**SUPPLEMENTARY INFORMATION**

**A multidisciplinary study of ecosystem evolution through early Pleistocene climate change from the marine Arda River section (Italy)**

Crippa et al.

**A1. Specimen counting**

*Bivalves and brachiopods*: it was considered if they were articulated or disarticulated. Following Di Geronimo and Robba (1976), we counted as one specimen: a) articulated shells, b) complete disarticulated valves and c) uncompleted disarticulated valves, which preserved the umbonal region or the hinge line, or more in general valves where it was possible to identify if they were right/ventral or left/dorsal ones. We counted for disarticulated bivalves/brachiopods the maximum number of valves of one type (right/ventral or left/dorsal) present in the highest number. Indetermined valve indicates a complete valve, but where the preservation was not enough to discern between right/ventral or left/dorsal.

*All other taxa* (gastropods, corals, scaphopods, echinoids, anellids, bryozoans and cirripeds): we counted one specimen when more than 2/3 of the shell/skeleton was preserved.

*Fragments*: fragments comprised shells/skeletons of specimens, whose preservation conditions did not fall in the categories described above.

Total counting in each level is given by:

number of articulated bivalves/brachiopods + number of disarticulated bivalves/brachiopods (highest number of valves of one type) + number of other taxa

We excluded from the total fragments and indetermined valves.

**A2. Taphonomic preservation**

*Biofacies 1*

The taphonomic preservation of deeper water species is generally good; ornamentation and the original color pattern are often preserved. Bivalves and brachiopods are mostly disarticulated, but not fragmented. Few specimens show corrasion, and encrustations/bioerosions on the external part of shells/skeletons. The presence of shallow water marine species such as *Chamelea gallina, Spisula subtruncata* and *Acanthocardia tuberculata*, showing high levels of corrasion suggests a transport from shallower settings [Table A1 (ACG24-ACG30)].

*Biofacies 2*

Almost all the specimens have an excellent taphonomic preservation, often with color pattern and ornamentation well preserved; rare are specimens corraded or bioeroded [Table A1 (ACG32, ACG35-ACG37, ACG46-48)].

*Biofacies 3*

Bivalves are disarticulated, frequently fragmented and corraded [Table A1 (ACG33-ACG34)].

*Biofacies 4*

Bivalves are mainly disarticulated, although articulated specimens occur; the majority of the fossils preserve their ornamentation and original color pattern, rarely showing corrasion and external encrustations and bioerosions [Table A1 (ACG49-ACG56; ACG80-ACG82)].

*Biofacies 5*

The specimens are often articulated/complete; these, generally preserve the ornamentation and the original color pattern, few of them show a low grade of corrasion and have mainly external encrustations/bioerosions [Table A1 (ACG242-ACG251; ACG256-264)].

*Biofacies 6*

Specimens of *Arctica islandica*, here in life position, lacks sediment filling inside the valves; all the other associated taxa show generally an excellent preservation [Table A1 (ACG253-ACG254)].

*Biofacies 7*

Commonly, bivalves present articulated valves and several specimens have also the original color pattern preserved, rarely showing corrasion and external bioerosions [Table A1 (ACG104-ACG130; ACG230-ACG234)].

*Biofacies 8*

Bivalves are either articulated or disarticulated and the preservation of the shells/skeleton is generally good, with only few specimens showing corrasion [Table A1 (ACG56bis-ACG65; ACG75-ACG78; ACG84-ACG85)].

*Biofacies 9*

Numerous bivalves present articulated valves and several specimens have the ornamentation and the original color pattern preserved, rarely showing corrasion and external bioerosions [Table A1 (ACG86-ACG103)].

*Biofacies 10*

Bivalves are mainly disarticulated and shells/skeletons often show corrasion and external and internal encrustations/bioerosions [Table A1 (ACG41/42-ACG43; ACG66-ACG70; ACG131-ACG229; ACG235-ACG239)]. However, some specimens are articulated and preserve the ornamentation and the original color pattern [Table A1 (ACG41-ACG43)]; within this Biofacies articulated *Pinna* sp. and infaunal echinoids in life position are found. Encrustations and bioerosions indicate that most of the specimens suffered for a long residence time on the sea floor before being transported and accumulated.

