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Sediments in Ancient Ruins in Jordan as Archives of Dust Deposition and Land Use

Abstract

Archaeological structures are usually subject to sedimentation after their abandonment. These sediments ("debris") come partly from collapse and are often removed as quickly as possible in order to study artifacts and the intact remains of the structures. However, in the semi-arid and arid climates of Jordan, sediments of the debris contain (or consist of) aeolian dust. Thus they represent a potential environmental archive comparable to the famous loess sequences of the Negev. The latter mostly lack Holocene layers, meaning that the debris preserved in archaeological sites might be suited to continue dust records through the Holocene. A systematic comparison of sediments preserved in different archaeological structures (hilltop ruins, cisterns, and terraces), actual dust storms, and natural sediments around Petra in southern Jordan is presented in this contribution. Results suggest that long-range deposition of silty, calcareous sediment continues until today and that the terrace sediments and the material culture associated with them allow for reconstructions of ancient land use patterns.

Introduction

Pleistocene desert loess deposits in the central and northern Negev desert have been investigated as important records of dust deposition, accumulation, and soil development (Yaalon and Dan 1974; Bruins 1976; Bruins and Yaalon 1979; 1992; Issar and Bruins 1983; Bowman *et al.*, 1986; Goldberg 1986; Gerson and Amit 1987; Goodfriend and Magaritz 1988; Zilberman 1992; Crouvi *et al.* 2008; 2009). In Jordan, loess-like sediments were postulated (Bender 1974; Cordova 2007), but have been documented only in few cases (see summaries in Lucke *et al.* 2013; 2019a). Holocene deposits of settling dust were hardly recorded (Faershtein *et al.* 2016).

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This limits interpretations of Pleistocene loess, because it is not certain whether its dust sources and climate were similar to the current situation.

In order to fully understand the significance of terrestrial archives of aeolian sediments, they should be compared with dust in the atmosphere. A comparison of Holocene aeolian sediments with current dust could therefore significantly improve the understanding of dust deposition in drylands. The absence of Holocene loess in the Negev has been attributed to pronounced rainfalls which lead to erosion rather than accumulation (Avni *et al.* 2006). In addition, stronger winds during the Pleistocene (with its comparatively longer time frame than the Holocene) have been proposed to produce silt-sized particles by abrasion of mobilized sand dunes (Crouvi *et al.* 2008; Enzel *et al.* 2010). However, Swet *et al.* (2019) could not identify abrasion of silt-sized particles from quartz grains during wind tunnel experiments. Therefore, it seems likely that other processes than aeolian abrasion governed dust supply. Silt deposition may have been mainly a result of medium-range transport (Roskin *et al.* 2014).

Variations of the dust dynamics may have played an important role for landscape changes in the southern Levant. Reduced amounts of settling dust at the onset of the Holocene were suggested by Faershtein *et al.* (2016) to lead to smaller sediment loads, and thus more intense runoff with stronger discharges. Changes of fluvial dynamics from sediment aggradation to incision and erosion and vice versa may thus have been less the result of rainfall variations or base-level changes, but could mainly have been triggered by dust supply.

Archaeological Structures as Holocene Dust Archives?

