The samples performed well with regard to the OSL properties and dose distribution: The OSL signal of the natural samples was bright and it decayed to background levels within 3 s (Fig. 10b). The dose response curve (inset in Fig. 10b) was well constrained and the recycling ratios were close to unity. The dose distribution was normal and with little scatter (Fig. 10c), as indicated by the overdispersion (OD) values that for all but one sample were below 15% (see appendix 1). This performance indicates that the sediment was homogenous, the quartz grains were well bleached at the time of deposition and no significant bioturbation had taken place after the dam had ceased to be cultivated.

Sampling for radiocarbon dating of the tree was carried out with minimum damage and without sampling living branches. A wood sample was collected from the base of tree II, 35 cm above surface (Fig. 9: section 1–1). The sample was polished and a fraction, closer to the most internal part of the sample, was selected for α-cellulose extraction and subsequent radiocarbon dating (Fig. 11, following Ehrlich et al., 2017). The calculated ^{14}C age was corrected for isotopic fractionation based on the stable carbon isotope ratio ($\delta^{13}C$ value), measured by the accelerator. Calibrated ages in calendar years were obtained from the atmospheric data from Reimer et al. (2013) and the software OxCal v4.4.2 Bronk (2020).

Eight soil samples were taken from section A1 for palynological analysis (Fig. 12A–B: samples 1–8). Sample no. 8, which was collected from the uppermost part of the section, served as a control. Since it was taken from the surface sediments below tree 1, it represents the recent pollen deposition. Two additional samples (9–10; Fig. 12A–C) taken for loess soil accumulation above the rocky cliffs, a hundred meters southeast of the olive trees, also served as control. Pollen sampling and extraction procedures followed the standard research protocol commonly used in desert environments (Langgut and Gleason, 2020).

Leaf samples were collected from three of the olives trees in Wadi Zetan (see above Fig. 4B–D); samples were also collected from a sucker in the base of the main trunk of tree II (Fig. 8) and from four "daughter trees" growing around it (T.II). DNA was extracted using the Invisorb Plant Mini Kit (Invitek), following the manufacturer's protocol. For the genetic analysis, we used 15 Simple Sequence Repeat (SSR) markers that had previously been screened and used for the clonal identification of local old olive trees, following a previously described procedure (Barazani et al., 2016; Barazani et al., 2014). The analysis included representatives of previously analyzed samples belonging to three main multi-locus lineage (MLL) groups: MLL1, MLL7 (mainly rootstocks of grafted old trees), and rootstocks that were identified as single occurrence MLLs, a result of sexual reproduction. This analysis provided us the basis preliminary observations to determine how the trees are closely related to other cultivars. Analysis of clonal genetic identity by analysis of multi-locus genotypes (MLGs) and grouping of MLGs into (MLLs) was done using Genotype 1.2 as previously described (Barazani et al., 2014).

4. Results

Trench A1 was excavated on either side of an agricultural boundary wall (W100) parallel to the wadi bed. The wall was constructed of large and medium-size local fieldstones interspersed with a fill of smaller stones. The wall was at least 12 m long with a 3.5 m-long portion of it being unearthed during the excavation. With a width of 1.1–1.2 m, W100 had survived to a height of four courses and was built on bedrock. Above the wall, colluvial brown soil was found, containing numerous small stones, to a depth of 45 cm (L103). Beneath this layer, to a depth of 1 m (L107), greyish soil and colluvial stones of various sizes were found. Beneath the wall a uniform layer of yellowish loess was uncovered, with no medium or large size stones, to a depth of 1.2–1.3 m, and separated into three loci: The upper locus (L102) featured small stones and a compact texture down to the upper course of W100. The texture of the middle locus (L109) was less compact, almost devoid of stones. At the bottom of the trench, at point above the bedrock (L114), the soil contained a relatively large quantity of small stones (ca. 30%) and appeared to be natural accumulation (Fig. 8).

Only a few fragments of pottery were found in the excavation, most of them on the upper surface level (L103). This includes a fragment of a Byzantine cooking pot and another fragment of a Byzantine–Early Islamic amphora (Fig. 13:1–2). Downstream a fragment of a Byzantine period cooking pot and another Early Islamic cooking pot was found (Fig. 13:3–4). In addition, a metal disk was discovered in Trench A3 (Fig. 13:5) and several cooking and tableware pottery sherds from the

