ANTHROPOLOGY

Earliest occupation of the Central Aegean (Naxos), Greece: Implications for hominin and *Homo sapiens*' behavior and dispersals

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We present evidence of Middle Pleistocene activity in the central Aegean Basin at the chert extraction and reduction complex of Stelida (Naxos, Greece). Luminescence dating places ~9000 artifacts in a stratigraphic sequence from ~13 to 200 thousand years ago (ka ago). These artifacts include Mousterian products, which arguably provide first evidence for Neanderthals in the region. This dated material attests to a much earlier history of regional exploration than previously believed, opening the possibility of alternative routes into Southeast Europe from Anatolia (and Africa) for (i) hominins, potentially during sea level lowstands (e.g., Marine Isotope Stage 8) permitting terrestrial crossings across the Aegean, and (ii) *Homo sapiens* of the Early Upper Paleolithic (Aurignacian), conceivably by sea.

INTRODUCTION

Understanding the global patterning of hominin and *Homo sapiens*' dispersal is a key research theme for Quaternary scientists (*1*–*2*). Until relatively recently, a convincing case could be made that certain environments were uninhabitable for hominins (e.g., islands, deserts, and mountain ranges), with such regions' subsequent colonization by anatomically modern humans (AMHs), a clear reflection of more evolutionarily advanced capabilities (*3*). Part of this larger argument held that major bodies of open water served as barriers to pre-*sapiens* populations, with seafaring seen as an index of behavioral modernity (*3*–*5*). Consequently, it was believed widely that hominin dispersals were restricted to terrestrial routes until the later Pleistocene.

Recent discoveries are requiring scholars to revisit these hypotheses. Excavation data now demonstrate that hominins were capable of occupying the high, semi-arid central Anatolian plateau with its strongly continental climate in the Middle Pleistocene (*6*), while Denisovans were capable of living at high altitude in East Asia (*7*). At another environmental extreme, debate has intensified over the role of coastal and marine environments in hominin and AMH evolution and dispersal, especially in areas that necessitate open-water travel (*8*–*12*). A case in point is the eastern Mediterranean's Aegean Basin, a region that has been conspicuously neglected in the larger narrative of hominin dispersal for over a century (*12*). The prevailing view has held that the Aegean Sea—separating western Anatolia from continental Greece—constituted an impassable barrier to pre-*sapiens* populations. The likeliest entry point to Europe was consequently hypothesized to be the Marmara-Thrace land corridor (*13*–*15*). Recent archaeological and paleogeographic research, however, challenges this model.

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Here, we detail evidence from excavations at the chert source of Stelida on what today is the island of Naxos in the middle of the Aegean Basin, where paleodosimetric dates suggest that hominins were present in the region by 200 ka ago, accessing the chert quarry during a glacial lowstand when exposed land connected Anatolia to continental Southeast Europe, by seafaring, or through some combination of the two (Fig. 1). Throughout the remainder of the Pleistocene, this region was occupied and/or traversed at least sporadically, including by early *H. sapiens* ~40 to 30 ka ago (who may have arrived by boat), and later by indisputably seafaring Mesolithic hunter-gatherers of the Early Holocene.

These data, coupled with global evidence of earlier Paleolithic human water-crossing abilities, a recent focus on Pleistocene coastlines and submerged landscapes, and increasingly refined paleo sea level reconstructions, suggest that the Aegean Basin's role in hominin and AMH dispersals needs to be rethought. That revision, in turn, emphasizes the need to revisit broader narratives of Pleistocene dispersals. The data presented here indicate that the Aegean was accessible to archaic and modern humans tens of millennia earlier than previously thought. Whether hominin presence in the region is conceptualized as exploration or colonization, if the Aegean was accessible, it could provide an alternative route into Europe for hominins and later AMH. Its accessibility also emphasizes human capacity to penetrate and exploit the insular and/or distinctive terrestrial-coastal-lacustrine mosaics of the Aegean Basin, with implications for models of the evolution and dispersal of our ancestors.