*Biofacies 11*

Fossil material is generally poorly preserved, corraded, disarticulated and fragmented and belong to taxa from different environments [Table A1 (ACG241; ACG252)].

**Table A1: Taphonomic tables**

The following tables illustrate, in stratigraphic order, the results of the taphonomic analysis for each taxa in each level of the Arda succession (ID of the sample and the corresponding meter are shown). TN: total number of specimens; Art/Complete: articulated specimens in case of bivalves and brachiopods (Biv/Brac), complete specimens in case of other taxa; Disarticulated bivalves/brachiopods: RV: right valve (bivalves), VV: ventral valve (brachiopods), LV: left valve (bivalves), DV: dorsal valve (brachiopods), V indet: indertermined valve, SF: sharp fragment, RF: rounded fragment; Corras: corrasion; Bioer.: external (Ext) or internal (Int) bioerosion; Encrust.: external (Ext) or internal (Int) encrustation; Ornam.: ornamentation.

The World Register of Marine Species (WoRMS) has been consulted for resolving critical issues of nomenclature (valid name and so on). In some cases, however, we preferred to maintain the specific name used for fossil specimens as the link with the modern species is not always verified and the modern species may differ a lot from the fossil one [*Tellina corbis* (fossil) rather than *Tellina* *carnicolor* (recent); *Turritella tricarinata pliorecens* (fossil) rather than *Turritella cingulata* (recent)]; 2) according to several authors (from Sacco in Bellardi & Sacco, 1898 to Sirna, 1978), synonyms of *Glycymeris insubrica* (Brocchi, 1814) are *G. violacescens* (Lamarck, 1819), *G. cor* (Lamarck, 1805) and *G. nummaria* (Linnaeus, 1758). *G. nummaria* is considered a nomen oblitum by Sirna (1978), although WoRMS considers this specific name as the valid one. *G. cor* has been invalidated because of the inadequate description given for it by Lamarck (1805).







































































































































































































































































































**Table A2: Major ichnofabric-forming traces**

Ethology, trophic strategy and tracemaker based on previous works (Clifton and Thompson, 1978; Pemberton and Frey, 1982; Keighley and Pickerill, 1995; Lobza and Schieber, 1999; Ekdale and Bromley, 2001; de Gibert and Goldring, 2008; Bromley et al., 2009; Pemberton et al., 2001, 2012; Baucon and Felletti, 2013a,b; Knaust, 2017).

