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Ground truth validated 3D electrical resistivity imaging of the archaeological deposits at Arma Veirana cave (northern Italy)

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**GROUND TRUTH VALIDATED 3D ELECTRICAL RESISTIVITY IMAGING
OF THE ARCHAEOLOGICAL DEPOSITS AT
ARMA VEIRANA CAVE (NORTHERN ITALY)**

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56

57 **Abstract**

58 We present 3D Electrical Resistivity Tomography (ERT) imaging of the archaeological
59 deposits at Arma Veirana cave (Northern Italy), to date only partially explored. The archaeological
60 importance of the cave is due to the presence of a rich Mousterian layer, traces of Late Upper
61 Palaeolithic (Epigravettian) temporary occupations and an Early Mesolithic burial of a female
62 newborn. ERT is rarely employed in Paleolithic cave contexts because Paleolithic remains are
63 typically disseminated in loose deposits and either do not possess high electrical resistivity contrasts
64 or are too small to be detected. Furthermore, some issues can derive from the confined environment

65 in caves. In this view, our study represents an opportunity to assess the capability of this geophysical
66 method to retrieve subsurface information of Paleolithic cave deposits and create a framework for the
67 improvement of ERT applications in such a peculiar cave context. The aim of this study was to define
68 the features of the deposits (i.e., geometry, thickness, and sediment distribution) and to map the
69 morphology of the underlying bedrock. Results reveal that the thickness of the deposits varies both
70 along the primary axis of the cave and transverse to it. This study allowed the recognition of shallow,
71 meter-sized, fine-grained sediment-filled structures with a longitudinal orientation with respect to the
72 primary axis of the cave, as well as a possible erosional-like structure. The cross-validation of
73 geophysical results with the archaeological evidence (the Early Mesolithic newborn burial and
74 Epigravettian artefacts) confirms that the low-resistivity unit could be the most promising from an
75 archaeological point of view.

76

77 **Keywords:** cave deposit, Pleistocene, Early Holocene, ERT, 3D resistivity imaging, geophysical
78 investigations

79

80 1. INTRODUCTION

81 In general, one of the primary goals of a new archaeological excavation project is to document
82 the formation of the site, as well as the extent of its deposit. At the Arma Veirana cave, which is the
83 topic of the present study, only a small portion of the deposit has been explored during the four recent
84 archaeological field seasons (Hodgkins et al., in review; Negrino et al., 2018). While recent
85 documentations of exposed sections have provided a fair amount of data on some of the depositional
86 history at the front of the cave, at present the depth and richness of the sediment remained unknown
87 for all portions of the cave. Given the destructive nature of archaeological excavations, non-
88 destructive in-depth investigation of the deposits is a valuable approach to help design future
89 excavations. Specifically, at this point in the project, it became important to assess the extent and

define the properties and volumes of potential artefact-bearing deposits before proceeding with further excavation.

In this context, the team turned to near-surface geophysical methods as an important tool to derive key information about underground properties and structures. Geophysical methods are an important component of geoarchaeological investigations. They allow non-invasive and rapid imaging of archaeological settings and help answer scientific questions by considering a site integrally within its geological surroundings. They are particularly useful in geoarchaeological investigations to define site stratigraphy, map site disturbance, and reconstruct palaeolandscapes (Sarris et al., 2018). However, geophysical techniques are seldom used to investigate Paleolithic archaeological sites (Obradovic et al., 2015; Abu Zeid et al., 2019), mostly due to those sites' sedimentary nature and the almost complete absence of architectural remains that can result in clear geophysical anomalies. The presence of numerous, thin, and closely packed occupation layers containing archaeological remains that are generally very small and would be destroyed by invasive investigations makes the contribution of geophysical methods significant (c.f. Abu Zeid et al., 2019). Schmidt et al. (2015) provide an overview of the issues to be considered when undertaking or commissioning geophysical survey in archaeology.

One of the most frequently used geophysical techniques is Electrical Resistivity Tomography (ERT). It is a quick and cost-effective method that provides a reliable imaging of the subsurface electrical resistivity pattern and allows identification of underground structures. ERT theory (cf., Dahlin and Loke, 1998; Loke et al., 2003) and application (cf. Griffiths and Barker, 1993; Guérin and Benderitter, 1995; Torrese, 2020; Torrese et al., 2021a) are well documented in geophysical research literature.

ERT is widely used in archaeological studies (Campana and Piro, 2008; Witten, 2017; El-Qady et al., 2019). It has been used to investigate site stratigraphy (Papadopoulos et al., 2006) and the sedimentological architecture (Yogeshwar et al., 2019), to detect changes in lithology and geology (Laigre et al. 2012; Scapozza and Laigre 2014), depositional targets and buried structures (Cozzolino

116 et al., 2020; Papadopoulos et al., 2007; Supriyadi et al., 2019; Tsokas et al., 2009), to map remnants
117 of past human occupation (Berge and Drahor, 2011a, 2011b; Matias et al., 2006; Papadopoulos et
118 al., 2010; Thacker et al., 2002; Tsokas et al., 2018), to reconstruct palaeolandscapes (Papadopoulos
119 et al., 2014) as well as to detect of offshore archaeological features (Sarris et al., 2014; Tonkov, 2014;
120 Simyrdanis et al., 2015). ERT is also widely used to choose the most promising areas to excavate
121 (Piroddi et al., 2020).

122 Paleolithic caves in temperate regions of Europe are often filled with deposits that are poorly
123 sorted and display a wide range of grain-sizes, from large blocks of roof fall (éboulis) to silt and clays
124 (Goldberg and Sherwood, 2006; Mallol and Goldberg, 2017). Differently from other archaeological
125 settings with localized and large sized anomalies easily detectable by ERT, the Paleolithic remains
126 contained in such loose deposits are disseminated and either do not possess high electrical resistivity
127 contrasts or are too small to be detected. This explains why ERT is rarely employed in Paleolithic
128 cave contexts. Furthermore, given that the depth of investigation provided by ERT is tied to the length
129 of the electrode array deployed, some issues can derive from the confined environment in caves (c.f.
130 Abu Zeid et al., 2019).

131 Previous geophysical studies performed in Paleolithic caves focused mainly on retrieving the
132 cave geometry and investigating the presence of voids (Beck and Weinstein-Evron, 1997; Jol et al.,
133 2002; Quarto et al., 2007; Shopov et al., 2008). To our knowledge, ERT-based studies meant to
134 document the features of the deposits and map the morphology of the underlying bedrock of
135 Paleolithic caves are so far limited (Abu Zeid et al., 2019).

136 In this view, our ERT based study of the archaeological deposits at Arma Veirana cave
137 represents an opportunity to assess the capability of this geophysical method to retrieve subsurface
138 information of Paleolithic cave deposits and create a framework to improve ERT applications in such
139 a peculiar context. As primary goals, the study aimed to create a three dimensional (3D) resistivity
140 model of the archaeological deposits at Arma Veirana cave, to identify the volume of the deposits (or
141 sediments, defined as detrital, loose, explorable materials, i.e., grains of clay, silt, sand and gravel)

142 with the highest archaeological potential in terms of geometry, thickness and sediment distribution,
143 and to map the morphology of the bedrock. This work leads to methodological insights about how to
144 improve both efficiency and effectiveness of future archaeological campaigns inside caves, especially
145 suitable for the Palaeolithic age. New insights on the development of Arma Veirana cave and on the
146 nature of its sedimentary infill are also provided, thereby enabling a better understanding of the
147 depositional processes involved in the formation of this important archaeological site. This
148 information will be useful in the planning of long-term field-investigations and to locate areas that
149 should be the focus of future excavations.

150

151 ***1.1. The ERT technique and the resistivity signature of the target***

152 Electrical Resistivity Tomography (ERT) is based on a multi-electrode system applying direct
153 current into the ground by means of two current electrodes and measures the resulting voltage via two
154 potential electrodes; each of the electrodes alternatively acts as a current and potential electrode. To
155 obtain a true resistivity model of the subsurface, an inversion procedure is needed (Loke and Barker,
156 1996). The arrangement of current and potential electrodes during the measurement is dependent on
157 the chosen electrode array. The most frequently used arrays are the dipole–dipole, the Wenner, and
158 the Wenner-Schlumberger arrays (e.g., Kneisel, 2006; Schrott and Sass, 2008). The dipole–dipole
159 array uses two current electrodes on one side and two potential electrodes on the other side. This
160 method is especially suitable for the detection of vertical structures, as it shows high lateral resolution,
161 but it is too sensitive to near-surface anomalies (Szalai and Szarka, 2008a). The Wenner array
162 comprises four equally spaced electrodes deployed in a line in which potential electrodes are located
163 between current electrodes. The method is especially suitable for the detection of horizontal structures
164 as it shows high vertical resolution, but it has shallower penetration and less subsurface information
165 than the dipole–dipole array (Szalai et al., 2009). The Wenner-Schlumberger array is similar to the
166 Wenner array; potential electrode spacing is constant but current electrode spacing is logarithmically
167 increased. This array is especially appropriate for the detection of horizontal structures since it shows

168 high vertical resolution like the Wenner array, but it has shallower penetration and less subsurface
169 information than the dipole–dipole array. As each array has different disadvantages, we combined all
170 of them here to get beyond their individual limits and obtain more accurate models.

171 ERT allows the characterization of subsurface materials based on their electrical properties.
172 Changes in electrical resistivity correlate with variation in solid material (minerals and rocks), water
173 saturation, fluid conductivity and porosity, which may be used to map stratigraphic units, geological
174 structure, fractures, groundwater, and anthropogenic structures. ERT has been successfully used to
175 identify and map low-resistivity volumes such as fine-grained archaeological deposits (Abu Zeid et
176 al., 2019; Becker et al., 2019), as well as typically high resistivity structures, including bedrock, wall
177 pipes, roads (Tsokas et al., 2009), foundations (Drahor et al., 2008), ditches, palaeochannels, internal
178 structures in mounds and barrows (Astin et al., 2007; Papadopoulos et al., 2020), buried chambers
179 and cavities (Cardarelli et al., 2006; Deiana et al., 2018), caves, karst features, sinkholes, and cavities
180 (e.g., Al-Zoubi et al., 2007; Carrière et al., 2013; Maillol et al., 1999; Rainone et al. 2015; Satitpittakul
181 et al., 2013; Smith, 1986; Torrese, 2020; Torrese et al., 2021a; Van Schoor, 2002; Zhu et al., 2011),
182 offshore archaeological features (Sarris et al. 2014; Tonkov 2014; Simyrdanis et al. 2015).

183 One of the most important targets of ERT application in archaeological studies is the depth to
184 the bedrock. Accurate information about bedrock's morphology and depth can vastly improve
185 excavation planning. Bedrock and sediments have typically different electrical resistivity; therefore,
186 the bedrock's buried surface can be measured as a high-contrast boundary in an electrical resistivity
187 model. In the case of irregular morphology of bedrock, 3D ERT is required to build a more complete
188 and accurate model of it.

189 The resistivity signature of the target depends on its size in relation to its depth and on the
190 contrast between its resistivity and that of the surrounding (host) rock. The amplitude of resistivity
191 anomalies is an inverse function of the distance between the measurement points and the cavity. The
192 depth of investigation and the vertical and horizontal resolutions of ERT surveys are linked to: i) the
193 electrode spacing, ii) the configuration array, iii) the quadrupole sequence, iv) the signal-to-noise

194 ratio (SNR), v) the contrast between the resistivity of the target, and v_i) the surrounding rock and/or
195 background resistivity.

196 The ERT method has been applied at Arma Veirana cave because it is particularly effective
197 in such a geological setting (i.e., where the target deposits consist mainly of fine deposits bounded
198 below and laterally by limestone rocks). In this context, we expected ERT to provide an accurate
199 model of the archaeological deposits' depth and position thanks to their low resistivity while the
200 hosting rocks are of high resistivity.

201

202 ***1.2. ERT application inside caves***

203 Applying ERT inside caves (Abu-Zeid et al., 2019; Hancock, 1999; Olenchenko et al., 2019;
204 Osipova et al., 2020; Pringle et al., 2002) entails several issues caused by limited space for
205 measurements and the complexity of the surrounding medium's structure as compared to above-
206 ground measurements. Olenchenko et al. (2020) performed numerical experiments to assess the effect
207 of the 3D cave geometry on the results of an ERT inversion. They found that variations of cave
208 geometry parameters result in unexpected false anomalies, and that considerable errors in bedrock
209 location and resistivity can occur. The authors suggested that two-dimensional (2D) ERT generally
210 cannot be applied inside a cave whose half-width is smaller than the thickness of sediments; 3D
211 surveys do not essentially improve the quality of results.

212 Findings from Olenchenko et al. (2020) on the use of ERT inside caves are consistent with
213 results obtained by Fikos et al. (2019) who evaluated the ability of 2D ERT to provide effective results
214 along profiles undertaken close and parallel to the vertical cave walls. By combining numerical
215 modelling with field data, the authors found that if the distance between ERT profiles and the cave
216 walls becomes too small, the high resistivity of the cave walls masks the conductive sediment layer.
217 Furthermore, the resistivity of the sediments is significantly overestimated thus posing possible
218 problems in the interpretation process.

219 However, as suggested by Olenchenko et al. (2020), in the case of downward diverging cave
220 walls, as occurs at Arma Veirana cave (Fig. 1), an accurate resistivity model can be obtained. In such
221 a case, despite being within a 3D cave geometry, the electric current is distributed approximately as
222 in 2D medium. Therefore, ERT in caves with similar geometry can yield reliable results on the
223 morphology of bedrock surface, the thickness of sedimentary layers, and size and position of
224 inclusions such as fallen fragments of roof therein. Under these conditions, 3D surveys improve the
225 quality of results, thus providing more complete and accurate models than 2D surveys.

226

227 **2. ARMA VEIRANA**

228 Arma Veirana, also known as Arma della Costa di Cerisola (Dal Bo et al., 1978), is located in
229 the municipality of Erli, in the Savona province (Liguria, Northern Italy). It is situated in calcareous
230 rocks of the Castelvechio-Cerisola Unit of the Ligurian Briançonnais domain (Decarlis & Lualdi,
231 2009) and consists of a SE/NW-orientated chamber 44 meters long with an upslope of 4 meters
232 between the cave entrance and its termination (Fig. 1).

233 The archaeological importance of the cave was first recognized in 2006 by Giuseppe Vicino,
234 curator of the Museo Archeologico del Finale (Savona), who collected Middle and Upper Palaeolithic
235 artefacts from the removed deposit. Formal excavations begun in 2015 and lasted until 2018.

236 To date, the main objective of the archaeological fieldwork was to document the cave's
237 stratigraphy, which was initially visible in pits exposed by looters. Excavations at Arma Veirana have
238 focused on several locations within the cave, exposing stratigraphic sections that span several
239 lithological units referred to as stratigraphic aggregates (StratAggs) in our excavation system
240 (equivalent to what are often called "layers"). The excavations exposed a rich Mousterian layer at the
241 bottom of the main trench (stratigraphic section a-b, Fig. 2), which is located near the entrance of the
242 cave, and traces of Late Upper Palaeolithic (Epigravettian) occupations in the upper aggregates. As
243 reported in Hodgkins et al. (in review), an Early Mesolithic burial (10.280-9.924 cal BP) of a 40-50
244 days-old female newborn (AVH-1, nicknamed "Neve") was recovered in 2017 within an

approximately 15 cm deep oval pit ($< 600 \text{ cm}^2$ in area) cut into underlying late Epigravettian deposits. The burial feature containing the newborn remains was exposed after removing a thin layer of surficial deposits and appears to be intrusive into the underlying stratigraphic aggregate “Yellow Silt” (YS).

Numerous radiocarbon dates have been obtained, DNA samples collected, and traces of cryptotephra identified in correspondence of the Middle Paleolithic layers (Hirniak et al., 2020). The analysis of the archaeological finds and other geoarchaeological evidence is underway.

3. GEOLOGICAL AND ARCHAEOLOGICAL SETTING OF THE CAVE

3.1. Geological setting

The entrance of the Arma Veirana cave is located in a tight antiform syncline (Goudie, 2004) (interlimb angle $> 30^\circ$) at the stratigraphic contact (Dallagiovanna et al., 2011) between the Val Tanarello limestone of the Kimmeridgian– Berriasian age (Bertok et al., 2011) at the top and the calcareous schists and shales of the Caprauna Formation of late Cretaceous-middle Paleogene period (Dallagiovanna et al., 2011) at the bottom (Fig. S2 in the Supporting Information); it is an uncommon case of an inner-fold cave, where the access opening corresponds to a rock fall related to the Rio Neva valley evolution (Fig 1d).

With regard to the cave genesis and evolution, we identify here the model that best fits with field observations and the results of the geophysical investigation. In short terms, even if carbonate dissolution may have had some role in the first stage of its development (Dubois et al., 2011; Quinif, 2014; 2018), Arma Veirana is not an epigenetic solution cave. According to the most recent classification (Oberender and Plan, 2018) it is a “pseudo-endokarst” produced first by “mechanical weathering” (first order type cave genesis according to Quinif and Bruxelles, 2011) followed by alterite removing through “piping” (second order cave genesis) with the final development of a “suffusion cave” (Sauro, 2005; Sola et al., 2007).

270 Speleogenesis models of the Veirana cave, its relationships with the paleo-evolution of the
271 Rio Neva paleovalley, the development of the other caves and canyons of the area and their relations
272 with prehistoric anthropic settlement are active areas of research.

273

274 ***3.2. Archaeological evidence***

275 To document the history of the cave, several archaeological pits have been excavated in
276 different parts of the cave, with the deepest trench dug near the entrance of the cave. This main trench
277 is about 1.2 m deep but has not yet reached the bedrock. Yet, the sediments exposed by this trench
278 have revealed interesting anthropic evidence pertaining to the Middle Palaeolithic. The stratigraphy
279 of this trench consists of five distinct stratigraphic aggregates (or layers) named, from top to bottom:
280 “Disturbed” (D), “Rocky Brown” (RB), “Consolidated Strong Brown” (CSB), “Granular” (Gr) and
281 “Black Mousterian” (BM) (Figs. 3 and S1 in the Supporting Information) that are differentiated from
282 each other through variation in grain size, color, fabric, and structures. Radiocarbon dates obtained
283 on material from those aggregates show that they are older than 50 ky BP.

284 Anthropic evidence is mainly concentrated in the layer at the base of the currently exposed
285 stratigraphy, the BM aggregate, a 20-30 cm thick silty-sand layer with medium to small gravel with
286 a dark greyish brown colour, due to the presence of manganese oxide staining but also numerous, silt
287 and sand-sized fragments of combustion residues (e.g., charcoal). This aggregate has provided
288 abundant fauna, which is often fragmented and bears anthropogenic cut marks, along with numerous
289 Mousterian lithic artefacts (Middle Palaeolithic).

