



# Ancient trash mounds unravel urban collapse a century before the end of Byzantine hegemony in the southern Levant

Guy Bar-Oz<sup>a,1,2</sup>, Lior Weissbrod<sup>a,1</sup>, Tali Erickson-Gini<sup>b</sup>, Yotam Tepper<sup>a</sup>, Dan Malkinson<sup>c</sup>, Mordechai Benzaquen<sup>d</sup>, Dafna Langgut<sup>d</sup>, Zachary C. Dunseth<sup>d,e</sup>, Don H. Butler<sup>e</sup>, Ruth Shahack-Gross<sup>e</sup>, Joel Roskin<sup>e</sup>, Daniel Fuks<sup>f</sup>, Ehud Weiss<sup>f</sup>, Nimrod Marom<sup>a,e</sup>, Inbar Ktalav<sup>a</sup>, Rachel Blevis<sup>a</sup>, Irit Zohar<sup>a</sup>, Yoav Farhi<sup>g</sup>, Anya Filatova<sup>a</sup>, Yael Gorin-Rosen<sup>h</sup>, Xin Yan<sup>i</sup>, and Elisabetta Boaretto<sup>i</sup>

<sup>a</sup>Zinman Institute of Archaeology, University of Haifa, 3498838 Haifa, Israel; <sup>b</sup>Archaeological Division, Israel Antiquities Authority, 84965 Omer, Israel; <sup>c</sup>Department of Geography and Environmental Studies, University of Haifa, 3498838 Haifa, Israel; <sup>d</sup>Sonia and Marco Nadler Institute of Archaeology, Tel Aviv University, 6997801 Tel Aviv, Israel; <sup>e</sup>Department of Maritime Civilizations, Leon H. Charney School of Marine Sciences and the Leon Recanati Institute for Maritime Studies, University of Haifa, 3498838 Haifa, Israel; <sup>f</sup>Martin (Szusz) Department of Land of Israel Studies and Archaeology, Bar-Ilan University, 52900 Ramat Gan, Israel; <sup>g</sup>Department of History, Ben-Gurion University of the Negev, 8410501 Beer-Sheva, Israel; <sup>h</sup>Glass Department, Israel Antiquities Authority, 91004 Jerusalem, Israel; and <sup>i</sup>Dangoor Research Accelerator Mass Spectrometer Radiocarbon Laboratory, Weizmann Institute of Science, 76100 Rehovot, Israel

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The historic event of the Late Antique Little Ice Age (LALIA) was recently identified in dozens of natural and geological climate proxies of the northern hemisphere. Although this climatic downturn was proposed as a major cause for pandemic and extensive societal upheavals in the sixth–seventh centuries CE, archaeological evidence for the magnitude of societal response to this event is sparse. This study uses ancient trash mounds as a type of proxy for identifying societal crisis in the urban domain, and employs multidisciplinary investigations to establish the terminal date of organized trash collection and high-level municipal functioning on a city-wide scale. Survey, excavation, sediment analysis, and geographic information system assessment of mound volume were conducted on a series of mounds surrounding the Byzantine urban settlement of Elusa in the Negev Desert. These reveal the massive collection and dumping of domestic and construction waste over time on the city edges. Carbon dating of charred seeds and charcoal fragments combined with ceramic analysis establish the end date of orchestrated trash removal near the mid-sixth century, coinciding closely with the beginning of the LALIA event and outbreak of the Justinian Plague in the year 541. This evidence for societal decline during the sixth century ties with other arguments for urban dysfunction across the Byzantine Levant at this time. We demonstrate the utility of trash mounds as sensitive proxies of social response and unravel the time–space dynamics of urban collapse, suggesting diminished resilience to rapid climate change in the frontier Negev region of the empire.

ancient urban trash mounds | societal collapse | Late Antique Little Ice Age | Byzantine period | southern Levant

Research on the Byzantine Empire's decline in the sixth century CE and its linkage with volcanic eruptions, rapid climate change, and pandemic raises broader concerns regarding the limits of human resilience in the face of environmental catastrophes. The recent documentation of the Late Antique Little Ice Age (LALIA) climatic event in dozens of natural and geological climate proxy archives of the northern hemisphere, and constraining of its beginning to the 530s and 540s CE (1, 2), has reinvigorated the climate and history debate in Byzantine and early Islamic histories (3–6). Societal collapse is a hotly contested ground, with considerable uncertainty and debate surrounding the impact of historical natural disasters and suggested societal consequences, and whether they alone could unleash direct and deeply transformative effects on ancient complex societies (7, 8). In this regard, the pertinent historical and archaeological records on Byzantine (late Roman) societal response to the LALIA event remain fragmentary, coarsely resolved, and subject to po-

larized interpretations (5, 9). Despite the pivotal significance of consilience frameworks of environmental and societal data for understanding grand historical trajectories of the first millennium CE, major gaps remain and the evidence continues to be heavily weighted in favor of the environmental data and weak on the side of the social record. Here we develop an explicit model of social response in-context, within the archaeological record of material culture. We apply an approach using trash mounds as archaeological social archives to document Byzantine urban decline in the Negev Desert of the southern Levant. The demise of Byzantine era intensive urbanization and agricultural development in this frontier arid region has long been discussed in connection with historic climate fluctuations, although the debate has been underscored by a general absence of direct and well-contextualized evidence for the timing and pattern of societal decline.

## Significance

Historians have long debated the role of climate in the rise and fall of empires of the 1st millennium CE. Drastic territorial contraction of the Byzantine Empire, societal decline, and beginning of the European Middle Ages have generally been linked to the Islamic conquests of the seventh century. This multidisciplinary archaeological investigation of trash mounds in the Negev Desert establishes the end date of organized trash management in the Byzantine-period city of Elusa and demonstrates urban collapse a century before the Islamic transition. Our findings, taken together with other evidence for Byzantine urban dysfunction, the Justinianic Plague, and recent research on the Late Antique Little Ice Age, flesh out the impact of the sixth century on broad historical trajectories.

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<sup>1</sup>G.B.-O. and L.W. contributed equally to this work.

<sup>2</sup>To whom correspondence should be addressed. Email: [guybar@research.haifa.ac.il](mailto:guybar@research.haifa.ac.il).