The Pleistocene Aegean and the Stelida Naxos Archaeological Project

Recent archaeological evidence from several regions around the globe has started to shift our understanding of hominin dispersal and evolution. Artifacts from the islands of Crete, Flores, Sulawesi, and Luzon (*16*–*20*) have been interpreted as products of intentional seaborne colonization by archaic populations of the Early to Middle Pleistocene (*21*). In the Aegean Basin, paleogeographic reconstructions suggest an island-filled sea during interglacial periods of the Quaternary, such as Marine Isotope Stage (MIS) 5e, MIS 7, and MIS 11, but a region that could have been traversed by foot during glacial periods MIS 8,

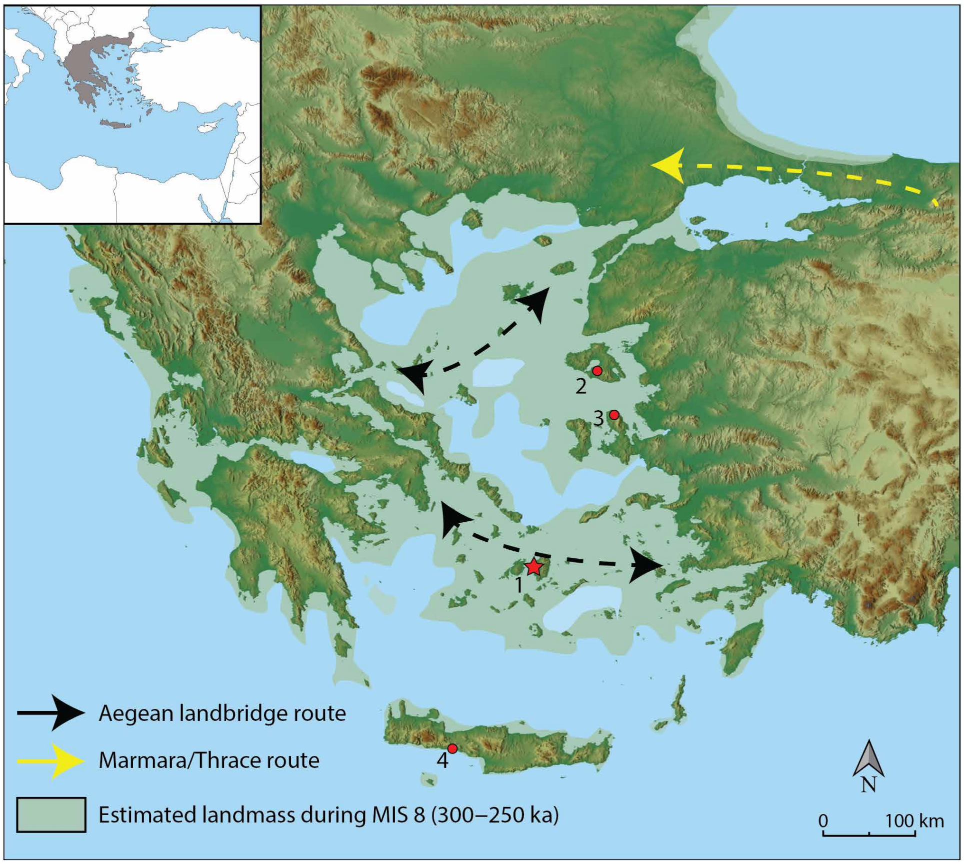

Fig. 1. Location of Stelida archaeological site and hypothesized hominin dispersal routes during Marine Isotope Stage 8. 1, Stelida; 2, Rodafnidia; 3, Karaburun; and 4, Plakias. Base map modified from Lykousis 2009 (*22*). Figure by J.H.

MIS 10, and MIS 12, when sea levels may have been sufficiently low to have exposed a land bridge between what is now Anatolia and the Greek peninsula (*22*). These reconstructions have led some to suggest that this region would have represented an attractive environment to hominins, a "terrestrial wetland" with ecologically rich coastal lowlands and prey-attracting lakes and freshwater sources (*23*). However, while these scenarios posit hominin activity in the Middle Pleistocene Cyc lades (*21*, *23*), there has to date been no direct evidence of such activity.

Stelida is located on what is today the Northwest Coast of Naxos, the largest of the Cycladic islands in the Aegean Sea, southern Greece (Figs. 1 and 2). This double-peaked hill (152 meters above sea level) is an uplifted outcrop of sediments silicified by hydrothermal alteration overlying Miocene shales, both partially buried beneath slope deposits (*24*). By southern Aegean standards, these silicified sediments constitute a substantial exposure of knapping-quality chert, with the flaking debris littering the site attesting to its past use (*24*, *25*). When found in 1981, Stelida was tentatively assigned to the Early Neolithic or Epipaleolithic (*26*). Dating was complicated by the lithics' dissimilarity to those from Cycladic later Neolithic and Bronze Age assemblages, as well as by the prevailing argument that no islands of this size in the Mediterranean were occupied in the Pleistocene (*4*). More recently, the colonization model for the insular Aegean has been pushed back to the Early Holocene through the excavation of a few Mesolithic sites (*27*). Earlier pre-*sapiens*' occupation of the island of Crete via seafaring has also been proposed (*16*), focusing attention on the region and inserting the Aegean into larger debates on hominin cognition and behavior (*5*, *28*–*30*). Further arguments have been made for the presence of hominins on what today are the Cycladic and Ionian islands, evidence for which is exclusively in the form of surface lithic finds of apparent earlier Paleolithic types (*21*).

