Pedology of archaeological soils in tells of the Judean foothills, Israel

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1. Introduction

The evolution of tells involves repeated human occupation of sites that built-up as a result of deposition and erosion processes of cultural materials (Davidson, 1976; Butzer, 1982, p. 77–97; Rosen, 1986; Wilkinson, 2003, p. 100–127; Matthews, 2017). Tells etymologize from the Semitic language of Akkadian (Tillu; tēlu, meaning mound, ruin heap; Sokoloff, 2002). The occurrence of tells is abundant in western Asia, southeastern Europe and North Africa (Matthews, 2017). The characteristic composition of many tells is either calcareous or gypsi-ferous (e.g., Matthews et al., 1994; Beach and Luzzadder-Beach, 2008; Pustovoytov et al., 2011; Love, 2012; Benz et al., 2015; Riehl et al., 2015; Ackermann et al., 2017a), indicating that tells commonly form under arid to temperate (Mediterranean) climatic conditions. Apparently, pedogenesis in tells occur simultaneously with sedimentation (Sedov et al., 2017). Different from the classic (gradual) pathways of soil forming processes (Schaetzl and Anderson, 2005, pp. 347–461; Blume et al., 2016, pp. 285–316), soil formation that is associated with concurrent sedimentation is regarded as “synlithogenic pedogenesis” (Khokhlova et al., 2001; Targulian and Goryachkin, 2004; Shishov et al., 2005).

Recently, Sedov et al. (2017) added a new pedo-archaeological approach to the study of tell formation processes by considering synlithogenic pedogenesis as having a key role in the formation and
stratigraphical development of tells. By inspecting deposits of two tells mentioned in the text are indicated in black. (For interpretation of the refer-}

\[ \text{Fig. 1. (a) Map of the Eastern Mediterranean, showing the location of the study area (yellow rectangle). (b) Study area, showing locations of recognized tells (white dots) and sites of case studies (yellow dots). Names of other sites that are mentioned in the text are indicated in black. (For interpretation of the reference to colour in this figure legend, the reader is referred to the web version of this article.)} \]

...excavations (Ortiz and Wolff, 2012; Faust, 2013; Sapir, 2016; Borowski, 2017) a large area is exposed in the three tells. The examination of these specific sites enables us to observe hundreds of square metres of open profiles with no need for further excavations. While most of this study refers to the upper 1–2 m of the studied tells, a large excavation space in Tell Gezer (> 10 m deep, 20 × 20 m wide), and the detailed work of Sapir (2016) at Tell 'Eton, provide us with a view and a reference to large portions of soil that could not be inspected in this study. The available archaeological records of the three tells (Ortiz and Wolff, 2012; Faust, 2013; Sapir, 2016; Borowski, 2017) enable to assess the maximum age boundaries for the formation time of the studied profiles. A combination of field survey, particle size distribution (PSD), pH, CaCO3 content, and organic carbon (OC) content has been applied in order to explore the nature of the groundmass of the tells and compare them with soils from their proximity. Soil micromorphology, that was proved to be most efficient for studies of tell soils (Stoops and Nijs, 1986; Matthews, 1995; Courty and Coqueugniot, 2013; Maghsoudi et al., 2014; Sedov et al., 2017) is taken as our main method. It is, however, accentuated that soil micromorphology is applied here as a tool for interpreting pedogenic features, rather than cultural materials. As opposed to the intense study of anthropogenic effects on soils in modern times (Howard, 2017), this study sheds light on a rarely discussed topic - the influence of humans on soil forming processes in history.

2. Background and previous studies

Early studies that described cultural mounds did not refer to their geoarchaeological features (Warren and Conder, 1884; Clermont-Ganneau, 1896; Rassam, 1897; Hilprecht, 1903, p.17). Such reference came only in the second half of the 20th century (Lloyd, 1963; Davidson, 1973, 1976; Liebowitz and Folk, 1980; Butzer, 1982, p.77–97), with the molding of geoarchaeology (Davidson and Shackley, 1976; Shahack-Gross, 2017). Further on, a milestone in the study of tells has been achieved with Rosen's (1986) seminal book “Cities of Clay: The Geoarchaeology of Tells”. Since then, marked efforts have been conducted in exploring various (geoarchaeological) materials and properties of tells (Albert et al., 2008; Matthews, 2016; Love, 2011; Maghsoudi et al., 2014; Regev et al., 2014, 2015; Sapir et al., 2016; Shahack-Gross et al., 2018), whereas only scarce studies focused on pedological processes in tells (Stoops and Nijs, 1986; Ryan et al., 2009), and not a much higher number of studies present a more holistic view on tell formation processes (Matthews et al., 1997; Davidson et al., 2010; Sapir, 2016; Sedov et al., 2017). Inspecting site formation processes is usually performed in the scope of ethnoarchaeological studies, mainly for the purpose of reconstructing past human activities (Schiffer, 1987; Weiss et al., 1993; Stein, 2001; Shahack-Gross et al., 2005; Matthews, 2010; Davidson et al., 2010; Riehl et al., 2015). Here, however, the terminology of “tell formation process” is discussed in a pedological context.

