Supplementary Information

Chronometric dating and stratigraphic data support discontinuity between Neanderthals and early *Homo sapiens* in the Italian Peninsula

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SUPPLEMENTARY NOTE 1 THE ARCHAEOLOGY OF THE ITALIAN PALAEOLITHIC

The Late Mousterian

The Late Mousterian techno-complex has been identified through archaeological findings spanning from the Iberian Peninsula to southern Siberia. In Italy, it is so far associated with Neanderthals. This techno-complex is characterized by its lithic flaking procedures which enabled the production of a variety of tools with predetermined shapes. In the Late Mousterian, there was a pronounced preference for sourcing raw materials locally or from nearby areas, although there are instances of materials being obtained from more distant locations. A wide range of block types, including pebbles, nodules, and slabs, are utilized in the reduction process. Direct percussion with a hard hammerstone is the primary technique employed, though some sites also show evidence of bipolar knapping on an anvil, albeit infrequently (Marciani et al., 2020a).

In terms of debitage concepts, integrated production methods like the Levallois, and to a lesser degree, the discoid method, are favoured over other strategies such as unidirectional volumetric debitage, orthogonal debitage, and Kombewa. The goal of debitage primarily focuses on the creation of flakes, elongated supports, blades, and occasionally bladelets. It is noteworthy that the bulk of technical effort is directed towards the initial production phase rather than later stages of transformation or curation. Furthermore, there is a consistent production of scrapers, particularly side-scrapers (Marciani et al., 2020a).

The Levallois show regional preferences highlighting its adaptability and widespread use. In the northeast, sites like Grotta di Fumane and Grotta San Bernardino show a marked preference for recurrent Levallois methods, transitioning from unipolar to centripetal modalities in their final stages (Peresani, 1996, 2012). Central Italy is marked by the dominance of Levallois with a particular application of small pebbles in the site of Grotta dei Santi, Grotta Breuil and Grotta del Fossellone (Moroni et al., 2019). In southern Italy, the Levallois debitage employs recurrent unidirectional and/or convergent strategies. As the reduction sequence progresses, a shift towards centripetal or preferential modalities is observed, a trend clearly visible at Riparo del Poggio, Grotta di Castelcivita, and Riparo L'Oscurusciuto (Boscato et al., 2009; Caramia and Gambassini, 2006; Gambassini, 1997; Marciani, 2018; Marciani et al., 2016, 2018; Ranaldo, 2017; Spagnolo et al., 2016, 2019). The Salento area, including Grotta Romanelli and sites like Grotta Mario Bernardini and Grotta-Riparo di Uluzzo C, is characterized by the recurrent use of centripetal Levallois (Carmignani, 2011; Spinapolice, 2008, 2018).

Alongside the Levallois, discoid method is present at Fumane and Grotta di Rio Secco (Delpiano et al., 2018; Peresani, 2012; Peresani et al., 2014). The Ligurian-Provencal arc, along with Apulian sites such as Grotta del Cavallo and Grotta Bernardini, presents a coexistence of Levallois and discoid, with some locations showing a preference for exclusively discoid debitage (e.g., Arma della Manie) (Carmignani, 2011, 2017; Romagnoli, 2012).

Towards the end of the Middle Paleolithic period, there was a noticeable increase in laminar and, to some extent, lamellar production, both in the Italian Mousterian and across Europe (Carmignani and Soressi, 2023; Marciani et al., 2020a). Notably, the Oscurusciuto and Cavallo sites in southern Italy have become key focal points for studying the characteristics of blade and bladelet production (Carmignani, 2017; Marciani, 2018; Marciani et al., 2016, 2018). Oscurusciuto (levels SU 1, 4, 11, 13, 14, 15) utilizes the Levallois to produce blades and long flakes through unidirectional and convergent modalities. While bladelet production is less common and involves volumetric debitage. In both cases pebbles are the primary raw material. In contrast, Cavallo (levels FIIIe – FIIId) focuses on producing quadrangular flakes via centripetal Levallois reduction, alongside specific volumetric debitage aimed at creating blades and bladelets. At Cavallo, pebbles are mainly used for centripetal Levallois debitage and, to a lesser extent, for discoid debitage in the upper layers (FIIIa, FII, FI), while slabs are reserved for volumetric debitage (Carmignani, 2017).

The production of bone tools in the Mousterian is mainly limited to unformal tools, not resulting from a planned sequence of actions. In general, Mousterian bone tools exhibit limited typological diversity and consist primarily of retouchers (Baumann et al. 2020; Malerba and Giacobini, 1996; Peresani et al., 2014; Romandini et al. 2018; Thun Hohenstein and Bertolini, 2012) or unmodified bone fragments that can only be classified as tools based on the presence of use-wear (Kozlikin et al., 2020). They are usually made on ungulate bone fragments (Malerba and Giacobini, 1996; Peresani et al., 2014; Romandini et al., 2018; Thun Hohenstein and Bertolini, 2012; Thun Hohenstein et al., 2018), or on bone of other animals including humans remains (Daujeard et al., 2014; Jéquier et al., 2012, 2018; Rougier et al., 2016; Verna and d'Errico, 2011). In some sites the occurrence of smooth-ended tools, used for processing hides, is attested (Baumann et al., 2020; Martisius et al., 2020a, 2020b; Soressi et al., 2013; Tartar et al., 2022).

The bone, along with shells (*Callista chione)*, was also utilized for manufacturing tools like scrapers and denticulates (Douka and Spinapolice, 2012; Freund, 1987; Hahn, 1976; Hardy et al., 2014; Romagnoli et al., 2014, 2016; Tromnau, 1983), using techniques borrowed from flint knapping.

The manifestation of symbolic behaviour among Neanderthals appears to be not systematic and widespread. Some aesthetic or artistic sensibility seems to be suggested by the occasional use of pigments, shells and feathers (e.g., d'Errico et al., 2003; Finlayson et al., 2012; Jaubert et al., 2022; Majkić et al., 2017; Morin et al., 2020; Peresani et al., 2011, 2013; Radovčić et al., 2015; Romandini et al., 2020; Zilhão et al., 2010) and the possible realization of figurative artifacts and musical instruments (e.g., Chase and Nowell, 1998; Diedrich, 2015; Marquet and Lorblanchet, 2003; Morley, 2006; Otte, 2000; Rodríguez-Vidal et al., 2014; Soressi and D'Errico, 2007; Tuniz et al., 2012; Zilhão, 2007). Anyway, the nature of the symbolic sphere of Neanderthals remains a topic of debate.

The Uluzzian

The Uluzzian technocomplex was first identified through materials discovered at Grotta del Cavallo in Salento, Apulia, southeastern Italy (Palma Di Cesnola, 1964b, 1989). It is associated with *Homo sapiens*, a connection supported by the discovery of two deciduous teeth at Cavallo (Benazzi et al., 2011). Behaviourally, the Uluzzian is marked by its distinctive lithic production and carcass exploitation strategies, alongside the use of colouring materials, systematic creation of bone tools, and ornament crafting (Arrighi et al., 2020a, 2020b, 2020c; Boscato and Crezzini, 2012a; Collina et al., 2020; Crezzini et al., 2023; Marciani et al., 2020a; Moroni et al., 2018; Rossini et al., 2022; Sano et al., 2019; Silvestrini et al., 2022).

In terms of lithic the procurement of raw materials predominantly focused on local and nearby sources during the earliest phases, with a notable increase in the use of exogenous flint in the final phases in the Salento region (Dini and Tozzi, 2012; Moroni et al., 2018; Ranaldo et al., 2017a; Villa et al., 2018). A hallmark of the Uluzzian is the extensive use of the bipolar technique on an anvil, signifying a conscious technological choice rather than a necessity dictated by available materials (Arrighi et al., 2020c; Collina et al., 2020; Marciani et al., 2020a; Moroni et al., 2018; Peresani et al., 2019; Rossini et al., 2022; Silvestrini et al., 2022). This technique was applied across all types of local raw materials, regardless of their siliceous content or quality. However, the later stages of the Uluzzian, especially evident at Grotta del Cavallo, show a shift towards lamellar reduction. Additionally, a smaller portion of flakes and bladelets were produced by unidirectional debitage using direct freehand percussion, either independently or in conjunction with the bipolar method.

Uluzzian artefacts are typically unstandardized, exhibiting significant variability in shape, size, and angles. Yet, the application of the bipolar technique consistently yields features like straight profiles, minimal bulbs, and fine, straight cutting edges, making these artefacts well-suited for use as inserts in composite tools (Collina et al., 2020; Marciani et al., 2020a; Moroni et al., 2013, 2018; Rossini et al., 2022; Sano et al., 2019). The Uluzzian toolkit primarily consists of backed pieces (notably lunates), short end-scrapers, and some side-scrapers. A distinct tool-making practice in the Salento region, involves the direct use of naturally fragmented silicified limestone thin slabs (15-5 mm) as blanks for retouched tools without prior debitage.