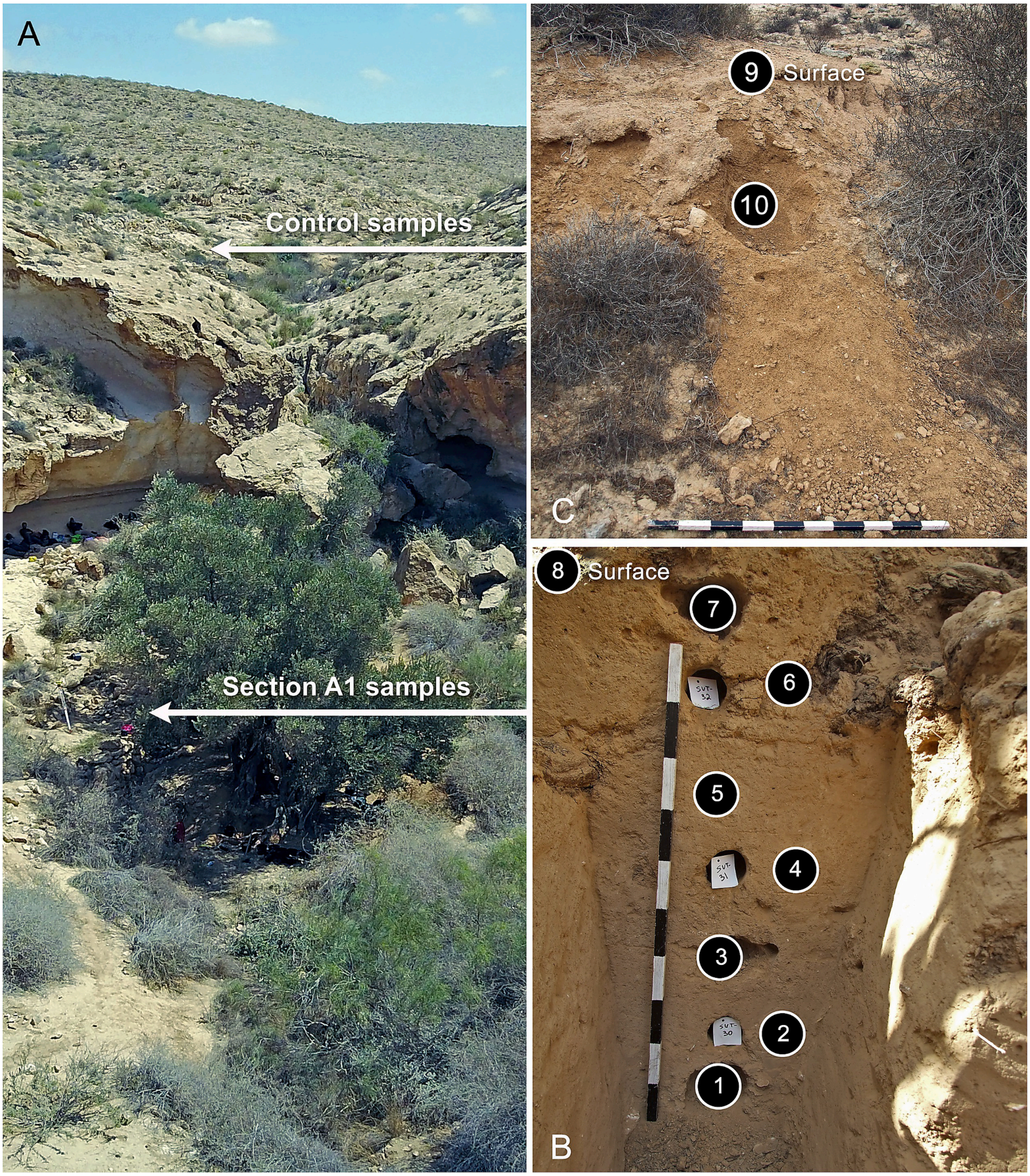

Fig. 12. Wedi Zetan, Location of soil samples taken for palynological analysis (A). Samples from A1 section (B). Control samples taken about a hundred meters south-east of the olive trees (C. photo: Yotam Tepper).

British Mandate period (1917–1948; Fig. 13:6–9) were collected ca. 2,000 m downstream.

Three OSL ages taken from the trench south-west of W100 revealed the period of accumulation of the colluvium above the dam wall (Figs. 8-A1). The earliest age, dated to the second half of the eighth century CE (Umayyad period) beginning of the ninth century CE (Early Abbasid period), was obtained from a soil sample taken at a height of 20 cm above bedrock (1270 ± 70 BP: SVT-30). The sample above it (60 cm above bedrock) was dated to the mid-ninth century CE (Early Abbasid period; 1170 ± 60 BP: SVT-31), and the third sample (90 cm above the bedrock) was of essentially the same age (1150 ± 60 BP: SVT-32). The precise location and age range of each of the samples are given in Table 2 and Figs. 9-A1.

Trench A2 was excavated near the foot of the dam wall (W101) built across the wadi bed near Tree II (Fig. 8). The wall has survived along a length of at least 5.5 m, 2.5 m of which were documented in the excavation. Two layers of soil were uncovered below the dam (W101). The upper one, greyish in color, contained numerous small and medium-size stones to a depth of up to 0.4 m (L105). The lower layer consists of loess soil of a uniform yellow color (L106). No pottery or other datable remains were found. Due to technical limitations we did not excavate deeper into the layer of loess down to bedrock. In the upper, southern, part of the wall, a single course was documented, which had been built at a later phase on top of the layer of loess (see Trench 4A). Two soil