Tells are amongst the most outstanding archaeological landforms of the Judean foothills (Fig. 1). Located in the southwestern area of the Fertile Crescent (Lev-Yadin et al., 2000), since prehistoric times this part of the Levant has attracted many civilizations (Stern and Urman, 1988; Dagan, 2000, 2011), as inferred from the dense distribution and distinctive appearance of tells across the landscapes of this region. As shown in previous studies (Khailali and Marder, 2010; Marder et al., 2011; Zaider et al., 2018) the earliest prehistoric sites known so far in the Judean foothills are related to the Lower Palaeolithic (Late Acheulean culture). The cultural peaks in this region occurred during the Late Bronze (1550–1200 BCE) and Iron ages (1200–586 BCE; Koch, 2017; Maeir and Lipschits, 2017), and later, during the Byzantine period (324–638 CE; Bar, 2004). The youngest finds are attributed to the Ottoman period (20th century CE; e.g., Dagan, 2011).

Archaeological excavations of tells in the Judean foothills initiated in 1890 with an expedition to Tell el-Hesi (Hesi in Fig. 1; Bliss, 1894, 1970; Goldberg, 1979; Rosen, 1986). Here we examine three tells from this region: Gezer, 'Eton and Halif (Fig. 1). As a result of previous
that ancient agricultural landscapes and how the soils and landscape of this tell. Additionally, Paz et al. (2017) found that standing of diatom valves can help map them. By examining the slopes and periphery of mounds, they reconstructed the long-term in situ pedogenesis, although he concluded by encouraging further study that these climatic conditions have prevailed during, at least, the last 17,000 years (Wiesl et al., 1986; Bar-Matthews et al., 1998).

The study area is situated in the Eastern Mediterranean and includes the western Judean foothills. Israel (Fig. 1). This region is characterized by westward descending mild hills with an elevation of 90–500 m a.s.l. (Bar et al., 2016). This hilly landscape is truncated by four main channels and is bounded in the north and south by alluvial valleys (Ayalon and Beer Sheba valleys, respectively). The western Judean foothills juxtapose the Judean Mountains to the east, and the coastal plain of the Mediterranean Sea to the west. The bedrock is predominantly composed of Upper Cretaceous and Eocene carbonate rocks (mostly chalk, and to a lesser degree limestone and marl) with some Quaternary alluvium and elastic sedimentary rocks (Sneh et al., 1998; Bar et al., 2016). Most of the exposed bedrock is capped with late Cenozoic calcrite, locally known as ‘nari’ (Itkin et al., 2012). The climate is mostly temperate (Csa; Peel et al., 2007; Mediterranean) with arid (BSH; Peel et al., 2007) conditions in its southern part (Goldreich, 2003, p.12–17). The mean annual precipitation is 530–200 mm/yr, declining southwards (Israel Meteorological Service, 2018). Generally, these climatic conditions have prevailed during, at least, the last 5000 yrs. (Wiel et al., 1986; Bar-Matthews et al., 1998).

The soil distribution (Soil Survey Staff, 2014, followed by IUSS Working Group WRB, 2015 in parentheses) includes: Mollisols (Leptosols, Pachezems), Alfisols (Luvisols), Entisols (Regosols, Fluvisols), Vertisols, Inceptisols (Cambisols), and Aridisols (Calcisols). The latter, only in the southern part of this area (Dan, 1988a, 1988b). Soils have a xeric moisture regime and a thermic temperature regime (Soil Survey Staff, 2014; Israel Meteorological Service, 2018). The soils of this area are human-disturbed and severely degraded since, at least, the Early Bronze Age, due to influences such as overgrazing and poor agriculture practices (Naveh and Dan, 1973; Dan, 1988a). Desert loess is a major constituent of the Luvisols (Alfisols) and Vertisols (Dan, 1988a). These soils, that are located mainly in the valleys and truncated hill tops, are fertile and being cultivated for growing a range of cereal crops and deciduous fruit trees (Soil and Pasture Survey Staff, 1983). Buried soils are also found in the Judean foothills (Soil and Pasture Survey Staff, 1983; Weiner-Bloch, 1989), some of which are highly human induced (Ackermann et al., 2004, 2017b).

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Later, during the Roman/Byzantine periods (200–600 CE) the tell was barely occupied, and then resettled and abandoned in the Early Arab period (approx. 700 CE; Borowski, 2017).

4. Methods

The methods applied in this study include: 1) Remote sensing using Google Earth images, 2) Field survey, including observations and field analyses of colour (Munsell Color, 1990), texture estimation, and CaCO₃ effervescence (dilute hydrochloric acid), 3) PSD, 4) Chemistry analyses; pH, %CaCO₃, OC, and 5) Soil micromorphology. The field survey was based on relevant topics in the guidelines of Schoeneberger et al. (2012) for describing and sampling soils. Our sampling strategy included the following stages: 1) Forty tells were mapped across the western Judean foothills (Fig. 1), 2) Three tells were selected for closer examination: Gezer, 'Eton, and Halif (Figs. 1, 2), 3) The surfaces of the examined tells and their vicinity were carefully observed, first by a dji phantom (3 pro) drone and then on foot, 4) Two representative soil profiles were sampled per tell, in its summit and backslope, 5) A third profile (reference profile) was studied and sampled at the footslope or toeslope outside each tell, in order to confirm whether soils outside the tells are genetically related to their cultural deposits, 6) Each soil profile was sampled in three depths, 7) Undisturbed samples for micromorphism were extracted by applying the "selective sampling" method (Courty et al., 1989, p. 40–43). Namely, samples were retrieved according to specific considerations in each profile (archaeological record and length of profile), 8) Special attention was taken to avoid from inspecting modernly disturbed groundmass of previous archaeological excavations (e.g., the early 1900s excavations of Macalister; Wolff, 2017), 9) Soil classification was made according to the USDA Soil Taxonomy (Soil Survey Staff, 2014, 2015).

