

Ichnological analysis of the Messinian-Zanclean (Miocene-Pliocene) transition at Eraclea Minoa (Sicily): Tracemaker response to the Terminal Messinian Flood

Francisco J. Rodríguez-Tovar^{a,*}, Gijs van Dijk^b, Jasper Maars^b, Federico Andreetto^b, F. Javier Hernández-Molina^c, Wout Krijgsman^b

^a Department of Stratigraphy and Palaeontology, University of Granada, Spain

^b Department of Earth Sciences, Utrecht University, the Netherlands

^c Department of Earth Sciences, Royal Holloway University London, Egham, Surrey TW20 0EX, UK

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ABSTRACT

A detailed ichnological analysis has been conducted, for the first time, of the Arenazzolo and Trubi formations of the Caltanissetta Basin in Sicily. Aim of this analysis is to evaluate paleoenvironmental changes affecting macrobenthic tracemaker communities during the re-flooding of the Mediterranean at the end of the Messinian Salinity Crisis. The uppermost Messinian Arenazzolo Formation is characterized by a scarcity of trace fossils, probably related to high energy depositional conditions, and perhaps no fully normal salinity level yet, resulting in an unfavourable habitat for macrobenthic tracemaker communities. The exclusive presence of small traces (*Chondrites*) sparsely distributed in several horizons is associated to intermittent phases of lower energy conditions facilitating colonization by opportunistic tracemakers. A significant change in trace fossil assemblages is observed at the transition to the Zanclean Trubi Formation. Here the ichnofossil assemblage consists of *Arenicolites*, *Chondrites*, *Halimedes*, *Palaeophycus*, *Planolites*, *Thalassinoides*, *Trichichnus* and *Zoophycos*, assigned to the *Zoophycos* ichnofacies, revealing an abundant, diverse, well-developed, multi-tiered, tracemaker community. This change observed at the Messinian/Zanclean boundary is related to the rapid establishment of normal, full-marine, conditions with well oxygenated bottom- and pore-waters, and food availability in a deep marine environment. Comparison with previous micropaleontological studies supports the magnitude of the paleoenvironmental change affecting both pelagic and benthic environments.

1. Introduction

During the Late Miocene, over a million cubic kilometers of salts accumulated on the Mediterranean seafloor, during a major environmental upheaval known as the Messinian Salinity Crisis (MSC), which lasted from 5.97 to 5.33 Ma (Krijgsman et al., 1999, 2002; Van Couvering et al., 2000; Manzi et al., 2013). An enduring scientific challenge is to understand the palaeoenvironmental processes involved during the MSC, as the Mediterranean allegedly experienced multiple, high-amplitude (>1 km) sea-level drawdowns (Rouchy and Caruso, 2006; Ben Moshe et al., 2020; Andreetto et al., 2022), unprecedented evaporite (gypsum and halite) accumulation (Ryan, 2009; Haq et al., 2020) and several ecological crises (Kouwenhoven et al., 2003; Roveri et al., 2014). The recovery of core material from the deep Mediterranean in the 1970s

led to the prevailing paradigm of a deep desiccated basin (Hsü, 1972; Hsü et al., 1973). Later, the shallow nature of these evaporites and thereby the deep desiccated basin model was questioned (Martínez del Olmo et al., 1996; Roveri et al., 2001; Manzi et al., 2005; Roveri and Manzi, 2006). This generated a wide range of scenarios for Mediterranean base-level changes and basin connectivity during the Messinian (Rouchy and Caruso, 2006; Roveri et al., 2014; Andreetto et al., 2021a, 2021b, 2022). Major controversy centers around the final 200 kyr of the crisis, directly following the supposed acme of sea-level drawdown, during MSC Stage 3 in the commonly used threefold stratigraphic scheme (Fig. 1, Roveri et al., 2014). Currently, three main hypotheses exist for Stage 3: 1) an isolated Mediterranean consisting of disconnected subbasins with shallow endorheic lakes (Fig. 1b; Rouchy et al., 2001; Ryan, 2009; Caruso et al., 2020), 2) an almost full Mediterranean

* Corresponding author.

E-mail address: fjrtovar@ugr.es (F.J. Rodríguez-Tovar).

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in which subbasins were interconnected and Atlantic water flowing in temporarily (Fig. 1c; Vasiliev et al., 2017; García-Veigas et al., 2018; Andreetto et al., 2021a), and 3) a Mediterranean with high-amplitude precession controlled base-level changes (fluctuating between Fig. 1b and c; Fortuin and Krijgsman, 2003; Andreetto et al., 2022).

The different paleogeographic scenarios of MSC Stage 3 have also major impact on numerical models that aim to explain the transition to marine environments that ended the MSC (Blanc, 2002; Garcia-Castellanos et al., 2009). After the MSC, open marine conditions abruptly reestablished throughout the entire Mediterranean at the base of the Zanclean (Van Couvering et al., 2000; Bulian et al., 2022). Assuming an isolated and desiccated Mediterranean, the refilling of the Mediterranean by Atlantic waters is considered to have happened through a megaflood coming in from the Strait of Gibraltar (Garcia-Castellanos et al., 2009, 2020; Micallef et al., 2018; Spatola et al., 2020; Amarathunga et al., 2022) either in the earliest Zanclean (Roveri et al., 2014; Flecker et al., 2015) or, as recent research suggests, in the latest Messinian (Van Dijk et al., 2023). Both imply a relatively abrupt termination of the MSC and a major paleoenvironmental change in the Mediterranean at the Miocene-Pliocene boundary. The exact pace of marine reestablishment and subsequent recovery towards fully normal open marine conditions remains a topic of debate (see the reviews from Roveri et al., 2014 and Andreetto et al., 2021a, and recent work by Amarathunga et al., 2022).

One of the most continuous Mediterranean records of the Miocene-Pliocene transition, covering MSC Stage 3 (Van der Laan et al., 2006; Manzi et al., 2009; Andreetto et al., 2022), the Messinian-Zanclean transition (Londeix et al., 2007; Van Dijk et al., 2023), and a deep marine Zanclean succession (Hilgen and Langereis, 1988) is exposed at Eraclea Minoa, in the Sicilian Caltanissetta Basin. The Eraclea Minoa section (see Fig. 2 for location) represents a relatively thick and complete upper Messinian to lower Zanclean succession (Ogniben, 1957; Decima and Wezel, 1973; Van Couvering et al., 2000). The uppermost Messinian comprises rhythmic couplets of evaporites and marls, referred to as the Second Evaporitic Cycle, Gessi di Pasquasi Formation (Selli, 1960) or Upper Gypsum (UG), and corresponds to the final 200 kyr of the MSC (Van der Laan et al., 2006; Hilgen et al., 2007; Manzi et al.,

2009). The last UG lithological cycle is followed by a clay unit with characteristic brackish water environment biofacies (Benson, 1976; Londeix et al., 2007; Grossi et al., 2015). These clays are overlain by the 5 to 10 m thick Arenazzolo Formation (see Fig. 2), directly underlying the open marine deposits of the Pliocene Trubi Formation (Ogniben, 1957; Brolsma, 1978; Cita and Colombo, 1979). The Arenazzolo Formation has recently been studied by means of detailed facies analysis (Van Dijk et al., 2023), and the Trubi Formation has been profusely studied through sedimentological, micropaleontological, mineralogical, geochemical, and integrated magneto- and cyclostratigraphic studies (i. e., Cita and Gartner, 1973; Hilgen and Langereis, 1988, 1993; Van Couvering et al., 2000).