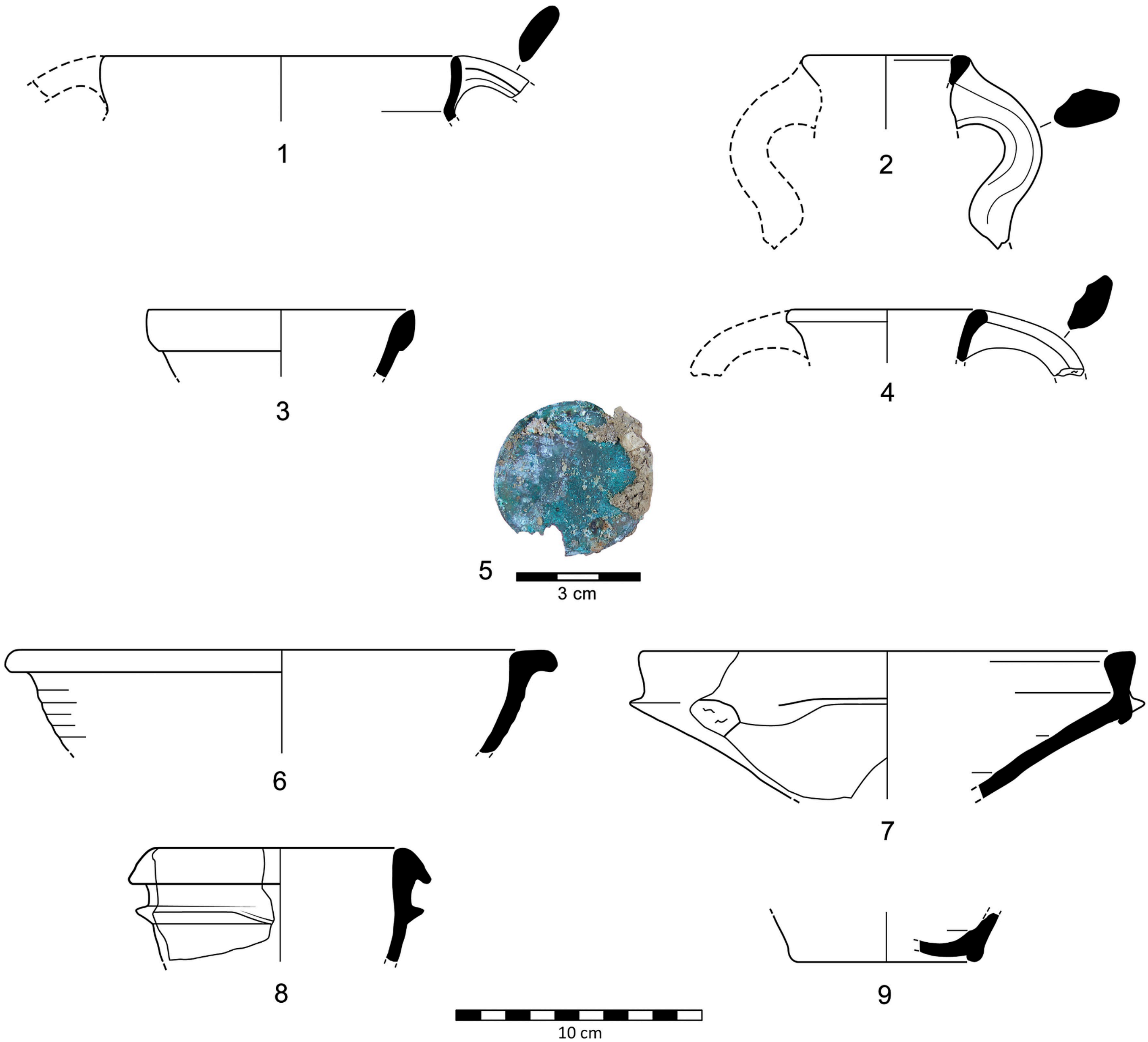

Fig. 13. Pottery and metal findings (drawing: Sapir Haad; photo: Yotam Tepper).

samples were retrieved for OSL dating (Table 1; Fig. 9): The lower sample, taken 30 cm above the bottom of the excavation (L106), sample SVT-37, was dated to 1350 ± 70 BP, the beginning of the Umayyad period. The upper sample taken, 100 cm above the bottom of the excavation (L105), SVT-38, was dated to 1310 ± 70BP, essentially indistinguishable from the lower sample.

Trench A3 was excavated near Tree II to a depth of 70 cm (Fig. 8). Two layers were documented, as in Trench 2A. The upper one, in greyish soil, contained a large quantity of stones of various sizes (L108), and the lower one consisted in yellowish loess soil (L110). At the surface, modern olive kernels were found, some of them perforated by rodents (Fig. 7B). A round bronze object (Fig. 13:5) was also found, which disintegrated upon cleaning. Trench 4A was excavated in an elongated mound of loess that had accumulated from the cliff downstream as far as the dam wall (W101). Two samples were taken for OSL dating (Fig. 9): one from beneath the foundations of the wall (W101), and dated to the beginning of the eleventh century (the Abbasid period: 990 ± 50 BP: SVT-35); and the other from the mound of loess that had accumulated above the wall to a height of 30 cm below the surface, and dated to the end of the tenth century CE (1030 ± 50 BP: SVT-36).

Trench 5A was excavated north of Tree II, east of W100, on the southern side of a large, broad natural depression, apparently created by floodwater (Fig. 8). The trench was excavated into the top of the layer of colluvium, uncovering small and medium-size stones and non-uniform, greyish-brown soil (L112). A yellowish, compacted layer of loess was discovered (L113) as the excavation deepened as far as the bedrock, at a depth of 0.6 m below the surface (Fig. 9). A sample retrieved 20 cm above the bedrock (L113) was dated by OSL to the late seventh century CE (the Umayyad period) 1320 ± 60 BP: SVT-33). The other soil sample, which was taken 30 cm above the previous one (L112), was dated to the first half of the eighth century CE (the Umayyad period; 1270 ± 60 BP: SVT-34).

Thus, the OSL ages range from 1350 ± 70 BP to 990 ± 50 BP, or in calendar years from 600 CE to 1070 CE (Appendix 1). In Pit A2, the deepest pit excavated, the OSL ages of the samples from the base and top of the section are indistinguishable, 1350 ± 70 BP and 1310 ± 70 BP, respectively, implying rapid infill of the terrace (Fig. 10a). However, in Pit A1 there appears to be some age differences from base to top, 1270 ±

Table 1
Summary of OSL ages.

