

A Syracusan hypothesis on the origin of the Riace Bronzes: new investigations and a historical-scientific revision of literature data through an interdisciplinary geological-archaeological approach



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ABSTRACT

The Riace Bronzes are a pair of 5th century BC Greek statues, discovered in 1972 in the offshore of Riace Marina, south-eastern Calabria (Italy). A study conducted in 1995 by the Italian Central Institute for Restoration (ICR) highlighted a significant difference in the geochemical composition between the clays used for casting individual sections of the statues and those used for the terracotta pins with which they were welded. Considering that the clays used for assembling the statues are highly indicative of their installation site, and that numerous historical, literary, archaeological, and archaeometric clues suggest an original placement in the ancient Greek town of Siracusa (Eastern Sicily) for the two statues, in this work a comparison was made between the geochemical composition of the welding material and clays from the ancient production area of the town. According to geo-archaeological data, this area was probably located in the alluvial plain between the mouth of the Anapo and Ciane rivers and the hill on which the Temple of Zeus Olimpio stands. The results show a surprising and significant correspondence between these clays and those used for the welding of Statue A and, in part, also for the restoration of Statue B. Furthermore, a review of literature data reveals a good correspondence between the mineralogical composition of the internal casting material of both statues and sediments present in the Sibari area (northern Calabria), the same used for the manufacture of the Auriga of Delphi. Finally, the analysis of the taphonomic characteristics of the bronzes and the geochemical analysis of the layered surface patinas, in relation to the hydrodynamic and geomorphological data of the Riace seabed, reveals a millennial primary deposition in different and much deeper seabeds. Aim of this study is to integrate the new data with a critical review of the most robust scientific evidence currently available in literature through an interdisciplinary geological-archaeological approach, to yield a unified, coherent, and comprehensive reading of the history of the two famous statues within a single interpretive proposal.

KEYWORDS: archaeometry, welding materials, Hyblean sediments, The Riace Bronzes.

INTRODUCTION

This work aims to provide a comprehensive overview of the documentation collected over the years on the Riace Bronzes, through an interdisciplinary geological-archaeological approach to increase knowledge about these two famous statues and help to shed light to aspects that require further analytical investigation.

The Riace Bronzes (Fig. 1) are a pair of Greek bronze statues, 197 and 198 centimeters tall, depicting nude, bearded warriors who were originally equipped with shields, spears, and helmets. They were made in the second quarter of the 5th century BC and were discovered by chance in 1972 in the offshore of Riace Marina (south-eastern Calabria, Italy). The statues are currently preserved in the National Archaeological Museum of Reggio Calabria (Museo Nazionale della Magna Grecia di Reggio Calabria).

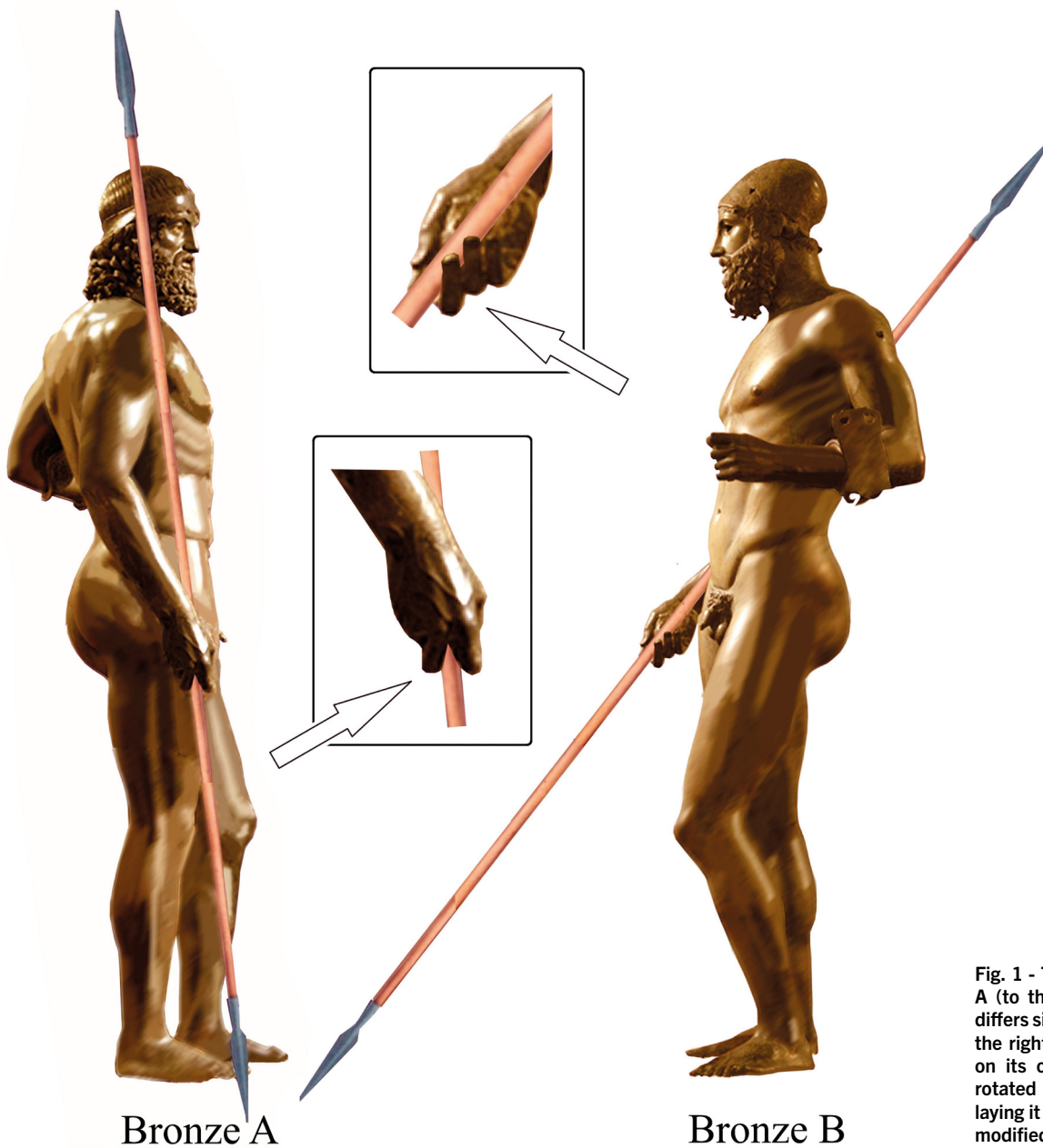


Fig. 1 - The Riace Bronzes. In Bronze A (to the left), the spear's position differs significantly from Bronze B (to the right). Bronze B holds the spear on its outstretched palm, which is rotated upwards, as if in the act of laying it down (from Madeddu, 2025, modified).

The Riace Bronzes have been the subject of extensive debate regarding their identity, origin, creators, and original context. While many questions remain open, various theories supported by different clues have emerged. It's generally believed that they were part of a more complex monument, probably depicting warrior heroes. Regarding the circumstances of their discovery, the most credited hypothesis is that they were transported on a ship coming from a Greek city, likely headed for Rome, when the vessel sank; however, no concrete evidence of a shipwreck has ever been found in Riace Marina. The statues underwent extensive restoration to remove concretions and ensure the preservation of the metal. These interventions revealed extraordinary details about their construction and provided numerous samples of the material used for both casting and welding the various parts (Formigli, 1984; Lombardi et al., 2003).

Regarding their provenance, various hypotheses have been formulated, even by renowned archaeologists such as Di Vita (1984); Paribeni (1984); Rolley (1984); Ridgway (1986); Stucchi (1986);

Moreno (1998); Castrizio (2000); Roma (2007), and Brinkmann (2016). These have fueled a heated debate that's still ongoing today. Equally robust is the controversial debate surrounding the identification of the subjects depicted by the two statues, for which the most disparate hypotheses have been put forward: 1) Athenian votive offering at Delphi by *Phidias* (Fuchs, 1983); 2) Athenian eponymous heroes by *Myron and Alkamenes* (Dontàs, 1984); 3) Achaean votive offering at Olympia by *Onatas* (Harrison, 1985); 4) *oikists* (founders) of Greek cities in Sicily (Holloway, 1988); 5) *Gelone and Ierone* of Siracusa (McCann, 2002); 6) warriors from an epic poem of the 1st century BC/AD (Ridgway, 1986); 7) Attic eponymous heroes by Athenian sculptors (Rolley, 1984); 8) *Aiace Oileo* and a *strategos* (general), heroes of Locri (Paribeni, 1984); 9) the *Dioscuri* replaced by *Saints Cosmas and Damian* (Roma), two *hoplitodromoi* (armored runners) by Attic artists (Di Vita, 1984); 10) the boxer *Euthymus of Locri* in two phases of his life, by *Pythagoras* (Stucchi, 1986); 11) *Tydeus and Amphiarus* from Argos by Ageladas and Akcamenes (Moreno, 1998); 12) *Eteocles*

and Polynices from Argos by *Pythagoras* (Castrizio, 2002); 13) *Eumolpus* and *Erechtheus* from Athens by *Myron* (Brinkmann, 2016). However, to this day, a definitive interpretation has yet to be reached.

In order to acquire further elements regarding their possible provenance, in this work we compared the chemical composition of the welding material, found inside the statues during restorations and whose data are available in literature (Lombardi et al., 2003), with that of the sediments present in the production area of the ancient Greek colony of Siracusa (one of the most powerful cities in the Mediterranean, second only to Athens in the 5th century BC). The choice of Siracusa was suggested by numerous historical, archaeological, and literary clues that will be illustrated afterwards. Samples of these sediments were taken from a core drilling performed in the alluvial plain south of Siracusa, in the locality of Pantanelli, near the mouth of the Anapo and Ciane rivers. The research was also extended to a review of literature data concerning the hypotheses on the provenance of the casting material of the two bronzes, which can be traced back, as we will see, to the plain of Sybaris in northeastern Calabria. Finally, a plausibility study was conducted on the entire Syracusan hypothesis for the provenance of the the Riace Bronzes, including that relating to the original underwater location of the statues. This latter study focused on the geochemical processes that affected the surface of the bronzes and their patinas, in order to reconstruct the dynamics of the interaction between the two statues and their depositional environment. The analysis was completed with a study of the marine biota that settled on the surface of the Bronzes, which provides insights into the habitat and bathymetry of the discovery context.

HISTORICAL-LITERARY AND ARCHAEOLOGICAL FRAMEWORK: THE SYRACUSAN HYPOTHESIS

The first archeologist to hypothesize a probable Sicilian origin of the Riace Bronzes was Robert Ross Holloway, who in 1988 wrote that he had collected rumors according to which the famous statues were originally found in the Ionian offshore of southeastern Sicily and then hidden by archaeo-traffickers in the Calabrian offshore, so that “*la scoperta degli Eroi a Riace non fu la scoperta di un carico antico ma del nascondiglio di un’operazione clandestina*” (the discovery of the Heroes in Riace was not the discovery of an ancient cargo but the hiding place of a clandestine operation; Holloway, 1988). The archaeologist, while hypothesizing their possible provenance from a Sicilian city founded by a couple of *oikists*, did not exclude their Syracusan origin, writing: “*Se l’esportazione degli Eroi di Riace fosse dovuta ai Romani, una sola città sarebbe stata capace di fornire loro statuaria del quinto secolo: Siracusa, che rimase indenne fino alla presa di Marcello nel 212 a.C.*” (If the export of the Heroes of Riace was due to the Romans, only one city would have been able to provide them with 5th century statuary: Siracusa, which remained unharmed until the capture of Marcellus in 212 BC; Holloway, 1988). Later, Anne Marguerite McCann also hypothesised their Syracusan origin, attributing the statues to *Pythagoras of Reggio* and proposing to identify them as the *Deinomenids* (tyrants of Siracusa), *Gelone* and *Ierone* (McCann, 2002).

Historical, literary, and archaeological findings

The hypotheses of Holloway (1988) and McCann (2002) have been taken up more recently by a revision of literary sources (Madeddu, 2025) that allowed to identify in Bronze B (Fig. 1) the statue of a naked *Gelone* laying down his spear, as described by Claudius Aelianus (“*autou eikòn gymnòn autòn*”, VI, 11), and in Bronze A one of the statues of heroes that must have flanked it in the original sculptural group. According to this hypothesis, the genesis of the sculptural group would be linked to the famous episode in the life of *Gelone*, also handed down by Polyaeus and Diodorus Siculus, according to whom the *stratègòs* after the Syracusan victory of Himera over the Carthaginians (480 BC) presented himself in assembly, stripped himself of his clothes (“*exèdu tèn esthèta*”, Polybius, Stratagemmi, I, 27), laid down his weapons (“*tòn òplon gymnòs*”, Diodorus, Bibl. Stor., XI, 26) and placed his mandate and his life in the hands of the people, who, precisely for that gesture, acclaimed him king and upon his death venerated him as the refounder of the city and paid him heroic honours (“*o mèn dèmos eroikais timais etimese tòn Gèlona*”, Diodorus, Bibl. Stor., XI, 38, 5), erecting the famous statue described by Aelian. Diodorus also wrote that in 396 BC the Carthaginian Himilco damaged all the monuments associated with *Gelone*, among which the statue of *Gelone* was most likely also included (Bibl. Hist., XIV, 63). It is remarkable to note how the presence of a different alloy in the arms of the Riace Bronze B attests to the traces of vandalism against the statue itself, which, in this hypothesis, would represent *Gelone*. According to Plutarch (Life of Timoleon, 23, 7-8) and Favorinus of Arles (Corinthian Oration, 21), when the Corinthian general Timoleonte freed Sicily from tyranny and ordered the melting down of all the statues of the tyrants to obtain bronze useful for minting coins, the Syracusans saved only that of *Gelone* and those surrounding it. From this detail, it can be deduced that, in the sculptural group, the statue of *Gelone* must have been flanked by at least two other statues. On the same occasion, the Corinthian general had a commemorative coin minted with the head of a bearded king-leader (Fig. 2; now on display in the Paolo Orsi Museum, Siracusa), probably identifiable with the statue of *Gelone*, the only bronze of a king-leader (the new *oikist*) saved by the people at the time. It is a head extraordinarily similar to that of the Bronze B of Riace, with the helmet and the *korinthie kynè* that originally must have surrounded his head, as can be seen from the traces present today on the nape of his neck (Fig. 2).

The description of the statue of *Gelone* handed down by historians seems to find many confirmations in the appearance of Bronze B, which appears naked, with the palm of the right hand extended forward in the gesture of laying down the spear (Fig. 1) and with the left wrist rotated externally in the act of moving the shield away from the chest; this latter probably appeared inclined outwards and fixed with a support to the hook still visible today on the left deltoid of the statue (Fig. 3). The effects of the outward tilt of the upper part of the shield are also evident in the deformation of the lower part of the brace, as observed by Rebaudo (2024).

The sculptural group must have remained in Siracusa until the Roman sacking by Consul Marcellus in 212 BC. Tito Livio (Storie, XXV, 40) recounts that on that occasion all the most beautiful



Fig. 2 - Syracusan coin, dating to around 340 BC, features the bearded head of a warlord king's statue from the 5th century BC. This figure is highly likely Gelone, the tyrant of Siracusa, and bears a striking resemblance to the head of Warrior B from Riace, complete with a helmet and the *korinthie kynè* (from [Madeddu, 2025](#)).

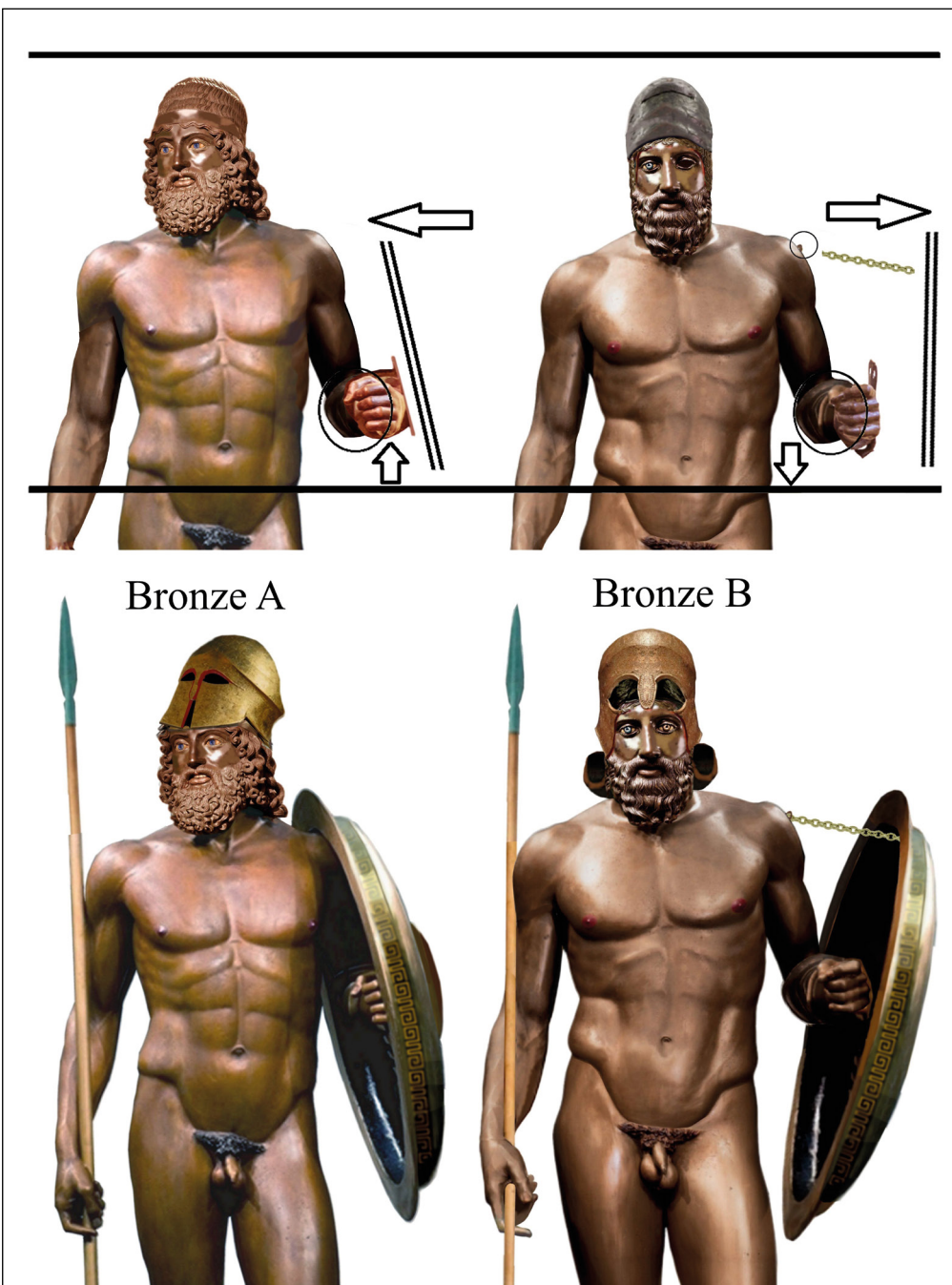


Fig. 3 - The shield's position is another key difference between the two Bronzes. Bronze B (to the right) holds the shield tilted outwards, supported by a hook on its shoulder, as if in the act of laying it down (from [Madeddu, 2025](#), modified).

bronze statues of the city were brought to Rome and displayed at Porta Capena, although some other subsequent historical episode cannot be excluded. In fact, it probably never reached Rome, as no source has ever recorded the presence of this sculptural group in the capital; furthermore, despite reproduction of Greek works being a common practice in Roman times, there are no marble copies of the Riace Bronzes. Along the Ionian coast of the island, a storm likely caused the statues to sink along with the ship that was transporting them to Rome (see Holloway, 1988).

Archeometric evidence

Alongside the historical-literary and archaeological clues that could hypothetically correlate the Riace Bronzes with the famous sculptural group described in ancient Siracusa, numerous archeometric evidence also seems to link the two statues to the hypothesis of a commission by the *Deinomenids*.

The radioisotopic analysis of the alloys reveals that the copper used for Bronze B did not come from the usual mines of Eastern Greece, but unusually from Tyrrhenian mines (Angelini et al., 2018), which, after the victories of Himera (480 BC) and Cumae (474 BC) over the Carthaginians and Etruscans, had come under the total control of the *Deinomenids*. Radiocarbon dating reveals that the statues were made in the 5th century BC and contemporaneously (Calcagnile et al., 2010; Calcagnile, 2014), excluding any hypothesis of a difference in age between the two statues, both attributable to the pre-chiasmatic phase of Polyclethus (Corso, 2020). Furthermore, the radioisotopic analysis of the metals reveals that the tenons (the anchoring pins) of the two statues

were made with the same batch of lead (Angelini et al., 2018), suggesting that the statues were placed together in the same monumental group at the same time (Fig. 4A). This lead came from the mines of Laurion, located in southern Attica between Thorikos and Cape Sounion (Greece), used in the 4th century BC, scarcely used from the 3rd century BC and abandoned in the 1st century BC (Aitchison, 1960). This suggests that the statues were moved for the last time from their original location in the 4th century BC and then they have never been relocated in Rome. Furthermore, according to Formigli (1984) the arms of Bronze B were refashioned with an alloy containing the same lead as the tenons, and with a percentage (around 11%) that began to be used precisely from the 4th century BC, especially for restorations and smaller objects (Fig 4A). This means that the restoration of the arms took place in the 4th century BC and contemporaneously with their transfer. The Bronzes were cast in separate sections and then welded, since the internal clays of the sections are completely different from those of the welds (Lombardi et al., 2003) (Fig. 4B). The clays from the restoration of Bronze B are very similar to those from the welding of Bronze A (Calcagnile, 2014; Jones et al., 2016), suggesting that the restoration took place in the same location where statue A had been placed the century before. Finally, the geochemical difference in the casting clays of A and B suggests that these were taken from distinct quarries (of the same or two different regions), while the slight differences in the construction techniques of the two statues suggest two distinct artists, without a priori excluding the hypothesis, albeit less probable, of two evolutionary phases of the same artist (Rebaudo, 2020).

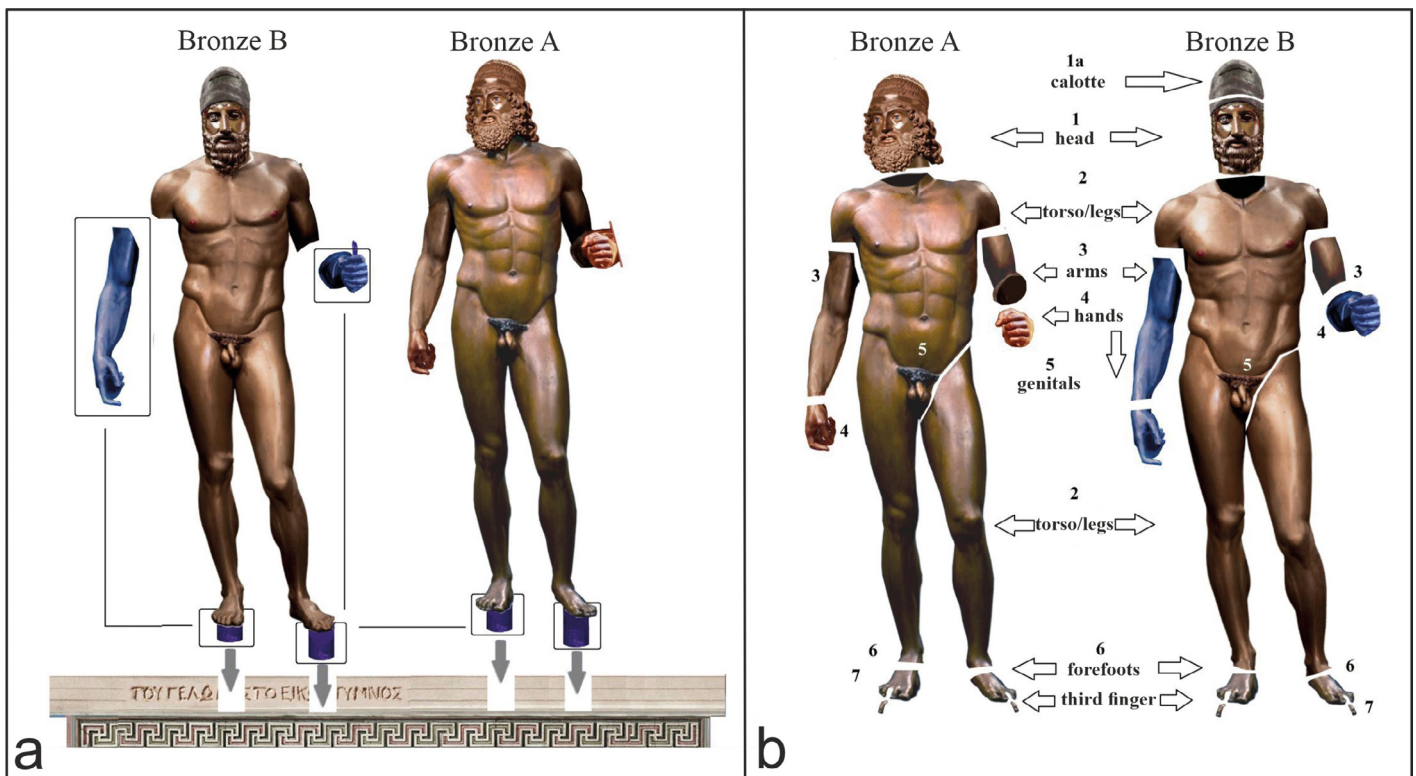


Fig. 4 - A) Radioisotope analysis reveals that the alloy in Bronze B’s arms (which were restored in antiquity) contains the same lead used for the tenons. This proves that during the restoration, both statues were reinstalled in the same monument and at the same time. B) Scheme of the 14 separate anatomical sections that make up the Riace Bronzes (from Madeddu, 2025, modified).

As regards the age of the sinking of the ship carrying the statues, the analyses conducted by Panella (1984) and Stucchi (1986) seem to date to the 3rd century BC, excluding the late Hellenistic age. This is an extremely interesting result, because the famous sack of Siracusa, carried out by the Romans in 212 BC, occurred in the same period. If this were the case, the shipwreck would have occurred during the voyage to Roma of the ship with the statues stolen from Siracusa, along the Ionian coast of Sicily, a route consistent with what Holloway (1988) stated about the original discovery of the statues in the Sicilian Sea (see below). The origin of the sculptural group from the Siracusa of the *Deinomenids*, the greatest patrons of bronze statuary of their time, and the possible shipwreck after the Roman sack of the town, have been considered very plausible hypotheses by Malnati (2025), given that in the 5th century BC Siracusa represented the largest and most powerful Greek city in the west Mediterranean, capable of even defeating Athens itself.