A few exceptions in our sampling procedure were made in the field: 1) Profile TG1 (Gezer) was extracted from the shoulder of the tell (instead of its summit), 2) Despite efforts to avoid from inspecting modernly disturbed material, in Tell Gezer it is nearly impossible to find such near-surface profiles. Therefore, profiles TG1 and sample TG2a (Gezer), were extracted from zones that have been anthroturbated during the early 1900s excavation of Macalister (Eli Yannai, pers. comm.), 3) Profile TH1 was sampled in four locations, rather than three, due to a suspected different material in its lower part (sample TH1d).

An overall of thirty-nine soil samples were analyzed: Twenty-five disturbed samples were extracted for soil analyses of PSD, pH, CaCO₃ content and OC, and fourteen undisturbed and oriented samples were taken for soil micromorphology. Twenty-one thin sections and twelve scanning electron microscopy (SEM) samples were produced out of the undisturbed samples. The exposed profiles enabled sampling to a depth of 100–200 cm. Profile TG2 (Gezer) was sampled to a depth of 445 cm.
All disturbed samples were air dried, sieved (< 2 mm) and split for further analyses. PSD analysis was performed with Malvern MS-2000 laser diffraction over the particle-size range of 0.02 to 2000 μm. Measurement procedure included dispersing (using sodium hexametaphosphate solution), stirring for 5 min, and ultrasonication for 30 s. Three to six replicate specimens of each sample were then subjected to three consecutive 5 s runs at a pump speed of 1800 RPM. The laser diffraction raw values were transformed into PSD using the Mie scattering model, with optical parameters of R1 = 1.52 and A = 0.1. Here, we present the full PSD results and also calculate the clay/silt/sand fractions using thresholds of 6 μm and 63 μm, respectively. We chose 6 μm as the upper clay fraction threshold since several studies had demonstrated that it is equivalent to the mostly used 2 μm threshold when using the sedimentation technique (e.g., Miller and Schaeztl, 2012; Fisher et al., 2017). Soil pH2O (1:1 water/soil) followed the protocol of Burt (2014). Carbonate content was estimated using the pressure calcimeter method (Evangelou et al., 1984), OC was estimated using the modified Walkley-Black titration method (Gelman et al., 2012). Samples for carbonate content and OC were crunched before analyses.

Soil micromorphology was performed with polarizing light microscopy and scanning electron microscopy. The preparation of the thin sections (after drying, impregnating, grinding etc.) was produced with 2.5 mm x 7.5 cm slides according to Gottlieb (2015, p.13–28). The samples were observed using an Olympus BX53 polarizing microscope and photographed using an Olympus DP23 digital camera mounted on the microscope. The micromorphological descriptions were made according to Stoops (2003). The SEM samples were observed using a SEM model FEI Quanta 450, in a presentation mode of a secondary electron image, which displays surface texture, morphology and surface roughness.

5. Results

5.1. Tells: field observations and lab analyses

The first and most straightforward field observation is that all tells have a secluded appearance in the landscape and a flat summit. Different from the way occasionally described in geological maps (e.g., Sneh and Avni, 2008) all three tells are situated on preexisting natural hills of Eocene chalk (at least partly altered by calcrite). The tells are composed of archaeological materials and erosional deposits, with no allochthonous input of soils or sediments (excluding a minor contribution of aeolian dust). Occasionally, remnants of ancient agricultural terraces are observed along the slopes. The surface of the tells show a mosaic of Mediterranean shrubs and annual plants, vast number of potsherds, dozens of recent mole-rats’ mounds, frequent cm-scale trails. One exceptional landform is a small bedrock outcrop at the site of Tell Eton (situated between pro- cesses (after drying, impregnating, grinding etc.) was produced with 2.5 mm x 7.5 cm slides according to Gottlieb (2015, p.13–28). The samples were observed using an Olympus BX53 polarizing microscope and photographed using an Olympus DP23 digital camera mounted on the microscope. The micromorphological descriptions were made according to Stoops (2003). The SEM samples were observed using a SEM model FEI Quanta 450, in a presentation mode of a secondary electron image, which displays surface texture, morphology and surface roughness.

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The results show homogeneity in the soil profiles of each tell and high similarity amongst all three of them (Table 1). The soils of the three tells show a massive weak structure when peds are not disturbed and a single grain weak to moderate structure, or granular in some discrete domains, when peds are slightly put under pressure by hand (Table 1). Carbonate in the observed profiles show strong effervescence throughout, with no (field) expression of induration. The dry colour of all samples (not indicated in Table 1) is similar to their moist colour. The moisture status of the profiles is dry, except for slightly moist buried soils in the lower part of profile TG2 (TG2b and TG2c; Tell Gezer). It should be noted that the buried soil samples TG2b and TG2c differ in their chemical characteristics as all other samples, except for TG2c which has a slightly darker colour and slightly less CaCO3 content (Table 1). Although not sampled, we documented an observation of a 700 cm deep profile in Tell Eton (situated between profiles TE1 and TE2) that highly resembles profiles TE1 and TE2 in its homogeneity of colour, texture and structure, throughout.