Lab code	Description	Depth (m)	Moisture (%)	Dose rate (µGy/a)	No. aliquots	OD (%)	De (Gy)	Age (years b. 2017)	CalendarYears CE
	Pit A1 L. 102, N. section								
SVT-32	Top of section, within root layer	0.30	7	1682 ± 57	18/19	18	1.91 ± 0.08	**1140 ± 60**	**820–940**
SVT-31	Middle	0.70	8	1661 ± 53	19/19	15	1.93 ± 0.08	**1170 ± 60**	**790–910**
SVT-30	Base	1.05	10	1566 ± 57	19/19	14	1.99 ± 0.07	**1270 ± 70**	**680–820**
	Pit A4 or A5? S. section, below wall 101								
SVT-33	Base of section	0.55	8	1524 ± 55	19/19	7	2.01 ± 0.05	**1320 ± 60**	**640–750**
	Pit A5 L.113, loess accumulating after abandonment								
SVT-36	S. section, latest sediment	0.30	7	1654 ± 56	18/18	13	1.70 ± 0.07	**1030 ± 50**	**940–1050**
SVT-35	N. section, below wall 101	0.30	7	1420 ± 43	19/19	14	1.41 ± 0.05	**990 ± 50**	**980–1070**
	Pit A2 L. 105–106, fill behind a large dam wall								
SVT-38	Middle	0.70	8	1572 ± 50	19/19	15	2.06 ± 0.08	**1310 ± 70**	**640–770**
SVT-37	base	1.60	10	1520 ± 55	19/19	11	2.06 ± 0.07	**1350 ± 70**	**600–730**

Table 2
Radiocarbon dates for samples from Nahal Zetan olive trees.

Sample RTD#	Sample name	pMC	pMC+/−	Cal 1σ	Cal 2 σ
9325	NZT-17 8	95.517	0.272	[cal CE 1461 : cal CE 1515] 0.715 [cal CE 1597 : cal CE 1617] 0.285	[cal CE 1450 : cal CE 1524] 0.609 [cal CE 1559 : cal CE 1564] 0.014 [cal CE 1568 : cal CE 1631] 0.377

70 BP and 1140 ± 60 BP, respectively, perhaps suggesting a more gradual accumulation (Fig. 10b).

The sample NZT-17/8 RTD 9325 (Table 2) from Wadi Zetan Tree II was measured for radiocarbon dating. The obtained calibrated date is between 1465 and 1620 CE (570–390 years old; for ± 1σ probability distribution, see Table 2 and Fig. 11C).

The palynological spectrum retrieved from the Umayyad and Early Abbasid layers of sections A1 provide supplemental information on the agricultural landscape of Wadi Zetan in Antiquity (Table 2; Fig. 14). Among the samples, five are characterized by a similar palynological spectrum and composed predominantly of desert elements, mainly members of the Chenopodiaceae (goosefoot) and Asteraceae (aster) (Table 3: samples number 1–3, 5–6). Significantly, two cultivated trees were also present in these samples: *Olea europaea* (olive) and *Cupressus* type. The latter is assumed to be *Cupressus sempervirens* (Italian cypress; Langgut et al., 2021).

Sample 4 seems to present the most interesting palynological spectrum: in addition to the presence of common desert elements and the cultivated trees of cypress and olive, it also contained pollen of *Vitis* (grape) and pollen of *Bunium* type, which belongs to the Apiaceae (umbel family). This latter type includes herbal plants such as *Petroselinum crispum* (garden parsley) and *Anethum graveolens* (dill) and may reflect additional agricultural activities. Since *Vitis* pollen is characterized by very low pollen dispersal efficiency (Fuks et al., 2020), and since olive reached a peak of pollen in sample 4, it is suggested that both olive trees and grape vines were cultivated in the immediate vicinity of the sampling location. This sample most probably represents all the ancient agricultural crops in Wadi Zetan.

Sample 7, which was collected 20 cm below the surface sediments, is characterized by a total absence of the cultivated trees, olive and cypress, as well as a lack of any other agricultural plants. This may point to the cessation of olive cultivation in Wadi Zetan. The presence of olive pollen in the uppermost sample of the section (sample 8), points to the revival of olives at this sampling location, below Tree I. As was previously demonstrated, olive pollen strongly responds to the cessation and resumption of cultivation, resulting in dramatic fluctuations in pollen production following the abandonment or rehabilitation of olive orchards consequently; olive pollen considered a reliable marker for identifying agricultural activities in Antiquity (Langgut et al., 2014; Langgut et al., 2016). The above palynological spectrum retrieved from the archaeological layers, can help restoration of the agriculture plot in Wadi Zetan during the Early Islamic period: vines, a few olive trees and, apparently, seasonal winter herbs (Fig. 14).

The preliminary genetic analysis of the olive trees provides further essential knowledge on the enigmatic origins of these trees. The MLL of the trees differs from any of the other previously characterized MLLs of scions and rootstock of local old olive trees. Multi-locus linage analysis revealed that the trees growing in Wadi Zetan (Fig. 4.B:I-II) were genetically close to MLL7, which was found to be the most common among rootstocks of grafted old trees. We assume that the small divergence from MLL7 can be attributed to somatic mutations that accumulated during the long lifespan of these trees (Barazani et al., 2014), which is probably also indicative to their antiquity. The analysis is incomplete and further research will refine the relationship between the old olive trees that are dispersed in different parts of the country. When accomplished the complete data will be lodged at https://doi.org/10.6084/m9.figshare.17025689.