LINES OF INVESTIGATION

Of all the scientific evidence presented above, the most important for the purpose of the present study is that relating to the different nature of the casting and welding materials of the two statues. To date, the prevailing orientation has been to attribute the provenance of these materials to the Peloponnese and Argive. This attribution was made by comparing the clays from the statues with similar lithotypes that crop out in those areas. This comparison relied only on the observation of large-scale geological maps of Greece, not on samples actually collected from the hypothesised location (Madeddu, 2025 and reference therein). However, according to Formigli (1984), the Riace Bronzes were created by casting 14 separate anatomical sections, with an additional calotte for Bronze B only (Fig. 4B). These sections were then welded together. During the restoration carried out by the Italian Central Institute for Restoration (ICR) in the 1990s, a marked difference was observed between the geochemical composition of the materials used to cast the individual sections and those used to create the terracotta pins onto which these sections were welded. This difference is so stark that it can only be explained by assuming that the anatomical parts of these statues were made in one place and then welded in another. This was a solution that even the ICR scholars at the time accepted: *“Un'altra possibilità è che la colata delle singole parti e la loro saldatura avvenisse in tempi e luoghi diversi: cosa che avrebbe un senso ammettendo che le varie parti fossero state realizzate in un laboratorio remoto dal luogo di destinazione dell'opera, trasportate in loco, e quindi assemblate tramite saldatura al momento della messa in opera della statua”* (“Another possibility is that the casting of the individual parts and their soldering occurred at different times and in different places: this would make sense if we assume that the various parts were made in a workshop remote from the work's destination, transported on-site, and then assembled by soldering at the time the statue was put in place”; Lombardi et al., 2003, p. 170). This practice is now well-known. For instance, a recent study by the French School at Athens on the casting material of the Charioteer (Auriga) of Delphi proved that this statue was made in Sybaris (Psalti et al., 2018), but was then placed in Delphi,

commissioned by the *Deinomenids* of Siracusa. This followed a pattern that in that case was: commission/Sicily, production/Sibari, placement/Greece. Therefore, the casting material inside the individual anatomical parts would be indicative of the place of production, while those from the solders would reveal the place of placement.

Starting from these premises, our investigation tried to verify:

- 1) the possible correspondence between the geochemical composition of the welding material of the famous statues and the sediments of the Siracusa area, in order to confirm the hypothesis of their original placement in the ancient Sicilian city;
- 2) alternative hypotheses about their provenance, attributed in the literature to the Peloponnese area (see above), through the analysis of the internal casting material;
- 3) the overall plausibility of the Syracusan hypothesis regarding the origin of the statues, in relation to the scientific consistency of the theory of an original shipwreck not in Riace but in Sicilian offshore (as argued by the archaeologist Robert Ross Holloway), through the study of the geomorphological evidence of the seabed, and in particular the taphonomic characteristics of the Bronzes and the microstratigraphic features of their surface patinas.

HYPOTHESIS ON THE PROVENANCE OF WELDING CLAYS: MINERO-PETROGRAPHIC AND GEOCHEMICAL ANALYSES OF SEDIMENTS FROM THE PANTANELLI AREA (SIRACUSA)

The first of the three objectives of this work is to study the possible correspondence between the geochemical composition of the material used to weld the Riace Bronzes and that of the sediments outcropping in the area where they were welded. The historical, literary, and archaeological evidence discussed above led us to narrow the research area to sediments originating from the ancient clay quarries located between the mouth of the Anapo and Ciane rivers and the Temple of Zeus Olympio (Pantanelli area, Fig. 5), a site within the productive area of Greek Siracusa.

Geological setting of the Siracusa area

Siracusa is located on the southeastern coast of Sicily at the border of the Hyblean Plateau (Fig. 5). The ancient Greek colony of Siracusa was built on a bedrock constituted by a Miocene limestone succession (Servizio Geologico d'Italia, 2025). This is evident in the landscape, including the coastal cliffs, the island of Ortygia, and the presence of ancient quarries (latomie) where this stone was extensively extracted for building the ancient city. The area displays a geomorphological architecture shaped by the interplay of tectonic uplift, eustatic fluctuations, and karst processes. Along this sector, several raised abrasion platforms and associated marine terraces carved into Miocene to Pleistocene carbonate bedrock testify to relative sea-level stability during Quaternary highstands (Meschis et al., 2020). The resulting flight of Pleistocene marine terraces, bordered by visible steps, hosts the distinct ancient quarters of the old Greek town (Bianca et al., 1999).



Fig. 5 - Schematic geological map of the Siracusa area and the Florida Graben (from Servizio Geologico d'Italia, 2025, modified). The quarters of the ancient Greek town are indicated.

South of Siracusa (Fig. 5), the structural depression of the Florida Graben (Ghisetti & Vezzani, 1980) is bounded by NW-SE trending normal faults and filled by a transgressive-regressive Quaternary sequence unconformably covering Miocene reef limestones (Grasso et al., 1979; Lentini, 1984). The filling sequence is mostly constituted by Lower Pleistocene clays and marly clays (Lentini synthem), unconformably covered by Middle-Upper Pleistocene calcarenites (Augusta synthem), also known as 'Panchina'. Holocene deposits of the Anapo river and coastal marshy sediments form the current alluvial plain. Submerged geomorphic elements, such as palaeo-cliffs, caves, and fossiliferous karst cavities, have been documented along the offshore between Santa Panagia and the Maddalena Peninsula (Fig. 5) and are interpreted as relict coastal landforms now submerged due to Holocene sea-level rise (Scicchitano & Monaco, 2006). Notably, at least two submerged palaeo-shorelines occur between depths of -10 to -22 m and -25 to -45 m, respectively, supporting the existence of former Pleistocene sea-level still-stands, likely during MIS 3 and MIS 5. Borehole stratigraphy and ¹⁴C AMS dating of lagoonal and beach deposits in the Siracusa coastal plain (Spampinato et al., 2011) confirm the occurrence of sea-level rise in the Holocene, as evidenced by transgressive sequences that directly overlie Lower Pleistocene marly clays. In this context, the Pantanelli area is

located within the Florida Graben (Fig. 6) and includes a coastal marshy environment (the Saline) that is periodically flooded by the sea, from which it is separated thanks to the presence of a sandy coastal barrier. It is characterised by inherited coastal morphologies, low topography and high preservation potential of fine-grained deposits, providing a favorable environment for geoarchaeological investigations and palaeoenvironmental reconstructions.

Sampling area and the stratigraphic context

By integrating archaeological data on ceramic and metal production areas with the geological and sedimentological survey (see Spampinato et al., 2011; Servizio Geologico d'Italia, 2025), we identified the alluvial plain south of Siracusa (the Florida Graben) as the supply area for both ceramic clays and foundry welding clays. Specifically, this area is at the foot of the clayey hill supporting the Temple of Zeus Olympio (Fig. 6).

To obtain samples not contaminated by human activities, core sampling from a drilling carried out for research purposes on behalf of the University of Catania in July 2005 was used. The drilling was located at an altitude of +0.50 m above sea level between the mouth of the Anapo and Ciane rivers and the Saline and reaches a depth of -16.00 m. Details regarding sampling depth, lithology, and mineral

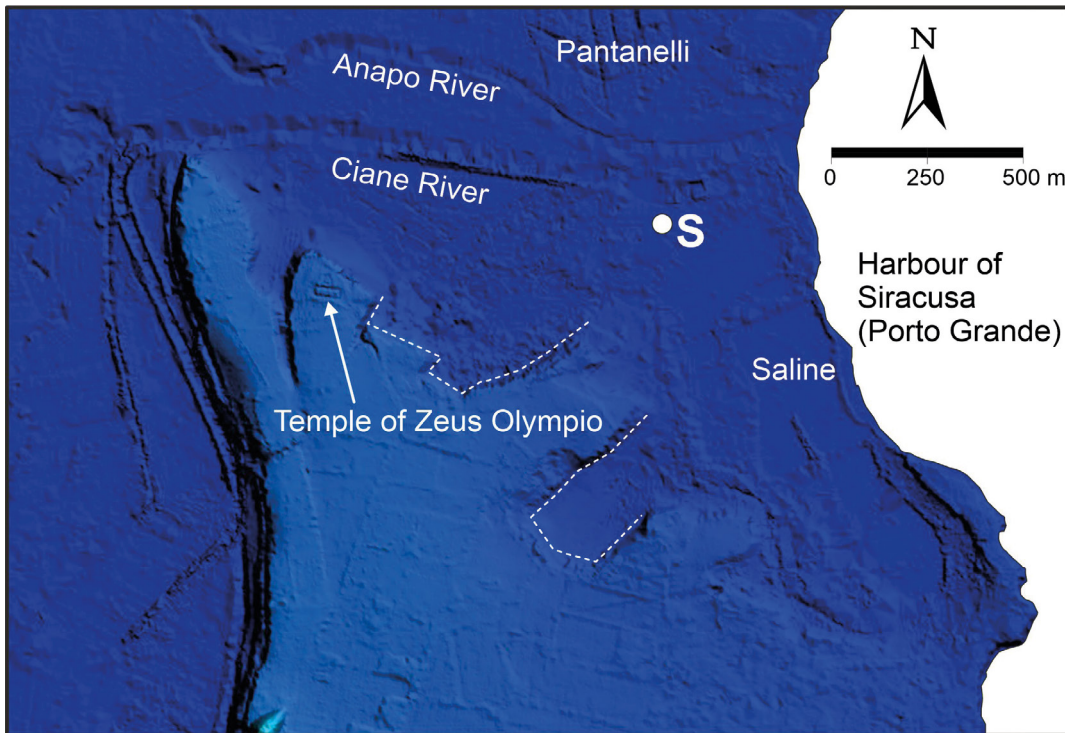


Fig. 6 - DTM map (from <https://www.sitr.regione.sicilia.it/geoportale/mobile/search.html?q=dtm>) of the studied area (location in Fig. 5). Point S indicates the location of the analyzed borehole. Dotted lines indicate the fronts of possible ancient Greek clay quarries.

content are provided in Tab. 1. From the stratigraphic analysis of the drilled core (Fig. 7), it emerged that up to a depth of 1.10 m the succession consists of dark muds with gravels that have been interpreted as soil. Below the soil, between -1.10 and -5.60 m, brown muddy sands and dark grayish sandy muds with brackish water shells were observed. The palaeoecological analysis (Spampinato et al., 2011) suggests that these sediments are representative of the lagoon environment. The ^{14}C Accelerator Mass Spectrometry dating of a fossil bivalve *Cerastoderma glaucum* sampled at -1.40 m a.s.l. and a gastropod *Cerithium vulgatum* sampled at -3.30 m a.s.l. revealed ages of 4089 ± 123 and 4321.5 ± 110.5 cal years BP, respectively (samples D and E in Fig.7). The lagoonal sediments rest on Holocene beach deposits, consisting of medium yellowish sands and gravels,

rich in shell fragments. The substrate, consisting of blue-grayish clays from the Lower Pleistocene and yellowish clays from the Middle Pleistocene (Spampinato et al., 2011), was reached at a depth of -7.30 m. The Pleistocene clays are the same ones that outcrop on the slopes of the hill on which the Temple of Zeus Olympio stands.

Sample selection and preparation

Samples from the first layer consist of sandy silts, characterised by an uneven, predominantly grey colour with localised pinkish areas. Within the matrix are millimetric to centimetric intercalations of carbonate clasts and bioclasts, including whole and fragmented shells of brackish water ostracods, bivalves (e.g., *Cerastoderma*

Table 1 - Main features of the samples drilled in 2005. For each sample, approximate depth, lithological features and mineral phases are reported.

Representative sample	Aprox. Depth (m)	Lithology	Mineral content (XRPD)
CIANE 1	1.6	Sandy silt with brackish-water ostracods, bivalves (<i>Cerastoderma glaucum</i>) and gastropods	Carbonates (i.e., aragonite, calcite,) > Sulfates (i.e., bloedite) > Quartz > Clays (i.e., vermiculite, illite) > Plagioclase (i.e., anorthite) > Phosphates (i.e., apatite) > Micas (i.e., muscovite) > Oxides (i.e., magnetite)
CIANE 2	4.4	Dark sandy silts with brackish-water molluscs	Quartz > Plagioclase (i.e., albite) > Micas (i.e., muscovite, biotite) > Clays (i.e., kaolinite, clinochlore) > Carbonates (i.e., aragonite, calcite) > Sulfates (i.e., bloedite, sodium magnesium iron sulfate) > Pyroxenes (i.e., enstatite, diopside) > Oxides (i.e. titanium oxide)
CIANE 3	7.1	Marine sands and fine gravels with sandy silts and basal calcarenitic pebbles (possible paleosoil)	Carbonates (i.e., calcite) > Quartz > Clays (i.e., clinochlore, chamosite) > Sulphates (i.e., bloedite) > Oxides (i.e., spinel, iron oxide) > Plagioclase (i.e., anorthite) > Pyroxenes (i.e., enstatite) > Micas (i.e., muscovite, biotite) > Phosphates (i.e., apatite)
CIANE 5	8.0	Yellowish marl clays (Middle Pleistocene)	Carbonates (i.e. calcite) > quartz > clays (i.e. clinochlore, chamosite) > sulphates (i.e. bloedite) > oxides (i.e. spinel, iron oxide) > plagioclase (i.e. anorthite) > pyroxenes (i.e. enstatite) > micas (i.e. muscovite, biotite) > phosphate (i.e. apatite)
CIANE 4	11.3	Grey-bluish marl clays (Early Pleistocene)	Clays (i.e., clinochlore) > Micas (i.e., muscovite) > Carbonates (i.e., calcite) > Quartz

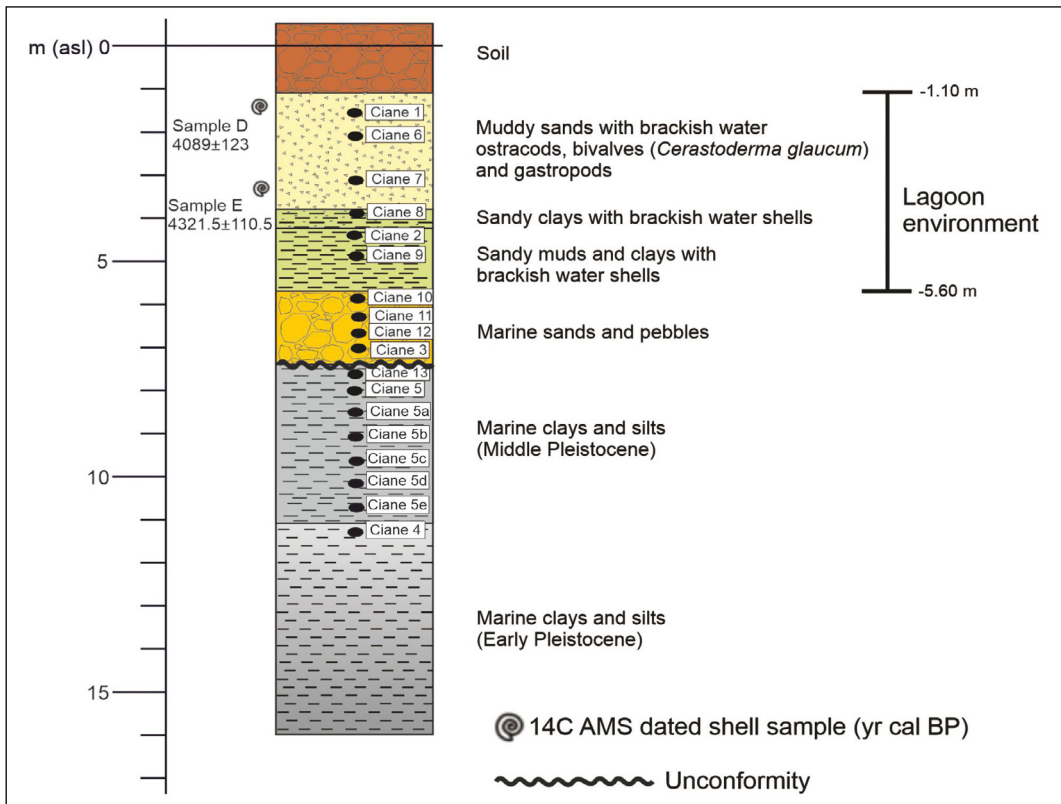


Fig. 7 - Log of the drilled borehole (see Fig. 6 for the location of the well), with the description of the lithofacies and position of the analyzed samples (from Spampinato et al., 2011, modified). Age determinations by Poznan Radiocarbon Laboratory (Poz) and R.J. Van de Graaff Laboratorium of the Utrecht University (Utc), calibrated using the program CALIB 5.0.1 (2-sigma, marine entry; see Spampinato et al., 2011).

glaucum), and gastropods (Fig. 8a). The second layer consist of dark grey siltstones with scattered, millimetric shells of brackish-water mollusc (Fig. 8b). The third layer is characterised by beige to yellowish-brown sandy siltstones containing 1-2 cm caliche nodules (pedogenic carbonate concretions). This layer is interpreted as palaeosol (Fig. 8c). The underlying layer is composed mainly of yellowish mudstones with subtle bluish-grey hues. It contains sparse, millimetric to sub-centimetric calcarenite lithic fragments (Fig. 8d). At higher depth the layer passes to an over-consolidated marl clay with a massive fabric and uneven colour, ranging from bluish-grey to yellowish-brown (Fig. 8e). Among these, five samples representative of each lithology were selected, labelled CIANE 1,2,3,4 and 5 (see Fig.7).

Analytical methodologies and protocols

To carry out mineralogical and chemical analyses on a selection of samples collected from cores drilled in the Pantanelli area, south of Siracusa (Tab. 1), the collected sediments were initially homogenised using an automatic sample splitter to obtain a representative and homogeneous aliquot for subsequent mineralogical and chemical analyses. From each representative aliquot, the grain-size fraction >63 µm was separated by wet sieving. The resulting grain-size fractions were then dried at 40 °C. Further sub-samples were ground to a particle size below 2 µm using a Laarmann LMMG 100 electronic mortar equipped with an agate grinding jar and pestle (Laarmann Group BV, Roermond, Netherlands). The powders obtained were then oven-dried at 105 °C to remove any residual moisture. Samples CIANE 1, 2, 3, 4, and 5 were subjected to the following analyses:

- 1) **Loss on Ignition (LOI) analysis**, performed to determine the amount of volatile phases. Approximately 0.5 g of powdered sample was dried at 50 °C, placed in platinum crucibles, and then heated in a muffle furnace at 500 °C for 24 hours to quantify organic matter content gravimetrically. The same

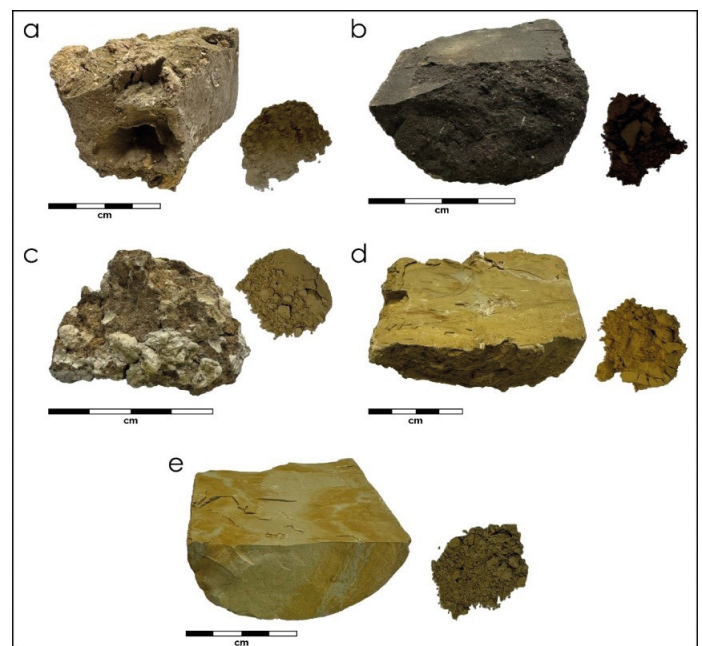


Fig. 8 - Representative specimens (bulk and pulverised, respectively) for each lithology: (a) Sandy silt with brackish-water ostracods, bivalves (*Cerastoderma glaucum*) and gastropods; (b) Dark sandy silts with brackish-water molluscs; (c) Marine sands and fine gravels with sandy silts and basal calcarenitic pebbles (possible palaeosol); (d) Yellowish marl clays (Middle Pleistocene); (e) Grey-bluish marl clays (Early Pleistocene).

crucibles were then heated at 1000 °C for a further 24 hours. After cooling in a desiccator, the crucibles were weighed to calculate the LOI percentage. Results are summarised in Tab. 2.

2) **Quantitative chemical analysis by wavelength dispersive X-ray fluorescence (WD-XRF)** was carried out using a Thermo ARL AdvantXP+ WD-XRF spectrometer (Thermo Scientific, Waltham, MA, USA). Analyses were performed on pressed pellets prepared by compacting approximately 3 g of powder onto a boric acid support. This allowed the determination of major element concentrations (expressed as oxide weight percentages: SiO₂, TiO₂, Al₂O₃, Fe₂O₃tot, MnO, MgO, CaO, Na₂O, K₂O, and P₂O₅) and trace element concentrations (Ba, Ce, Co, Cr, Cu, Ga, Hf, La, Nb, Nd, Ni, Pb, Rb, Sc, Sr, Th, V, Y, Zn, Zr) expressed in parts per million (ppm). Instrumental accuracy evaluated using certified geological standards from the United States Geological Survey (USGS GXR-2 and GXR-4) and the National Institute of Standards and Technology (NIST, sample JSd3), and precision (expressed as standard deviation of replicate analyses) ranged from 2% to 5%. Detection limits were approximately 0.01%. Data processing and matrix effect correction were performed according to the [Lachance & Trail \(1966\)](#) model.

3) **Quantitative chemical analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS)** was performed to determine concentrations (in ppm) of trace elements such as Li, Be, B, Na, Mg, Al, P, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Mo, Ag, Cd, Sn, Sb, Te, Ba, Tl, Pb, Bi, Nb, Hf, Th, U, Y, and the lanthanides. Analyses were performed using a Thermo Electron Corporation X-Series mass spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). A 0.20 g portion of the powdered sediment was placed into a 50 mL Teflon digestion vessel (43 × 60 mm, VWR International) and mixed with 3 mL of HNO₃ (65% in distilled water, Suprapur®, Merck KGaA, Darmstadt, Germany) and 6 mL of HF (40%, Suprapur®). The mixture was heated on a hot plate at 180–190 °C for 4–5 hours until dry. Then, 3 mL of HNO₃ and 3 mL of HF were added, and the mixture was heated again for 3 hours. The resulting dry residue was redissolved in 4 mL of HNO₃ and dried once more. Finally, the residue was resuspended in 2 mL of HNO₃. The final solutions were transferred into plastic vials (VWR International) and diluted to 100 mL with Milli-Q® ultrapure water. Each solution was spiked with an internal standard containing Rh, Re, In, and Bi at a concentration of 10 ppb. Detection limits were 1–10 ppb for Al, Ca, and Fe, 0.1–1 ppb for Mg, K, and Na, and <0.1 ppb for all other elements. Analytical accuracy was assessed using international certified reference standards from the USGS and NIST. The deviation between measured values and reference materials was generally below 15% for all elements. Losses due to HF digestion were considered negligible, with differences below 14%.

4) **X-ray powder diffraction analysis (XRPD)** was performed on each sample to identify mineral phases. The analyses were conducted at ARPA Sicilia (Catania headquarters) using a Rigaku SmartLab diffractometer (Rigaku Europe SE, Germany), equipped with a CuKβ radiation source and an SC-70 detector, operating at 40 kV and 150 mA. Scans were performed in the 2θ range of 3–70°, with a step size of 0.02° and scan speed of 0.75 s. Mineral phases were identified using the SmartLab

Table 2 - Loss on Ignition (LOI) results for representative samples. Values include LOI at 500°C (LOI500), LOI at 1000°C (LOI1000), and differential LOI (ΔLOI).

Sample	LOI ₅₀₀ (wt%)	LOI ₁₀₀₀ (wt%)	ΔLOI (wt%)
CIANE 1	5.86	34.41	28.55
CIANE 2	10.13	12.86	2.73
CIANE 3	7.07	20.28	13.21
CIANE 5	5.75	26.41	20.66
CIANE 4	9.05	17.82	8.77

Studio software by comparing experimental peaks with reference patterns from the ICDD database (PDF2.DAT).

5) **Microtextural observations** were performed using a Zeiss EVO MA 15 Scanning Electron Microscope (SEM; Zeiss, Oberkochen, Germany), which provided both topographic/morphological and compositional images using secondary electrons (SE) and back-scattered electrons (BSE), respectively. The SEM was equipped with an advanced Bruker QUANTAX 200 energy-dispersive X-ray spectroscopy (EDS) system, enabling both spot and area semi-quantitative microanalyses. SEM images were processed using Leica Application Suite (LAS, Leica) software to quantify microstructural features.

Results

Mineralogical and petrographic features

From a mineralogical perspective, XRPD analyses revealed that samples CIANE 1–5 are ubiquitously characterised, albeit in variable amounts, by mineral phases such as carbonates, quartz, clay minerals, micas, and oxides. Aluminosilicates, mafic minerals, phosphates, and sulfates are also present in some of the specimens. Aragonite, likely derived from mollusc shells, was identified in samples CIANE 1 and CIANE 2. Plagioclase minerals were found in almost all samples (CIANE 1, 2, 3, and 5), whereas pyroxenes were detected in CIANE 2, 3, and 5 specimens. As for the oxide minerals, magnetite and spinel-group minerals were observed. Phosphates (specifically apatite) were present in samples CIANE 1, 3, and 5. Among sulfates, bloedite, a hydrated sodium magnesium sulfate (Na₂Mg(SO₄)₂·4H₂O), was identified. Two selected diffractograms of samples CIANE 2 and CIANE 5 are set out on Fig. 9.