|  |  |  |  |
| --- | --- | --- | --- |
| **Trace fossil** | **Data** | **Interpretation** | **Notes** |
| **General** **form** | **Wall** | **Branching** | **Fill** | **Spreite** | **Width** **(cm)** | **Ethology** | **Trophic strategy** | **Tracemaker** |  |
| Asterosoma | Horizontal | Lined, irregular outer margin | Unbranched | Passive? | No | >1cmLumen: ~1 cm | Fodinichnion | Deposit-feeding, suspension-feeding | Worm-like organisms, crustaceans | The irregular outer margin fits with the specimens of Asterosoma described by Chamberlain (1978) |
| Bergaueria | Vertical, cup-shaped  | Unlined | Unbranched | Passive | No | ~0.5-3 | Domichnion, cubichnion | Predation | Sea anemones |  |
| Bichordites | Horizontal | Unlined | Unbranched | Active, single draft fill | No | ~3 | Fodinichnion | Deposit-feeding | Irregular echinoids |  |
| Diplocraterion | Vertical U-shaped | Unlined | Unbranched | Passive? | Yes | 0.5 | Domichnion | Suspension-feeding | Crustaceans, polychaetes |  |
| Entobia | Vertical  | Unlined | Branched? | Passive if present | No | ~0.1 | Domichnia | Filter-feeding | Bioeroding sponges |  |
| Lockeia | Vertical | Unlined | Unbranched | - | No | 0.2-0.3Length: ~1.5 | Domichnia | Suspension-feeding | Bivalves |  |
| Macaronichnus | Horizontal  | Lined | Unbranched | Active  | No | ~0.1-0.3 | Fodinichnion | Deposit-feeding | Opheliid polychaetes |  |
| Mantle and swirl structures | Horizontal structures with circular section (mantle), rarer swirls | Elliptical ring | Unbranched | - | No | ~0.1-1 | Repichnion | ? | Worm-like animals | Mantles predominant |
| Oichnus | Vertical boring | Unlined | Unbranched | Passive if present | No | ~0.3 | Praedichnion | Predation | Gastropods |  |
| Ophiomorpha | Vertical | Thick (0.2-0.5 cm) pelleted lining | Branched | Passive | No | 1.8 -2.6  | Domichnion | Deposit-feeding, suspension-feeding | Thalassinidean shrimps, particularly callianassids |  |
| Palaeophycus | Horizontal | Lined | Unbranched | Passive | No | 0.9-3  | Domichnion | Predation, suspension-feeding | Polychaetes |  |
| Planolites | Horizontal | Unlined | Unbranched | Active,often darker than the surrounding sediment | No | ~0.2-0.4 | Fodinichnion | Deposit-feeding | Polychaetes | Margins can be sharp or smooth |
| Rosselia? | Vertical, laminated with apical bulb-like structure | Lined | Unbranched | Active? | No | ~5-10 | Domichnion | Detritus-feeding | Polychaetes |  |
| Schaubcylindrichnus? (morphotype A) | Inclined, comma-shaped  | Lined | Unbranched | Passive | No | 0.1-0.3  | Domichnion | Funnel-feeding | Enteropneust, polychaete |  |
| Schaubcylindrichnus? (morphotype B) | Vertical to inclined  | Lined | Unbranched | Passive | No | 0.3 | Domichnion | Funnel-feeding | Enteropneust, polychaete |  |
| Scolicia | Horizontal | Unlined | Unbranched | Active, double draft fill | No | ~3-4 | Fodinichnion | Deposit-feeding | Irregular echinoids |  |
| Siphonichnus | Vertical | Unlined | Unbranched | ? | No | ~0.3-0.5 | Domichnion | Suspension-feeding, deposit-feeding | Bivalves |  |
| Skolithos | Vertical | Lined by organic carbon | Unbranched | ? | No | 0.3-0.5  | Domichnion | Suspension feeding,autotrophy | Polychaetes, plants |  |
| Teichichnus (morphotype A) | Horizontal  | Unlined? | Unbranched | Passive | Vertical retrusive | ~2.5 | Fodinichnion, Equilibrichnion | Deposit-feeding | Worm-like animals, arthropods, bivalves, holoturians | Resembles the burrow of Solecurtus strigilatus (Bromley, 1996: p. 69) |
| Teichichnus (morphotype B) | Horizontal  | Unlined? | Unbranched | Passive | Vertical retrusive | ~1 | Fodinichnion, Equilibrichnion | Deposit-feeding | Worm-like animals, arthropods, bivalves, holoturians | Resembles the Teichichnus figured by Knaust (2017): fig. 5.155d |
| Thalassinoides | Horizontal boxwork | Unlined | Branched | Passive | No | 4.8-7  | Domichnion | Suspension-feeding, deposit-feeding | Callianassid shrimps |  |
| “Columnar burrow sets” | Vertical structure formed by juxtaposed tunnels | Unlined? | Unbranched | Passive? | No | 14-19 | ? | ? | ? | Forming tunnels are 2-4.3 cm |
| “Lined light filled burrows” | Horizontal | Lined | ? | Light fill contrasting with the host rock | No | Lumen: 1.9-2.5 | ? | ? | ? | May represent Thalassinoides, Scolicia, Bichordites |
| “Sharp-walled traces”  | Horizontal and vertical | Unlined | Branched and unbranched | Passive | No | ~0.5-3 |  Domichnia? | Suspension-feeding?, deposit-feeding? | Crustaceans?, worm-like animals? | “Sharp-walled traces” probably include different ichnotaxa (Thalassinoides?, Planolites?) with similar preservation |
| “Shell-filled burrows” | Vertical | Unlined | ? | Passive fill consisting of shell debris | No |  | ? | ? | ? | May represent passively filled Thalassinoides |
| “Unlined light filled burrows” | Horizontal | Unlined | ? | Light fill contrasting with the host sediment | No | ~2.5 | ? | ? | ? | May represent Thalassinoides, Scolicia, Bichordites? |
| “Winding trails” | Horizontal | Unlined | Unbranched | Unfilled | No | ~1 | Repichnion | ? | ? | ~1 m long |
| “Y-shaped burrows” | Vertical, Y-shaped | Unlined | Branched downward  | Passive | No | 0.8  | Fodinichnia? | Deposit-feeding? | Polychaetes?, bivalves? | Resembles the incipient Chondrites described by Hertweck et al. (2007) |