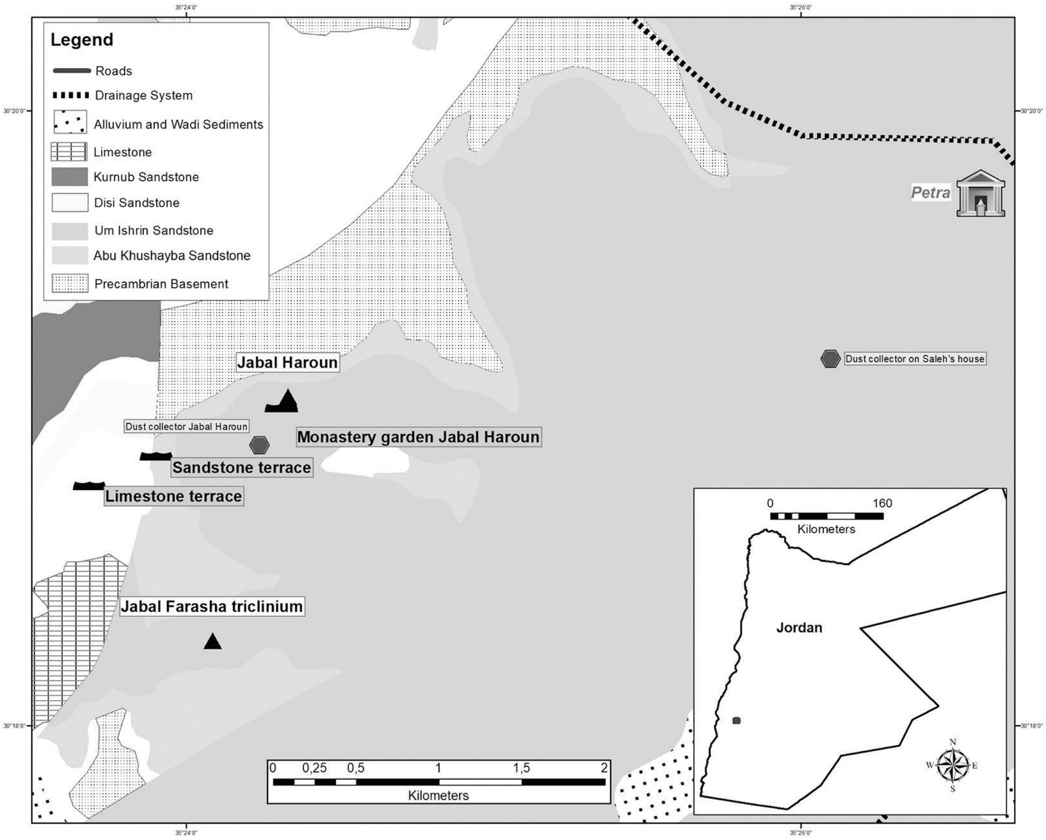
The Negev loess provides fertile soils for agriculture where irrigation by collected runoff or from cisterns is practiced. Ancient agricultural terraces in the Negev reduced runoff and consequently, incision and erosion diminished (Avni *et al.* 2019). Sediments that accumulated behind ancient terrace walls were found to contain a significant portion of (partly reworked) aeolian dust (Bruins and Jongmans 2012). Aeolian dust accumulated, as well, in the ruins of houses and other built structures (Lucke *et al.* 2005; 2019a; 2019b; Lucke 2008; Porat *et al.* 2013; Junge *et al.* 2016; 2018). Sediments in archaeological ruins, hitherto unexplored, are thus potential environmental archives of Holocene dust dynamics in the southern Levant.

We investigated sediments potentially comprising Holocene dust from the following structures at Jabal Hārūn near Petra in Jordan (Fig. 1):

- Ruins on hilltops: aeolian sediments were deposited after their abandonment.
- Agricultural terraces: accreted sediments until they reached the top of the terrace walls.
- Current dust collected in dry traps: standard marble traps were continuously sampled.

Study Area: The Sandstone Mountains near Petra

The study sites lie in the vicinity of Petra, at the mountain Jabal Hārūn (site of the pilgrimage sanctuary of Aaron/Haroun) where comprehensive surveys of off-site archaeological material were carried out by the Finnish Jabal Hārūn Project (FJHP; Kouki and Lavento 2013). The climate is arid (BWh classification according to Köppen–Geiger system, Peel *et al.* 2007), with rains occurring mostly from November to March. Mean annual rainfall in the Petra region is 153 mm (Wādī Musā weather station, 1984–2011), with high variations: 274 mm in the wettest season 1987/88 during the above-mentioned period, or 42 mm in the



1. Overview and geological map of the study area. Hilltop ruins are marked with triangles, terraces with wall symbols, and collectors of current dust with hexagons.

driest season of 2010–2011.

The area is dominated by Cambrian continental sandstones of 900–1200 m elevation, with Horst structures related to the Dead Sea transform fault that led to a highly diverse geology. Patches of limestones and igneous rocks are present at the surface (Barjous 2003). Soils and sediments in the region have a significant sand fraction, derived from local fans and eroded sandstones (Lucke and Bäumler 2007). However, calcareous sediments within archaeological structures have a significant silt fraction, which represent long-range dust transport during the Holocene (Lucke 2017; Lucke *et al.* 2019a; 2019b).

The various archaeological ruins investigated during our project have been described elsewhere in detail (Lucke *et al.* 2019a; 2019b; forthcoming). This contribution focuses on summarizing evidence from two hilltop ruins and three terraces. One of the latter is situated in remains of a rectangular enclosure next to the ruins of a monastery on Jabal Haroun, which is suspected to represent the remains of a garden (Silvonen *et al.* 2013).