Bulk chemistry

Regarding the overall chemistry, the sample powders were initially subjected to “ignition” in order to determine both the LOI (Tab. 2) and the ΔLOI. The highest ΔLOI value was observed in sample CIANE 1 (28.55 wt%), followed by samples CIANE 5 (20.66 wt%), CIANE 3 (13.21 wt%), and CIANE 4 (8.77%); sample CIANE 2 showed the lowest ΔLOI value (2.73 wt%), indicating, compared to the other samples, a much lower presence of carbonate phases.

Major and trace elements

Results obtained from the chemical analyses of major, minor, and trace elements are presented in Tab. 3. Samples CIANE 1–5, collected at various depths, exhibit variable contents of major and

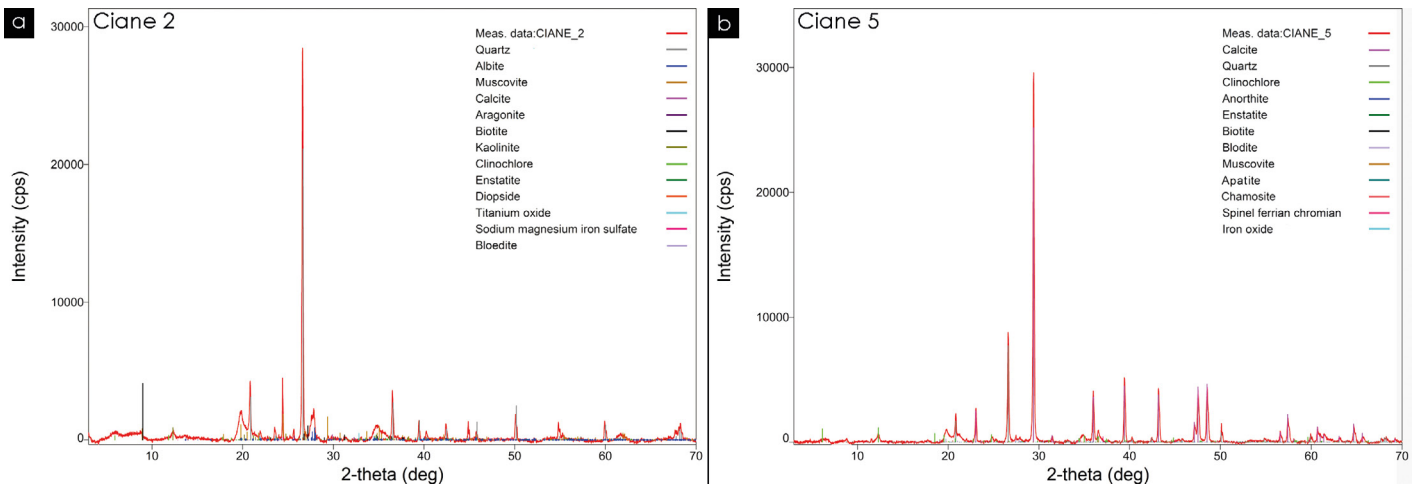


Fig. 9 - Diffractograms of two selected specimens: a) CIANE 2 and b) CIANE 5, showing the mineralogical composition obtained by XRPD analysis.

minor elements. For instance, SiO₂ content ranges from 20.86 wt% (CIANE 1) to 57.72 wt% (CIANE 2), and Al₂O₃ ranges from 5.03 wt% (CIANE 1) to 19.96 wt% (CIANE 2). Iron content, expressed as total Fe₂O₃ (wt%), varies from 2.36 (CIANE 1) to 8.53 (CIANE 2). A wide range is also observed in CaO content, from 2.34 wt% (CIANE 2) to 39.79 wt% (CIANE 1), likely indicating the presence of shell fragments. MnO concentrations are relatively similar, ranging from 0.02 to 0.06 wt%, with the exception of sample CIANE 5 (0.29%). MgO contents range from 1.57 (CIANE 1) to 3.12 wt% (CIANE 2). As for the alkalis (Na₂O and K₂O), their concentrations are fairly consistent, with

slightly higher values in sample CIANE 2. Similarly, P₂O₅ content is quite uniform across all samples, with an average value of 14.6 wt%. The data concerning the welding clays and the average values of the casting clays from statues A and B were compared with the data from all the “CIANE” samples in the binary correlation diagram of CaO vs Al₂O₃ shown in Fig. 10, which highlights a strong affinity between the welding clay US 2227 and the sample CIANE 5e; it should be noted that although the casting clay from Statue B plots close to the CIANE 5c and 5d samples, the comparison of other chemical elements did not reveal further affinities.

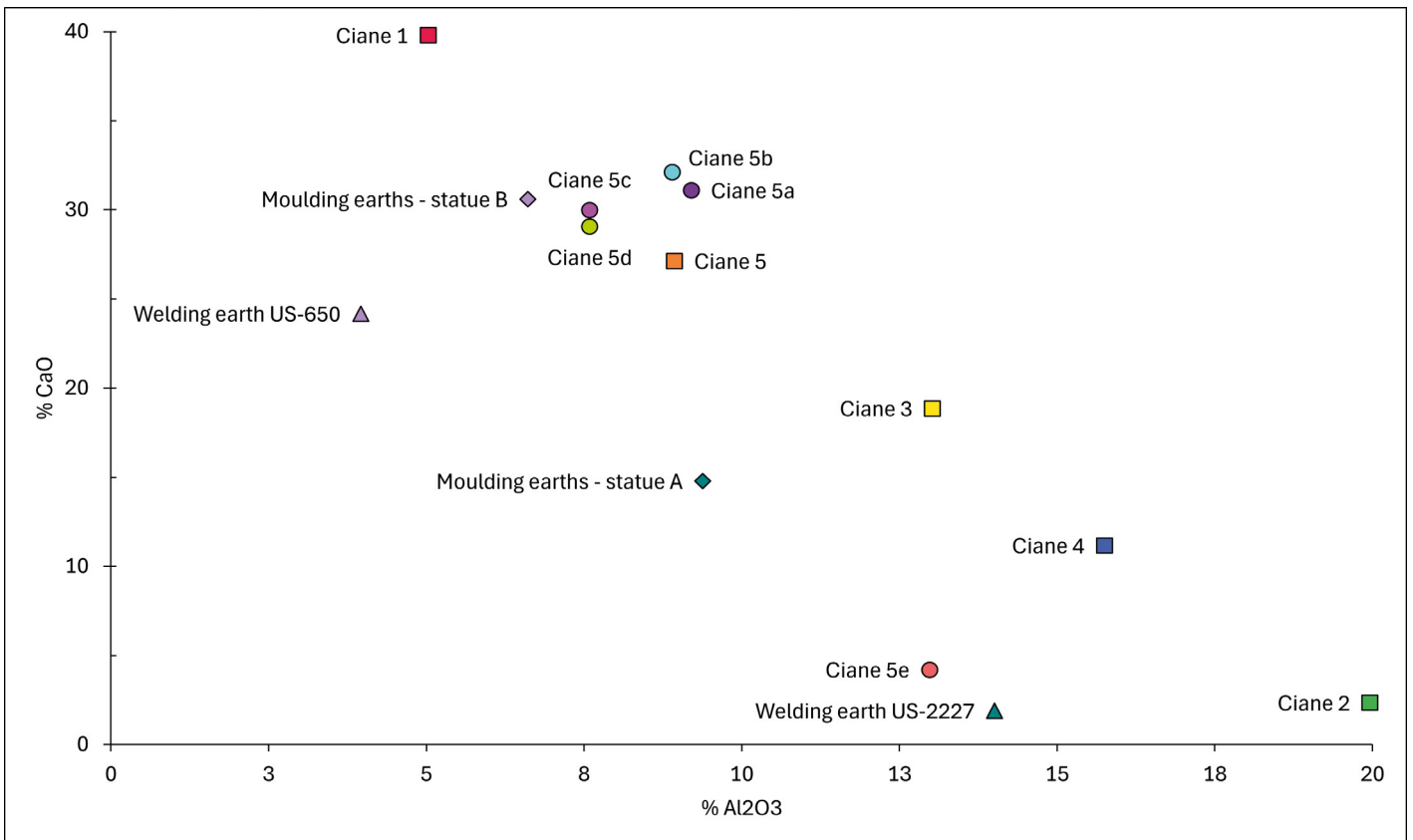


Fig. 10 - Correlation diagram between CaO and Al₂O₃, showing the values of the casting and welding clays from statues A and B (Lombardi et al., 2003) and all the CIANE samples presented in this study.

Table 3 - Compositions of major, trace, and rare earth elements (REE) on whole rock for samples CIANE 1-5. Major elements were determined by XRF. Trace elements and rare earth elements (REE) were analyzed by ICP-MS, with the exception of Gallium (Ga), which was determined by XRF. The results are expressed in wt.% for major elements and ppm for trace elements and REE. LOI = Loss on Ignition.

	Ciane 1	Ciane 2	Ciane 3	Ciane 5	Ciane 4
<i>XRF (wt.%)</i>					
SiO ₂	20.86	57.72	41.91	32.60	50.87
Al ₂ O ₃	5.03	19.96	13.02	8.93	15.75
Fe ₂ O ₃	2.36	8.53	6.86	6.17	6.02
MnO	0.02	0.05	0.02	0.29	0.06
MgO	1.57	3.12	2.57	1.62	3.00
CaO	39.79	2.34	18.86	27.13	11.17
Na ₂ O	0.59	1.04	0.96	0.69	1.21
K ₂ O	0.58	2.88	1.47	1.26	2.16
TiO ₂	0.48	1.50	1.01	0.50	0.83
P ₂ O ₅	0.16	0.15	0.11	0.14	0.17
DLOI	28.55	2.73	13.21	20.66	8.77
Total	100	100	100	100	100
<i>ICP-MS (ppm)</i>					
Li	17.17	31.40	33.05	26.76	51.11
Rb	26.18	3.51	35.53	46.83	72.38
Cs	2.20	0.82	1.64	5.30	4.05
Sr	631.78	87.90	148.38	210.62	255.73
Ba	90.27	210.70	183.35	189.30	179.20
Pb	3.51	9.38	7.33	7.88	13.19
Tl	0.18	0.39	0.25	0.19	0.28
U	2.01	1.06	1.16	2.00	2.43
Th	0.18	7.45	7.14	3.21	8.91
Zr	32.77	191.78	129.74	80.33	121.54
Hf	0.94	5.34	3.28	2.15	3.39
Nb	13.62	37.36	25.94	12.21	18.51
Ta	1.27	2.27	1.38	0.95	1.29
Mo	0.56	0.79	0.41	1.41	1.26
Y	3.93	11.84	18.44	15.52	19.39
La	10.00	15.43	33.34	21.57	30.61
Ce	13.56	65.11	62.11	41.42	54.25
Pr	2.28	4.20	6.90	4.94	6.57
Nd	8.82	17.29	24.62	18.11	23.89
Sm	1.52	3.66	4.45	3.36	4.50
Eu	0.37	1.09	1.15	0.71	1.01
Gd	1.32	3.33	3.71	2.85	3.69
Tb	0.20	0.57	0.60	0.48	0.63
Dy	0.99	2.91	2.93	2.37	3.12
Ho	0.20	0.61	0.60	0.50	0.65
Er	0.51	1.66	1.59	1.35	1.78
Tm	0.08	0.28	0.27	0.23	0.31
Yb	0.39	1.88	1.57	1.31	1.96
Lu	0.06	0.26	0.24	0.22	0.29
Sc	6.14	11.46	16.44	10.40	10.33
V	72.46	170.87	203.49	122.16	182.08
Cr	94.75	148.29	252.37	73.19	94.08
Co	7.32	23.96	17.13	10.44	10.59
Ni	28.06	54.21	45.63	27.88	30.50
Cu	12.28	32.43	17.63	10.95	15.05
Zn	19.91	59.35	41.30	49.18	72.80
Be	0.48	1.95	1.04	1.08	1.80
B	26.82	73.55	36.73	58.22	76.80
In	0.03	0.08	0.07	0.04	0.08
Sn	1.21	2.17	1.29	1.46	2.33
As	4.01	10.26	8.62	16.06	15.96
Sb	0.40	0.46	0.68	0.55	0.53
Bi	0.04	0.21	0.07	0.10	0.15
Se	0.57	0.43	0.15	1.16	0.44
Ag	0.07	0.16	0.09	0.06	0.10
Cd	0.18	0.31	0.23	0.27	0.20
<i>XRF (ppm)</i>					
Ga	4.90	21.10	12.70	10.50	18.60

Minor and trace elements are shown in multi-element diagrams normalised to chondritic meteorites (cf. [McDonough & Sun, 1995](#)) (see Fig. 11: spider diagrams and REE patterns for samples CIANE 1–5 with welding clays). The overall chemical composition of the “CIANE” samples was compared with literature data ([Lombardi et al., 2003](#)), specifically regarding the welding clays from statue A (sample US A2227, right arm) and statue B (sample US 650, right arm) (Tab. 3, Fig. 11). The chemical data comparison reveals that sample US 650 shows similarities only for certain elements, such as the middle rare earth elements (MREEs). However, a strong match was found between sample US 2227 (welding clay of statue A) and sample CIANE 5. As a result, further samples were taken from level CIANE 5 and analyzed via X-ray fluorescence. These additional samples were labeled CIANE 5a–e, each representing distinct sub-levels observed at the mesoscale. As shown in Tab. 4 (CIANE 5a–e) and Fig. 12 (multi-element spider diagrams of the subsamples), there is a strong compositional correspondence between samples CIANE 5a–e and the welding clay from statue A (US 2227), with sample CIANE 5e exhibiting the closest match.

The results of the WD-XRF and ICP-MS analyses allowed us to verify the affinity between the “CIANE” samples and the welding clays: as can be seen from the data presented, this affinity

emerges both from the comparison of major elements and from the comparison of minor and trace elements.

SEM-EDS

SEM analyses were performed on representative samples from the stratigraphic levels considered relevant for this study; in particular, attention was focused on sample CIANE 2, believed to belong to the Greek-era ground level, and sample CIANE 5, whose geochemical evidence showed a marked similarity with the welding clays. Observations were made at both low and high magnifications with images acquired using both secondary electrons (SE) and back-scattered electrons (BSE). SEM-EDS analyses highlighted a significant terrigenous contribution in all samples, consisting of quartz sands (Fig. 13). In all samples, the presence of quartz grains with subspherical morphology and strongly rounded edges is notable; these grains are composed of quartzites, granitoid plutonites, and ortho- and para-derived metamorphic rocks, all embedded in a marly matrix.

The CIANE 2 sample is characterised by a bimodal grain size distribution: the clay fraction, low in carbonate content, predominates, within which a medium-to-coarse sand fraction is

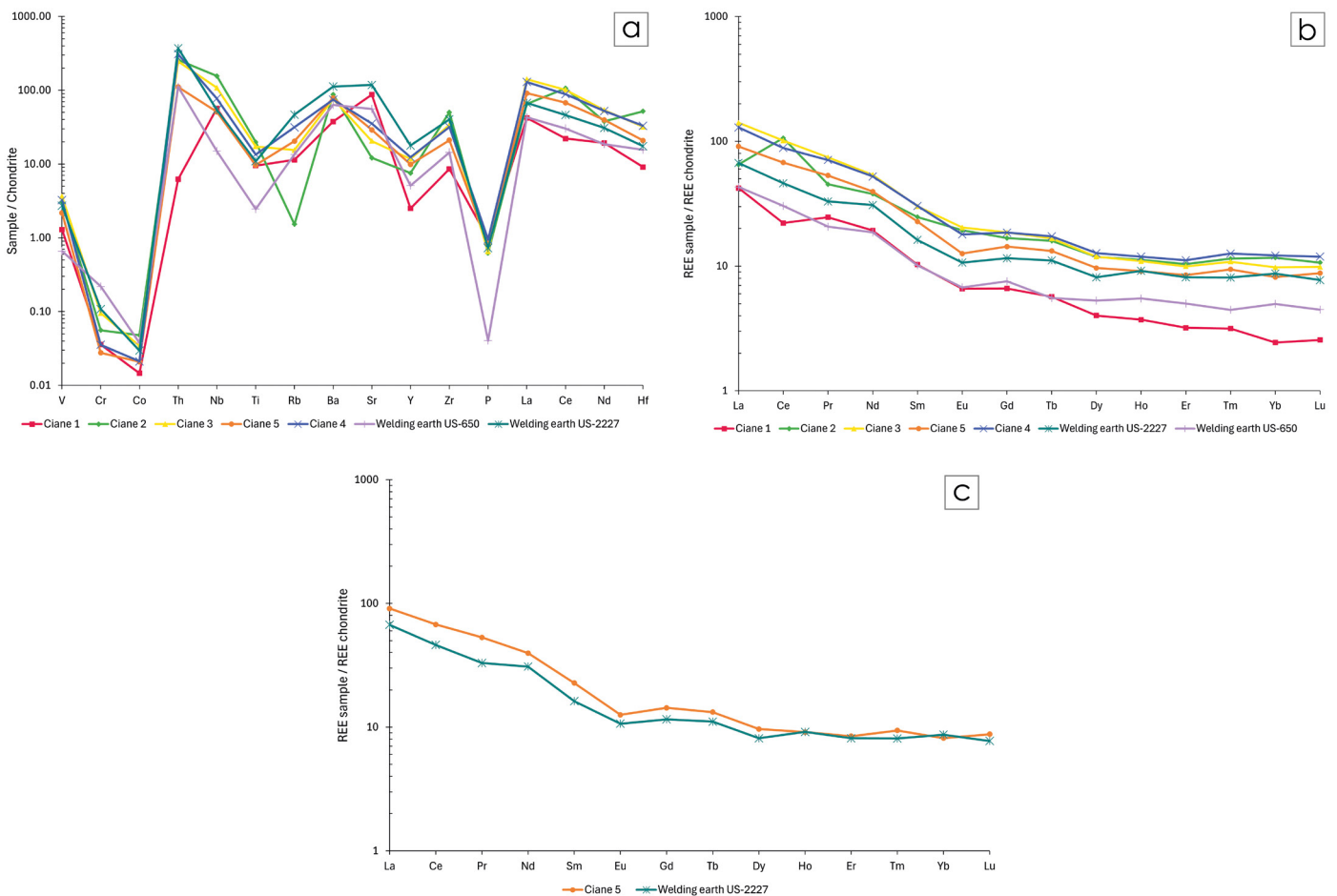


Fig. 11 - Normalisation diagrams of: a) trace elements (spider diagram) and b) REE (Rare Earth Elements) of samples CIANE 1–5, and of the welding soils from Statue A (sample US2227) and Statue B (sample US650). Normalisation to chondrite values according to [McDonough & Sun \(1995\)](#). c) Comparison between the REE pattern observed in sample CIANE 5 and that of the welding clay US 2227. Chondrite-normalized values according to [McDonough & Sun \(1995\)](#).

Table 4 - Compositions of major, trace, and rare earth elements (REE) on whole rock for samples 5 a-e.

	Ciane 5a	Ciane 5b	Ciane 5c	Ciane 5d	Ciane 5e
<i>Major (wt.%)</i>					
SiO ₂	31.68	33.12	32.98	30.96	56.12
Al ₂ O ₃	9.20	8.90	7.59	8.36	12.98
Fe ₂ O ₃	5.98	4.59	5.12	4.83	7.01
MnO	0.10	0.06	0.09	0.05	0.06
MgO	2.00	1.55	1.10	2.10	0.85
CaO	31.09	32.12	29.98	29.06	4.20
Na ₂ O	0.40	0.58	0.57	0.68	0.32
K ₂ O	0.99	0.59	0.74	1.14	1.89
TiO ₂	0.49	0.51	0.61	0.55	1.10
P ₂ O ₅	0.15	0.19	0.21	0.30	0.25
DLOI	17.92	17.79	21.01	21.97	15.22
Total	100	100	100	100	100
<i>Minor and trace (ppm)</i>					
Rb	66.20	91.00	101.00	58.70	112.90
Cs	4.00	2.03	5.10	0.20	4.11
Sr	490.00	710.00	642.00	717.00	801.20
Ba	185.00	162.00	190.00	225.00	254.30
Pb	36.00	14.00	38.00	989.00	46.00
Th	9.51	9.24	16.00	11.60	11.90
Zr	51.00	147.00	97.00	41.00	165.00
Hf	2.20	1.40	2.40	1.50	2.10
Y	19.00	16.00	21.00	33.00	26.50
La	11.00	12.60	13.50	14.20	16.80
Ce	27.90	32.00	26.85	25.70	26.70
Nd	15	10	11	13	15
Sm	13.00	13.50	19.00	12.90	12.60
Gd	0.29	2.59	3.13	0.87	0.95
Yb	0.74	0.81	1.23	2.12	0.96
Sc	16.00	12.50	6.30	15.90	14.20
V	161.00	89.00	144.00	112.00	163.00
Cr	501.40	301.00	609.00	253.00	301.00
Co	17.13	11.00	15.20	5.00	16.20
Ni	231.00	89.00	178.00	56.00	201.00
Cu	1652.00	856.00	1296.00	2364.00	967.00
Zn	74	6	62	156	11
Be	0.90	2.00	1.50	0.69	1.40
B	63.00	44.90	52.10	66.00	62.00
<i>XRF (ppm)</i>					
Ga	19	16	15	14	17

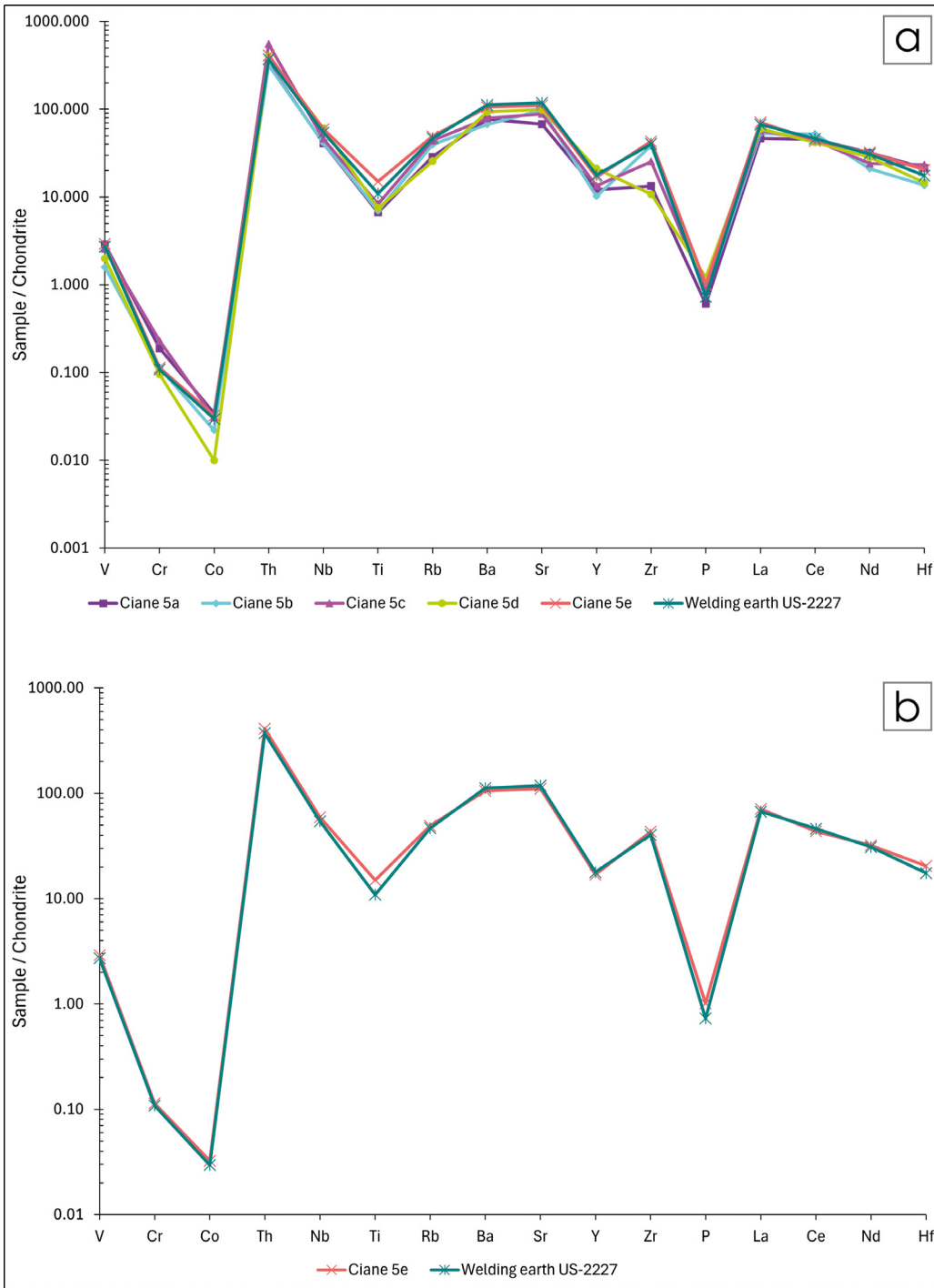


Fig. 12 - Trace element normalisation diagrams: a) comparison between samples CIANE 5 a–e and sample US 2227; b) comparison between sample CIANE 5e and sample US 2227. Normalisation to chondrite values (McDonough & Sun, 1995).

dispersed, mainly composed of idiomorphic monomineralic grains of mafic phases (clino-pyroxene, ortho-pyroxene, and Mg-chromite spinel) (Fig. 14) and grains of basic rocks (doleritic basalts with ophitic intersertal texture) (Fig. 15). From this, it can be inferred that the formation of the stratigraphic layer occurred in a marsh environment with periodic inputs of a sandy fraction rich in mafic phases. Actinolite amphibole crystals were also observed, whose origin requires further investigation, as these minerals form by metamorphic transformation of basic and ultrabasic rocks.

Based on the observations made on the CIANE 2 sample, it is plausible to hypothesize that the sampling level corresponds to the walking surface, which can be identified as the palaeosurface

exposed during the Greek period and subject to productive settlements in the alluvial plain. Indeed, investigations at this level revealed an abundant presence of traces of metalworking (microslag of metallic iron with evident surface oxidation structures); in some metallic artifacts, globular microstructures are observed, which can be explained by fusion under eutectic conditions (Fig. 16). Human presence at this level is also confirmed by the presence of bone fragments and numerous fragments of burnt wood, within which octahedral microlites of framboidal pyrite have developed (Fig. 17).