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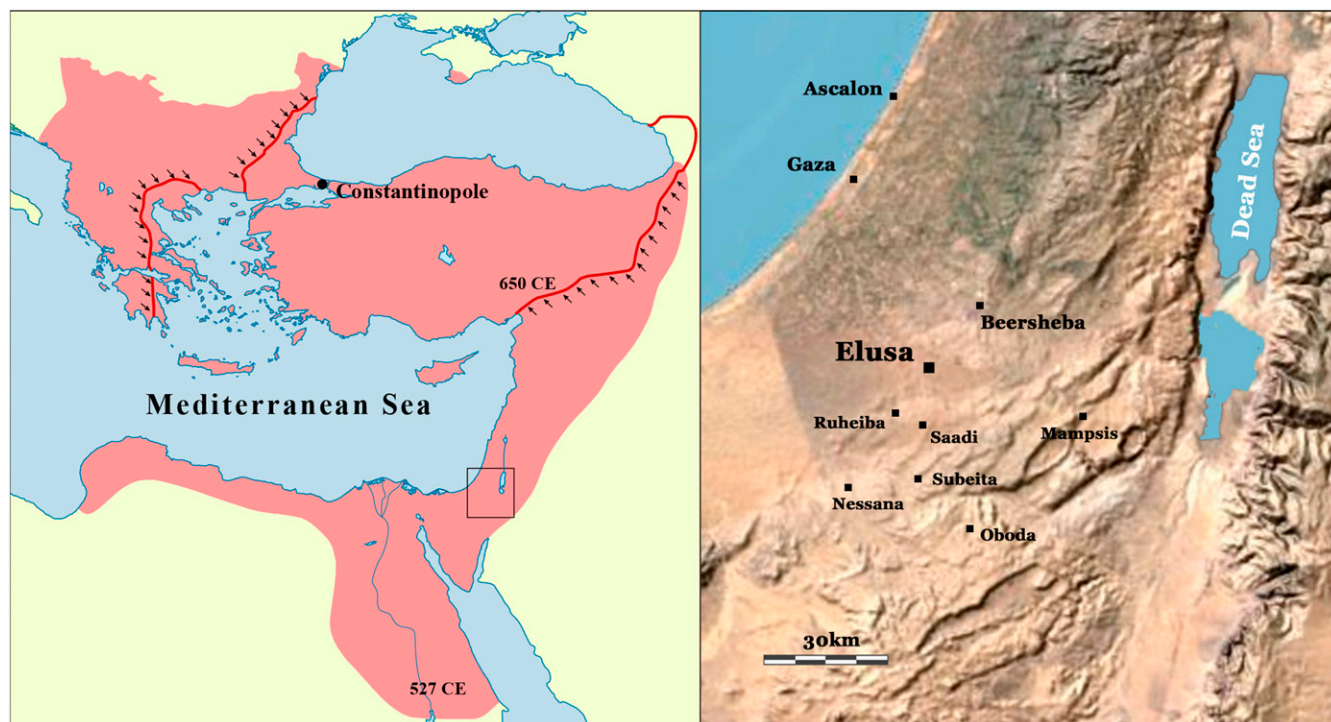
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The historical impact of the sixth century CE in the eastern Roman Empire (Byzantium) (Fig. 1), although it is considered a time of relative political stability and great imperial territorial expansion, has been highlighted by recent arguments drawing on the LALIA-related cold climate events and their suggested triggering effect on outbreaks of the Justinianic Plague. The Negev Desert, with its spectacular and unusual spike in settlement and economic activity beginning around the fourth century CE, and enhanced ecological sensitivity of its arid environment, make it a veritable litmus case for detecting regional decline in the urban record and societal response to LALIA-associated developments by the sixth century CE. It has been suggested that at this time the Levant saw a radical transformation in the organization of Byzantine cities, bringing to an end a 1,000-y-old classical concept of city planning and administration. The work of Kennedy in the 1980s and of later scholars on the sixth century archaeology of Levantine cities overturned previous conceptions of a seventh century Islamic decent into a “Dark Age,” revealing instead an earlier and more gradual process of transformation and decline in the urban arena, the focal point of Byzantine social and political hegemony (10–12). In parts of modern Syria, Jordan, and Israel reductions in the upkeep and expansion of cities from the mid-sixth century was suggested by studies of public architecture, monumental construction projects, and major infrastructure. Diminished rebuilding combined with disruptions to existing wide street layouts, baths, and theaters, which were the hallmark of the classical ideal of urban planning and basic services. These signal the shifting conceptions of the role and function of cities (see also ref. 13). However, urban change through the late Byzantine and early Islamic periods remains largely an invisible process lacking in decisive physical evidence, where archaeologists continue to be at odds regarding the timing, pace, and political context of change. Much of this debate

centers on methodological complexities in tracing decline within the archaeological record of the urban domain. Challenges to current research include the limited exposure of most excavations, partial preservation, coarse resolution of relative chronologies, and infrequent application of absolute dating. This reality often results in ambiguous temporal sequences of structural reuse and abandonment, difficulties in setting the end date of many classical period structures, and incoherent picture of the connection between urban decline and potential causes.

Our approach employs ancient urban landfills as a type of archaeological proxy for social processes, and a highly complementary record to that of architectural remains. Within the urban domain, dense and dynamic human occupation over time created an exceedingly complex architectural record. Ancient landfills, on the other hand, were located away from residential areas, formed by habitual and organized trash disposal in designated locations, and have the potential to form less disturbed and more continuous records. These valuable archives have largely been overlooked by researchers interested in questions of societal collapse. The archaeology of formal trash deposits in urban settings is underdeveloped, lagging greatly behind recent advances in elucidating the social dimensions of waste-related behavior in modern urban societies (14, 15). Although large mounds found outside many important ancient cities across imperial Romano–Byzantine territories indicate the widespread practice of organized trash collection and disposal (15–18), only a handful of these have been systematically probed by archaeologists, and none in the context of research on urban collapse.

In this study we apply a multidisciplinary program to large-scale trash mounds surrounding the Byzantine city of Elusa (Fig. 2), Negev Desert, tailoring a trash-based model of social response to



**Fig. 1.** (Left) Map of the Byzantine Empire at the beginning of the reign of Justinian in the year 527 CE (area in red), shortly before the territorial gains following from the Justinianic wars in Asia, Africa, and Europe. Black arrows represent the devastating territorial contraction of the Byzantine Empire in the wake of the Sasanian Wars and early Islamic conquests of the seventh century. (Right) Location map of the city of Elusa and Byzantine period village network of the Negev. Base map generated from intellectual property of Esri and its licensors and are used under license. Copyright © 2009–2019 Esri and its licensors. All rights reserved.