An underexplored technique in studying this specific transitional interval is ichnology. Trace fossil analysis is based on the relationship between trace fossils and palaeoenvironmental conditions. Tracemaker behavior records the response to biotic and abiotic factors (e.g., salinity, oxygen, nutrients, hydrodynamic energy, rate of sedimentation, and substrate, among others), in some cases associated to particular facies and processes (i.e., see recent reviews in Rodríguez-Tovar, 2021, 2022). Particularly in recent years, usefulness of trace fossils to characterize bio-events has been proven, including major and minor extinction events with variable impact on living biota, with special attention to post-event recovery (Rodríguez-Tovar and Uchman, 2006, 2017; Rodríguez-Tovar, 2005, 2021; Uchman et al., 2008, 2013a; Rodríguez-Tovar et al., 2009, 2020a, 2022; Monaco et al., 2012, 2015, 2016a; Labandeira et al., 2016; Łaska et al., 2017; Lowery et al., 2018). Ichnological analyses of the Messinian-Zanclean transition are rare. Particularly, with respect to the Trubi Formation, only a preliminary ichnological study was conducted in Calabria (Italy), revealing an ichnoassemblage composed of *Chondrites*, *Halimedes*, *Pilichnus*, *Planolites*, *Rhizocorallium*, *Thalassinoides*, *Trichichnus* and *Zoophycos*, typical of the *Zoophycos* ichnofacies (Caruso et al., 2011). Trace fossils from the Trubi Formation in Sicily have only punctually been observed; to our knowledge, only Sciuto and Baldanza (2020) indicate the presence of common trace fossils attributable to *Zoophycos* spp., in northern Sicily (Villafraanca Tirrena area). The aim of the present research is to conduct an ichnological analysis of the Arenazzolo and Trubi formations in the

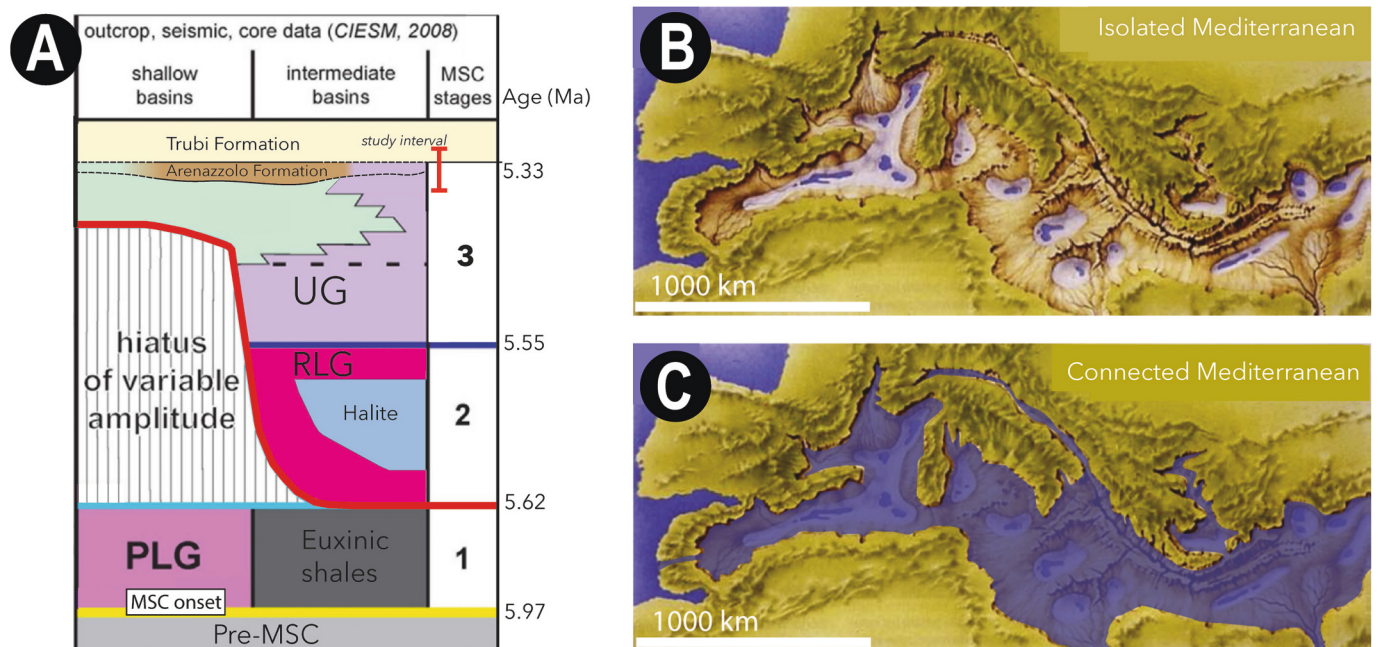


Fig. 1. A) Consensus threefold stratigraphic scheme for the Messinian Salinity Crisis (MSC) event, with a subdivision in three main stages. Two scenarios for the third stage of the MSC are depicted in B and C. B) Scenario of an isolated, lake-dotted Mediterranean. C) Scenario of a half-full (at least partially) connected Mediterranean. Modified after Roveri et al. (2014), Krijgsman et al. (2018) and Andreetto et al. (2021).

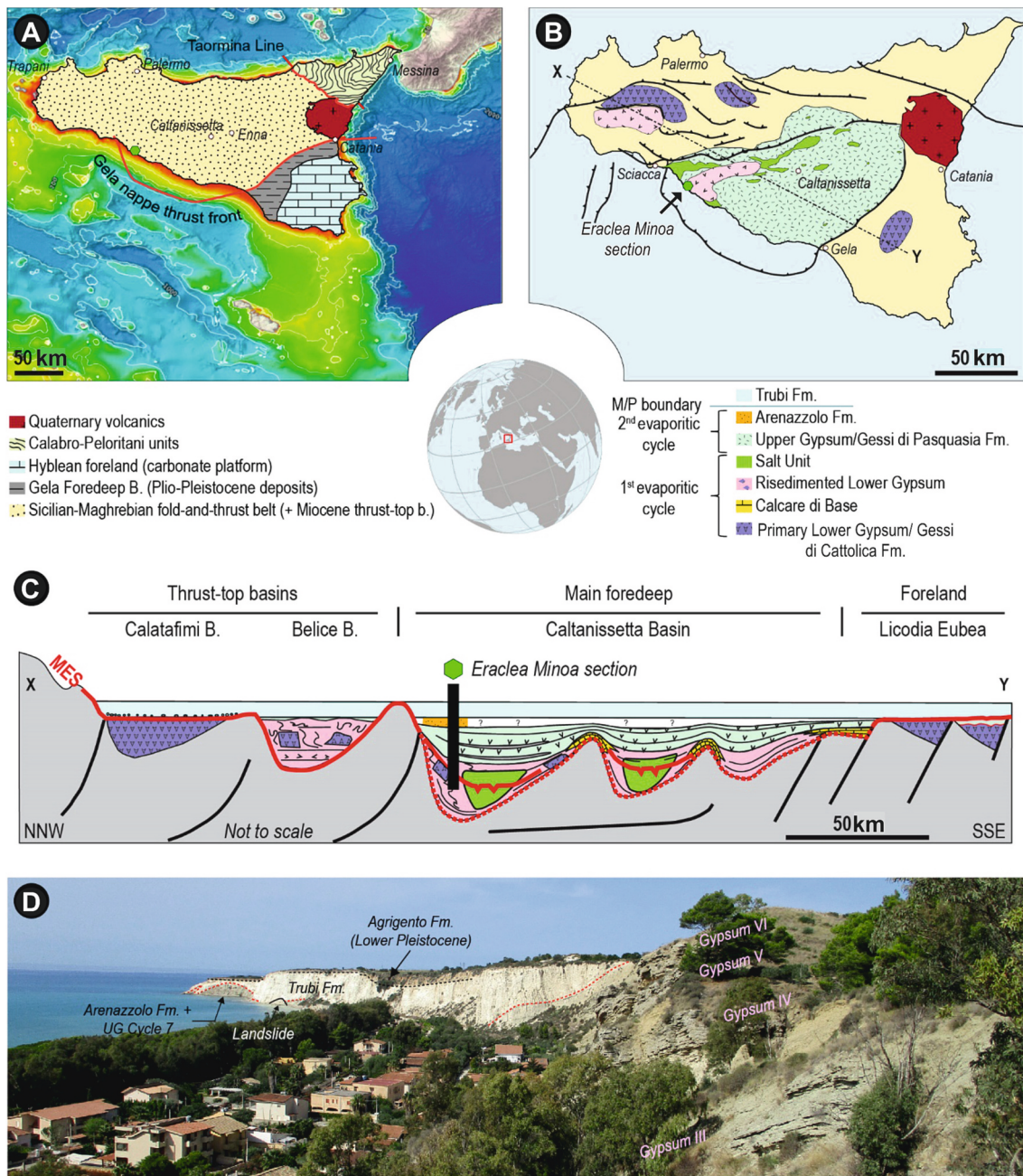


Fig. 2. Simplified geological map of Sicily showing A) the main structural domains and B) the distribution of the gypsum-bearing lithostratigraphic units PLG, RLG and UG (modified from Manzi et al., 2021). C) NW-SE-oriented geological cross section showing the stratigraphic relationships between the lithological units deposited during the Messinian Salinity Crisis (modified from Manzi et al., 2021). The location of the profile trace is indicated. D) Panoramic view of the Eraclea Minoa section with the cliff of Eraclea/Capo Bianco in the background where the Arenazzolo and Trubi Fm. are studied here.