In summary, from a technological standpoint, the Uluzzian is characterized by an industry primarily focused on flakes and bladelets, with a minimal presence of blades. This lithic industry shows two distinct functional categories: "domestic use" tools (such as endscrapers) and armatures (including backed points and lunates). This division mirrors the organizational structure found in other Upper Palaeolithic complexes (Moroni et al., 2018; Tartar et al., 2005).

The Uluzzian has a distinct cultural identity, evident in shared behaviours across the groups involving not only lithic production but also bone technology and the use of ornament. It is characterized by the emergence of a straightforward bone technology dedicated to the production of formal tools, especially awls and cylindrical and conical elements. These tools were obtained from specific anatomical parts, like metapodials of red deer and fibulae and metapodials of horses.

A well-established ornamental tradition is also documented in the Uluzzian groups, characterized by the intense use of tusk shells (*Antalis* sp.) that can be considered as a hallmark of the Uluzzian techno-complex (Arrighi et al., 2020a, 2020b). The ornamental scenario is also defined, to a lesser extent, by the intentional use of perforated gastropods such as *Tritia neritea* and *Homalopoma sanguineum,* as well as bivalves like *Glycimerys nummaria* (syn. G. *insubrica*) (Arrighi et al., 2020a, 2020b). Also, the use of coloring substances could be ascribed to the symbolic sphere, as evidenced by ochred tusk shells recovered at Riparo Broion and Grotta del Cavallo (Arrighi et al., 2020a; Peresani et al., 2019). So far, no artistic evidence has been found in the Uluzzian sites, except for a splintered flake with linear engravings on the cortical back (Peresani et al., 2019). However, the symbolic meaning of this artifact requires further investigation.

The Aurignacian

The Aurignacian is an Upper Paleolithic techno-complex that has garnered significant scientific interest in recent decades, primarily due to its early association with Homo sapiens (Mellars, 2004), recently confirmed thanks to the identification of two deciduous teeth at Grotta di Fumane and Riparo Bombrini (Benazzi et al., 2015). This techno-complex unified a vast geographic area, encompassing the northern Mediterranean Basin and expanding towards Atlantic and continental Europe (Hublin, 2015; Le Brun-Ricalens and Bordes, 2007). Recent dating efforts and renewed excavations have also improved our understanding of the beginning of the Aurignacian across Europe, with the earliest sites dating back approximately 43–42,000 years ago (e.g., Barshay-Szmidt et al., 2018; Frouin et al., 2022; Higham et al., 2009, 2011, 2012; Wood et al., 2014).

The Aurignacian has been divided into successive chrono-cultural phases, thanks to the variability of lithic and osseous technologies (Bordes, 2006; Dinnis et al., 2019; Teyssandier and Zilhão, 2018). The earliest phases are known as Protoaurignacian (PA) and Early Aurignacian (EA). Despite marked regional variability, when both cultural variants are found at the same sites, the PA is always found stratigraphically below the EA, particularly in southern and western Europe (d'Errico and Banks, 2015; Wood et al., 2014).

In terms of lithics, both PA and EA are characterized by the use of high-quality raw materials, predominantly chert and jasper. When these materials were not locally available, raw material nodules and finished tools could be transported several hundred kilometers, as evidenced at sites such as Riparo Mochi and Riparo Bombrini (Grimaldi et al., 2014; Porraz et al., 2010; Riel-Salvatore and Negrino, 2009). The necessity for raw materials with high knapping properties is correlated with the modifications in the modes of production of lithic implements. Unlike the Uluzzian, Aurignacian knappers employed freehand direct marginal percussion to detach regular blanks, usually bladelets, from cores with plain striking platforms (Le Brun-Ricalens et al., 2005). The differences between the PA and EA are clearly observable in the modes of production of bladelets. While the PA is characterized by the use of volumetric platform cores, frequently resulting in the simultaneous production of blades to initialize and maintain the cores' flaking convexities (Falcucci et al., 2017; Lombao et al., 2023), the EA relies almost exclusively on carinated cores (e.g., carinated endscrapers and carinated burins) to obtain comparatively shorter bladelets. From a typological standpoint, PA bladelets were frequently modified using marginal retouching (Falcucci et al., 2018; Laplace, 1966), whereas in the EA, bladelets were in most cases left unretouched. A notable exception to this pattern is Castelcivita, where miniaturized bladelets from the EA layers (i.e., gic and ars) were modified by direct retouching (Gambassini, 1997).

Another key difference between PA and EA lies in the use of osseous materials (i.e., bone and antler) to obtain tools such as awls and bone points (Arrighi et al., 2020c; Tejero and Grimaldi, 2015). Specifically, the EA is characterized by an increased use of antler, as observed at sites like Riparo Mochi (Tejero and Grimaldi, 2015), and the production of split-based points (Doyon, 2020; Kitagawa and Conard, 2020), which were likely apically hafted and used as mechanically delivered projectiles (Yeshurun et al., 2024).

The Aurignacian is also distinguished by an increased evidence for symbolic behavior, including figurative representations and the use of personal ornaments. In Italy, a notable example of figurative art is found in the ochre painted stones from Grotta di Fumane, depicting zoomorphic and anthropomorphic figures (Broglio and Dalmeri, 2005; Sigari et al., 2022). Regarding personal ornaments, there is significant regional variability, possibly associated with distinct cultural groups and underlying social networks (Vanhaeren and d'Errico, 2006).

During the PA, marine and freshwater seashells, particularly the *Homalopoma sanguineum*, were predominantly used (Arrighi et al., 2020c; Peresani et al., 2019). These marine shells not only held symbolic significance but also offer critical insights into the geographic movements and exchange networks established during the Aurignacian. They have been in fact found at sites located several hundred kilometers away from the modeled coastlines (Broglio, 2000; Peresani et al., 2019). In the EA, there is a notable increase in ornaments made from teeth, bone, or ivory, especially in northern Italy and north of the Alps (Vanhaeren and d'Errico, 2006). However, Aurignacian foragers in southern Italy continued to exclusively use seashells throughout the Aurignacian period, as evidenced by sites such as Grotta di Castelcivita, Grotta della Cala, and Grotta Paglicci (Arrighi et al., 2020c).

Excavation, history of archaeological research and stratigraphic successions at the sites of Cavallo, Cala, Castelcivita and Oscurusciuto

Excavation activities at Cavallo, Cala, Castelcivita and Oscurusciuto are still ongoing and are carried out following stratigraphic methods. Layers were identified according to their lithostratigraphic characteristics. Stratigraphic units at Riparo

L'Oscurusciuto are used according to Harris (1989) and to the directives of the Ministry of Culture. The excavation area was covered by a grid coordinate system formed by 1x1m squares, identified by a letter and a number, further subdivided into sectors of 50x50 cm named by Roman numerals (I, II, III, IV) in a clockwise direction. The different layers/stratigraphic units (SUs) have been identified with numbers (Oscurusciuto, Cala), letters (Cavallo) or acronyms (Castelcivita). When required, each layer was subdivided into sub-layers. To improve the chronological resolution, each layer/SU was dug, if necessary, using 5 cm thick spits, that followed discontinuities within the layers/sub-layers. If visible, archaeological finds larger than 1 cm were recorded according to their three-dimensional spatial coordinates and assigned to square, sector, layer-sub-layer/SU, and spit. Sediments divided by square, sector, layer, and spit were dry and wet sieved (1 mm mesh) and further screened by tweezers to avoid any loss of small things. Finally, all findings were stored in plastic bags according to their provenance. Sediment samples were taken for different kinds of analyses. All the excavation activities, notable archaeological features and the excavated surfaces were recorded in personal notebooks and with photos, graphic reliefs and photogrammetries.

Grotta del Cavallo (Nardò, Lecce, Apulia, Southern Italy) (40.15525708N, 017.96051057E, 17 m a.s.l.)

Research at Grotta del Cavallo began in the 1960s through the work of A. Palma di Cesnola of the University of Siena (years 1961-66 and 1976-1978) and has been continued until today by the same University under the direction of P. Gambassini (years 1978-86 for the Uluzzian) and L. Sarti (1978 - today for the Mousterian and the Romanellian) (Sarti, 1987-88). Grotta del Cavallo is the site where the Uluzzian was discovered and described for the first time and, except, perhaps, for Roccia San Sebastiano (Oxilia et al., 2022), the only site to have returned human remains confidently associated with this technocomplex. The impressive archaeological deposit of the cave encompasses a long-lasting time interval, including the evolution of the local Middle Palaeolithic (layers N-H), which ends with the Late Mousterian (layer F), the Early Upper Palaeolithic (layers E, D - Uluzzian) and, after a considerable chronological hiatus, the Final Upper Palaeolithic (layer B – Romanellian) and the Holocene (layer A) (Palma di Cesnola, 1967; Romagnoli et al., 2016). Although 1961-1966 excavations at Grotta del Cavallo were merely intended as a test trench (Palma di Cesnola, 1965b), Palma di Cesnola carried out research with absolute respect for the stratigraphy, following lithostratigraphic macro-units (A, B, C, etc.), which were subdivided into layers (EI, EII, EIII etc.) and, when necessary, into sub-layers (CIa, DIa, DIb etc.), in order to record any meaningful sedimentological variation.