Nevertheless, as recently as 2018, the existence of Middle and Lower Paleolithic sites in the insular Aegean was deemed sub judice due to the paucity of excavated and well-dated/published assemblages (*31*). It is generally accepted that if conclusive proof of island-visiting/dwelling pre-*sapiens* populations were forthcoming, then it would have major implications for our understanding of hominin capabilities and cognitive evolution (*5*, *21*, *32*). Given this potential significance, it has been argued that robust supporting data are required (*29*), not least "adequate sample sizes, diagnostic lithic types, and technologies" together with sound scientific dates from a stratified excavation (*31*, *33*). With these issues in mind, the Stelida Naxos Archaeological Project was initiated in 2013 to characterize and date the site, with excavations commencing after two seasons of geoarchaeological survey (*25*). This paper details the first excavated stratigraphic sequence in the central Aegean with cultural material from well-sealed and dated contexts spanning the Holocene through the Middle Pleistocene.

EXCAVATION AND RESULTS

Excavation trench DG-A/001 was established on a debris cone at the base of a low cliff of outcropping chert on Stelida's uppermost western flanks; the 2 m by 2 m unit exposed 3.8 m of stratified colluvial

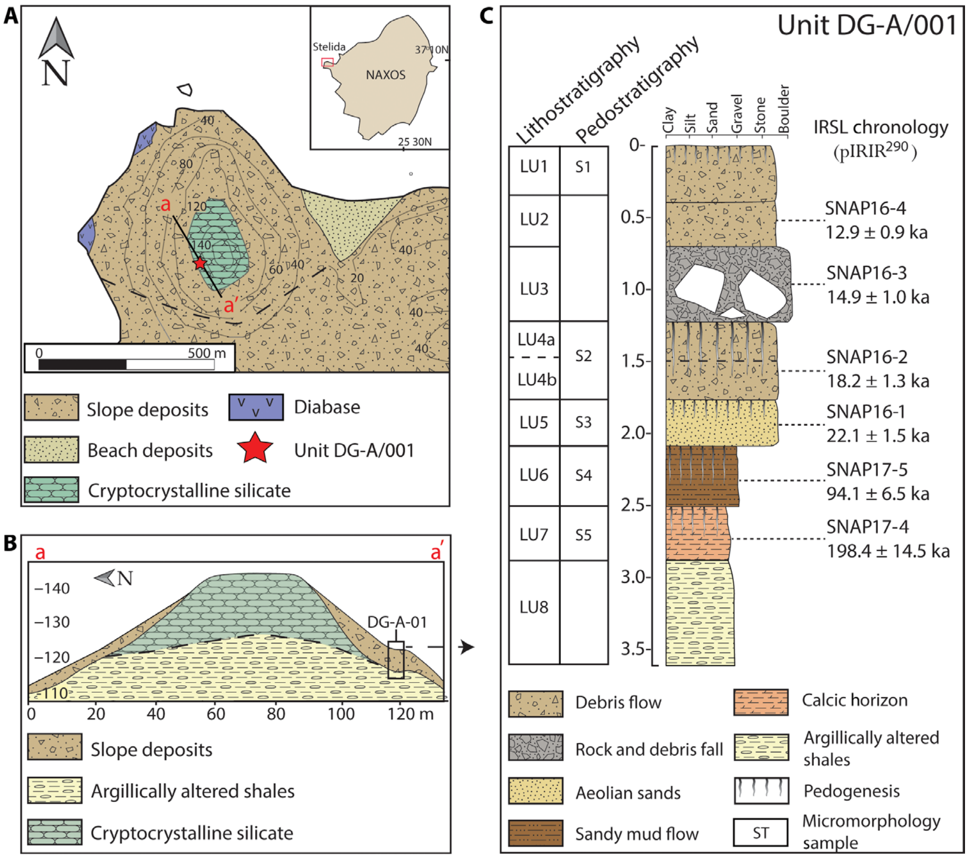

Fig. 2. Geoarchaeological framework and stratigraphic interpretation of the Stelida hillslope and excavation unit DG-A/001. (**A**) Generalized plan view of key geomorphic units observed on Stelida hillslope and location of Unit DG-A/001 [base map modified from (*24*)]. (**B**) Generalized profile of cross-section a-a′ illustrating the upper half of the Stelida hillslope. (**C**) Stratigraphic profile, geoarchaeological interpretation, and geochronology of unit DG-A/001 with dates expressed as 68% confidence intervals. Figure by J.H. and P.K.

deposits derived from the hilltop (Fig. 2 and fig. S1). Thirty contexts were excavated, representing eight lithostratigraphic units (LUs) that include four buried paleosols; lithic artifacts are abundant in all but the deepest LU. These LUs are the product of colluvial deposition punctuated by distinct periods of aeolian deposition. Six sediment samples were collected from this sequence for infrared stimulated luminescence (IRSL) dating (Fig. 2). These ages, measuring the time elapsed since the last exposure of colluvial material to light, provide terminus ante quem (TAQ) ages for the deposition of each LU (and the artifacts contained therein), expressed below as 68% confidence intervals.