All profiles are embedded with variable quantities of miscellaneous material, mostly fragments that includes pottery coated with thin calcareous accumulations (Fig. 3), mud bricks, charred wood and carbonate rock, mostly chalk. Occasionally, earthworm channels, shales of land snails and fragments of bones are also observed. The tells are canopied by annual plants. The rhizosphere of the annual plants extends to a depth of ~20 cm below the surface. Shrub roots reach a depth of 1 m and more in a few places. The most pronounced field differences amongst the profiles of the three tells concerns the cultural context and quantity of artifacts in each (not specified in this study). The soils of the three tells show similar PSD characteristics (Table 1; Fig. 4a). All are characterized by a bimodal distribution with modes at the coarse silt fraction (30–50 μm) and at the clay fraction (~1 μm). The main grain fraction is silt (60–70%), followed by clay (15–30%) and sand (5–15%).

5.2. Tells: micromorphological observations

The groundmass of the studied tells share high similarity but show different soil fabric, mainly in the quantity and size of common constituents. All tell profiles include the following fabric elements, unless otherwise indicated: Vughy microstructure with open porphyric coarse/ fine(c/f)-related distribution (c/Iμm limit) and porous crumb peds (“peds” as alternatively to “aggregates”; Stoops, 2003, p. 58). Peds are partly welded and composed of micrite, small amounts of Fe-stained clay, charred particles (wood ash), and minor content of other organic matter. The groundmass shows discontinuous carbonate recrystallization (Figs. 5, 6, 7). Different from the observed contact between peds, most of the micrite grains that compose the peds are not welded, i.e., they are held mainly by cohesion (only slightly cemented or not at all). That implies that the slight precipitation of calcium carbonate is (still) not sufficient for indurating the tell soils. The formation of vughs is apparently disturbed by bioturbation and anthroturbation. A massive microstructure is occasionally observed (e.g., Tell Halif; TH1). Commonly observed are angular to sub-angular reddish/brownish blocky peds with massive microstructure and moldic voids, interpreted as degraded earth construction materials (e.g., Friesem et al., 2017), or vesicle voids, related to faunal activity. The calcitic fine material show interference colours that indicate a micritic crystallitic birefringence (b-fabric). This expresses the calcareous nature of the groundmass.

The groundmass includes fragments of varied species of angular and sub-angular carbonate rocks. Fragments of chalk are identified by their dense micritic micromass and embedded foraminifers while fragments of nari-calcrete are identified by a heterogeneous micromass and impregnated pedofeatures. Also observed in the groundmass are quartz grains (mostly silt) and other fine siliceous constituents (possibly phytoliths), potsherds, mud brick material, discrete iron-rich material, bones, shells, well-rounded calcium carbonate spherules (interpreted as faunal excrements), plant residues and root remains with different degree of preservation, and organic fine material (Figs. 5, 6, 7). Much of the organic components are calcified, meaning that they have gone through decomposition and calcification. The occurrence of organic material is related to the influence of biota on the groundmass, unnecessarily associated with human action. Accumulations of needle fibre calcite are infrequently observed. As explained by Verrecchia and Verrecchia (1994), such needle-like features are related to a biogenic source. The observed intensity of micritic hypo-coatings and infillings, which is common in cracks of rock fragments (Fig. 7) is related to incipient calcium carbonate cementation of the groundmass. These micritic features are also interpreted as early diagenesis in the rock fragments.

It is worthwhile to stress two issues regarding the thin sections of this study: 1) Peds and some calcified pedofeatures show calcitic rims that highly resembles micrite hypo-coatings (e.g., Fig. 5d). Described as “wedging effects” (Stoops, 2003, p.15–17), or “edge effects” (Murphy
and Kemp, 1984), these are in fact not pedogenic coatings but rather an apparent (pseudo-) coatings that are related to the production process of the thin sections. 2) Some photographs show slightly different colours compare to others due to the use of different light filters and (transmitted) light intensity during photography (Figs. 5, 6, 7).

The SEM results show variable quantities of micrite cement, quartz grains (most of which are silt size and show rounded surfaces), biogenic filaments, needle fibre calcite, fecal spherulites, calcified rhizospheric filament, charred particles, Eocene micro fauna, including foraminifera (species not identified) and coccolithopore (Umbilicosphaera sp. and Chiasmolithus sp.; e.g., Fig. 8). SEM observations were not sufficient to determine the associated clay minerals. However, the clay fraction in the study area is mostly of interstratified illite-smectite composition (Sandler, 2013).