290 The aggregates above BM have lower artefact density, suggesting that the cave was not
291 occupied as intensely during the accumulation of the deposit. The Gr is a narrow aggregate
292 characterised by medium sandy silt with granules and gravel, with color varying around 10YR 4/4 to
293 10YR 4/3 (brown to dark yellowish brown). It exhibits a coarse crumb structure. It has a relatively
294 high proportion of éboulis, which is mostly dominated by sub-angular to sub-rounded clasts that
295 appear weathered and are on average 5-10cm in size. The proportion of éboulis decreases to the east,

296 however, where éboulis is rarer. Portions of Gr appear cemented by secondary carbonate, forming a
297 weak breccia.

298 Above Gr, the CSB is a clayey silt with fine sand and gravel. It appears more compact than
299 Gr and displays a massive structure. The color is dark yellowish brown (10YR 4/4). Larger blocks
300 of éboulis are relatively rare and consist mostly of 5cm-sized sub-angular to angular clasts which are
301 locally organized into horizontally oriented lenses.

302 The RB sits on top of the CSB. RB is a clayey silt with fine sand and gravel and displays a
303 weakly developed subangular blocks structure; the color is dark yellowish brown (10YR 4/4). RB
304 contains a relatively high proportion of subangular to angular blocks of éboulis which are generally
305 10-15cm in size. These occur in higher proportion than in CSB.

306 An erosional unconformity distinguishes RB from the overlying D aggregate. D is a clayey
307 silt with minor sand and gravel components with a dark greyish brown color. It appears to be modern
308 surficial deposits, which are expressed either as sedimentary infillings within the rill system or as
309 alteration surfaces formed directly on RB.

310 Higher in the cave deposits, (south of the main excavation trench), the YS aggregate is a 20
311 cm thick layer containing Late Upper Palaeolithic artefacts (Epigravettian). YS appears to be a clayey
312 silt with minor sand and gravel components. Larger blocks of éboulis are rare, and most are between
313 5-7cm in size. They appear subrounded and display no preferred orientation. The color of YS is
314 similar to RB (10YR 4/4) although it locally appears more yellowish in color. The Early Mesolithic
315 burial was found inside a pit dug into the YS, ~2 m from the east wall of the cave (excavation square
316 2N1E in Fig. 2) (Hodgkins et al., in review). YS was readily distinguishable from the burial pit which
317 was darker in color and had a high proportion of coarse material, including charcoal and bone.

318 The aforementioned erosional unconformity crosscuts several of the aggregates, so that
319 towards the entrance of the cave D unconformably covers RB, whereas it covers YS towards the back
320 and near the burial (Fig. 3). It is currently unknown whether the unconformity is local or cave-wide.
321 Fig. S1 in the Supporting Information provides detailed images of the aggregates.

322 Dates of stratigraphic aggregates reported in this paper derive from ^{14}C Accelerator Mass
323 Spectrometry (AMS) dating of faunal bone. Calibrations were done using IntCal20 (Reimer et al.,
324 2020) in the OxCal 4.4 program (Ramsey, 2009).

325

326 **4 MATERIALS AND METHODS**

327 **4.1. Data collection**

328 3D ERT data were collected on June 27th 2018 with a fully automatic multi-electrode
329 resistivity meter SYSCAL Jr Switch-48 by IRIS Instruments. A surface snake grid comprised of 8 x
330 6 electrodes spaced ~1.5 m apart both along the X and Y axes was used (Fig. 2). The electrodes could
331 not be placed in a perfectly regular grid due to the presence of blocks, boulders, and calcite
332 concretions on the ground (Figs. 4a-c). Despite this, the grid created allowed analysing an area of
333 10.5 m x 7.5 m with a maximum depth of ~ 2 m.

334 Data were collected using different electrode arrays: 202 dipole-dipole (DD) measures, 96
335 Wenner (W) measures, 134 Wenner-Schlumberger (WS) measures, 328 Pseudo Pole-Dipole
336 measures (PsPD), for a total of 760 quadrupole measures for the whole model. The Pseudo Pole-
337 Dipole array was comprised of two remote electrodes (one for forward and the other for reverse
338 measurements, aligned along the axis of the cave) placed 25 m away from the centre of the grid (Fig.
339 4d). Because it uses a remote electrode with a finite distance location instead of a remote electrode
340 with an infinite distance location provided for by theoretical Pole-Dipole (Razafindratsima and
341 Lataste, 2014; Robain et al., 1999), this array has been named Pseudo Pole-Dipole rather than Pole-
342 Dipole. Only forward measurements (no reverse measurements) were simulated with the PsPD array.

343 The data obtained with these arrays differed in resolution. Following Szalai et al. (2009), they
344 were merged to deliver better detectability and imaging and, therefore, provide more accurate inverse
345 models.

346 Details on raw data quality are provided in Table S1 in the Supporting Information.

347

348 **4.2. Data inversion**

349 No data processing (pre-inversion) was required to remove outliers from apparent (raw)
350 resistivity data. The dataset, indeed, does not present any problematic data such as, for example,
351 unrealistically high resistivity ($>10000 \Omega \cdot \text{m}$) or too-high standard deviation ($>10 \Omega \cdot \text{m}$).

352 Then, ERTLlab Solver (by Multi-Phase Technologies LLC, Geostudi Astier srl) based on
353 tetrahedral Finite Element Modelling (FEM) was used for data inversion. Tetrahedral discretization
354 was used in both forward and inverse modelling. The foreground region was discretized using a \approx
355 0.74 m element size along the X and Y, i.e., half the average electrode spacing and a ≈ 0.07 m element
356 size along the Z direction to give the model higher accuracy. This created a 3D resistivity grid, 11 m
357 x 8 m x ≈ 2 m in size. The background region was discretized using an increasing element size towards
358 the outside of the domain, according to the sequence: 1 \times , 1 \times , 2 \times , 4 \times and 8 \times the foreground element
359 size.

360 The forward modelling was performed using mixed boundary conditions (Dirichlet-
361 Neumann) and a tolerance (stop criterion) of 1.0E-7 for a Symmetric Successive Over-Relaxation
362 Conjugate Gradient (SSORCG) iterative solver. Data inversion was based on a least-squares
363 smoothness constrained approach (LaBrecque et al., 1996). Noise was appropriately managed using
364 a data-weighting algorithm (Morelli and LaBrecque, 1996) that allows the adaptive changes of the
365 variance matrix after each iteration for those data points that are poorly fitted by the model. The
366 inverse modelling was performed using a maximum number of internal inverse Preconditioned
367 Conjugate Gradient (PCG) iterations of 5 and a tolerance (stop criterion) for inverse PCG iterations
368 of 0.001. The amount of roughness from one iteration to the next was controlled to assess maximum
369 layering: a low value of reweight constant (0.1) was set with the objective of generating maximum
370 heterogeneity.

371 The inverse resistivity models (i.e., models with true resistivity rather than apparent or raw
372 resistivity) were obtained by inverting the datasets acquired through single arrays, or by merging and
373 jointly inverting datasets from different arrays which can deliver better detectability and imaging and,

374 hence, provide more accurate inverse models (Szalai et al., 2009; Torrese, 2020) and more reliable
375 ERT imaging (de la Vega et al., 2003; Seaton and Burbey, 2002). Inversion involved the application
376 of homogeneous starting models that set the average measured apparent resistivity value at each node.
377 The final inverse resistivity models were chosen based on the minimum data residual (or misfit error).

378 Details on the misfit of inverted data are provided in Table S2 in the Supporting Information.

379

380 **4.3. Bulk total porosity estimation**

381 A realistic, albeit presumed and rough (in the absence of specific measurements), estimate of
382 the bulk total porosity \emptyset for the different resistivity units revealed by ERT was obtained by applying
383 the empirical relationship proposed by Archie (1942)

384

$$385 \quad C_t = \frac{1}{a} C_w \emptyset^m S_w^n \quad (1)$$

386

387 where C_t is the electrical conductivity of the fluid impregnated deposit/rock, a is the tortuosity factor,
388 C_w is the electrical conductivity of the fluid impregnating the deposit/rock, \emptyset is the total porosity of
389 the deposit/rock, m is the cementation exponent of the deposit/rock, S_w is the fluid saturation, and n
390 is the saturation exponent.

391 The tortuosity factor a , dimensionless, is related to the path length of the current flow and is
392 used to correct for variation in compaction, pore structure and grain size. Its value typically ranges
393 between 0.5 and 1.5. The cementation exponent m , dimensionless, indicates reduction in the number
394 and size of pore openings. It is affected by lithology, porosity, degrees of compaction and
395 cementation, and age. Its value typically ranges between 1.3 and 2.35 (Salem and Chilingarian, 1999).
396 These factors can be obtained from core analysis. Log–log plot of total porosity \emptyset versus formation
397 factor (Archie, 1942) is used to determine a and m : the tortuosity factor a is the intercept of the least

398 square fit straight line of the plotted points where $\emptyset = 1$, while the cementation exponent m is
399 determined from the negative slope of the line (Rezaee et al., 2007).

400 Archie's law relates the in-situ electrical conductivity of a porous rock to its total porosity and
401 water saturation. It is a purely empirical law attempting to describe ion flow in clay-free porous rocks,
402 with varying intergranular porosity. Electrical conduction is assumed not to be present within the rock
403 grains or in fluids other than water.

404

405 **5. RESULTS**

406 **5.1. Resistivity units**

407 The inverse resistivity results are provided as 3D block models and plane slices extracted from
408 the block models. All models shown here represent merged data obtained from dipole-dipole (DD),
409 Wenner (W) and Wenner-Schlumberger (WS) arrays which delivered better detectability and imaging
410 than single arrays only and, therefore, provided more accurate inverse models. Data acquired with
411 Pseudo Pole-Dipole arrays were excluded from data merging because the difference in elevation
412 between the remote electrodes installed inside and outside the cave affected their results and therefore,
413 they did not provide any imaging improvements.

414 Misfit in terms of chi-squared errors (330 chi-squared error, 2.6 ohm·m Root Mean Square
415 (RMR) error for the final iteration, Table S2 in the Supporting Information) suggests that inverse
416 models are free of artifacts due to an inversion over-fit or excessive smoothing due to an inversion
417 under-fit.

418 ERT models revealed that resistivity data could be separated into four resistivity units defined
419 on the expected resistivity values for different lithological units (Figs. 5, 6): 1) the low-resistivity unit
420 (L) ranging from 30 to 150 $\Omega\cdot\text{m}$ is associated with fine-grained deposits (silty-sand); 2) the middle-
421 low resistivity unit (ML) ranging from 150 to 300 $\Omega\cdot\text{m}$ is related to fine to coarse-grained deposits
422 (silty-sand with gravel and sporadic blocks); 3) the middle-high resistivity unit (MH) ranging from
423 300 to 440 $\Omega\cdot\text{m}$ is associated with coarse-grained deposits (gravel and blocks in silty-sandy matrix)

424 and heavily cracked/karst bedrock; 4) the high resistivity unit (H) ranging from 440 to 2.000 $\Omega\cdot\text{m}$ is
425 related to bedrock/boulders/breccia (limestone)/calcite concretions. The measured resistivity values
426 suggest that the geological bodies corresponding to the resistivity units have a low clay content. Only
427 the lowest resistivity deposits (approximately $<100 \Omega\cdot\text{m}$) included in the low-resistivity unit (30-150
428 $\Omega\cdot\text{m}$) have some clay content.

429 The spatial distribution of the different resistivity units related to detrital (loose) deposits
430 shows a longitudinal orientation that follows the primary axis of the cave. The thickness of the
431 archaeological deposits (different types of unconsolidated deposits, such as silty-sand with gravel and
432 sporadic blocks) is highly variable along the primary axis of the cave and ranges between more than
433 1.5 meters at the entrance of the cave to less than 10 centimetres in the innermost part of the cave
434 where it is discontinuous (Figs. 6-9). Fine-grained deposits (silty-sand) show greater consistency
435 towards the entrance of the cave where they reach a maximum thickness of about 1 meter, in the
436 northeast (Figs. 6, 7).

437 Transverse to the primary axis of the cave, the bedrock is relatively close to the surface at the
438 southwest and deepens towards the northeast. Obviously, this change affects both volume and
439 geometry of the overlying archaeological deposits which follows a gentler slope (Figs. 6-9).

440 The geometry, thickness, and distribution features of the different resistivity units revealed by
441 plan (Fig. 5) and perspective views (Figs. 6-8) are also evident on the cross-section view (Fig. 9). The
442 latter shows X-Y plane slices (x, y in Fig. 2) extracted from the 3D block model. The analysis of the
443 cross-sections (Fig. 9) shows that the thickness of the archaeological deposits increases longitudinally
444 towards the entrance of the cave and transversally towards the northeast.

445 From an archaeological point of view, the low-resistivity unit (30-150 $\Omega\cdot\text{m}$) associated with
446 fine-grained deposits (silty-sand), is the most promising unit; i.e., this unit could represent the target
447 deposits. This hypothesis is based on considerations inherent to the electrical resistivity found for this
448 unit, which indicate the presence of fine-grained deposits that should be easy to excavate.

449

450 5.2. Bulk total porosity

451 The estimated bulk total porosity value \emptyset ranges between 0.44 and 0.16 for the L unit, 0.16
452 and 0.13 for the ML unit, 0.13 and 0.1 for the MH unit and is equal to 0.1 for the H unit (Table 1).

453 This estimation, which was based on the application of equation (1), involved:

454 C_t ranging between $3.3333\text{e-}2$ S/m and $6.6667\text{e-}3$ S/m for the L unit, ranging between
455 $6.6667\text{e-}3$ S/m and $3.3333\text{e-}3$ S/m for the ML unit, ranging between $3.3333\text{e-}3$ S/m and $2.5\text{e-}3$ S/m
456 for the MH unit and ranging between $2.5\text{e-}3$ S/m and $5\text{e-}4$ S/m for the H unit which are the electrical
457 conductivity values equivalent to the limits of the electrical resistivity range measured for the
458 resistivity units;

459 α (dimensionless) ranging between 0.5 and 0.7 for the L unit, ranging between 0.7 and 1 for
460 the ML unit, and equal to 1 for MH and H units;

461 $C_w = 0,1$ S/m which has been assumed as a representative value for the water impregnating
462 the deposit/rock (a low mineralized/total dissolved solids water due to poor water-rock interaction);

463 m (dimensionless) equal to 1.3 for L, ML, MH units and ranging between 1.3 (breccia) and 2
464 (bedrock) for the H unit;

465 $S_w = 0.7$ (dimensionless) which has been assumed for not fully water saturated deposit/rock;

466 $n = 2$ (dimensionless).

467

468 6. CROSS-VALIDATION OF GEOPHYSICAL RESULTS WITH OBSERVED 469 STRATIGRAPHY

470 To compare resistivity units with stratigraphic aggregates, stratigraphic limits were plotted on
471 the plane slice α (Fig. 2) extracted from the 3D block model (Figs. 10-14). Slice α lies on the same
472 plane as the stratigraphic section a-b (main trench) (Fig. 2), which allowed correlating the two.
473 Geophysical results are consistent with the stratigraphic section (Fig. 10) in identifying the top
474 stratigraphic aggregates of the cave (Negrino et al., 2018) as revealed from previous archaeological
475 surveys.

476 The erosional surface distinguishes the D aggregate from the underlying aggregates RB, CSB,
477 Gr, and BM, which are well defined by the resistivity model (Figs. 10-13). The D, RB, and CSB
478 aggregates correspond to the low resistivity unit (30 to 150 $\Omega\cdot\text{m}$, fine-grained deposits). The Gr
479 aggregate is between the low and the middle-low resistivity unit (150 to 300 $\Omega\cdot\text{m}$ fine to coarse-
480 grained deposits) due to the presence of coarser deposits. The BM aggregate correspond to the
481 middle-low resistivity unit (Figs. 10-13).

482 The D aggregate appears irregular in shape, with a heterogeneous resistivity, affected by some
483 disturbance that disrupted the horizontal stratigraphic sequence, with a sharp, erosional contact with
484 the underlying aggregate. Underlying aggregates appear more regular in shape, their resistivity is
485 more homogeneous, and they display smoother contact with older aggregates.

486 The resistivity model fits particular stratigraphy characteristics identified from the sections exposed
487 during excavation, such as:

- 488 - the D aggregate dips westward along slice α , but it dips southward along the northern portion
489 of the transversal slice γ . These findings suggest a south-westward dipping of D aggregate (in
490 this restricted area);
- 491 - the erosional surface rises slightly in the central part of slice α ;
- 492 - the RB aggregate dips slightly westward along slice α ; it also dips southward along the
493 northern portion of the transversal slice γ . These findings suggest a south-westward dipping
494 of RB aggregate (in this restricted area);
- 495 - CSB and Gr aggregates rise slightly in the west part of slice α ; they also dip slightly southward
496 along the northern portion of slice γ .

497 All stratigraphic aggregates show a south-westward dipping in the northeast portion of the
498 geophysical model, at the intersection between slices α and γ . Further south, the aggregates appear to
499 fold upwards (Figs. 10-13). In the central part of the geophysical model, the aggregates seem to be

500 slightly bent downwards, as if to form a syncline. This is well defined by the transversal slices x and
501 y (Fig. 9) and the 3D distribution of the low-resistivity unit merged with slices α and γ (Fig. 14).

502 At a local scale (along the slices), the resistivity pattern shows near continuous and slightly
503 curved units. Some pattern distortion interrupts the continuity of the units. This could be due to the
504 heterogeneity in the grain size distribution within the same stratigraphic aggregate, as shown for the
505 CSB aggregate (Fig. 10). Conversely, RB and Gr aggregates may show similar resistivity values due
506 to comparable coarse-grained deposit content (Fig. 10).

507 At the scale of the geophysical model, the resistivity pattern shows a discontinuous
508 distribution of fine-grained (low resistivity) deposits (Fig. 14) and the recognition of shallow, meter-
509 sized structures with a longitudinal orientation with respect to the primary axis of the cave.

510 In addition to the erosional surface exposed in excavations of the main trench, the geophysical
511 model also identifies a sharp and irregularly shaped erosional-like surface extending along the
512 primary axis of the cave. This structure is well defined by the resistivity pattern (Figs. 8-10, 14) where
513 it appears as a high resistivity unit ($440\text{--}2.000\ \Omega\cdot\text{m}$) as it is filled with mostly coarse deposits.

514 The cross-validation of geophysical results with observed stratigraphy supports the hypothesis
515 mentioned above that the low-resistivity unit ($30\text{--}150\ \Omega\cdot\text{m}$), associated with fine-grained deposits
516 (silty-sand) represents the most promising unit from an archaeological point of view. Here, this
517 hypothesis is based on considerations of inherent age and grain size distribution of the corresponding
518 stratigraphic aggregate.