SEM observations carried out on sample CIANE 5 indicate that it is a silty marl, whose silt component consists of rounded quartz grains smaller than 100 microns and grains of carbonate

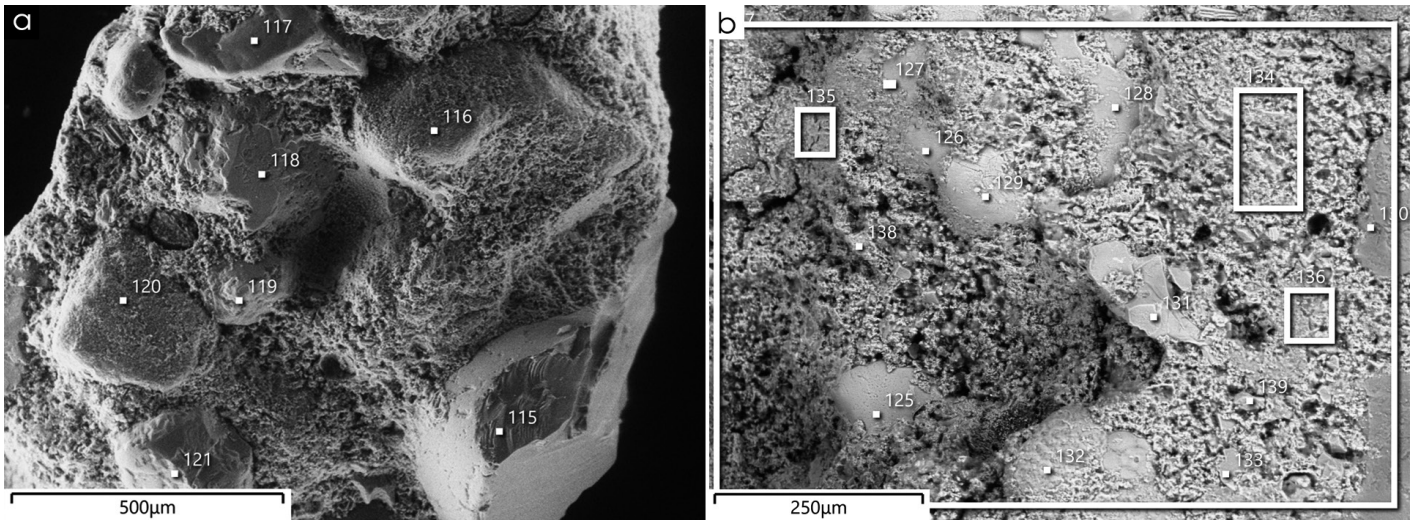


Fig. 13 - Sample CIANE 5: electron microscopy images (a: image acquired in SE; b: image acquired in BSE) of quartz silt grains within a carbonate matrix. The individual grains are strongly rounded, compact, and porosity-free, while the matrix consists of clay mineral microlites and carbonate cement.

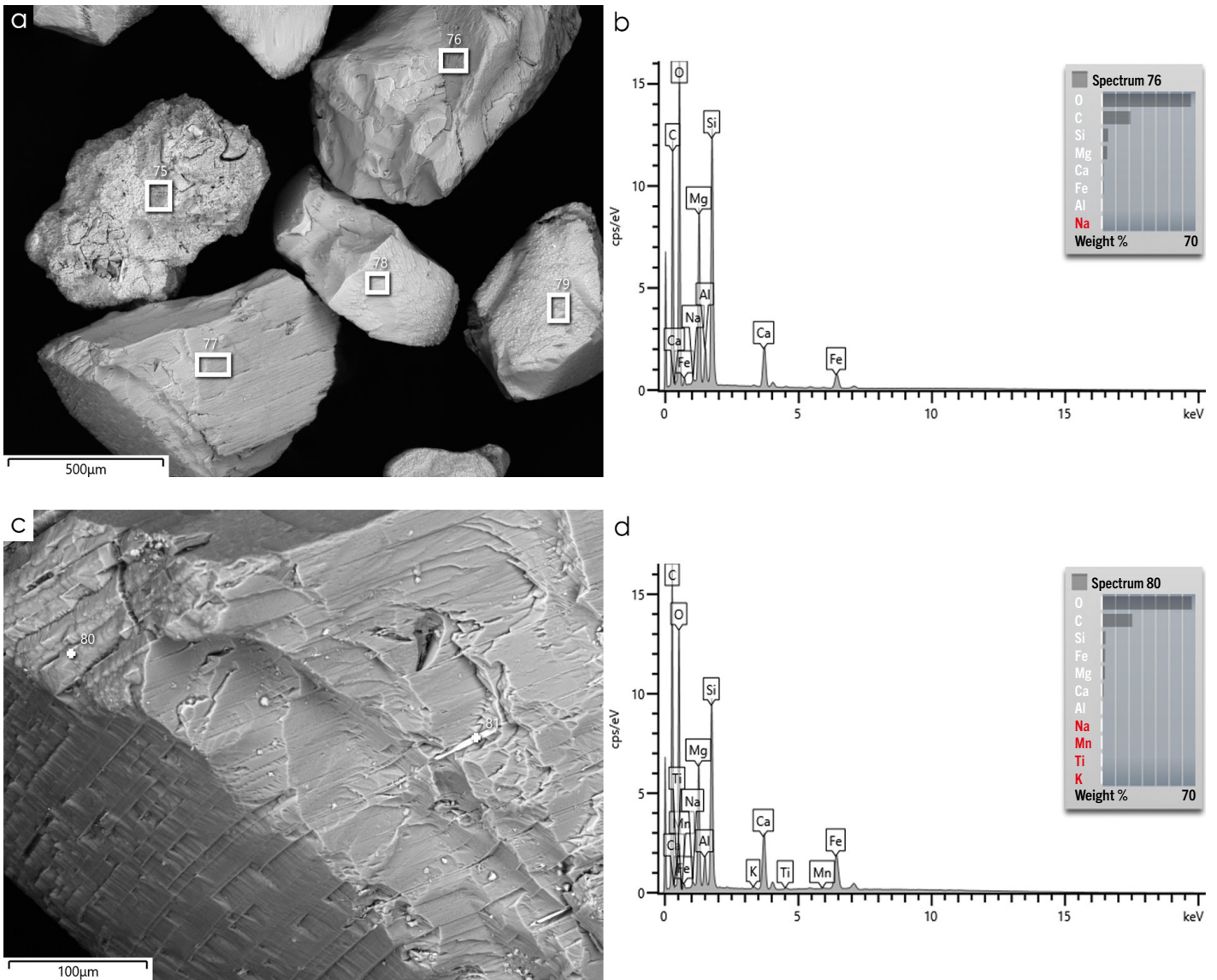


Fig. 14 - a) Image acquired in BSE at very low magnification showing the presence of millimetric idiomorphic grains of mafic minerals; b) EDS microanalysis performed on an augite crystal; c) Higher magnification analysis of an augite crystal, showing the presence within the crystal of orthopyroxene exsolutions and spinel microlites developing parallel to cleavage traces; d) EDS microanalysis of clinopyroxene.

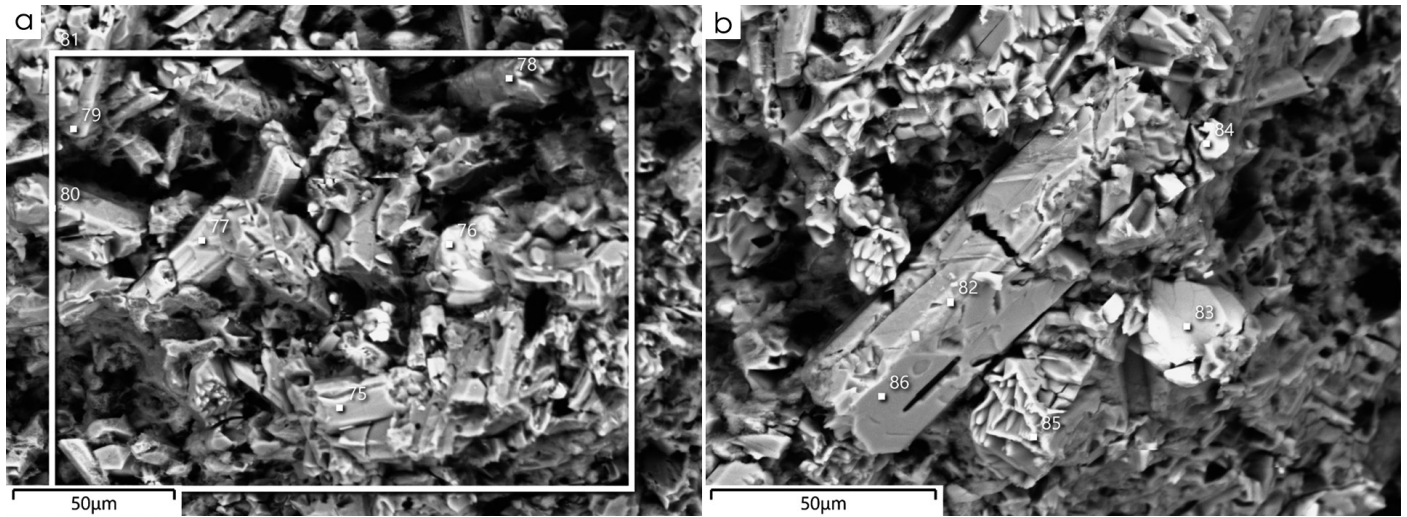


Fig. 15 - Sample CIANE2 – a) BSE image of a basalt with an intersertal ophitic matrix; b) BSE image highlighting the relationship between plagioclase microlites and the matrix rich in pyroxene and subhedral ilmenite crystals.

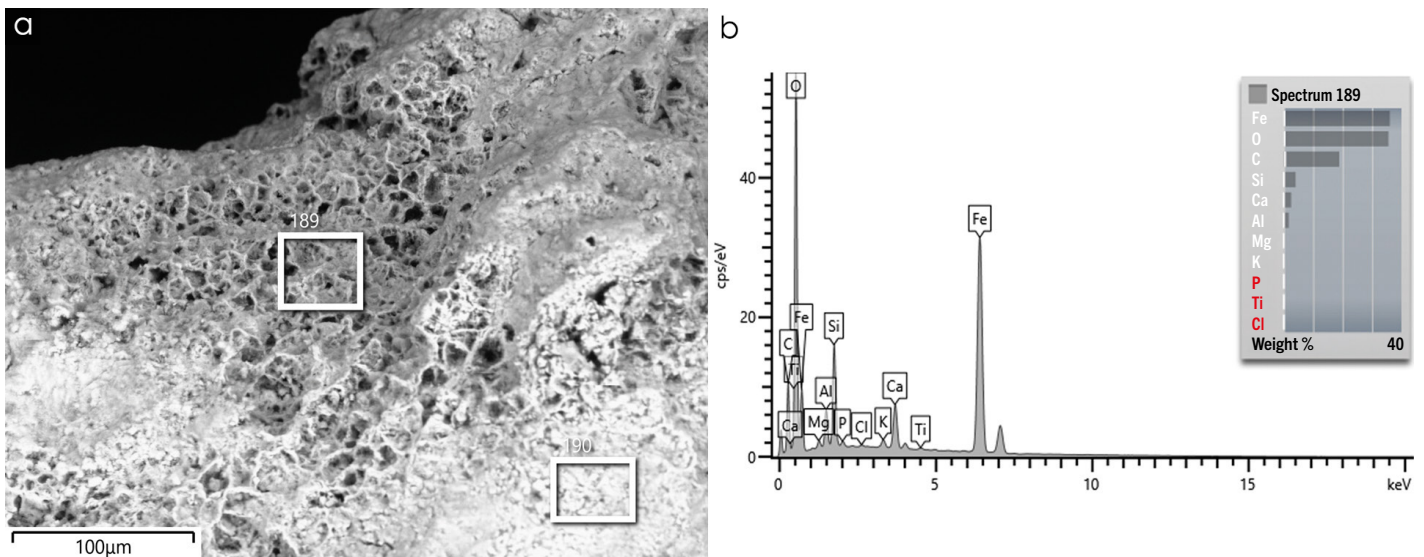


Fig. 16 - CIANE2 sample – a) EDS image showing a detail of the surface of a millimeter-sized iron microslag, which is a metallurgical slag consisting of a metal fragment exhibiting globular microstructures on its surface that are sensitive to oxidation processes. b) Spectrum of the analysis performed in the area where the fragment shows the highest oxidation.

rocks containing Foraminifera, also about 100 microns in size (Fig. 18). Locally, iron oxides have been observed, sometimes even as metasomatism on the walls of the microfossils (Fig. 19). The presence of iron sulfides is rare, indicating a weakly reducing depositional environment.

**HYPOTHESIS ON THE PROVENANCE OF CASTING MATERIAL:
ANALYSIS OF ALLUVIAL DEPOSITS FROM THE SIBARI PLAIN**

The second of the three objectives of the present study is to verify whether, regarding the internal casting material of the two famous statues, previously attributed to the Peloponnese area, alternative hypotheses concerning their origin can be scientifically supported, to identify the possible *ateliers* of provenance of the

statues. To this end, some clues, better specified below, have led to limiting the investigation area to the alluvial deposits of the Sibari Plain in Calabria (Fig. 20), where the Crati river forms a wide deltaic system (Critelli & Le Pera, 1998).

Geological setting of the Sibari area

The Sibari Plain is located in the northeastern sector of Calabria (Fig. 20) and has a surface of about 470 km². It is important for the cultural appeal due to the ancient town of Sybaris. The Calabrian terranes represent a continental fragment within the central Mediterranean orogen, related to subduction and rollback of the Ionian oceanic lithosphere and the slow convergence between the Eurasian and African-Adriatic continental plates (e.g., Critelli & Martín-Martín, 2022, 2024). The lithological framework of the

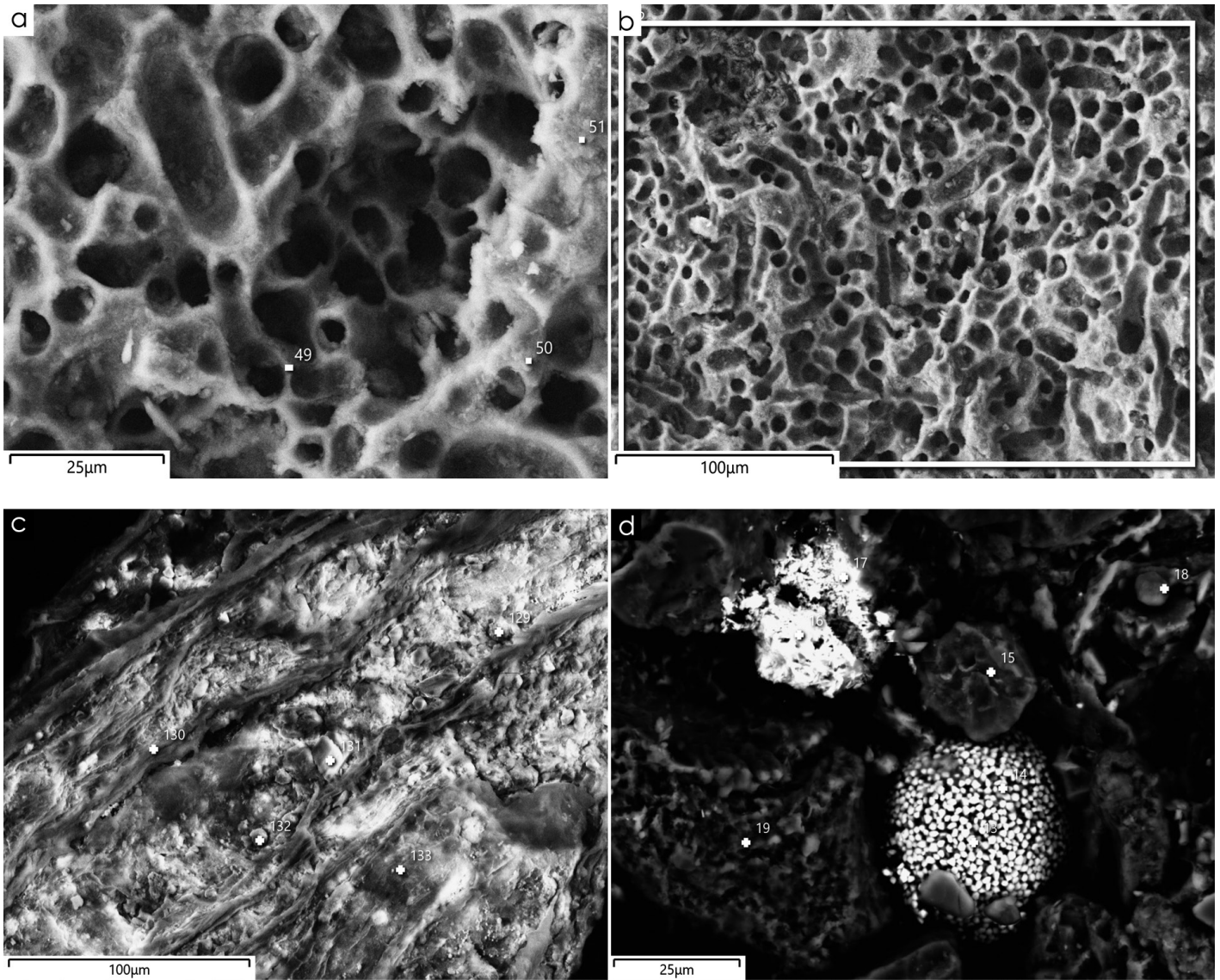


Fig. 17 - a) BSE image showing a close-up of the spongy part of a bone tissue fragment; b) the same fragment observed at lower magnification; c) BSE image of a burnt wood fragment; d) BSE image of framboidal pyrite.

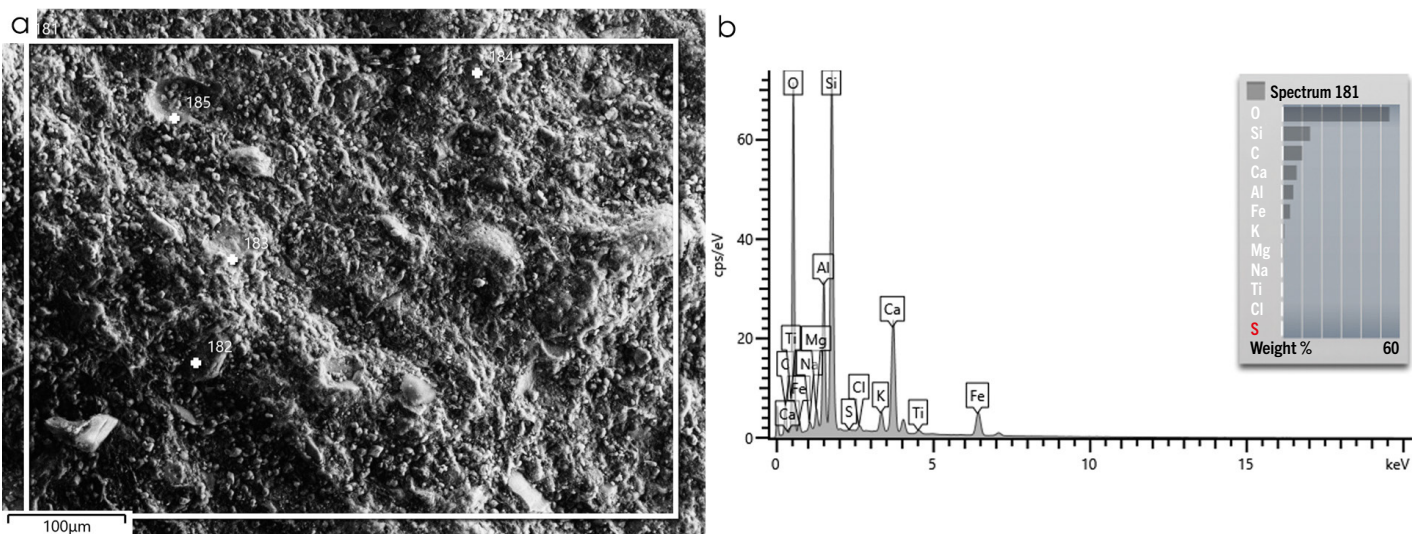


Fig. 18 - Sample CIANE5 - a) Image acquired using secondary electron (SE) detection at low magnification of sample CIANE5, confirming the predominance of a clayey matrix mainly composed of aluminosilicates, with the silt fraction consisting of quartz and carbonate grains; b) area microanalysis of the sample.

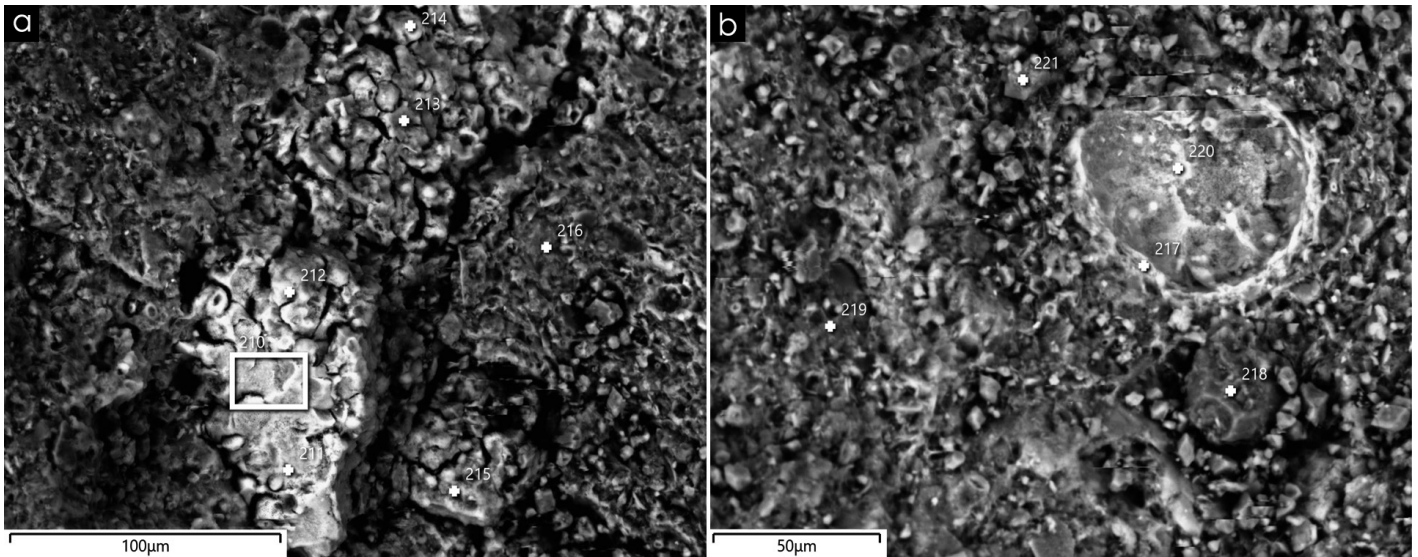


Fig. 19 - Sample CIANE5 - a) Image acquired in BSE highlighting the presence of iron oxides; b) iron oxides are also observed as metasomatism on the walls of Foraminifera.

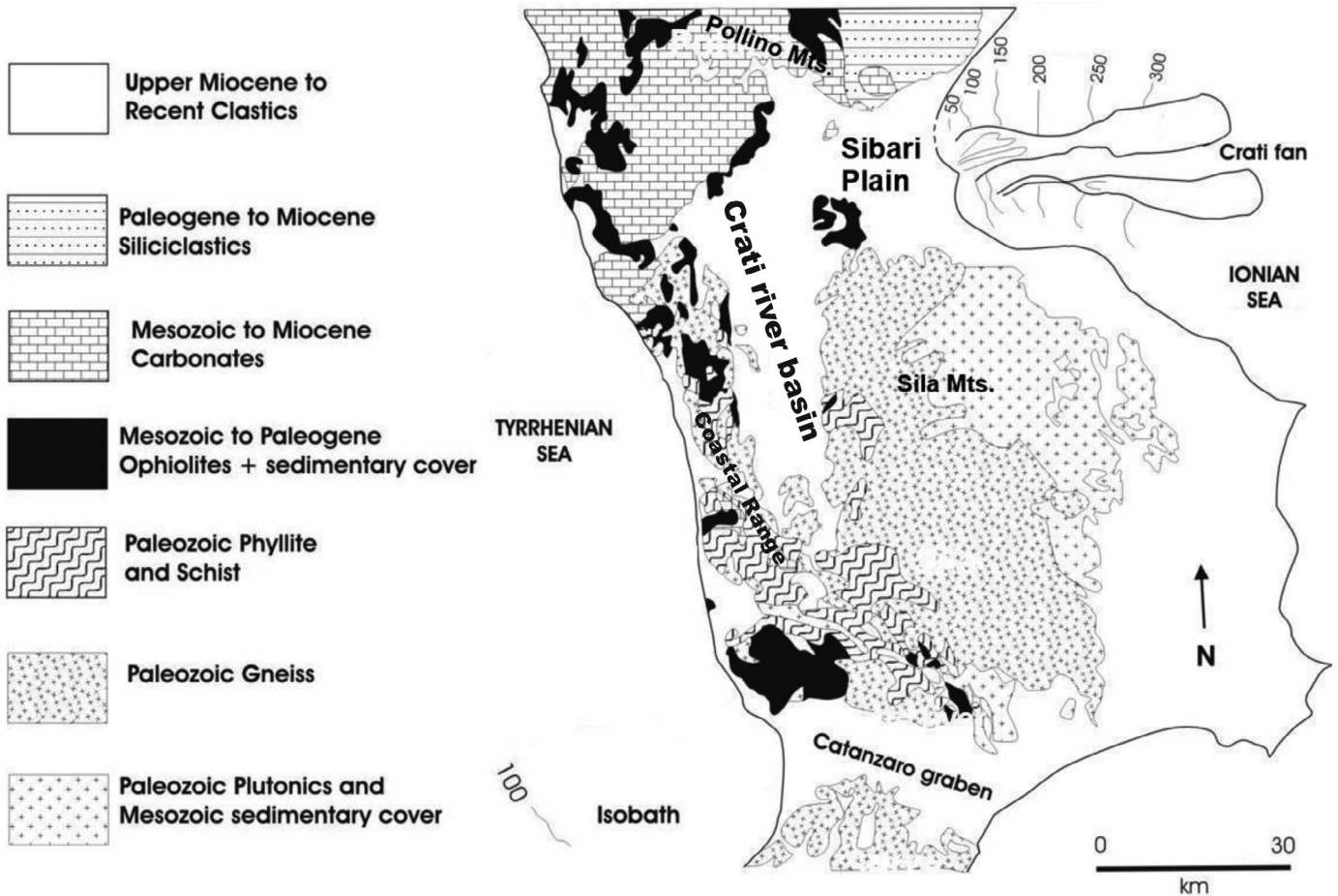


Fig. 20 - Schematic geological map of northern Calabria. The source rocks of the Crati river basin are evidenced (from Critelli & Le Pera, 2003, modified).