The whole Uluzzian deposit is sealed at its top by two tephra layers (CII and CI) characterized by different colours and showing a total maximum thickness of 60 cm. Based on the recognized stratigraphic sequence, Palma di Cesnola subdivided the Uluzzian of Grotta del Cavallo into three main chrono-cultural phases. The most recent one corresponds to layers DII, spits D4 to D3, and layer DI, spits D2 to D1 (Final Uluzzian). This is preceded by the so-called "evolved phase", which is represented by layers EII-I, spits E4 to E2, and by layer E-D, spit E1. The most ancient phase, the so-called Archaic Uluzzian, was found in layer EIII, spits E7 to E5. This bed overlays layer FI (Mousterian). In the inner part of the cave, the occurrence of dripping pools on the top of FI (Gambassini, fieldwork notes 1981) suggests a depositional hiatus between the sedimentation of the two layers, corresponding to a period in which humans abandoned the cave. Close to the entrance of the cave, layers FI-EIII are separated by the tephra Fa and a few cm thick coarse-grained and sterile layer (Fs). More in detail, Fa seals layer FI (Late Mousterian) and, along with Fs, forms a diaphragm between layer FI and the subsequent Uluzzian occupation (Carrera et al., 2021, Palma di Cesnola, 1964b, Sarti et al., 1998-2000; Zanchetta et al., 2018, 2020). The layer Fs is described by Palma di Cesnola as "crushed stone with scarce industry of the archaic Uluzzian which had most probably filtered from the overlying layer EIII" (1969, p. 342).

Notably, the two volcanic layers delimiting the Uluzzian deposit, Fa at the base and CII at the top, are key chronological markers, as they have been respectively attributed to tephras Y-6 (Green Tuff of Pantelleria) dated at 45.5 ± 1.0 ka (Zanchetta et al., 2018) and Y-5 (Campanian Ignimbrite) dated at 39.85± 0.14 ka (Giaccio et al., 2017).

In 1964 two deciduous teeth (Cavallo B and Cavallo C) were recovered in spits 7 (Cavallo B) and 5 (Cavallo C) of the earliest Uluzzian layer (EIII – Messeri and Palma di Cesnola 1976, p. 7). Tooth B was found in a hearth at the base of layer EIII, while tooth C was found in the same layer but about 15-20 cm higher (Palma di Cesnola and Messeri 1967, p. 251). In 2011, a study by Benazzi and colleagues allowed the attribution of the two teeth from Grotta del Cavallo to modern humans. Following this publication, which identified *Homo sapiens* as the maker of the Uluzzian, some scholars (Banks et al., 2013; Zilhão et al., 2015) raised doubts about the integrity of the stratigraphic sequence brought to light in 1963-64 by Palma di Cesnola, by arguing that the teeth found in the Uluzzian layers were intrusive, due to post-depositional disturbances that had affected the site (erosional events). However, the revision of the materials and a careful cross-reading of both fieldwork notes and reports published by Palma di Cesnola at the end of each fieldwork season (Palma di Cesnola, 1961, 1963, 1964a, 1964b, 1965a, 1965b, 1966a, 1966b, 1966c, 1978, 1979, 1989, 1993, 2001, 2004; Palma di Cesnola and De Borzatti, 1963) allowed us to confirm the integrity of the deposit excavated in 1964, and, consequently, the association between the Uluzzian techno-complex and teeth B and C (Moroni et al., 2018).

In September 2019, three of the authors (A.M., P.B. and F.B.) returned to Grotta del Cavallo to verify the stratigraphic sequence recognized in the last century. The undisturbed Uluzzian deposit was explored entirely from the top of layer CI to the top of layer F by opening a small test trench. During the excavation, samples were taken for aDNA from sediments and ^{14}C dating (the results are presented in this paper), and lithics, faunal remains and shell ornaments were recovered from all the layers. But, most interesting, the unearthed archaeological and sedimentological succession perfectly corresponded to the reports provided by Palma di Cesnola, fully confirming the stratigraphic observations carried out in the '60s.

The trench, 50 x 30 cm wide, was opened in square L12, sector II, in an area of the cave where the Romanellian layers had been already excavated and the Uluzzian deposit was exposed. The excavated sedimentological succession is (from top to bottom):

- Unit 1 _ Reddish volcanic sediments (15-30 cm thick) lying on unit 2 through an unconformity. Some erosional pockets irregularly penetrate the underlying layer. Sterile. This level corresponds to the lower part of CI of the old excavations.
- Unit 2 _ Slightly cemented silver-grey volcanic sediments (5-20 cm thick) lying on unit 3 through a sharp unconformity. Sterile. This level corresponds to layer CII (Campanian Ignimbrite) of the old excavations.
- Unit 3 _ Strongly cemented reddish sandy silt (12-17 cm thick). It corresponds to layer DI of the old excavations.
- Unit 4 _ Reddish sandy silt sediment looser than unit 3 (about 15 cm thick). It corresponds to layer DII of the old excavations.
- Unit 5 _ Dark grey-brown sand (15-20 cm thick). It corresponds to layer EI of the old excavations.
- Unit 6 _ Grey-brown sandy silt (10-15 cm thick). It corresponds to layer EII of the old excavations.
- Unit 7 _ Very loose grey-brown sand with abundant clasts, 27-35 cm thick, lying through an unconformity on the underlying layer (FI of the old excavations). It corresponds to layer EIII of the old excavations.

In 2019, layers Fs and Fa were not found because the trench was opened towards the bottom of the cave in an area where these two layers are absent.

Grotta di Castelcivita **(Castelcivita – Salerno – Campania – Southern Italy)** (40.49563600N, 015.20922177E, 94 m a.s.l.)

Grotta di Castelcivita, hereafter referred to as Castelcivita, is located in the Cilento region and opens at the foot of the Alburni massif in the Calore River valley. The ~2.6 m-thick archaeological deposit is located at the entrance of more than 5 kms of tunnels and caverns extending inside the Mesozoic-Cenozoic limestone and covers the period of the Middle to Upper Palaeolithic transition (Late Mousterian, Uluzzian and Protoaurignacian).

Systematic research at Castelcivita was started by P. Gambassini of the University of Siena in 1975 and continued until 1988 over an area of 14 m^2 (Gambassini, 1997). The succession is more than 5 m thick, with a thickness of sediments containing archaeological materials of around 2.6 m. Research at Grotta di Castelcivita has been resumed by the University of Siena, under the direction of two of the authors (A. Ronchitelli and A. Moroni) in 2015 and is still ongoing.

The main sedimentological, stratigraphic, and archaeological features are listed here in stratigraphic order. The descriptions are based on Fumanal (1997), and new observations performed in the framework of this study.

- Layer cgr (= cemented grey; spits 33-29), Late Mousterian. This level corresponds to the base of the succession and consists of a thick level (about 2 m) of rock fall deposits formed by large limestone blocks collapsed from the cave vault and walls. Fine-grained sediments are infiltrated within the blocks. This level possibly lies on the cave bedrock.
- Layers upper cgr and gar (= cemented grey and yellow clay; spits 28-24), Late Mousterian. Fine-grained sediments (silt and clay) with scattered debris and clasts, at places forming cemented layers. These deposits locally incorporate pyroclastic materials. Large breakdown limestone blocks occur at places, especially at the top of layer gar.
- Layer lower rsi (= lower red; spits 23-lower 18), Late Mousterian. Fine-grained sediments (clay, silt, and fine sand) with scattered debris and a faint plane-parallel lamination. The interval also contains cemented layers.
- Layers upper rsi, pie, rpi and rsa" (lower red, stones, red with stones and red sand; spits upper 18-11), Uluzzian. These deposits are discontinuous with respect to the previous one due to a change in sedimentation which becomes dominantly allochthonous with autochthonous sediments expressed only by scarce breakdown sediments (Fumanal, 1997). According to Fumanal and Gambassini 1997 (ps. 23 and 109) "the contact plane between Mousterian and Uluzzian is situated within spit 18. The transition between the two cultural horizons is marked by a clear-cut sedimentological change associated to erosive episodes, that reveals a hiatus in the stratigraphic sequence […] the lithic industry contains just eight tools".