The uppermost stratum (LU1) comprised a lag deposit overlying an exhumed Late Pleistocene to Holocene debris flow, with a modern soil developed at the surface. LU2 is a second debris flow (IRSL age of 13.8 to 12.1 ka) that unconformably overlies a mass movement boulder-filled stratum (LU3); the latter is interpreted as resulting from a period of increased depositional energy at the end of the Pleistocene (IRSL age of 16.3 to 14.2 ka). This rock and debris fall capped units LU4a/4b, which constitute two further colluvial events (the latter dated IRSL age of 19.7 to 17.3 ka), followed by a period of stability indicated by the development of a colluvial soil at the contact between LU4a and LU3. A shift in depositional regime to aeolian sand is indicated by LU5, a sand deposit that draped the hillslope during the Last Glacial Maximum (IRSL age of 24.2 to 21.2 ka), with a subsequent period of stability indicated by a moderately developed soil. A major erosional unconformity separates LU5 and LU6, the latter a sandy mud flow that underwent another period of stability, leading to a well-developed paleosol forming on aeolian sand (IRSL age of 100.1 to 86 ka) within or at the end of the Last Interglacial (MIS 5) (*34*). LU7, the oldest artifact-bearing stratum, consists of a well-developed calcareous colluvial soil developed on a final debris flow during the MIS 7 interglacial (IRSL age of 219.9 to 189.3 ka). Last, LU8 represents the underlying saprolitic bedrock.

The DG-A/001 colluvial sediments effectively aggregated material both from the excavation location and upslope; as donor material included abundant lithics, these were incorporated into the colluvium. As a result, each LU may contain material relatively closely temporally associated with the TAQ for that LU and older material that was present on the surface in the DG-A/001 catchment. The cultural material is exclusively lithic; organics rarely survive in Stelida's calcareous soils (pH 7.4 to pH 8.6 in DG-A/001). Approximately 12,000 artifacts were recovered (excluding heavy residue), >9000 of which came from sealed and dated Pleistocene strata (Table 1). As at other earlier prehistoric quarries (*35*–*37*), the Stelida assemblages are dominated by material from early stages of reduction. The formal end products that archaeologists often rely upon for chronological and cultural assignations are underrepresented, having presumably been removed for use elsewhere.

Table 1. Quantity of lithic artifacts per LU.

LU	Count	Weight (kg)	Average gram per lithic	Estimated excavated volume (m^3)*	Density of lithics (pieces/m^3)
LU1	4607	49	10.6	0.97	4739
LU2	1353	24.7	18.2	3.86	350
LU3	2387	36.5	15.3	0.37	6403
LU4	2723	50.1	18.4	0.82	3317
LU5	2303	94.7	41.1	0.23	10,153
LU6	548	22.1	40.3	0.13	4208
LU7	104	5.3	51.0	0.08	1361
LU8	0	0	0.0	0.50	0

*Does not account for varying proportions of sediment:rock in each LU.