519

520 **7. CROSS-VALIDATION OF GEOPHYSICAL RESULTS WITH ARCHAEOLOGICAL** 521 **FINDINGS**

522 The archaeological evidence collected during previous field seasons drove the hypothesis that
523 low-resistivity units are the most promising deposits from an archaeological point of view. This can
524 be further tested by determining if the low-resistivity units identified by this study actually correspond
525 to the deposits where archaeological remains have been found. The discovery of a human burial in

2017 provides a good case study to test this, as part of the burial pit was still covered at the time of the geophysical survey. The Early Mesolithic burial, its accompanying grave goods, and Epigravettian artefacts located nearby were found in excavation square 2N1E (Fig. 2), which is located near the main trench, towards the entrance of the cave, at the northeast portion of the geophysical survey. These archaeological remains were found within the low-resistivity unit, which is composed mostly of fine-grained deposits (silty-sand) (Fig. 5a). The geophysical survey also shows that the burial was located in the part of the cave with the deepest fine-grained deposits (Figs. 6, 7). These geophysical findings are consistent with stratigraphic observations from the main trench.

Conversely, no archaeological remains were found in excavation squares -3N4E and -2N4E (Fig. 2), which are located far from the cave entrance, in the southeast portion of the geophysical survey. Interestingly, the low-resistivity unit does not outcrop here or outcrops with negligible thicknesses (Figs. 6, 7). Geophysical results of those squares suggest the presence of the middle-low resistivity unit (Fig. 5b) and a partially middle-high resistivity unit (Fig. 5c), which are composed of fine to coarse-grained deposits (silty-sand with gravel and sporadic blocks) and coarse-grained deposits (gravel and blocks in silty-sandy matrix), respectively.

The correlation between low resistivity units and archaeological remains discussed here supports further the hypothesis that the low-resistivity unit (30-150 $\Omega\cdot m$) associated with fine-grained deposits (silty-sand) represent the most promising unit from an archaeological point of view.

8. DISCUSSION

The subsurface electrical resistivity pattern allowed us to define the geometry, thickness and sediment distribution of the explorable deposits (Fig. 6), and to map the morphology of the bedrock (Fig. 7). The recognition of variable thicknesses of the loose deposits following the primary axis of the cave and increasing towards the entrance is consistent with field observations. A change in the thickness of the loose deposits has also been observed transversally from the primary axis of the cave, where the thicker part is found in the northeast portion. These findings suggest that the most

552 significant volumes in terms of archaeological excavation are found towards the entrance of the cave
553 on the northeast side.

554 The cross-validation of geophysical results with the observed stratigraphy revealed that the
555 stratigraphic aggregates are well defined by the resistivity model. Although the resistivity pattern
556 shows near continuous and slightly-curved units with some pattern distortion interrupting the
557 continuity of the units at a local scale, it shows a discontinuous distribution of fine-grained (low
558 resistivity) deposits and the recognition of shallow, meter-sized structures with a longitudinal
559 orientation with respect to the primary axis of the cave at the larger scale. The presence of pattern
560 distortions within individual units could be due to heterogeneity in grain size distribution.

561 The geophysical model also allowed the recognition of a possible sharp and irregularly shaped
562 erosional-like surface, filled with mostly coarse deposits, which extends along the primary axis of the
563 cave.

564 The cross-validation of geophysical results with the archaeological evidence collected during
565 previous field seasons suggests that deposits associated with the low-resistivity unit, i.e., fine-grained
566 deposits (silty-sand) are the most archaeologically promising (Figs. 5-7, 14). Although potential
567 archaeological materials are likely to be found everywhere, fine-grained deposits are easier to dig.
568 Therefore, these deposits might have been favored by humans when burying their dead. For this
569 reason, we believe that the low-resistivity unit have the highest potential to contain human remains.
570 Geophysical results thus suggest that future archaeological excavations targeting potential burials
571 focus on the low-resistivity unit (Fig. 14), especially on the north-eastern side of the cave where this
572 unit has greater thicknesses (Figs. 6, 7). It is worth underlining that the middle-low resistivity unit,
573 i.e., fine to coarse-grained deposits (silty-sand with gravel and sporadic blocks) (Figs. 5, 6) also
574 includes promising deposits as revealed by the rich Mousterian layer exposed by the excavations. In
575 addition, as the geophysical survey did not extend to all portions of the cave, the presence of
576 archaeological remains on the north-western side of the cave, near the entrance of the cave, cannot
577 be excluded.

ERT proved to be an effective technique to define the geometry, thickness, volume, distribution of sediments infilling the cave, and to recognize potential archaeologically interesting structures, specifically shallow, meter-sized, fine-grained structures or pit fill-like structures (e.g., in the burial area, “human remains” in Fig. 5a). These are crucial data for designing future archaeological field surveys at Arma Veirana cave.

In this strongly heterogeneous geological setting, ERT provided an accurate model, because the electric field tends to flow mainly inside loose, in-cave deposits, which are low resistive, rather than flowing through high resistive hosting rocks. Our resistivity model may also have benefited from the 3D cave geometry. At the middle of the surveyed area, the average thickness of sediments is 1.33 m and the cave’s half-width at floor level is 4.48 m; moreover, the cave has downward diverging walls. This is consistent with findings from Olenchenko et al. (2020) who suggested that accurate resistivity models can be obtained by ERT inside a caves whose half-width is larger than the thickness of sediments and in the case of downward diverging cave walls.

This study also showed that the main drawback of the ERT method is that the properties of heterogeneous cave deposits can be characterized by a wide range of possible resistivity values depending on the heterogeneity in the grain size distribution (e.g., Schrott and Sass, 2008), as well as by actual physical and chemical states of the deposits. Furthermore, as some of these parameters are environmentally dependent (e.g., water saturation conditions), a homogeneous stratigraphic aggregate may also show resistivity variations. For these reasons, the resistivity measured in this study can vary even within the same stratigraphic aggregate or be similar for different stratigraphic aggregates. In this sense, it is worth underlining that RB and Gr aggregates may show similar resistivity values due to similar coarse-grained deposit content; conversely, the CSB aggregate appears to be affected by some disturbance that disrupts its horizontal continuity even if it is locally strongly heterogeneous. This eventuality is well shown by slices α and γ that have been cross-validated with stratigraphic observations.

603 As regards the application of equation (1) for the bulk total porosity estimation, although the
604 applicability of Archie's law may be argued and is questionable for the investigated in-cave deposits,
605 its adoption is motivated by the evidence that these materials are affected by a negligible clay content.
606 Only the lowest resistivity deposits (approximately $<100 \Omega \cdot m$) included in the low-resistivity unit
607 ($30\text{-}150 \Omega \cdot m$) have some clay content. However, clay-related electrical conductivity (Waxman and
608 Smits, 1968) appears to give a negligible contribution to the bulk electrical conductivity of the
609 materials considering that clay is dispersed in the solid matrix of the deposits.

610 We believe that our resistivity data are not significantly influenced by heavy-mineral
611 composition in the sediments. Although cave sediments may represent low oxygen and chemically
612 reducing environments, evidence of manganese oxides was found only in the BM aggregate at the
613 base of the currently exposed stratigraphy. Field and micromorphological analyses do not indicate
614 extensive reducing conditions in the deposits. We do not have any evidence of the manganese origin
615 associated with a past inner-cave reducing environment; vice versa, the BM aggregate with its
616 anthropic content suggests that manganese origin may be associated with soil humification after the
617 human occupation of the Veirana.

618 As a result of anthropogenic activities, a high content of organic matter was deposited and
619 decomposed in the typical environmental conditions of the cave vestibule, where darkness and
620 humidity promoted the growth of saprophyte microorganisms that led to the decomposition and
621 mineralization of organic matter, in turn generating humic acids and chelate coordination complexes,
622 which increased metal solubility and mobility (Marìn Arroyo et al., 2008).

623 Due to these conditions, the evolution of the sediment itself and carbonate percolation from
624 the surrounding rocks (the Val Tanarello limestones and the dolomitic breccia) slowed down the
625 sediments humification, thus increasing the pH and causing the manganese precipitation in the form
626 of oxides and hydroxides (Hill, 1982). The origin of the manganese in the BM layer may therefore be
627 due to the degradation of its organic materials and to its later evolution as a buried anthropic sediment
628 inside a carbonatic system subject to percolation.

629

630 ***8.1. Speleogenesis model of the Arma Veirana cave***

631 Reiterating that the study of the cave and its valley are at an early stage, the data collected in
632 the last years of field surveys allowed us to offer an early interpretation of its genesis and evolution.

633 The first consideration deals with the stratigraphy of the rock in which the cave opens and the
634 cave mesoscale morphology: the proto-Veirana fold generated into a sedimentary sequence that runs
635 from Late Jurassic (the Kimmeridgian-Berriasian Val Tanarello limestone) to Eocene (the “late
636 Cretaceous-middle Paleogene” rocks of the Caprauna Formation).

637 Above the Val Tanarello limestone, we find a tectonic contact with a dolomitic breccia
638 referred to as the “Brecce Dolomitiche Vacuolari” of Scitic-Anisic age; down from the Veirana
639 entrance and from the Costa Losera flank, the evolution of the Neva valley cut away all proximal
640 carbonatic formations, which directed the Rio Neva flow to an impermeable substratum, the
641 formation of the “Quarziti di Ponte di Nava” of Lopingian/Lower Triassic epoch: the contact between
642 the “Caprauna Formation” and the physically lower “Quarziti di Ponte di Nava” is tectonic too.

643 Therefore, the geology of the area is very complex both for its tectonic setting and for its
644 geomorphological evolution (Seno, 2003), but for the present study, it is important to note that the
645 sequence of the mother-rock’ fold is inverted and that the ceiling and the lateral walls of the Veirana,
646 located inside the fold, are related to the folded strata of the “Val Tanarello limestone”, locally
647 covered by secondary carbonate depositions of the cave.

648 At first glance, we cannot see clear evidence of strata related to the “Caprauna Formation”
649 inside the cave itself, which suggests that the empty space of the cave replaced the missing strata.
650 The flanks of the fold at the cave entrance confirm this idea, as this is where we find the schists of
651 the “Caprauna Formation” in their correct stratigraphic position and with the appropriate parasite
652 folds.

653 The lack of strata of the “Caprauna Formation” inside the cave needs explaining, as it is the
654 reason why the cave was formed. When thinking about karst systems genesis, it is easy to embrace

655 the paradigm of the karstification by “total remover,” where carbonate caves are the result of a
656 chemical dissolution – i.e., the physical transition of solid state compounds into a liquid phase where
657 both the residual insoluble deposit and the dissolved elements are then carried away from water flow.
658 However, this is not the case of the Arma Veirana, as it never had a cave river system. Therefore, we
659 cannot refer to the cave as a “karst system” or even part of an old one.

660 The Arma Veirana is a “void” inside an antiform syncline. The potential energy of the system
661 was near zero before the deepening of the rio Neva paleovalley; therefore, epigenesis could not
662 produce the cave because the water’s very low flow rate would not have allowed the undissolved
663 elements to be flushed out of the system. Instead, the initial solid phase was formed by the less
664 competent rock layers that were fractured during the folding because of the high strain concentrated
665 in the hinge region (Cosgrove, 2015). The fractured solid phase was then separated into a liquid phase
666 that took away the soluble ions and colloids through a very low fluid flow, and then into a residual
667 solid phase which remained in place in the form of an alterite: this latter is what we call “ghost-rock”
668 (Quinif, 2014, 2018). The residual alterite could not go out of the system, thus fitting the concept of
669 karstification “without total remover” (Quinif et al, 2014).

670 In a following stage of a cave forming through such a process, the potential energy usually
671 grows due to some geological event like glacial rebound, eustatic regression and so on. In the case of
672 the paleo-Veirana, the potential energy likely grew due to the deepening of the Rio Neva
673 paleovalley: in such a situation, the residual solid phase may have been removed by “piping”
674 phenomena with the genesis of a suffusion cave stage (Bartolomé et al, 2015).

675 We are still evaluating the role of the paleo-Neva in the removal of the “ghost rock” from the
676 cave: we do not have yet any evidence of an ingression of the rio Neva inside the cave, but it is clearly
677 possible. In addition, the morphological regularity of the bedrock made visible by our geophysical
678 model could be related to an erosion surface generated by water flow during the deepening of the
679 valley. In this sense, the gully-like morphology that we see in our geophysical model is of particular
680 significance if we think that the survived vertical strata beds of different competence, at the bottom

681 of the cave, were subjected to an erosional water sheet flow inside the open fold after the pseudokarst
682 genetical stages formerly suggested. There are similar situations described in other caves of this kind,
683 like the Ladies Cave Anticline at Sandersfoot (Pembrokeshire, UK), the Cave of Harpea (Basque
684 Country, Pyrenees) and the Anticline Cave at Wellington (Australia): the last one is an hypogene
685 multiphase cave (Osborne, 2010). However, to confirm and clarify all the hypothesized ideas
686 presented here, we need to perform more field studies. In particular, we plan on creating a geological
687 trench far from the archeological deposits, which will uncover the “bedrock,” thus allowing us to
688 evaluate its geological characteristics more precisely.

689

690 **9. CONCLUSIONS**

691 We presented the 3D Electrical Resistivity Tomography (ERT) imaging of the archaeological
692 deposits at Arma Veirana cave (Northern Italy), to date only partially explored during a series of four
693 archaeological field seasons.

694 We obtained the subsurface electrical resistivity pattern with the main aims to define the
695 geometry, thickness and sediment distribution features of the deposits, and map the morphology of
696 the underlying bedrock. This study revealed that the thickness of the deposits is variable along the
697 primary axis of the cave and ranges between more than 1.5 meters towards the entrance of the cave
698 to less than 10 centimetres towards its innermost part, where they show a discontinuous distribution.
699 A change in the thickness of the deposits has also been revealed transversely to the primary axis of
700 the cave, with a thickening towards the northeast side of it. The study allowed the recognition of
701 shallow, meter-sized, fine-grained sediment filled structures with a longitudinal orientation with
702 respect to the primary axis of the cave, as well as a possible erosional-like structure, filled with mostly
703 coarse deposits, which extends along the primary axis of the cave.

704 The results of the geophysical survey were cross-validated with the exposed stratigraphy as
705 well as with the presence of archaeological material culture. Both cross-validation supported the
706 hypothesis that the low-resistivity unit, which includes fine-grained structures, is the most

707 archaeologically promising. The results also suggest that the middle-low resistivity unit can also be
708 linked to rich archaeological layers.

709 These results will be useful to design future archaeological surveys at Arma Veirana cave and
710 they provide further insights on 3D ERT applicability and effectiveness in investigating any in-cave
711 deposits. Although ERT has rarely been employed in Paleolithic cave contexts because Paleolithic
712 remains are typically disseminated in loose deposits and either do not possess high electrical
713 resistivity contrasts or are too small to be detected, an accurate resistivity model was obtained in this
714 study. Even though this model did not recognize any specific remains, it defined the properties and
715 volume of the explorable deposits and identified the most promising areas to excavate, i.e., likely
716 artefact-bearing deposits.

717 As regards the issues deriving from the application of ERT in such confined cave environment,
718 the results of our study are consistent with previous findings that accurate resistivity models can be
719 obtained by ERT inside a cave whose half-width is larger than the thickness of sediments and in the
720 case of downward diverging cave walls.

721

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736

737 **Supplementary Data**

738 Data used in this study are available on Zenodo, <http://doi.org/10.5281/zenodo.4544550>,
739 (Torrese et al., 2021b).

740

741 **References**

- 742 Abu Zeid, N, Bignardi, S., Russo, P., Peresani, M., 2019. Deep in a Paleolithic archive: Integrated
743 geophysical investigations and laser-scanner reconstruction at Fumane Cave, Italy. Journal of
744 Archaeological Science: Reports, 27, 101976, ISSN 2352-409X,
745 <https://doi.org/10.1016/j.jasrep.2019.101976>.
- 746 Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir
747 characteristics. Journal of Petroleum Technology 1, 55–62.
- 748 Astin, T., Eckardt, H., Hay, S., 2007. Resistivity imaging survey of the Roman Barrows at Bartlow,
749 Cambridgeshire, UK. Archeological Prospection, 14: 24– 37.
- 750 Al-Zoubi, A. S., Abueladas, A. E. R. A., Al-Rzouq, R. I., Camerlynck, C., Akkawi, E., Ezarsky, M.,
751 ... Al Rawashdeh, S. (2007). Use of 2D multi electrodes resistivity imagining for sinkholes
752 hazard assessment along the eastern part of the Dead Sea, Jordan. American Journal of
753 Environmental Sciences, 3(4), 229–233. <https://doi.org/10.3844/ajessp.2007.230.234>
- 754 Bartolomé, M., Sancho, C., Moreno, A., Oliva-Urcia, B., Belmonte, A., Bastida, J., Cheng, H.,
755 Edwards, R.L., 2015. Upper Pleistocene interstratal piping-cave speleogenesis: The Seso
756 Cave System (Central Pyrenees, Northern Spain), Geomorphology, Vol.228, 1th January
757 2015, 335-344
- 758 Beck, A., Weinstein-Evron, M., 1997. A geophysical survey in the el-Wad cave, Mount Carmel,

759 Israel. *Archaeological Prospection*, 4 (2), pp. 85-91. 10.1002/(SICI)1099-
760 0763(199706)4:23.3.CO;2-3

761 Becker, R.J., Janković, I., Ahern, J.C.M., Komšo, D., 2019. High data density electrical resistivity
762 tomography survey for sediment depth estimation at the Romuald's Cave site. *Archaeological*
763 *Prospection*. 2019; 26: 361– 367. <https://doi.org/10.1002/arp.1749>

764 Berge, M.A., Drahor, M.G., 2011a. Electrical resistivity tomography investigations of multilayered
765 archaeolog-ical settlements: part I – modelling. *Archaeological Prospection*, 18: 159–171.

766 Berge, M.A., Drahor, M.G., 2011b. Electrical resistivity tomography investigations of multilayered
767 archaeolog-ical settlements: part II – a case study from Old SmyrnaHöyük, Turkey.
768 *Archaeological Prospection*, 18: 291–302.

769 Bertock, C., Martire, L., Perotti, E., d'Atri, A., & Piana, F. (2011). Middle-Late Jurassic
770 syndepositional tectonics recorded in the Ligurian Briançonnais succession (Marguareis-
771 Mongioie area, Ligurian Alps, NW Italy). *Swiss Journal of Geosciences*, 104, 237–255.

