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

Gaia Crippa [a], Andrea Baucon [b, c], Fabrizio Felletti [a], Gianluca Raineri [d] and Daniele Scarponi [e]

[a] *Università degli Studi di Milano, Dipartimento di Scienze della Terra 'A. Desio', via Mangiagalli 34, Milano, 20133, Italy. Corresponding author: gaia.crippa@unimi.it, +39 - 02503 15527*

[b] *Università di Modena, Dipartimento di Chimica e Scienze Geologiche, Via Campi 103, 41125 Modena, Italy.*

[c] *Geology and Palaeontology Office, Geopark Naturtejo da Meseta Meridional – UNESCO Global Geopark. Municipality of Idanha-a-Nova – Centro Cultural Raiano. Av. Joaquim Morão, 6060-101 Idanha-a-Nova, Portugal.*

[d] *Parco Regionale dello Stirone e del Piacenziano, Loc. Scipione Ponte 1, Salsomaggiore Terme, 43039, Italy*

[e] *Università di Bologna, Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Via Zamboni 67, Bologna, 40126, Italy*

ABSTRACT

The Arda River marine succession (Italy) represents an excellent site to apply an integrated approach to palaeoenvironmental reconstructions, combining the results of sedimentology, body fossil palaeontology and ichnology, to unravel the sedimentary evolution of a complex marine setting in the frame of early Pleistocene climate change and tectonic activity. The succession represents a subaqueous extension of a fluvial system, originated during phases of advance of fan deltas affected by high-density flows triggered by river floods, and overlain by continental conglomerates indicating a relative sea level fall and the establishment of a continental environment. An overall regressive trend is observed through the section, from a prodelta to a delta front and intertidal settings. The hydrodynamic energy and the sedimentation rate are not constant through the section, but they are influenced by hyperpycnal flows, whose sediments are mainly supplied by an increase in the Apennine uplift and erosion, especially after 1.80 Ma. The Arda section documents the same evolutionary history of coeval successions in the Palaeo-Adriatic region, as well as the climatic changes of the early Pleistocene. The different approaches used complement quite well one another, giving strength and robustness to the obtained results.

Keywords: early Pleistocene; Facies analysis; Body fossils; Trace fossils; Palaeo-Adriatic

INTRODUCTION

The complex interactions between organisms and their environments are an important aspect of the planet evolution. Biotic and abiotic systems evolve in time and leave tracks in the biosedimentary record (e.g., Kowalewski et al., 2015; Wyosocka et al., 2016; Martinelli et al., 2017; Scarponi et al., 2017a,b). However, unfolding such a record to pinpoint how ecosystems changed in time responding to palaeoenvironmental modifications requires a multidisciplinary approach including a well-established stratigraphic framework, a careful taxonomy and a comprehensive ecological background (Dodd and Stanton, 1990). The basic data for palaeoecology are body fossils, adequately identified, and trace fossils, which record the behavioral patterns of organisms through time, both correctly positioned within the stratigraphic framework. Though such a multidisciplinary approach is widely recognised to be powerful in reconstructing palaeoecosystems and their evolution, it is seldom implemented in the literature.

The lower Pleistocene marine succession of the Arda River (northern Apennines, Italy), represents an excellent site where to apply multidisciplinary investigations (Crippa et al., 2016). The wealth of sedimentary structures and the excellent preservation of body and trace fossils make this marine succession a case study where we can integrate the abiotic and biotic components to resolve past ecosystems dynamics within a key-time interval of climate change.

The early Pleistocene was characterised by climatic oscillations related to glacial/interglacial cycles, with the Mediterranean area being affected by these changes in both marine and continental settings (e.g., Bertini, 2010; Fusco, 2010; Scarponi et al., 2014; Combourieu-Nebout et al., 2015; Crippa et al., 2016; von Leesen et al., 2017). The most important biotic events recorded in the marine environment of the Mediterranean are the disappearance of taxa of subtropical affinity and the occurrence of "northern guests", i.e. organisms presently living at higher latitudes in the Northern Hemisphere, such as the bivalve *Arctica islandica* and the foraminifera *Hyalinea balthica* and *Neogloboquadrina pachyderma* left-coiling, which migrated into the entire Mediterranean Sea through the Strait of Gibraltar during glacial periods since the Calabrian (early Pleistocene) (Suess, 1883–1888; Raffi, 1986; Martínez-García et al., 2015). Recently, by analysing the isotopic composition of the bivalve shells from the Arda River section, Crippa et al. (2016) observed that seawater temperature seasonality was the main variable of climate change within the study area during the early Pleistocene, in turn controlled by the Northern Hemisphere Glaciation dynamics. In particular, strong seasonality and low winter palaeotemperatures were assumed to be the main drivers for the widespread establishment of "northern guests" populations in the Palaeo-Adriatic Sea.

Here, we pursue an integrated approach involving facies analyses and palaeoecological observations to investigate the relationships between body and trace fossils and their environment in the early Pleistocene of the Arda Section. The purpose of this paper is twofold: first, to compare the results of the analyses of sedimentology, body and trace fossils, evaluating to which extent these three different approaches complement one another and derive general implications for their combined use; second, to reconstruct the palaeoenvironmental evolution of the Arda River sedimentary succession comparatively based on the integration of three different tools and to interpret it taking into account the interplay between tectonic and climatic factors (both local and global).

