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Article

Foraminifera and Calcareous Nannofossils in Archaeological Ceramics of Eastern Sicily: Survivors or Archaeometric Tool?

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Abstract

The identification of calcareous foraminifera and nannofossils in archaeological ceramics (tiles and bricks from the Archaic to Roman ages) of Naxos and Taormina (Sicily) has, along with other evidence and archaeometric analyses, addressed aspects of technology and raw material source areas. Microfossils, like the other aplastic inclusions, help to interpret ceramic pastes. This paper provides, for northeastern Sicily, a contribution demonstrating the importance of an integrated approach in the study of archaeological ceramics; micropaleontological analysis supports mineralogical, petrographic and chemical data to constrain interpretations of provenance and technology. The preservation of foraminifera calcitic tests and coccoliths is an additional key to identifying errors, failures and strategies during the ancient ceramic firing process. Comparisons with the micropaleontological content of locally outcropping clay deposits have allowed for the unambiguous identification of the clay sources used for ancient ceramic production in the region.

Keywords: calcareous foraminifera and nannofossils; archaic–roman ceramics; raw materials; firing process; eastern Sicily

1. Introduction

Thin-section observations of archaeological ceramics from various geographic areas and ages often highlight the presence of calcareous skeletal remains of microscopic organisms within the clay matrix. Detailed studies that use microfossils as technological and provenance markers for ancient pottery have gradually emerged from the 1950s to the present. Several authors have highlighted the discovery of microfossils in such artifacts [1–15].

As is known, microfossils, specifically planktonic and benthonic foraminifera, are indicative of the geological age and paleoenvironment in which they lived, giving them high informative potential. The micropaleontological analysis of ceramics can provide information on: (a) the type of raw materials used (continental or marine sediments), based on the presence or absence of marine microfossils; (b) the age of the used raw materials; (c) reworking processes, both natural (from primary sedimentation or resedimentation) and artificial (from the mixing of clay raw materials of different ages by ancient potters), based on the recognized micro- and nannofossil assemblages; and (d) the firing conditions of artifacts through evaluation of the abundance and preservation state of micro- and nannofossils.

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In 1998, the term "ceramic micropaleontology" was coined by P.S. Quinn, highlighting the importance of microfossils in studying the provenance of raw materials used to produce ceramics. The first detailed research on the potential of microfossils in archaeological ceramics was reported by [16,17], who developed a methodology for the study of microfossils to advance ceramic compositional analysis.

Nevertheless, detailed micropaleontological analyses of archaeological ceramics that compare the microfossil assemblages in the clay matrix with those in field samples of potential raw materials in order to reconstruct ancient ceramic technology or to obtain information about the nature and origin of raw materials used in ceramic manufacture are currently few in number [13,16–24]. In terms of ceramic provenance, attempts have been made in the past by other authors (e.g., [5,11]) to locate the source of raw materials exploited in the ancient manufacture or individuate non-local artifacts, but most of the studies have utilized microfossils in a similar way to other inclusions seen in thin sections to characterize the composition of the artifacts.

Regarding the technological aspects, most of the previous studies have used microfossils mainly to determine methods of mix preparation (e.g., the mixture of different clays or the addition of temper) [7,12,17,25–29] while only a few papers have focused on the behaviour of microfossils during firing, which is one of the most heavily studied aspects of ceramic technology [1,12,20,30].

In this context, our research contributes to corroborating the importance of an integrated approach in the study of archaeological ceramics.

The archaeological ceramics examined in this paper consist of bricks and tiles dating from the Archaic to Roman Ages, coming from two relevant sites of Naxos and Taormina in the province of Messina (northeastern Sicily) (Figure 1). A detailed first study on the same ceramic samples has been carried out by the authors [31], focusing the attention on the volcanic temper present in the pastes to determine their provenance. Based on the identification of the source area of the temper used in ancient ceramic production in this area, a local origin was hypothesized. The inclusions showed marked similarities with the textures and mineral phase compositions of the mugearitic volcanics outcropping along the Alcantara River Valley, which is located near the ancient settlement of Naxos.

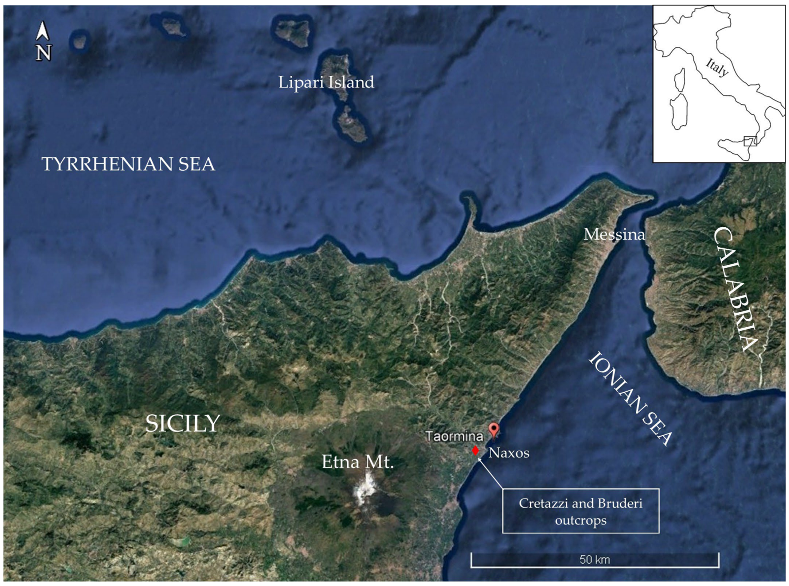

Figure 1. Sketch map of northeastern Sicily (rectangle in the small outline of Italy, right the top) showing the locations of the archaeological sites of Taormina and Naxos and the clay sources (red rhombus) at the Bruderi and Cretazzi outcrops.