772 Campana, S., and Piro, S., 2008. *Seeing the Unseen. Geophysics and Landscape Archaeology* (1st
773 ed.). CRC Press. <https://doi.org/10.1201/9780203889558>

774 Cardarelli, E., Di Filippo, G., Tuccinardi, E., 2006. Electrical resistivity tomography to detect buried
775 cavities in Rome: a case study. *Near Surf Geophys* 4:387–392

776 Carrière, S. D., Chalikakis, K., Sénéchal, G., Danquigny, C., & Emblanch, C. (2013). Combining
777 Electrical Resistivity Tomography and Ground Penetrating Radar to study geological
778 structuring of karst Unsaturated Zone. *Journal of Applied Geophysics*, 94, 31–41.
779 <https://doi.org/10.1016/j.jappgeo>. HYPERLINK
780 "https://doi.org/10.1016/j.jappgeo.2013.03.014"2013.03.014

781 Cosgrove, J.W., 2015. The association of folds and fractures and the link between folding, fracturing
782 and fluid flow during the evolution of a fold-thrust belt: a brief review, in: Richards, F. L.,
783 Richardson, N. J., Rippington, S. J., Wilson, R. W. & Bond, C. E. (eds) *Industrial Structural*
784 *Geology: Principles, Techniques and Integration*. Geological Society, London, Special

785 Publications, 421, <http://dx.doi.org/10.1144/SP421.11>

786 Cozzolino, M., Calì, L.M., Gentile, V., Mauriello, P., and Di Meo, A., 2020, The Discovery of the
787 Theater of Akragas (Valley of Temples, Agrigento, Italy): An Archaeological Confirmation
788 of the Supposed Buried Structures from a Geophysical Survey. *Geosciences* 2020,
789 10(5),161; <https://doi.org/10.3390/geosciences10050161>

790 Dahlin, T., & Loke, M. H., 1998. Resolution of 2D Wenner resistivity imaging as assessed by
791 numerical modelling. *Journal of Applied Geophysics*, 38(4), 237–249.
792 <https://doi.org/10.1016/S0926-98> HYPERLINK "https://doi.org/10.1016/S0926-
793 9851(97)00030-X"51(97)00030-X

794 Dal Bo, G., Laiolo, G., Lazzarini, G., 1978. L’Arma di Costa di Cerisola, “Stalattiti e stalagmiti –
795 Gruppo Speleologico Savonese” 16, 14 (in Italian).

796 Dallagiovanna, G., Gaggero, L., Seno, S., Felletti, F., Mosca, P., Decarlis, A., Pellegrini, L., Poggi,
797 F., Bottero, D., 2011. Note Illustrative della Carta Geologica d’Italia alla scala 1:50.000, foglio
798 228, Cairo Montenotte. ISPRA – Servizio Geologico d’Italia.

799 Decarlis, A. & Lualdi, A., 2009. A sequence stratigraphic approach to a Middle Triassic shelf-slope
800 complex of the Ligurian Alps (Ligurian Briançonnais, Monte Carmo-Rialto unit, Italy).
801 *Facies*, volume 55, Article number: 267.

802 Deiana, R., Bonetto, J. & Mazzariol, A., 2018. Integrated Electrical Resistivity Tomography and
803 Ground Penetrating Radar Measurements Applied to Tomb Detection. *Surv Geophys* 39,
804 1081–1105. <https://doi.org/10.1007/s10712-018-9495-x>

805 Dellagiovanna, G., Gaggero, L., Seno, S., Felletti, F., Mosca, P., Decarlis, A., Pellegrini, L., Poggi,
806 F., Bottero, D., 2011. Note Illustrative della Carta Geologica d’Italia alla scala 1:50000, foglio
807 228, Cairo Montenotte. ISPRA-Servizio Geologico d’Italia.

808 de la Vega, M., Osella, A., and Lascano, E., 2003, Joint inversion of Wenner and dipole-dipole data
809 to study a gasoline-contaminated soil. *Journal of Applied Geophysics*, 54(1-2): 97-109.

810 Dubois, C., Lans B., Kaufman, O., Maire, R., Quinif, Y, 2011. Karstification de type fantomes de

811 roche en Entre-deux-Mers (Gironde, France): Implications en karstogenèse et morphologie
 812 karstique. *Karstologia: revue de karstologie et de spéléologie physique*, n.57, 1er semestre,
 813 19-27. https://www.persee.fr/doc/karst_0751-7688_2011_num_57_1_2690
 814 Drahor, M.G., Berge, M.A., Kurtulmus, T.Ö., Hartmann, M., Speidel, M.A., 2008. Magnetic and
 815 electrical resistivity tomography investigations in a Roman legionary camp site (Legio IV
 816 Scythica) in Zeugma, Southeastern Anatolia, Turkey. *Archaeological Prospection* 15: 159–
 817 186.
 818 El-Qady, G., Metwaly, M., Drahor, M.G., 2019. Geophysical techniques applied in archaeology. In
 819 *Archaeogeophysics: State of the Art and Case Studies*. Cham: Springer, pp. 1–25.
 820 Fikos, I., Vargemezis, G., Pennos, C., Lønøy, B., Jensen, K., Tveranger, J., 2019. Processing 2D
 821 ERT
 822 Data in 3D Environment-A Case Study Inside a Karstic Cave in Greece. 25th European
 823 Meeting of Environmental and Engineering Geophysics, Volume 2019, p.1 – 5,
 824 <https://doi.org/10.3997/2214-4609.201902389>
 825 Goudie A. S., 2013. *Encyclopedia of Geomorphology*, Vol. I, International Association of
 826 Geomorphologists, Routledge.
 827 Goldberg, P., and Sherwood, S.C., 2006. Deciphering human prehistory through the
 828 geoarcheological study of cave sediments. *Evol. Anthropol.*, 15: 20-36.
 829 <https://doi.org/10.1002/evan.20094>
 830 Griffiths, D. H., & Barker, R. D., 1993. Two-dimensional resistivity imaging and modelling in areas
 831 of complex geology. *Journal of Applied Geophysics*, 29(3–4), 211–226.
 832 [https://doi.org/10.1016/0926-9851\(93\)90005-J](https://doi.org/10.1016/0926-9851(93)90005-J)
 833 Guerin, R., & Benderitter, Y., 1995. Shallow karst exploration using MT-VLF and DC resistivity
 834 methods. *Geophysical Prospecting*, 43(5), 635–653. [https://doi](https://doi.org/10.1111/j.1365-2478.1995.tb00272.x) HYPERLINK
 835 "https://doi.org/10.1111/j.1365-2478.1995.tb00272.x".org/10.1111/j.1365-
 836 2478.1995.tb00272.x

837 Hancock, A.J, 1999. An investigation of the soils and sediment contained within the entrance
 838 chamber (or The Vestibule), Peak Cavern, and the assessment of their archaeological
 839 significance through the integration of geophysical techniques. BSc Project, Department of
 840 Archaeological Sciences, University of Bradford, 71pp.

841 Hill C.A., 1982. Origin of black deposits in caves. National Speleological Society Bulletin, 44, 15-
 842 19.

843 Hirniak, J. N., Smith, E. I., Johnsen, R., Ren, M., Hodgkins, J., Orr, C., Negrino, F., Riel-Salvatore
 844 J., Fitch, S., Miller, C. E., Zerboni, A., Mariani, G. S., Harris, J. A., Gravel-Miguel, C., Strait,
 845 D., Peresani, M., Benazzi, S., Marean, C. W., 2020. Discovery of cryptotephra at Middle–
 846 Upper Paleolithic sites Arma Veirana and Riparo Bombrini, Italy: a new link for broader
 847 geographic correlations, Journal of Quaternary Science 35 (1-2), 199–212.

848 Hodgkins, J., Orr, C.M., Gravel-Miguel, C., Riel-Salvatore, J., Miller, C.E., Bondioli, L., Nava, A.,
 849 Lugli, F., Talamo, S., Hajdinjak, M., Cristiani, E., Romandini, M., Meyer, D., Drohobytsky,
 850 D., Kuester, F., Pothier Bouchard, G., Buckley, B., Mancini, L., Baruffaldi, F., Silvestrini, S.,
 851 Arrighi, S., Keller, H.M., Griggs, R.B., Peresani, M., Strait, D.S., Benazzi, S., Negrino, F., In
 852 review. Infant funerary rites and female personhood in early Mesolithic Europe.

853 Jol, H.M., Schroder, J.F., Reeder, P., Freund, R.A., 2002. Return to the Cave of Letters (Israel): a
 854 ground penetrating radar archaeological expedition. D.A. Noon, G.F. Stickley, D. Longstaff
 855 (Eds.), Proceedings of the Eighth International Conference on Ground Penetrating Radar
 856 (GPR 2000). SPIE 4084 (2002), pp. 882-886

857 LaBrecque, D. J., 1996. The effects of noise on Occam's inversion of resistivity tomography data.
 858 Geophysics, 61(2), 538. <https://doi.org/10.1190/1.1443980> HYPERLINK
 859 "https://doi.org/10.1190/1.1443980"90/1.1443980

860 Laigre, L., Reynards, E., Arnaud-Fassetta, G., Baron, L., Glenz, D., 2012. Characterisation of the
 861 Rhône river palaeodynamics in Central Valais (Switzerland) with the electrical resistivity
 862 tomography method. Géomorphol Relief Processus Environ 4:405–426

863 Loke, M. H., Acworth, I., & Dahlin, T., 2003. A comparison of smooth and blocky inversion methods
 864 in 2D electrical imaging surveys. *Exploration Geophysics*, 34(3), 182–187.
 865 <https://doi.org/10.1071/EG03182> HYPERLINK "https://doi.org/10.1071/EG03182"71/EG03182

866 Loke, M. H., & Barker, R. D., 1996. Rapid least-squares inversion of apparent resistivity
 867 pseudosections by a quasi-Newton method. *Geophysical Prospecting*, 44(1), 131–152.
 868 <https://doi.org/10.1111/j.1365-2478.1996.tb00142.x>

869 Maillol, J. M., Seguin, M. K., Gupta, O. P., Akhauri, H. M., & Sen, N. (1999). Electrical resistivity
 870 tomography survey for delineating uncharted mine galleries in West Bengal, India.
 871 *Geophysical Prospecting*, 47(2), 103–116. <https://doi.org/10.1046/j.1365-2478.1999.00126.x> HYPERLINK
 872 "https://doi.org/10.1046/j.1365-2478.1999.00126.x"oi.org/10.1046/j.1365-
 873 2478.1999.00126.x

874 Mallol, C., and Goldberg, P., 2017. Caves and Rockshelter Sediments. In C. Nicosia and G. Stoops
 875 (eds.), *Archaeological Soil and Sediment Micromorphology*. Hoboken, NJ: Wiley, pp. 359-
 876 377.

877 Marìn Arroyo, A.B., Landete Ruiz, M.D., Vidal Bernabeu, G., Seva Romàn, R., Gonzàles Morales,
 878 M.R., Straus, L.G., 1982. Archaeological implications of human-derived manganese coatings:
 879 a study of blackened bones in El Miròn Cave, Cantabrian Spain, *Journal of Archaeological*
 880 *Science* 35, 801-813.

881 Matias, H.C., Monteiro Santos, F.A., Rodrigues Ferreira, F.E., Machado, C., Luzio, R., 2006.
 882 Detection of graves using the micro-resistivity method. *Ann. Geophys.* Vol. 49 No. 6
 883 <https://doi.org/10.4401/ag-3102>

884 Morelli, G., & LaBrecque, D. J., 1996. Advances in ERT inverse modeling. *European Journal of*
 885 *Environmental and Engineering Geophysics*, 1, 171–186.

886 Negrino, F., Benazzi, S., Hodgkins, J., Miller, C., E., Orr, C., Peresani, M., Riel-Salvatore, J., Strait,
 887 D., De Santis, H., 2018. Erli (SV). Arma Veirana, in *Archeologia in Liguria, Nuova Serie*, VI,
 888 2014-2015, Soprintendenza Archeologia, Belle Arti e Paesaggio per la città metropolitana di

889 Genova e le province di Imperia, Savona e La Spezia, Genova, 460-461.

890 Oberender, P. & Plan, L., 2018. A genetic classification of caves and its application in eastern Austria.
891 From: *Advances in Karst Research: Theory, Fieldwork and Applications*, Geological Society,
892 London, Special Publications, 466, 121-136.

893 Obradovic, M., Abu Zeid, N., Bignardi, S., Bolognesi, S., Peresani, M., Russo, P., and Santarato,
894 G., 2015, High Resolution Geophysical and Topographical Surveys for the Characterisation
895 of Fumane Cave Prehistoric Site, Italy: *Near Surface Geoscience 2015: 21st European*
896 *Meeting of Environmental and Engineering Geophysics*, [https://doi.org/10.3997/2214-](https://doi.org/10.3997/2214-4609.201413676)
897 [4609.201413676](https://doi.org/10.3997/2214-4609.201413676).

898 Olenchenko, V., Tsibizov, L., Osipova, P., 2019. Electrotomography in a cave: a numerical
899 experiment. *Interexpo GEO-Siberia 2(2)*:111-115. DOI: 10.33764/2618-981X-2019-2-2-111-
900 115 Papadopoulos, N.G., Yi, M.-J., Kim, J.-H., Tsourlos, P., Tsokas, G.N., 2010. Geophysical
901 investigation of tumuli by means of surface 3D electrical resistivity tomography. *Journal of*
902 *Applied Geophysics* 70: 192– 205.

903 Olenchenko, V.V., Tsibizov, L.V., Osipova, P.S., Charginov, T.T., Viola B.T., Kolobova K.A.,
904 Krivoshapkin A.I.,
905 2020. Peculiarities of Using 2D Electrical Resistivity Tomography in Caves. *Archaeology,*
906 *Ethnology & Anthropology of Eurasia*, 48(4):67-74. [https://doi.org/10.17746/1563-](https://doi.org/10.17746/1563-0110.2020.48.4.067-074)
907 [0110.2020.48.4.067-074](https://doi.org/10.17746/1563-0110.2020.48.4.067-074)

908 Ortega, A.I., Benito-Calvo, A., Porres, J., Pérez-González, A, Martín Merino, M.A., 2010. Applying
909 electrical resistivity tomography to the identification of endokarstic geometries in the
910 Pleistocene Sites of the Sierra de Atapuerca (Burgos, Spain). *Archaeol. Prospect.*, 17, pp.
911 233-245, 10.1002/arp.392

912 Osborne R.A.L., 2010. Rethinking eastern Australian caves. Geological Society, London, Special
913 Publications 2010; v.346; 289-308

914 Osipova, P.S., Olenchenko, V.V., Tsibizov, L.V., and Krivoshapkin, A.I., 2020. The Study of

915 Paleolithic Monuments in Karst Caves by Electrotomography. Engineering and Mining
 916 Geophysics 2020, Volume 2020, p.1 – 8.

917 Papadopoulos, N., Tsourlos, P., Tsokas, G., & Sarris, A., 2006. Two-dimensional and three-
 918 dimensional resistivity imaging in archaeological site investigation. Archaeological
 919 Prospection, 13(3), 163181.

920 Papadopoulos, N.G., Tsourlos, P., Tsokas, G.N., Sarris, A., 2007. Efficient ERT measuring and
 921 inversion strategies for 3D imaging of buried antiquities. Near Surf. Geophys. 2007, 5, 349–
 922 362.

923 Papadopoulos, N.G, Yi, M-J., Kim, J-H., Tsourlos, P., Tsokas, G.N., 2010. Geophysical investigation
 924 of tumuli by means of surface 3D Electrical Resistivity Tomography, Journal of Applied
 925 Geophysics, Volume 70, Issue 3, Pages 192-205, ISSN 0926-9851,
 926 <https://doi.org/10.1016/j.jappgeo.2009.12.001>.

927 Papadopoulos, N.G., Sarris, A., Parkinson, W.A., Gyucha, A., Yerkes, R.W., Duffy, P.R., Tsourlos, P.,
 928 2014.
 929 Electrical Resistivity Tomography for the Modelling of Cultural Deposits and
 930 Geomorphological Landscapes at Neolithic Sites: a Case Study from Southeastern Hungary.
 931 Archaeol. Prospect., 21, 169-183, DOI: 10.1002/arp.1480

932 Piroddi, L., Calcina, S.V., Trogu, A., Ranieri, G., 2020. Automated Resistivity Profiling (ARP) to
 933 explore wide
 934 archaeological areas: The prehistoric site of Mont'e Prama, Sardinia, Italy. Remote Sens.
 935 2020, 12, 461.

936 Pringle, J. K., Westerman, A. R., Schmidt, A., Harrison, J., Shand ley, D., Beck, J., Donahue, R. E.
 937 and Gardiner, A. R., 2002. Investigating Peak Cavern, Castleton, Derbyshire, UK: integrating
 938 cave survey, geophysics, geology and archaeology to create a 3-D digital CAD model. Cave
 939 and Karst Science, 29(2), 67-74.

940 Quarto, R., Schiavone, D., Diaferia, I., 2007. Ground penetrating radar survey of a prehistoric site in

941 Southern Italy. *J. Archaeol. Sci.*, 34, pp. 2071-2080.

942 Quinif, Y., 2014. La fantomisation – Une nouvelle manière de concevoir la formation des
 943 cavernes. *Regards N.79 – Deuxieme semestre*, 42-72.

944 Quinif, Y., 2018. Fantomisation et spéléogenèse: implications et questionnement. *Karstologia: revue*
 945 *de karstologie et de spéléologie physique*, n.69, 32-46

946 Quinif, Y. & Bruxelles, L., 2011. L'altération de type "fantome de roche": processus, évolution et
 947 implications pour la karstification. *Géomorphologie: relief, processus, environnement*, Vol.17 –
 948 n.4, 349-358.

949 Kneisel, C., 2006. Assessment of subsurface lithology in mountain environments using 2D resistivity
 950 imaging. *Geomorphology*, 80(1–2), 32–44. <https://doi.org/10.1016/j.geomorph.2005.09.012>

951 Rainone, M. L., Rusi, S., & Torrese, P., 2015. Mud volcanoes in central Italy: Subsoil characterization
 952 through a multidisciplinary approach. *Geomorphology*, 234, 228–242.
 953 <https://doi.org/10.1016/j.geomorph.2015.01.026>

954 Ramsey, C.B., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337-360.

955 Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M.,
 956 Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton,
 957 T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G.,
 958 Pearson, C., Van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R.,
 959 Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-
 960 Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reining, F., Sakamoto,
 961 M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age
 962 calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725-757.

963 Rezaee, M.R., Motiei, H., and Kazemzadeh, E., 2007. A new method to acquire m exponent and
 964 tortuosity factor for microscopically heterogeneous carbonates. *Journal of Petroleum Science*
 965 *and Engineering*. 56 (4): 241-251.

966 Salem, H.S., and Chilingarian, G.V., 1999. The cementation factor of Archie's equation for

967 shaly sandstone reservoirs: *Journal of Petroleum Science and Engineering*, March, pp. 83–93.