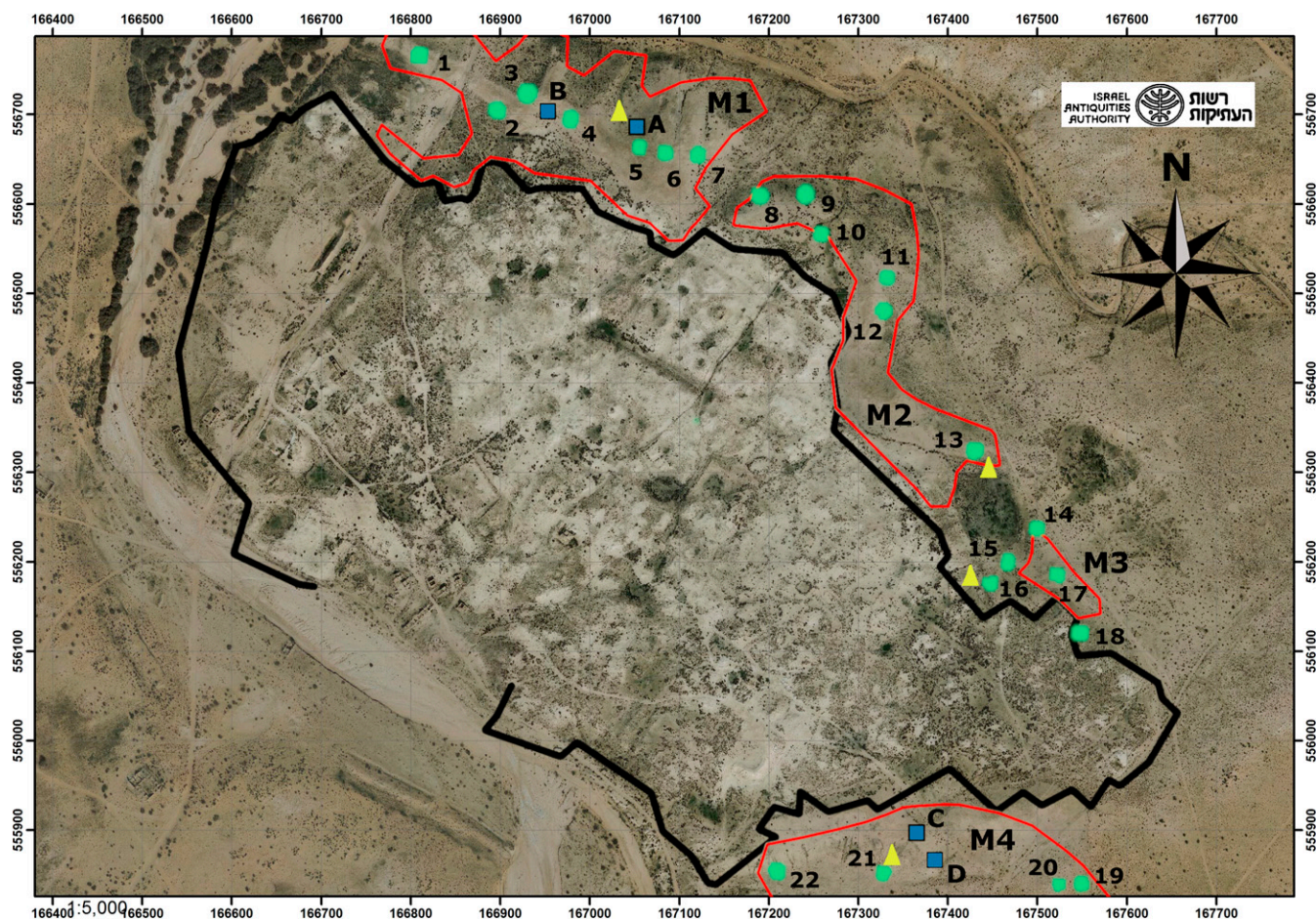


Fig. 2. Survey, probing and excavation locations in Mounds M1 to M4 shown on an aerial photo of Elusa: circles 1–22, survey quadrants; triangles, dating probes; squares A–D, excavation trenches. Mound polygons in red identified from our DEM and the reconstructed outline of the ancient settlement taken from Saidel and Christopherson (23) (Fig. 5).

the particular archaeology and history of the site. We analyze organized trash disposal as a proxy for high-level societal functioning in the urban complex. We specifically use the end date of formal trash disposal on the scale of an entire city as a proxy for systemic urban decline. The Elusa mound phenomenon is analyzed in terms of its scale, geomorphology, sedimentology, stratigraphy, chronology, and material culture contents, to determine the temporal span, spatial pattern, and especially the terminal date of trash deposition. We quantify the overall scale of Elusa's peripheral mounds through a combination of spatial survey and geographic information system (GIS) analysis, and assess the contribution of trash to mound formation through geoarchaeological sediment analysis. To determine the terminal date of this phenomenon on a city-wide scale, a composite dating strategy of both absolute and relative techniques is applied (radiocarbon dating and ceramic, glass, and coin typologies), together with an analysis of large quantities of surface survey artifacts. Finally, we analyze the contents of mound deposits (botanical and zoological remains) to assess continuity in trash accumulation activities in the centuries before their demise.

Our findings reveal the terminal date of orchestrated trash removal at Elusa around the mid-sixth century CE, nearly a century before the Islamic conquest of the southern Levant, commensurate in time with a series of well-dated volcanic eruptions, cold climate events, and initial outbreak of the Justinian plague. Given the international ties of the Negev with trade networks of the Byzantine Empire, particularly with respect to

the export of the famed “Gaza wine” from the southern Levant (19, 20), we situate our findings in the broader context of economic relations and connections with central Imperial administrations.

### Byzantine City of Elusa

The Byzantine period city of Elusa in the northwestern Negev Desert lowlands was the hub of a network of seven smaller, village-scale settlements and hundreds of scattered farmsteads (Fig. 1). The urban nature of Byzantine Elusa is evidenced by its estimated size of 39 ha and the remains of extensive public buildings, including a theater, gymnasium, public baths, churches, and pottery workshops (21–26). This reality is also echoed in literary sources of the fourth–seventh centuries CE, which describe the site as a regional administrative center (27). Elusa evolved from a small waystation on the Nabataean trade route between the third century BCE and second century CE to an important regional urban center of the Byzantine period from the fourth century CE. During its florescence the city was sustained by an extensive food-producing hinterland, spread across the northern Negev highlands (estimated area: approximately 2,000 km<sup>2</sup>), widely attested by relict field systems of terraces, dams, infrastructure for run-off irrigation and floodwater control, and a wide range of agricultural installations suited to desert farming (28, 29).

Much less is known in regards to the end of the Negev's Byzantine settlement system, although it is clear that its major phase of expansion was followed by severe depopulation of the



region sometime between the late Byzantine period and Middle Ages. In the rural farming sector of the Negev, some degree of continuity into the Islamic period has been established, although this was likely on a much reduced scale of activity (12). Archaeological evidence from Elusa itself, and literary references to it in the Nessana Papyri, indicate that the site may have continued to function as late as the seventh century CE, possibly across the Islamic transition of 640 CE. However, on present evidence, it appears that Elusa did not survive as a functioning urban center into the Islamic period. Early Islamic period ceramic sherds found at the site in earlier excavation campaigns were sporadic (21, 22, 25, 26), and more recently it was shown that Umayyad period (seventh–eighth centuries CE) remains were present in only one of five excavation areas within Elusa, and were associated with insubstantial architectural remnants of this period (24). The question that we address in this study concerns the timing of collapse of urban functions within Elusa, when it is also highly likely that the organization of the Negev's Byzantine settlement system as a whole around a major urban center began to deteriorate. By focusing our investigation on the trash mounds of the city and relating organized trash disposal to high-level urban functioning, we consider the possibility that the urban decline of Elusa began long before its eventual abandonment.

**Delineating the Urban Scale of Elusa's Trash Management.** This study is concerned with a series of conspicuous mounds of varying shapes and sizes flanking the contour of Elusa to the north, east, and south of the settled area. Using a digital elevation model obtained from high-resolution drone photography (1.8 pixel/cm), we estimate the total volume of Elusa's mounds at over 1,200,000 m<sup>3</sup>, covering an area of >10 ha (*Materials and Methods* and *SI Appendix, Table S1*). Our GIS data, ground-truthed through field survey, uncovered four main mound areas: three located immediately to the northeast of Elusa (M1, M2, and M3) and one (M4) to the south, with M1, M2, and M4 each larger than 3 ha and M3 of considerably smaller extent, approximately 0.36 ha (Fig. 2). Our documentation efforts capture the entire phenomenon of mounds in the vicinity of Elusa. No additional mounds were recorded by us or are known from previous surveys in the Elusa catchment area.

Despite the settlement's position within the northwestern Negev dune field, it was protected from extensive sand build-up due to its location on a natural ridge at the confluence of two streambeds. Further assessment of geomorphic features of the mounds indicates their good state of preservation and anthropic origin. The circular to oval shape of the mounds generally indicates the limited impact of attrition or accretion due to aeolian or fluvial processes. With elevations of 2.45–5.09 m above the present day surface, these mounds have moderate slope angles, 5–20°, well below the repose angles of aeolian sand dunes in the region (32°–36°). Few signs of slope wash could be detected other than the occurrence of several shallow gullies. The base of the mounds lacks evidence of fluvial erosion or marked colluvial wedges or aprons, the characteristic erosional features of natural loess slope deposits in the region.