5. Discussion

Intensive agriculture, of the type whose remains have been documented on the slopes of Wadi Zetan near Shivta requires extensive knowhow and familiarity with the environmental conditions. In addition, significant wealth and labour must have been invested in the construction of these sophisticated agricultural settings, and the efforts to maintain them must have persisted over a long period of time. In previous research we found that the agricultural system near Shivta dated over a span of several centuries, beginning in the Roman period, peaking in the Byzantine period, and being abandoned in the Early Islamic period (Tepper et al., 2020). It is reasonable to assume that these plots in Wadi Zetan were created upstream in tributaries: first in the lower parts where surface runoff is optimal; and then, as exploitation of

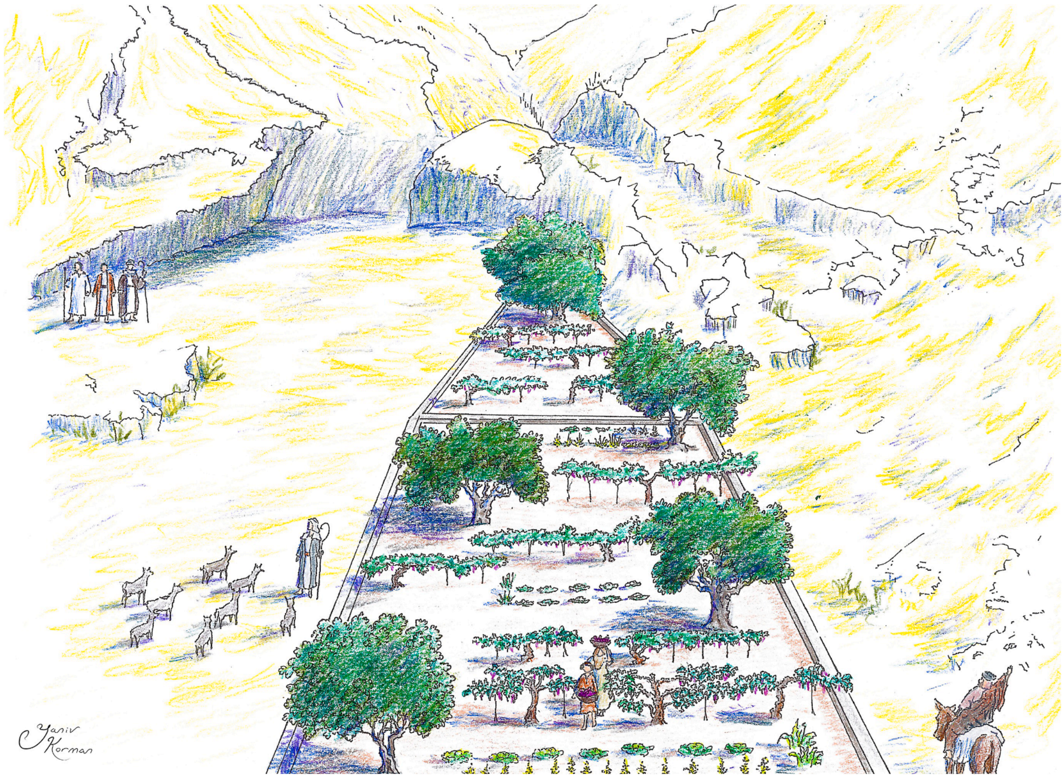

Fig. 14. Agricultural plot in Wadi Zetan (artisan reconstruction drawing: Yaniv Korman).

this area increased, the systems expanded and spread upstream, maximizing the harvest of runoff from the slopes. If this assumption is correct, the plots in the bed of Wadi Zetan where the olive trees are planted were established later in the long process of creation of this runoff system (Fig. 15).

The radiocarbon calibrated range of the olive tree I in Wadi Zetan, reveals the tree as hundreds of years old, with a minimal age dated to the late Mamluk- beginning of the Ottoman period, ca. 550 years ago (1465–1620 CE). This range should be considered as a *terminus ante quem* for the beginning of the tree. While the original tree could be much older, its remains have, unfortunately disappeared due to degradation (Bernabei, 2014). It is a characteristic of ancient olive trees the core of the tree as empty, or missing. Any attempt to extrapolate the initial period of the growth of this tree would result in uncertainty (Ehrlich et al., 2017). In contrast, the soil that had accumulated behind the dam in the wadi, where the olive tree is rooted is older than the tree. OSL dating allows us to determine the age of the soil as not before the Byzantine period, according to the pottery findings and to the beginning of the Early Islamic period (8th-9th century CE).

The results of our research indicate that no additional soil has accumulated here for at least the last thousand years. The agricultural system was therefore probably not maintained or repaired over a long interval beginning in the Early Islamic period and including the Ottoman period. The complete absence of post-Early Islamic pottery sherds across the entire wadi supports this observation. The pollen tests from the archaeological probes that were dated by OSL, show that olives and grapes were growing nearby at the end of the Byzantine–beginning of the Umayyad period. The presence of olive pollen in a few samples located in the soil layer, above this period, supports the idea that the olive trees had existed for at least several centuries (in contrast to the grape pollen which is present only in the sample synchronized with the Byzantine–beginning of the Umayyad period layer). In light of our knowledge of olive trees and their longevity, and the way they can survive under harsh growth conditions (Camarero et al., 2021), it is also possible that the olive trees were planted earlier than the currently estimated minimal age.