Crati river basin consists of Paleozoic plutono-metamorphic rocks of the Sila Massif and the Coastal Ranges (Fig. 20), Mesozoic oceanic-derived rocks, both metavolcanic and sedimentary rocks, and Cenozoic-to-Quaternary sedimentary successions (Critelli & Le Pera, 2003). The Pollino Massif borders the Crati river basin

to the north and is mainly made up of Meso-Cenozoic carbonate sedimentary rocks and by a tectonic mélangé made of oceanic metavolcanic rocks and sedimentary rocks both mudstone and clastics (Critelli, 1993; 2018; Monaco et al., 1995). The Sibari Plain stays between Sila Massif to the South and Pollino Massif to

the North and represents a tectonic subsiding area bounded by Pliocene-Quaternary high-angle faults (Ferranti et al., 2011) that controlled the stratigraphic architecture and the arrangement of the depositional environments (Cianflone et al., 2018; Critelli et al., 2018).

The sand composition of the Crati river delta

The main channel modern sands of the Crati river are lithofeldspathoquartzose (on average Q42.96, F33.79, L23.25) in composition from upstream to the lower reaches (e.g., Critelli & Le Pera, 2003). In the upper reaches (0-25 Km) of the Crati main channel sandy sediment supply is characterised by abundant coarse-grained, medium to high rank metamorphic rock fragments, reflecting derivation from mixed metamorphic and plutonic-gneissic source rocks from the Hercynian crystalline basement of the Sila massif (Messina et al., 1991). After 25 km, Crati river receives detrital input from tributaries draining rocks of the pre-alpine metamorphic complex. A downstream change in the Crati River sand composition is related to a sedimentoclastic input from the largest of Crati river tributaries, the Coscile river, which drains the sedimentary units of the Pollino Massif (Critelli & Le Pera, 2003).

The modern sands of the Crati river deltaic-shoreface system exhibit compositional variability ranging from lithofeldspathoquartzose (Q40.87, F36.69, L22.44) to lithoquartzofeldspathic (Q36.56, F45.17, L18.27). Lithic fragments (L) of the deltaic sand are dominated by metamorphic rock fragments (Rm 53.99%) more abundant than granitic ones (Rg 37.34%), with minor contributions from sedimentary lithics (Rs ~6%) such as dolostones, micritic limestones, and sparitic limestones. Fossil fragments are sparse and likely sourced from carbonate-rich tributaries inputs draining the Pollino Massif.

In the sands of the river mouth beach the quartz content increases significantly (Qm 56.60, Qt 54.75) compared to the delta, while feldspar (F 25.37) and lithic fragments (Lt 18.03) decrease. These sands are lithofeldspathoquartzose (Q 56.60, F 25.37, L

18.03). Lithic fragments are dominated by metamorphicclastic (Rm 63.84%) (Fig. 21A) and plutonicclastic detritus (Rg 28.60). Carbonate lithics, including microsparitic and micritic limestones, occur in trace amounts, while fossil fragments are rare, consisting of isolated skeletal grains. In the lower reaches of the Crati river basin, metabasite grains, derived from oceanic crustal rocks (e.g., Liberi & Piluso, 2009), include grains of serpentine, serpentineschists and chloritoschists in the Crati tributaries sand draining the Coastal Range metaultramafic source rocks (Fig. 21B). Moreover, a rarer contribution comes from metabasalts with lathwork and microlitic textures, whose lithic grains are also supplied to the sand of the Crati lower reaches by tributaries from the Coastal Range.

Specifically, bulk chemistry of the pillow basalts in the source area shows a chromium content as trace element in both bedrock and soil horizons (e.g., Tangari et al., 2018). In the lack of information from detrital geochemistry of these fluvial and deltaic modern sands, the ultramaficlastic grains of the alluvial-deltaic-beach system of the Sibari Plain could explain the high chromium content of the material used to cast the two statues.

TAPHONOMIC AND GEOCHEMICAL CHARACTERISTICS OF CONCRETIONS AND PATINAS ON THE BRONZES

The third of the three objectives of this work is to verify the scientific validity of the hypothesis that the statues originally sank not in Riace but in another underwater context more compatible with the “marks” left on the two Bronzes by their interaction with the environment. More specifically, the scientific validity of the hypothesis of their original deposition in Sicilian marine waters (and at greater depth), as supported by the archaeologist Holloway (1988), was investigated through the study of geomorphological features of the seabed, as well as of taphonomic aspects of organogenic and terrigenous concretions formed on the Bronzes and geochemical characteristic of the corrosion patinas on their surface.

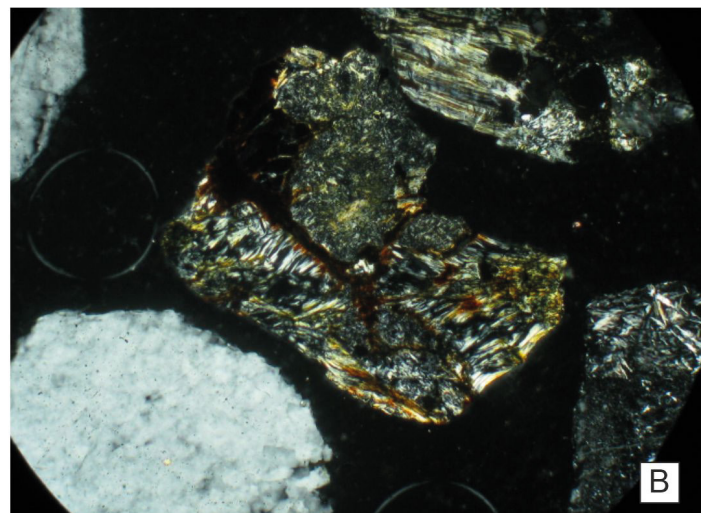
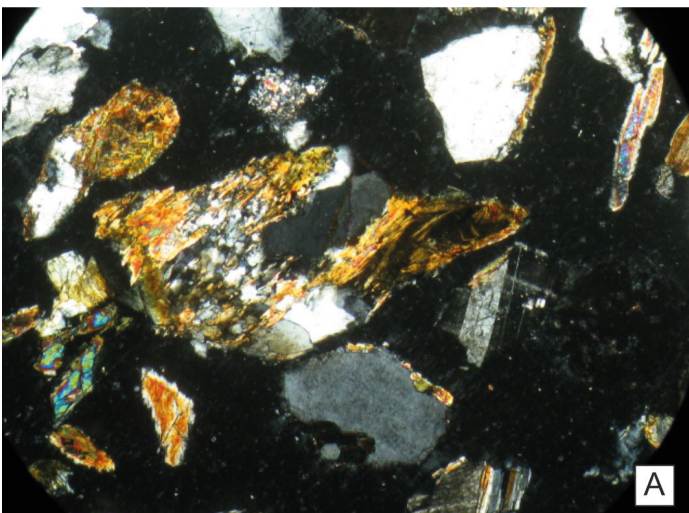


Fig. 21 - A) Metamorphic rock fragments in the Crati river sands. B) Grains from the serpentinites of ophiolitic sequences.

Taphonomic characteristics of the Bronzes from the observation of the organogenic and terrigenous concretions

The state of conservation of the Bronzes was studied by examining the taphonomic characteristics on their surface through observations of details of published photographic documentation, mainly from Mello et al. (1984) and Malacrino (2023). Taphonomic processes include physical, chemical, and biological transformations that affect any marine remains lying on the seabed (Efremov, 1940), be it a shell or an archaeological find, and which vary depending on the depth and other related parameters, such as hydrodynamics, oxygenation, grain size of the seabed sediment, etc. They intensify over time and cease with the definitive burial of the artifact in the sediment after a more or less prolonged period of exposure, leaving clear evidence of the depositional environment on the exposed surface. Recognizing these processes on an artifact that has remained on the seabed for a certain period of time is a highly effective investigative tool for reconstructing its history and depositional environment. Taphonomic processes in submerged marine environments consist of biological encrustations and various corrosion and abrasion processes.

Serpulids-rich organogenic concretions attributable to the so-called “Coralligenous” biocenosis are easily recognizable on the Bronzes (see above). This is a typical organogenic concretion widespread in the Mediterranean, generally at depths between 30 and 80 meters, consisting of carbonate crusts made of calcareous algae and invertebrates, mainly serpulids and bryozoans (Ballesteros, 2006; Basso et al., 2022; Bracchi et al., 2022; Donato et al., 2024), cemented by micritic carbonates (Cipriani et al., 2023, 2024). Serpulids are distinguishable even by simple observation of the numerous images from published articles, such

as those on plates XI and XII in Mello et al. (1984) where a well-preserved carbonate crust with micrite and serpulids is found on the inside of the left hand and on the left foot and tenon of statue B (Fig. 22).

The general morphologies allow us to recognize different shapes and sizes of carbonate tubes, with cross-sections ranging from triangular to subcircular, surely belonging to different species, although not identifiable. However, in the photo in Fig. 22A it is possible to identify a specimen with a medium-sized tube with a circular cross-section and typically coiled in a flat spiral encrusting the right-hand part of the bronze B. This most certainly can be attributable to *Serpula lobiancoi* (Rioja, 1917), a sciaphilous species well known in coralligenous concretions (Rosso et al. 2013). This species, with a Mediterranean and NE Atlantic distribution, is the most abundant serpulid on submerged bronzes and marble statues from other Mediterranean finds at similar depths (Ricci et al. 2019; Gravina et al. 2021) and has never been found on shallower seabeds such as that of Riace. The ecological significance of the species therefore allows us to state with good certainty that the carbonate concretions testify that the Bronzes must have rested on the seabeds at a depth of around 70 meters.

A different concretion observed on the bronzes, not as hard and compact as the previous one but very little cemented and disintegrable, is of terrigenous nature, being formed by a polygenic conglomerate (Fig. 23). The granulometric and compositional characteristics of this concretion are perfectly compatible with those of the sediments currently present on the seabed of Riace. In this shallow marine environment, the oxidation of the metals would have determined the weak cementation of the sediment around the statues, likely over a period of a few months. Therefore, this second type of concretion would be much more recent than the coralligenous concretion, which instead would have formed over

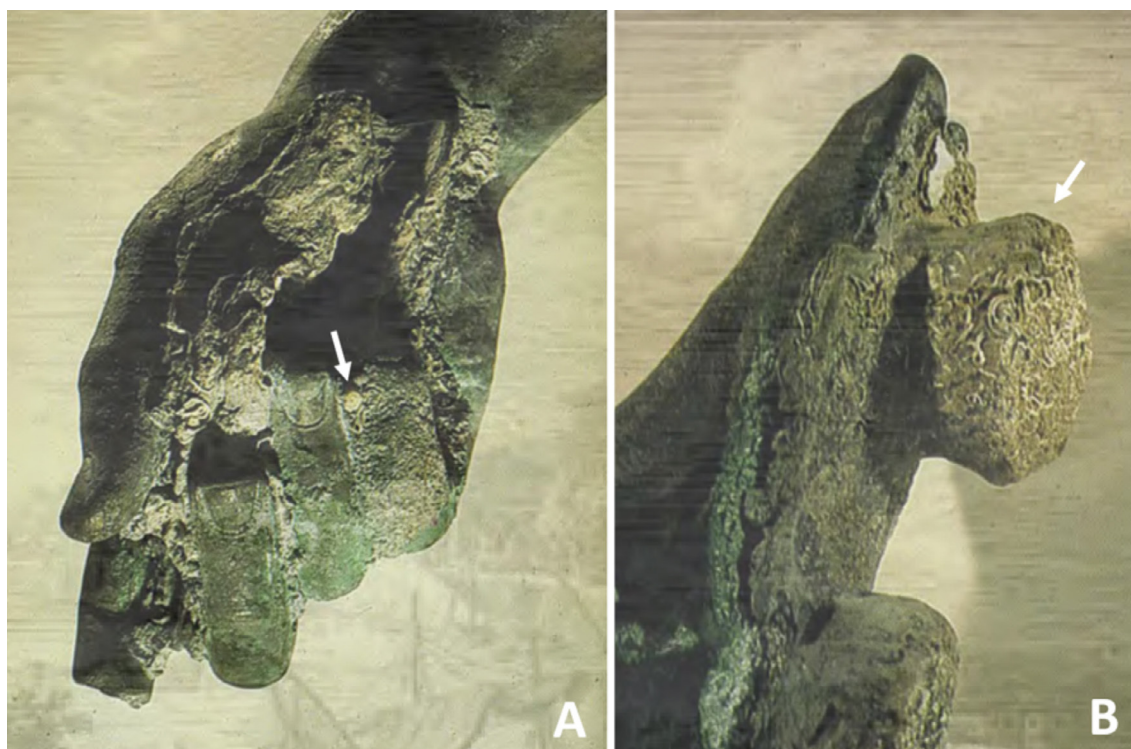


Fig. 22 - A) Carbonate crusts with numerous serpulids in the internal portions of the right hand. The arrow indicates the typically spiral encrusting tube of the species *Serpula lobiancoi* (from Mello et al., 1984: plate XII, Fig. a, modified). B) Arrows indicate the thick carbonate crust with serpulids on the left foot and tenon of statue B (from Mello et al., 1984: plate XI Fig. c, modified).

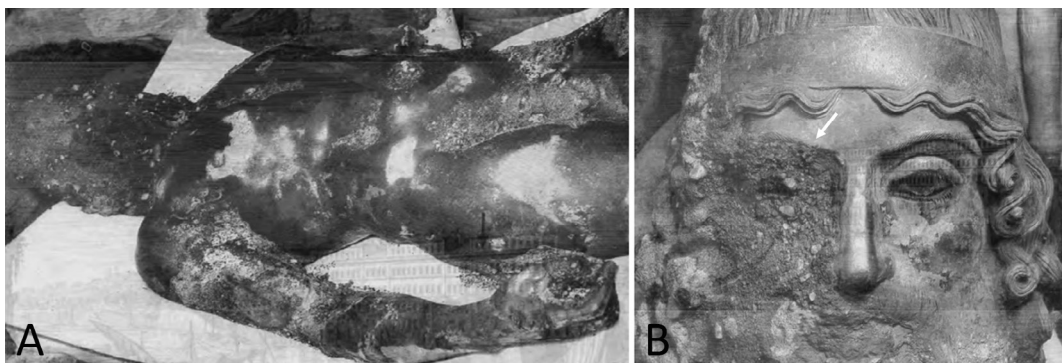


Fig. 23 - A) Statue B before removal of the terrigenous conglomerate. B) Detail of the head of Statue A, partially encrusted by sediment (arrowed). Much of the remaining surface appears smooth and in good preservation state (from Mello et al., 1984: figg. 3, 7, modified).

the course of millennia, as confirmed by literature data, which date the coralligenous to the Holocene (6,000 years) (Sartoretto et al., 1996).

Overall, the taphonomic observations on the statues showing well-preserved surfaces with portions of coralligenous crusts only in the most sheltered and inaccessible parts (Fig. 22), suggests that they had undergone a rough removal of this organogenic concretions from the surface (Fig. 23B). Furthermore, the weakly cemented conglomeratic concretions of Bronze Age A appear to be of recent formation, as they were removed with simple finger pressure during the restoration operations (Sabbione, 1984).

Review of corrosion patinas and terrigenous encrustations on bronzes

The study of patinas and encrustations represents an important step in understanding the history of the Riace Bronzes. Defining the various processes is not simple, however, because when a bronze object is immersed for a prolonged period in a marine environment, it undergoes a series of chemical, mineralogical, and physical transformations due to interaction with seawater, marine flora and fauna, and seabed sediments, which essentially depend on depth and various other related factors. A comparative analysis of data from the scientific literature highlights a complex picture of the microstratigraphy of the deposits present on the statues, which is not homogeneous across the entire surface, as electrochemical and chemical processes occurred at different times and in different ways. Added to these are the cleaning and restoration operations, which involved the removal of some encrustations and patinas, and which further complicated the understanding of the history of the statues over the course of approximately two millennia.

However, based on several chemical, physical, and mineralogical investigations conducted using various analytical techniques, both destructive and non-destructive (e.g., Mello et al., 1984; Mello, 2003; Buccolieri et al., 2015), the results revealed a fairly clear stratified evolutionary picture (over time) of the various deposits formed on the external surfaces of the Bronzes. This detailed evolutionary record corroborates several theories about the environment where the statues were originally placed.

The investigations carried out before the restoration identified a series of layers of surface patinas and encrustations varied in composition, thickness, sediment grain, and adhesion patterns between them and to the surface of the bronze alloy, attributable to

the long period spent at sea. The results indicate that the stratigraphy around the bronze alloy, although almost never complete and not evenly distributed across the entire surface (as was the case at the time of the discovery in 1972 in Riace), is equally repetitive between the two statues (Mello et al., 1984), despite objective and normal differences attributable to their different orientation on the seabed and also to the different treatment of the Bronzes during restoration (Buccolieri et al., 2015). This indicates that the statues have evidently undergone the same alteration processes, also due to the alloy's primary chemical composition, which is essentially copper and tin, along with other elements in the form of impurities, without significant differences between the two statues.

Optical microscopy and SEM analyses (Mello et al., 1984; Mello, 2003) on the surface of the original alloy of the statues (after removing the superficial encrustations that covered it before restoration) revealed a partial alteration in the superficial portion of the matrix (attributable to the initial period of interaction with seawater). Typical selective corrosion processes occur, such as dealloying, which leads to the removal of tin (de-tinning), with the local formation of small concentrated Cu islands, leaving a porous and fragile structure, and local decuprification, with the dissolution of Cu (Mello, 2003). These processes, together with the oxidation of Sn (Robbiola et al., 1998; Oudbashi, 2015; Abu-Baker, 2023), represent the main mechanisms through which corrosion proceeds.

Stress corrosion cracking have also been observed in the bronze sheet, especially in the areas of the statues where the mechanical stress is greatest. In the fractures, which partly originated during the production phase, corrosion began and continued along lines parallel to the grain plane [111] (Mello, 2003), with the deposition of typically reddish cuprous oxide (cuprite), evidently formed by slow oxidation in the presence of water. The general corrosion process of the bronze alloy, already from this initial stage, could have been slowed down by the presence of the iron armour bars placed inside the statues which, by virtue of the different oxidation-reduction potentials between bronze and iron, acted as sacrificial anodes, corroding more than the bronze sheet which remained almost unchanged. Furthermore, the release of metallic copper into the water immediately in proximity to the external bronze surface, due to its high biological toxicity, could have led to a significant slowing down in the development of flora and fauna around the statues, especially in the initial phases of the corrosion process.

THE SCIENTIFIC PLAUSIBILITY OF THE SYRACUSAN HYPOTHESIS

The main elements to test the Syracusan hypothesis are related to: i) a comparison with the mineralogical and geochemical data of the Pantanelli sediments, in relation to the welding (par. 7.1) and restoration (par. 7.2) materials; ii) a comparison with the sedimentological data of the alluvial deposits of the Sibari Plain, in relation to the casting material (par. 7.3); iii) scientific evidence demonstrating the impossibility of the long-term presence of the statues in the shallow sea of Riace (par. 7.4); iv) the plausibility of their original and millenary location in the deep sea of the Sicilian Ionian coast (par. 7.5).

Interpretation of the mineralogical and geochemical data of the Siracusa sediments and comparison with the welding material of Bronze A

The chemical and mineralogical analyses performed on samples from the alluvial plain of the Anapo river have made it possible to characterize the sediments corresponding to those of the probable original quarry site. Mineralogical analyses, conducted using XRPD and SEM-EDS, provided detailed information on the composition, structure, and texture of the samples. The results showed consistency and highlighted clear differences in the mineral assemblages across various depths of the sampling area. Quartz was identified in all samples, indicating a widespread detrital input. Carbonates (calcite and aragonite) were found in varying proportions. Calcite is prevalent in the CIANE 4 sample, while aragonite is more abundant than calcite in the other samples, likely due to the presence of bioclasts (e.g., bivalves, ostracods, gastropods). Other identified mineral phases include bloedite and various clay minerals (e.g., clinocllore, montmorillonite, muscovite). Additionally, samples CIANE 1, 2, 3, and 5 contain mineral phases such as clino- and ortho-pyroxenes, Cr spinel, iron and titanium oxides, and plagioclase. These findings suggest a provenance from the degradation of basic and ultrabasic rocks.

The LOI values are in strong agreement with the mineralogical data. Samples with a significant change in LOI (Δ LOI) (CIANE 1, CIANE 3, and CIANE 5) do, in fact, contain carbonates. This confirms that the main factor for mass loss between 500 °C and 1000 °C is their decomposition process. Similarly, the low Δ LOI in the CIANE 2 sample is consistent with the scarce presence of carbonate phases. LOI500 values are also well-explained by the content of hydrated minerals. The CIANE 2 sample has the highest LOI500 and contains abundant clay minerals, including clinocllore, which undergo dehydration or dehydroxylation below or around 500 °C, and bloedite. Overall, the variable distribution of different clay minerals, such as clinocllore and micas (e.g., muscovite), highlights the mineralogical heterogeneity among the samples and reflects distinct provenances or diagenetic pathways. This is consistent with the chemical composition of the samples, including major, minor, and trace elements. The mineralogical data obtained allowed a comparison with the mineralogical characteristics of welding material, as described through microscopic observation by both Micheli & Vidale (2003) and Jones et al. (2016).

Finally, it is worth noting that, according to literature data, the welding material on Statue A are completely different from those found within the individual sections. This supports the hypothesis, already advanced by the ICR (Lombardi et al., 2003, p. 170), that the statue was cast in separate sections in a workshop and then welded together where it was placed. In this regard, a detailed geochemical study of samples taken at various depths in the Pantanelli area, south of Siracusa, highlighted a strong correspondence between sample CIANE 5 (and particularly sample CIANE 5e) and the material from the right arm of Statue A (sample US 2227), which was identified by Lombardi et al. (2003) as the welding material of Statue A. As previously mentioned in the introduction, this correspondence can be explained by hypothesizing that Statue A, regardless of the workshop where its individual sections were made, was assembled and placed in ancient Siracusa, the *polis* of the commission. This finding should not be surprising: the case of the Auriga of Delphi, in fact, indicates that in the 5th century BC the place of fabrication very often did not coincide with the place of commission and placement (Psalti et al., 2018), demonstrating a very intense circulation of sculptors, sculptures and sometimes entire itinerant workshops (Cadario, 2019).

Review and interpretation of literature data on the restoration material of the right arm of Bronze B and a comparison with clays from the Siracusa area

The welding material of statue A (US 2227) is fully compatible with the clays of the sample CIANE 5 collected from the Pantanelli site in the Siracusa area. On the contrary, the presence of granitoid rocks and other characteristics (Lombardi et al., 2003) seem to link the welding material of statue B to the Sibari area in northern Calabria, the place of its probable fabrication. In Bronze B, however, the presence of an ancient restoration on the right arm could give us an important clue about its final location in a site different from its place of fabrication. Formigli (1984) had already demonstrated that this arm had been replaced with the original one, as can be deduced from the composition of its bronze alloy, which is quite different from that used in the rest of the statue due to a higher lead content. In the subsequent restoration of 1992-95, a clear difference was observed between the material of the restored arms and that of the rest of the body. In fact, according to Rebaudo (2020, pag. 26), in the restored elements “*l'argilla è chiara, di natura sabbiosa, contiene inclusi litici ed è agglomerata in massarelle disordinate e relativamente poco coerenti. Nel resto della figura è scura, quasi priva di inclusi e applicata per strati*” (“the clay is light, sandy in nature, contains lithic inclusions and is agglomerated in disordered and relatively incoherent clumps. In the rest of the figure, it is dark, almost devoid of inclusions and applied in layers”). Furthermore, according to the author, the arms resulted to have been cast with the indirect method, unlike the rest of the statue which was made with the direct method: “*Alla luce di ciò, il fatto che le braccia siano state rifatte a distanza di tempo e in un luogo diverso da quello di esecuzione delle statue risulta incontrovertibile*” (“In light of this, the fact that the arms were redone at a later time and in a different place from that of the execution of the statues is incontrovertible”).

Unfortunately, in the tables of major, minor, and rare earth elements from the valuable work edited by the I.C.R. (Lombardi et al., 2003; Figs. 139-144), the geochemical data for the sample of material inside the restored arm (US 660) are not included. Therefore, in this case, it was not possible to compare the geochemical data of this material with the sediments from the Siracusa area. However, through a careful review of the existing literature, it is possible to advance some hypotheses with due caution. More precisely, inside the restored right arm a yellowish sandy sediment was found, composed mainly of gypsum (considered “secondary”), calcite, and quartz, with a chemical composition similar to the material used for the welding of statue A. Moreover, according to I.C.R. analyses, the material used for restoring the arm contains large fragments of calcarenites, limestone pebbles, and abundant remains of Pliocene fossils (lamellibranch shells). These sediments, therefore, are compositionally very different from those of the rest of the body and very similar to those of the welding of statue A (Fiorentino, 2003; Fig. 154, p. 174).

According to the observations of Lombardi et al. (2003), the welding material of the restored arm is also characterised by “calcite with microgranules cemented by iron-rich sediment.” From the set of data reported by the author, elements emerge that strongly correspond to the “pietra giuggiulena”, a yellow-ochre organogenic calcarenite, particularly iron-rich, abundant in the Siracusa area (Giuffrida, 2010). The FeO content in the sediments inside the restored arm is comparable to that observed in the welding sediments of statue A (US 2227) (7.17%) and in the Ciane 5 level (7.01%), and significantly higher than the values found in both statue B (3.61%) and in the original welding material of its right arm (2.02%), further confirming their diversity. It must be noted, however, that the overlapping of two contiguous welds (the original one, performed at the time of assembly, and the subsequent one related to the restoration) caused a certain mixture of elements from the two different materials. More specifically, the layer of whitish sediments, presumably attributable to the clays used to weld the new restored arm, appears contaminated by “residues of previous, different casting clays baked in an oxidizing atmosphere and occasionally included in the whitish layer,” which can be explained both by the contiguity with the material of the previous weld and by “a secondary contamination induced by washing” (Lombardi et al., 2003, p. 169).