Based on this research, some of the authors of this work were also able to create comparative distribution maps of the clay sequences used for ceramic products, bricks and vases at various archaeological sites in the provinces of Messina and Reggio Calabria [32].

This paper aims to increase the knowledge of both the clay raw material sources exploited in the past for ceramic production in this area and the key role of micro- and nannofossil assemblages in identifying the ancient production technology, with inferences about the firing process and duration. Thus, microfossils become a tool for archaeometric research.

2. Geological Framework of the Area Surrounding the Archaeological Sites

The field exploration, conducted to identify adequate raw materials along the Ionian coast near Taormina and Naxos, revealed two outcrops of clay deposits in the Cretazzi and Bruderi localities to the northwest of the archaeological site of Naxos [22,32]. The deposits belong to the Quaternary marine succession, and the *Argille grigie-azzurre* Formation is represented here by an estimated 30 m of marly clays and gray-blue clays (Figures 1 and 2). The basal portion is attributed to the Early Pleistocene (MPl6 biozone *sensu* [33] and MNQ19a subzone, *sensu* [34]) while the uppermost portion corresponds to the late Early Pleistocene (MNQ19c subzone, *sensu* [34]). The widest outcrop is in the Bruderi area (Figure 2a,c), consisting of marly clays with chaotically embedded decimetric to metric olistoliths of selenitic gypsum in the lower portion (ascribed to the Tortonian–Lower Messinian by [35] and clays in the upper portion. The Cretazzi outcrop (Figure 2b,c) consists of gray-blue marine clays belonging to early Pleistocene deposits.

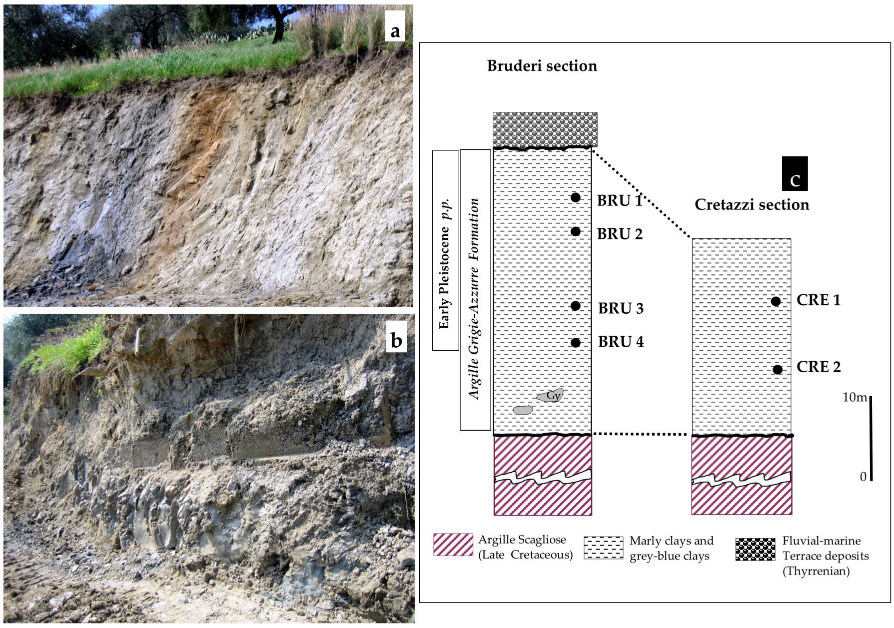

Figure 2. Panoramic view of the two sections emerging near the modern urban center of Giardini Naxos: Bruderi (**a**), Cretazzi (**b**) and related schematic stratigraphic logs (**c**).

3. Materials and Methods

3.1. Archaeological Ceramics and Contexts

The examined ceramic materials include seven bricks and four tiles from the archaeological sites of Naxos and Taormina. These samples cover a wide chronological range from the Archaic (Naxos) to the Roman (Taormina) Ages.

The Naxos samples consist of: (a) two bricks, one (NF-VI) from the firing chamber of a kiln (VI century B.C.) and the other (NM-V) from a tomb (V century B.C.); (b) three tiles dating to the V century B.C., two of which (NT1-V, NT2-V) are from a house and one is (NT3-V) from a tomb.

The Taormina samples (Figure 3) include: (a) five bricks, two (TAG1 and TG3) from a house (II century A.D.), two (TTRM, TTRS) from the Thermae (I-II century A.D.) and one (TTM-II) from the Antique Theatre (II-III century A.D.); and (b) one tile from the Thermae (TTRT, I-II century A.D.).

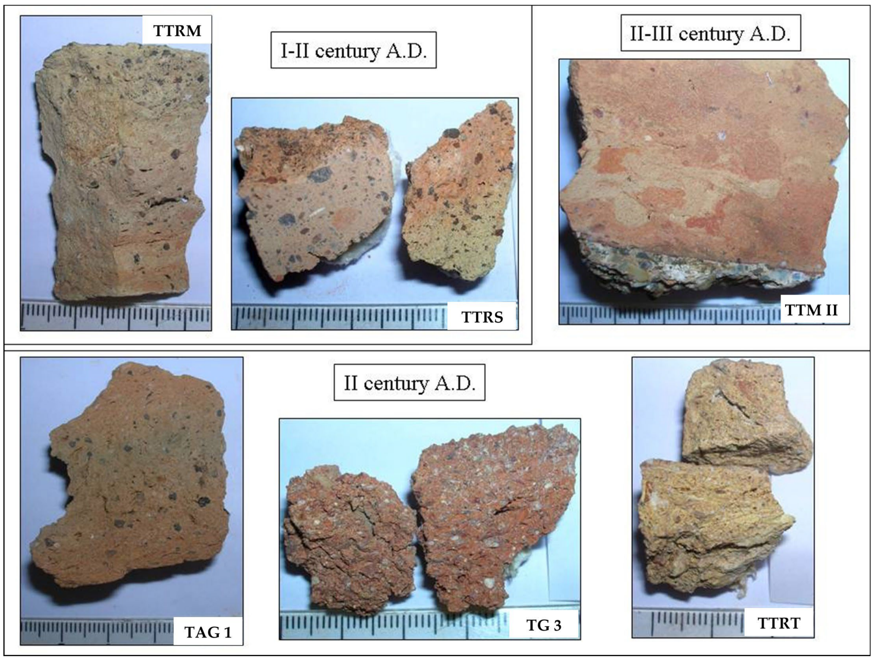

Figure 3. Archaeological ceramic fragments and related chronological attributions: bricks and tile (TTRT) from Taormina.