Lithic artifacts from DG-A/001 include pieces that are consistent in production, form, and modification to those from well-dated Mesolithic and Lower to Upper Paleolithic sites in continental Greece and/or Anatolia (see the Supplementary Materials). LU1 contained typical Aegean Mesolithic material (*27*), while Upper Paleolithic diagnostics were recovered from LU1 to LU5. The Upper Paleolithic tools, including a few Aurignacian types (e.g., carinated scrapers), comprised blanks with linear retouch, followed (in order of decreasing abundance) by notches, denticulates, scrapers, combined tools, backed pieces, burins, and piercers on larger flakes, blades, and bladelets (figs. S2 and S3) (*38*).

LU1 to LU5 also contained artifacts from Middle Paleolithic Levallois and discoidal core technologies, including a Mousterian point (fig. S3); on mainland Greece, these products are associated with Neanderthals (*12*, *39*). These strata also contained products associated with eastern Mediterranean non-Acheulean flake-based traditions from the early Middle to Lower Paleolithic (*40*, *41*). The latter include scrapers, denticulates, notches, piercers, combined tools, and a tranchet (Fig. 3), as well as a Lower Paleolithic biface (fig. S4). LU6 contained Levallois and pseudo-Levallois products (Middle Paleolithic), as well as early Middle to Lower Paleolithic tools on larger flake and blade-like flakes, with denticulates (one convergent, a "Tayac point"), scrapers, combined tools, piercers, and burins. The LU7 artifacts are highly weathered, and only three retouched tools were discernible in the relatively small assemblage ($n = 106$): two denticulates (Fig. 3) and a scraper. On the basis of the TAQ for LU7, this material is 219.9 to 189.3 ka ago or earlier, which is to say early Middle Paleolithic or Lower Paleolithic. The date alone makes this modest assemblage of early Middle or Lower Paleolithic tools compelling; activity of this date at Stelida is also suggested by 159 artifacts diagnostic of the period recovered through surface survey (*25*).

DISCUSSION

The excavation, artifact analysis, and chronometric program at Stelida provide first evidence for Middle Pleistocene cultural activity in the central Aegean; previously, only adjacent continental Greece and Anatolia were believed to have been inhabited by Neanderthals and earlier hominins (*12*). That Neanderthals may have visited Stelida is arguably no great surprise, given the numerous sites with Mousterian assemblages in neighboring southern Greece (three of which also have yielded Neanderthal remains) (*12*, *39*). While Naxos was insular for at least some of the Middle Paleolithic, indirect evidence from elsewhere in Greece argues that Neanderthals were capable of short-distance waterborne crossings (*42*). Moreover, recent discoveries of putatively Lower Paleolithic material from western Anatolia's Karaburun peninsula (currently undated) (*43*) and the nearby island of Lesbos (continental at the time), dated to 164 ± 33 and 258 ± 48 ka ago (*41*), indicate the presence of nearby populations that might have entered the Aegean Basin from the east (Fig. 1). The possibility that Neanderthals—or other hominin populations—were capable of accessing the Aegean Basin suggests that pre-*sapiens* populations had an alternative means of reaching mainland Europe (Fig. 1) and need not necessarily have used the Marmara-Thrace route as assumed previously (*13*). Their presence at Stelida is also consistent with current models of Eurasian hominin dispersal routes, which suggest a focus on locales offering tool-making raw materials and freshwater supplies (*12*, *44*).

The Stelida data add to the emerging discussion of the importance of coastal and marine routes in hominin evolution and dispersal. They provide a tantalizing complement to hypotheses of pre-*sapiens*' seafaring in the Aegean (*21*), but the evidence for Stelida's Middle Pleistocene exploitation cannot as yet be proven to imply access via waterborne craft. This is because our chronostratigraphic framework is based on sedimentation events, which provide a minimum (TAQ) age for cultural activity at the chert source, rather than giving an exact date for hominin presence that could be related to reconstructed Pleistocene sea levels (whose chronology is also of limited precision). Stelida's Lower to Middle Paleolithic exploitation might have been intermittent, with the chert source only visited during those colder periods when lower sea levels exposed a terrestrial connection to neighboring continents, for example, during MIS 6 and MIS 8 (*22*). This by no means rules out Neanderthal or earlier seafaring to Naxos, but establishing Pleistocene seafaring requires (i) the application of direct dating methods [e.g., (*45*)] to cultural features or hominin fossil remains and (ii) the development of precise chronologies for Pleistocene sea levels.