Finally, it's interesting to note that in the welding material of statue A and the bronze elements reconstructed after the damage to statue B's right arm, detailed analyses performed by Lombardi & Vidale (1998) and later by Jones et al. (2016) show the presence of fragments of basic volcanic rocks. The presence of these lithotypes is compatible with the composition of the deposits of the Pantanelli area, where monomineralic clasts of orthopyroxene and clinopyroxene and fragments of basic slag are abundant. Their nature can be traced back to the ash emissions of the Etna volcano or the erosive activity on the volcanic rocks that are abundant in the Anapo river basin.

The review of literature data does not exclude the possibility that the material inside the restored arm of statue B may be compatible with that of the welding of statue A and therefore come from the Siracusa area, although confirmation could only come from a direct

geochemical comparison with the material inside the arm of statue B. However, a further and important clue regarding the possible restoration of the arm in ancient Siracusa comes from radioisotopic investigations, which have shown that the lead from the tenons (the anchoring pins at the base of the two statues) belongs to the same batch of lead used for the fabrication of the arm. The same analyses attributed the origin of the lead to the Laurion mines in Greece (Formigli, 1984; Angelini et al., 2018). This means that at least a century after their fabrication (that is, starting from the 4th century BC, a time when this mine was particularly active) the two statues must have been reinstalled at the same time and in the same monumental group (Rebaudo, 2020, p. 34). Therefore, since statue A had to be assembled and placed in Siracusa, as the study of its welding material has shown, it is very likely that statue B, after its creation, was also brought to Siracusa, since it was then placed in the same monumental group that housed statue A.

Interpretation of the sedimentological and compositional data of the Sibari Plain and comparison with the casting material of the Bronzes

One of the goals of this paper is to suggest an alternative hypothesis to the Argive provenance of the casting material of the two statues because this is the most substantiated origin. Studies (e.g., Lombardi et al., 2003), published after the 1992-1995 restoration period, have excluded the Calabria region as a source site due to a lower chromium content in the Calabrian source rocks compared to that of the Bronze casting material. Moreover, these authors compared the chromium content of archaeological samples and that of the fluvial and coastal sediments of the Ionian margin of southern Calabria studied by Ibbeken & Schleyer (1991), all characterised by chromium content lower than that of the two statues. The source rocks of the Aspromonte massif, which provide clastic supply to the fluvial and coastal sediments of southern Calabria, analyzed by Ibbeken & Schleyer (1991), are very different from those that feed the sedimentary system of the Sibari plain in northern Calabria, because the Aspromonte terrains are devoid of ultramafic rocks. On the contrary, these latter, largely outcrop as source rocks in the Coastal Chain of northern Calabria and are made up of peridotite-pyroxenite-gabbros containing both chromium-bearing brown spinel and hercynitic spinel (e.g., Morten et al., 1999). This ultramaficlastic detritus is eroded and transported as bed load and suspended load along a complete transect extending in northern Calabria from the tributaries of the Crati river in the Coastal Chain to the alluvial plain (Fig. 20). Therefore, unlike the study by Lombardi et al. (2003), we suggest that multiple eroded source rocks such as peridotite-pyroxenite-gabbro rocks (e.g., Morten et al., 1999) could explain the high chromium content of the Riace Bronzes casting material.

In the casting material of the Bronzes both siliciclastic and carbonaticlastic compositional features have been recognised (Lombardi et al., 2003). In Bronze A the siliciclastic component prevails over the carbonaticlastic one. The siliciclastic components are represented by quartz, metamorphic rock fragments including ophiolitic detritus, and magmatic rock fragments both intrusive (granitoids) and effusive (basalts). In Bronze B the carbonaticlastic

component, represented by carbonate lithics and bioclasts, prevails over the siliciclastic one, characterised by metamorphic particles, including ophiolitic and granitoid grains. The comparison between the siliciclastic and carbonaticlastic components in sediments of the Crati river delta and of the Sibari coastal plain and those of the casting material of the Bronzes could suggest, in addition to the Argo and Peloponneso sites of provenance, also the Sibari site. Furthermore, the slight difference between the composition of the casting materials of the two bronzes, one more siliciclastic and the other more carbonaticlastic, could be the expression of two different sedimentary facies of the Sibari site where the casting sediment was collected, which could have undergone hydraulic control of selective sorting of the different sediment particles. Thus, we suggest that the Sibari Plain, where also the Auriga of Delfi was created (Psalti et al., 2018), could be considered a valid alternative to the Argos and Peloponneso sites of provenance for the casting sediments of the Riace Bronzes.

Scientific evidence that the two statues could not have remained on the seabed of Riace for millennia

The third of the three objectives of this work is to verify the scientific validity of the hypothesis that the statues did not originally sink at Riace, but in a different underwater context more compatible with the “marks” left on them by their interaction with the submarine environment. The discovery of the two Bronzes in the Riace offshore at a depth of 8 meters and 220 meters from the shore, in a site devoid of any archaeological context, has, from the very beginning, raised significant questions about their presence for millennia along a coastline that has, moreover, undergone profound geomorphological changes over the centuries (Caputo & Pieri, 1972). The submerged archaeological remains of Kaulonia, located just 7 km north of Riace Marina at a depth between 5 and 7.5 meters (<https://www.progettomusas.eu/kaulonia>), demonstrate that around 470 BC, the period to which the remains of the submerged archaeological area date back, the coastline was probably further out to sea. Therefore, two millennia ago, the seabed where the Riace Bronzes were found must have been shallower and closer to the shore than it is today.

The following sections will illustrate the scientific evidence that makes the hypothesis of a centuries-long presence of the Bronzes in the shallow waters of Riace implausible. This evidence is based on both the environmental and hydrodynamic context of the seabed, and on the taphonomic features present on the two statues and the geochemical characteristics of their surface patinas.

Characteristics of the Riace seabed and the absence of a relevant archaeological context

It seems unlikely that in two thousand years no one would ever have noticed their presence, nor that a fishing net would not have become entangled in them. The appearance of the statues at the time of their recovery also raised significant doubts, with Bronze B being substantially cleaned of large concretions and marine organisms, except in the most inaccessible parts, while Bronze A was partially covered by recently formed gravelly concretions

that came off with simple finger pressure (Sabbione, 1984). These details are incompatible with a millennia-long presence on that seabed. Not a single trace of a shipwreck was ever found, neither during the first survey in 1973 (Pallarès, 1984), nor the second in 1981 (Freschi, 1984), nor the one completed in 2024. The 28 rings recovered by Nino Lamboglia in that area in 1973 were initially attributed to the equipment of a ship but were later identified as fishing nets entangled in the rocks (Mariottini, 2009), while an anchor found nearby was dated to a “rather recent” period (Pallarès, 1984).

The hypothesis that the statues were abandoned during a storm to lighten their load also appears unconvincing, since in that case the Bronzes could never have settled on the bottom so neatly, one next to the other. Finally, even the hypothesis of their voluntary deposition in the sea by human hands (Roma, 2000) does not appear convincing, given that the shallow depth could never have protected them from the intense hydrodynamic processes that have profoundly altered the geomorphological configuration of that shallow seabed over the centuries. Instead, the analysis of the patinas and marine concretions (organogenic and terrigenous) seems to prove that the two statues came from a different marine context and, above all, from a millennia-long permanence in much deeper seabed.

Relationship between the hydrodynamic, geomorphological and bathymetric aspects of the Riace area and the state of conservation of the Bronzes

The Bronzes were recovered in August 1972 at a depth of approximately 8 meters in the Ionian Sea, off the coast of Riace. While the corrosion patinas on these statues include copper sulphides, typically indicative of reducing conditions, such compounds can form within localised microenvironments, such as beneath biofilms or within sediment pockets, without requiring widespread anoxia. Persistent anoxic conditions, especially those favoring the long-term preservation of sulphide-rich patinas, generally necessitate a stable, stratified water column with minimal physical disturbance. However, consistent geochemical indicators of such euxinic settings, like laminated black sediments, abundant pyrite framboids, or persistent sulfidic layers, have not been documented at the Riace site (Buccolieri et al., 2015). Oxygen Minimum Zones (OMZs), which are defined by sustained low oxygen concentrations in the water column, typically occur at intermediate depths between 200 and 1,000 m and are associated with restricted circulation and high biological oxygen demand (Helly & Levin, 2004). These conditions are not relevant to the open shallow shelf environments of the Ionian Sea, where the Riace Bronzes were found. In Mediterranean coastal zones, transient hypoxia can develop, but such events are usually confined to semi-enclosed, eutrophic basins rather than open coastal shelves like that off Riace (Kralj et al., 2019). In these open shelf settings, particularly those composed of coarse-grained sands, oxygenated waters easily penetrate the upper layers of the sediments. This permeability is enhanced by physical mixing due to wave action and biological reworking by benthic fauna, such as polychaetes and crustaceans, which contribute to sediment aeration and inhibit the formation of sustained anoxic conditions (Kristensen, 2001).

Wave dynamics play a particularly important role in the nearshore environment off Riace. Extreme sea states along the Ionian coast exhibit significant wave heights (Hs) ranging from 6 to over 10.5 m for return periods of 1 to 100 years, with corresponding wave periods between 8.1 and 10.4 seconds (Arena et al., 2013). Applying the linear dispersion relation for deep-water waves, these periods translate into wavelengths of approximately 100 to 160 m. Orbital motions associated with such waves are capable of reaching the seabed at depths exceeding 50 m and are especially pronounced within the 10–50 m depth range. Given the relatively gentle slope of the Riace coastal shelf, the 8–10 m depth at which the statues were discovered falls well within the active wave orbital motion zone during major storm events. In such a dynamic hydrodynamic regime, the seabed is subject to intense physical forcing, including periodic resuspension of sandy substrates, scouring, and mechanical abrasion. These conditions are incompatible with the formation or long-term preservation of stable anoxic microenvironments necessary for the undisturbed development of sulphide-rich corrosion layers. Moreover, the integrity of the patinas on the Riace Bronzes, especially the presence of multilayered corrosion products containing copper sulphides and chlorides, raises further questions. Such patinas are generally sensitive to physical disturbance, and their preservation would be unlikely under conditions of recurrent sediment movement and wave-induced shear stress. Therefore, the hypothesis of a prolonged in situ burial under calm, chemically reducing, and physically undisturbed conditions appears inconsistent with the documented local wave climate and seabed dynamics. The environmental setting strongly suggests periodic exposure to storm-induced energetic processes, rather than continuous burial within a stable, reducing milieu.

Relationship between the characteristics of the Riace seabed and the taphonomic and alteration state of the Bronzes

The taphonomic conditions occurring at shallow depths such as those of Riace (8 m), in marine environments characterised by coarse-grained bottoms subject to high hydrodynamics, would certainly be unfavourable to the preservation of any artifact lying on the seabed for a period even much less than 2,000 years. In these environmental conditions, destructive processes prevail, such as mechanical abrasion due to wave motion and coastal currents, as well as corrosive chemical action of oxygen-rich waters, with the formation of oxidative crusts and patinas of secondary minerals on the artifact's surface. Furthermore, a significant colonisation by soft (green and brown) algae and subordinate sessile invertebrates occurs rapidly on the artifact just three months after its exposure on the seabed (Casoli et al., 2014). These taphonomic conditions significantly alter the original state of the artifact lying on the seabed even after just a few decades and, over time, can even lead to its complete destruction. This is confirmed by the almost total absence of literature data documenting the occurrence of large bronzes or other important artifacts in the Mediterranean at shallow depths such as those of Riace. Even more, literature records documenting bronze artifacts that at such shallow depths have maintained the same exceptional state of preservation as the Bronzes, are lacking at all.

A rare example of the appearance of a bronze artifact subjected to intense hydrodynamic action is the bronze Lion's Head (50 cm base), discovered on August 16, 2012, off Capo Bruzzano (Africo, Reggio Calabria). This find occurred 55 km south of Riace Marina, 80 meters from the shore, and at a depth of about 6 meters, in a seabed devoid of archaeological context (Felici, 2012). As can be seen from the images (Fig. 24), the lion's head appears corroded and smoothed by mechanical abrasion.

Only by extending the search for bronze artefacts in the Mediterranean to greater depths there are some findings, albeit rare and in poor condition, such as those of the famous Antikythera wreck at depths of 40–60 m, with incomplete remains of heavily encrusted and corroded bronzes (Zapheirou, 2012; Kaltsas et al., 2012) together with marble statues also in bad preservation status (Ricci et al., 2019), and such as that of the naval ram found off the coast of the Egadi Islands at 75–95 m (Tusa, 2020; Gravina et al., 2021). These findings reveal a considerable carbonate crust, clearly showing the effects of taphonomic processes undergone after a period of over 2,000 years. In fact, at these depths the taphonomic alteration on artifacts, including the production of coralligenous crusts (see above), is still high, although less destructive than those likely occurring in the shallower bottoms of Riace. Here, at a depth of 8 meters, given the high lightness, hydrodynamics and high oxygenation of water, in place of the Coralligenous, the biocenosis of "Photophilic Algae" forms, with dominant soft algae and spirorbids (Catra et al., 2017), quite different and smaller than the serpulids of the Coralligenous. However, the encrustations on the bronze Dancing Satyr from Mazara del Vallo, Trapani (Petriaggi, 2004; Ricci & Bartolini, 2005), found at a depth of 400 m in complete darkness, are not coralligenous crusts, since algae are completely absent and mainly serpulids and corals are present, with species ecologically compatible with the bathyal depth of the find (Ricci &



Fig. 24 - A bronze lion's head was discovered in 2012 off Capo Bruzzano (Africo). The head exhibits a remarkably smooth, polished surface, a result of the intense hydrodynamic forces present in the shallow seabed where it rested (from Felici, 2012).

Bartolini, 2005). These 5-6 mm thick calcareous concretions are mixed with silica sand and appear very hard and compact, similar to those of the Riace Bronzes here described. Interesting is the presence of “a smooth and compact dark patina,” also found on the Bronzes. In some portions very close to the metal surface, this patina tends to peel off locally, revealing a porous light green layer underneath. This black patina has been attributed to the action of sulfate-reducing bacteria and identified as “carbonaceous organic matter” (Petriaggi, 2003).

In light of the above considerations, discrepancies between the state of preservation of the Bronzes and the presumed depth of discovery at Riace are evident. Rather, a depth of 70 meters is compatible with the recognised serpulid coralligenous crust on the Bronzes, attributable to the sciaphilic conditions of the depositional environment (Rosso et al., 2013). At this depth, the bottom sediments are remarkably rich in mud that facilitates the preservation of the finds, as demonstrated by the lack of corrosion and abrasion of the Bronzes. In some parts of the Bronzes, as documented by photographic images, a carbonate crust with associated serpulid tubes and bryozoans is clearly visible, although unfortunately they are not distinguishable with the naked eye due to their microscopic size.

Relationship between the Riace seabed characteristics and the geochemical aspects of the Bronzes surface patinas

Important information about the history of the interaction of the Riace Bronzes with the underwater environment that hosted them for millennia comes from a review of the geochemical study of their surface patinas. Since their original sinking, as the corrosion process progresses on the surface of the bronze alloy, the formation of secondary products begins, meaning more stable patinas in the environment in which the statues resided.

The Bronzes exhibit three main types of patina, depending on the chemical-corrosive mechanisms and the environments in which they were deposited (Mello et al., 1984; Mello, 2003; Buccolieri et al., 2015):

- a) a predominantly reddish patina composed primarily of cuprite [Cu₂O], adherent to the bronze alloy, partly already subject to selective corrosion, which is partly repeated later in the microstratigraphy, for example over the subsequent dark patina;

- b) a second dark patina (greyish-black), compact, of uniform thickness, composed of copper sulfide based primarily on chalcocite (Cu₂S), adhering to the previous layer;
- c) a third superficial patina composed primarily of copper chlorides, varying in greenish hues, rather irregular and thin in thickness, spread heterogeneously across the surface.

The first two patinas, often intertwined, are found primarily in the best-preserved parts of the statues, while in other areas, likely more exposed to degradation or more affected by restoration, the dark sulfide patina is absent. These patinas are associated with the overlying carbonate layers and sandy encrustations (i.e., terrigenous concretions) cemented by secondary corrosion products found in a disordered fashion across the statues’ surfaces (Fig. 25).

Various hypotheses can be formulated regarding the modalities and relative timing of the formation of this stratigraphy. Based on available data and evidence from the literature, the first two layers would appear to be linked to a progressive alteration cycle of the Bronzes and probably correspond to the first long depositional phase of the statues once immersed in the sea. Cuprite is a typical corrosion phase of copper. The conditions favourable to the formation of cuprite are environments with limited oxygen presence, unlike strongly oxidising environments which lead to the more copious formation of the oxide (tenorite) with a lower copper/oxygen ratio than cuprite. Considering that the formation of such patinas also requires stable conditions for long periods, a poorly oxygenated environment of medium depth (50-100 m), with a low-energy seabed, represents a favourable situation for the metallic copper dissolved in the bronze to oxidise in the initial layers of corrosion products, forming a homogeneous cuprite layer [4Cu+O₂→2Cu₂O]. This likely occurred in the initial phases of exposure of the Bronzes on the seabed. After this more or less long period, during which biological activity was inhibited by the presence of dissolved metallic copper, and the formation of an initial (more stable) patina of copper oxides, it is possible to imagine a slow and light partial covering of the statues. According to this logic, the formation of the dark sulphide patina, as previously proposed by various authors (Gettens, 1970; Vlad Borrelli, 1975; Frazzoli et al., 1973; Formigli, 2013; Mello, 2003), would therefore be linked to poorly oxygenated and/or partially anaerobic natural environments. In such environments, sulphate-

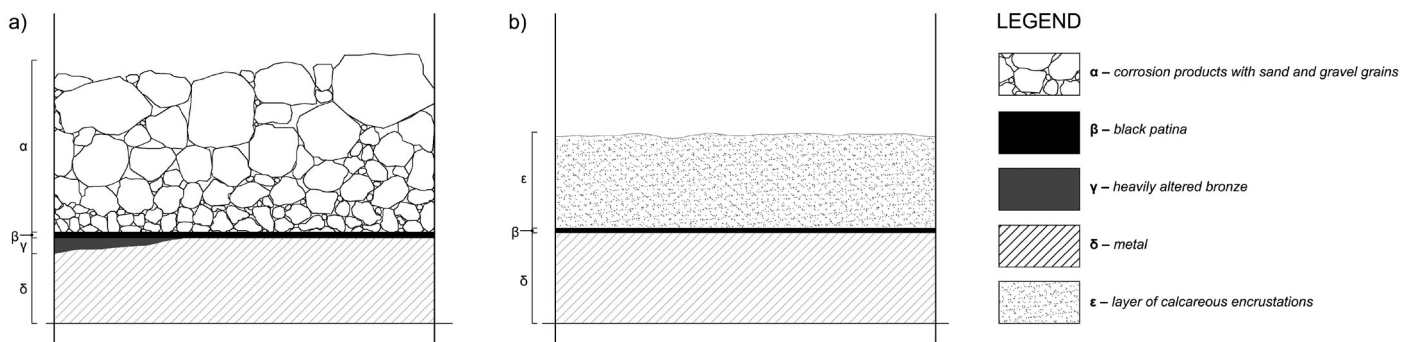


Fig. 25 - Schematic representation of the sandy (a) and calcareous (b) encrustation layers adhering to the bronze surface (from Mello et al., 1984, modified).

reducing microorganisms (e.g., *Desulfovibrio* spp.) develop, producing hydrogen sulphide (H_2S), which reacts with cuprite (or directly with the copper of the underlying alloy) to form copper sulphides. The susceptibility of metal substrate to the formation of microbiologically produced sulfides (by Sulfate-Reducing Bacteria: SRB) is predicted by a thermodynamic model proposed by McNeil & Odom (1994). The model for predicting SRB-influenced corrosion is based on the probability of a metal reacting with microbiologically produced sulfide, where the MIC (minimum microconcentration) of SRB is triggered by sulfide-rich reducing conditions in the biofilm, and under such conditions the oxide layer on the metal (or the metal itself) is destabilised and acts as a source of metal ions. On the outer surface of the SRB, sulfide ions react to produce sulfur compounds in micrometer-sized particles that are in some cases crystalline. The consumption of metal ions at the microbial surface is balanced by the release of surface ions until the oxide is completely consumed. If the reaction to convert metal oxide to metal sulfide has a positive Gibbs free energy at surface conditions, the sulfides will not remove the protective oxide and no corrosion will occur. If the Gibbs free energy for that reaction is negative, the reaction proceeds, the sulfide microcrystals redissolve and reprecipitate into larger crystals, generally richer in sulfur, ultimately altering the sulfide minerals stable under biofilm conditions.

In the specific case of Riace Bronzes, in agreement with Little et al. (2008), the sequence of secondary product formation during SRB-influenced corrosion reactions is chalcocite (Cu_2S) in the initial stage and covellite (CuS_{1+x}) as the final product. Indeed, the XRD analysis results of Mello et al. (1984) indicate that, in addition to the predominant presence of gray-black chalcocite (Cu_2S), dark-coloured digenite ($Cu_{1.8}S$) and, to a lesser extent, covellite (like CuS), a bluish-black sulfide with an even lower Cu/S molar ratio than chalcocite and digenite, are present on the dark patina. Covellite forms in an even more anoxic microenvironment where microbial activity has been more intense (a more reducing environment). Such conditions are likely to arise in the case of seabeds with depths >70 m, characterised by low energy on the seabed and the presence of predominantly muddy sediments. The sulfide patina, although limited in thickness (10-50 μm), has thus formed a compact, protective, and stable layer, which has undoubtedly slowed corrosion over the centuries.

Considering all possible scenarios, it cannot be ruled out a priori that the statues, even in their initial phase, remained deposited for millennia in a substantially anoxic marine environment, at greater depths (80-120 meters). The sulphide patina would represent the first layer adhering to the bronze alloy, while the formation of cuprite-based copper oxides (under and above the sulphide patina) would represent the result of partially oxidizing alteration processes that the statues underwent in a second phase, in depositional conditions evidently different from the first phase mentioned above. In the latter case, the second phase would not involve such a short timeframe (at least a few years), as cuprite does not form in a matter of days. The alteration process through oxidation of the copper sulphide would have pervasively affected the protective dark patina layer, starting especially from the areas where the latter had already been partially removed and continuing along the interface between the bronze alloy layer and the sulphide layer.

Given the compactness, shiny appearance, and uniform thickness of the sulfide patina, some authors (Mello et al., 1984) and other scholars have discussed the possibility that it was artificial, created through a treatment with hydrogen sulfide vapors (Zenghelis, 1910) for aesthetic and conservation reasons by the artisans/artists who produced the statues, hypothesizing that the patina would have been removed by abrasion following immersion in seawater. If this path were followed, a very wide range of possibilities would open up. While it would be easier to explain some aspects of the evolutionary history of the Bronzes, including the absence of the dark patina in the parts of the statues most exposed to mechanical action (or perhaps because it was already partially absent when the statues fell into the sea), rather than its absence on the internal faces of the fissures induced by cracking (which would need to be further investigated if a natural origin for the dark patina were chosen), on the other hand, it would raise some questions that would require further explanation, such as the formation of the cuprite layer, linked to a partially oxidizing environment, positioned immediately beneath the sulfide patina. In other words, it would be difficult to argue that the artificial copper sulfide patina was not applied directly to the surface of the Bronzes but over a layer of cuprite that formed naturally in environments with limited oxygen.

Regardless of what has been hypothesised above, given the heterogeneous distribution of the sulphide patina on the surface of the statues, which is preferably concentrated in the best-preserved areas (e.g., the area between the buttocks), it remains to be understood which processes, and at what time and in what period, may have led to the removal of the original dark patina which evidently at an early stage may have covered perhaps a large part of the external surface of the statues. The dark patina may have been removed by alteration induced by a new, more oxidizing environment compared to the initial deposition phase of the statues, in which the copper sulfides may have been chemically degraded to cuprite and/or abraded by the natural mechanical action of angular silicate sediments belonging to the seabed. Added to this is the anthropogenic action of the recent 20th century (including restoration), which may have resulted in the removal of part of the sulphide patina.

Above this and the bronze alloy, as already highlighted by Mello et al. (1984), the presence of two main types of secondary encrustations is observed: one of essentially calcareous composition with no sandy component; a sandy encrustation, typically terrigenous polygenic, consisting of sediments with varying grain sizes (from sands to conglomerates with grains well over 2 mm; see photographs, MCHE, 1984), with a silicate composition (mainly quartz), cemented by cupric oxides (cuprite) in the innermost part and by chlorides in the outermost part. As highlighted by the mechanical cleaning interventions during the ICR restoration (Mello et al., 1984), the encrustations, especially the sandy ones, did not show great adhesion to the substrate consisting of the black patina which instead appears to adhere well to the bronze alloy. These encrustations must be associated with the widespread presence of various copper chloride patinas, variously distributed on the external surface of the statues, which formed over the calcareous encrustations and over the exposed

layers of the dark sulphide patina and the bronze alloy (Buccolieri et al., 2015).

Given the presence of evident coralligenous crusts dominated by serpulids (see previous section) and likely associated bryozoans (hardly recognizable from images of the statues immediately after their discovery), the calcareous encrustation is likely associated with a long phase of carbonation that occurred over centuries by marine fauna typical of mid-shelf seabed (70-100 m b.s.l.), where algal development is limited due to the low light. The calcareous encrustations undoubtedly further protected the statues over the centuries. Conversely, the different layers of subsequent sandy encrustations and chloride patinas indicate distinct secondary product formation patterns, distinct from the previous conditions that led to the formation of the first copper oxide layers, the sulphide patina, and the subsequent calcareous encrustations. Therefore, beyond the long period of millennia that preserved the statues, there would appear to have been a further phase with partially different environmental conditions and decidedly short in time. In this second phase, initially there was an increase in the degree of oxygenation compared to the original poorly oxygenated environment, with reactivation of the corrosive processes on the alloy, dissolution and release of copper on the surface with consequent formation of cuprite, which incorporated and consolidated the sandy-conglomeratic matrix deposited above the stratigraphy described above. Subsequently, as confirmed by XRD analyses (Mello et al., 1984), there was the formation of copper chlorides, of a greenish colour, typical of an oxygenated and chloride-rich environment (probably open sea), which highlight, in addition to the underlying cuprite [Cu₂O], the main presence of atacamite [Cu(OH)₃Cl] and subordinate chalconatronite [Na₂Cu(CO₃)₂·23H₂O]. In the prolonged presence of oxygen and chlorides, cuprite itself can transform into other secondary products such as atacamite, paratacamite, malachite, and nantokite.