In experiments conducted in the 1960s on the slopes next to the ancient settlements of Shivta and Avdat, researchers succeeded in cultivating a large variety of fruit trees in field plots that were supplemented with fertilizers and irrigated with surface runoff. Many of these trees bore fruit, including olive trees (Evenari et al., 1982:129-199). In this context, some studies have suggested that the remains of the olive trees near Shivta and other Byzantine settlements in the Negev are evidence of the activity of the more recent local Bedouin, who planted the trees (Ashkenazi et al., 2011). However, the Bedouin tribes, who have lived in the Negev for the past few hundred years, arrived there from the Arabian Desert. They were nomads whose traditional livelihood was based on raising and pasturing goats; whereas farming and cultivating fruit trees was certainly foreign to them (Perevolotsky, 1981). We do not consider it likely therefore, that the fruit trees in Wadi Zetan were planted by local Bedouin. Since the tree that we studied in our research is still fruit-bearing, we cannot suggest whether it originated from the seed of a random germ olive; was planted at the site; or was grafted onto a propagating shoot.

Papyrus documents from the 6th-7th centuries CE found in nearby Nitzana mention fruit trees raised in the area, and include evidence of commerce in their produce and taxes levied on them (Kraemer, 1958:107, 213–232, 306–308). Particularly prominent in these documents is evidence of the cultivation of grapes and wine production (Kraemer, 1958: papyri 34, 79 and 75). Olives, and especially olive oil, are also mentioned (Kraemer, 1958:60–67, 69, 89, 93 and 95), always as a product used to pay taxes, particularly in the Early Islamic period. Thus it may be presumed that, as opposed to grapes, large olive groves, which could have produced a large amount of oil olives, was apparently not planted in the Negev. In the renewed excavations at Shivta (2016–2019), well-developed agricultural systems were documented and the botanical findings were extensive, including many grape pips and olive kernels (Ramsay et al., 2016; Fuks et al., 2020). Remains of the pollen and charcoal of these species have also been found at sites in the Negev, including at Shivta, Nitzana and other settlements (Colt,

Table 3
Pollen results of Nahal Zetan.

Pollen lab ID Field ID/Archaeological context	Zetan #1 Section A1 (lowermost sample)- Below OSL sample – SVT30.		Zetan #2 Section A1- Same as OSL sample – SVT30-		Zetan #3 Section A1- Between OSL Samples –SVT 30/31		Zetan #4 Section A1– Same as OSL sample SVT31-		Zetan #5 Section A1- Between OSL samples –SVT 31/32		Zetan #6 Section A1- Same as OSL sample SVT32		Zetan #7 Section A1- Above OSL samples-SVT 32		Zetan #8 Control –surface sediment (uppermost sample of section A1= #13)		Zetan #9 Control –#50, surface sediments -a 100 m. southeast of the olive trees		Zetan #10 Control –#51, 50 cm below surface) -a 100 m. southeast of the olive trees	
Pollen type		%		%		%		%		%		%		%		%		%		%
Pinus (pine)		0.0		0.0		0.0	2	1.7		0.0		0.0		0.0	9	1.9		0.0		0.0
Cupressus type (cypress)	10	11.2	21	18.1	25	27.8	9	7.6	16	11.4	31	27.0		0.0	2	0.4	96	29.2	64	25.0
Olea europaea (olive)	11	12.4	4	3.4		0.0	59	49.6	6	4.3	9	7.8		0.0	213	44.9		0.0		0.0
Tamarix (tamarisk)		0.0	1	0.9		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
Zygophyllim		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
Vitis (grape)		0.0		0.0		0.0	9	7.6		0.0		0.0		0.0		0.0		0.0		0.0
Casuarina		0.0		0.0		0.0		0.0		0.0		0.0		0.0	2	0.4		0.0		0.0
Poaceae (grasses)		0.0	2	1.7	2	2.2	3	2.5		0.0		0.0		0.0		0.0		0.0		0.0
Cereal type (cereals)	2	2.2		0.0		0.0	2	1.7		0.0		0.0		0.0		0.0		0.0		0.0
Bunium type		0.0		0.0		0.0	19	16.0		0.0		0.0		0.0	1	0.2	1	0.3	1	0.4
Chenopodiaceae (goosefoot)	37	41.6	27	23.3	19	21.1	6	5.0	64	45.7	41	35.7	9	29.0	211	44.5	31	9.4	22	8.6
Daphne type (Daphne)		0.0		0.0		0.0		0.0		0.0		0.0		0.0	2	0.4		0.0		0.0
Plantago (plantains)		0.0	4	3.4		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
Asteraceae Asteroideae type (aster-like)	21	23.6	41	35.3	31	34.4	4	3.4	36	25.7	33	28.7	13	41.9	5	1.1	172	52.3	125	48.6
Asteraceae Cichorioideae type (dandelion-like)	4	4.5	8	6.9	7	7.8		0.0	6	4.3		0.0	8	25.8		0.0	5	1.5		0.0
Centaurea (knapweeds)		0.0		0.0		0.0		0.0		0.0		0.0	1	3.2		0.0		0.0		0.0
Artemisia (sagebrush)	2	2.2	6	5.2	4	4.4	4	3.4	6	4.3		0.0		0.0	4	0.8		0.0		0.0
Echinops (thistles)		0.0		0.0		0.0		0.0		0.0		0.0		0.0	2	0.4		0.0		0.0
Fabaceae (legumes)		0.0		0.0		0.0	2	1.7		0.0		0.0		0.0		0.0		0.0		0.0
Ephedra (Mormon-tea)		0.0	2	1.7		0.0		0.0		0.0	1	0.9		0.0	4	0.8	9	2.7	9	3.5
Liliaceae (lilies)		0.0		0.0		0.0		0.0	5	3.6		0.0		0.0	12	2.5		0.0		0.0
Brassicaceae (crucifers)	2	2.2		0.0	2	2.2		0.0		0.0		0.0		0.0	7	1.5	2	0.6	2	0.8
Caryophyllaceae (pink family)		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0	0	0.0
Geranium (geraniums)		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0	2	0.6		0.0
Nimphaea (water lily)		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0	11	3.3	0	0.0
Polygonum (knotweed)		0.0		0.0		0.0		0.0	1	0.7		0.0		0.0		0.0		0.0		0.0
Unidentifiable	4	4.5	13	11.2	6	6.7	14	11.8	22	15.7	19	16.5	23	74.2	45	9.5	49	14.9	34	13.2
Total pollen counted	89	100.0	116	100.0	90	100.0	119	100.0	140	100.0	115	100.0	31	100.0	474	100.0	329	100.0	97	100.0
Spores	25		214		48		92		24		72		51		5		48		1020	
Lycopodium	178		225		86		32		207		94		107		13		562		185	