Naxos was the first Greek colony of Sicily, founded in the second half of the VIII century B.C. from Calcidesi of the Eubea and from Nassi from the homonym Naxos of the Cicladi. Naxos prospered as a commercial center in the Archaic period for about three centuries and declined after the destruction carried out in 403 B.C. by Dionisio I, the tyrant of Syracuse. In the 358 B.C., the urban life moved on top of the nearby Mt. Tauro where a town was founded: this town became the Roman *Tauromeniun* (in our time Taormina). The urban and necropolis areas of Naxos provided the analyzed ceramic samples.

The Thermae complex discovered on the north side of the Piazza Vittorio Emanuele, in the courtyard behind the Carabinieri barrack in Taormina, extended north under the so-called "Zecca" neighborhood, where the remains of walls and brick arches are incorporated into eighteenth-century houses. The construction of the thermal building, located on the northern side of the Forum, took place during the early centuries of the Roman imperial age (end of the I-II century AD). The remains of a previous public building, perhaps a Hellenistic Bouleuterion, below the level of the Baths, were identified by excavation tests carried out on the west side of the area. In this area, four bases of honorary inscribed statues were found, dedicated to illustrious citizens and notable figures, dating back to the Hellenistic age. Of the thermal baths, three large rooms remain, functioning as calidarium or tepidarium, with marble slab floors (*crustae*) heated by *praefurnia* (rooms intended for combustion). The round or square brick pillars are also visible, which allowed the circulation of hot air under the floors (*suspensurae*) and are also fed through terracotta tubules placed close to the plaster-covered walls of the rooms [36].

The Ancient Theatre of Taormina, located within the Archaeological Park of Naxos-Taormina (Naxos was the first Greek colony in Sicily), stands along the ridge of the hill bearing the same name, which was completely excavated to create the "cavea" and to obtain the large blocks used in its construction during the Greek era. With a cavea measuring 109 m in diameter, it is the second largest theater after that of Syracuse, not only in Sicily but also in all of mainland Italy and Africa. Its origins date back to the 3rd century B.C., as evidenced by the remains of the isodomic block walls incorporated into the stage building and some of the inscribed seats in the cavea. However, what is visible today is the result of Roman renovation, particularly that which was carried out in the first half of the 2nd century A.D. under Emperor Trajan [37]. During this period, the theater was rebuilt entirely in brick, a material readily available in the nearby clay formations of the Giardini-Naxos plain, which is the subject of the current study.

3.2. Samples from Clay Deposit Outcrops

To obtain information on the source area of the clay raw materials used to produce the examined ceramics, local clay samples were collected for comparison from two clay outcrops in the Bruderi and Cretazzi areas (NW of the archaeological site of Naxos, Figure 2), where the so-called "potters' neighborhood" is located. The outcrops were identified and reported by [32]. These deposits are currently the only significant ones identified along the entire Ionian coast of the Messina province and represent a suitable local source of clay for ancient ceramic production in this area.

Two samples (BRU 1 and BRU 2) were collected at 70 m a.s.l. and two samples (BRU 3 and BRU 4) at 50 m a.s.l. in the first outcrop (Figure 2a,c).

The second outcrop (Figure 2b,c), located on the Cretazzi Hill about 300 m northeast of the first outcrop, consists of gray-blue clays. Two samples were taken from this outcrop: CRE 1 (at ca. 45 m above sea level) and CRE 2 (at ca. 40 m).

Analytical techniques for the complete characterization of microfossils within the examined sherds include:

(a) polarizing optical microscopy (POM) for both thin sections and smear slides; the latter prepared by adapting the technique of Bown and Young [38] for incoherent sediments;

(b) micromorphological investigation using an Environmental Scanning Electron Microscope (ESEM-FEI Inspect-S) coupled with an Oxford INCA PentaFETx3 energy-dispersive spectrometer at the MIFT Department of the University of Messina. The system is equipped with a Si(Li) detector fitted with an ultra-thin window (ATW2), providing an energy resolution of 137 eV at 5.9 keV. Measurements were conducted under environmental conditions at a working distance of 10 mm with an acceleration voltage of 20 kV. Data acquisition employed counting times of 60 s, maintaining approximately 3000 counts per second with dead time below 30%. Spectral processing and quantification were performed using INCA Energy software, which implements the XPP matrix correction scheme developed by Pouchou and Pichoir [39] to account for atomic number, absorption and fluorescence effects.

The preparation of clay outcrop samples (standard chemical treatment with water solution of H_2O_2) to obtain washed micropaleontological residues and the preparation of smear slides [37] were carried out at the laboratory of the Department of Physics and Geology of the University of Perugia.

4. Results

Thin-section observations of the tiles and bricks revealed a marked compositional and textural homogeneity in their fabric, characterized by abundant (25 to 40%) coarse inclusions of volcanic origin [31]. As shown in Figure 4, the groundmass varies in colour from orange to gray and dark brown, depending on the sample. The inclusions consist of: (a) predominant volcanic rock fragments, along with single crystals of zoned plagioclase and augitic clinopyroxene, which are compositionally similar to the locally outcropping mugearitic products attributed to the eruptive activity of Mt. Mojo; (b) common metamorphic rock fragments (gneiss and micaschist); (c) a few olivine and quartz grains, along with argillaceous rock fragments; (d) rare quartzarenite fragments and microcline crystals; and (e) very rare micas [31].