Eraclea Minoa section to reconstruct the paleoenvironmental changes at the end of the Messinian Salinity Crisis and right after the Terminal Messinian Flood (Van Dijk et al., 2023) based on their incidence on the macrobenthic tracemaker community.

2. Geological setting

Sicily is a segment of the Alpine collisional belt and is composed of four, well-distinguished structural domains (Fig. 2a): the Hyblean carbonate Plateau, the Gela foredeep, the Calabro-Peloritani Units and the NE-SW-trending Maghrebic-Sicilian fold-and-thrust belt (Catalano et al., 2013; Basilone, 2018; Henriquet et al., 2019). The Messinian successions of Sicily were deposited in wedge-top basins located above

growing thrust sheets that, during the Miocene, deformed the Mesozoic-Cenozoic carbonatic and terrigenous successions of the orogenic belt into a sequence of anticlines and synclines and in the Caltanissetta Basin, the largest depozone of the Sicilian-Maghrebic foredeep system (Fig. 2b; Butler and Grasso, 1993; Butler et al., 1995, 2014; Catalano et al., 1996, 2013; Grasso et al., 2004).

The pre-evaporitic Messinian deposits of Sicily comprise Milankovitch-controlled alternations of homogeneous marls, sapropels and diatomites (Hilgen and Krijgsman, 1999) deposited in deep-water conditions of ~1200 m (Kouwenhoven et al., 2003). Above rests the “First evaporitic cycle” (after Decima and Wezel, 1973), which more recent studies framed between 5.97 and 5.55 Ma (Roveri et al., 2014) or 5.53 Ma (Manzi et al., 2009). The “First evaporitic cycle” consists of the

informal lithostratigraphic units Calcare di Base (CdB), Gessi di Cattolica Formation/Primary Lower Gypsum (PLG), Resedimented Lower Gypsum (RLG) and Salt Unit (Fig. 2). The CdB, controversial for both its origin and stratigraphic position (Rouchy and Caruso, 2006 and Caruso et al., 2015 vs Manzi et al., 2011, 2016), is mainly composed of a complex array of carbonate facies (Ziegenbalg et al., 2010; Tzevahirtzian et al., 2022). The PLG consists of up to 13 precession-controlled primary gypsum-shale couplets (Lugli et al., 2010). The RLG is a chaotic unit composed of a fine-grained matrix enveloping up to m-sized blocks derived from the subaerial dismantling of the PLG and older units (Lugli et al., 2010). The up to 600 m-thick Salt Unit includes cm-thick annual-scaled lithological cycles of halite and mudstones with minor amounts of bitter salts (Decima and Wezel, 1971; García-Veigas et al., 1995; Lugli et al., 1999). The “Second evaporitic cycle” (after Decima and Wezel, 1973) spans from 5.55 or 5.53 to 5.332 Ma (Roveri et al., 2014). It comprises the seven gypsum-marl alternations of the Gessi di Pasquasia Formation/Upper Gypsum unit and the sandy Arenazzolo Formation (Manzi et al., 2009).

The stratigraphic work of Roveri et al. (2008) indicates that the PLG unit is not associated laterally or vertically with the other MSC-related units (Fig. 2c). In contrast, Caruso et al. (2015) and Tzevahirtzian et al. (2022, 2023) conclude that the evaporitic limestones of the Calcare di Base are its lateral equivalents. The PLG is only found in restricted satellite basins sealed by the Pliocene Trubi Formation (Fig. 2b). The PLG-Trubi contact corresponds to an erosional surface (the Messinian Erosional Surface, MES) associated to an angular unconformity (Decima and Wezel, 1973; Butler et al., 1995). The genesis of this surface is linked to the main Mediterranean drawdown event thought to be responsible of the emplacement of the RLG and of the deep salt giant at Mediterranean scale (Roveri et al., 2014). The RLG, instead, accumulated in basins (e.g., Belice and Caltanissetta Basin; Fig. 1c) facing the PLG-hosting basins and is considered to represent deeper depositional settings. Only in the deepest depocenters of the Caltanissetta Basin are the RLG and the Salt Unit present together (Fig. 2c). However, the physical disconnection of the Salt Unit from all other units makes stratigraphic relationships difficult to reconstruct and ambiguous. In fact, halite deposition has

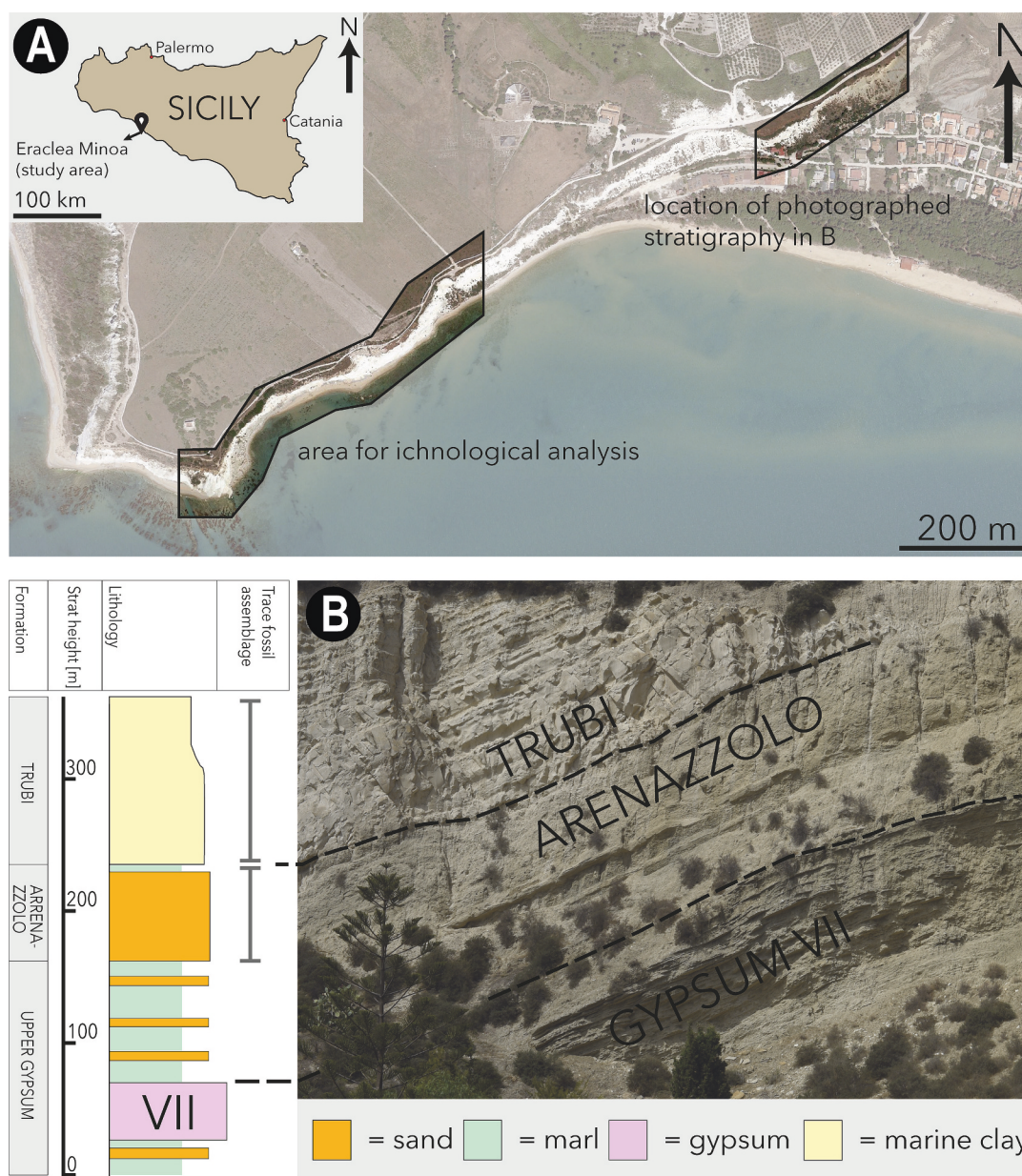


Fig. 3. A) Google Earth image highlighting the outcrops used for ichnological analysis, located southwest of the village of Eraclea Minoa, Sicily. B) General stratigraphy of the Messinian to Zanclean succession at Eraclea Minoa, including the stratigraphic position of the two ichnofossil assemblages described in the text.