5.3. Reference profiles: field observations and lab analyses

The land cover of the reference profiles is characterized by a heterogeneity of artifacts, rock fragments and a mosaic of shrubs and annual plants. Also evident at the surface are signs of human presence (agriculture and architecture), various tracks of animals, mounds of mole-rats, and ant nests. The reference profiles differ from the soils of the tells by their slightly darker and/or redder colours, granular to blocky moderate structure, and the occurrence of incipient horizonation (excluding profile TH3a; Table 1). The reference profiles have a dry moisture status and identifiable secondary carbonates. Apart from profile TH3b, all reference profiles are 60–100 cm and includes either one or two Apuk horizon(s) which are embedded with sparse amounts of calcareous rock fragments, archaeological artifacts, shales of land...
parent materials. The sequence consists of two distinct soil profiles. Note that PSD of reference profile TH3 is not presented as an average as this sequence consists of two distinct soil profiles that developed within different parent materials.

snails, occasionally charcoal, and fine roots throughout. The parent rock is calcrete (nari). Most reference soils have a silt loam texture, moderate pH values (7.9–8.4), and a minor content (0.5–1.3%) of OC (Table 1). The reference soil profile of Tell Gezer was exposed to a depth of 60 cm (out of ~100 cm, due to technical difficulties at the time of sampling). This profile is located on a moderate toeslope of a south-eastern aspect along the untilled margins of an active agricultural field, ~680 m east of Gezer (Figs. 2, 5). Two horizons were identified in this profile. The upper horizon (TG3a; 25 cm) has a very dark grayish brown colour and the lower horizon (TG3b; only 35 cm exposed) is very dark brown (Table 1). The reference soil of Gezer exhibit bi-modal PSD that is similar to the tell, but with smaller coarse mode (~15 μm; Fig. 4b). This profile is interpreted as Anthropic Calcic Haploxerepts (Anthric Calcaric Cambisols).

The reference soil profile of Tell 'Eton is located on a moderate toeslope of an eastern aspect at the margins of an ancient agricultural terrace, ~200 m west of the tell (Figs. 2, 6). The profile includes two horizons. The upper horizon (TE3a; 25 cm) has a (grayish) dark brown colour and the lower horizon (TE3b; 30 cm) is dark brown (Table 1). Alike Gezer, the PSD of the reference profile of 'Eton is also finer than the tell soils, but exhibit a tri-modal PSD, with an additional mode at ~8 μm. This profile is interpreted as Anthropic Calcic Haploxerepts (Calcaric Irragic Anthrosols).

The reference soil profile of Tell Halif is located on a moderate toeslope of an eastern aspect and is a part of an erosion gully wall, ~950 m east of the tell (Figs. 2, 7). This profile has a stratigraphy of two soil units; an upper unit (TH3a; 60 cm) overlying a thick buried unit (TH3b; only 160 cm exposed). The upper unit has a dark yellowish brown colour, lack of horizonation and is embedded with noticeable amount of angular carbonate rock fragments, sized 2–5 cm. The boundary between the two units has an abrupt distinctness and smooth topography. The upper soil unit correspond to Calcareous Anthric Haploxerepts (Anthric Calcaric Cambisols). The buried soil has a reddish brown colour, a wedge to prismatic strong structure with vertical cracks, a silty clay loam texture, high content of secondary carbonate accumulations, slickensides, clay coatings, and is embedded with sparse rock fragments (Table 1; Fig. 7). The upper reference soil at Halif presents similar PSD to the tell, whereas the lower reference soil exhibit a tri-modal PSD that is different from all other samples. Thus we refer to the upper soil unit of this profile when comparing it to the soil at Tell Halif. The parent material of the lower unit is loess, as indicated by the content and morphology of its silt quartz grains and PSD (Figs. 4b, 7). The lower soil unit includes three horizons: Bkbs1, Btbs (Jahn et al., 2006; Btbi horizon) and Bkbss3, and it is interpreted as a buried Chromic Calcixererts (Calcic Chromic Vertisols).

5.4. Reference profiles: micromorphological observations

Except for profile TH3b, all reference profiles show complex, mainly vugly, microstructure with open porphyric c/f-related distribution (c/ f4μm limit), and moderately separated sub-angular and angular peds, occasionally including few vesicle voids. The groundmass includes fragments of chalk, ferric material, silt and scarcely also sand quartz grains, shells of land snails, potsherds and organic matter. More frequently observed than in the tells are micritic hypo-coatings and infillings. The Vertisols (TH3b) show sub-angular blocky microstructure with accommodated to partly accommodated planes, moderately to highly separated peds, groundmass with chalk fragments and silt quartz grains. Pedofeatures include micritic infillings and micritic hypo-coatings. Slickensides are probably masked by calcium carbonate. Organic material includes rounded calcium carbonate spherulites, plant residues and root remains, with different degrees of preservation. Organic fine material is also observed but less than in the other reference profiles (Figs. 5, 6, 7).

Summarizing the results, the main observations are as follows: Comparison of the thin sections show that the content of silt quartz grains increases southwards. It also seems that pore systems are more developed in the northern part of the study area than in its southern part (Figs. 5, 6, 7). The reference soil profiles are similar compared to each other by their properties of texture, structure, colour, pH, CaCO₃ content and OC, excluding profile TH3b (Tell Halif; Table 1). Besides differences in colour, horizonation and nature of coarse material (more natural fragments vs. more artifacts in the tells), the reference soils are highly similar to the profiles of the tells (Table 1). Further data regarding the soils in the study area can be found in previous studies (Dan et al., 1972; Marish and Hetzroni, 1983; Dan, 1988a; Koyumdjisky et al., 1988; Singer, 2007, p.86-123; Sapir, 2016).