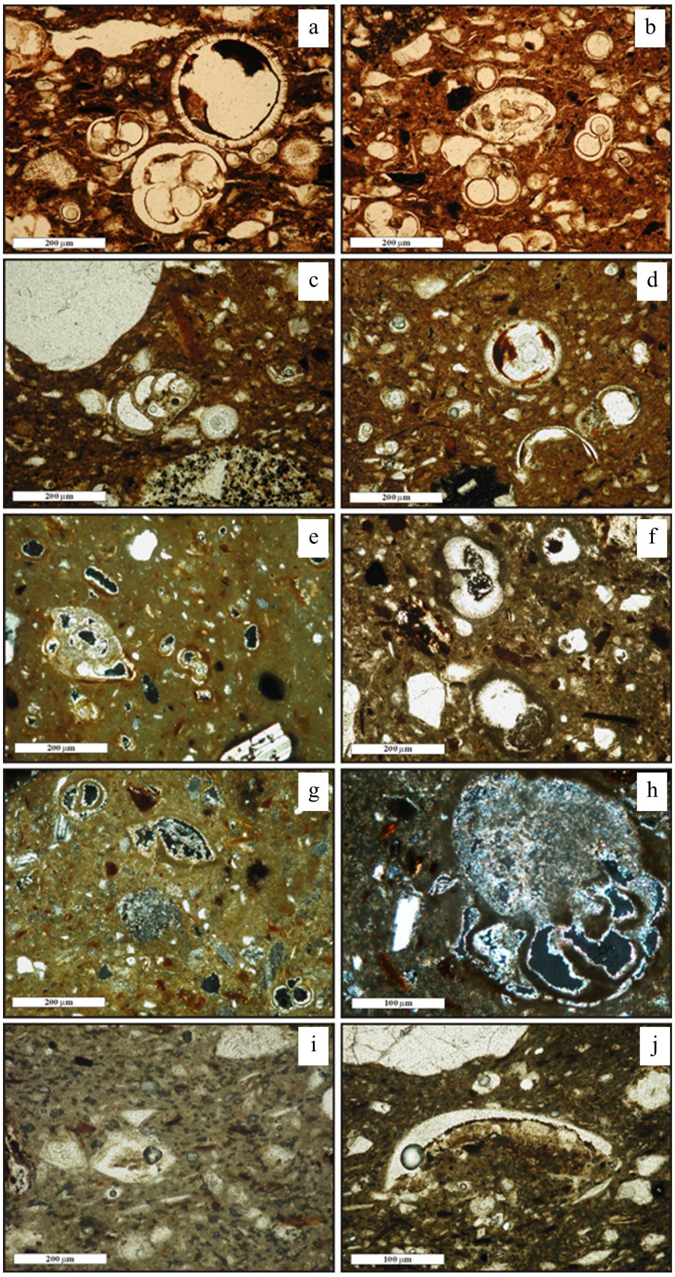

Figure 4. Photomicrographs of selected ceramics, showing the presence of planktonic and benthonic foraminifera and other skeletal remains. (**a**,**b**) Brick sample TAG1 (PPL; 2.5×): *Globigerinoides* spp., *Orbulina universa* and *Amphistegina* sp.; (**c**,**d**) tile sample NT1-V (PPL; 2.5×): *Bulimina marginata*, *O. universa* and Globigerinids; (**e**) brick sample TTRS (XPL; 2.5×): *Amphistegina* sp. and Globigerinids; (**f**) brick sample TG3 (PPL; 2.5×): small Globigerinids; (**g**,**h**) brick sample TTRM (XPL; 2.5× and 10×): poorly preserved *Amphistegina* and benthonic specimen; (**i**) tile sample NT2-V (PPL; 2.5×): poorly preserved benthonic specimens; (**j**) tile sample NT2-V (XPL; 10×): ostracod carapace. PPL: plane parallel light; XPL: crossed polarized light.

4.1. Foraminifera

Calcareous skeletal remains of benthic and planktonic foraminifera within the groundmass of all examined ceramic samples have been analyzed.

Microfossils identified among planktonic foraminifera include *Orbulina universa*, *Globigerinoides* spp., *Globorotalia inflata*, *Globigerinoides ruber* and *Globigerina bulloides*, while the benthic foraminifera are represented by *Bolivina spathulata, Bulimina marginata* and *Amphistegina* spp. (Figures 4 and 5). The other invertebrate fossils, such as ostracods and thin bivalve shells, are also present. The planktonic assemblage is indicative of early Pleistocene age (MPl6 biozone, *sensu* [33]).