Whether hominins at Stelida during the Lower and Middle Paleolithic arrived to an island Naxos or to a hill connected by marshy plains to adjacent continents, their presence challenges simple models of hominin dispersal. Early seafaring likely implies that pre-*sapiens* populations had more advanced cognitive faculties, including standardized communication, such as language or speech, along with the technical capabilities to manufacture and successfully

Fig. 3. Select artifacts from LU5 to LU7. Flakes unless otherwise noted. a, scraper; b, backed flake; c, bladelet; d, piercer; e, piercer on blade-like flake; f, piercer; g, combined tool (burin and scraper on chunk); h, nosed scraper; i, combined tool (inverse scraper/denticulate/notch); j, denticulate (LU5); k, flake; l, denticulated blade-like flake (LU7); m, piercer; n, denticulate; o, denticulate; p, piercer; q, combined tool (linear retouch/denticulate); r, scraper; s, convergent denticulate (Tayac point); t, blade; u, scraper; v, denticulate; w, linear retouch; x, tranchet; and y, blade-like flake (LU6). Photographed by J. Lau and modified and page set by N. Thompson.

navigate the waterborne transport (*32*, *42*). A Middle Pleistocene terrestrial-access model also has behavioral significance, as paleogeographic reconstructions suggest that the Aegean Basin would have been a region quite unlike anywhere else in contemporary Eurasia; thus, while it offered hominins a range of attractive lacustrine and raw material resources, occupying or even traversing such an environment would have required innovative adaptive strategies.

The Balkan Peninsula and the Aegean Basin, due to their more consistently temperate conditions, have long been suggested as likely refugia for hominins during the climatic fluctuations of the Pleistocene (*12*, *44*–*47*). If hominins were accessing Stelida during those coldest periods when glacial lowstands facilitated terrestrial connections to Naxos, then as sea levels gradually rose, the exploitation of Stelida chert would have become increasingly difficult. The pace of this inundation of a known resource would (if slow) have invited continued access, producing first shallow waters that could be waded through, and then deeper channels that might be crossed with some form of rudimentary raft (woodworking being attested in Eurasia from the Lower Paleolithic onward) (*32*, *48*). Such conditions would provide an ideal incubator for the development of short-distance seafaring. The fluctuating terrestrial/lacustrine—maritime character of the Aegean Basin during the Pleistocene—would have provided optimal "nursery" conditions for nascent seagoing (*49*), with seaborne voyages over short distances to intervisible (insular) landmasses that were known locales with known resources. Southeast Asia, which currently provides the best and earliest evidence for hominin (likely *Homo erectus*) seafaring (*17*–*19*, *32*), is a region whose Pleistocene paleogeography would have similarly provided a geographically optimal zone for the development of seafaring (*12*).

Even if the exploitation of Stelida during the Middle Pleistocene was purely terrestrial, confined to those glacial periods when access was possible via a land bridge, that exploitation testifies to a particular suite of hominin abilities and interests. As argued above, this area, with its freshwater supplies and varied prey (*23*), would have been attractive to hominins, while its diverse sedimentary and volcanic lithologies provide not only Stelida chert (*24*) and Naxian emery (*50*) but also the basalt and obsidian of nearby Melos (*21*). These desirable resources, however, would have been situated in a mosaic of coastal, riverine, and lacustrine lowland environments that would have posed foraging opportunities and adaptive challenges. These distinct arrays of aquatic and terrestrial resources would have required innovative modes of procurement, as well as providing different and potentially hazardous combinations of fauna, flora, and diseases to cope with (*8*, *11*).

Paleogeographic reconstructions of the region during the Late Glacial Maximum indicate that Naxos formed part of a mega-island (Cycladia), suggesting that throughout most of the Upper Paleolithic different means of transportation to the chert source were required (*22*, *51*). Aurignacian lithics, traditionally associated with the spread of AMH (*52*), attest to Early Upper Paleolithic activity at Stelida (*25*); such material is known from the southern Greek mainland at much the same time [~40 to 30 ka ago calibrated years before the present (*53*)]. Given *H. sapiens*' well-established colonization of Australia by boat between 65 and 47 ka ago (*54*), evidence of their exploitation of Stelida suggests that the insular Aegean may have been as much destination as obstacle. If early humans were comfortable exploring the island Aegean, then a terrestrially oriented model of Thrace as *H. sapiens*' exclusive entry point into Europe (*52*) is founded upon overly conservative assumptions about early human desires and capacities.