been variably interpreted to either post-date the emplacement of the PLG and RLG units (Decima and Wezel, 1973) or to have taken place coevally to PLG (Garcia-Veigas et al. 1995; Rouchy and Caruso, 2006) or RLG deposition (Roveri et al., 2008).

Sediments belonging to the “Second evaporitic cycle” are typically found above the Halite/RLG and below the Trubi Formation in deeper settings (Roveri et al., 2008; Manzi et al., 2009). Fragmented, m-thick outcrops have been recently found also in PLG-hosting basins (Sciuto et al., 2018; Fig. 2c). The Upper Gypsum (UG) unit is exposed in several outcrops all over the Caltanissetta Basin (of which the most complete one is Eraclea Minoa; Fig. 3). According to Manzi et al. (2009), the UG succession is composed of repeating cycles of similar facies successions of either marls and gypsum (cycle 1 to 6, and 7) or marls and sandstones (cycle 6 to 6’). A model to explain the cyclic deposition of the Upper Gypsum was established by Manzi et al. (2009), and later amended by Andreotto et al. (2022). Both are built on recurring cyclical changes in base-level expressed in repeated facies associations of marls and sand or gypsum. The Arenazzolo Formation is located at the transition from the UG to the Zanclean Trubi Formation. Initially, the sandstones of the Arenazzolo Formation were considered as deltaic deposits (Cita and Colombo, 1979; Manzi et al., 2021), but recent work shows that the Arenazzolo Formation is rather a distinct contouritic deposit formed during the Terminal Messinian Flood (Van Dijk et al., 2023).

3. Materials and methods

The Arenazzolo and Trubi formations were studied along the beach southwest of Eraclea Minoa (Eraclea Minoa section; 37°23’24.18”N, 13°16’36.09”E, Figs. 2, 3). A detailed sedimentological analysis of the 5–7 m thick sandy interval of the Arenazzolo Formation (Van Dijk et al., 2023), revealed three distinct facies associations. A first facies association comprises alternating planar and laminated very fine sandstones, with paleocurrents directed along the regional slope physiography. This has been interpreted as a contourite deposit marking the reconnection of the western and eastern Mediterranean over the Sicily Sill. The overlying facies association is similar in composition, but has massive bedding, dm-scale convolute laminations, and is *syn*-depositional to gravitational gypsum deformation on the regional slope. The final facies association before the Pliocene, is mud-dominated and penetrated by burrows filled by the Trubi Formation. The latter consists of cyclic alternating calcareous and marly pelitic deposits, rich in planktonic foraminifera, with abundant back filled trace fossils. The marly rhythmites consist of a gray layer and a white more indurated calcareous layer in which an additional beige less indurated layer is intercalated (Hilgen, 1991).

Analysis of the ichnological features in outcrop focused on ichnotaxobases (i.e., overall shape, orientation, ornamentation, internal structure; Bromley, 1996; Bertling et al., 2006, 2022). Ichnodiversity and abundance of the trace fossil assemblages were studied, together with infilling material of burrows, size, depth from the bed surface, and cross-cutting relationships. The abundance of trace fossils is expressed by the bioturbation index (BI) (Taylor and Goldring, 1993), where grade 0 means no bioturbation and grade 6 designates completely bioturbated rock. Ichnological features, including trace fossil assemblage, allow characterization of archetypal ichnofacies (i.e., Buatois and Mángano, 2011). Photographs were taken to characterize ichnotaxa, and the relationships of trace fossils with sedimentary structures, bed surfaces, and facies. Due to outcrop limitations, ichnological work that was done on the Zanclean Trubi Formation is partially based on fallen blocks at the base of exposed cliffs (in the area indicated in Fig. 3A). This has allowed us to perform an extensive analysis but one that is limited in terms of precise stratigraphic control.

4. Ichnological analysis

4.1. Trace fossil assemblage

The ichnological analysis from the uppermost Messinian Arenazzolo Formation shows scarce bioturbation, consisting exclusively of small traces (*Chondrites*), observed as circular to elliptical spots, sparsely distributed in several horizons of the Arenazzolo deposits penetrating up to 5–6 cm from the surface (Figs. 4A–C). The punctual record of *Planolites* cannot be totally discarded. Thus, BI fluctuates between 0 and 1.

In contrast to the Arenazzolo Formation, the Zanclean Trubi Formation is characterized by an abundant and diverse trace fossil assemblage. Eight ichnogenera have been differentiated, including abundant *Chondrites*, *Planolites*, *Thalassinoides*, and *Zoophycos*, common? *Arenicolites*, and *Trichichnus* and rare *Palaeophycus* and *Halimedes* (Figs. 5, 6). Trace fossils generally show a dark infill except for *Trichichnus* which has a ferruginous filling. Crosscutting relationships are frequent mainly with *Chondrites* cross-cutting other traces, including *Planolites*, *Thalassinoides*

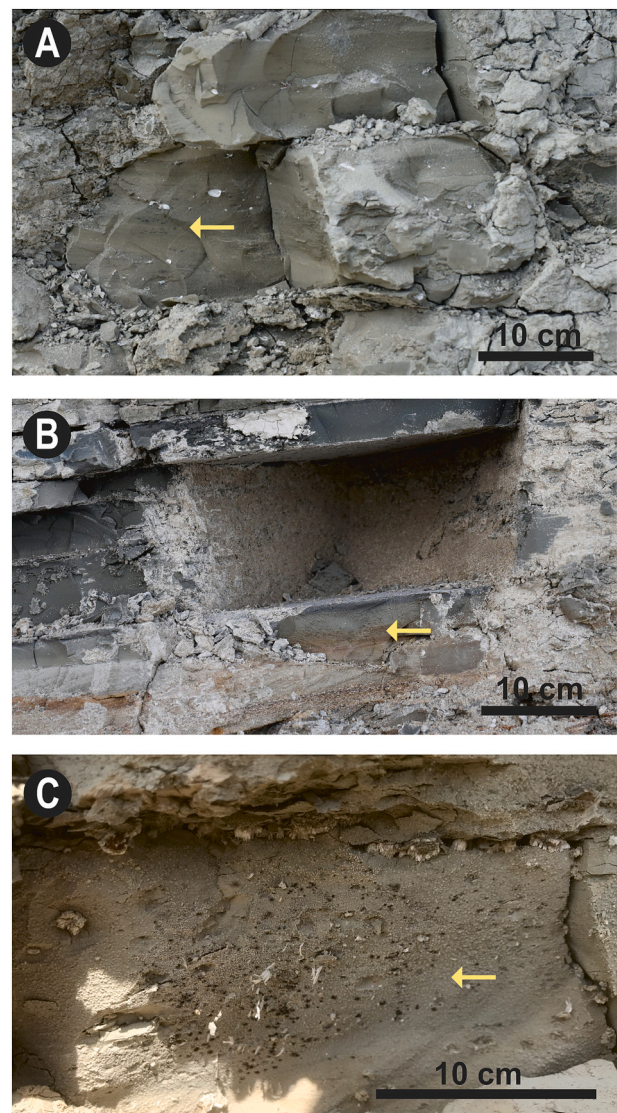


Fig. 4. A–C) Trace fossils from the uppermost Messinian Arenazzolo Formation. Small traces (*Chondrites*; yellow arrows), observed as circular to elliptical spots, sparsely distributed in several silty horizons into the Arenazzolo Formation sediments, penetrating up to 5–6 cm from the surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