We further employed excavation and geoaerological analysis to show that trash dumping at the periphery of the settled area of Elusa was the primary process of mound formation (*Materials and Methods*). Trenches of different sizes excavated into the mounds revealed complex stratigraphy with variation in sediment color, texture, proportions of anthropic and geogenic constituents, and whether or not sediments have been heated in the past. A tight succession of dumping events through 14 distinct sediment layers was uncovered in a 1.3-m-deep section dug into the tallest peak [Figs. 2 (M1: Trench A) and 3 and *SI Appendix, Table S2*]. Evidence for postdepositional disturbance is minimal. Using mineralogical analysis by Fourier transform in-

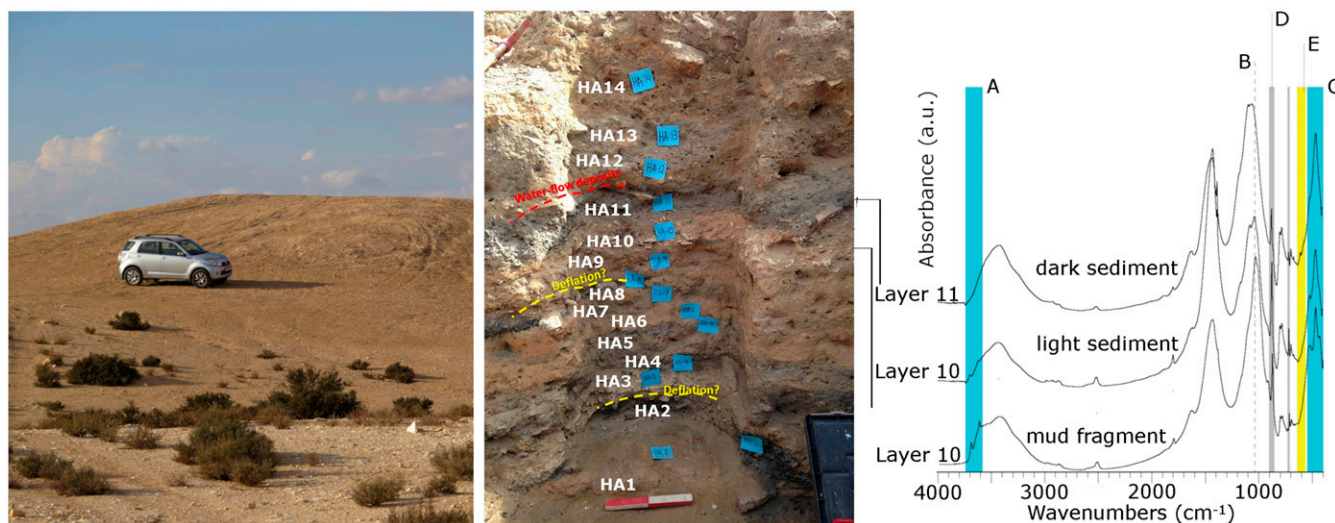
frared spectroscopy, we were able to confirm the anthropogenic origin of the layers and identify multiple discrete dumping episodes. We distinguished between layers comprised of refuse from domestic fire installations (dark colored) and other layers comprised of construction debris (light colored).

Dark colored, fine-grained layers were primarily characterized by mixtures of heated clays (~500 °C), calcitic ash, gypsum, and carbonated hydroxylapatite (Fig. 3). This mineralogical assemblage is typical of ashes, especially those formed by mixed fuel sources (i.e., wood and dung). No evidence was detected for in situ burning, as such a process typically generates a distinct macrostratigraphic basin-shaped deposit comprised of a sequence of rubified, charred, and ashy layers. Hence, the burned materials appear to be the result of dumping of cool ash refuse from rake-out of domestic fire installations originating within the city.

Other light-colored layers were primarily coarse-grained. None of these layers showed any indication of heat alteration, and we suggest that they are the remains of dumped construction materials (Fig. 3). The source of some of the construction waste in these layers seems to be mud mortar similar in composition to that of modern mortar we observed between building stones in recent abandoned Bedouin structures near Elusa. Few large pieces of construction waste (<5) were also uncovered in the excavation.

**Timing the End of Trash Mound Formation.** To date the end of Elusa's phase of intensive urban trash management with high fidelity, we employed a composite dating design combining relative and absolute chronometric techniques. We first retrieved close to 15,000 ceramic sherds by conducting a systematic, expansive field survey of surface ceramics, covering the entire northwestern-southern periphery of the site and all existing mounds with 22 quadrants (5 × 5 m) (*Materials and Methods* and Figs. 2 and 4). By current conventions of south Levantine ceramic typology and seriation for the classical period, we classified the ceramic sherds as Hellenistic (fourth–first century BCE), Roman (first century BCE–fourth century CE), Byzantine (fourth–seventh centuries CE) and Early Islamic (seventh–eighth centuries CE), and subdivided the Byzantine period into phases of early (approximately 350–450 CE), middle (450–550 CE), and late (550–640 CE) (*SI Appendix, Fig. S1*). Analysis of this ceramic collection showed that it encompasses all main temporal phases of the Hellenistic–early Islamic timeframe, but with wide variation in numerical representation and spatial distribution of the different temporal phases (*SI Appendix, Table S3*). Our findings indicate a high-intensity of trash accumulation during the early–mid Byzantine period, and markedly decreasing intensities in subsequent periods. Sherds of Gaza storage jars—the hallmark of early–mid-Byzantine ceramic assemblages and purported vessel of the well-known Byzantine wine of the Negev (30; see also ref. 31)—account for over a third of our collection. In overall numbers, they overwhelm those of bag-shaped jars, which gained prominence in the southern Levant only from the late sixth century Byzantine period following a decrease in circulation of Gaza jars at that time. Bag-shaped jar to Gaza wine jar ratios ≤ 1:10 appear in nearly all survey quadrants where both types occur (*SI Appendix, Table S3*). Only in a single quadrant are the two types more or less on par (1:2).

We also examine whether there are statistically significant differences in the probability of sherd presence between successive periods in the survey quadrants, using only the time-sensitive specimens ( $n = 305$ ; 2%). We use these probabilities as a proxy for the intensity of trash production during the different periods. Logistic regression analysis was conducted, where period was the independent explanatory variable of sherd presence. The analysis reveals a clear peak in the early–middle Byzantine (approximately 350–550 CE) with sherds of the middle Byzantine being present in 78% of the sampled survey quadrants (Fig. 4). This proportion was not significantly different from the early



**Fig. 3.** (Left) View of trash mound M1 of Elusa (Photo by G.B.-O.); (Center) 1.3-m-deep east section in Trench A, mound M1, with its sequence of alternating layers of dark and light color sediment (HA1–HA14) (Photo by R.S.-G.). Macroscopic signs of slight erosion were observed in the field in HA12 (red-dotted line: fine bedding of water-laid deposits) and in HA8 and HA2 (yellow-dotted line: possible wind-deflation of fine sediment particles leading to high abundance of macro charcoal pieces). (Right) Infrared spectra of the mineralogy of dark- and light-colored sediment layers. The darker-colored sediment of HA11 contained clay heated to temperatures between 500 and 600 °C, shown by the absence of clay hydroxyl groups in the 3,600-cm<sup>-1</sup> region [A: clay hydroxyl groups (OH) 3,697, 3,620 cm<sup>-1</sup>], a leftward shift in the main clay peak from 1,035 to 1,045 cm<sup>-1</sup> [B: clay (Si-O-Si) 1,035–1,045 cm<sup>-1</sup>], and the loss of the valley separating the clay peaks at 519 and 462 cm<sup>-1</sup> [C: clay (Si-O-Al) 519 cm<sup>-1</sup>; clay (Si-O) 462 cm<sup>-1</sup>]. The presence of ash in this sediment was evidenced by the characteristics of the calcite peaks [D: calcite (C-O) 875, 713 cm<sup>-1</sup>], and the accompanying hydroxylapatite [E: hydroxylapatite (P-O) 605, 565 cm<sup>-1</sup>]. Light-colored sediment from HA10 showed no signs of heated clay or ash, and the characteristics of its calcite peaks indicated that the mineral is of geogenic origin. HA10 also contained mud fragments likely derived from mud mortar.