968 Sarris, A., Kalayci, T., Moffat, I., Manataki, M., 2018. An Introduction to Geophysical and
969 Geochemical Methods in Digital Geoarchaeology. In: Siart C., Forbriger M., Bubbenzer O.
970 (eds) *Digital Geoarchaeology. Natural Science in Archaeology*. Springer, Cham.
971 https://doi.org/10.1007/978-3-319-25316-9_14

972 Sarris, A., Papadopoulos, N., Soupios, S., 2014. Contribution of geophysical approaches to the study
973 of Priniatikos Pyrgos. In: Molloy BPC, Duckworth CN (eds) *A cretan landscape through time: Priniatikos Pyrgos and environs*, BAR International Series, vol 2634. Archaeopress, Oxford,
974 pp 61–69

976 Satitpittakul, A., Vachiratienchai, C., & Siripunvaraporn, W. (2013). Factors influencing cavity
977 detection in Karst terrain on two-dimensional (2-D) direct current (DC) resistivity survey: A
978 case study from the western part of Thailand. *Engineering Geology*, 152(1), 162–171.
979 <https://doi.org/10.1016/j.enggeo.2012.10.015>

980 Sauro, U., 2005. Closed Depressions. From: Culver, D.C. & White, W.B., *Encyclopedia of Caves*.
981 Elsevier Academic Press, Burlington-London, 108-122

982 Scapozza, C., Laigre, L., 2014. The contribution of electrical resistivity tomography (ERT) in
983 Alpine dynamics geomorphology: case studies from the Swiss Alps. *Géomorphol Relief*
984 *Processus Environ* 20(1):27–42

985 Schmidt, A.R., Linford, P., Linford, N., David, A., Gaffney, C.F., Sarris, A., and Fassbinder, J.,
986 2015.
987 EAC Guidelines for the use of Geophysics in Archaeology: Questions to Ask and Points to
988 Consider. EAC Guidelines 2. Namur, Belgium: Europae Archaeologia Consilium (EAC),
989 Association Internationale sans But Lucratif (AISBL). ISBN 978-963-9911-73-4. 135p.

990 Schrott, L., & Sass, O., 2008. Application of field geophysics in geomorphology: Advances and
991 limitations exemplified by case studies. *Geomorphology*, 93(1–2), 55–73.
992 <https://doi.org/10.1016/j.geomorph> HYPERLINK

993 "https://doi.org/10.1016/j.geomorph.2006.12.024".2006.12.024

994 Seaton, W. J. and Burbey, T. J., 2002. Evaluation of two-dimensional resistivity methods in a
 995 fractured crystalline-rock terrane. *Journal of Applied Geophysics*, 51(1): PII S0926-
 996 9851(02)00212-4. DOI: 10.1016/S0926-9851(02)00212-4

997 Seno, S., Dallagiovanna, G., and Vanossi, M., 2003. Palaeogeography and thrust development in the
 998 Penninic Domain of the Western Alpine chain: examples from the Ligurian Alps.
 999 *Boll.Soc.Geol. It.*, 122 (2003), 223-232

1000 Shopov, Y., Stoykova, D., Petrova, A., Vasilev, V., Tsankov, L., 2008. Potential and limitations of
 1001 the archaeo-geophysical techniques. R.I. Kostov, B. Gaydarska, M. Gurova (Eds.),
 1002 *Proceedings of the International Conference, 29–30 October 2008, Geoarchaeology and*
 1003 *Archaeomineralogy*, Sofia, Publishing House “St. Ivan Rilski”, Sofia, pp. 320-324.

1004 Simyrdanis, K., Papadopoulos, N., Kim, J.H., Tsourlos, P., Moffat, I., 2015. Archaeological
 1005 investigations in the shallow seawater environment with electrical resistivity tomography.
 1006 *Surf Geophys* 13:601–611.

1007 Sola, F., 2007. Tesi di Laurea: Geomorfologia carsica del monte Fenera (Vc). Relatore prof. Alfredo
 1008 Bini, correlatore dr. Stefano Turri, Università degli Studi di Milano – Facoltà di Scienze
 1009 Matematiche, Fisiche e Naturali, Corso di Laurea in Scienze Geologiche, A.A. 2006-2007 (in
 1010 Italian, unpublished)

1011 Smith, D. L. (1986). Application of the pole-dipole resistivity technique to the detection of solution
 1012 cavities beneath highways. *Geophysics*, 51(3), 833–837. <https://doi.org/10.1190/1.1442135>

1013 Supriyadi, A., Suprianto, A., Priyantari, N., Cahyono, B.E., Sholeha, I., 2019. Assessment of
 1014 validated geoelectrical resistivity methods to reconstruct buried archaeological site (case
 1015 study: Beteng Site-Sidomekar, Jember Regency). *J. Phys. Conf. Ser.*, 1153, 012026.

1016 Szalai, S., Novak, A., & Szarka, L., 2009. Depth of Investigation and Vertical Resolution of Surface
 1017 Geoelectric Arrays. *Journal of Environmental & Engineering Geophysics*, 14(1), 15–23.
 1018 <https://doi.org/10.2113/JEEG14.1.15>

1019 Szalai, S., & Szarka, L. (2008). Parameter sensitivity maps of surface geoelectric arrays I. Linear
 1020 arrays. *Acta Geodaetica et Geophysica Hungarica*, 43(4), 419–437.
 1021 <https://doi.org/10.1556/AGeod.43.2008.4.4>

1022 Thacker, P.T., Ellwood, B.B., Pereira, C.M.C., 2002. Detecting Palaeolithic Activity Areas Through
 1023 Electrical Resistivity Survey: An Assessment from Vale de Óbidos, Portugal, *Journal of*
 1024 *Archaeological Science*, Volume 29, Issue 6, Pages 563-570, ISSN 0305-4403,
 1025 <https://doi.org/10.1006/jasc.2001.0691>.

1026 Tonkov, N., 2014. Geophysical survey at the early Neolithic site of Yabalkovo. In: Roodenberg J,
 1027 Leshtakov K, Petrova V (eds) *Yabalkovo vol 1*, ATE- Ars et Technica Expicatus, Sofia
 1028 Univeristy “St. Kliment Ohridski”, Sofia, pp 73–78

1029 Torrese P., 2020. Investigating karst aquifers: Using pseudo 3-D electrical resistivity tomography to
 1030 identify major karst features. *Journal of Hydrology*, 580,
 1031 doi.org/10.1016/j.jhydrol.2019.124257

1032 Torrese, P., Pozzobon, R., Rossi, A.P., Unnithan, V., Sauro, F., Borrmann, D., Lauterbach, H.,
 1033 Santagata, T., 2021a. Detection, imaging and analysis of lava tubes for planetary analogue
 1034 studies using electric methods (ERT), *Icarus*, 357, doi.org/10.1016/j.icarus.2020.114244.

1035 Torrese P., Zucca F., Martini S., Benazzi S., Drohobytsky D., Gravel-Miguel C., Hodgkins J., Meyer
 1036 D., Miller C., Peresani M., Orr C., Riel-Salvatore J., Strait D.S., Negrino, F., 2021b. 3D
 1037 electrical resistivity data collected at Arma Veirana cave (Northern Italy) [Data set]. Zenodo.
 1038 <http://doi.org/10.5281/zenodo.4544550>.

1039 Tsokas, G.N., Tsourlos, P.I., Stampolidis, A., Katsonopoulou, D., Soter, S., 2009. Tracing a major
 1040 Roman road in the area of ancient Helike by resistivity tomography. *Archaeological*
 1041 *Prospection* 16: 251– 266.

1042 Tsokas, G.N., Tsourlos, P.I., Kim, J.H., Yi, M.J., Vargemezis, G., Lefantzis, M., Fikos, E., Peristeri,
 1043 K., 2018. ERT imaging of the interior of the huge tumulus of Kastasi in Amphipolis (northern
 1044 Greece).

1045 Archaeol. Prospect., 25, 347–361.

1046 Van Schoor, M., 2002. Detection of sinkholes using 2D electrical resistivity imaging. Journal of
1047 Applied Geophysics, 50(4), 393–399. [https://do](https://doi.org/10.1016/S0926-9851(02)00166-0) HYPERLINK
1048 "https://doi.org/10.1016/S0926-9851(02)00166-0"i.org/10.1016/S0926-9851(02)00166-0

1049 Yogeshwar, P., Hamacher, S., Reçi, H., Hauck, T., Onuzi, K., Tezkan, B., 2019. Investigating
1050 Sedimentological Architecture Using Electrical Resistivity Tomography: A Case Study from
1051 the Archaeological Open-Air Site Shën Mitri, Southern Albania. Pure Appl. Geophys. 176,
1052 843–856. <https://doi.org/10.1007/s00024-018-1987-6>

1053 Zhu, J., Currens, J. C., & Dinger, J. S., 2011. Challenges of using electrical resistivity method to
1054 locate karst conduits-A field case in the Inner Bluegrass Region, Kentucky. Journal of Applied
1055 Geophysics, 75(3), 523–530. <https://doi.org/10.1016/j.jappgeo.2011.08.009>

1056 Waxman, M.H., Smits, L.J.M., 1968. Electrical Conductivities in Oil-Bearing Shaly Sands. SPE J. 8:
1057 107–122. doi: <https://doi.org/10.2118/1863-A>

1058 Witten, A., 2017. Handbook of Geophysics and Archaeology. New York: Routledge.

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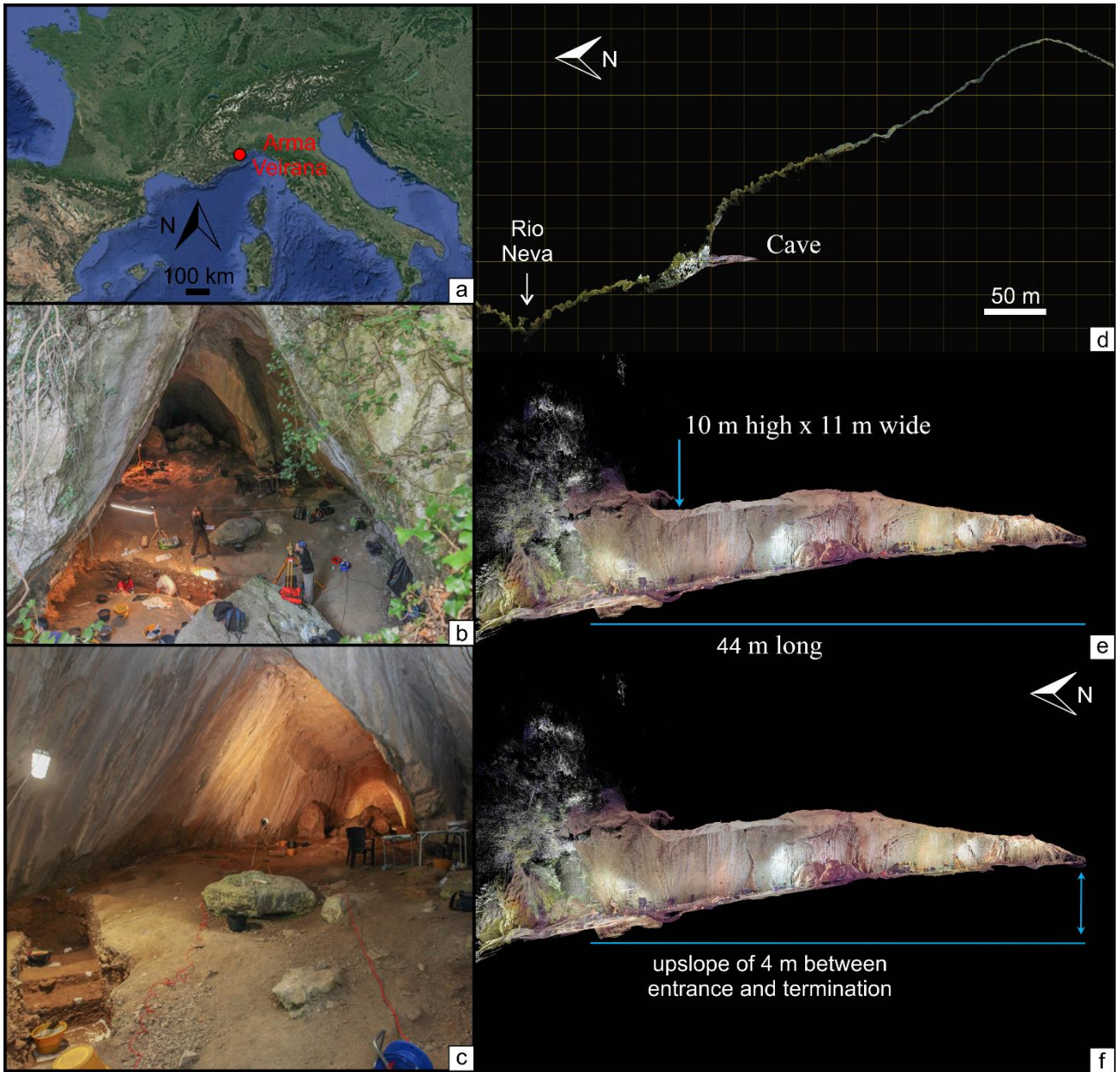
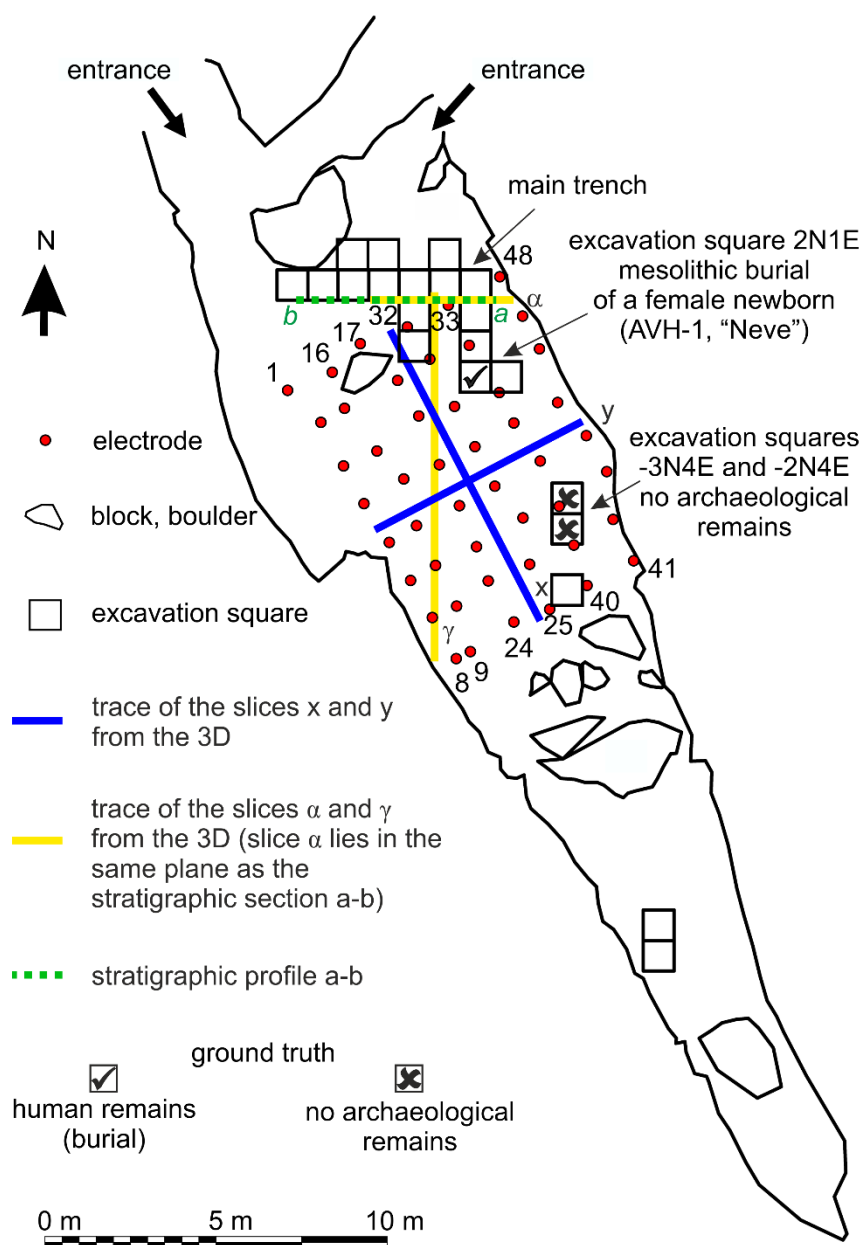


Fig. 1: Arma Veirana: (a) geographical setting, (b) picture from outside the cave, (c) picture from inside the cave, (d) location of the cave in cross section with respect to the slope and Rio Neva, (e, f) cross section and geometric features of the cave; the cross sections (d-f) were derived from a LiDAR reconstruction of the cave.



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1072 **Fig. 2:** Experimental layout of the 3D ERT survey along with the traces of the slices and of the
 1073 stratigraphic profiles, location of excavation pits and main archaeological material.

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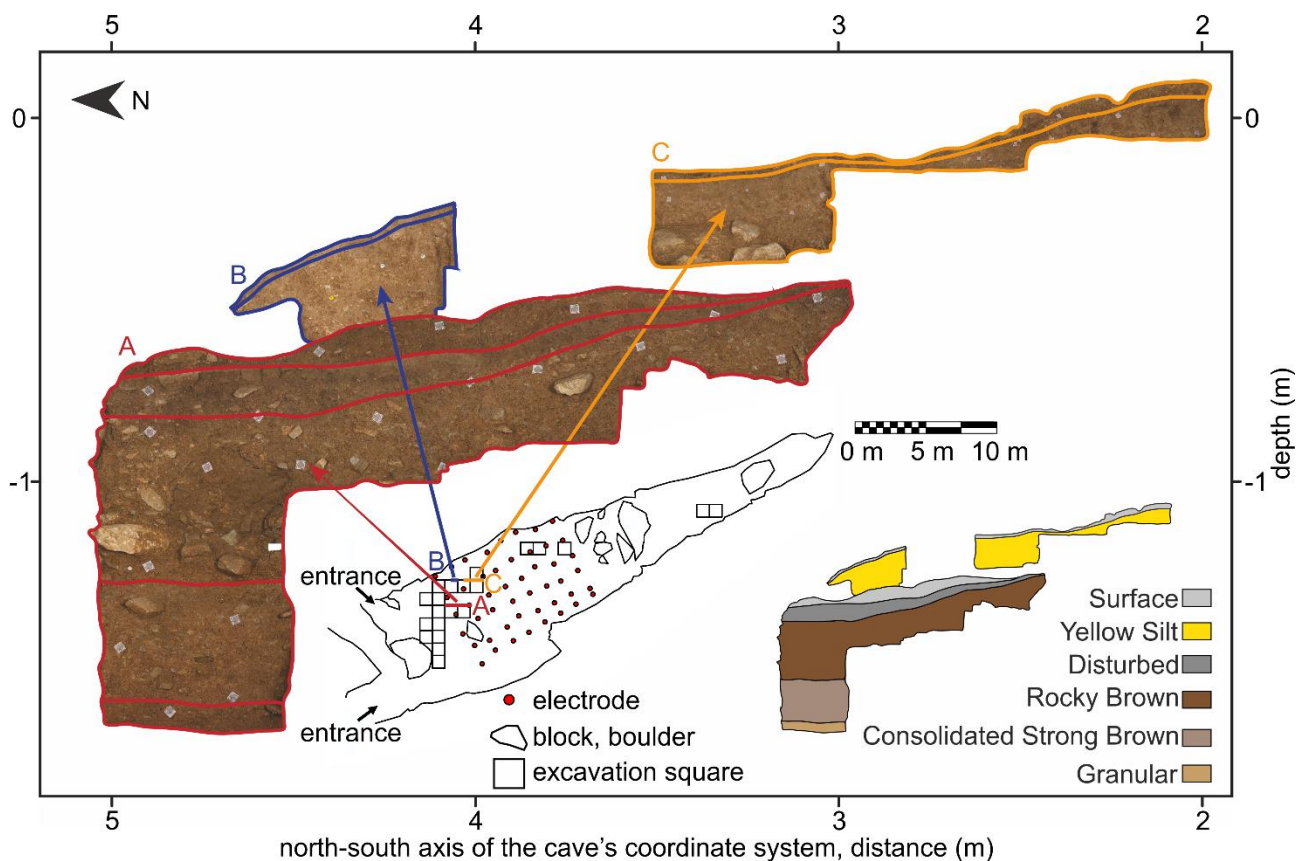
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Fig. 3: Photograph and stratigraphic drawing of N-S profile. The composite image is a projection of two profiles. The more western profile is located closer to an erosional rill, and therefore does not contain Yellow Silt (YS) aggregate, which is only exposed in excavations along the flank of the cave as represented in the more eastern profile. Excavations have exposed deposits (Black Mousterian, BM) below Granular (GR), but they have not been reached yet in the excavation units.