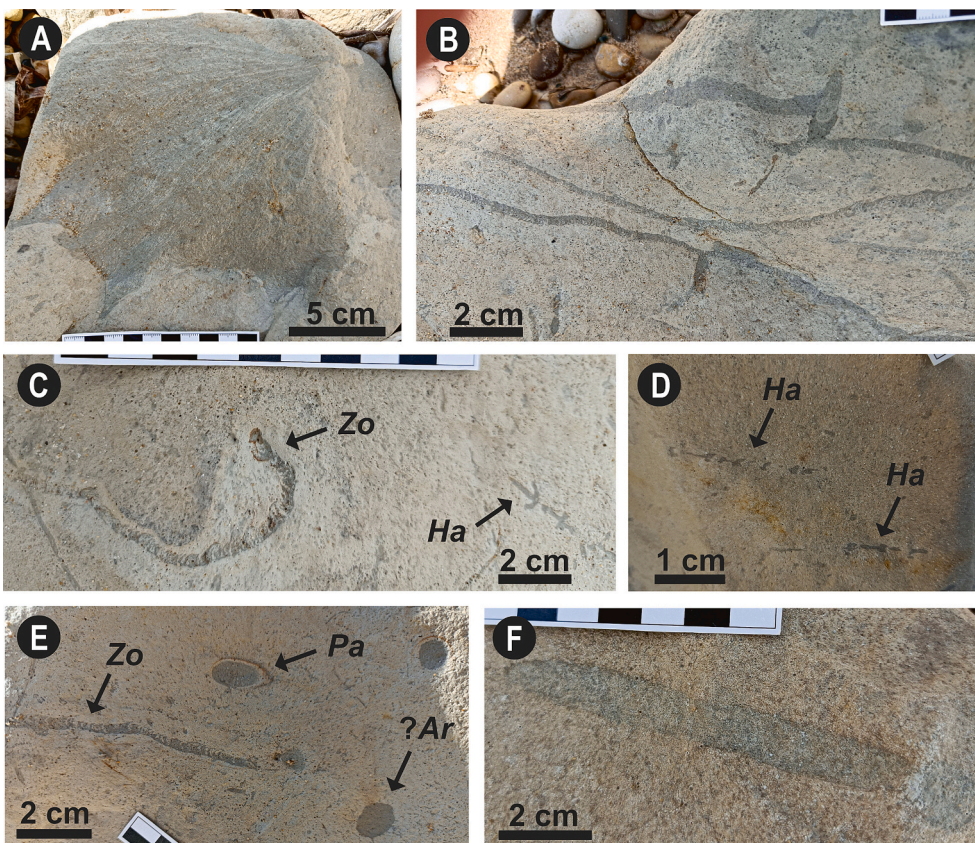


Fig. 5. Trace fossils from the Zanclean Trubi Formation A-C) *Zoophycos* (Zo), showing, a near complete specimen (A), more or less horizontal, spreiten structures (B), and helicoidal form with *Halimedes* (Ha) (C). D) *Halimedes* (Ha) with heart-chambers separately distributed on the string. E-F) *Palaeophycus* (Pa) as subcircular lined burrows together with *Zoophycos* (Zo) and ?*Arenicolites* (?Ar) (E) and as cylindrical burrows (F).

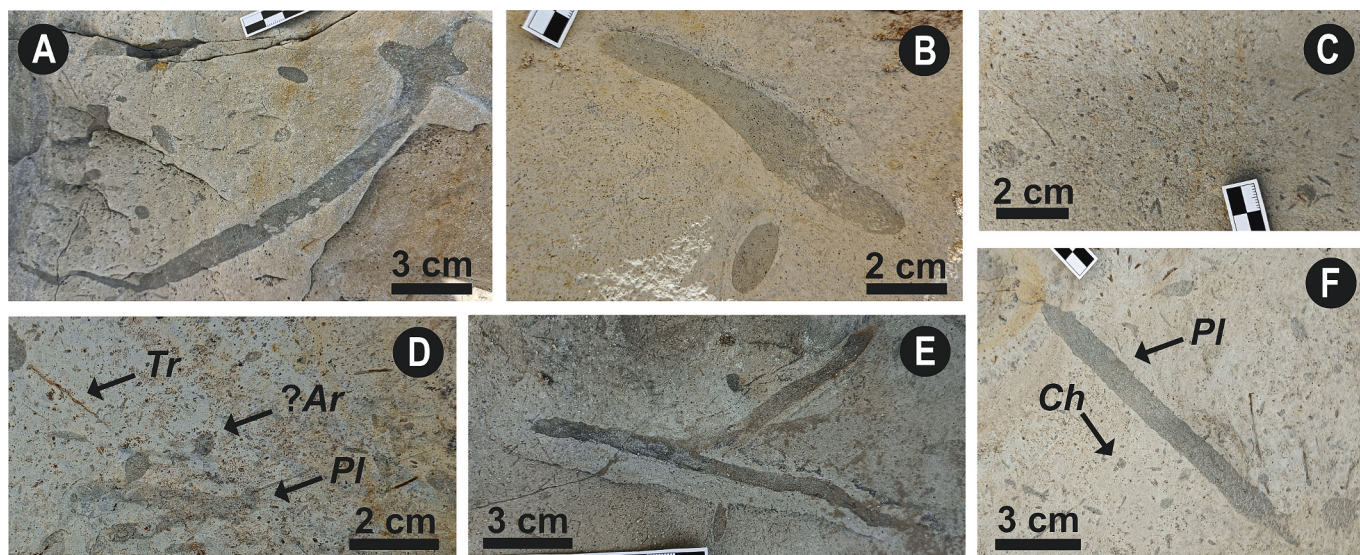


Fig. 6. Trace fossils from the Zanclean Trubi Formation A-B) *Thalassinoides*, as slightly winding cylinders with occasional branching (A) and as straight cylinders (B). C) *Chondrites* as small circular to elliptical spots between 1 and 3 mm wide, occasionally branched. D) *Trichichnus* (Tr) as straight cylinders filled with ferruginous material, together with ?*Arenicolites* (?Ar) and *Planolites* (Pl). E-F) *Planolites* (Pl) as horizontal, unbranched, cylindrical tubular forms, unlined, showing false branching (E), together with *Chondrites* (Ch) (F).

and *Zoophycos*, *Trichichnus* cross-cutting *Thalassinoides*, and also *Zoophycos* cross-cutting *Thalassinoides* (and viceversa) are also observed (Figs. 7, 8). Trace fossils are relatively abundant, with BI = 1–4. Brief description of the differentiated ichnogenera is as follows:

?*Arenicolites* occurs as pairs of circles, 3 to 8 mm in diameter, in

horizontal section without spreite (Figs. 5E, 6D, 8B). Vertical, sub-parallel U-shaped burrows have been not observed that preclude a conclusive assignment. *Arenicolites*, interpreted as a domichnia structure, is related to polychaetes or amphipod crustaceans (Goldring, 1962; Fürsich, 1974; Rindsberg et al., 2005; Fernández-Martínez et al., 2021a).