6. Discussion

Explaining synlithogenic pedogenesis requires evidence for soil formation that acts in concert with sedimentation (Khokhlova et al., 2001; Targulian and Goryachkin, 2004; Shishov et al., 2005; Sedov et al., 2017). Our results show that rocks and mud bricks are the main parent materials in the tells, and that their related fragments are either altered by early diagenesis or aggregated with fine material and organic matter (Figs. 5, 6, 7).
6.1. Evidence of sedimentation

Two main processes are responsible for the high content of carbonate rock fragments: 1) Degradation of earth construction materials associated with dispersal of their coarse calcareous components, possibly with additional contribution of tempers from degraded potsherds, and 2) Disintegration of carbonate rocks, mainly chalk, e.g., the microfauna in the tell soils includes addition of materials from rock weathering (Fig. 8). The mud bricks and rocks must have been subjected to external forces in order to become fragmentized. The human related causes could be architectural and industrial works, midden disposal, and/or violent destruction (Bullard, 1970; Butzer, 1982, p. 89–90; Rosen, 1986, p. 10–15). The main natural causes are most probably rain (that can initiate runoff and mass movement) and
earthquakes (Schiesser, 1987; Friesem et al., 2011, 2014). Records of local earthquakes history extends to the Iron Age IIB (760–750 BCE; Zohar et al., 2017). Today, humans are the main cause of tell erosion in the Judean foothills, mainly through excavations but also through destruction of plant canopies.

6.2. Evidence of pedogenesis

The occurrence of peds, discontinuous carbonate recrystallization, coatings and infillings, are the most prominent indication of pedogenesis in the studied tells. Pedoturbation is interpreted by poor aggregation of the groundmass that is indicated by the weakly welded porous crumb peds that form a vughy microstructure. We relate these features to the massive weak structure of the tell soils. The abundance of carbonate rock fragments in the groundmass with discontinuous recrystallization indicates a fairly low mobilization of CaCO$_3$. That implies that the calcification of tells is contributed mainly by disintegration of geogenic materials (rather than pedogenic). The chalk and calcite fragments are therefore the main source of calcium carbonate in the soil system of the tells.

6.3. Role of biogenic agents

The dense rhizosphere and many signs of recent faunal activity implies that biogenic action might also influence pedogenic processes in tells. The plant canopies increase the stability of soil aggregates and reduce the erosion potential of slopes (Gyssels et al., 2005; Duran-Zuazo and Rodriguez-Plequezuelo, 2008; Erktan et al., 2015). Specifically, basic soil environments favour the interaction of species of the carbonic acid system (CO$_2$, HCO$_3^-$, CO$_3^{2-}$) and Ca ions, to produce calcium
Fig. 7. (a) Drone photo of the Tell Halif, showing locations of the studied profiles. Field photos: (b) Tell profile TH1 showing a hand specimen (small box). (c) Tell profile TH2. (d) Reference profile TH3 (sampling locations are indicated by yellow circles). Thin section scans: (e) Tell profile TH1. (f) Tell profile TH2. (g) Reference profile TH3a. (h) Reference profile TH3b (slides are 2.5 × 7.5 cm). Thin sections photographs, PPL above the same in XPL: material from Tell Halif showing (i) TH1 and (j) TH2: discontinuous recrystallization of the groundmass; massive microstructure; groundmass with calcitic (micritic) crystalitic b-fabric, chalk fragment (cf), quartz grain (qz; noticeably higher content than in Tell Gezer), bone fragment (bf) and organic matter (om); micritic infillings (mi). Discontinuous micritic cementation in crack of an altered chalk fragment (j) shows groundmass that is very much alike sample TH1. (k) TH3a: material from the upper soil unit of the reference profile of Tell Halif; Vughy microstructure, including few vesicle voids (V); groundmass with calcitic crystalitic b-fabric, silt (and scarcely sand) quartz grains (qz) and organic material (om). (l) TH3b: material from the Btss horizon of the lower soil unit of the reference profile; sub-angular blocky microstructure with accommodated to partly accommodated planes (v), peds are moderately to highly separated; groundmass with chalk fragment (cf), silt quartz grains (qz). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Scanning electron microscope images. (a) Material from Tell ‘Eton (sample TE1): Chalk fragment showing coccolithopore (co; Umbilicosphaera sp. and Chiasmolithus sp.), and spherulite (sp). (b) Material from Tell Halif (sample TH1): Rounded silt quartz (qz; > 40 μm sub-angular feature) and calcitic rhizospheric filament (crf).
carbonate (Monger and Wilding, 2017). Further related to calcification, components of anthropogenic wood ash can enter the soil system following the decomposing of calcium oxalate crystals (Liebowitz and Folk, 1980; Regev et al., 2010; Shahack-Gross and Ayalon, 2013). Ca ions can also derive from decomposition of bones (Shinomiya et al., 1998), plants and plant roots (Verrecchia et al., 1993; Franceschi and Nakata, 2005), fungi, and lichens (Verrecchia, 2000; Verrecchia, 2011). The occurrence of needle-fiber calcite indicate a near-surface biogenic influence (Verrecchia and Verrecchia, 1994). It is possible that Ca and CaCO₃ are also related to activity of microorganisms (Pentecost and Riding, 1986; Monger et al., 1991; Gadd, 2007), and that CO₂ derives from rhizospheric respiration (Monger and Martinez-Rios, 2000; Monger et al., 2009). Soil macro-organisms such as earthworms can also contribute as biogenic agents of calcium carbonate redistribution (Canti and Piercare, 2003; Hudson et al., 2015).  