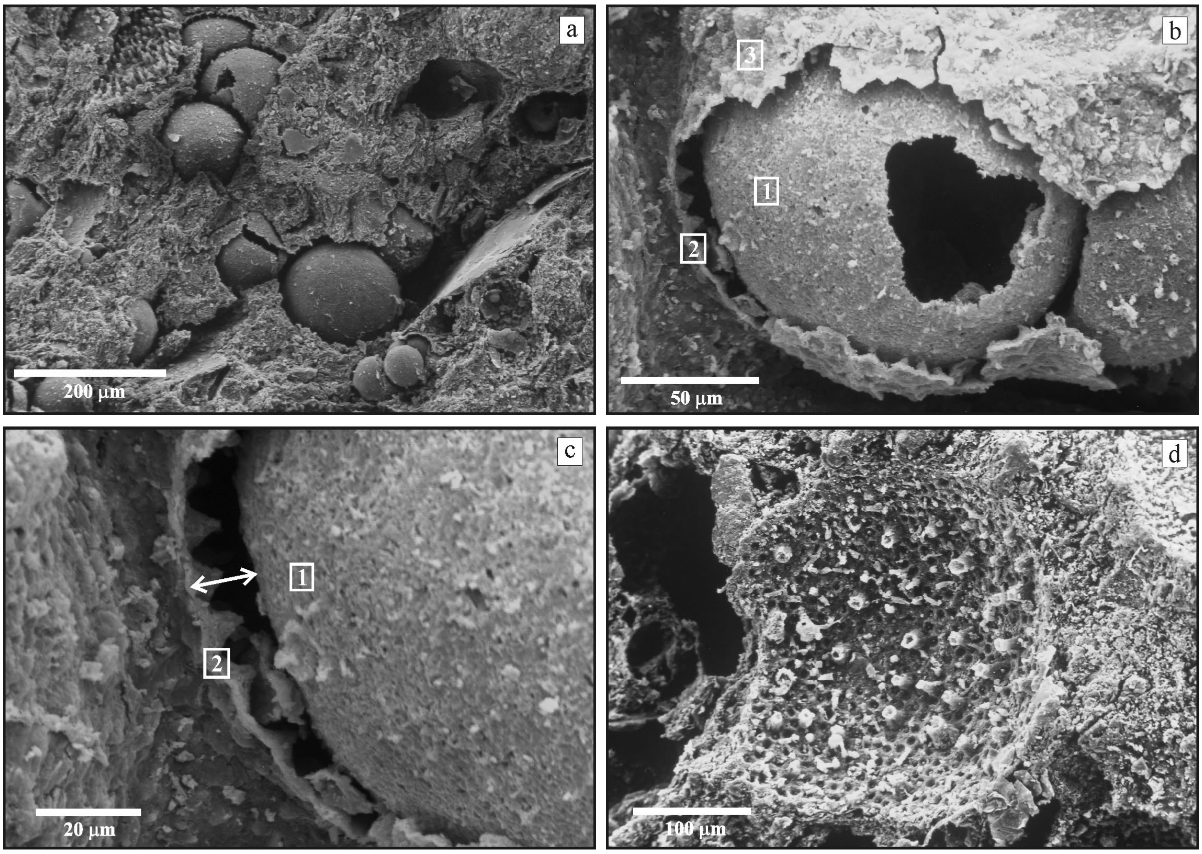

Figure 5. Scanning Electron Microscope (SEM) images of brick sample TAG1 show well-preserved morphological features of microfossil tests: (**a**) planktonic foraminifera (Globigerinids and Globigerinoids) present within the clay matrix; (**b**) test of a planktonic foraminifer displaying detachment between internal and external layers caused by the firing process of the brick (1 = internal layer; 2 = external layer; 3 = clayey coating); (**c**) detail of the detachment between internal and external layers of the test wall; (**d**) proximal side of the external wall layer with a detail of conical-shaped channels.

The abundance and preservation state of calcareous microfossils in the examined pastes are quite variable, depending on the sample (Table 1). Specifically, the amounts range from very abundant (TAG1) to abundant (NT1-V, TTRM, TTRS) to common (TTM-II, TG3) to rare (NM-V, NF-VI, NT2-V, NT3-V, TTRT).

Regarding preservation state, three of the examined thin sections (NF-VI, NT3-V, TG3) show only traces of microfossils, so their preservation state is considered poor.

Conversely, in other samples, the preservation state of the morphological features of the foraminifera tests was observed to be medium to medium/good (NM-V, NT1-V, NT2-V, TTM-II, TTRT), good (TTRS, TTRM) or even very good (TAG1).

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Table 1. Micropaleontological and chemical information for the bricks and tiles from Naxos as well as Taormina sites and firing temperature estimates and raw materials from the Bruderi and Cretazzi outcrops. Keys: **** very abundant; *** abundant; ** common; * rare; IV degree—initial vitrification; V degree—extensive vitrification. Yellow colour to medium/good and sky blue colour for medium/poor microfossil preservation state.

Samples	Typology	Locality	CaO%	Age	Foraminifera	Calcareous Nannofossils	Microfossil Preservation State	Vitrification Degree [31]	Firing Temperature [31]
NM-V	Brick	Naxos	10.99	V B.C.	*	Yes	poor/medium	IV	<800–850 °C
NF-VI			0.84	VI B.C.	*	-	poor	IV	<800–850 °C
NT1-V	Tile		7.59	V B.C.	***	Yes	medium	V	>850–900 °C
NT2-V			9.11		*	Yes	medium/good	V	>850–900 °C
NT3-V			8.34		*	-	poor	IV	<800–850 °C
TTRM	Brick	Taormina	16.62	I–II A.D.	***	Yes	good	V	>850–900 °C
TTRS			15.26		***	Yes	good	V	>850–900 °C
TTM-II			14.37	II–III A.D.	**	-	medium	V	>850–900 °C
TAG 1			5.65	II A.D.	****	Yes	very good	V	>850–900 °C
TG 3			12.69		**	-	medium/poor	V	>850–900 °C
TTRT	Tile		9.39	I–II A.D.	*	-	medium/poor	V	>850–900 °C
CRE 1	clay	Cretazzi	12.15	Early Pleistocene	*	Yes	medium		
CRE 2	clay	Cretazzi	15.60		**	Yes	medium		
BRU 1	clay	Bruderi	15.84		***	Yes	good		
BRU 2	clay	Bruderi	14.29		***	Yes	med/good		
BRU 3	clay	Bruderi	3.89		barren	Yes	-		
BRU 4	clay	Bruderi	5.43		barren	Yes	-		

4.2. Calcareous Nannofossils

Observations of smear slides (prepared from artifact sherds) under a polarizing microscope revealed that six of the eleven investigated samples (NM-V, NT1-V, NT2-V, TTRM, TTRS, TAG1) contain calcareous nannofossils (Table 1). The assemblages, which range from well to moderately preserved, are mainly composed of Small and Medium *Gephyrocapsa* (markers for the Early Pleistocene age, MNQ 19a subzone *sensu* [34]), *Coccolithus pelagicus* and *Helicosphaera sellii*. The genera *Gephyrocapsa* and *Coccolithus* are commonly present, while *Calcidiscus* and *Helicosphaera,* as well as reworked specimens of *Discoasters*, are more rare. Micromorphological analysis performed under SEM examination confirmed the presence of the same species found in the smear slides, along with a few reworked specimens such as *Discoasters* sp. (Figure 6).