The Monastery Garden (Rectangular Enclosure) of Jabal Hārūn

This area may have been irrigated with water from large cisterns in the monastery,

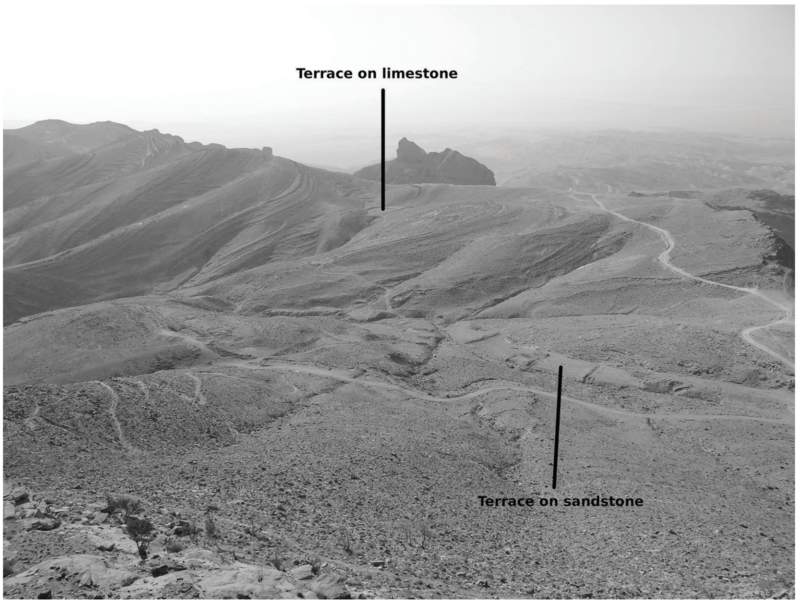
2. View from the summit of Jabal Hārūn at the remains of a rectangular structure next to the ruins of the monastery.

as its potential catchment for the collection of runoff is very small. We excavated a profile near the center of the enclosure (N 30.31665, E 35.40518; Fig. 2). It was 70 cm deep and contained various pieces of charcoal, bones, and pottery, suggesting the deposition of garbage probably representing manure (Lucke *et al.* forthcoming). The soil was classified as Protic Arenosol (Alcalic, Ochric) according to WRB (2015). Our survey of the pottery cover found 0.24 pieces/m^2, preliminarily dated to the Byzantine-Umayyad (transitional?) period, with a small Nabatean component and probably some Late Islamic sherds. The profile contained a few Late Byzantine and Early Islamic pottery sherds at the surface, two Early Byzantine pottery pieces in 40 cm depth, and some Late Roman pottery at the bottom. For more detailed description, see Lucke *et al.* (2019a; forthcoming).

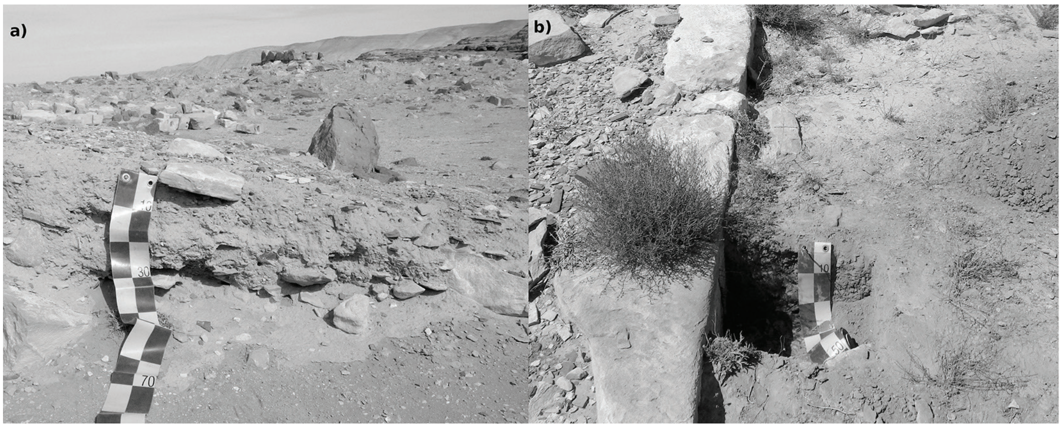
The Terraces

The western slope of Jabal Hārūn hosts one of the largest runoff cultivation systems of the mountain, associated with a sandstone scarp and ridge of dolomitic limestone (Fig. 3). We excavated one profile in a terrace on sandstone, in the center of sector C of site 33 of the FJHP (N 30.31404, E 35.39839). It was 140 cm deep, with silt-dominated sediment from 140–70 cm depth. From 70 cm to the top, the soil was sand-dominated. Sediments reached the top of the wall, *i.e.*, the structure had completely filled. The soil was classified as Protic Calcaric Arenosol (Colluvic) over Protic Calcaric Regosol (Colluvic). Our pottery survey found 0.06 pieces/m^2, mainly Nabatean from the 1st–2nd century AD, and few Late Roman, Byzantine, Early Islamic, and Late Islamic sherds. For more detailed descriptions, see Lucke *et al.* (2019; forthcoming).