6.4. Synolithogenic pedogenesis in tells  

It is interpreted from the micromorphological observations that the brownish colours of the tells (Table 1) are derived from the combination of rubefied (Fe-stained) clay and fine charred particles in a calcareous (greyish) groundmass (Figs. 5, 6, 7). Clay coatings and infillings are occasionally observed, suggesting dry moisture status and poor translocation of clay during pedogenesis. The strong flocculating (clay aggregation) power of Ca ions demands sufficient decalcification in order for clay particles to disperse and be transported by percolating water (Torrent, 2005). Thus we infer that clay rubefaction formed outside the tell system and that they originated from desert dust. The major input of desert dust to soils in the Eastern Mediterranean occurred during the late Pleistocene (Yaalon, 1987; Crouvi et al., 2017). Locally, the content of silt quartz grains is higher in the southern tells Eton and Halil compared to Tell Gezer which is located 40–55 km respectively to the north (Fig. 1). This difference points to a proximal source of dust located south of the study area (Crouvi et al., 2008, 2017). Therefore, we argue that soils with strong influence of aeolian dust (Yaalon and Ganor, 1973; Fedoroff and Courté, 2013) in the western Judean foothills (Dan, 1988a) are the most likely source of rubefied clay in the tells. The source of charred particles is burnt wood that derive from degraded mud bricks, bonfire remnants and other sources of combusted ligneous matter. It is also possible that some of the charred particles are related to atmospheric aerosol processes rather than human actions (Courty and Coqueugniot, 2013; Courty and Martinez, 2015; Courté, 2017). The buried soils in Tell Gezer possess the same general characteristics as other tell profiles.  

The dominant silt fraction is related to the high content of disintegrated chalk, quartz grains and charred particles. The minor variations in PSD throughout the profiles (Table 1; Fig. 4) are related to pedoturbation and incipient pedogenesis. The archaeology of the studied tells (Faust and Katz, 2015; Sapir, 2016; Borowski, 2017; Ortiz and Wolff, 2017) together with the field and micromorphological observations, suggest that bioturbation and anthropoturbation are the two dominant mechanisms of pedoturbation. The causes of bioturbation are evident by mounds of mole-rats, earthworm channels, ants mounds, and rhizospheric action. The anthropoturbation is related to both ancient (Ortiz and Wolff, 2012; Faust, 2013; Sapir, 2016; Borowski, 2017) and modern human actions (e.g., Macalister’s 1900s excavations; Wolff, 2017).  

The lack of horizonation and the rather uniform content of CaCO₃ in a groundmass of a silt loam texture, together with very low content of organic carbon, suggest a prolonged shortage of moisture in the soil system. This understanding is fortified by the fairly uniform pH values and the discontinuous carbonate recrystallization, both indicating dominance of solid-phase CaCO₃ in the groundmass and its low mobility in the soil solution. One exception is the high pH value found in the upper part of profile TH2 (Table 1; Tell Halil). Sodium has a strong influence on pH in alkali soil solutions (Robbins and Gavlak, 1989; Gupta and Abrol, 1990). It is therefore suggested that this pH value derives from high concentration of Na ions in the groundmass, probably from Na₂CO₃ and/or NaHCO₃ (Goffier, 2007, p.116, 368, 398; Rothenberg, 2014).  

All of the above processes can be put in timeframes. The archaeological record of the studied tells (Ortiz and Wolff, 2012; Faust, 2013; Sapir, 2016; Borowski, 2017) provides maximum age boundaries for the development of the inspected profiles (Table 1). These boundaries define our results with specific chronological context in each profile. The profiles in Tell Gezer, which have been harshly disturbed about 100 yrs. ago, prove that pedogenesis initiated rapidly. Assuming that pedogenesis in the Judean foothills maintained similar rates during the last 3500 yrs., suggests that it acted concurrently with the deposition of cultural materials in the tells, i.e., synolithogenically.  

6.5. Pedogenetic relations between the tells and their peripheral soils  

Comparing the soil fabric and groundmass of the tells with soils of the reference profiles shows that the pedogenic features of the tells are genetically related to those developed outside the tells (Table 1, Figs. 4, 5, 6, 7). However, the stronger structure, incipient horizonation and occasionally darker colours of the reference profiles indicate that the peripheral soils are older and more mature. This could support the broad understanding that tell soils are genetically related with their peripheral soils and that most of the earth materials which were used by ancient cultures, derived from proximal sources (Stoops and Nijs, 1986; Rosen, 1986; Goldberg, 2004; Goldberg and Macphail, 2006, p.227–235; Sapir, 2016; Matthews, 2017). Additionally to differences in pedogenic maturity between the tells and the reference soils, there is also a difference in the distribution of calcium carbonate. While the concentrations of CaCO₃ of the tells are very similar to the reference profiles (Table 1), it is evident that the occurrence of calcium carbonate in the tells is mainly in the form of carbonate fragments. Compared to the tells, the presence of calcium carbonate in the reference profiles is mainly in the form of micritic accumulations and calcified organic matter (Fig. 5, 6, 7).  