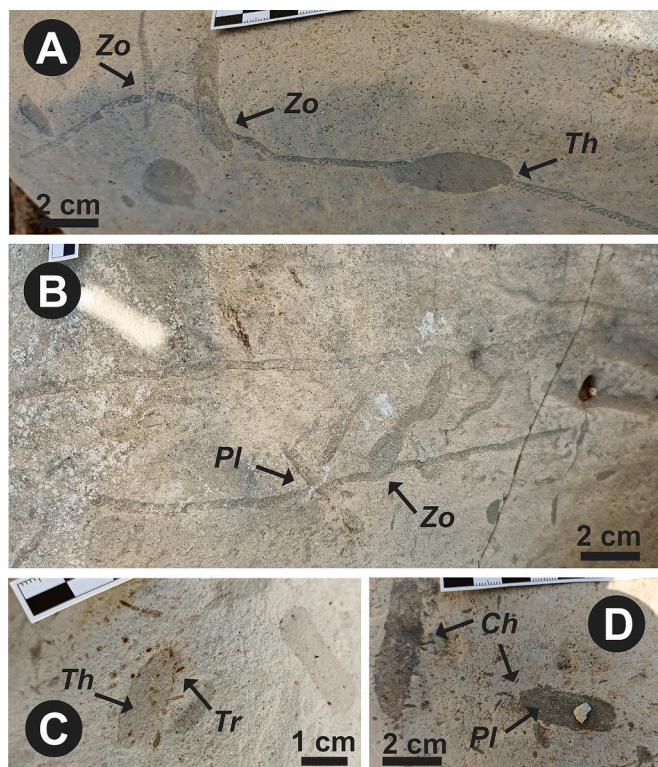


Fig. 7. Crosscutting relationships of trace fossils from the Zanclean Trubi Formation A) Vertical Zoophycos (Zo) and Thalassinoides (Th) cross-cutting horizontal Zoophycos. B) Zoophycos (Zo) cross-cutting Planolites (Pl). C) Trichichnus (Tr) cross-cutting Thalassinoides (Th). D) Chondrites (Ch) cross-cutting Planolites (Pl).

Chondrites appears as circular to elliptical spots and horizontal to subhorizontal tubes, 1–3 mm wide, occasionally branched, at times in patches, scattered in the bed or reworking other traces (Figs. 4, 6C, F, 7D, 8A, B). *Chondrites* is considered as a feeding structure, produced by an unknown organism, but mainly related to vermiforms (polychaetes), but also bivalves and other organisms. Several interpretations have been traditionally proposed, as fodinichnia, chemichnia or agrichnia behavior (Seilacher, 1990; Kotake, 1991; Fu, 1991; see Baucon et al., 2020 for a recent review). The *Chondrites* trace maker is considered to be a low oxygen-tolerant organism (Bromley and Ekdale, 1984).

Halimedes is represented by heart-chambered (dominant), semi-circular and rectangular bodies separately distributed on the strings (1 mm wide, up to 30 mm long), showing no branching (Fig. 5C, D). Tracemaker is unknown though infaunal crustaceans are considered. The record of *Halimedes* associated to oceanic anoxic event intervals (e.g., OAE-1, OAE-2) has been related it to an improvement of seafloor oxygenation (Uchman et al., 2013b; Rodríguez-Tovar et al., 2019). Agrichnia, and/or sequestrichnia, behaviours have been considered, favouring the colonization of comparatively oligotrophic seafloors (Uchman, 1999; Gaillard and Olivero, 2009; Rodríguez-Tovar et al., 2019; Fernández-Martínez et al., 2021b).

Palaeophycus appears as unbranched forms, mainly as circular to subcircular cylindrical burrows, smooth and lined, up to 10 mm wide and 10 cm long (Figs. 5E, F, 8A). It is interpreted as an open tube produced by carnivorous or omnivorous invertebrates, mostly polychaetes, and associated to pascichnia or domichnia (Pemberton and Frey, 1982; Keighley and Pickerill, 1995, 1997; Rodríguez-Tovar et al., 2009).

Planolites are observed as horizontal, unbranched, mainly circular to subcircular cylindrical tubular forms, clearly unlined, with variable size (diameter 3–10 mm, length up to 12 cm), and occasional false branching (Figs. 6D, E, F, 7B, D, 8A, B). *Planolites* features actively filled burrows,

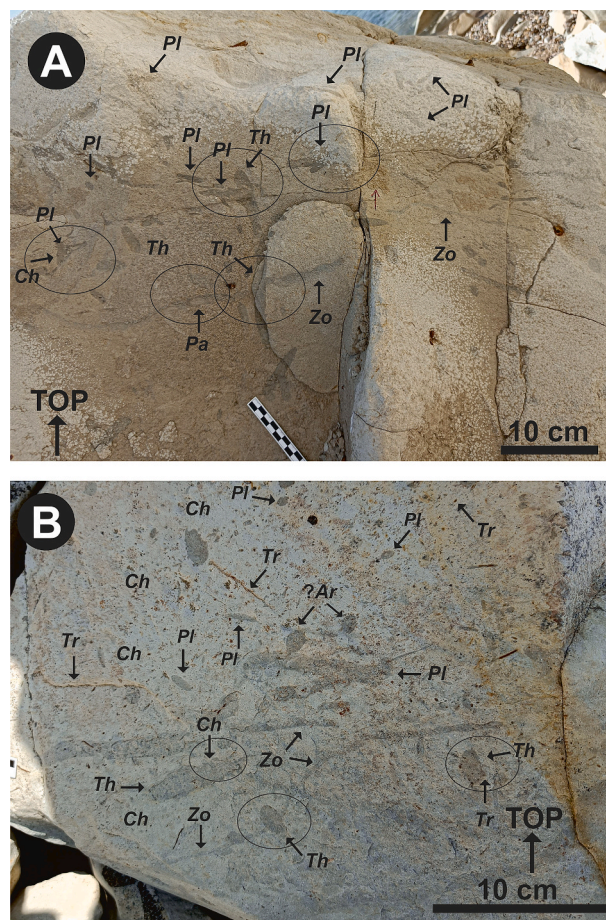


Fig. 8. Vertical distribution of trace fossils from the Zanclean Trubi Fm, from the upper bed surface. Note: TOP and Arenicolites (Ar), Chondrites (Ch), Palaeophycus (Pa), Planolites (Pl), Thalassinoides (Th), Trichichnus (Tr) and Zoophycos (Zo). Note cross-cutting relationships (circles) between Pl-Pl, Pl-Th, Ch-Pl, Pa-Zo, and Th-Zo (A) and Ch-Th, Th-Zo and Tr-Th (B).

interpreted as a pascichnia, occurring in diverse environments, probably produced by different organisms, mainly soft bodied invertebrates (see Pemberton and Frey, 1982; Keighley and Pickerill, 1995; Knaust, 2017). Occasionally, *Planolites* has been interpreted as a previously open burrow that was passively filled with overlying sediment (Locklair and Savrda, 1998).

Thalassinoides are observed as oval spots, circular to subcircular (10–15 mm wide), together with straight or slightly winding horizontal smooth cylinders with occasional branching (Figs. 6A, B, 7A, C, 8A, B). *Thalassinoides* is mainly interpreted as a dwelling and feeding structure (domichnia and fodinichnia), typically produced by crustaceans (thalassinid shrimps), but also by arthropods, anemones, fish and other vermiform organisms (Fürsich, 1973; Ekdale et al., 1984; Ekdale, 1992; Schirf, 2000; Ekdale and Bomley, 2003; Rodríguez-Tovar et al., 2008, 2017). *Thalassinoides* is registered in several marine facies (e.g., Monaco et al., 2007).

Trichichnus is observed as horizontal, vertical to oblique, straight or almost straight, smooth cylinder, circular or elliptical in cross-section (Figs. 6D, 7C), 1 to 3 mm wide, up to 30 mm long, and filled with ferruginous material. *Trichichnus* is produced by opportunistic deeply burrowing organisms with higher tolerance for dysoxia than *Chondrites* (McBride and Picard, 1991; Uchman, 1995; Kotlarczyk and Uchman, 2012; Łaska et al., 2017). *Trichichnus* is interpreted as a chemosymbiotic feeding traces (Uchman, 1999) and as fossilized filaments of sulphur bacteria living in the transition from anoxic to dysoxic sediments (Kędzierski et al., 2014). *Trichichnus* occurs in both shallow- and deep-

marine fine grained deposits (Frey, 1970; Wetzel, 1983).