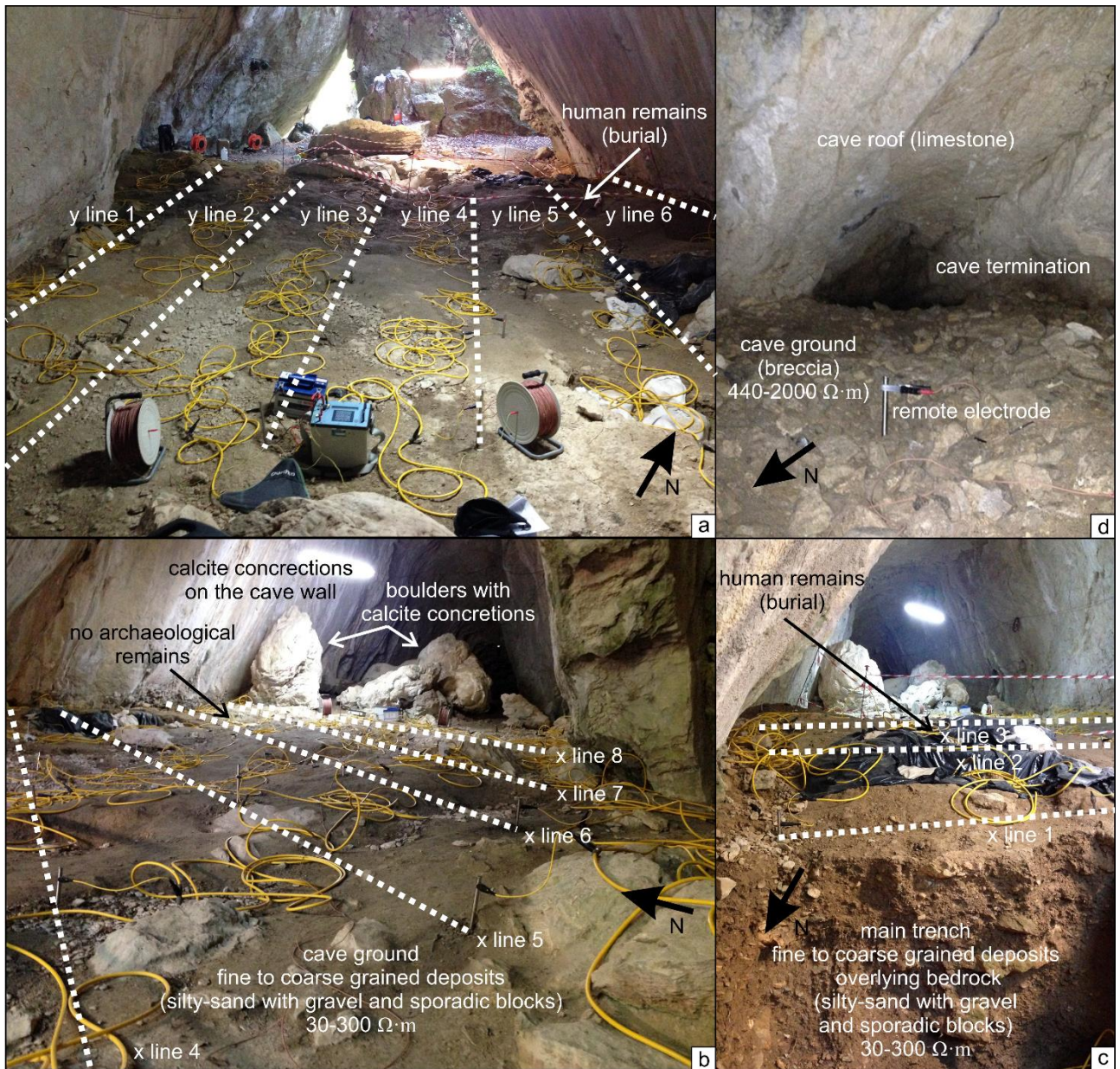
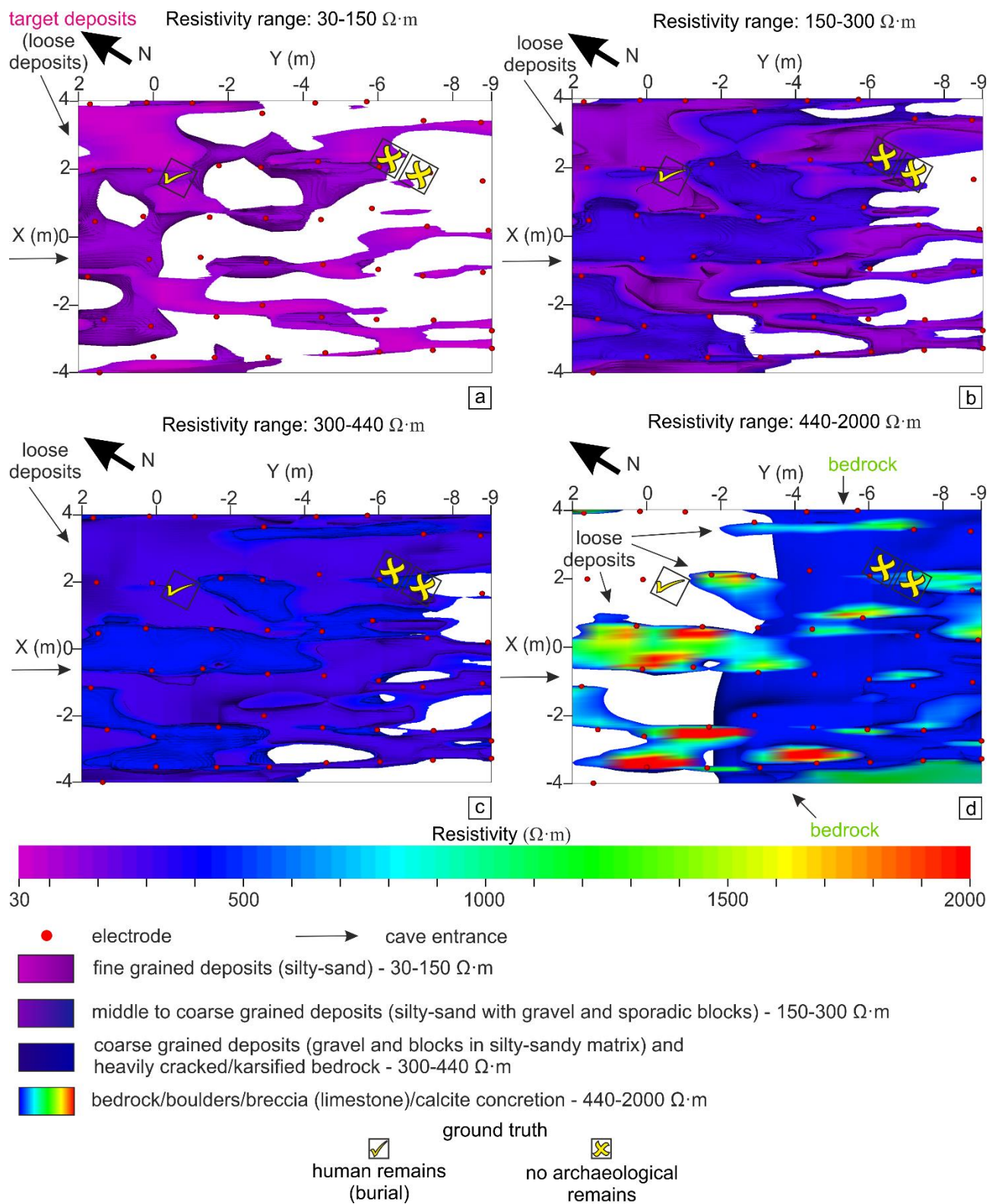


Fig. 4: Pictures showing different views of the 3D ERT survey grid along with lithological description.

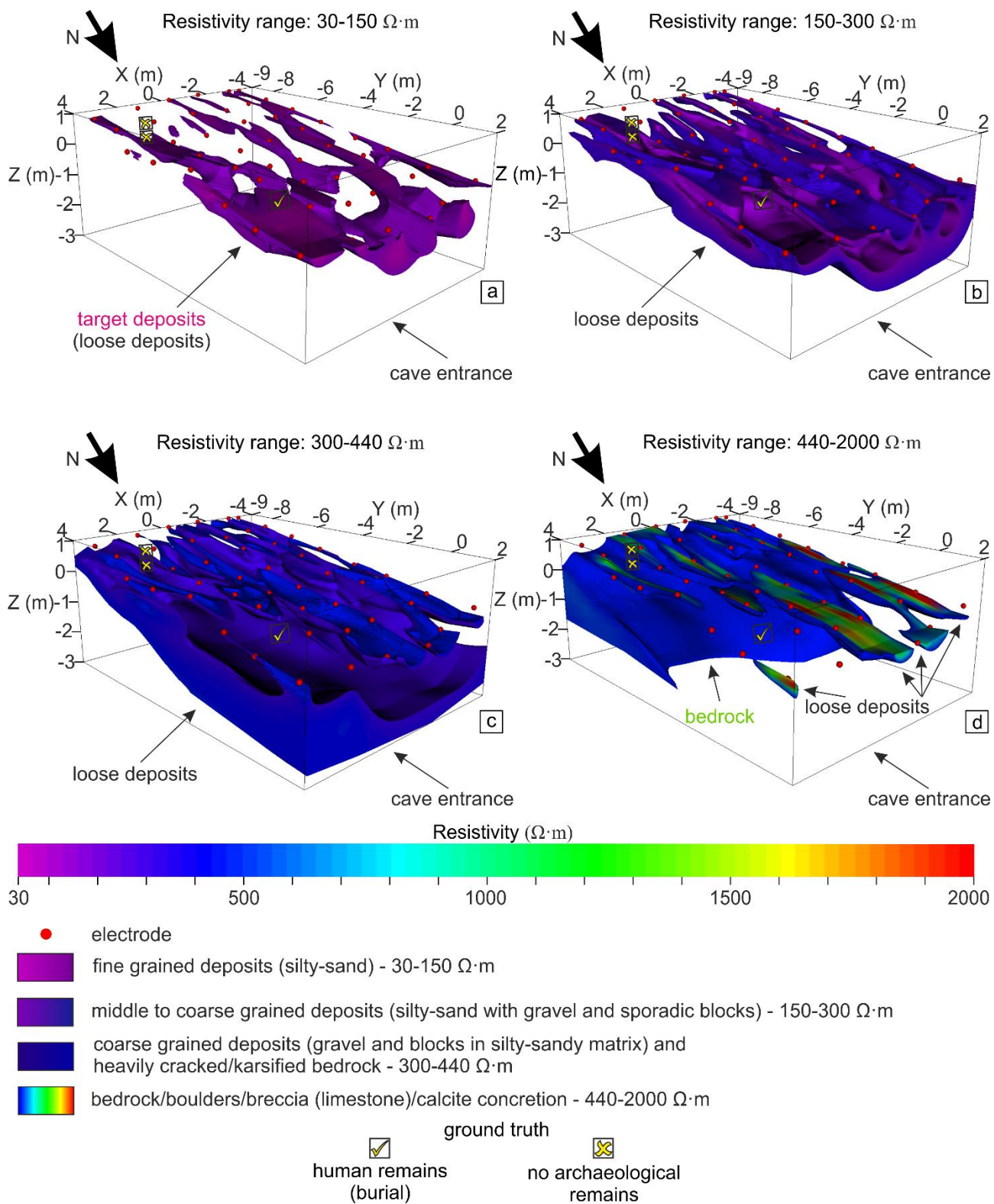


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1099 **Fig. 5:** Plan view of different resistivity range extractions from the 3D inverse resistivity model along
 1100 with lithological description.

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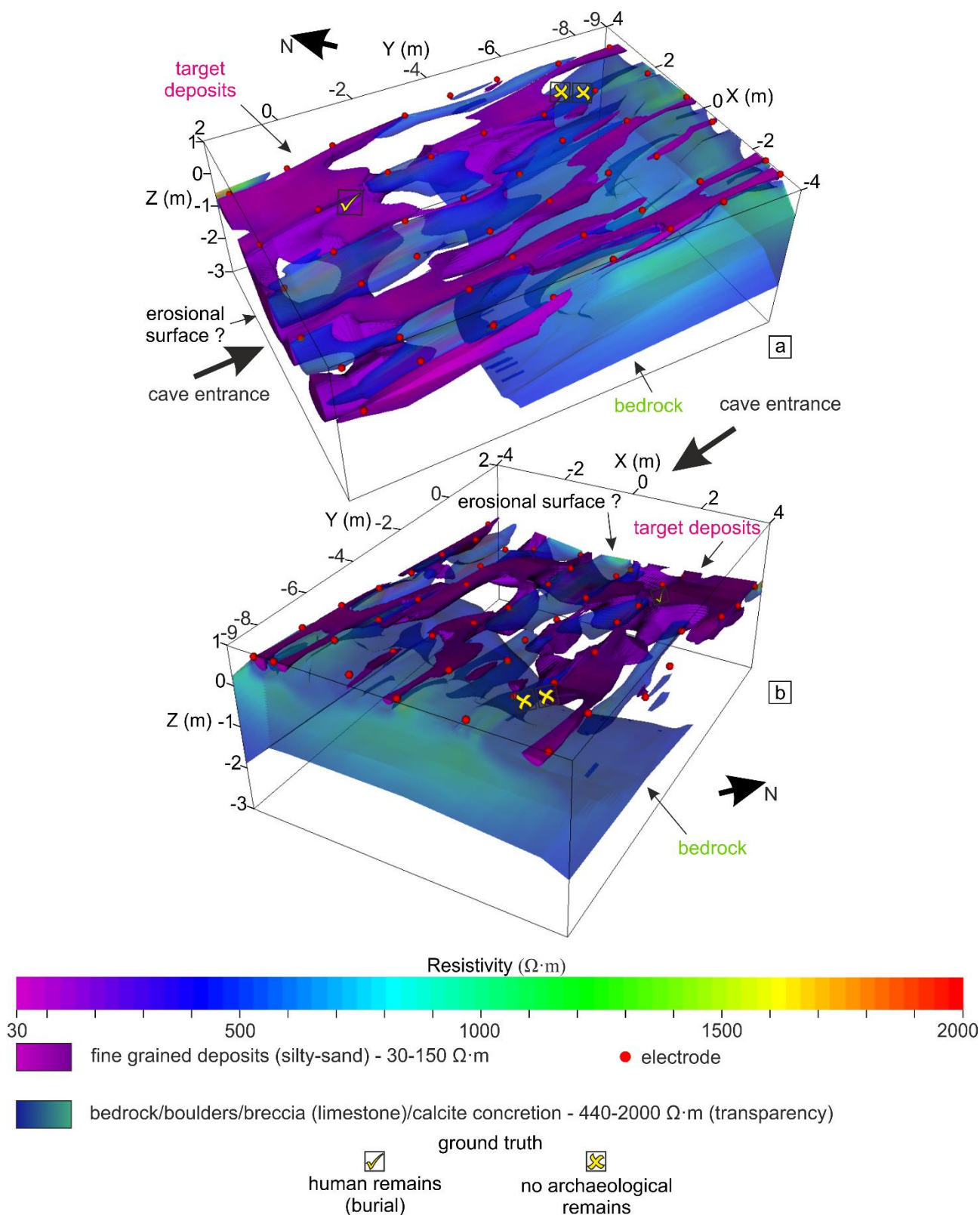


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1104 **Fig. 6:** Perspective view from above of different resistivity range extractions from the 3D inverse
 1105 resistivity model along with lithological description.