  These deposits, ~80 cm-thick, are generally made of fine-grained materials (silt and clay), occasionally mixed with more coarse-grained materials like sand and granules and contain common breakdown debris.
- Layer rsa' (red sand; spits 10 – 8), Protoaurignacian with marginally backed bladelets (Dufour). Fine-grained reddish sediments dominated by silt and sand with scattered debris. Rounded clasts up to 2-3 cm in diameter also occur. The occurrence of rounded clasts supports a completely allochthonous origin for these sediments. Layers rsa' and rsa'' are almost identical from a sedimentological point of view but are different for the material culture.
- Layer gic (cemented yellow; spits upper 8– 7), Early Aurignacian with micro-points of the Castelcivita type. Yellowish fine-medium-grained sand, locally rich in a muddy matrix. Rounded clasts are common in the lower part of the interval, while debris fragments are invariantly scarce. Some clasts are made of poorly consolidated pyroclastic material. Deposits of this layer are slight to firmly cement.
- Layer ars (orange sand; spit 6-4), Early Aurignacian with micro-points of the Castelcivita type. Reddish to yellowish fine-grained sand with a silty

matrix. Pyroclastic materials occur as small clasts within the bed.

- The top of the anthropogenic sequence is represented by a multilayered flowstone that sealed the whole deposit, reaching the cave ceiling. The flowstone layers are separated by thin strata made of fine- to medium-grained sand. These sands are made of pyroclastic sediments whose origin has been attributed to the Y5 (Campanian Ignimbrite) eruption dated 39.85 ± 0.14 ka BP (Giaccio et al., 2017).

Grotta della Cala (Camerota, Salerno, Campania, Southern Italy)
(40.00108243N, 015.38095416E, 3 m a.s.l.)

Systematic investigations at the cave site of La Cala were started in the '60s (1966-71) by A. Palma di Cesnola of the University of Siena, who opened a trench of about 10 m^2 and around 3 m deep, located in the middle sector of the cave and known as "internal series". From 1971 P. Gambassini took over the direction of the excavations at the site, firstly continuing to investigate the Mousterian layers. Much later (2000-2006), Gambassini extended Palma di Cesnola's trench towards the bottom of the cave in the Holocene deposits. In the '70s Gambassini opened a second area, 28 m^2 wide, closer to the cave entrance, which he called the "atrium series". Research at Grotta della Cala was resumed by the University of Siena, under the responsibility of one of the authors (A. Moroni), in 2014 and is still ongoing.

The internal series includes, from base to top (cf. Benini et al., 1997; Martini et al., 2018): i- two Mousterian layers (S and R); ii- a thick multilayered flowstone subdivided into two main banks (βI, the upper one, and βII, the lower one) separated by thin sandy layers with sparse lithics; iii- a tick Upper Palaeolithic siliciclastic sequence (Evolved Gravettian - layer Q, Evolved and Final Epigravettian – layers P, N, O, M, L, I, H and G); iv- a flowstone (α); and, finally, v- siliciclastic Holocene deposits (Mesolithic – layer F/7; Neolithic layers D-E/5; Copper Age – layers B-C/4-3; Bronze Age – layers A/2-1).

The atrium series includes layers containing techno-complexes not represented in the internal series, i.e., the Early Gravettian (EG), the the Aurignacian (AU), and the Uluzzian (UL). The succession starts with Mousterian (MU) strata which directly overlay a marine conglomerate (Benini et al., 1997; Boscato et al., 1997; Martini et al., 2018). The complete anthropogenic sequence found in the atrium series and the correlation with the internal series are here briefly presented in stratigraphic order:

- MU (Mousterian): 10 cm thick cemented red sand. According to Benini et al. (1997), this level can be correlated with layer R of the internal series;
- UL (Uluzzian): about 15 cm (spit 14 in the fieldwork) thick light grey cemented breccia. According to Benini et al. (1997), this level can be correlated with the flowstone βII of the internal series;
- AU (Aurignacian): about 40 cm thick (spits 13-10 in the fieldwork) sandy breccia at place cemented. At their top, these deposits are characterised by a carbonate cemented layer with circular pools due to protracted dripping

from the cave vault, which attests to a temporal gap that occurred between the Aurignacian occupation and the start of the Early Gravettian;

- EG (Early Gravettian): about 30-40 cm thick (spits 3-1 in the fieldwork) fine-grained sand at place cemented.
- Q (Evolved Gravettian): 10-20 cm thick dark brown sand containing abundant faunal remains. It can be correlated with the basal part of layer Q in the internal series (Bernini et al., 1997). Above layer Q, other archaeological layers are exposed due to natural erosional phenomena, but these were never archaeologically excavated in the atrium. These sediments correspond to layers M, N, O, and P of the internal series (Martini et al., 2018).

In the Atrium series a sedimentological difference between the Uluzzian, the underlying Mousterian and the overlying Aurignacian is clearly visible (Fig S3).

A more detailed sedimentological interpretation of the sedimentary succession was provided by Martini et al. (2018). Here the succession is subdivided into four allostratigraphic units based on the recognition of three main unconformities. Such unconformities correspond to phases of stasis in deposition and/or erosion. The most important unconformity is easily recognizable both in the internal series and in the atrium. It separates the deposits of layer Q from the overlying deposits of layers P and N. The features of the erosional surface and the overlying sediments suggest that the erosional phase is due to the activation of stream settings within the cave (Martini et al., 2018).

Riparo L'Oscurusciuto (Ginosa, Taranto, Apulia, Southern Italy) (40.58842614N, 016.75782152E 241 m a.s.l.)

Oscurusciuto is a rock-selter located in a narrow ravine incised into Pleistocene calcarenites near Ginosa. The site contains a sedimentary succession about 5.7 m thick (Martini et al., 2021). Excavation began in 1998 and is still in progress. Currently, only the first upper 3 m of the sequence have been investigated from an archaeological point of view. All the excavated levels are characterized by a great abundance of archaeological materials such as lithic artifacts (Ranaldo, 2017; Ranaldo et al., 2017b; Marciani, 2013, 2018; Marciani et al., 2016, 2018, 2020b; Ronchitelli et al., 2011; Villa et al., 2009) and faunal remains (Boscato and Crezzini, 2006, 2012b; Boscato et al., 2011). Some of these levels also returned numerous and combustion features (Boscato and Ronchitelli, 2008, 2017; Spagnolo et al., 2020). The spatial analysis carried out on some of these levels returned interesting evidence of articulated management of the living space, inferring clues about the settlement behaviour and dynamics (Spagnolo, 2013, 2017; Spagnolo et al., 2016, 2019, 2020).

Sedimentological and stratigraphic analysis of the succession was presented by Martini et al. (2021). The sequence is divided into three parts based on principal sedimentological features:

· The lower part of the succession (currently not investigated from an archaeological point of view) is mainly made of breakdown deposits mixed with allochthonous sand and silt. Breakdown deposits collapsed from the shelter vault.

· A fine-grained volcanoclastic sand layer, 60-cm-thick (stratigraphic unit 14), abruptly interrupts the succession. The sedimentological features indicate that these deposits accumulated inside the shelter due to aeolian processes (Martini et al., 2021). These sediments show a mineralogical and geochemical affinity to the Mount Epomeo Green Tuff (Marciani et al., 2020b), i.e., a pyroclastic event dated at ~55 ky BP.

· Above stratigraphic unit 14, the succession is dominantly siliciclastic with strata mainly composed of medium- to coarse-grained sand, with scattered granules and pebbles and a common silty matrix. One layer (stratigraphic unit 8) shows an open framework texture (i.e., matrix is absent). Rockfall deposits are relatively scarce from stratigraphic unit 14 up to the top of the succession. Some large debris have been found during the excavation in stratigraphic unit 4 (Spagnolo et al., 2019). Some of these debris show an allochthonous composition (limestone) unrelated to the shelter's ceiling (calcarenite). Spagnolo et al. (2019) suggest that humans may have brought these blocks into the shelter (i.e., manuports). The top of the stratigraphic sequence (bottom of stratigraphic unit 1) is dated to 38,500 ± 900 BP, cal. 42,724 ± 716 BP Beta 181,165 (cal Ramsey and Lee 2013) (Boscato and Crezzini, 2012b).