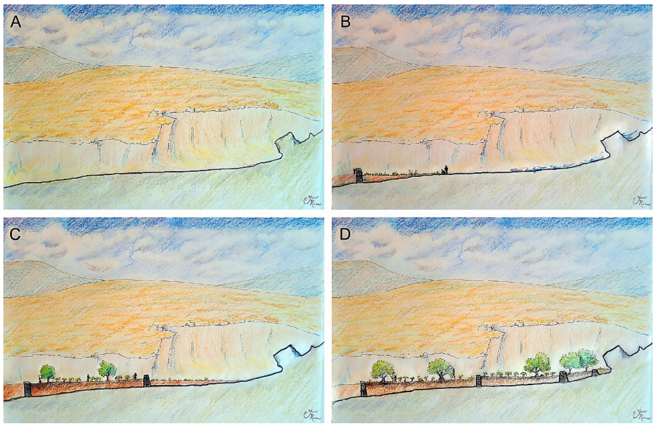

Fig. 15. Chronological development of the agricultural system in Wadi Zetan: A. Pre- human/agricultural activity. B. First establishment of a dam construction system and initial accumulation of soil. C. Accumulation of sediment and water behind the dams and the beginning of plantation farming. D. The agricultural system at its peak spreads the plots to the foothills of the cliff (artisan reconstruction drawing: Yaniv Korman).

1962:59-60; Langgut et al., 2021). This archaeological evidence supports the presence of intensive cultivation of olives and grapes in that period and reinforce the historical evidence provided in the papyri (Fig. 14).

Despite the historical data regarding olive oil, and the supporting archaeological evidence, the relative completeness of the majority of olive kernels found in the domestic refuse of Shivta supports the assumption that at least some of the olives were consumed as food ('table olives'). Olive oil production, as we know, involves a process of crushing, pressing and separating, in which the kernels are also crushed. However, only a few installations related to olive oil production (olive press) have been discovered in Byzantine and Early Islamic settlements in this area (Rubin, 1990; Schöne et al., 2019:149). Contemporaneous olive presses were documented in numerous sites across the southern Levant and the eastern Mediterranean basin (recently reviewed in Taxel, 2013). Another major center of olive cultivation and production was along the North Africa coastal strip (Mattingly, 1988; Barker et al., 1996). The Mediterranean coast of Libya and mainly Cyrenaica characterized by a cool, rainy winter, with an average annual precipitation of 400–650 mm (see also Gilbertson et al., 2000). However, the Negev region is different. The Shivta area is missing from abundant water sources all year round and the average annual precipitation is less than 100 mm and the region is south of and beyond the boundaries of the distribution of olive trees and the hot climate and natural conditions may inhibit the oil accumulation (Nissim et al., 2020) necessary for oil olives.

6. Conclusions

The extensive agricultural systems in the vicinity of Shivta, which peaked at the end of the Byzantine period, reached as far as the southern cliff edge of Wadi Zetan. At that specific location we studied two olive trees and researched the topographical conditions that have enabled their survived in an arid environment. One of the trees has been dated back to about 500 years, while all trees rooted in agricultural soil have been dated back to the Early Islamic period. These remains of runoff agricultural plots have not been rehabilitated or treated in any way; according to our research for, at least 1,000 years. The pollen evidence supports the contention that olive trees have existed in Wadi Zetan for several centuries.

The results of this research demonstrate the importance of multidisciplinary studies in order to uncover those important heritage trees that are rooted in an historic terroir and bear important cultural values.

Fig. 16. A. Shivta olive cuttings in the Gilat Research Center. B. Olive tree rotted cuttings from Wadi Zetan, Ramat Ha'Nadiv nursery. (Photos: Arnon Dag, Hugo Jan Trago).

Table A1
Field and laboratory data for OSL dating.