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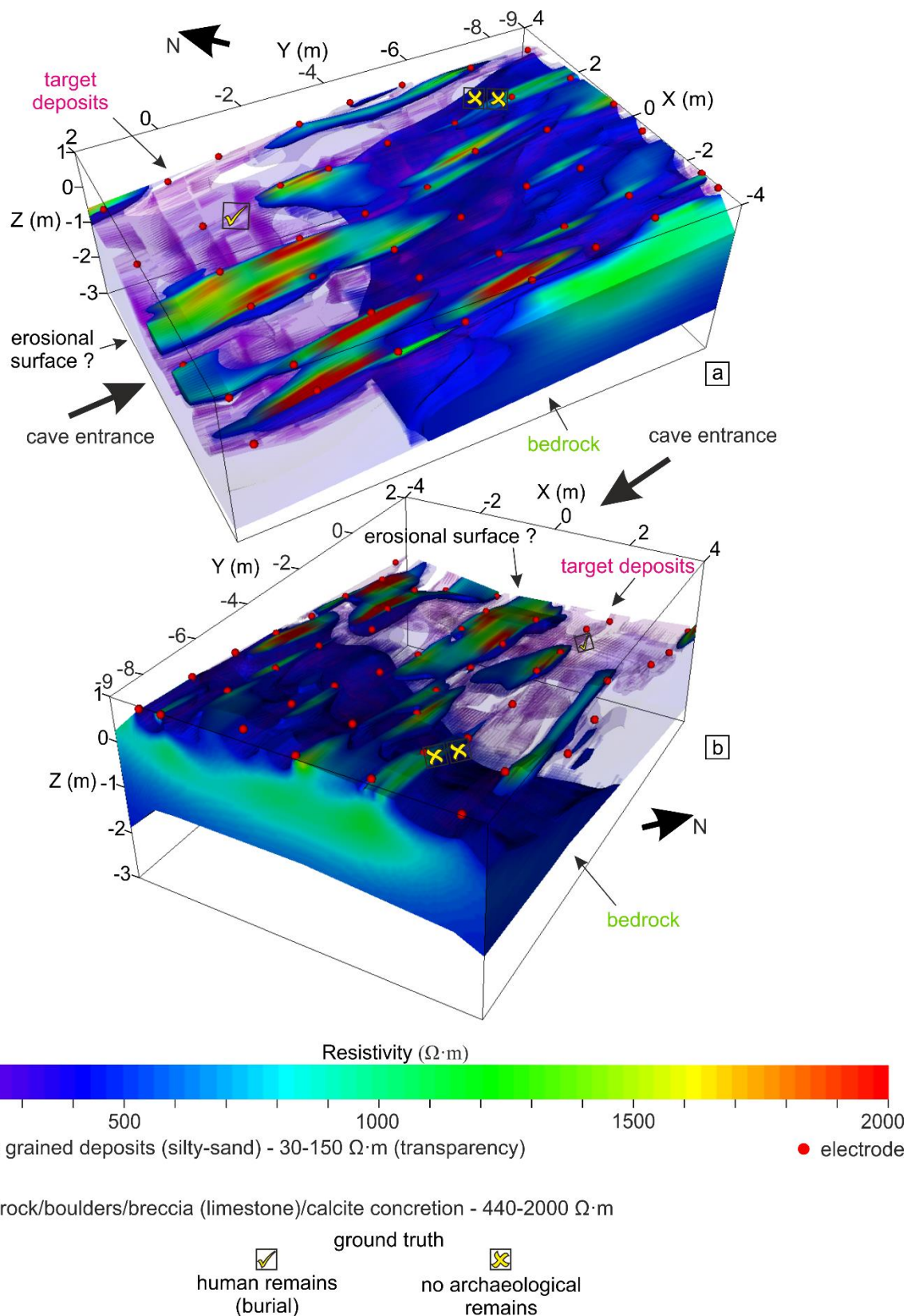
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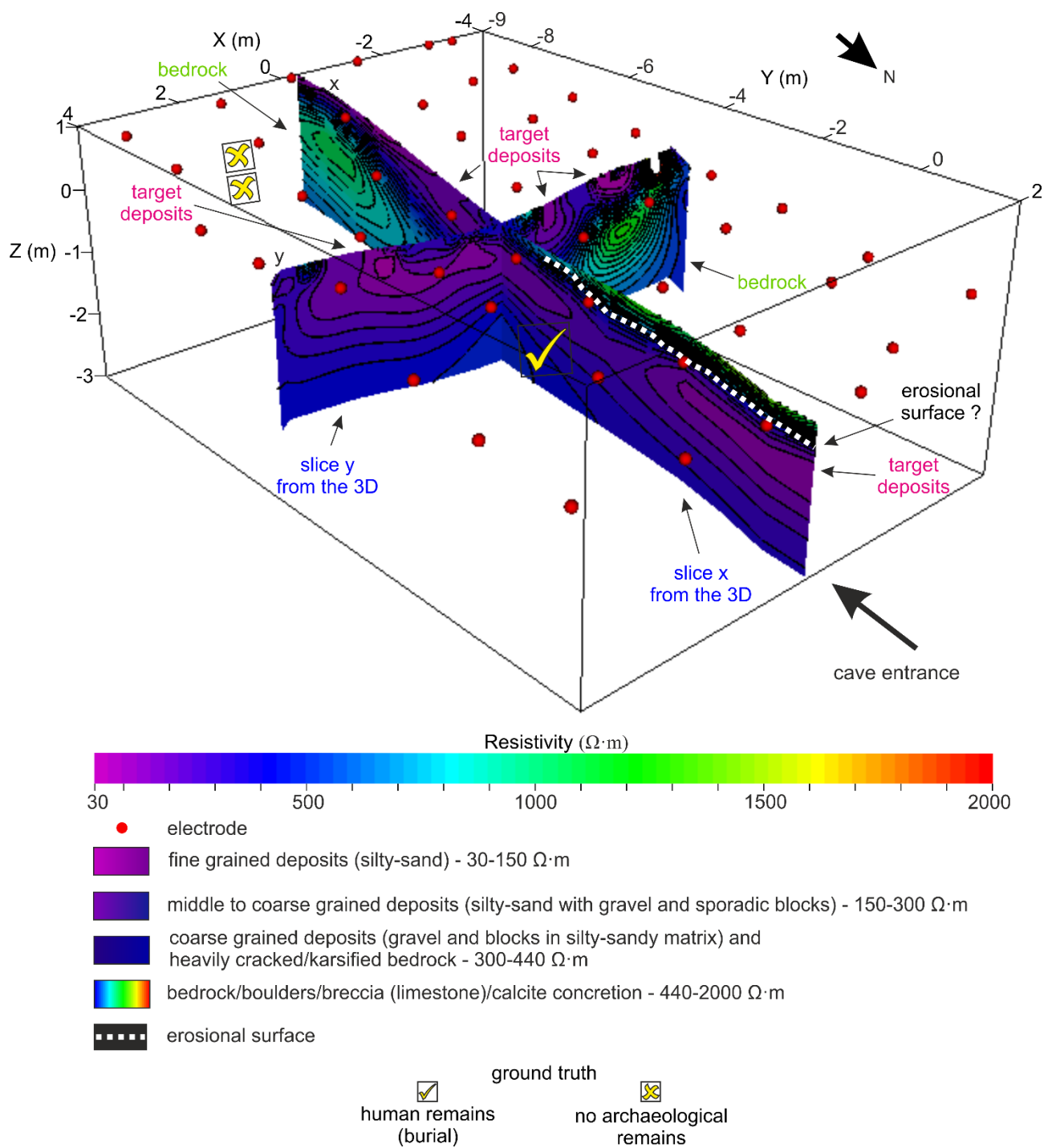
1109 **Fig. 7:** Perspective views from above of different resistivity range extractions from the 3D inverse
 1110 resistivity model: the low-resistivity unit (the most promising from an archaeological point of view)
 1111 highlighted in opaque plot and the high-resistivity unit shown in transparent plot.

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1114 **Fig. 8:** Perspective views from above of different resistivity range extractions from the 3D inverse
 1115 resistivity model: the high-resistivity unit highlighted in opaque plot and the low-resistivity unit (the
 1116 most promising from an archaeological point of view) shown in transparent plot.



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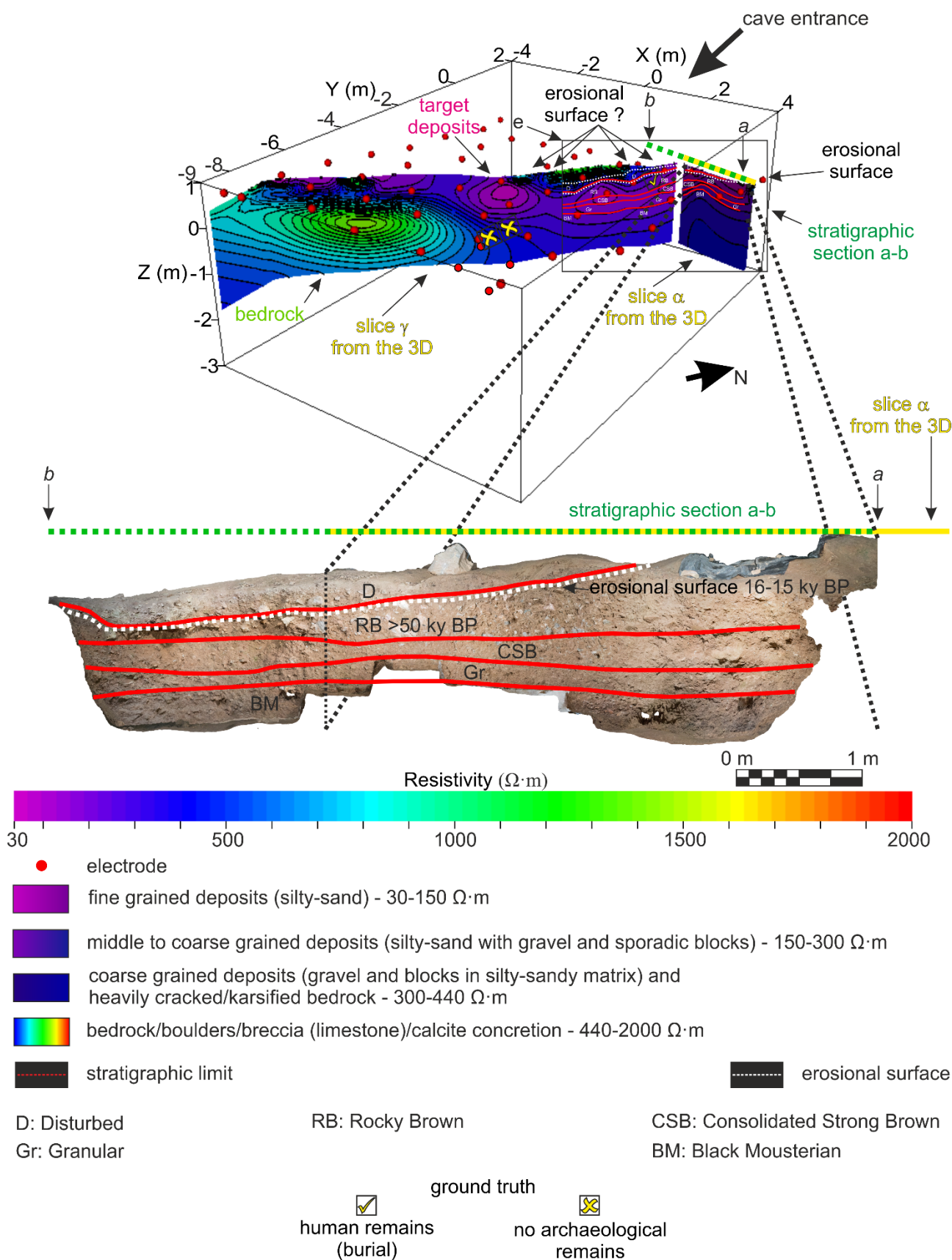
1118 **Fig. 9:** Perspective view of X and Y plane slices extracted from the 3D inverse resistivity model
 1119 showing the resistivity pattern along with lithological description.

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1125 **Fig. 10:** Perspective view of α and γ plane slices extracted from the 3D inverse resistivity model

1126 along with the stratigraphic section a-b (main trench): the limits of the stratigraphic aggregates were

1127 plotted on slice α which lies on the same plane as the stratigraphic sections a-b, to verify any

1128 correlation with the resistivity pattern and extrapolate the stratigraphic limits on slice γ .

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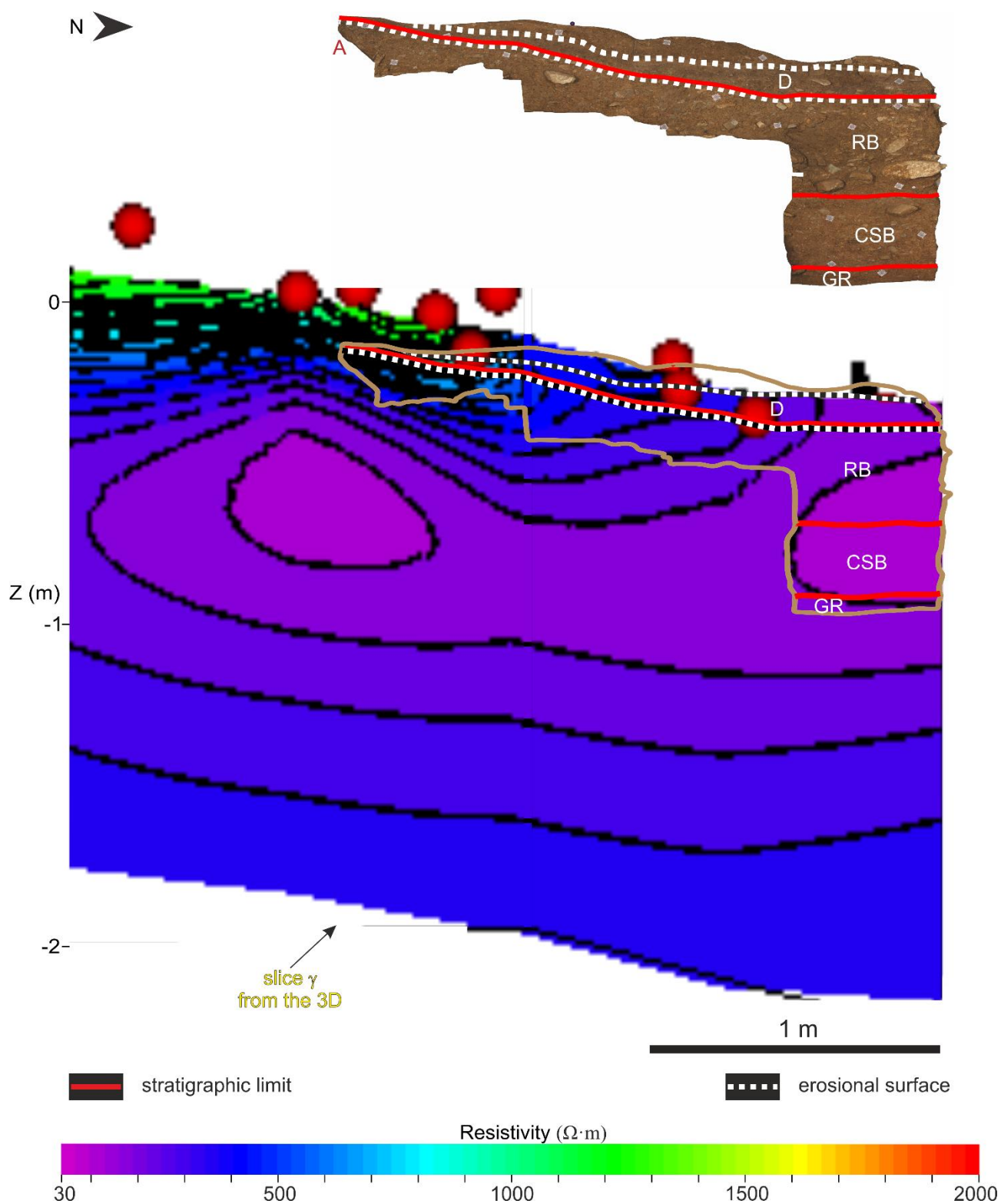
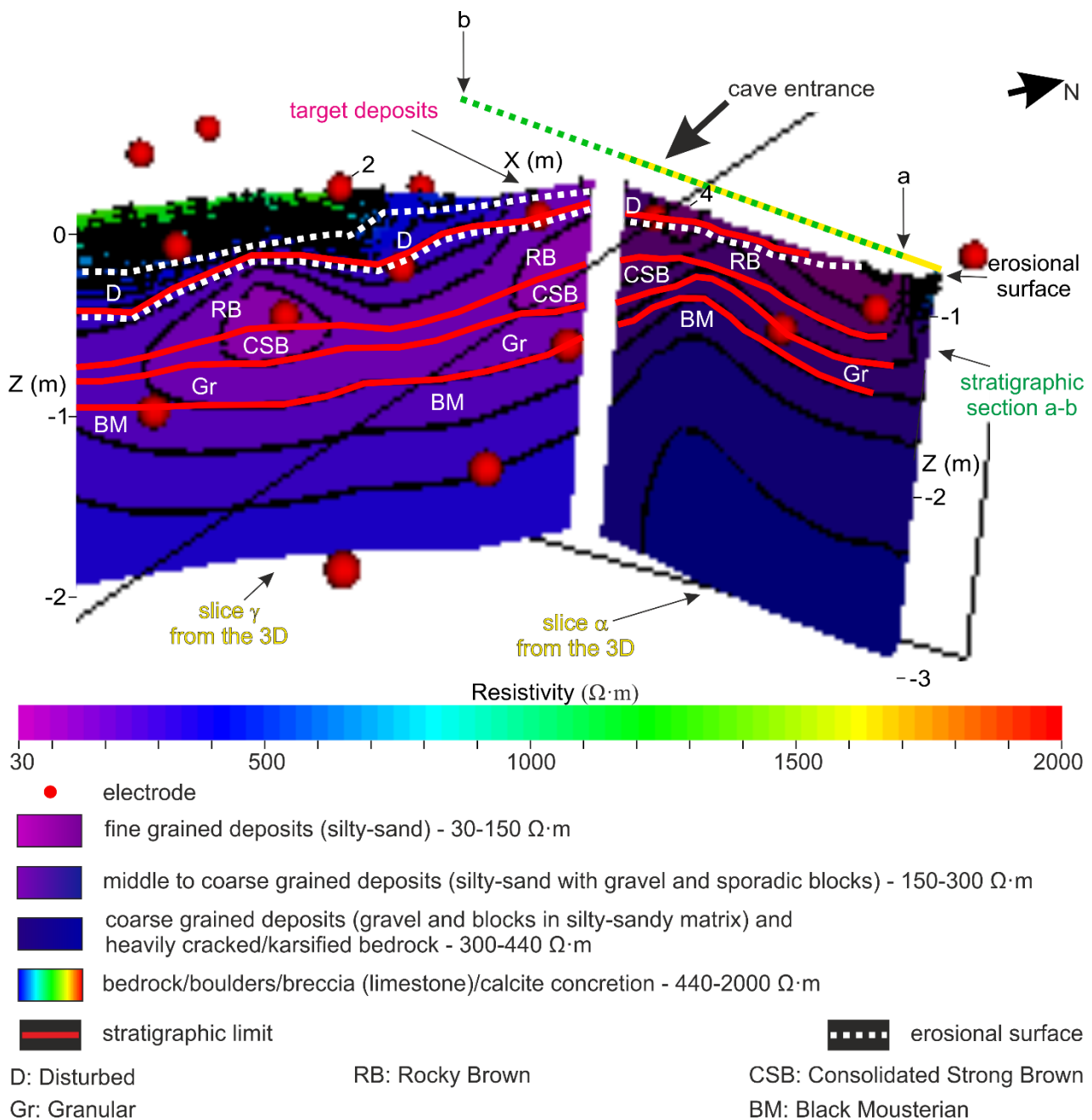


Fig. 11: Portion of the γ plane slice extracted from the 3D inverse resistivity model along with photograph and stratigraphic drawing of a portion of N-S profile: the limits of the stratigraphic aggregates were plotted on slice γ to verify any correlation with the resistivity pattern.