In sum, the excavation of trench DG-A/001 at Stelida has produced the kind of robust data required to support a claim for earlier Paleolithic cultural activity in the Aegean Basin (*31*). The evidence presented here provides (i) the first stratified, large, and well-dated Pleistocene lithic assemblage from the Cyclades, (ii) the earliest archaeological site in the central Aegean Basin [previously ninth millennium cal BC Mesolithic (*27*)], (iii) first indirect evidence for Neanderthals in this region, and (iv) evidence that hominin and AMH dispersals included spread to and/or through areas, like the Aegean Basin, previously viewed as inaccessible. Early human presence in the Aegean suggests that the region represented an opportunity as much as did a barrier, emphasizing that human dispersals were as likely to follow idiosyncratic paths as optimal routes. The implications for dispersals into continental Europe are clear: While the Marmara-Thrace corridor may represent the optimal route into continental Europe, privileging such a route presupposes a goal. Evidence from Stelida, to the contrary, suggests that dispersals were about the journey rather than the destination. This evidence for Pleistocene hominins' and early modern humans' facility at accessing landscapes generally understood to be inaccessible or undesirable argues that the search for early sites should be more wide ranging.

MATERIALS AND METHODS

Excavation

DG-A/001 was excavated in 2015–2017, following natural stratigraphic deposits. All soil was screened (mesh size 0.5 cm by 0.5 cm), with 30 liters of sediment per context wet-sieved for archaeobotanical materials and microdebitage; targeted samples were taken for scientific dating, micromorphology and phytoliths (the latter producing insufficient quantities for analysis).

Field descriptions of sediments and soils were recorded using the U.S. Department of Agriculture Soil Survey nomenclature (*55*) following the North American Stratigraphic Code (*56*). Thus, stratigraphic divisions (e.g., lithostratigraphy, pedostratigraphy, and allostratigraphy) were based on texture, sorting, color, structure, consistency, and boundaries. LUs were defined on the basis of grain-size distribution, mineralogy, and geometric orientation to underlying and overlying units in the field (fig. S1). Selected field observations were complemented with thin-section micromorphology.

Luminescence dating

Luminescence dating methods determine the time elapsed since the last exposure of minerals to sunlight (or heat).

Optically stimulated luminescence

Optically stimulated luminescence (OSL) (*57*) measures the time of deposition of sediments. Luminescence signals are linked with natural ionizing radiation because natural crystals behave as natural dosimeters: They record the irradiation doses to which they are exposed and can deliver, when stimulated, a signal correlated to the total dose they absorbed. The method requires the determination of two quantities: the equivalent dose (D_e), on one hand, corresponding to the total irradiation dose absorbed by minerals since their last zeroing (when bleached by sunlight at the time of deposition), obtained by luminescence measurements. The dose rate (D_r), on the other hand, corresponds to the dose absorbed per unit time, which is largely the product of radioactivity within an area 30 to 50 cm around the sample. It is determined by measurements of radioelements concentration in the laboratory, combined with in situ dosimetric measurements.

Feldspars IRSL

Feldspars IRSL dating requires, contrary to quartz OSL dating, considering anomalous fading (a loss of charge from stable traps) or using protocols to overcome it. Laboratory-measured fading rates can be used to correct ages (*58*). The post-infrared IRSL (pIRIR) signal, measured at elevated temperature (e.g., 290°C), can also be used to avoid anomalous fading effects and lead to accurate ages (*59*, *60*).

Sampling and analyses

Six sediment samples were collected from the DG-A/001 stratigraphic sequence in 2016–2017 and dated in the Bordeaux Montaigne University Luminescence Laboratory of the Centre de Recherche en Physique Appliquée à l'Archéologie (CRP2A), a laboratory with long experience of dating Paleolithic sites (*61*–*63*). All samples were collected at night, under controlled red lighting, by excavating sediment from the trench section. Subsamples were collected in all cases for radioelement contents measurements. Dosimeters (aluminum tubes), containing three Al_2O_3:C crystal chips were inserted into the stratigraphic profiles at the exact location of the luminescence samples to measure gamma and cosmic dose rates. These dosimeters remained buried for a year, after which they were also measured at the CRP2A (*64*).

Each sample was prepared mechanically and chemically in the conventional manner (*65*). The first tests with the quartz fraction indicated that the quartz was not suitable for luminescence measurement: No OSL (neither natural nor regenerated) signal could be measured. Conversely, the K-feldspar fraction was dated using an adapted SAR (Single-Aliquot Regenerative Dose) protocol (*66*, *67*) using two different signals: (i) the IR_{50} signal, corresponding to the signal measured during a stimulation at 50°C, which is affected by anomalous fading (*68*). To correct the results from this phenomenon, *g* values were measured for all aliquots, and the DRC (Dose Rate Correction) (*68*) was applied; (ii) the $pIRIR_{290}$ signal was measured during a stimulation at high temperature (290°C) after a first stimulation at 50°C (*69*, *70*).