Lab code	Description	Depth (m)	Moisture (%)	K (%)	U (ppm)	Th (ppm)	Ext. α (μGy/a)	Ext. β (μGy/a)	Ext. γ (μGy/a)	Cosmic (μGy/a)	Dose rate (μGy/a)	No. aliquots	OD (%)	De (Gy)	Age (years b. 2017)	Calendar Years CE
	Pit A1 L. 102, N. section															
SVT-32	Top of section, within root layer	0.30	7	0.88	1.6	4.8	7	871	575	229	1682 ± 57	18/19	18	1.91 ± 0.08	**1140 ± 60**	**820–940**
SVT-31	Middle	0.70	8	0.83	1.7	5.5	8	857	599	196	1661 ± 53	19/19	15	1.93 ± 0.08	**1170 ± 60**	**790–910**
SVT-30	Base	1.05	10	0.76	1.8	5.4	8	800	574	184	1566 ± 57	19/19	14	1.99 ± 0.07	**1270 ± 70**	**680–820**
	Pit A4 or A5? S. section, below wall 101															
SVT-33	Base of section	0.55	8	0.77	1.5	4.7	7	779	531	207	1524 ± 55	19/19	7	2.01 ± 0.05	**1320 ± 60**	**640–750**
	Pit A5 L.113, loess accumulating after abandonment															
SVT-36	S. section, latest sediment	0.30	7	0.81	1.6	5.1	8	839	578	229	1654 ± 56	18/18	13	1.70 ± 0.07	**1030 ± 50**	**940–1050**
SVT-35	N. section, below wall 101	0.30	7	0.69	1.4	4.0	6	707	478	229	1420 ± 43	19/19	14	1.41 ± 0.05	**990 ± 50**	**980–1070**
	Pit A2 L. 105–106, fill behind a large dam wall															
SVT-38	Middle	0.70	8	0.75	1.6	5.4	8	797	571	196	1572 ± 50	19/19	15	2.06 ± 0.08	**1310 ± 70**	**640–770**
SVT-37	base	1.60	10	0.75	1.7	5.3	8	781	559	172	1520 ± 55	19/19	11	2.06 ± 0.07	**1350 ± 70**	**600–730**

Methods:
88–125 μm quartz was purified by wet-sieving to the selected grain size, dissolving carbonates by 8% HCl, removing heavy minerals and some feldspars by magnetic separation, and dissolving the remaining feldspars and etching the quartz with 42% HF (for 40 min), followed by soaking in 16% HCl overnight to dissolve any fluorides which may have precipitated.
Samples were measured using a preheat of 10s @ 260°C, a test dose of ~4.5 Gy and a test dose preheat of 5 s @ 200 °C. De was measured on 2 mm aliquots using a modified single aliquot regenerative (SAR) protocol. All samples show recycling ratios within 8% of 1.0 for most aliquots and negligible IR depletion ratios.
Alpha, beta and gamma dose rates were calculated from the radioactive elements measured by ICP-MS (U&Th) or ICP-OES (K). Moisture contents were estimated from burial depths (Rosenzweig et al., 2015). Cosmic dose rates were estimated from current burial depths.
The average De and errors were calculated using the central age model (CAM) after removing distinct outliers.
OD – Over-dispersion, a measure of the scatter in the sample beyond that expected from instrumental noise. No. aliquots – the number of aliquots used for the average De out of those measured.
Ages are rounded to the nearest decade.

Here we applied this approach to the old olive trees in Wadi Zetan, which encapsulates a major component of bygone arid-environment agricultural history. Following our excavations, several dozen propagating plants from these heirloom trees were planted in a rescue garden in the Negev and are currently being grown and studied.

We hope that the results of our study will inspire further research on additional authentic and traditional cultivars in their genuine desert terroir. Future effort should be invested in searching, decoding and preserving these ancient heirloom olive varieties adapted to hot and arid environments. Genomic sequencing of the wadi Zetan olive trees, and additional present-day marginal area relicts, together with genetic analysis of archaeological olive kernels, can facilitate and guide the selective growth of cultivars that are more resilient and adapted to harsh growing conditions, thereby protecting diversity loss due to global warming (Fig. 16). Such research has the potential to fuel a wide range of evolutionary, palaeo-ecological and palaeo-environmental research questions. Our work is clearly just a first step in this direction, and further research should be targeted at arid-adapted fruit tree cultivars in marginal areas with a rich cultural history of varietal lineages, and which have been selected and bred for centuries.

CRediT authorship contribution statement

Yotam Tepper: Project administration, Conceptualization, Writing – original draft. **Naomi Porat:** Formal analysis, Investigation, Resources, Writing – review & editing. **Dafna Langgut:** Formal analysis, Investigation, Resources, Writing – review & editing. **Oz Barazani:** Formal analysis, Investigation, Resources, Writing – review & editing. **Prabodh Kumar Bajpai:** Formal analysis, Investigation, Resources, Writing – review & editing. **Arnon Dag:** Formal analysis, Investigation, Resources, Writing – review & editing. **Yael Ehrlich:** Formal analysis, Investigation, Resources, Writing – review & editing. **Elisabetta Boaretto:** Formal analysis, Investigation, Resources, Writing – review & editing. **Guy Bar-Oz:** Supervision, Funding acquisition, Conceptualization, Writing – original draft.

Acknowledgments

This work was supported by the European Research Council under the European Union's Horizon 2020 Research and Innovation Program Grant 648427 and Israel Science Foundation Grant 340-14. The study was conducted under licenses from the Israel Antiquities Authority (30/2017-G). The radiocarbon research was supported by the Exilarch Foundation for the Dangoor Research Accelerator Mass Spectrometer (D-REAMS) Laboratory and the George Schwartzman Fund. Y. Ehrlich was supported by the Max Planck-Weizmann Center for Integrative Archaeology and Anthropology and the Kimmel Center for Archaeological Science. We thank Y. Jacobi for processing the OSL samples; V. Epstein for her help in the palynological analyses, A. Blumenkrantz for the field surveys, and R. Shahack-Gross and Y. Avni for field observations.

Appendix 1

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