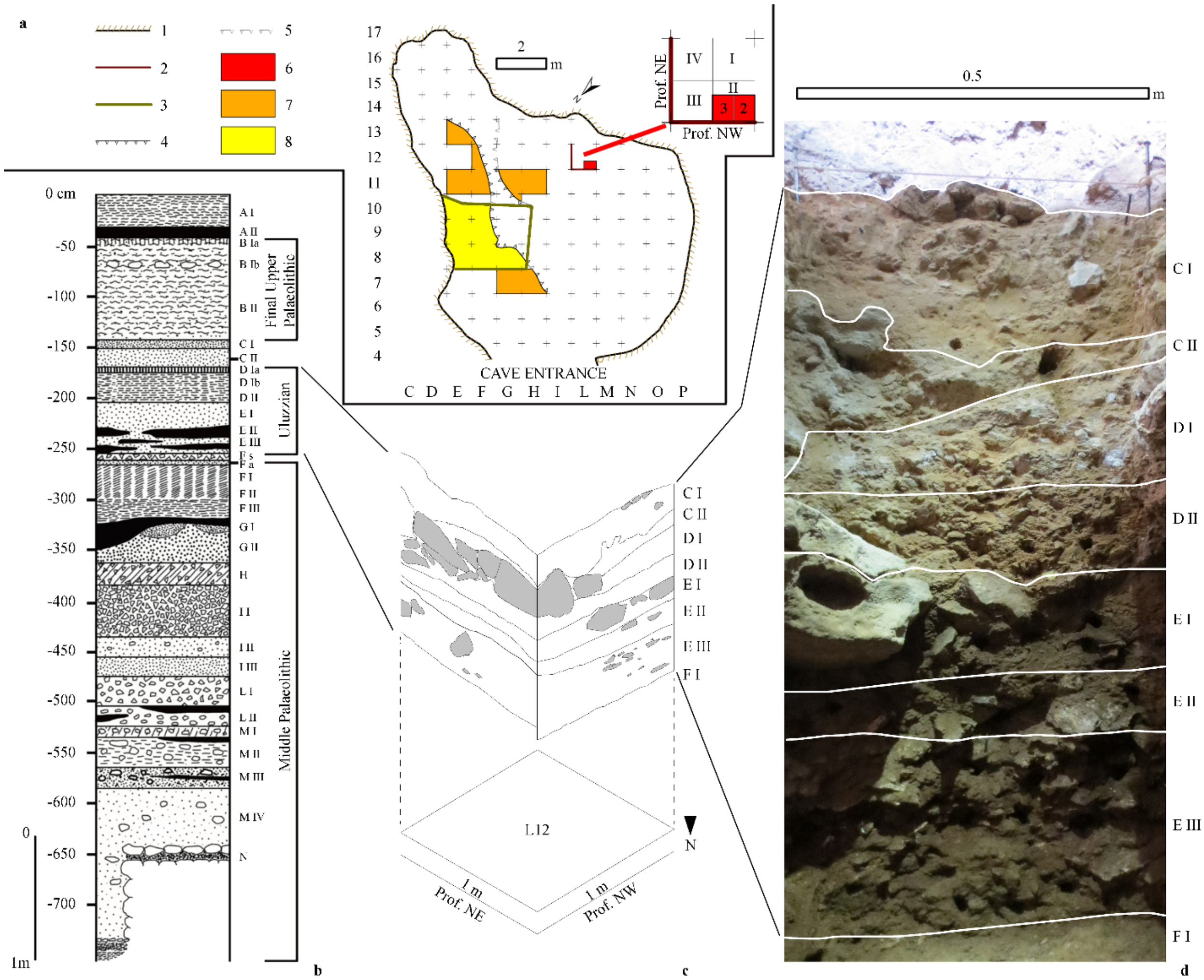


Figure S1 - Grotta del Cavallo: a) cave planimetry with the indication of the Uluzzian excavated areas (excavation 2019 in red); 1 = cave wall; 2 = profile line (2019 excavation); 3 = Palma di Cesnola's trench; 4 = erosion line; 5 = reconstructed erosion line; 6 = undisturbed deposit (fieldwork 2019); 7 = undisturbed deposit (Gambassini's excavations 1978-1986); 8 = undisturbed deposit (Palma di Cesnola's excavations 1963-1966). b) Stratigraphic profile according to Palma di Cesnola; c-d) stratigraphic profiles of the Uluzzian deposit brought to light during 2019 excavation.

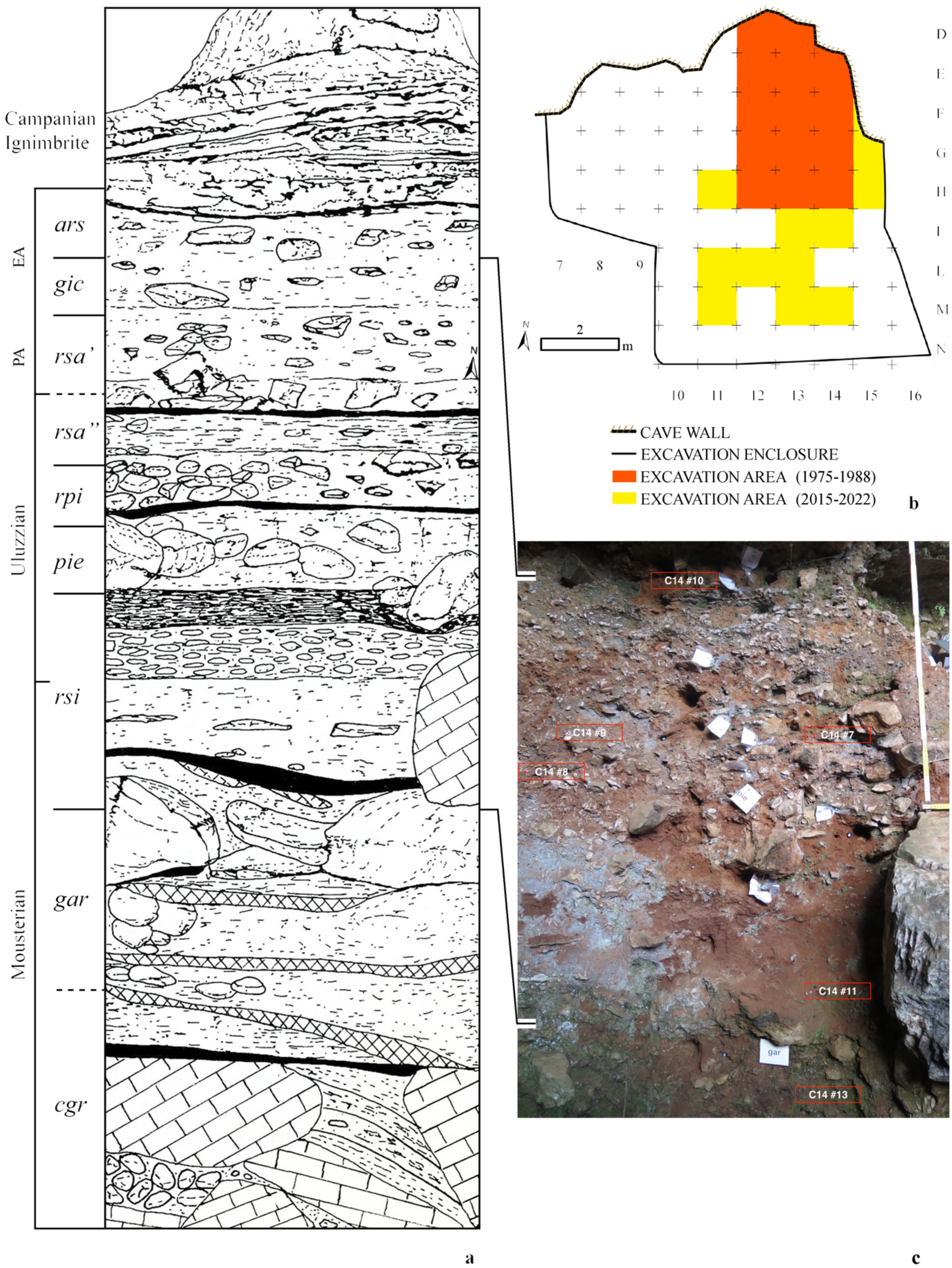


Figure S2 – Grotta di Castelcivita: a-c) stratigraphic profiles and b) cave planimetry with the indication of the excavated areas.