The identified calcareous nannofossil assemblages are important because they confirm the type and age of the clay raw materials used in ancient manufacturing, as already indicated by microfossil assemblages. The Early Pleistocene marine clay sediments were the raw materials used for ceramic production.

4.3. Microfossils and Age of Outcrop Samples

The analysis of the micropaleontological content of local clay samples revealed varying abundances of the biogenic component between specimens from the two outcrops as well as among samples from the same outcrop.

In particular, the two samples from the Cretazzi outcrop (CRE1 and CRE2) furnished a scarce amount of washing residues (ca. 0.20 g/100 g of total sample) indicating a very low contribution of the biogenic component to the original sediment. In these samples, the planktonic foraminifera association consists of *Globigerina bulloides*, *Neogloboquadrina* spp. and *Globorotalia inflata* (markers of the Early Pleistocene age, MPl6 biozone *sensu* [33]),

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while the rare benthonic foraminifera present include *Bolivina spathulata*, *Bulimina marginata* and *Gyroidina altiformis*.

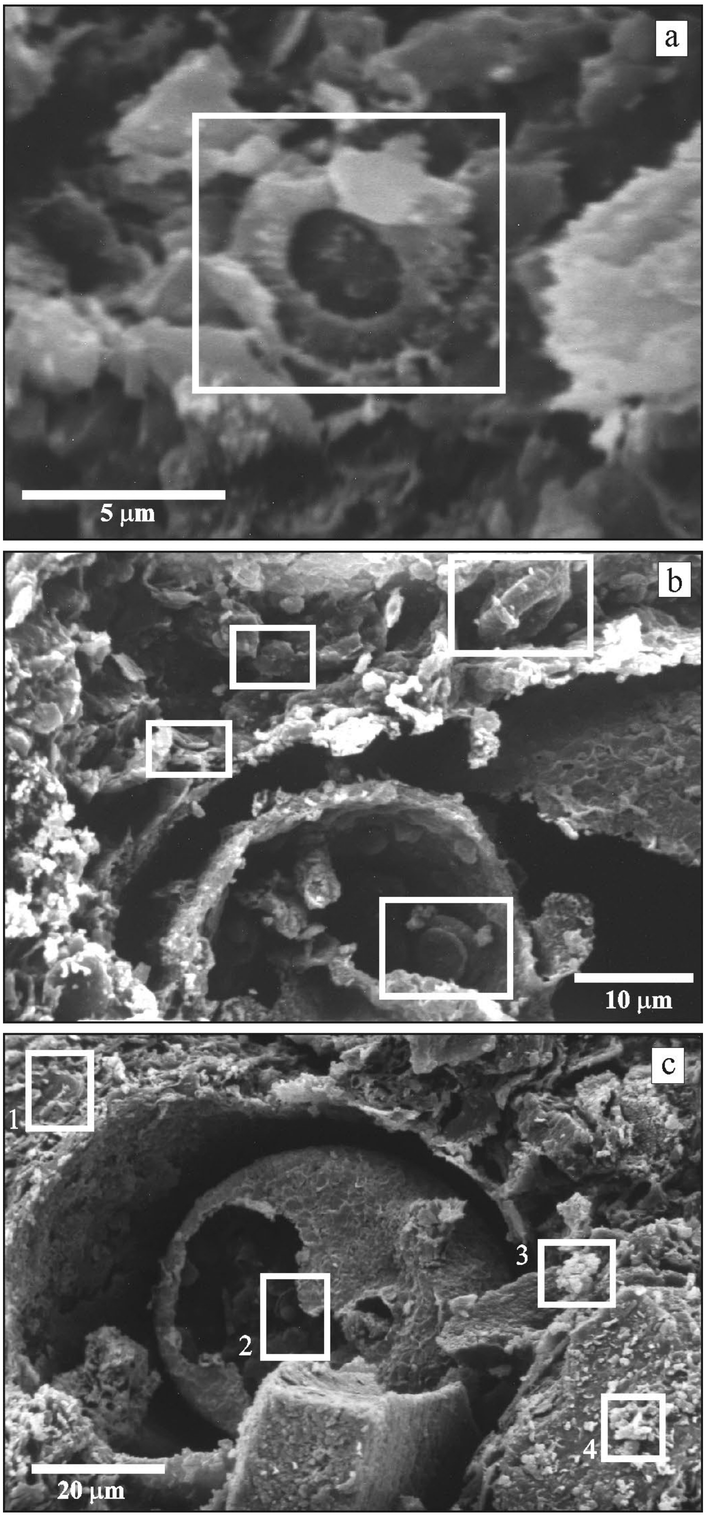

Figure 6. SEM images showing several species of nannofossils identified in brick sample TAG1: (**a**) *Coccolithus pelagicus*; (**b**) *Gephyrocapsa* sp., *Calcidiscus* sp., *Helicosphaera* sp. (within rectangles) and others coccolith species, occurring both in the clay matrix and within the test chambers of foraminifera; (**c**) 1–2: coccoliths; 3–4: rosette-shaped nannofossils (*Discoaster* spp.).