Zoophycos are mainly observed as repeated, more or less horizontal, spreiten structures, and only occasionally as a more or less complete specimen (Figs. 5A–C, E, 7A–B). In cross section, lamellae into the lamina are obliquely distributed, consisting of alternating dark and light material. In some cases more or less circular tube sections are observed. *Zoophycos* displays several morphological varieties (Vinn and Toom, 2015; Mekki et al., 2019; Vinn et al., 2020; Bouchemla et al., 2021), probably constructed in diverse ways by different organisms (e.g., Olivero, 2007; Monaco et al., 2016b), which may include siphunculids (Wetzel and Werner, 1980), polychaete annelids, arthropods (Ekdale and Lewis, 1991), or echiuran worms (Kotake, 1992). Ethological interpretations are variable, with several ethological models being proposed (deposit feeder, detritus feeding, refuse dump, cache, gardening, or chemosymbiosis; Bromley, 1991; Bromley and Hanken, 2003; Löwemark et al., 2004, and Zhang, 2014 for a review). Occasionally *Zoophycos* has been used to characterize high seasonal organic-matter deposition and primary productivity (Dorador et al., 2016, 2019, 2021).

4.2. Trace fossil distribution

Occasionally, in the Trubi Formation, larger, well-exposed, rocks allow observation of the trace fossil distribution downward from the upper bed surface, revealing a clear variation in ichnodiversity and abundance (Fig. 8).

Thus, just below upper bed surface, in the uppermost part, discrete traces mainly consisting of dispersed *Planolites* are observed, in cases showing cross-cutting relationships between different specimens (Fig. 8). Moreover, *Chondrites* and *Trichichnus* are also randomly distributed. Bioturbation index is between 1 and 2. Downward, increase in diversity and abundance is observed, as well as a variety of cross-cutting relationships. Thus, *Planolites* occurs in the upper part and deeper dominant *Thalassinoides*, in some cases cross cut by *Planolites*, and locally *Palaeophycus*. *Zoophycos*, and common *Chondrites* and *Trichichnus*, in cases cross cutting *Planolites* and *Thalassinoides* are observed in the lower part. Bioturbation index increases to 3 or 4. Downward, in the lowermost part *Zoophycos* become dominant, together with *Chondrites* and *Trichichnus*, showing a general decreasing in the BI to 2. Observed variations in ichnodiversity, bioturbations index, and cross-cutting relationship allow interpreting vertical partitioning of the endobenthic community, thus position of trace maker community in relation to substrate-water interface or tiering (Ekdale and Bromley, 1991; Bromley, 1996; Rodríguez-Tovar and Uchman, 2004; Buatois and Mángano, 2011; Fig. 8). Thus, the upper tier, up to 1 cm below the boundary surface, is characterized by the scarcity of discrete trace fossils, mainly disperse *Planolites* representing the activity of shallow, vagile deposit-feeders. The middle tier displays the highest trace fossil diversity and abundance, with *Planolites*, *Palaeophycus*, *Halimedes*, and dominant *Thalassinoides* produced by mobile crustaceans feeding at slightly a deeper level. In the lower part of this middle tier and mainly in the deepest tier *Zoophycos*, *Chondrites* and *Trichichnus* mainly represent sessile to semisessile deposit-feeders, farming or chemichnial structures.

5. Discussion

5.1. Tracemaker community and palaeoenvironmental conditions during deposition of the uppermost Messinian Arenazzolo and the Zanclean Trubi formations

The scarcity of trace fossils in the Arenazzolo Formation sandstones is most probably related to high energy depositional conditions in agreement with the abundant presence of traction structures, and soft sediment deformation. The local record of bioturbated horizons reveals intermittent phases of lower energy facilitating colonization by opportunistic tracemakers as those producing *Chondrites*. Variations in energy

can be considered in the context of bottom-current processes determining deposition of the Arenazzolo Formation sandstones as contouritic deposits (Van Dijk et al., 2023). Other ecological factors inducing depauperated tracemaker communities related to anoxic/suboxic conditions can be discarded, as common “black” sediments are absent. The importance of salinity as a major limiting factor is well-known for coastal, brackish-water benthic faunas (i.e., Jaglarz and Uchman, 2010; Buatois and Mángano, 2011), but less considered in “full-marine” distal environments. However, considering the particular environment at the end of the Messinian Salinity Crisis, we cannot discard the role of salinity in explaining the observed impoverishment in the tracemaker community.

The trace fossil assemblage recognized in the calcareous pelitic deposits of the Trubi Formation at Eraclea Minoa consists of abundant *Chondrites*, *Planolites*, *Thalassinoides*, and *Zoophycos*, common? *Arenicolites*, and *Trichichnus* and rare *Halimedes*. This assemblage is typical of the *Zoophycos* ichnofacies. This ichnofacies is usually associated with fine-grained, pelagic and hemipelagic, non-turbiditic sediments typified by very low sedimentation rates (Buatois and Mángano, 2011; MacEachern et al., 2012; Uchman and Wetzel, 2012; Miguez-Salas and Rodríguez-Tovar, 2019). Frequent cross-cutting relationships reflect the progressive upward migration of a single, multi-tiered benthic association, a single ichnocoenosis, during continuous sediment accretion, determining autocomposite ichnofabrics (Ekdale and Bromley, 1983, 1991; Buatois and Mángano, 2011; Savrda, 2016; Miguez-Salas and Rodríguez-Tovar, 2019; Rodríguez-Tovar et al., 2020b). In this interpreted multi-tiered association of tracemakers, the upper tier association displays the highest trace fossil abundance and diversity, consisting of *Planolites*, *Palaeophycus* and? *Arenicolites* as representing a shallower deposit-feeder fauna, the middle tier consists of *Thalassinoides* and *Halimedes*, and *Zoophycos* in deeper levels. *Zoophycos* cross-cutting *Thalassinoides*, and *Thalassinoides* cross-cutting *Zoophycos* could reveal a simultaneous colonization of this middle tier. The deeper tier is mainly/exclusively occupied by the small *Chondrites* and *Trichichnus*, and the later colonization is reflected by the crosscutting relationships of *Chondrites* cross-cutting *Planolites*, *Thalassinoides* and *Zoophycos*, and *Trichichnus* cross-cutting *Planolites* and *Thalassinoides*. This multi-tiered trace-fossil assemblage with abundant bioturbation structures and relatively high ichnodiversity reveals full-marine conditions with well oxygenated bottom- and pore-waters, and food availability. *Zoophycos* ichnofacies mainly occurs in quiet water settings below the storm wave base, particularly in shelfal to slope areas, but it also occurs at shallower and deeper water (Buatois and Mángano, 2011). Dominance of *Zoophycos* in the registered assemblage supports deep settings. Registered trace fossils are mainly associated to softgrounds, although the presence of well-defined, undeformed burrows suggests an increase in substrate consistency. The proposed palaeoenvironmental interpretation of the ichnofossil assemblage of the base of the Trubi Formation agrees with existing micropaleontological data. Information obtained from ostracods and benthic foraminifers have been used to interpret palaeoenvironmental conditions during the deposition of the lowermost Trubi Formation above the Messinian/Zanclean boundary at Sicily (i.e., Decima and Wezel, 1973; Cita and Colombo, 1979; Sgarrella et al., 1997, 1999; Barra et al., 1998; Sciuto and Baldanza, 2020). According to these interpretations, bottom waters were constantly cold, probably with little mixing of water masses, and food availability was generally high, in the form of nutrients and organic fluxes which stimulated the proliferation of benthic infaunal/shallow infaunal and epifaunal species. Although the paleobathymetry of the Caltanissetta Basin at the Messinian/Zanclean boundary is debated, most of the micropaleontological data point towards a deep-water depositional environment (>500 m b.s.l.) during the early Zanclean: 200–500 m (Decima and Wezel, 1973), 600–800 m (Sgarrella et al., 1997, 1999; Barra et al., 1998), 1400–2400 m (Cita and Colombo, 1979). These water depths correspond to current day Mediterranean Deep Water (MDW), which represents the colder water mass (comparing with the intermediate and surface water masses) flowing

below 500 m water depth, along the slope, continental rise and abyssal plains. The Western MDW has a temperature of 12.7 °C and a salinity of 38.4 psu (practical salinity units), while the Eastern MDW is characterized by a temperature of 13.6 °C and a salinity of 38.7 psu. (Millot, 1999, 2009; Sparnocchia et al., 1999; Astraldi et al., 2001; Lermusiaux and Robinson, 2001). Therefore, the Trubi Formation could represent the onset of deep-marine conditions with a water mass stratification and a cold proto-MDW.