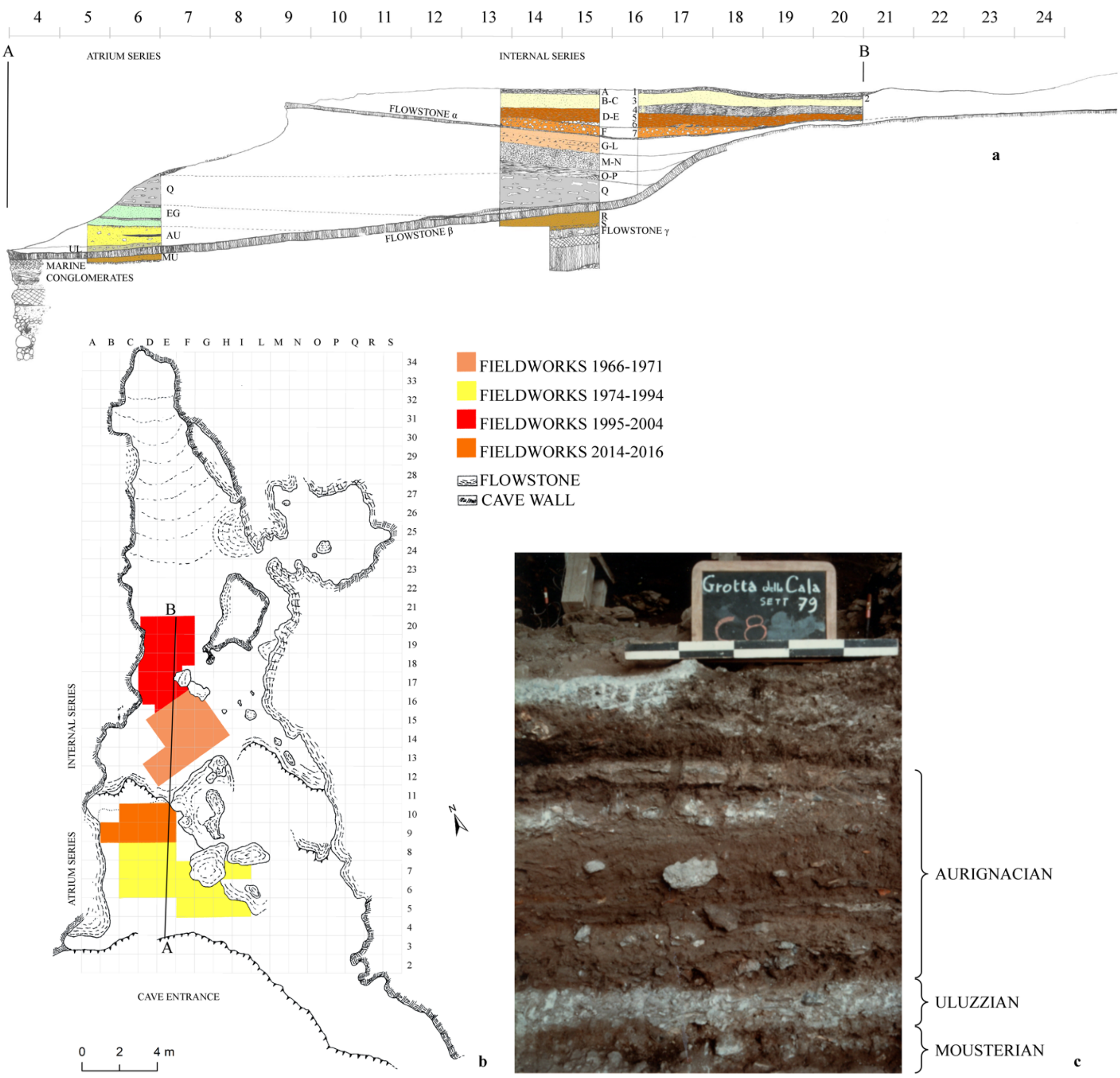


Figure S3 – Grotta della Cala: a) longitudinal stratigraphic profile; b) cave planimetry with the indication of the excavated areas and c) stratigraphic profile of the Atrium series (Aurignacian, Uluzzian and Mousterian). The sedimentological difference between the Uluzzian (the lowermost grey layer), the underlying Mousterian and the overlying Aurignacian is clearly visible.

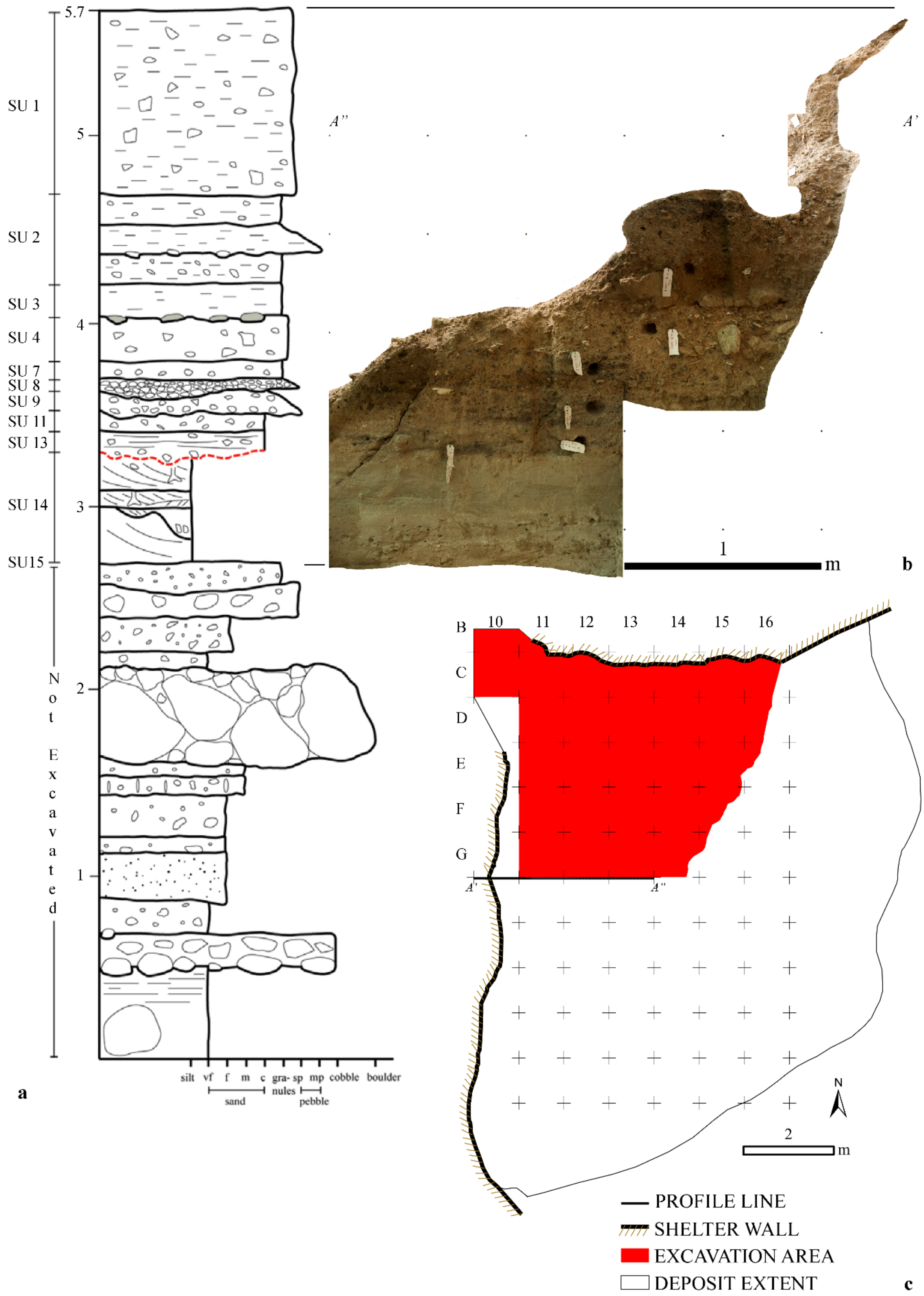
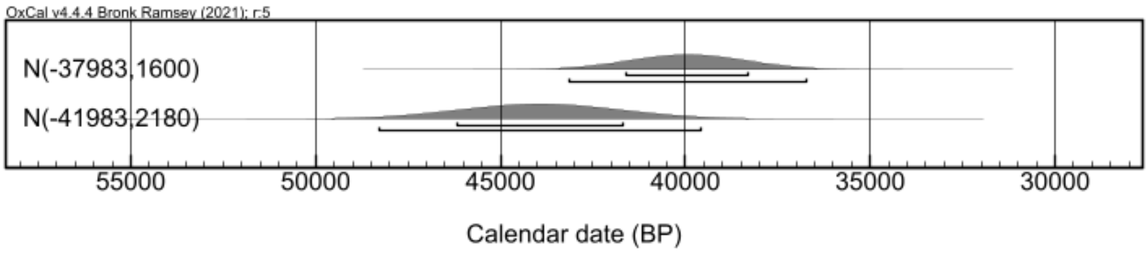


Fig. S4 - Riparo l'Oscurusciuto: a) sedimentary log of the clastic succession (modified from Martini et al., 2021); b) stratigraphic profile on the southern edge of the excavated area; c) site's planimetry and excavated area highlighted in red.