In conclusion, we can state that the different observed microstratigraphy, combined with the different environmental conditions, resulting from both natural and anthropogenic processes, evidently refers to at least two distinct alteration phases in time. These phases are currently difficult to interpret archaeologically, except for sudden environmental changes in the evolutionary history of the statues after sinking into the sea. These phases are in fact reflected in the stratification found in investigations carried out by numerous authors; in chronological order: (i) first phase: poorly oxygenated environment (depth of 70-100 m), in which there was initially corrosion and oxidation of the bronze alloy with formation of the layer of copper oxide (cuprite) (1a), and subsequently the formation of the dark sulphide patina (1b) due to bacterial activity of sulphate-reducers, and of coralligenous crusts (1c) with obvious serpulid tubes and carbonate micrite; and (ii) second phase: oxidizing environment, probably shallow sea (depth < 20 m), partly locally with conditions of lower oxygenation due to burial by sediments (e.g., Boccaccini et al., 2024; Wadsak et al., 2000) or, as described in literature (Oudbashi, 2018; Nord et al., 2005; de Caro et al., 2023; Boccaccini et al., 2024), in the subsoil in the presence of percolating/circulating waters loaded with chloride-based compounds. During this phase, the oxidation of the sulphide patina and of the metallic copper accumulated on

the surface of the statues took place, with the formation of sandy encrustations (whose crystalline grains derive from the incoherent sandy-conglomeratic sediment) cemented initially by copper oxides (2a) and subsequently by copper chlorides (2b).

The excellent preservation of the bronze alloy can therefore be attributed to the first phase, in marine environmental conditions with low oxygenation, relative hydrodynamic stability, and the likely subsequent gradual partial covering of muddy sediments. Given the relatively slow corrosion process, the statues would have been well preserved for a likely very long period of time (millennia). During this first phase, the following factors certainly had a positive impact and slowed corrosion: (i) the formation of the sulphide patina, due to its high stability (as demonstrated in the literature) in a partially oxygenated environment; (ii) the covering and protection of the calcareous encrustations; (iii) the presence of the internal reinforcing rods, which served as sacrificial anodes; and (iv) the low concentration of Fe (<0.1%) in the original bronze alloy of the statues, which, as explained above, would have been a strong alteration agent (Oudbashi & Wanhill, 2021). Conversely, the second phase, which refers to the deposition of the Bronzes in more oxidizing environments (e.g., shallow seabeds), negatively impacted their state of conservation. This phase, in chronological order, involved: (i) the removal of part of the sediments and calcareous encrustations formed in the first phase (later completely removed during restoration operations); (ii) the abrasion removal of part of the more superficial patinas; (iii) the subsequent reactivation of corrosive processes with the chemical alteration of the patina to sulphide; (iv) the accumulation of copper and related cuprite oxides on the surface; and (v) the formation of sandy encrustations initially cemented by copper oxides and then by copper chlorides. In particular, the formation of these latter corrosion products (Doménech-Carbó et al., 2008; Cosano et al., 2018; De Caro et al., 2023) severely attacked the bronze alloy, as evidenced by the presence of Cl and Na ions, together with that of oxygen, immediately below the surface portion (at a distance of approximately 1.1 µm), indicating a significant penetration of chlorides (e.g., NaCl), oxides and hydroxides into the surface part (Mello, 2003). The second phase processes are evidently attributable to new environmental conditions that can be represented by typically shallow-sea environments (depth < 10 m) with higher energy, likely coinciding (at least in the last stage) with those of Riace. The times of action of the corrosion processes and formation of chloride patinas in this case are much faster than those of a poorly oxygenated medium-deep sea environment where the statues probably remained deposited for millennia.

Scientific evidence on the possibility of a millenary deposition of the two statues on the deep seabed of the Sicilian Ionian coast

Considered the lack of scientific evidence for a millenary burial of the Riace Bronzes on the seabed of Riace, it is particularly interesting to study the ideal characteristics of a seafloor that could have ensured their exceptional state of preservation. Three key characteristics stand out: i) high depth, which would create anaerobic conditions; ii) a rich presence of sulfates, which are

generally abundant in marine environments; iii) most importantly, a reducing habitat composed of clayey mud, which would be best suited to preserving the statues for thousands of years. In light of the hypothesis put forward in the 1980s by archaeologist Robert Ross Holloway (Holloway, 1988) regarding the supposed discovery of the statues off the Sicilian coast, and also considering recent publications (Archeo, XXXIX n. 478, December 2024; Archeologia Viva, XLIV n. 231, May/June 2025) that suggest a potential original discovery in the offshore of Brucoli (the ancient Greek city of Trotilon) in Sicily, below we will examine the scientific, as well as historical and literary, compatibility of this hypothesis (Fig. 26). The area where the statues were supposedly found, according to the testimonies published by Archeologia Viva (231/2025, p. 56), is located near a shoal 1.8 miles northeast of Punta Tonnara. The seabed there is silty and clayey and reaches depths between 70 and 90 meters (Fig. 27).

Characteristics of the seabed off Brucoli

A detailed description of the seabed off Brucoli is provided by the data sheet published by the Ministry of the Environment on the Sites of Community Importance in the Sicily Region, specifically the SIC ITA090026 sheet, "Fondali di Brucoli-Agnone". The seabed is characterised by clayey and silty muds resting on a rocky substrate of carbonate limestones and volcanic rocks. Over centuries, this muddy layer has been fed by the fluvial input of the Simeto and San Leonardo rivers, whose mouths are located in the Gulf of Catania (Fig. 26), transported by the strong north to south currents that prevail for most of the year. The promontory on the eastern side of the bay of Brucoli (Punta Tonnara) marks the southern limit of the Gulf of Catania and slows the flow of material from the two northern rivers, causing a significant accumulation of clay sediments directly in front of Brucoli. At the same time, the seabed has been enriched by fluvial gravels deposited by the Porcaria stream, the ancient Pantakias river (Fig. 27), which is now the Brucoli channel port

(Russo, 2004). An important geochemical characteristic of the Brucoli bay is the historic presence of hydrosulfurous emissions, which are particularly abundant near the channel (Russo, 1997) and were described as early as 1777 by Jean Houel: "in the middle of the channel, a very strange spring gushes from a sheer rock face and emerges almost at water level. The water is extremely clear, but it is rich in sulfur. The sailors assured me that when the wind blew from the west, an infinite amount of it could be seen on the surface of the water" (Houel, 1782, Plate CLXXV). The occurrence of sulfurous water was also reported in the late 19th century by the naturalist Consiglio Ponte (1894).

From a geomorphological point of view, the seabed of Brucoli extends for just over a mile along a shallow sandy platform. This platform then slopes down rapidly, reaching great depths around a shoal that rises two miles northeast of Capo Tonnara (Fig. 27). The seafloor descends in progressive terraces limited by ancient coastlines to depths of 70, 80, and 90 m. b.s.l., before reaching much greater depths beyond two and a half miles out. A little-known but important characteristic of the Brucoli seabed is the presence of corals along the rocky walls of the shoal. This presence is attested to as early as the 18th century by Gargallo (1791): "boats from Trapani, Favignana, and Lipari fished for white, red, and black coral near the Augusta coast, yet without bringing any added economic value to the poor people of Augusta, as the coral branches were collected and immediately shipped to be sold elsewhere in the Mediterranean markets" ("le barche trapanesi, favignanesi e di Lipari, esercitavano la pesca del corallo bianco, rosso e nero presso la costa augustana, pur tuttavia senza portare un valore economico aggiunto alla povera gente di Augusta, in quanto i rami di corallo, venivano raccolti e subito imbarcati per essere venduti altrove nei mercati del Mediterraneo", A.C.G., 2023).

It is worth noting that the Brucoli seabed at the above-mentioned depths hosts significant coralligenous reefs, built by dominant calcareous algae and invertebrates, as reported in Appendix A of the aforementioned document on Sites of Community Importance

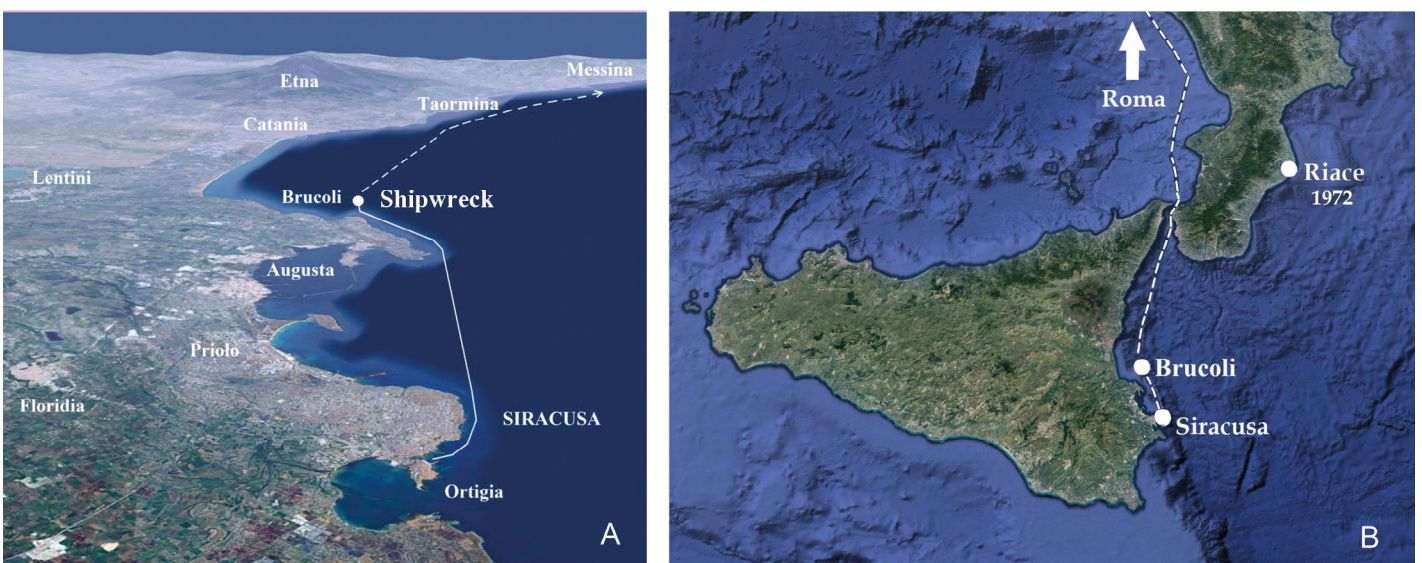


Fig. 26 - A) Ionian coast of Sicily and the presumed shipwreck site, along the ancient naval route to Rome (B), according to the testimonial hypotheses collected and published by Archeo (2024) and Archeologia Viva (2025) (from Madeddu, 2025, modified).

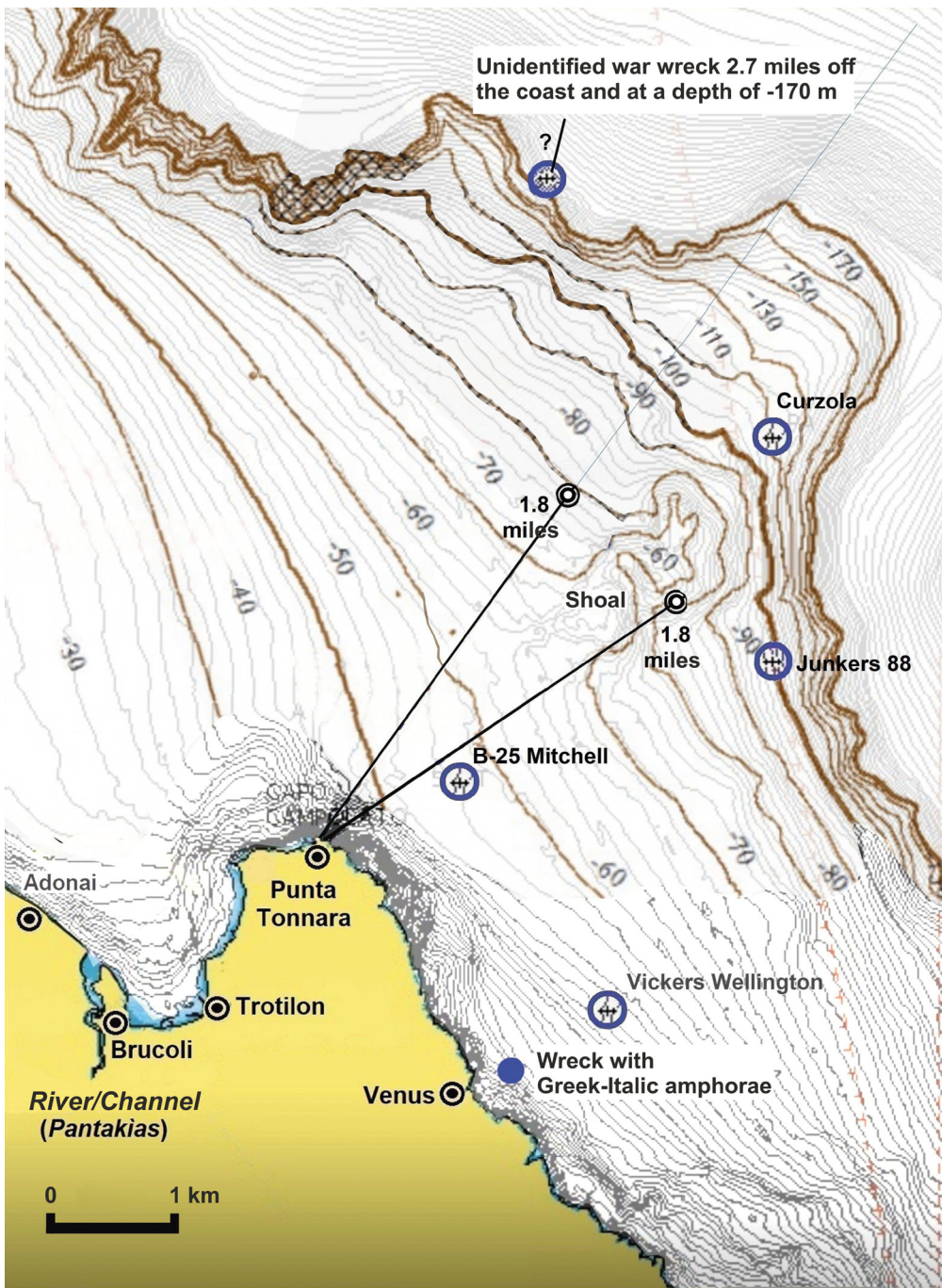


Fig. 27 - Map of the seabed off Brucoli showing bathymetry, the shoals, the wrecks known to date, and the area 1.8 miles northeast of Punta Tonnara, indicated by the testimonial hypotheses collected and described in *Archeo* (2024) and *Archeologia Viva* (2025) (from Madeddu, 2025, modified).

published by the Ministry of the Environment, “Conservation Measures of SIC ITA090026: Fondali di Brucoli-Agnone,” which indicates the conservation measures for this precious habitat. This is consistent with the presence of coralligenous concretions on the surface of the Bronzes, confirming the hypothesis that the Bronzes originated from bottoms at depths compatible with the coralligenous development, just like those off the coast of Brucoli.

Presence of shipwrecks and archaeological artifacts from the Classical age in seabed off Brucoli

Since antiquity, Brucoli has been a crucial transit point for all naval routes that from Siracusa (or Africa) travelled north towards the Strait of Messina to reach Rome, or east along the Calabrian

coast to reach Greece (Fig. 26). This strategic location, combined with its proximity to the coast and the intense currents, winds, and storms, has led to numerous shipwrecks over the centuries. All of this has made the Brucoli seabed one of the richest in shipwrecks and archaeological artifacts along the entire Ionian coast of the island (Mentesana, 1979). Unfortunately, starting in the 1960s, the seabed of Brucoli was savagely plundered by Italian and foreign underwater tomb raiders, who took away artifacts of considerable value. According to oral and photographic testimonies collected from fishermen and divers from the surrounding area by the archaeologist Fabio Portella, an honorary inspector for the Superintendency of the Sea of Sicily, various anchors, precious objects, and hundreds of amphorae were recovered (and often looted) from the Brucoli seabed. Some were jettisoned, while

others were linked to shipwrecks from various historical periods, from the 5th century BC to the Hellenistic Roman, Late Antiquity, and even the Spanish domination eras. According to diver Filippo Tringali from Augusta (south of Brucoli, see Fig. 26b), between the 1960s and 1970s, three French divers recovered numerous swords and helmets off Punta Tonnara (Fig. 27) from the wreck of a 16th-century Spanish galleon. Finally, in more recent times, the seabed of Brucoli has also become site to modern wrecks, including the royal tugboat Curzola, which sank at a depth of 118 meters in 1935, and three World War II planes: a British Vickers Wellington at 52 meters, an American B-25 Mitchell at 57 meters, and a German Junkers 88 at 102 meters. An unidentified military wreck has also been found at a depth of 170 meters, 2.7 miles northeast of Punta Tonnara.

It's worth to note that in December 2022, Fabio Portella, on behalf of the Superintendency of the Sea, discovered traces of a likely Roman shipwreck just 5 meters deep, northwest of Punta Castelluccio. The site showed imprints of several artifacts that had been stolen, along with numerous ceramic fragments and perfectly squared stone blocks. The person who reported the find had also claimed the presence of two intact amphorae (which were later stolen), one of which had the inscription "XVII." During other surveys in 2023, Fabio Portella found traces of a possible wreck with ceramic fragments—likely remnants of pottery damaged by storms and years of looting—one mile southwest of Punta Tonnara and 200 meters off the coast of the present-day Hotel Venus. Following further investigations and thorough photographic documentation, he was informed of the recovery of an anchor (delivered to the Melilli Museum) and the illegal removal of numerous MGS II type Greco-Italic amphorae. These amphorae, dating from the 5th to the 4th century BC, were taken between the 1970s and 1980s from a depth of about 25 meters in the same wreck area.

Finally, the discovery of three large anchors from Greek ships recovered between Brucoli and Augusta dates back to 1968-1970. This recovery was supervised by Mario Montesana, who was then an archaeological inspector for the Superintendency of Siracusa (Montesana, 1979). The largest of these anchors, which is 2.10 meters wide and weighs 650 kilograms, is now located at the Paolo Orsi Archaeological Museum (A.C.G., 2019). Many anchors recovered along the Siracusa coast are currently displayed in the gardens of the Siracusa Archaeological Museum.

The relationship between the characteristics of the Brucoli seabed and the state of preservation of the statues

The Brucoli seabed around the shoal are characterised by terraces located between 70 and 90 m b.s.l. This depth is compatible with the protective effects against marine hydrodynamics that, according to the linear dispersion relation illustrated in paragraph 7.4.2., beyond 50 m b.s.l. loses the destructive capacity of wave action. In such a static hydrodynamic regime, like the one observed between 70 and 90 m b.s.l., the seabed is no longer subjected to the intense physical stresses that, at shallower depths, lead to the periodic resuspension of sandy substrates, erosion, and mechanical abrasion. Furthermore, these depths are also compatible with the formation and long-term preservation of stable anaerobic

microenvironments necessary for the undisturbed development of sulfide-rich corrosion layers, such as those observed on the surface of the Riace Bronzes. The presence of circalittoral *serpulids* of the species *Serpula lobbiancoi*, observed on the less accessible parts of Bronze B, is also consistent with deep, poorly lit environments like caves or the depths found around the Brucoli shoal. Finally, the presence of coralligenous crusts dominated by serpulids on some parts of the surface of the Bronzes has no justification in the Riace seabed, which lacks them, while it is compatible with the Brucoli seabed, which is very rich in coralligenous along the rocky walls of the shoal.

In conclusion, the Brucoli seabed is compatible with the hypothesis considered in this study for several reasons: i) it is rich in clayey muds, an ideal habitat for the perfect preservation of metallic artifacts; ii) it is characterised by sulfurous emissions and by a deep, anaerobic, and reducing environment, which are well correlated with the generation of black copper sulfide patinas on bronze artifacts; iii) last but not least, the presence of a rich archaeological heritage in a strategic transit site for all ancient routes between Siracusa and Rome has been documented.

THE HISTORICAL AND LOGICAL PLAUSIBILITY OF THE SYRACUSAN HYPOTHESIS

Having analyzed the scientific plausibility of the hypothesis - based on geochemical data, on a review of existing literature, and on the taphonomic characteristics of the two Bronzes and their patinas - we must now assess its historical, logical, and archaeological plausibility. First, it is interesting to review the literature on the significant statuary commissions and the enormous bronze heritage that historical sources document in ancient Greek Siracusa. It is also useful to focus on the two fundamental historical moments in the history of the statues: the era of their commission, which helps us shed light on the patrons, sculptors, and the subjects depicted, and the age of their sinking. The hypothesis is plausible with respect to the historical moment they were created, the second quarter of the 5th century BC, a period when Siracusa, under the *Deinomenids* dynasty, became the leading city of the Hellenic West. But it also appears plausible with respect to the geographical location and the historical moment of the shipwreck, namely the Roman sack of Siracusa in 212 BC. This event is perfectly compatible with both the period (the 3rd century BC) and the location of the sinking (the Sicilian Ionian coast), although other historical possibilities cannot be entirely ruled out.

The great bronze statuary heritage of ancient Siracusa

A careful re-reading of historical sources on ancient Siracusa clearly reveals the impressive bronze heritage that accumulated over centuries, from the age of the *Deinomenids* until the Roman conquest. This also attests to the intense metallurgical activity and the extraordinary circulation of statues, sculptors, and workshops in the city, placing the Aretusan polis among those that could boast one of the largest bronze statuary collections in antiquity. The sources identify the *Deinomenids* as the greatest patrons of

bronze statuary of their time. Indeed, as *Pausanias* and other ancient historians tell us, their commissions filled not only Siracusa but also the Panhellenic sanctuaries of Olympia and Delphi with masterpieces. This was done to celebrate their victories in the Olympic and Pythian games, but also, and above all, to extol the historic victories of Himera and Cumae and, in this way, exercise their powerful political propaganda throughout Hellas.

A *Survey of Major Commissions by the Deinomenids and Their Circles to the Leading Artists of the Early Classical Period (480–466 BC)*. This study examines the principal sculptural commissions promoted by the *Deinomenids* and their entourage during the fifteen years in which they dominated the political and cultural scene of the Hellenic World, between 480 and 466 BC. These are celebrated sculptural ensembles, attested in literary and epigraphic sources, all attributable to the patronage of the *Deinomenids* during the second quarter of the Vth century BC—the same chronological horizon as the Riace Bronzes. The scale and consistency of this bronze statuary program found no parallels in contemporary *poleis*, nor among any other aristocratic elite of the Hellenic world of the time (Pafumi, 2015).

Among the most notable commissions are: a statue of *Gelone* on a chariot, by *Glaukias* of *Aigina*, sent to *Olympia* (*Pausanias, Periegesis*, VI, 9, 4–9); a *Nike* and golden tripod, by *Bion* of *Miletos*, dedicated by *Gelone* at *Delphi* (*Diodorus Siculus, Bibliotheca Historica*, XI, 26, 7); a statue of *Zeus* erected by *Gelone* in the *Treasury of the Carthaginians* at *Olympia* (*Pausanias, Periegesis*, V, 19, 7); a statue of *Zeus* draped in gold, housed in the *Olympeion* of *Syrakousai* (*Valerius Maximus, De Neglecta Religione*, I, 2); equestrian and charioteer statues representing *Phormis*, general under the *Deinomenids*, sculpted by *Dionysios* of *Argos* and *Simon* of *Aigina*, located at *Olympia* (*Pausanias, Periegesis*, V, 27, 1–2); statues of four warriors dedicated by *Lykortas*, officer of the *Deinomenids*, at *Delphi* (*Pausanias, Periegesis*, V, 27, 7); a statue of *Gelone* offered by his brother *Ierone* at *Delphi* (*Plutarch, De Pythiae Oraculis*, 8); a nude statue of *Gelone* depositing his arms, located in *Syrakousai* (*Claudius Aelianus, Varia Historia*, VI, 11); a cult statue of *Zeus Aitnaios* commissioned by *Ierone* at *Aitna* (*Pindar, Olympikoi*, VI, 93); a *Nike* and golden tripod offered by *Ierone* at *Delphi* (*Athenaeus, Deipnosophistai*, VI, 231 f.); statuary groups dedicated by *Praxiteles*, a *Deinomenid* officer, executed by *Argeidas*, *Atatos*, and *Asopodoros* of *Argos*, sent to *Olympia* (*Dittenberger, Olympia V: Die Inschriften von Olympia*, 266; 330–331); the *Charioteer of Delphi*, likely the quadriga of *Ierone*, commissioned by the *Deinomenid Polyzelos*, now housed in the *Delphi Archaeological Museum*; a statue of *Philoctetes* limping and of *Apollo* slaying the serpent, both works by *Pythagoras* of *Rhegion*, originally displayed in *Syrakousai* (*Pliny the Elder, Naturalis Historia*, XXXIV, 59); a statue of *Astylos*, also commissioned from *Pythagoras* of *Rhegion*, sent to *Olympia* (*Pausanias, Periegesis*, VI, 13, 1); a statue of *Ierone* on a chariot, sculpted by *Kalamis* and *Onatas*, and dedicated at *Olympia* by his son *Deinomenes II* (*Pausanias, Periegesis*, VI, 12, 1).