The calcareous nannofossil assemblages contain Small *Gephyrocapsa*, Medium *Gephyrocapsa*, *Coccolithus pelagicus*, *Helicosphaera sellii*, *H. carterii*, Large *Gephyrocapsa* and rare

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reworked Cretaceous and Miocene nannofossil species. The identified assemblages allow these clay samples to be assigned to the Early Pleistocene (MNQ19b subzone, *sensu* [34]).

Regarding the clay samples from the Bruderi outcrop, some differences were observed among the four specimens collected. Specifically, samples BRU3 and BRU4 were barren of foraminifera, while the calcareous nannofossils showed a very poor association with Small *Gephyrocapsa* and rare *Calcidiscus leptoporus*.

In contrast, samples BRU1 and BRU2 showed an abundant biogenic component, with numerous planktonic foraminifera such as *Globorotalia inflata*, *Globigerina bulloides*, *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Orbulina universa* and *Neogloboquadrina* spp. (Figure 7), along with rich calcareous nannofossil associations (Large *Gephyrocapsa*, *Helicosphaera sellii*, *Coccolithus pelagicus*, Medium *Gephyrocapsa* and *Pseudoemiliania lacunosa*). The planktonic foraminifera assemblage is referable to the MPl6 biozone (Early Pleistocene, *sensu* [33]) and the calcareous nannofossil association identified in these clay samples can be dated to the Early Pleistocene (MNQ19d subzone, *sensu* [34]). In addition, sample BRU1 is characterized by a very abundant specimens of benthonic foraminifera *Amphistegina lessonii* and *Amphistegina radiata* (Figure 7), identified by [22] within the Early Pleistocene clayey sediments of the Sicilian Ionian coast.

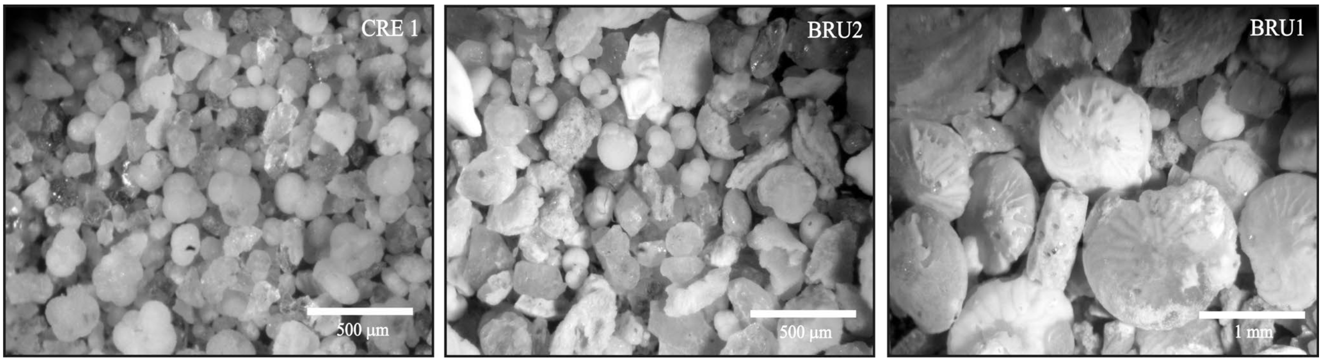

Figure 7. Stereomicroscope photographs of the washed residues show the biogenic component of representative clay samples from the Cretazzi (CRE1) and Bruderi (BRU 1–2) outcrops. The Bruderi 1 sample contains abundant specimens of *Amphistegina lessonii* and *Amphistegina radiata*.

5. Discussion

5.1. Microfossil Preservation vs. Firing Temperature, Duration and Factors: Resolving the Paradox

The coexistence of well-preserved calcareous microfossils and mineralogical evidence for high firing temperatures (>850–900 °C), such as diopside, anorthite, gehlenite and matrix vitrification, in most examined samples presents an apparent paradox. As is known, calcareous microfossils are very sensitive to the various steps of manufacture, both in terms of composition and state of preservation. The experiments of Quinn [20] demonstrated that calcareous nannofossils are degraded by heating above 600 °C and can survive a maximum firing temperature of 800 °C in an oxidizing atmosphere and 700 °C in a reducing atmosphere. Therefore, ceramics containing well-preserved microfossils have traditionally been considered low-fired, while samples with poorly preserved microfossil assemblages are assumed to have been subjected to higher firing temperatures. However, as reported in Table 1, the firing temperatures (>850–900 °C) and the vitrification grades (V) estimated by [31] for samples containing abundant and well-preserved foraminifera appear to contradict this expectation. This apparent contradiction can be resolved by considering multiple factors related to the kinetic nature of calcite decomposition and the specific characteristics of ancient ceramic production.

The thermal decomposition of calcite ($CaCO_3 \rightarrow CaO + CO_2$) is a kinetically controlled process rather than an instantaneous phase transition. Although equilibrium temperature at atmospheric pressure is approximately 898 °C, the decomposition rate under real firing conditions depends on temperature, time, atmosphere and local CO_2 partial pressure [40,41]. High-temperature mineral phases require only brief exposure for nucleation, while complete calcite decomposition demands prolonged heating [42]. Experimental studies demonstrate that time at maximum temperature is as critical as temperature itself [43,44]. Short "flash firing" cycles, common for mass-produced construction materials, allow matrix vitrification and Ca-silicate formation while preserving carbonates in the ceramic interior [45]. The bricks and tiles examined here, produced to meet building demands, were likely fired using such rapid cycles.

Quinn and Day [46] noted that open porosity significantly influences calcite decomposition during firing. In our samples, the poorly sorted mixture of marine clays and coarse volcanic temper creates heterogeneous porosity, visible as voids, channels and planar voids in thin sections (Figure 4). In porous ceramic bodies, CO_2 released during incipient calcite decomposition accumulates in low-permeability zones, shifting local equilibria toward carbonate stability and protecting microfossils from thermal degradation [47–49].