Byzantine period ( $\chi^2 = 0.51$ ,  $P = 0.474$ ), but was significantly different from the late Byzantine sherd presence of only 45% ( $\chi^2 = 5.82$ ,  $P = 0.016$ ). This decreasing trend also continues into the early Islamic (Umayyad) period, although without statistical significance for the change between the late Byzantine and early Islamic phases ( $\chi^2 = 0.04$ ;  $P = 0.83$ ).

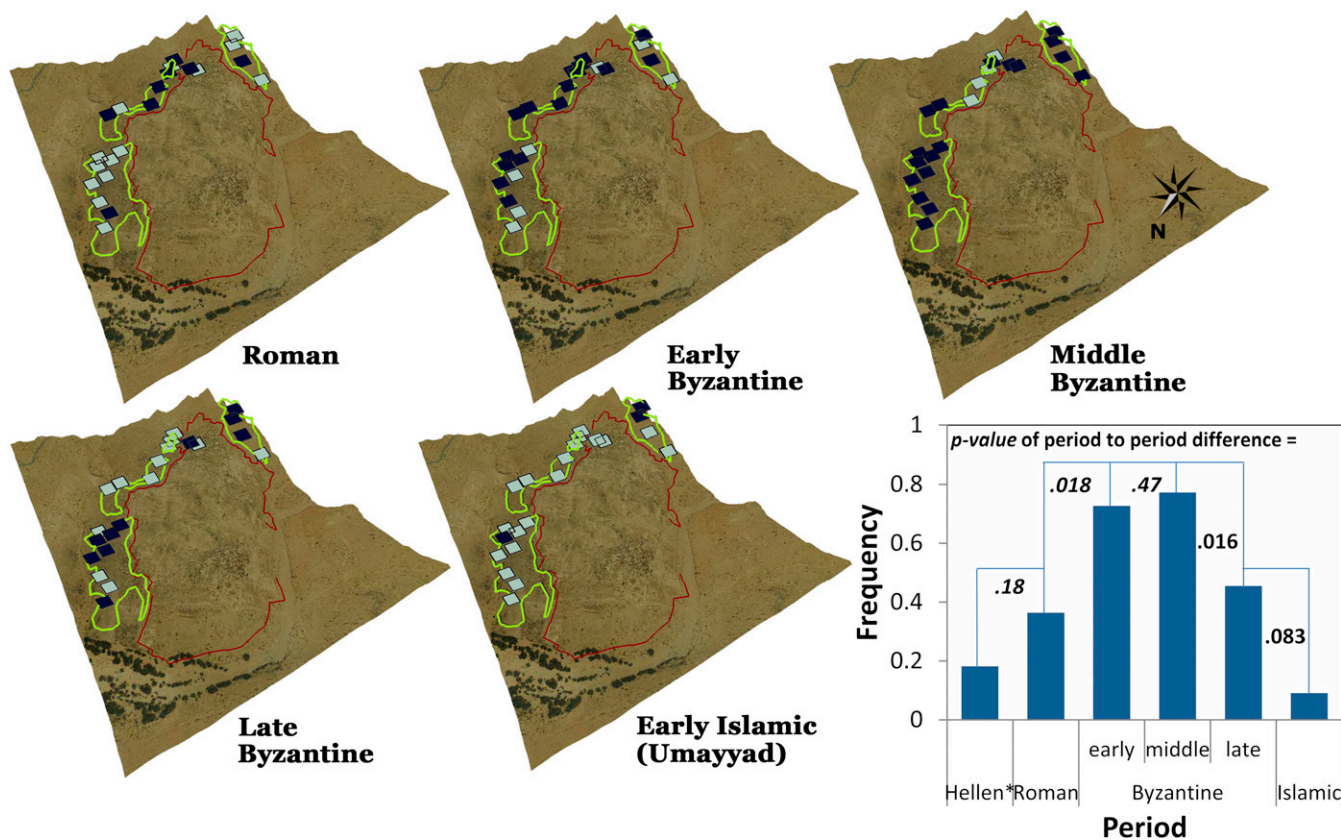
In a second stage, we analyzed ceramic assemblages from four excavated trenches (2 × 2 m) of varying depths in two of the main identified mound areas, two probes in the southern mound area (70-cm depth), and two in the northern area (130-cm depth) (*Materials and Methods* and Fig. 2, Trenches A–D). In support of the survey results, excavation produced assemblages with only early–mid Byzantine diagnostic sherds, lacking late Byzantine or any later material (*SI Appendix*, Fig. S1). This is demonstrated mainly by the widespread presence of Gaza jar sherds, Majcherek's Form 2–3 (30), the ceramic “type fossils” of the early–mid Byzantine period. Additional analysis of diagnostic coins ( $n = 32$ ) (*SI Appendix*, Fig. S2 and Table S4) and fragments of glass ware ( $n = 2,350$ ) (*SI Appendix*, Fig. S3 and Table S5) from the survey and excavated trenches further verifies these observations. No late Byzantine or early Islamic ceramics or other find categories were identified within any of the excavated trenches.

Using carbon dating of short-lived materials (seeds and charcoal), we further fine-tune the terminal date of Elusa's trash accumulation. Datable materials were extracted from charcoal-rich lenses or layers in four excavated probes, which were strategically located in relation to the four identified mounds and near survey quadrants containing late (late Byzantine–early Islamic) ceramics (*Materials and Methods*, Fig. 2, and *SI Appendix*, Fig. S4). The dating samples represent the topmost layers of the mounds (approximately 0.5-m depth; four dates), and in Trench A also a vertical succession running to a depth of approximately 1 m (four additional dates). None of the obtained eight calibrated dates with their probability distributions of  $\pm 2\sigma$  extend beyond the mid-sixth century CE (Fig. 5 and *SI Appendix*, Table S6): seven dates cover a range of approximately 150 y in the middle Byzantine

(400–550 CE), whereas a single earlier date falls in the third century CE (late Roman). As these absolute determinations also sample the topmost layers of domestic trash found in each of the probes, they provide the best possible estimation of the *terminus ante quem* for the final use of the trash dumps at Elusa.