The commissions described above do not only reflect the political ambitions and ideological agenda of the *Deinomenids*, but also represents one of the most coherent and prolific artistic programs of the early Classical period. The bronze heritage of *Syrakousai* did not end with the age of the *Deinomenids*. Historical

sources attest to the presence of numerous other bronze statues in the city. Among them are the statue of *Lygdamis*, Olympic champion in *Pankration* (*Pausanias*, V, 8, 8); the *Zeus Eleutherios* (*Diodorus Siculus*, XI, 27); the colossal *Apollo Temenites* on the terrace of the Greek theatre (*Verrines*, IV, 53, 118); the *Apollo Pean* of the *Temple of Asklēpios* (*Verrines*, IV, 53, 119); statues of *Epicharmos* (*Theocritus, Epigrams*, 17, 5) and *Aristeus* (*Verrines*, IV, 57, 128), both located in the *temenos* of *Dionysos*; the *Sappho* by *Silanion* at the *Prytaneion* (*Verrines*, IV, 57, 126); the riverine *Artemis* near the *Arethousa* Spring (*Pindar, II Pythian*, 11–12); the winged *Nike* in gold, commissioned by *Ierone II* (*Livy, Ab Urbe Condita*, 25); statues of *Ierone II* on foot, on horseback, and on a chariot, all sent to *Olympia* (*Pausanias*, VI, 12, 4 and VI, 15, 6); the *Nike* sacrificing a bull, by *Mykon* (*Tatian*, 34); and the famous *Aphrodite Kallipygos* (*Athenaeus*, XII, 80, 1–22). And the list could go on. The circulation of sculptors within *Hellenic Syrakousai* was extensive and well documented. The level of artistic refinement reached by bronze statuary in the city can, for instance, be appreciated in the remarkable Hellenistic bronze *ram* exhibited in the *Museo Archeologico Regionale* of Palermo (Ranieri, 2019).

From *Diodorus*, we know that *Bion* of *Miletos*, after the destruction of his city by the Persians in 494 BC, settled in *Syrakousai*, where he established his workshop and remained until the fall of the *Deinomenids*. That court was, moreover, frequented by numerous other prominent artists, most notably *Pythagoras* of *Rhegion*, *Kalamis*, and *Onatas*. According to *Cicero*, the Athenian sculptor *Silanion* was also active in *Syrakousai* in the 4th century BC, where he created a refined statue of *Sappho*. *Pausanias* later records the name of a significant *Syracusan* sculptor, *Mykon* son of *Nikeratos*, who in the 3rd century BC executed large-scale sculptural ensembles commissioned by *Ierone II* and his son *Gelone II* for dedication at *Olympia*.

That bronze workshops were active in ancient *Syrakousai* is beyond doubt. The small bronze figurine known as the “*Ephebe of Mendolito*”, now housed in the *Museo Paolo Orsi* in Siracusa, has been interpreted by some scholars as bearing clear postural affinities with the Riace Bronzes, and thus attributable to the school of *Pythagoras*. This provides tangible evidence for the presence of *Sikelic* workshops in the *Syracusan* territory as early as the 5th century BC (Holloway, 1988; McCann, 2002) (Fig. 28). In the southeastern part of Sicily, the ancient indigenous metalworking tradition developed into a specifically Siceliote production (Albanese Procelli, 1993), which, during the historical period in Siracusa, took on an industrial character. It has been ascertained, in fact, that a certain *Kephalos*, son of *Lysanias* and father of the famous orator *Lysias*, at the invitation of *Perikles*, moved from Siracusa to the Piraeus to establish a weapons factory there, an indication of the very high technical and qualitative level reached by bronze foundries and metallurgy in Siracusa at that time (Scerra, 2022).

Metalworking traces have also been found in the *Ciane 2* layer, drilled in the area of *Pantanelli* near Siracusa, which evidently constituted the palaeosurface level of the ancient Greek city. Moreover, the fact that a renowned school of bronze artisans had developed over time in the city of Siracusa is confirmed by a valuable report from *Pliny the Elder*, who states that the capitals of



Fig. 28 - Stylistic comparisons with the Epebe of Mendolito, dated 470 BC, from the school of Pythagoras, Siracusa, Paolo Orsi Museum (from McCann, 1991, modified).

Agrippa's Pantheon in Rome were made of "bronze from Siracusa," revealing the high esteem in which the workshops of Greek bronze artisans from Siracusa were held in Rome: "Syracusana sunt in Pantheo capita columnarum a M. Agrippa posita" (*Naturalis Historia*, XXXIV, 13). It is perhaps no coincidence, then, that in his "Oratio Corinthiaca" *Favorinus of Arelate* wrote that Siracusa excelled above all other Greek cities in the very large number of bronze statues it possessed: "οἱ δὲ πολλοὶ ἕσαν παρ'αυτοῖς χαλκοῦ πεποιμένοι" (*Orations*, 37, 21). As Holloway concluded, therefore, if the Riace Bronzes were taken away by the Romans, from the Greek West "only one city, Siracusa, ... would have been capable of providing them with fifth-century statuary" (Holloway, 1988).

Hypotheses on the patronage: the Deinomenids

The dating of the Riace Bronzes and the study of their welding clays provide us with two valuable starting points from which to answer three other questions: i) who commissioned them, ii) who made them, and, most importantly, iii) who they depicted. Following the deductive logic, if their original location was the ancient Siracusa and the period was the second quarter of the 5th century BC, there is no doubt that their patrons were the *Deinomenids*. Politically and economically, they were the only ones who could have afforded such a commission. At the time, the *Deinomenids* made Siracusa the leading city of the entire Hellenic West, hosting *Aeschylus*, *Pindar*, *Simonides*, *Bacchylides*, and the greatest artists of the time. A careful re-reading of *Pausanias's Periegesi* clearly shows that the

Deinomenids were also the greatest patrons of bronze statuary of their period. These were self-celebratory works and votive offerings that the lords of Siracusa sent for political propaganda to the major Panhellenic sanctuaries of Greece, primarily to Delphi and Olympia. Among these, the most famous example is the *Auriga of Delphi* itself, a work associated with the Riace Bronzes because of their shared *Deinomenid* patronage and close stylistic and constructive similarities (Stucchi, 1990).

Hypotheses on the sculptors: Pythagoras of Reggio, the Sibari Workshop, and the Second Sculptor

The *Deinomenid* commission, in turn, narrows down the circle of probable authors of the Bronzes to sculptors whom literary sources have strongly linked to the circles of the Lords of Siracusa. We know, for example, that *Calamis* and *Onatas* created the *Chariot of Ierone* described by *Pausanias* at Olympia for them. But it was certainly *Pythagoras of Reggio* who worked most extensively for the Sicilian court during those years. Native to Samos, *Pythagoras* must have arrived in Reggio in 496 BC following refugees who fled the Persians and were welcomed by the tyrant *Anaxilas*. However, it was only after *Anaxilas* death (476 BC) and the rise of *Micythus* to power in Reggio that *Pythagoras* gained favor with the *Deinomenids*, particularly *Ierone* (*Anaxilas's* son-in-law) and *Polyzelus*, for whom he worked between 476 BC and 466 BC, the year of *Ierone* death. His first work for the Lords of Siracusa was the statue of the runner *Astylos*, awarded for having left Croton to compete for the *Deinomenids* (*Pausanias, Periegesis*, VI, 13, 1). But his most

famous work was the *limping Philoctetes*. From *Pindar's First Pythian Ode* (Epode III, 50-51) we know it was created between 474 BC (Battle of Cumae) and 470 BC (*Ierone's* Pythian victory). *Pliny* recounts that this "limping" statue was so lifelike that it caused pain to passers-by: "Syracensis autem claudicantem, cuius ulceris dolorem sentire etiam spectantes videntur, item Apollinem serpentemque eius sagittis configi" (*Naturalis Historia*, XXXIV, 59). From the same passage, we also learn that *Pythagoras* made in Siracusa an Apollo piercing the serpent. The work most recently attributed to him by a study from the French School of Athens is the *Auriga* (Charioteer) exhibited at the Delphi Museum ([Psalti et al., 2018](#)). This sculpture was once again commissioned by the *Deinomenids*, specifically *Polyzelus*, as the dedicatory inscription suggests, likely to celebrate the victory of his brother *Ierone* with the quadriga at Delphi in 470 BC ([Rolley, 1984](#); [Madeddu, 2025](#)). Consequently, this work must have been made after 470 BC and before *Ierone's* death in 466 BC. All these works, therefore, prove that *Pythagoras* worked consistently for the *Deinomenids* during the decade between 476 and 466 BC. From the same 2018 French study, we also know that his workshop was probably located in Sibari, as evidenced by the origin of the casting clays used for the *Auriga* (Charioteer). The choice of Sibari was likely no coincidence. In 476 BC *Ierone* sent his brother *Polyzelus* to Calabria to defeat the Crotoniates and allow the Sibarite refugees to return to their city (Diodorus Siculus, *Bibliotheca Historica*, XI, 48, 3-5). From a scholium on Pindar (Olympian Ode II, 29b) we also know that on this occasion *Polyzelus* carried out a true *anoikismos*, that is, a "refounding," a "resettlement" with Syracusan and Calabrian colonists connected to the *Deinomenids*. The newly refounded city remained autonomous for about ten years, as demonstrated by the issuance of some of its coins ([Kraay, 1958](#)), until 467 BC, when after *Ierone's* death, Sibari was destroyed again by Croton. It was probably on this occasion that *Pythagoras* moved to Sibari in 476 BC with the colonists sent by *Polyzelus*, for whom, a few years later, he made the *Auriga* (Charioteer). Thus, *Pythagoras* kept his workshop in Sibari for about ten years, continuing to work for the Lords of Siracusa. These historical data thus gain great importance in light of new scientific evidence linking the casting clays of Bronze B from Riace, and perhaps even those of Bronze A (see par. 7.3), precisely to Sibari. Although a careful stylistic analysis of the leg positions (identical for both statues) seems to contradict the hypothesis of a 30-year gap between the two ([Corso, 2020](#)), the question remains open concerning the short chronological sequence of the two masterpieces and the different construction techniques used in the two statues, including the fact that statue B was cast and welded in Sibari (and then transported to Sicily), while statue A was cast either in Sibari or Argos and welded directly in Siracusa. These details could suggest two evolutionary phases of the sculptural technique of the same artist (with statue B possibly preceding A by a few years) or even two distinct artists from the same workshop and sculptural school. From *Plinio*, we know, for example, that *Pythagoras's* workshop also employed his nephew *Sostratus* (N.H., XXXIV, 60).

If statue A was cast in separate sections in Argos (and not in Sibari like statue B), the hypothesis of Calamis, an Argive school sculptor ([Anti, 1930](#)) favored by *Ierone's* son *Deinomenes*, cannot

be excluded. What appears certain, as highlighted by *Moreno*, is that the substantial uniformity of the vertical measurements of the two Bronzes must imply a prior agreement on the design between the two authors ([Moreno, 1998](#)). But this goes beyond the aims of this study and deserves further detailed analysis elsewhere.

Hypotheses on the depicted subjects: warrior heroes linked to the history of Siracusa

The historical introduction has already mentioned the hypothesis of identifying Bronze B as the statue of *Gelone*, naked and laying down his arms, cited by *Claudius Aelianus* (*Histories*, VI, 11), *Plutarch* (*Life of Timoleon*, 23, 7-8), and *Favorinus of Arles* (*Oratio Corinthiaca*, 21), who in turn likely drew on contemporary Syracusan historians such as *Antiochus* (5th century BC), *Philistus* (5th–4th century BC), and *Atanis* (4th century BC). *Gelone*, moreover, as *Diodorus Siculus* writes, was not only remembered as the hero of the victorious Battle of Himera against the Carthaginians (480 BC) but was also venerated as the refounder of Siracusa and, above all, enjoyed heroic cult status (*Bibliotheca Historica*, XI, 38, 5). However, beyond this, following once again deductive logic, what is certain is that if the statues were placed in Siracusa in the second quarter of the 5th century BC at the commission of the *Deinomenids*, independently from the aforementioned historical sources, they could only represent heroes connected to the history of Siracusa. In fact, the nudity could suggest either deities or heroes, for example *oikists* (founders). But the presence of arms seems to narrow the scope to deities and heroes connected in some way to a military role or achievement, and especially to heroes closely tied to the political-strategic ideals of those who commissioned them, namely the *Deinomenids*, whose artistic commissions were often used as means of political propaganda and to assert the identity of their city and family. Statues depicting *Gelone* and *Ierone* victorious in the Olympic and Pythian games mentioned by *Pausanias*, and even more so the tripods and Nike statues sent to Delphi to celebrate the historic victories of the *Deinomenids* over the Carthaginians and Etruscans, as well as the votive offerings sent to Olympia by the Lords of Siracusa themselves, are very emblematic of such ostentatious intent. In this sense, the hypothesis that the two statues in question represented works commissioned by the *Deinomenids* to celebrate a great military achievement just accomplished by the patrons themselves does not seem far from reality, as does the idea that they simultaneously celebrated the protective deities of the identity pride of their own polis. The presence of the *korinthie kynè* (Corinthian helmet) on one of the two statues (Bronze B), furthermore, further restricts the field to a hero of Siracusa history who was also a commander and king.

Starting from the fixed points of location (Siracusa), period (second quarter of the 5th century BC), patronage (the *Deinomenids*), and the presence of arms and signs of command (indicative of a high military rank), the identification of the statues seems to narrow down either to a warrior deity or, more probably, to warrior heroes from Siracusa history linked to a great military achievement (*strategoï*), to the city's identity (*oikists*), and to the propaganda strategy of the *Deinomenids*. Therefore, if this is the identification, it is truly difficult not to think of the heroes of the

Battle of Himera or the city's founders—and in any case, little changes: whether it is *Gelone* or *Archia*, these statues could only depict deities or heroes tied to the great history of Greek Siracusa at that time.

Hypotheses on the time and place of their sinking

The recovery of the two statues from a marine environment, with the tenons still attached to their feet, suggests that they sank after the sack of a Greek city, probably at the hands of the Romans. Assuming that the Bronzes originally belonged to a sculptural group located in Siracusa, as hypothesised in this study, the historical occasions for their possible looting from the Sicilian city, according to the sources, are essentially three. The first is known from the Byzantine lexicon *Suda*, which recounts the curious story of *Pyrrhus*, king of Epirus, who in 276 BC, at the end of his military campaign in Sicily, stole some treasures from the temple of *Kore*, but incurred the wrath of the goddess, who unleashed a storm that wrecked his ships with the loot along the route from Siracusa to Taranto (*Suda*, fr. 2332, “Pyrrus”). The second occurred during the Roman conquest of the city in 212 BC, when, after a two-year siege, one of the most colossal art theft operations of antiquity took place. On that occasion, according to *Livy*, the Roman consul *Marcellus* brought many of the finest artworks to Rome, because Siracusa abounded with statues and paintings: “*Marcellus, captis Syracusis, ... ornamenta urbis, signa tabulasque quibus abundabant Siracusae, Romam devexit*” (History, XXV, 40). *Livy* specifies that from that time on began the Romans' admiration for Greek art: “*ceterum inde primum initium mirandi Graecorum artium opera.*” These masterpieces were later displayed in temples dedicated by *Marcellus* near *Porta Capena*, becoming an attraction even for foreigners, who admired them for their excellence: “*Visebantur enim ab externis ad portam Capenam dedicata a Marcello templa propter excellentia eius generis ornamenta.*” The Roman sack of 212 BC is compatible both with the second ceramic dating made by *Panella (1984)* and with the probable shipwreck along the Ionian coast of the island. In this case, the discovery of the statues off the Ionian coast of Calabria could be explained by *Holloway's* hypothesis, which suggested that the works were looted from the Sicilian coast by criminal organisations (*Holloway, 1988*).

The third occasion for the transfer of artworks from Siracusa to Rome may be linked to the historic visits of certain emperors. The first of these was *Tiberius*, who in 36 BC visited Siracusa and had the colossal statue of *Apollo Temenites* brought to Rome, probably along with other works (*Suetonius, De vita Tiberi, 74*). The last was *Emperor Hadrian*, a great lover of Greek art, who enriched the famous *Villa Adriana* with masterpieces from various Hellenic cities. It is known that around 136 BC he visited Sicily (*Spartianus, De vita Hadriani, 51*), leaving a trace also on a contemporary coin from the Siracusa mint bearing his image and the legend “*Restitutor Siciliae*” (*Perassi, 2004*). Although the sack of 212 BC remains the most probable hypothesis, the possibility of some subsequent Roman emperor initiative cannot be excluded. From a passage of *Cicero*, we know that *Marcellus* left in Siracusa the works depicting its kings and tyrants, housed in the temple of *Minerva* (*Athena*), which must have represented a sort of dynastic treasury for the

city rulers: “*Aedis Minervae ... quam Marcellus non attigit, quam plenam atque ornatam reliquit*” (*Verrine*, II, IV, 55). Therefore, if the sculptural group to which the Bronzes belonged was that of *King Gelone* mentioned by the sources, it is very likely that it was placed, together with images of other rulers, in the *Athenaion*, a temple commissioned by *Gelone* himself to celebrate his historic victory at Himera over the Carthaginians. *Cicero* visited the temple in 70 BC and reported that *Verres*, unlike *Marcellus*, had robbed it of 27 paintings of kings and tyrants of Siracusa and of panels depicting the battles of *Agathocles*. In this case, *Cicero's* silence about the sculptural group can be logically explained by his intention to list only the works stolen by *Verres* and not those left behind. This would also make a later removal of the sculptural group possible, up to the time of *Hadrian* (136 AD), although the dating to 212 BC remains the most probable.

DISCUSSION AND CONCLUSIONS

According to *Holloway (1988)*, the Riace Bronzes were originally discovered in Sicilian waters and then hidden in the seabed off Riace by an organisation of illegal antiquities dealers, where they were awaiting sale abroad. According to *McCann (2002)*, the two statues depicted the *Deinomenids*, *Gelone* and *Ierone*, rulers of Siracusa, and were created by *Pythagoras of Rhegion*. These studies inspired the so-called “*Syracusan hypothesis*,” which posits that the Bronzes were part of a larger sculptural group—widely cited by ancient sources (*Aelian*, *Plutarch*, *Favorinus*)—that depicted the heroes of the history of Siracusa. This group was commissioned between 470 and 466 BC by the *Deinomenids*, likely from *Pythagoras of Rhegion* (and another sculptor?) and was ultimately removed from the city after the Roman sack in 212 BC. More recently, various historical, literary, archaeological, and archaeometric clues have emerged to support this theory (see *Madeddu, 2025*). Our work attempted to evaluate the scientific plausibility of this hypothesis, both by conducting new investigations and by thoroughly reviewing and re-examining the existing scientific literature. Our goal was also to provide a systematic overview of the documentation collected over the years on the Riace Bronzes and to offer a further contribution to the knowledge of these two important statues, which certainly require additional study. Below, in summary, are the three main clues that led us to support the “*Syracusan hypothesis*”.

Hypothesis on the location: study on the compatibility between the welding material of the Riace Bronzes and the sediments of the Pantanelli area in Siracusa

It is generally accepted that the Riace Bronzes were created in separate anatomical sections and then later assembled and welded together (*Formigli, 1984*). A 1995 study by the Central Institute for Restoration (I.C.R.) highlighted a significant difference in the geochemical composition between the clays used to cast the individual sections and the clays used for the terracotta pins that welded the statues together (*Lombardi et al., 2003*). Since the clays used for the assembly are a strong indicator of the location where the work was completed, and since numerous historical,

literary, archaeological, and archaeometric clues suggest that the statues were originally located in Siracusa, a comparison was made with sediments outcropping in the Siracusa area. This comparison looked at the geochemical composition of the welding clays, known from the I.C.R. published literature (Lombardi et al., 2003), and sediments from the alluvial plain of the Anapo river near the Temple of Zeus Olympio—an ancient production area of Greek Siracusa. The analysis revealed a significant match between samples taken from one level of the stratigraphic section (CIANE 5a-e) and a sample of welding material from Statue A (sample US2227). The results therefore suggest that, regardless of where the individual sections were made, the statue was then assembled and installed in Siracusa.

The study of Statue B appears more complex. Its arms were reconstructed in antiquity using a different bronze alloy (Formigli, 1984). Unfortunately, the I.C.R. did not publish the geochemical data for the clays used in the arm restorations, making it impossible to compare this data with the CIANE 5 level (or any other levels) from the Pantanelli area of Siracusa. However, a careful review of existing literature (Calcagnile, 2014; Jones et al., 2016) allows for some cautious hypotheses. Specifically, the macroscopic characteristics of the internal clays from the restoration of the right arm appear to be compatible with both the sample taken from Pantanelli and the welding clays of Bronze A. This suggests that, at the time of the restoration, Bronze B was in the same location as Bronze A, which was welded in Siracusa. Furthermore, radioisotopic analysis of the lead in the tenons of both statues and the lead used in the alloy of the restored arm shows that the two statues were located (or relocated) in the same monumental group at the time of the restoration. Ultimately, only an analysis of the clays inside the restored arm will be able to provide further information on the true location of the Bronze B restoration.

Hypothesis on the manufacturing site: study on the compatibility between the casting material of the Riace Bronzes and the sediments of the Sibari alluvial plain

The second of the three objectives of this work is to verify any alternative hypotheses regarding the Argive origin of the internal casting material of the two statues. This material indicates the place where the individual sections were made, rather than where they were ultimately placed. To date, the Argive origin is the most considered for both statues. However, the internal clays of Bronze A and Bronze B have a distinctly different composition. This has led some scholars to explain the difference by suggesting the clays came from the same region (Argos, Greece), but from two distinct quarries. Other scholars, however, believe that the clays originate from completely different regions. However, even in studies published after the 1995 restoration, alternative hypotheses regarding the Magna Graecia (and even Calabrian) origin of the internal material of the two statues were not geologically incompatible. These hypotheses were essentially ruled out due to the supposedly low levels of chromium detected in Calabria compared to the Bronzes. In fact, the great geological variety of the Calabrian mountain ranges can perfectly provide both the terrigenous and carbonate clastic contributions found in both statues.

In conclusion, it seems very likely that the casting material of Statue B can be attributed to the Sibari area in Calabria. This is the same location where, according to studies by the French School at Athens (Psalti et al., 2018), the famous Auriga of Delphi was made, another commission by the Sicilian *Deinomenids*. It is also believed to have been the location of the workshop of *Pythagoras of Reggio*, the favorite sculptor of the *Deinomenids*, particularly *Ierone*. *Pythagoras* worked for *Ierone* between 476 and 467 BC, also creating the famous limping Philoctetes described by Pliny. In our opinion, the identification of the origin of the casting material for Statue A remains an open question. While we cannot rule out the Sibari hypothesis (from a different collection site), the hypothesis of Argos and the Peloponnese also remains valid. In this case, we cannot exclude the artistic authorship of Calamide, a sculptor from the Argive school (Anti, 1930) who was a favorite of *Deinomenes*, *Ierone*'s son. Calamide made the monument of his father's quadriga at Olympia. What seems certain is that the substantial uniformity of the vertical measurements of the two Bronzes must have required a preliminary agreement on the design between the two artists (Moreno, 1998). However, this falls outside the scope of this study.

Hypothesis on the place of deposition: a study on the compatibility of the taphonomic characteristics and patinas of the Bronzes with the possibility of a thousand-year deposition on the Riace seabed

A careful review of the scientific literature and available photographic documentation allowed us to reconsider the hydrodynamic and geomorphological phenomena of the Riace seabed, as well as to reinterpret the surface patinas of the Bronzes and the taphonomic processes that affected them. These elements provide information on the interaction of the statues with the environments that hosted them for millennia and, consequently, important details about their "history."

The statues schematically feature three main types of patinas: i) the first consists of a layer of cuprite [Cu₂O], which adheres to the bronze alloy and also reappears in the layering; this patina forms in low-oxygen environments at medium depths (50–100 m); ii) the second is a dark (gray-blackish), compact patina of consistent thickness, composed of copper sulfide based on chalcocite (Cu₂S), adhering to the previous layer; its formation requires a partially anaerobic and reducing environment (70–100 m deep) to favor the development of sulfate-reducing microorganisms; iii) the third is a more superficial patina composed of copper chlorides of various greenish shades; this patina is quite irregular and thin, typical of shallow, highly oxygenated environments (less than 10 m deep), and it is interspersed with much more recent sandy-conglomerate incrustations. The geochemical analysis of the patinas of the Riace Bronzes allows us to conclude that their post-sinking history was characterized by a first thousand-year phase (related to the genesis of the first two patinas and the coralline crusts) during which the statues rested on a seabed of medium to high depth, between 70 and 100 m. This is also demonstrated by photographic evidence of occurrence of circalittoral serpulids of the species *Serpula lobbiancoi*. This long initial depositional phase in deep, low-energy seabeds rich in very protective muddy sediments (to which the

exceptional state of preservation of the Bronzes is attributed) was followed by a second, very brief phase (one or a few years). This phase was characterised by a drastic change in habitat, to shallow, sandy seabeds that were highly oxidizing and subject to intense hydrodynamics, perfectly corresponding to the shallow, sandy seabeds of Riace. This change generated clear corrosive phenomena (with the copper chloride patina) and the most recent sandy-conglomerate incrustations.

Scientific evidence from a careful review of available literature excludes the possibility that the Bronzes could have rested on the seabed off Riace for more than a few months or years. It proves instead that their state of preservation and the taphonomic and geochemical characteristics of their patinas are linked to a thousand-year deposition in much deeper seabed of a different geological nature. This is compatible with the seabed occurring in the offshore North of Siracusa, which in the bank of Brucoli reaches depth of 70-90 m. It is muddy and rich in coralligenous along its walls, and it is the site of an hydrosulfurous spring. The choice to evaluate the compatibility of the taphonomic characteristics of the Riace Bronzes with the seabed of Brucoli derives both from what has been supported by the archaeologist Robert Ross Holloway since the 1980s regarding the presumed discovery of the two statues along the Sicilian coast (Holloway, 1988), and from what has recently been published in the journals *Archeo* (2024) and *Archeologia Viva* (2025), which launched the testimonies of their alleged original discovery right off the coast of Brucoli, a site located along the ancient routes of ships heading from Siracusa to Rome.

Evaluation of the scientific and historico-logical plausibility of the “Syracusan hypothesis”

In conclusion, a careful review of historical and literary sources and a critical analysis of them also led to an in-depth evaluation of the historico-logical plausibility of the “Syracusan hypothesis.” This hypothesis appears confirmed on all the fields examined:

- the immense statue collection of the city, according to the sources;
- the economic and political power of the Sicilian polis during the years the Riace Bronzes were created;
- the political and economic power of the Deinomenids themselves (the most significant patrons of bronze statuary of their time);
- the historical and stylistic plausibility of the sculptors who were then in the service of the *Deinomenids*;
- the historical and documentary consistency of the probable warrior heroes depicted in the statues;
- the historical circumstances of their theft (i.e., the Roman sack of 212 BC);
- the compatibility of the possible sinking site of the statues with the historical and geographical circumstances.

In light of the scientific evidence resulting from this complex work of analyzing new data and critically reviewing existing data, we can conclude that the “Syracusan hypothesis” finds significant support, both in terms of scientific and historico-logical plausibility.

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