Significant temperature gradients develop between the surface and core during firing: microfossils in the inner portions may experience 50–100 °C lower peak temperatures than vitrified surfaces [50,51]. Additionally, ancient updraft kilns produced heterogeneous atmospheric conditions with fluctuations between the oxidizing and reducing phases. The variable groundmass colours (orange to gray-brown) in our samples reflect these fluctuations [20,52,53].

Preservation Patterns in Samples: Who Are Survivors?

In the studied samples, preservation varies systematically among microfossil groups: robust benthic foraminifera such as *Amphistegina* (thick hyaline walls) are better preserved than thin-walled planktonic and delicate nannofossils (2–20 μm), whose survival also depends on matrix position [17,46]. Most examined ceramics contain foraminifera in medium–good to very good preservation, sometimes with well-preserved nannofossils (NM-V, NT2-V, TTRM, TAG1) (Table 1). Sample TAG1 shows exceptional preservation suggesting rapid heating–cooling cycles. Only a few samples (NF-VI, NT3-V, TG3) contain poorly preserved foraminifera, indicating higher temperatures or longer exposure. This confirms that microfossil preservation reflects the complex interplay of kinetic factors, firing duration, paste characteristics and atmospheric conditions.

Microfossil preservation alone cannot provide reliable firing temperature estimates. However, integrating micropaleontological and mineralogical data allows for a distinction between high-temperature/short-duration regimes (vitrification with preserved microfossils) and lower-temperature/long-duration firing (greater microfossil degradation despite lower peaks). Our samples indicate that Naxos–Taormina potters employed rapid firing techniques driven by construction demands. Future research should include controlled firing experiments using local Pleistocene clays from Bruderi and Cretazzi outcrops, varying temperature (700–1000 °C), soaking time (0.5–8 h), heating/cooling rates and atmosphere. This would establish a regional framework for interpreting microfossil preservation and ancient firing technologies in northeastern Sicily.

5.2. Archaeometric Tools

The determination of provenance and technology remains the principal aim of most analytical research on archaeological ceramics. Micropaleontology can support and increase the data obtained by conventional methods such as petrography and chemistry.

In two case studies [23,24] concerning Richborough 527 amphorae (I–III century A.D.) and architectural ceramics (antefixes, VI–V century B.C.) from Lipari Island (Figure 1), micropaleontological analyses provided fundamental results. The foraminifera identified in antefixes suggest that early Pleistocene marine clay deposits along the Tyrrhenian coast of the Peloritani Mountains are possible sources. The mixture components (Pleistocene marine clays and sands with metamorphic elements) are unrelated to Lipari's geological context but show strong affinity with Sicilian materials. Comparisons with Messina terracottas indicate a probable use of the same raw materials by a single production center in *Zancle-Messana* [24]. Similarly, microfossil content in Richborough 527 amphorae supports the hypothesis that Messina area clays, rather than Lipari clays, were used [23].

In our research, provenance interpretation was made possible by comparing microfossil assemblages in sherds with field samples from potential sources. The foraminifera and nannofossil assemblages in sampled clay sediments are equivalent to those in our ceramics, identifying Bruderi and Cretazzi outcrops (early Pleistocene marine clays) as the local supply area for brick and tile production from VI–V centuries B.C. to I–III centuries A.D. Moreover, the presence of *Amphistegina* in various artifacts unequivocally indicates the use of Bruderi clays, where this genus is abundant. This demonstrates how micropaleontology, combined with archaeological evidence, addresses provenance and technology aspects, providing a complete picture of past ceramic production. By applying microfossil biostratigraphy within archaeological and petrographic frameworks, specific raw material sources can be identified, as shown in our case study. The approach referred to as 'ceramic micropalaeontology' [46] has become an indispensable tool in archaeometric research.

6. Conclusions

The clay formations in the area surrounding Taormina have led to its continuous use over time, as demonstrated by the etymology of some districts (for example, Contrada "Cretazzi", which refers to clay deposits, and Contrada "Calcarone", linked to kilns for firing clay and limestone), as well as street names (Via delle Fornaci). Also noteworthy is the large kiln complex located within the archaeological site of Naxos, which was the center of a significant industrial activity focused on the production of bricks and terracotta pots since VI century B.C. This production tradition continued beyond the classical age, persisting in the modern era through specialized local workshops.

The approach adopted in this study highlights how an interdisciplinary and diversified methodology allows the origins of the clays used in various construction phases to be distinguished and characterized paleontologically, to the point of identifying the individual quarries of origin.

The new data from Taormina and Naxos, along with the previous research (Lipari Island [23,24]) developed over the last seven years on archaeological ceramics, demonstrate that microfossils are not only an archaeometric tool but can also indirectly indicate the periods of exploitation of raw material areas. The bricks and tiles of Taormina and Naxos analyzed here have been produced for centuries, and the archaeological ceramics of Lipari also show that the exploitation of the eastern Tyrrhenian coast for ceramic production in *Zancle-Messana* was continuous from the Archaic period, from the 5th century B.C. to the 3rd century A.D.

The study also addresses the apparent contradiction between the high firing temperatures indicated by mineralogical analysis and the presence of well-preserved calcareous microfossils. Key factors include the kinetic nature of calcite decomposition, firing duration, the effect of paste porosity on CO_2 pressure and thermal gradients within ceramics. Evidence shows that bricks and tiles were produced using rapid firing cycles that reached high temperatures for short periods, allowing matrix vitrification without completely destroying the microfossils. This suggests that microfossil preservation and high-temperature mineralogical indicators can coexist when firing duration is considered.

This approach can establish a regional framework for interpreting microfossil preservation in archaeological ceramics and enhance our understanding of ancient firing technologies in northeastern Sicily.

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