The possibility that any later materials of the sixth or seventh century were present within the Elusa trash mounds in consequential amounts but evaded our dating sampling strategy is highly unlikely, given the combination of exhaustive GIS documentation of the mound distribution, extensive surface survey coverage of the mounds, and multiple subsurface probes. This conclusion is strongly supported by the fact that different artifact types (ceramics, glass, and coins) from survey and excavation, together with direct dating of short-lived botanical remains, all point in the same direction of the rare aboveground presence of such late materials across the mounds and their absence in the subsurface probes. Nor is there any reason to suspect that putative later trash deposits existed but were eroded with time. Allowing for some degree of erosion of the mounds, although our geomorphic and sedimentological observations indicate that erosion was minimal in deposition and postdepositional phases, we would still expect the heavier surface artifacts from different periods to remain generally in situ and in reach of our surface survey effort. Long-term continuity preceding the end of mound formation is indicated in a comparison of excavated material contents (remains of livestock, charcoal, cultivar seeds, fish, and mollusks) (*SI Appendix*, *SI Text 1* and Tables S7–S9) in two of our trenches, which are separately dated by ceramic typology and radiocarbon to the early and middle phases of the Byzantine period (Fig. 2, Trenches A and B). Quantitative comparison of contents between the two trenches reveals only slight variations between the two temporal phases of trash deposition, with minimal indication for any subsistence shift that could be related to environmental stress before the end of trash accumulation. It is possible that at that time trash disposal shifted from the mounds to within the settled area of the city, and that ad hoc



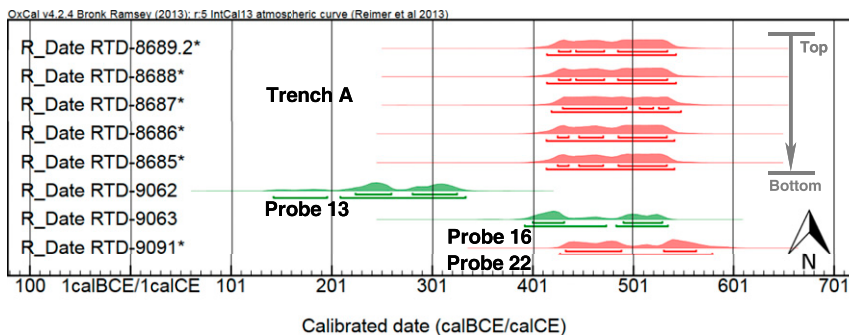


**Fig. 4.** Distribution of period-sensitive ceramics from survey data (22 quadrants: 5 × 5 m) in the Elusa trash mounds, indicated by yellow polygons (identified in our DEM), surrounding the reconstructed outline of the ancient settlement [adapted from Saidel and Christopherson (23)] (Fig. 5). In each period map, filled rectangles represent the presence of diagnostic ceramics attributed to that temporal phase (notice orientation of northing arrow). (Lower Right) The *P* values of period to period differences of sherd occurrence from logistic regression analysis, showing a clear and significant peak in the early–middle Byzantine followed by a decline into the late Byzantine and continuing into the early Islamic period (\*Hellenistic).

dumping replaced organized removal, although evidence for this is not available from excavations within Elusa.

**Interpretation of the Elusa Mound Phenomenon.** Our findings from Elusa accord with previous interpretations of the archaeology and historical context of the site, showing that the Byzantine period constituted the height of settlement activity in the Negev (12). The varied datasets from the mounds taken together demonstrate the massive extent of trash dumping between the fourth and sixth centuries. Although the base of the mounds was not reached in our excavation trenches, the results from relative

and absolute dating of both survey and excavation materials clearly suggests the existence of mounds predominantly from the early and middle phases of the Byzantine period, and establish the lengthy duration and high intensity of trash accumulation near the site. The preserved dynamic sequence of dumping episodes seen in the dense alternation of thin layers and lenses in the excavation trenches varyingly represents household ash and construction waste. This strongly supports a reconstruction of habitual removal of trash from the city to designated dumping locations in the mounds over a long period of time. The estimated overall rate of trash accumulation in these mounds is



**Fig. 5.** OxCal (54) plot of calibrated AMS carbon 14 dates from Trench A in mound M1 (five dates in stratigraphic succession) and in three 1 × 1-m excavation probes; charcoal, red dates (catalog numbers with asterisks); seeds, green dates (*Materials and Methods* and Fig. 2; wiggle-matching curve of the carbon 14 dates in *SI Appendix*, Fig. S4). See also ref. 55.

approximately 6,000 m<sup>3</sup> per year (1,200,000/200 y), only about three orders-of-magnitude less than in modern urban landfills of megacities in developing world countries (10,000 tons per day) (32), not controlling for population size and volume reduction methods. The tight stratigraphic succession of five dates with significant 2σ overlaps through a meter of depth in our Trench A suggests an accumulation span anywhere between a century and a decade. This could indicate an extremely rapid accumulation rate, although a plateau effect within the sixth century calibration curve with somewhat inflated 2σ ranges is also a possibility.

The fall-off in trash accumulation in the Elusa mounds occurred between the middle and late Byzantine phases, as shown from our combined dating efforts. Given that the mounds represent material trash that could only have been brought from inside the settled area of Elusa, and that was hauled on a massive scale over time, the mounds should provide a sensitive proxy of the mode and level of intensity of organization within the urban context. Trash management at the municipal level was already known in the Mediterranean world as early as the fifth century BCE. Although ad hoc trash disposal—inside the living quarters of cities—was also widespread throughout antiquity, it is reasonable to assume that trash collection and disposal, sanctioned and financed by centralized city authorities, was a widespread ideal in the Roman and Byzantine worlds, especially in contexts of economic affluence and of notions of public hygiene (33). The end of trash accumulation at the Elusa mounds could be an indication of a shift from organized trash clearance at the municipal level to a different strategy of trash management, which discontinued the use of designated dumping locations in outside mounds. Ad hoc dumping by individuals within the city limits is a likely possibility, although the information presently available from excavations in the settlement is insufficient to assess this hypothesis. The cessation of use of the outside dumps of Elusa for urban maintenance, and possible shift to dumping inside the settlement, indicate a drastic change in the local population organization and density, and in the function of the site as a regional urban center. As the settlement seems to have outlived its trash dumps, continuing at least into the late Byzantine period and possibly into the early Islamic, this terminal event should signal the beginning of urban decline for Elusa and the Negev's wider settlement system organized around it. Judging from our survey evidence for a marked reduction in the frequency of surface ceramic types between the middle and late phases of the Byzantine period (sixth century), the intensity of human activity and occupation at this time may have reverted to that of pre-Byzantine times (<450 CE).

**Reevaluating Byzantine History in the Negev.** The Byzantine period settlement boom of the Negev Desert, with its heights of population density and agricultural productivity, was an exceptional event in this region's history, not to be seen again until the modern era. The existing records from both history and archaeology, which abundantly document the Negev's unusual Byzantine spike in settlement intensification (12, 27, 34, 35), have remained ambiguous as to its terminal date and underlying reasons for the decline. This decline has often been attributed to the decades and even centuries following the Islamic conquest (reviewed in ref. 12). What little can be deduced with confidence from the fragmentary historical documents of mainly bureaucratic letters in the Nessana Papyri suggests that Elusa retained certain administrative functions as late as the latter half of the sixth century and early seventh century CE, such as a record office (letter 24 in ref. 36) (569 CE), a court (letter 29 in ref. 36) (590 CE), and the church (letter 51 in ref. 36) (early seventh century CE). The latest of the dated papyri (674–690 CE) show that by the early Islamic period Elusa had lost its standing as a provincial capital to the coastal city of Gaza (letter 32 in ref. 36). At Nessana itself, the local military unit in charge of defense of

the region, which is the subject of the “soldiers’ archives” section of the papyri, is believed to have been disbanded much earlier by the final decade of the sixth century (37). Hence, the degree to which these records speak to a reality of settlement gradual decline, abrupt break, or continuity in the Byzantine Negev is entirely unclear.