The second terrace profile is located on a slope of dolomitic Turonian limestone (Wādī as-Sīr formation; Barjous 2003—FJHP area K, site 60; N 30.31244, E 35.39476; Fig. 3). It was 70 cm deep and contained homogeneous, silt-dominated sediments. The soil was classified as Protic



3. View from Jabal Hārūn at the two investigated terraces.



4. a) Soil covering the hilltop ruin of the monastery on Jabal Hārūn, b) soil covering the hilltop ruin of Jabal Farāsha.

Calcaric Regosol (Colluvic) according to WRB (2015). Our pottery survey found 0.06 pottery pieces/m^2, all dating to the 1st–2nd century AD.

The Hilltop Ruins

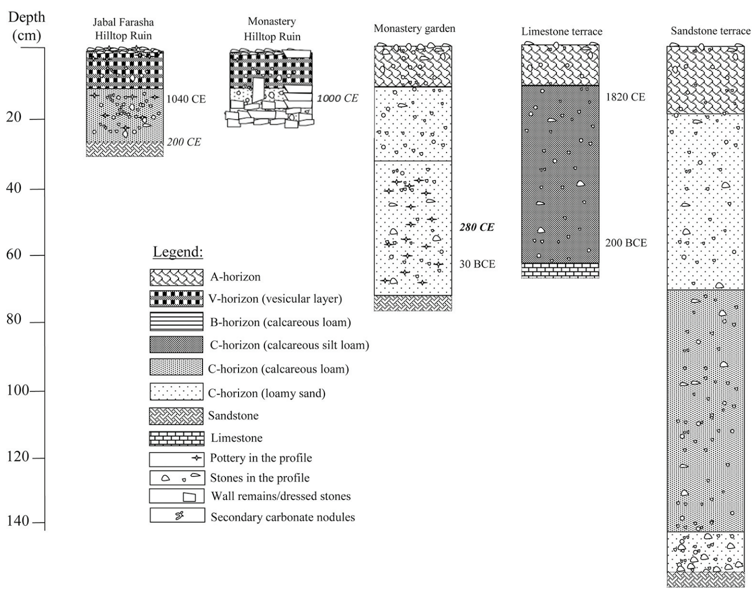
The debris covering ruins of archaeological structures in the investigation region comprise significant shares of calcareous silt, which are most likely of aeolian origin, in particular in case of hilltop ruins. As the ruins of the monastery on Jabal Hārūn are located on a flat sandstone plateau surrounded by ravines, they represent such a hilltop situation. The uppermost 10 cm of sediments exhibited a vesicular layer below a clast cover, and showed strong reaction to HCl (Fig. 4a; N 30.31734, E 35.40418). Vesicular layers are known to result from processes of aeolian sedimentation (Turk 2012). At the remaining walls of the monastery, it could be observed that mortar made from mud had been used to close gaps in the walls during their construction. Therefore caution was exercised not to sample such mud mortar remains, but only the aeolian, post-abandonment sediments covering the monastery. Due to the elevated position of the sampled profile, fluvial deposition seemed very unlikely. The soil was classified as Protic Arenosol (Aridic, Aeolic) according to WRB (2015).

In addition, sediments covering the remains of a Nabatean triclinium on Jabal Farāsha were sampled, facing Jabal Hārūn to the south-west (N 30.30445, E 35.40141; Fig. 4b). Again, a clast cover and vesicular layer were present at the surface. The soil that developed in these aeolian sediments was classified as Calcaric Leptosol (Protic) according to WRB (2015).