SUPPLEMENTARY NOTE 2 Sites not included in our analysis

We left some sites out of the data analysis. One is the Grotta La Fabbrica. The site represents further confirmation of the time interval between the Mousterian and the Uluzzian both from a chronological and a stratigraphic standpoint (Villa et al., 2018). An erosional surface separates the thin Uluzzian layer (layer 2) from the underlying Mousterian (layer 1a). The OSL dates also suggest a temporal interval, but the problem is the underlying precision of the results. Layer 1a is dated to 44±2.1 and layer 2 is dated to 40 ± 1.6 ka. As shown in the illustration below, they are spread so widely in terms of their uncertainties that it becomes extremely difficult to reliably interpret their meaning (see image below). The GeGLF1 OSL date for the Mousterian level, for example, has a ± 2100-year error and in calibrated space (as shown in the figure below) the result at 95.4% spans 39,500—48,500 cal BP.



Colle Rotondo is another site of potential interest, but the dates obtained for the Uluzzian layer of this site are completely out of the range covered by this technocomplex elsewhere. Both dates fall within the Epigravettian (Villa et al., 2018). OSL dating performed on three samples collected at the base (CR3) and at the top (CR2, CR1) of the layer incorporating the artifacts yielded unexpectedly young ages, ranging from 18,180 ± 950 ka for CR3, 15,870 ± 1,100 ka for CR 2 and 14,640 ± 960 ka for CR1. At the time indicated by the OSL dates there are in Italy only Epigravettian assemblages The lithic assemblage, unaffected by aeolian transportation, is likely to have remained close to the exposed surface until around 14 ka, and then rapidly buried: a fact that fully justifies the OSL dates yielded by the sediment immediately below the artifacts (CR 3 sample, 18 ka) and immediately above them (CR2 and CR 1 samples, 15–14 ka). Thus, the quoted OSL ages do not refer to the depositional event but probably to a later exposure to light: specifically the last time of exposure before rapid burial of the archaeological layer. The assemblage remains undated but the similarity of the lithic component to the La Fabbrica assemblage suggests that they may be broadly contemporaneous. Finally, the Uluzzo C site ought to be mentioned. Here, as at Fabbrica, the issue is dating precision. Spinapolice et al. (2022) obtained some OSL dates, but the precision on the dating of the Uluzzian levels at the site spans several thousand years (optical ages for layers C, D and E ranged from 38.1±2.2 ka to 42.7±2.6 ka (with a weighted mean of 40.6±1.4 ka). The results are useful, then, only in the broader sense.

SUPPLEMENTARY NOTE 3 Luminescence methods

In July 2018, ten sediment samples were collected at Castelcivita during the night in the shadow of the rockshelter and under an artificial opaque shelter for extra protection using filtered lighting (low-intensity LEDs with peak emission at 559 nm). Under these conditions, samples were taken by cleaning the exposed section, manually excavating a core underneath, and then collecting the resulting sediment unexposed to ambient light in opaque plastic bags. Additional bulk sediment was collected at the sample location to determine the dose rate. At Cala, seven samples were collected in the evening by hand under an opaque shelter, and four samples (CALA_X7033_SB24 to CALA_X7036_SB21) were collected as blocks (10cmx10cmx5cm) extracted using a drill as the sediment was fully cemented. In the laboratory, the outer 2 cm of each face of the blocks was removed before luminescence analyses. At Oscurusciuto, eleven sediment samples were collected at night, by hand, under an artificial opaque shelter to block out bright moonlight. The samples and their contexts are given in Table 5 in the main paper.

Radionuclide concentrations are reported in Supplementary Table 6. The water content of each sample was measured in the laboratory as the ratio between the wet mass and the dry mass of the sediment. For the entire sequence at Castelcivita, the water content has been measured at ~10%, between 0 and 10 % at Cala, and <1% at Oscurusciuto. At Castelcivita and Cala, we assumed these values approximate the average value throughout the burial period. At Oscurusciuto, however, the samples were taken during a particularly hot and dry season where, contrary to Castelcivita and Cala, which are cave sites, the entire sequence is exposed. We, therefore, assumed a water content of 10±3% as more representative of the water content at Oscurusciuto over burial time. The water-corrected beta and gamma dose rates, cosmic ray dose rates, and total dose rates are reported in Table 1. The total dose rates for quartz range from ~2.1 to 3.6 Gy/ka at Castelcivita, ~1.1 to 2.4 Gy/ka at Cala, and ~1.1 to 2.9 Gy/ka at Oscurusciuto.

A standard multi-grain Single-Aliquot Regenerative (SAR) procedure was used for the equivalent dose (De) determination. After measuring the natural optically stimulated luminescence (OSL) signal, the aliquots were subjected to seven regenerative-dose cycles (including a duplicate dose and zero dose). The induced OSL signals were measured for 40 s at 125°C prior to heating at higher temperatures. To determine the preheat conditions for OSL measurement, preheat plateau and dose recovery tests were performed on two samples per site.

For all samples, the OSL signal was determined from the first 0.22s of stimulation, and the count rate over the last 0.44s was taken as a background. At the end of the SAR sequence, a check was made to detect the potential contamination of feldspar using the IR depletion ratio test, as described in Duller (2003). The De and their uncertainties were estimated by interpolating the normalized natural OSL signal onto the normalized regenerated growth curve fitted with a single exponential function with Analyst software (Duller, 2015). The overdispersion (OD) value and the mean De were calculated using the Central Age Model (Galbraith et al., 1999), using the function calc CentralDose (Burow, 2020) from the package Luminescence in R v. 0.9.18 (Kreutzer et al., 2012: 2022).

At Castelcivita, between eight to thirty-one aliquots were measured for each sample depending on the amount of quartz available. The OD values are lower than 21% for all the samples, except for sample CTC_X7029_SB12 which has a significantly higher OD of 31± 4%. It is challenging to determine the origin of high OD in the De's from multi-grain aliquots because of the averaging effects. The additional scatter might be caused by micro-dosimetry variations, heterogeneous bleaching, and/or post-depositional mixing. The sedimentary layer rsi, from which CTC_X7029_SB12 is coming, has been described as fine-grained sediment with scattered debris and a faint place-parallel lamination containing cemented layers. Based on this description, we think that microdosimetry effects and heterogeneous bleaching might contribute to the large overdispersion in the De's for this sample.

At Cala, the Mousterian and Uluzzian layers are cemented sand and cemented breccia, respectively. These layers did not provide much datable material; therefore, only a few aliquots were measured. Only three aliquots were measured for sample CALA_X7034_S23, and the results should be interpreted as informative only. For the rest of the samples, the OD ranges between 0 to 30±5 %, but for most of the samples, the OD is around 20%. Such large OD was predictable at this site regarding the composition of the sedimentary layers, their thickness (10cm thick for the Mousterian layer and 15 cm-thick for the Uluzzian layer), and the cementation of these layers over time). At Oscurusciuto, between thirty-six and forty aliquots were measured for the De's determination, and the overdispersion was equal to or lower than 20%.

Dose rate calculation

At Castelcivita, the gamma dose rates were estimated using dosimeters buried in the stratigraphy between 5 to 20 cm from the sample location for 785 days. These dosimeters consisted of three carbon-doped alumina pellets (Al_2O_3:C, diameter: 5 mm, thickness: 1 mm) placed at the extremity of a metal tube of ~30 cm length as described in Kreutzer et al. (2020). Before burial, the pellets were heated at 350°C to reset any remaining luminescence signal. Measurements were done at the IRAMAT-CRP2A laboratory using a Daybreak 2200 OSL reader system (Bortolot, 2000), combining green light LED stimulation (Nichia NSPG310) and 7.5 mm of Hoya U-340 filter for detection. The measured luminescence signal of each pellet was compared to that induced by an artificial beta source, which was calibrated against dosimeters dosed using a reference block (Mercier et al., 1994).

At Cala, the gamma dose rates were determined from the radioelement content of the sediment for most samples or using dosimeters for samples CALA_X7040_SB17 to_SB20. The dosimeters were left in the sequence for 785 days.

At Oscurusciuto, the gamma dose rates were determined from the radioelement content of the sediment for most samples. When possible, *in situ* gamma

measurements were obtained using a portable Canberra detector (Inspector 1000 fitted with a stabilized 2-inch probe). The probe was calibrated using the reference blocks at Oxford University, and the spectra were analyzed using OxGamma software and applying the windows approach (see Kumar et al., 2022).
The cosmic contribution was estimated by considering the burial depth of each sample, the sediment density, the configuration, and the site's location (Prescott and Hutton, 1994). The internal dose of the quartz grains has been assumed at 0.02 ± 0.01 Gy.ka $^{-1}$.