**References**

Baucon, A., Felletti, F., 2013a. The IchnoGIS method: Network science and geostatistics in ichnology. Theory and application (Grado lagoon, Italy). Palaeogeography Palaeoclimatology Palaeoecology 375, 83–111. doi:10.1016/j.palaeo.2013.02.016

Baucon, A., Felletti, F., 2013b. Neoichnology of a barrier-island system: The Mula di Muggia (Grado lagoon, Italy). Palaeogeography Palaeoclimatology Palaeoecology 375, 112–124. doi:10.1016/j.palaeo.2013.02.011.

Bellardi, L., Sacco, F., 1872-1904. I Molluschi dei terreni terziarii del Piemonte e della Liguria.

Mem. Reale Accademia delle Scienze di Torino. C. Claudsen Ed., Torino, 30 Vol.

Bromley, R.G., Milàn, J., Uchman, A., Hansen, K.S., 2009. Rheotactic *Macaronichnus*, and Human and Cattle Trackways in Holocene Beachrock, Greece: Reconstruction of Paleoshoreline Orientation. Ichnos 16: 103-117.

Chamberlain, C.K., 1978. Recognition of trace fossils in cores; trace fossil concepts. SEPM Short Course, 5: 133-183.

Clifton, H.E., Thompson, J.K., 1978. *Macaronichnus segregatis*: a feeding structure of shallow marine polychaetes. Journal of Sedimentary Petrology 48, 1293–1302. doi:10.1306/212F7667-2B24-11D7-8648000102C1865D.

de Gibert, J., Goldring, R., 2008. Spatangoid-produced ichnofabrics (Bateig Limestone, Miocene, Spain) and the preservation of spatangoid trace fossils. Palaeogeography, Palaeoclimatology, Palaeoecology 270, 299–310. doi:10.1016/j.palaeo.2008.01.031

Di Geronimo, I., Robba, E., 1976. Metodologie qualitative e quantitative per lo studio delle biocenosi e delle paleocomunità marine bentoniche. CNR Gruppo Paleobenthos, Rapporto di lavoro 1, 1-35.

Ekdale, A.A., Bromley, R.G., 2001. A day and a night in the life of a cleft-foot clam: *Protovirgularia – Lockeia – Lophoctenium*. Journal of Sedimentary Petrology 34, 119–124.

Hertweck, G., Wehrmann, A., Liebezeit, G., 2007. Bioturbation structures of polychaetes in modern shallow marine environments and their analogues to *Chondrites* group traces. Palaeogeography, Palaeoclimatology, Palaeoecology 245, 382–389. doi:10.1016/j.palaeo.2006.09.001

Keighley, D.G., Pickerill, R.K., 1995. The ichnotaxa *Palaeophycus* and *Planolites*: historical perspectives and recommendations. Ichnos 3, 301–309.

Knaust, D., 2017. Atlas of Trace Fossils in Well Core. Springer, Cham, 209 pp.

Lamarck, J.B., 1805. Suite des mémoires Sur les fossiles des environs de Paris. Ann. Mus. Paris 6,

214-221, 337-345.

Lobza, V., Schieber, J., 1999. Biogenic sedimentary structures produced by worms in soupy, soft muds: observations from the Chattanooga Shale (Upper Devonian) and experiments. Journal of Sedimentary Research 69, 1041–1049.

Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the *Planolites–Palaeophycus* dilemma. Journal of Paleontology 56, 843–871.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001. Ichnology & Sedimentology of Shallow to Marginal Marine Systems. Geological Association of Canada, Short Course Notes Volume 15. AGMV Marquis, St. John’s.

Pemberton, S.G., MacEachern, J.A., Dashtgard, S.E., Bann, K.L., Gingras, M.K., Zonneveld, J.-P., 2012. Shorefaces, in: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology 64. Elsevier, Amsterdam, pp. 563–603.

Sirna, G., 1978. Problemi di nomenclatura: la priorità di *Glycymeris insubricus* (Brocchi). Conchiglie 14 (9-10), 181-184.

WoRMS Editorial Board, 2017. World Register of Marine Species. Available from http://www.marinespecies.org at VLIZ.