5.2. Evolution of the trace maker community: the post-Messinian Salinity Crisis climax

Ichnological analysis from the uppermost Messinian Arenazzolo Formation to the lowermost Zanclean Trubi Formation shows significant differences in the tracemaker community, revealing variations in the paleoenvironmental conditions of the latest Messinian and early Zanclean. Exclusive presence of small traces (*Chondrites*) sparsely distributed in several horizons into the Arenazzolo Formation sandstones, progress to an abundant, diverse, well-developed, multi-tiered, trace fossil assemblage with *Arenicolites*, *Chondrites*, *Halimedes*, *Palaeophycus*, *Planolites*, *Thalassinoides*, *Trichichnus* and *Zoophycos*, registered in the calcareous pelitic deposits of the Trubi Formation (Fig. 9).

The significant change in trace fossil assemblage corresponds to the transition between mud dominated FA5 of the Arenazzolo Formation and calcareous pelitic deposits of the Trubi Formation, without a major erosional surface in between. The abundant and relatively diverse trace fossil assemblage of the Trubi Formation reveals the establishment of normal, full-marine, conditions with well oxygenated bottom- and porewaters, and food availability. These conditions could evidence increased distality and deepening from the uppermost Messinian Arenazzolo Formation to the lowermost Zanclean Trubi Formation, in agreement with the establishment of the typical *Zoophycos* ichnofacies. Darker infill

of the traces registered into the host whitish pelitic sediments supports the presence of intercalations of dark muddy sediments into whitish pelitic sediment deposition. However, the interpreted softground conditions during bioturbation of whitish pelitic sediments allow discarding significant hiatuses or erosive phases determining increase in substrate consistency.

5.3. Pelagic to benthic marine conditions: an integrative approach

Integrative analysis of the obtained ichnological information with the previous paleontological data from the studied area supports the presumed paleoenvironmental change occurring at the Messinian/Zanclean boundary associated to the generalized favorable marine conditions during deposition of the Zanclean Trubi Formation. Micropaleontological works on the Arenazzolo Formation revealed the presence of oligotypic faunal associations with shallow-water benthic foraminifera and ostracods (Brolsma, 1978; Cita and Colombo, 1979; Bonaduce and Sgarrella, 1999; Grossi et al., 2015). In addition, flaser stratification was interpreted as suggesting high-energy conditions in littoral environments at the edge of a lake or a delta lobe (Cita and Gartner, 1973; Basilone, 2018). The scarce presence of ostracods was also interpreted as representing deposition in lacustrine-fluvial environments with fluctuating salinity (Grossi et al., 2015). In contrast, the Arenazzolo Formation was also interpreted as deep marine deposit with similar cyclic sedimentation as in the Trubi Formation (Bache et al., 2012). Integrative sedimentological analysis, however, indicated that the Arenazzolo Formation sandstones were deposited by persistent bottom currents, flowing parallel to the regional slope during a general transgression (Van Dijk et al., 2023). These currents have been interpreted to be associated to a Terminal Messinian Flood, when a contouritic drift formed on the northwestern flank of the basin-bounding Gela thrust front, reconnecting the eastern and western Mediterranean (Van Dijk et al., 2023).

The ichnological record agrees with unfavourable, high energy conditions associated to bottom currents, hampering the establishment of a well-developed tracemaker community. A significant, rapid, environmental change is observed at the Messinian/Zanclean boundary affecting pelagic to benthic environments. Planktonic foraminifers and calcareous nannofossils have been profusely recognized in the Trubi Formation, evidencing a habitable water column (Basilone, 2018; Sciuto and Baldanza, 2020). Planktonic assemblages indicate a water column with stable warm shallow oligotrophic waters and highly productive intermediate warm waters (Sciuto and Baldanza, 2020). At the benthic habitat, the bottom was constantly cold, oxygenated, and food availability stimulated the proliferation of microbenthic assemblages, represented by ostracods and foraminifera, including epifaunal and infaunal, mainly shallow ones (Sciuto and Baldanza, 2020). The ichnological record, and especially particular ichnotaxa as *Planolites* with no connection to the sea floor, reveals that favorable benthic environment is registered not only in the first centimeters below the seafloor, as micropaleontological data suggest (Sciuto and Baldanza, 2020), but deeper into the sediment. Tiering structures of the macrobenthic tracemaker communities, dominated by the shallow and middle tiers, reflect the activity of tracemakers just below the seafloor, and a few centimeters deep within the substrate. The abundant record of *Zoophycos*, and especially *Chondrites*, representing the recolonization of deep tiers, shows activity down to some tens of centimeters within the substrate.

6. Conclusions

Ichnological analysis of the Arenazzolo and Trubi formations in the Eraclea Minoa section of the Sicilian Caltanissetta Basin reveals important differences in trace fossil assemblages related to paleoenvironmental changes affecting the macrobenthic tracemaker community at the end of the Messinian Salinity Crisis. The uppermost Messinian

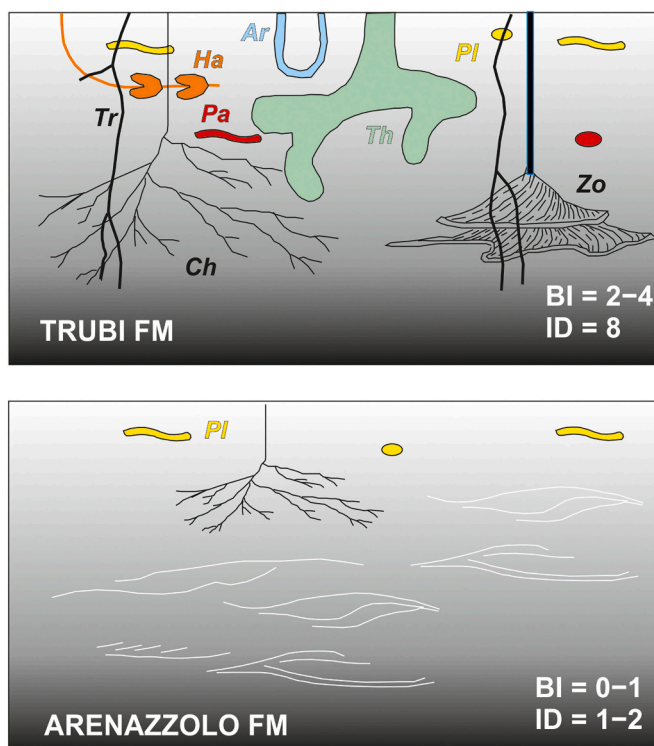


Fig. 9. Sketch showing evolution of tiering structure from the Arenazzolo Formation and Trubi Formation, with indication of ichnodiversity (ID) and bioturbation index (BI). Note: *Arenicolites* (Ar), *Chondrites* (Ch), *Halimedes* (Ha), *Palaeophycus* (Pa), *Planolites* (PI), *Thalassinoides* (Th), *Trichichnus* (Tr) and *Zoophycos* (Zo).

Arenazzolo Formation is characterized by exclusive presence of small traces (*Chondrites*) sparsely distributed in several horizons, while the calcareous pelitic deposits of the Trubi Formation consist of a trace fossil assemblage with *Arenicolites*, *Chondrites*, *Halimedes*, *Palaeophycus*, *Planolites*, *Thalassinoides*, *Trichichnus* and *Zoophycos* assigned to the *Zoophycos* ichnofacies. The scarcity of trace fossils in the Arenazzolo Formation sandstones is most probably related to high energy depositional conditions, and perhaps, not fully normal salinity yet, determining an unfavourable habitat for macrobenthic tracemaker community. The local record of bioturbated horizons is associated to intermittent phases of lower energy facilitating colonization by opportunistic tracemakers. A significant, rapid, environmental change is observed at the Messinian/Zanclean boundary affecting pelagic to benthic environments, determining an abundant, diverse, well-developed, multi-tiered, tracemaker community. This is related to the establishment of normal, full-marine, conditions with well oxygenated bottom- and pore-waters, and food availability in a deep environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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