SUPPLEMENTARY NOTE 4 Bayesian Modelling

The models comprise the excavated `Sequence` of layers and/or `Phases`, with individual radiocarbon likelihoods and OSL ages. Where appropriate, `Boundary` terms were included to reflect the cessation of one `Phase` and the start of another. Double `Boundary` commands were used to indicate the presence of a sterile horizon. We included radiocarbon dates from the pre-40,000 cal BP layers as "fraction modern" (`R_F14C`) values to account for the asymmetric error terms implicit in conventional radiocarbon dates toward the limit of the technique. We used the `C_Date` command to incorporate the tephra Ar/Ar dates for the Y-5/CI and Y-6 ash layers. OSL ages were included using the `Date` command with the measurement year specified as in the following code:

```
Date("X7030",N(2015-48600,2100))
```

For error terms in the OSL dates, we subtracted the systematic errors from the OSL ± values and used only the random errors for the modeling work. We used outlier detection methods based on a `General` *t* outlier model. We used an `SSimple` model to measure the offset between sets of duplicate determinations (Bronk Ramsey 2009b), to consider whether certain likelihoods were outliers with respect to the prior framework of the model. Significant outliers detected were downweighted in the posterior results generated, reducing their influence in the final models. We include the CQL code for the models below.

For the Cavallo model, we tested whether the inclusion of two Firenze determinations was significant or not for determining the start of the Uluzzian. With the Firenze dates included the range was 42,930—42,360 cal BP at 68.3% prob. and 43,650—42,150 cal BP at 95.4%. Without them, the range was 42,750—42,300 cal BP at 68.3% prob. and 43,270—42,150 cal BP at 95.4%. We conclude the model is not sensitive to either their exclusion or inclusion.

It is also important to note that in the Cavallo Bayesian age model (Figure 4 of the main paper), the age *a posteriori* for the Y-6 tephra appears to sit somewhat later than 45,000 cal BP. Its age estimate is, however, entirely consistent with the independent tephra age, due to the large error term. We tested the model constraining the tephra age in different ways, and we found it was robust to variations in the priors (e.g., as the current model, as well as nesting it in an `After` command, and with, and without, the Firenze determinations for the Mousterian as described above).

For the End Mousterian model, we used `boundary` distributions as priors in a single `Phase` model. We were cautious regarding the data from Grotta Reali, since there are no constraining post-Mousterian dates and several of the results are not on humanly-modified bone. Below we show a comparison of the End Mousterian boundary with (left) and without (right) the Reali final boundary. One can see the estimated end of the Mousterian across Italy shifts around 1300-1500 years if we include the Reali end `boundary` compared with the result on the right if we are cautious and simply include the Reali `Date` for the last Mousterian phase in the model. In the paper we use the latter method and the HPD on the right-hand side.

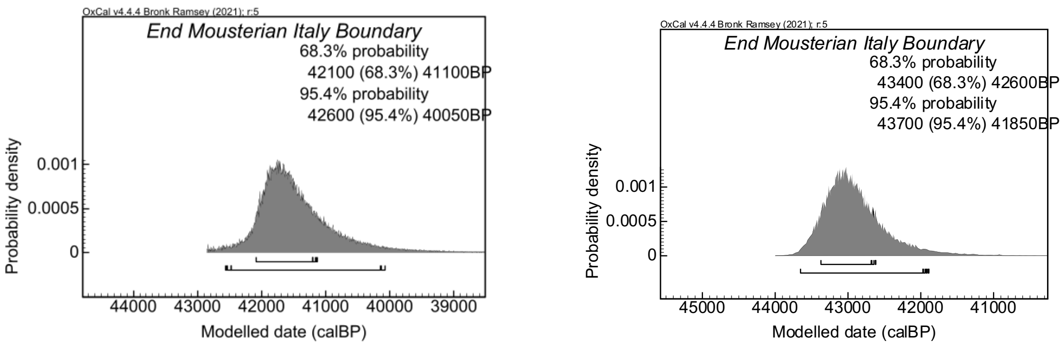


Figure S5: End Mousterian boundaries run with two different priors for the Grotta Reali site (Peretto et al., 2020). On the left, the boundary included in Figure 7 in the main paper, which has the `Date` calculated for the end boundary for the uppermost Mousterian at the site, and on the right the end boundary based on includes the end boundary for the uppermost Mousterian at the Reali site.

SUPPLEMENTARY NOTE 5 ZooMS methods applied at Cavallo and Castelcivita.

For the Cavallo samples, we applied ZooMS using established protocols (Brown et al., 2020; Buckley et al., 2009; Welker et al., 2015), available here: dx.doi.org/10.17504/protocols.io.bf5djq26. Extraction was performed at the Research Laboratory for Archaeology and the History of Art (Oxford) and the dried samples were sent for analyses to the Max Planck Institute for the Science of Human History in Jena. The peptides were analyzed using a Bruker (Autoflex Speed LRF) MALDI-TOF mass spectrometer. Using R, the mass spectrometer readouts were converted into mzML files. Each triplicate was then analyzed using mMass version 5.5.0. The species library was compiled from Buckley et al. (2009), Welker et al. (2016), and Brown et al. (2020). Each triplicate was analyzed individually, then combined into one identification so any possible contamination could be discerned. Palaeoproteomic data from Cavallo Cave are currently being prepared for publication (McCarty 2021, unpublished Master thesis). At Castelcivita, we analyzed bones using a similar preparation method (Oertle et al., submitted).

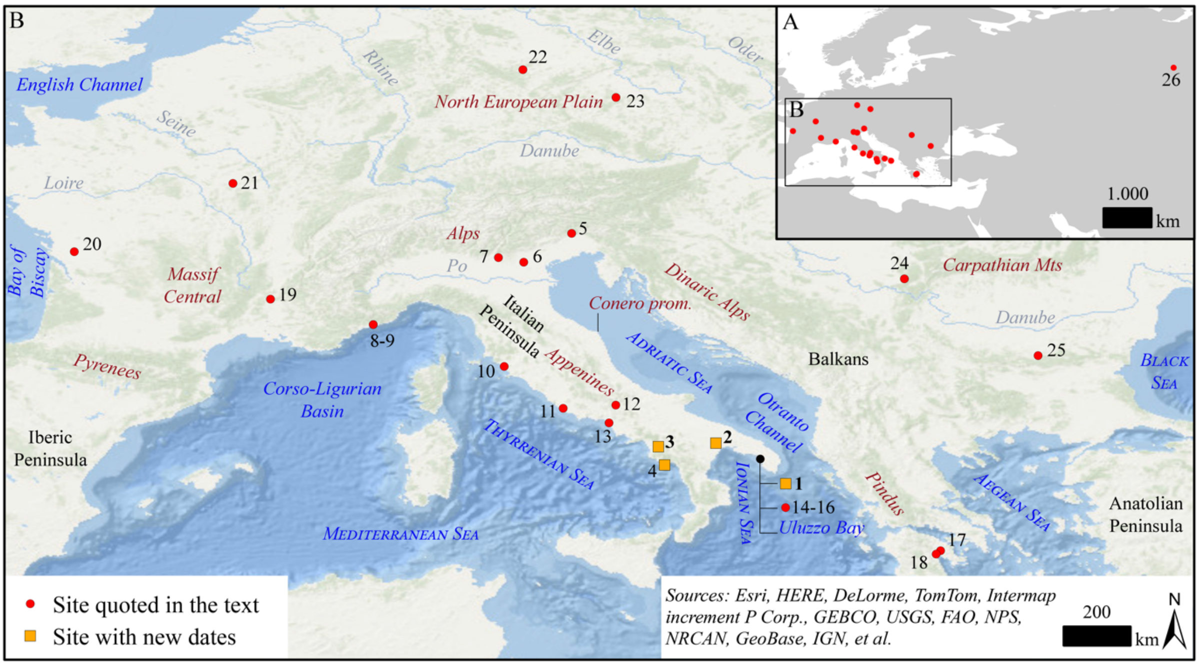


Figure S6. Map of the Italian Peninsula showing the location of the sites mentioned in this paper. 1) Grotta del Cavallo; 2) Riparo L'Oscurusciuto; 3) Grotta di Castelcivita; 4) Grotta della Cala; 5) Grotta di Rio Secco; 6) Riparo del Broion; 7) Grotta di Fumane; 8) Riparo Bombrini; 9) Riparo Mochi; 10) Grotta della Fabbrica; 11) Colle Rotondo; 12) Grotta Reali;13) Roccia San Sebastiano; 14) Grotta di Serra Cicora; 15) Grotta di Uluzzo C; 16) Grotta Mario Bernardini; 17) Klissoura;18) Kephalari; 19) Grotte Mandrin; 20) La Roche-à-Pierrot, Saint-Césaire; 21) Grotte du Renne, Arcy-sur-Cure; 22) Ilsenhöhle in Ranis; 23) Zlatý kůň; 24) Peștera cu Oase; 25) Bacho-Kiro; 26) Ust-Ishim. Sources of the basemap: Esri, HERE, DeLorme, TomTom, Intermap increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, et al. The map was generated using ArcGIS®10

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