During exposition to sunlight in nature, the IR_{50} signal is bleached faster than the $pIRIR_{290}$ signal because the latter signal from more distant electron-hole pairs (*71*). However, the $pIRIR_{290}$ signal does not seem to be affected by anomalous fading (*69*, *70*, *72*).

In the present work, all six samples were dated with $pIRIR_{290}$ signal measurements, based on 10 to 12 aliquots for each sample; for younger sediment samples in the present study, IR_{50} age estimates (based only on three aliquots for each sample) were obtained after fading correction. For older samples (when approaching the field saturation level of the IR_{50} signal), the fading correction is no longer possible.

$pIRIR_{290}$ ages have been determined using the ADM (Average Dose Model) (*73*) and are presented in table S1; they are in good agreement, within uncertainties, with the stratigraphy (Fig. 2). IR_{50} ages are presented in table S2 and are consistent with $IRpIR_{290}$ ages within uncertainties (2σ).

Note that these experiments allow dating of the last exposure of the feldspar grains to light; in sites with complicated taphonomic histories, similar to the present one, only terminus post quem and TAQ can initially be deduced from luminescence dating results (*36*). In this specific case, the fact that no high dispersion of D_e values has been detected for any of the samples [D_e SDs vary between 3 and 7%; see table S1 for the overdispersion values calculated with the Central Age model (*74*)]. Even when measuring small aliquots (1 mm in diameter), this allows us to hypothesize a unique deposition event for all grains (same last time of light exposure). The D_e distributions are presented in the radial plots in fig. S7 and show very low dispersion in the data. This dated moment can be contemporaneous with human occupation or with reworking of one or several sedimentary levels containing one or several archaeological assemblages (during which either light exposure led to a complete signal resetting or to no resetting at all). Moreover, sample SNAP16-1 came from an aeolian deposited sand layer, suggesting that exposure to sunlight most likely was sufficient to fully reset the $pIRIR_{290}$ signal. The observation that the three colluvial levels (SNAP16-1 to SNAP16-3) above it in the stratigraphy simultaneously displayed similar dispersion in D_e values and appeared younger in age than the well-bleached aeolian level reinforces the hypothesis that bleaching of the $pIRIR_{290}$ signals was complete during the deposition of the colluvial layers at the site. IR_{50} age estimates (even if based on few aliquots) and their congruence with $pIRIR_{290}$ ages also confirmed that no partial bleaching needs to be considered.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/10/eaax0997/DC1

Supplementary Materials and Methods

Supplementary Text

Fig. S1. Geomorphic context of excavation unit DG-A/001.

Fig. S2. Select Upper Paleolithic diagnostic artifacts from LU3 to LU5.

Fig. S3. Select Upper and Middle Paleolithic diagnostic artifacts from LU2 to LU5.

Fig. S4. Lower Paleolithic biface (LU4b).

Fig. S5. $pIRIR_{290}$ typical shine-down curve and dose response curve for sample SNPA17-04.

Fig. S6. Residual dose measurements as a function of time, after 15 min to 48 hours of light exposition in a solar simulator, for samples SNAP16-02 and SNAP17-04.

Fig. S7. Radial plots of the pIR-IR290 measurements for SNAP16-01, SNAP16-02, SNAP16-03, SNAP16-04, SNAP17-04, and SNAP17-05.

Fig. S8. Output of the Markov Chain Monte Carlo calculations for the $pIRIR_{290}$ age palaeodose, and dispersion of equivalent doses of sample SNAP16-4, as generated by the R 'BayLum' package.

Fig. S9. Bivariate scatterplot of a sample of observations from the joint posterior distribution of the IRSL ages generated by Markov Chain Monte Carlo calculations, using the "BayLum" R package.

Table S1. Main characteristics of the $pIRIR_{290}$ ages measurements for the DG-A/001 stratigraphic sequence.

Table S2. Main characteristics of the IR_{50} age measurements.

Table S3. Radioelements contents determined by high-resolution gamma spectrometry.

Table S4. IR_{50} and $pIRIR_{290}$ dose-rate information.

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