The evidence from urban trash mounds is presently by far the most direct proxy for societal decline predating the Islamic transition in the Negev. It builds on predictable integrated connections between Elusa's trash management on the one hand and its overall functioning as an urban settlement in the classical style on the other, and between the level of societal organization of the Negev settlement system as a whole and that of Elusa as its urban center. The amalgam of relative and absolute dates from the ancient trash mounds of Elusa establishes a clear mid-sixth century *terminus ante quem* for the region's Byzantine-period bout of intensive urbanization. The end date of coordinated and large-scale trash clearance at Elusa signals the decline in the city's high municipal standards of living introduced during the Roman and Byzantine periods, indicating an overall downgrading in the regional level of socio-political organization. It is likely that some degree of continuity beyond this benchmark was experienced in the momentum of settlement within Elusa itself and in farming of the surrounding rural sector. This is evident from scattered seventh century archaeological findings in Elusa (21, 24), and references to it in the Nessana Papyri (36). The decline that we see at Elusa might, on a regional scale, reflect the decentralization and ruralization of the local settlement system. In the smaller-scale nearby agricultural settlements of Sobota and Nessana occupation seems to have persisted through this period, although here as well depopulation and administrative lapse at some level may have begun by the Byzantine period (*SI Appendix, SI Text 2*). Within the agricultural sphere, dating studies of agricultural installations (radiocarbon) near Sobota and Elusa point to a sixth century abandonment, although dating of terraces (optically stimulated luminescence) elsewhere in the Negev provides a general time range that surpasses the sixth century and continues well into the Islamic period (28). However, the historical and archaeological evidence that is securely assigned to the sixth century in the Negev is exceedingly meager. Recent excavations have begun to uncover a more complicated picture of settlement dynamics than has been previously appreciated, pointing to the varied trajectories of different sites within the Negev settlement system (*SI Appendix, SI Text 2*). There is presently nothing in the regional record to counter the evidence for reduced urban functionality and collapse in the sixth century.

Historians generally agree that the initial surge of Byzantine settlement and demographic expansion across the eastern Mediterranean followed from the east–west division of the Roman Empire in the fourth century and the establishment of Constantinople as the second Rome (20, 37–39). At its core, the Byzantine political and territorial hold in the eastern provinces was vested in urbanization and cities by promoting local elites with ties and obligations to imperial authorities, rather than direct military control using stationed armies. The most dramatic, on-the-ground evidence for Byzantine peak settlement expansion comes from the archaeological record of frontier regions, such as the Negev, where agricultural production was marginal due to the arid climate (38). Here and in similar areas, such as the Syrian Limestone Massif and Hauran regions, we see the large-scale transformation of rural into an urban settlement and unparalleled development of sophisticated arid-land farming systems, a dynamic that has been termed the “greening of the desert” (40). It could be argued that the downturn trend that this study documents at Elusa reflects only a localized phenomenon of the Negev. However, by the sixth century declining investment in cities throughout the Levant has been linked to the diminishing role of urban centers in the imperial administrative

structures and dwindling civic autonomy, with the effect of dampening the urban lure among the wealthy class of landowners residing in the countryside (10). Archaeological evidence from important Byzantine urban centers and regional capital cities of the southern Levant as Gerasa, Scythopolis, and Caesarea indicates the widespread transformation in the urban arena of the sixth century, although its interpretation in the context of decline or continuity is subject to considerable ambiguity and has been disputed among scholars (10, 12). Why, then, did Elusa and the Negev experience the decline more vigorously than in these major population centers, to the level of collapse in municipal functioning and eventual population abandonment at its urban core?

The demise of the Negev's unique and likely labor-intensive system of arid-land development in the mid-sixth century occurred at a time of military expansion for the Byzantine Empire when geopolitical circumstances were comparatively stable. Instead, it is suggested that the marginal Negev system was inherently vulnerable and dependent to an extent on access to external markets or outside subsidies, leading to its decline in the context of wider urban crisis and climatic upheavals. It is possible that over time the societal ramifications of these external stressors were highly variable across different regions, depending on the local conditions of environmental carrying capacity and social and economic strategies for buffering unpredictability. In all likelihood, within such a challenging environment as that of the Negev, climate change and its wider demographic and economic consequences for international ties to commercial networks would have interacted with local societal factors to produce a compound effect. Urban decline could have been more visible in the Negev because of the region's enhanced sensitivity and delicate ecological balance.

**The Role of Climate in Byzantine Sixth Century History.** This study addresses a deep structural imbalance in present consilience frameworks of the joined history of climate, disease, and society of the sixth century CE. The present near-invisibility of large-scale climatic disasters or pandemic in the archaeological record of this period is striking, whereas widespread climate change has been widely documented in geological and historical records. The documentation of pandemic in historical and genetic archives has been less complete. This archaeological reality is partly an artifact of existing methodological challenges in research on the architectural record of complex urban settlements, underscoring the need to pull together information from multiple different and more sensitive types of proxy records in the study of societal decline. The combined weight of the evidence from survey, excavation, sediment, and spatial GIS analysis, and radiocarbon dating of the Elusa trash mounds reveals clear discontinuity in trash build-up around the mid-sixth century CE. These data indicate the collapse of the city's Byzantine era urban infrastructure well in advance of the terminal date of regional Byzantine hegemony. The sixth century of the eastern Byzantine Empire has been associated with climatic upheavals, pandemic, urban transformation, and internal societal and political unrest (37, 38), preceding by as much as a century the geopolitically turbulent period of the early seventh century CE recurrent warfare with the Sassanid Empire, and subsequent historic conquest of the southern Levant by a rising Islamic power. The LALIA is an extreme cold climatic anomaly of the last two and a half millennia, with its beginning anchored to a series of massive volcanic eruptions in the 530s and 540s CE (5, 6). Apart from its proposed general association with major historical events of widespread warfare, pandemics, droughts, and famines over a broad timespan of more than a century, the LALIA event is yet to have been unequivocally linked to specific evidence of human response or systemic societal decline in any particular locality or site of the Byzantine Empire. This study does not purport to

establish a direct causal or mechanistic link with the LALIA, nor is archaeology generally able at present to provide the kind of fine temporal resolution coupled with the potential for wide spatial correlation of most geological climate archives. However, it does furnish archaeological, socially contextualized evidence for a breakdown in societal functioning on a city-wide scale that is chronologically well-constrained to the onset of the LALIA climatic event and the concomitant Justinianic plague outbreak of the year 541 CE.

The Byzantine settlement anomaly of the Negev Desert, occurring on a background of millennia of small-scale and largely nomadic human presence, has long piqued scholarly fascination and generated debate surrounding the role of climate in its rise and fall (9, 41). The crux of the question has always been whether to attribute this anomaly to human ingenuity or changing climatic conditions. Recent attempts by paleoclimatologists to detect definitive connections between historical events in the Negev and specific, localized, and relatively short-term fluctuations in the climate record of the first millennium CE have come up short due to insufficient chronological and regional resolution in natural archives, such as the Dead Sea sediment cores and beach exposures and Soreq cave speleothems (42–44). Presently, the most direct paleoclimatological evidence for the Negev comes from data on local dune-field mobilization and encroachment due to increased cold weather and windiness, which is generally dated to the mid-late part of the first millennium (600–900 CE) (45). Although this may also indicate drier conditions, disentangling climatic effects from those of human vegetation clearance in dune exposure is still problematic.