6.6. Classification of the tell deposits  

Asking whether cultural deposits are sediments or soils appear to be an issue of interest in geoaarheology (Goldberg and Macphail, 2006, p.11–27, 33–71). Considering that tell deposits are soils, as we show in this study, they can be accordingly classified. Having said that, we argue that tell soils in the Judean foothills are classified as archaeological Calcareous Anthraelitic Xerotherms (‘archaeological’ is currently informal in Soil Taxonomy). The correlative WRB classification would be Calsic Urbic Technosols (Archaic). Soils which are sufficiently classified can be marked on a map. It is therefore suggested that same as with the need of mapping modern anthropogenic soils (Lehmann and Stahr, 2007; Charzyński et al., 2017) tells will be considered as separate mapping units. This might change the situation with archaeological soils which are usually disregarded in soil distribution maps, even in highly dense archaeological environments (e.g., Marish and Soil Survey Staff, 1980; Marish and Hetzroni, 1983; Soil and Pasteure Survey Staff, 1983; Crouvi et al., 2013). Currently, tells are being erroneously designated (even) in low-scale soil maps same as their surrounding soils (Marish and Hetzroni, 1983).  

6.7. Highlighting the need for multidisciplinary cooperation  

“Soils mean different things to different people” (Yaalon, 1993). Tell deposits are often being referred to as ‘fill material’ and are commonly being neglected during archaeological excavations. However, these deposits bear invaluable information for both the reconstruction of past cultural actions (Weiss et al., 1993; Matthews et al., 1997; Stein, 2001; Shillito and Matthews, 2013; Matthews, 2017) and human induced
pedogenesis (Stoops and Nijs, 1986; Ryan et al., 2009; Sedov et al., 2017). It is therefore important to treat tell soils with knowledge of both archaeology and pedology. The necessity of performing multidisciplinary studies when exploring site formation processes has already been strongly underscored (Rapp 1975; Macphail et al., 2017). The sound wake-up call made by Shahack-Gross (2016) regarding the disciplinary studies when exploring site formation processes has also both archaeology and pedology. The necessity of performing multidisciplinary studies when exploring site formation processes has already been strongly underscored (Rapp 1975; Macphail et al., 2017). The sound wake-up call made by Shahack-Gross (2016) regarding the disciplinary studies when exploring site formation processes has also both archaeology and pedology.

2017). It is therefore important to treat tell soils with knowledge of both pedology, requisite to include basic geology in teaching programs of archaeology, should also be applied for soil scientists who seek to explore archaeological environments. Regarding the tools for studying tell deposits, soil micromorphology is found to be amongst the most important methods for analyzing cultural deposits (Courty et al., 1989; Macphail and Cruise, 2001; Tsatskin and Zaidner, 2014; Nicosia and Stoops, 2017; Macphail and Goldberg, 2017). Goren (2013) proved that a relatively low cost and simple micromorphological procedures can easily be applied during active excavations. In light of the above discussion, it would be interesting to correlate pedogenetic processes of Near Eastern tells with other archaeological landforms alike (e.g., Sherwood and Kidder, 2011).

7. Conclusions

Field observations and lab analyses of tell soils of the western Judean foothills show that they are genetically related with their peripheral soils and that they form in a multi-phased synlithogenic pedogenesis. The dominant soil forming processes in tells are disintegration and partial dissolution of archaeological materials, that are associated with pedoturbation, aggregation and limited occurrence of both calcium carbonate redistribution and organic matter accumulation. Buried tell soils are formed by the same synlithogenic pedogenic mechanism. Relative rates of soil formation in tells can be assessed when archaeological records are established. In this study, the tell profiles have formed in either 3500 yrs. to 3000 yrs. Pedogenesis of 100 yrs. has also been demonstrated and discussed, strengthening the hypothesis of synlithogenic pedogenesis. This study provides an example of how archaeological record and pedological characteristics allow the assessment of formation time. The main differences found amongst the soils of the tells and the reference soils are related to time of formation (the reference soils are more mature) and type of coarse material content. The colour and texture of tells is influenced by local disintegrated cultural geogenic materials, degraded mud brick material and charred particles. The overall (macro-scale) structure of tell is determined by the degree of their internal cohesiveness and state of their plant canopies, if present. Incipient cementation might also influence structure development of tells. Pore system of tells is controlled by the intensity of biogenic activity and rainfall. Tell soils are as calcareous as the natural soils, but due to human action, carbonates in the tells are distributed mostly as coarse material rather than in fine (micritic) masses. Synlithogenic soils in tells have been classified as archaeological Calcic Ubric Technosols (Archaic). The scarcity of pedological studies of tells necessitates further study of this subject. These conclusions imply that pedological approach should also be put into practice in studies of other ancient anthropogenic landforms, such as agricultural terraces.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.catena.2018.03.014. These data include the Google maps of the most important areas described in this article.

References