Results

Substrates of Soils Covering Archaeological Ruins

Fig. 5 summarizes the sampled profiles. More detailed results were presented elsewhere (Lucke *et al.* 2019a; 2019b), and this contribution summarizes those results relevant for archaeology. The hilltop ruin soils exhibit vesicular layers below a crust and clast pavement, which clearly demonstrate their formation directly during aeolian deposition processes. Current dust samples deposited with precipitation in the Petra region consists of similar, calcareous silt loam (Lucke *et al.* 2019a; 2019b). Vesicular horizons could not be discerned in terrace soils, but the substrates are very similar. This suggests that fluvial deposition processes and plowing destroy bedding structures and homogenize substrates, but that the parent material of terrace soils is mainly of aeolian origin, too (Lucke *et al.* 2019b).



5. Summary of substrates and soil horizons of the studied profiles. Available OSL-ages are given in normal letters, ages from archaeological context in italics, and 14C-ages in bold and italics (see Lucke *et al.* 2019a; 2019b for detailed age results).

While the terrace on dolomitic limestone showed very homogeneous soil cover, a sandy layer poor in $CaCO_3$ was present in the upper part of the sandstone terrace profile. This indicates an increasing contribution from weathering sandstones, probably connected with a lack of maintenance of terraces covering the sandstone scarp during the Middle Ages (Lucke *et al.* forthcoming).

Compared to the triclinium on Jabal Farāsha, the monastery ruin soil showed elevated sand contents. This indicates that either weathered sandstone rocks surrounding the plateau provided a significant aeolian sand contribution, or that mud mortar was blown out of the walls (Lucke *et al.* 2019a).

In the hilltop ruins, there was no evidence of hiati. Average sedimentation rates in the hilltop ruin of the triclinium on Jabal Farāsha could be calculated as 0.14 mm/a, or ~125 g m^2 a^{-1} (Lucke *et al.* 2019b), which is very similar to results from current dust collection in the Negev (Kidron *et al.* 2014), and higher than those of Pleistocene hilltop loess (Crouvi *et al.* 2009). On Jabal Hārūn, however, deposition rates were twice as high than on Jabal Farāsha. This seems connected with the presence of rock cliffs overlooking the plateau where the monastery is located, providing a significant, aeolian sand fraction from weathering sandstones (Lucke *et al.* 2019b). As well, an aeolian contribution of the dolomitic limestone could clearly be identified in both terrace profiles due to elevated Mg-contents (Lucke *et al.* 2019b). This points to a prominent role of local dust sources.

Fluvial processes such as runoff irrigation of the terraces seem to play a role for the speed of sediment aggradation, but not the composition of the substrates. There is no connection between fluvial catchment size and sediment properties. Aeolian processes and sources dominate; therefore, the composition and primary deposition of substrates in all archaeological soils is dominated by aeolian sediments, which are only re-distributed by runoff.

In-Situ Soil Formation?

Parameters of soil weathering intensity suggest that in-situ soil development is minimal or absent, but that the soils covering archaeological ruins in the Petra region consist of mixtures of diverse pre-weathered materials from various sources (Lucke *et al.* 2019b). These mixtures could be modeled statistically, indicating that a certain grain size distribution including most particle size classes, plus rather high concentrations of various major and trace elements, is characteristic of soils covering archaeological structures (Lucke *et al.* 2019b). They can be distinguished from dust, rocks, and natural soils with high certainty. Their composition points to an important role of accretion processes, whereas deflation seems absent. Soils covering archaeological ruins are characterized by higher shares of fine fractions, in particular a relative enrichment of silt associated with elevated contents of various major and trace elements (Lucke *et al.* 2019a; 2019b).

Role of Precipitation

Dust samples associated with snow and rain show a very different composition than other dust samples. They are characterized by higher contents of silt and $CaCO_3$, and are depleted in SiO_2, but enriched by all other major and trace elements (Lucke *et al.* 2019b). This suggests that these elements, as well as extractable iron and magnetic susceptibilities, are bound to a calcareous silt fraction that settles to a higher degree when associated with precipitation. In addition, the snow dust sample was exceptionally large, and snowfall in the Petra region associated with minimal runoff. As the snow melts slowly, water infiltrates more or less completely into soils, minimizing erosion and fostering vegetation and biological soil crusts (Lucke *et al.* 2019a). If snowfall was more frequent in the Negev during the Pleistocene, this could be one explanation of increased dust deposition during that time.

Role of Wall Remains, Clast Covers, (Biological) Soil Crusts, and Vegetation

Biological soil crusts are known to trap and fix dust < 50 µm (Danin and Ganor 1991), and similar sediment-fixing effects could be connected with the clast covers at the surface (similar to "desert pavements," McFadden *et al.* 1998). Vegetation, in contrast, could so far only be shown to trap sand (Kidron 2019). Sediment accretion in hilltop ruins could therefore be connected with the presence of biological soil crusts and clast covers. The ruins reduce or prevent runoff, provide wind shadow, retain rainwater to some degree, and vegetation is usually minimal. All surfaces of hilltop ruins soils were covered by clasts and crusts. These conditions could explain why dust accumulates there, but not in most of the natural landscape.