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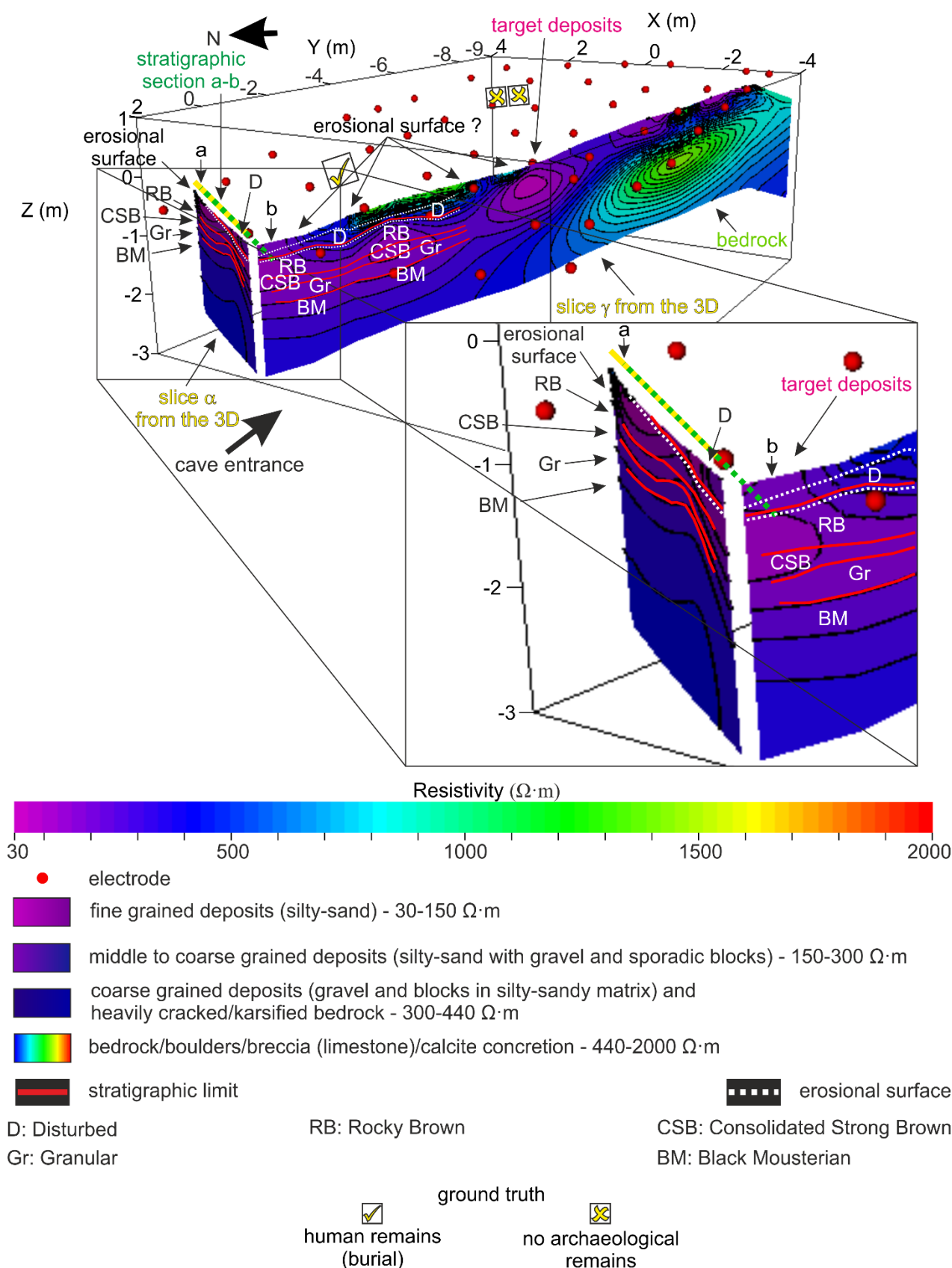
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Fig. 12: Enlargement of the e portion of Fig 10: perspective view of α and (partly) γ plane slices extracted from the 3D inverse resistivity model along with stratigraphic limits derived from the stratigraphic sections a-b (main trench): the limits between the stratigraphic aggregates were plotted on slice α , which lies on the same plane as the stratigraphic sections a-b, to verify any correlation with the resistivity pattern and extrapolate the stratigraphic limits on slice γ .



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1147 **Fig. 13:** Perspective view of α and γ plane slices extracted from the 3D inverse resistivity model

1148 along with the stratigraphic section a-b (main trench): the limits of the stratigraphic aggregates were

1149 plotted on slice α which lies on the same plane as the stratigraphic section a-b, to verify any
1150 correlation with the resistivity pattern and extrapolate the stratigraphic limits on slice γ .

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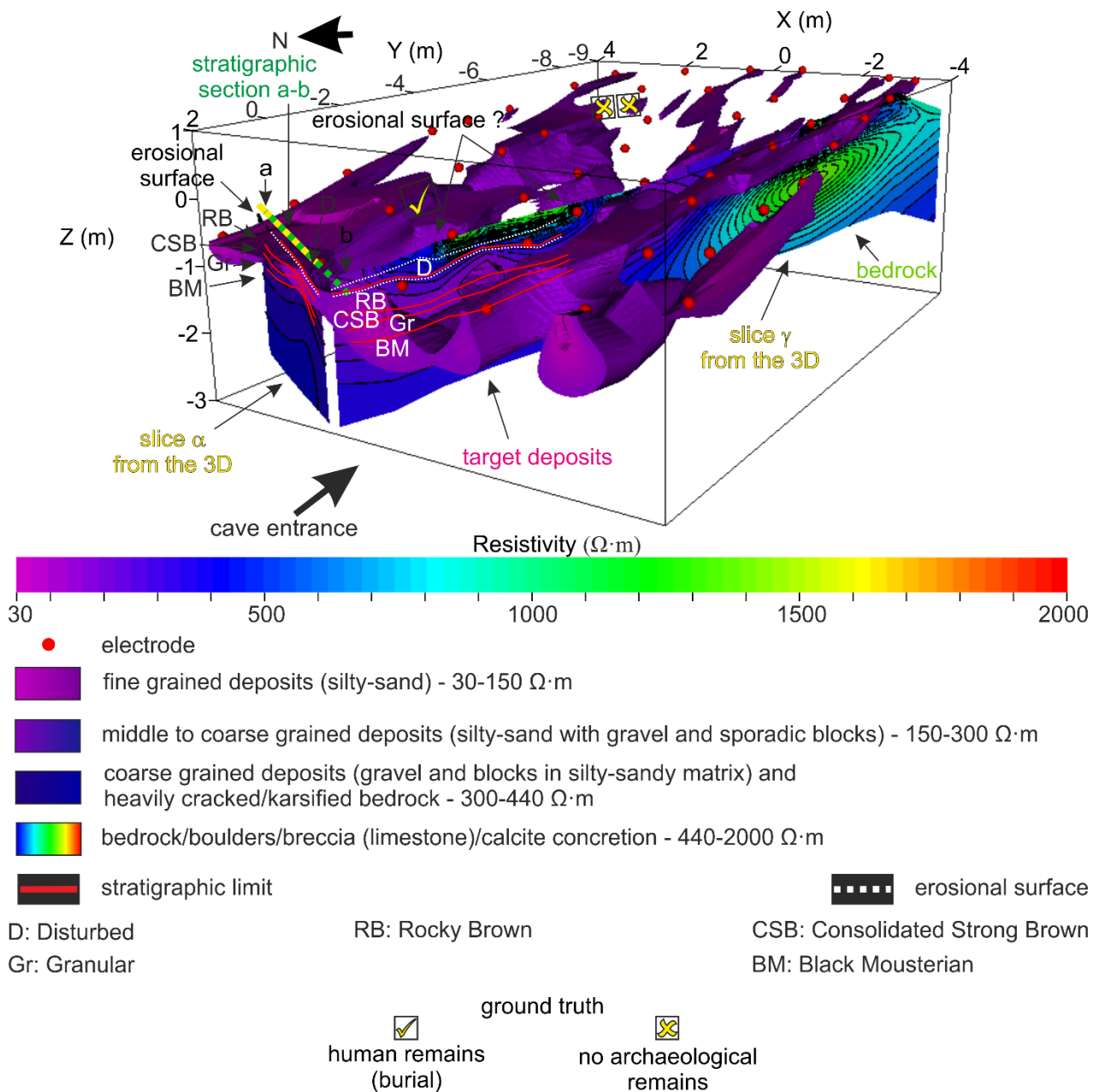
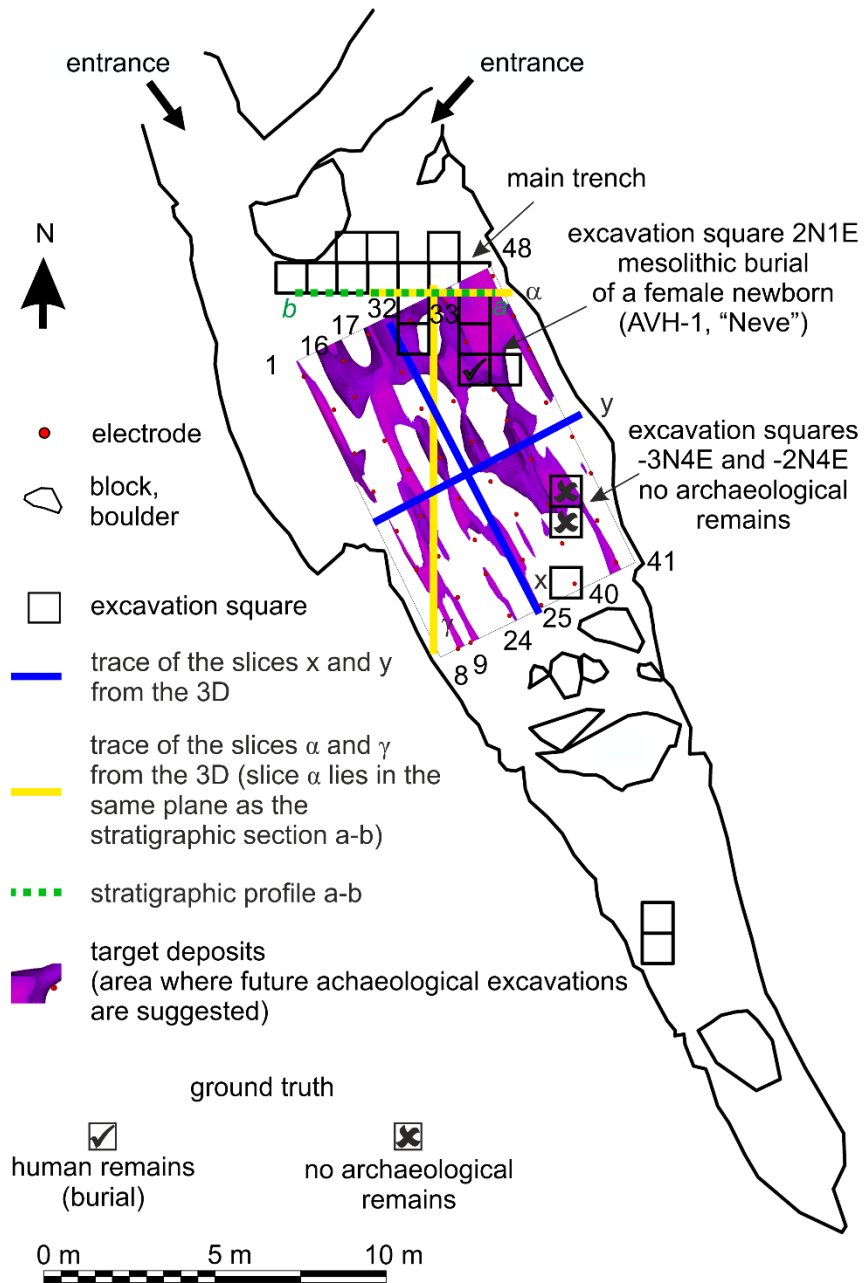


Fig. 14: Perspective view of α and γ plane slices extracted from the 3D inverse resistivity model along with the stratigraphic section a-b (main trench): the limits of the stratigraphic aggregates were plotted on slice α which lies on the same plane as the stratigraphic section a-b, to verify any correlation with the resistivity pattern and extrapolate the stratigraphic limits on slice γ ; the 3D distribution of the low-resistivity unit, the most promising from an archaeological point of view has been also plotted for comparison.



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1171 **Fig. 15:** Plan distribution of the low-resistivity unit (30-150 Ω·m, fine-grained deposits), the most
 1172 promising from an archaeological point of view, along with the experimental layout of the ERT
 1173 survey.

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	Bulk electrical resistivity of the deposit/rock ($\Omega \cdot m$)	Bulk electrical conductivity of the deposit/rock, C_t (S/m)	Tortuosity factor, a	Cementation exponent of the deposit/rock, m	Bulk total porosity, \emptyset
Low-resistivity unit (L)	30 to 150	3.3333e-2 to 6.6667e-3	0.5 to 0.7	1.3	0.44 to 0.16
Middle-low resistivity unit (ML)	150 to 300	6.6667e-3 to 3.3333e-3	0.7 to 1	1.3	0.16 to 0.13
Middle-high resistivity unit (MH)	300 to 440	3.3333e-3 to 2.5e-3	1	1.3	0.13 to 0.1
High resistivity unit (H)	440 to 2.000	2.5e-3 to 5e-4	1	1.3 to 2	0.1

Table 1: Bulk total porosity estimation \emptyset for the different resistivity units derived from the empirical relationship proposed by Archie (1942), along with the quantities involved in the estimation. The estimate involved the following values: electrical conductivity of the fluid $C_w = 0,1$ S/m, fluid saturation $S_w = 0.7$, saturation exponent $n = 2$.

1199 **Supplementary material**

1200

1201 **Text S1:** Excavation, laboratory methods and documentation

1202

1203 Geological data on the StratAggs presented in this paper was collected in the field through
1204 standardized description of exposed profiles and in the laboratory using soil micromorphology. Field
1205 descriptions focused on defining stratigraphic units based on the morphology, extent and nature of
1206 stratigraphic contacts and definition of key lithological characteristics defining the stratigraphic units.
1207 In the field we characterized the grain-size, angularity and fabric of large blocks of roof spall. For
1208 finer grained sediments we emphasized frequency of grain-sizes using field texturing techniques to
1209 identify the proportion of clay, silt and sand. Color was determined using a Munsell soil chart. The
1210 presence of bedding or soil structures were also noted. Field observations were cross-checked using
1211 soil micromorphology, which is the study of intact blocks of sediment under the microscope. The
1212 blocks were wrapped in plaster and extracted directly from the excavated sediment profile, and loose
1213 soil samples. The blocks were hardened with a polyester resin and thin sectioned into 3 x 5 cm slides.
1214 The thin sections were examined using the naked eye and petrographic microscopes under plane-
1215 polarized light (PPL), cross-polarized light (XPL), oblique incident light (OIL), and blue-light fluo-
1216 rescence at magnifications ranging from 20-200x, following descriptive and analytical guidelines es-
1217 tablished by Bullock et al. (1985), Courty et al. (1989), and Stoops (2003). We were able to determine
1218 the composition of sedimentary components and the spatial and stratigraphic relationship between
1219 aggregates using petrographic analyses of thin sections. Grain-size classification followed the Went-
1220 worth scale.

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1222 **References**

1223 Courty, M. A., Goldberg, P., Macphail, R., Soils and micromorphology in archaeology. (Cam
1224 bridge University Press, Cambridge, 1989).

- 1225 Stoops, G., Guidelines for analysis and description of soil and regolith thin sections. (Soil
1226 Science Society of America, Madison, 2003).
- 1227 Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T., 1985. Handbook for Soil
1228 Thin Section Description. Waine Research Publications, Wolverhampton, UK.

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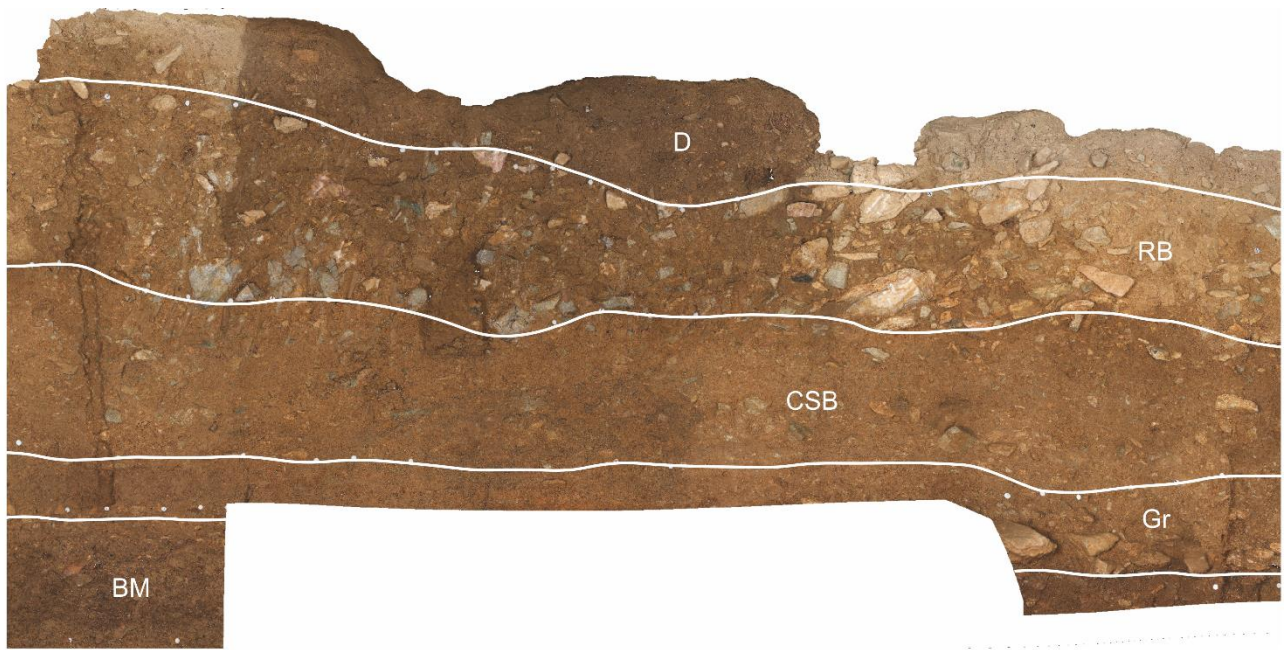
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Combined array	Number of measures	Minimum resistivity (ohm·m)	Maximum resistivity (ohm·m)	Average resistivity (ohm·m)	Standard deviation (ohm·m)
DD+W+WS)	432	46	1265	289	0

Table S1: Quality of resistivity raw data

Iteration	Number of measures	Chi-squared error	RMR error (ohm·m)
1	432	62481	36.1
2	432	5133	10.3
3	432	330	2.6

Table S2: Misfit of inverted resistivity data



Clayey silt with minor sand and gravel components with a dark greyish brown color.



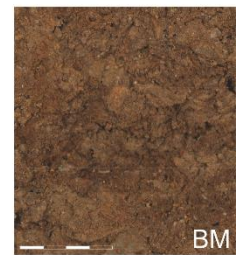
Clayey silt with fine sand and gravel with a dark yellowish brown color. It displays a weakly developed subangular blocks structure.



Clayey silt with fine sand and gravel with a dark yellowish brown color. It appears more compact and displays a massive structure.



Medium sandy silt with granules and gravel with a brown to dark yellowish brown color. It exhibits a coarse crumb structure.



Silty-sand with medium to small altered gravel with a dark greyish brown color.

Fig. S1: Photographs from main trench (stratigraphic section a-b, E-W profile, Fig. 2), lithological description of the aggregates and associated images.