With the evidence for the LALIA climatic anomaly in records from several continents, its global repercussions and well-constrained contemporaneity with the plague outbreak, all beginning near the mid-sixth century, it is time to reconsider the role of climate in the settlement history of the Negev. The societal consequences of climate change need neither be direct nor abrupt, as often envisaged in images of collapse, even within the more sensitive environment of the Negev. Settlement and urban decline, triggered by external stressors, could have been a long, drawn-out, and ultimately additive process, especially considering the lengthy overall duration of the LALIA event of over a century (1), and the fact that the Justinian pandemic had a recurrence cycle of about a decade over roughly the same period (6, 13). Intensified local drought events could have directly depressed agricultural production in a system highly dependent on artificial water-harvesting technologies. However, indirect effects on the Negev could have also flowed down the line from regions in the northern hemisphere, which were more directly impacted by the extreme volcanic winters of the third and fourth decades of the sixth century (1, 2). Recent ice-core data from the European Alps demonstrates a sharp drop in lead pollution around the mid-sixth century tied to reduced production and circulation of silver coinage, with far-reaching implications for the overall volume of the imperial monetary economy and trade (46). It is possible that diminished purchasing power in the imperial centers of Byzantium, coupled with demographic declines due to the pandemic outbreak around that period [although mortality rates have been greatly debated (see, for example, ref. 47)], could explain diminishing investments in the provincial cities, and in exported agricultural produce of the Negev by external markets. The abundant evidence from grapevine farming in the Negev, its connections to the nearest port at Gaza through the Incense Road routes, local importance of overland transport of goods using camel caravans, and distribution of different types of amphorae—the likely wine containers of the period—all point to the strong connections of the Negev to international markets (20). It has also been suggested that the Byzantine period wine trade linking the Negev to these global economic networks was of sufficient high profitability to rationalize the tremendous



expenses involved in overland transport to the port of Gaza (20). Steep declines in market trade during the sixth century, also seen in the sharp drop in numbers of Mediterranean shipwrecks of that century (figure 3.12 in ref. 20), may have crippled the local economy of the Negev, where a costly urban-centered and economically dependent settlement system could no longer be sustained.

The sixth century collapse that we see at Elusa refers to its urban infrastructure, whereas the settlement itself in all likelihood survived this benchmark to begin a lengthy trajectory of decline alongside a process of devolving political complexity and decentralization in the Negev Byzantine settlement system. Societal resilience has been emphasized in recent debates on collapse, largely in reaction to oversimplified approaches in the history and archaeology of complex societies (7). However, identifying significant historical tipping points and the contexts of when and where the usual safety nets failed and collapse began within ancient complex societies, remains a major challenge for research. It has been argued that the height of the Roman Empire between the second century BCE and fourth century CE coincided with an extended period of climate warming termed the “Roman Climatic Optimum,” and that its termination beginning in the third century CE signaled the historic downturn in Rome’s fortunes (48). Still, the large and complex societies of the Roman and Byzantine Empires were also extraordinarily resilient, surviving through centuries of adversities, including the massive setbacks caused by the barbarian invasions, erupting social class tensions, and inflationary trends (37, 49). During the sixth century, when the eastern Byzantine Empire saw relative military success and territorial expansion, debilitating pressure may have continued to build up due to the combined impacts of climate change and pandemic. Nonetheless, in present multidisciplinary consilience frameworks of climate and history, cause-and-effect equations are unbalanced, where there is substantial evidence for major natural hazards, such as climate change, volcanism, or plague, but remarkably weak evidence on the side of the societal response to such hazards, its nature and magnitude (5, 8, 9). Much of this evidential imbalance is because of a deficiency in suitable, quality proxy records for detecting and measuring societal response, akin to the natural archives of paleoclimate. Ancient urban trash mounds offer prevalent and accessible archives useful for unraveling the time–space dynamics of societal decline and the end of empires.

## Materials and Methods

**GIS.** Mound perimeters were delineated on an aerial photograph by field survey. The polygons were then digitized using the ArcMap GIS platform. A digital elevation model (DEM) of Elusa and its vicinity was obtained using remotely sensed data at a resolution of  $12.5 \times 12.5$  m/pixel, generated by the Alaska Satellite Facility. Mound polygons were then used to mask their DEM and isolate them individually. To estimate mound volume, the underlying assumption was that the topography along the fringe of the mounds represents ground levels before trash disposal. A linear interpolation was used to reconstruct the pre-mound topography. This facilitated the assessment of mound volumes based on present day topography.

**Geoarchaeology.** Bulk samples (10–20 g) were collected in the field in plastic vials from each visible layer. Their location in the section was tagged and photographed. Mineralogical analysis was conducted using a Fourier transform infrared spectrometer (Nicolet 380; Thermo Electron Corp), focusing on the spectrum between  $4,000$  and  $250$   $\text{cm}^{-1}$ . Sample preparation was fol-

lowed by the potassium bromide (KBr) standard procedure (50), and interpretation aided by a reference library at the Kimmel Center for Archaeological Science, Weizmann Institute. Identification of heat-altered clay minerals is based on criteria given by ref. 51, and of heat-altered calcite based on criteria in ref. 52. Nine of 14 samples (HA-2, -3a, -5, -6, -7, -10b, -11, -13a, -14) were further analyzed using optical microscopy in the form of grain mounts, prepared by mounting approximately 1 mg of sediment with a few drops of Entellan (Merc) on microscope slides, and analyzed under plane (PPL) and cross-polarized light (XPL) using a Nikon 50i POL polarizing light microscope.

**Survey.** All mounds located at the outskirts of the site in our DEM were surveyed. The  $5 \times 5$ -m quadrants were deployed across mounds 1–4, with systematic collection of pottery fragments larger than  $1$   $\text{cm}^2$ , glass fragments, and collection of metal objects and coins using a metal detector.

**Probing.** Following the survey and analysis of the survey finds, we excavated three probes where the latest surface artifacts were found. Organic material was collected from the probes for radiocarbon dating. Excavation was conducted in 10-cm spits. Each of the probes was excavated down to 60-cm depth at most. Soil samples and organic materials were collected from the upper in situ spit of each of the probes to sort out short-lived specimens suitable for dating.

**Excavation.** Four trenches ( $4$   $\text{m}^2$  each) were excavated, two on the northern boundary of the site (mound M1) and two along its southern boundary (mound M4) (Fig. 2). Care was taken to meticulously control and separate the excavated material, whereby each square was subdivided into four squares of  $1$   $\text{m}^2$  each, and a separate basket was assigned to each subsquare for every 10 cm of depth, as the excavation descended. All of the excavated material was sifted through a 0.5-cm mesh. About a quarter of all of the excavated material underwent fine-sifting (1-mm mesh) and floatation (10 L for every 10 cm of depth) to collect small archaeozoological and archaeobotanical finds, coins, and other finds. Sediment samples and charred botanical material for radiocarbon dating were collected from exposed sections.

**Artifact Analysis.** All pottery fragments collected during survey and excavations were washed and then identified by T.E.-G. A selection of diagnostic sherds from each of the excavation areas was drawn (SI Appendix, Fig. S1). The Majcherek (30) classification was used for diagnosing the forms and dates of Gaza wine jars. This classification is based on large corpora of well-seriated ceramic data from excavations in Kom el-Dikka, Alexandria, Egypt, where an extremely large series of finds of Gaza wine jars were discovered, making up between 50% and 70% of all identified sherds. Presently, this source provides the most relevant and updated typology for Byzantine assemblages of the southern Levant and a tested, highly reliable tool for relative dating from ceramic material. Similarly, glass fragments were identified by A.F. and Y.G.-R. Coins were studied by Y.F.

**Carbon 14 Dating.** Small charred branches (5–10 mm in size and 22–38 mg) were collected from sieved samples using a sequence of sieves from 4 to 1 mm. All samples were pretreated for radiocarbon dating according to procedures in ref. 53, and provided sufficient carbon for Accelerator Mass Spectrometry analysis.  $^{14}\text{C}$  ages were corrected for fractionation, and calibrated ranges using OxCal v4.2.4 (54).

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