Terraces as Archives of Past Land Use

Lucke *et al.* (forthcoming) were able to retrieve palynofacies debris, pollen, and phytoliths from terrace soils. Remains of aquatic species suggest standing water in puddles behind terrace walls, and possibly also in reservoirs for several months, indicating that massive barrages originally served for the collection, storage, and re-distribution of runoff water. This indicates the presence of a sophisticated irrigation system. As well, contents of plant-extractable phosphate as well as elevated biomarker ratios marking the presence of human excrements indicate manuring (Lucke *et al.* forthcoming). These were largest in the monastery garden, suggesting that densities of off-site pottery scatters likely correspond to manuring intensities, as found elsewhere in Jordan (Lucke *et al.* 2019). This points to a systematic agricultural use of the terraces near Petra during antiquity.

Discussion and Conclusion

One basic premise of most studies dealing with desert loess is that primary (hilltop) terrestrial sediments represent more or less directly the material that was moved through the atmosphere (*e.g.*, Crouvi *et al.* 2008; 2009; 2010). Formation of desert loess was therefore mainly approached from the supply side, based on the assumption that its genesis depended primarily on generation and transport of sufficient silt through the atmosphere (see summary in Smalley *et al.* 2019). Considered silt-generating processes were mainly collision of dune sand grains during aeolian transport (Enzel *et al.* 2010) as an origin from glacial grinding seems unlikely.

However, various other processes such as fluvial comminution, aeolian abrasion, insolation weathering, salt weathering, frost shattering, volcanism, and deep weathering of saprolite can produce silt and develop a range of local dust sources (Wright 2007; Ojha *et al.* 2018). Fluvial comminution in turbulent flow, such as during the frequent flash floods in the southern Levant, was found the most effective short-time process of silt production (Wright *et al.* 1998). This suggests that local sources such as fans of wadis may provide significant amounts of silt-sized sediment. In addition, settling and suspended dust in the atmosphere were found to differ (Singer *et al.* 2003; 2004). This could be due to changing local sources that are mobilized during variable storm events (Yaalon and Ginzbourg 1966; Offer and Goossens 2001; Ganor and Foner 2001; Crouvi *et al.* 2017), mix with suspended dust, potentially form aggregates or coatings during transport (Mahowald *et al.* 2014; Kok *et al.* 2017) and thus possibly "harvest" suspended dust from remote sources (Lucke *et al.* 2019b). Formation of aggregates and/or clay and oxide coatings might be enhanced under precipitation, which could explain the different composition of dust samples that were associated with rainfall and snow

(Lucke *et al.* 2019a, 2019b). In this context, the sampling method of current dust plays a role: Kidron *et al.* (2014) showed systematic differences between dry and wet dust samplers.

Aeolian sediments in archaeological structures near Petra indicate that vegetation, surface crusts, and clast pavements play key roles for dust fixation (Kidron 2019; Lucke *et al.* 2019a). The formation and composition of desert loess might therefore not only be a function of remote dust sources, but also of local dust supply, and of deposition processes leading to (possibly selective) fixation of aeolian material (Lucke *et al.* 2019a; 2019b).

The importance of local sources for dust deposition in the Levant could in general have been underestimated due to a focus on well-rounded or subangular quartz grains indicating aeolian abrasion. Earlier studies found that hilltop ruins in northern Jordan likely comprise a significant dust component but disregarded the evidence from soil structure and substrate composition as particles proved under the microscope to consist largely of angular or weakly rounded calcite fragments (Lucke *et al.* 2005; 2014; Lucke 2008; Kemnitz and Lucke 2019). However, in light of the evidence for a significant contribution of local sources from southern Jordan, it seems well possible that such particles are transported by wind from the surrounding limestone rocks. This suggests that aeolian deposition in hilltop ruins is a common process in arid and semi-arid areas, which may have supplied approximately 20 cm of hilltop ruin soil cover during the past 2000 years in northern Jordan (Lucke 2008; Lucke *et al.* 2019).

Archaeological missions excavating hilltop ruins should consider investigating debris as important, hitherto unexplored environmental archive of post-abandonment dust deposition.

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