GEOLOGICAL SETTING

The Arda River section is located in northern Italy near the town of Castell'Arquato at the margin of the northern Apennines facing the Po plain (Fig. 1). The northern Apennines are an orogenic wedge which started to form since the Oligocene as a result of the collision between the Corsica-Sardinia microplate and the Adria promontory, following the closure of the Mesozoic Ligurian-Piedmont Ocean (Carminati and Doglioni, 2012). Deformation migrated through time toward the east-northeast, gradually involving the Ligurid oceanic units and the Adria continental margin.

The Arda River section belongs to the Castell'Arquato basin, a small wedge-top basin developed since the Messinian (Miocene) at the eastern edge of the northern Apennine orogenic wedge as a result of the fragmentation of the Po Plain foredeep (Roveri and Taviani, 2003; Artoni et al., 2010) (Fig. 1). It forms part of the northwestern extension of the Palaeo-Adriatic Sea and is bounded to the north by the Cortemaggiore thrust and to the south by the emerged front of Ligurid units (Monegatti et al., 2001) (Fig. 1A). Several basin-wide, unconformity-bounded sedimentary cycles, recognised both on the outcrops and in the subsurface of the Po Plain and the central Adriatic Sea, characterise the basin infill (Pieri, 1983; Ori et al., 1986; Ricci Lucchi,1986). The Castell'Arquato basin is filled by a sedimentary succession of late Messinian (upper Miocene) to Holocene age, organized in a large-scale transgressive-regressive cycle controlled by tectonics, with beds forming a regular monocline dipping towards the north-northeast (Monegatti et al., 2001). The basal part of the filling succession comprises deep sea sediments postdating the Messinian salinity crisis (Ceregato et al., 2007; Calabrese and Di

Dio, 2009), when marine conditions were restored in the Mediterranean Sea; upward they pass into slope and shelf facies associations and then through a regressive trend to the middle Pleistocene alluvial continental deposits, which represent the final retreat of the sea in this area and the establishment of a continental environment with vertebrate faunas and freshwater molluscs (Cigala Fulgosi, 1976; Pelosio and Raffi, 1977; Ciangherotti et al., 1997). Detailed studies carried out in recent years through the integration of surface and subsurface data resulted in a comprehensive stratigraphic and evolutive model of the Castell'Arquato basin during the Pliocene and the early Pleistocene (Roveri et al., 1998; Monegatti et al., 2001; Roveri and Taviani, 2003). Insights into the palaeogeography of the Po basin at the first major regression of the coastline in consequence of the lowstand during the late early Pleistocene climate turnover (EPT), have been recently provided in Fig. 8 of Monesi et al. (2016). The studied succession crops out along the Arda River and extends downstream the bridge located at the entrance of the town of Castell'Arquato (northern Italy) (Fig. 1B, C); the marine part, which is the subject of the present study, is 237 m thick and bounded at the top (44°52'9.95"N; 9°53'1.35"E) by continental conglomerates (Fig. 2). The lowermost portion of the section is cut by a fault (Figs. 1B and 2), causing the repetition of the first 36 m of the succession (base at 44°51′18.52″N; 9°52′26.7″E); the succession described here begins stratigraphically above the fault. The Arda River marine succession has a Calabrian (early Pleistocene) age, ranging from ~1.8 to 1.2 Ma, based on magnetostratigraphy (Monesi et al., 2016), and calcareous nannofossil and foraminifera biostratigraphy, which allowed identifying respectively three nannofossil (CNPL7, CNPL8 and CNPL9) and one foraminiferal (*Globigerina cariacoensis*) biozones (Crippa et al., 2016).

MATERIALS AND METHODS

Sedimentology

The Arda River section has been measured bed-by-bed at 1 cm resolution. Bed thickness measurements were performed mainly with a Jacob's staff (e.g., a 1.5 metre high rod equipped with a clinometer and a flat sighting disc on top). The log was measured, recording the internal subdivisions of the individual beds or "depositional intervals" (i.e., depositional divisions or bed intervals in the sense of Ghibaudo, 1992). The thickness, grain size, presence of erosion surfaces, mud clasts and structure of every internal division of the beds were recorded separately for each bed in addition to the total bed thickness. The grain size was measured using a grain-size comparator chart. In order to account for amalgamation of beds, partially amalgamated beds were measured as individual layers. This was possible through detecting the subtle grain-size breaks that are associated with amalgamation surfaces. To make the measure of the section reproducible and available also for other analyses labeled nails were fixed every metre from the base to the top of the section, according to the attitude of the bedding.

Body fossils

Fossils were collected bed by bed, from a total of 144 beds over the whole studied section; for each of the targeted beds, two rectangles (50 cm wide and 10 cm tall) were delimitated and all fossil exposed sampled. Fossil specimens (mainly molluscs) were then washed and cleaned from the encasing sediment using an air drill, in case of hard sediment, or a scalpel, in case of soft sediment, and a unique ID was assigned to each of them; they were identified at generic and/or specific level (where feasible) based on relevant literature (e.g., Ceregato et al., 2007; Williams et al., 2000, 2006; Crippa and Raineri, 2015) and subsequently counted (see Appendix A1 in the Supplementary information online for a detailed explanation). In addition, to aid environmental interpretation of fossil assemblages, it was observed if the specimens (bivalves and brachiopods) were articulated or disarticulated and each specimen retrieved was carefully inspected looking for the presence of the following taphonomic features: a) roundness vs sharpness of fragments; b) corrasion, due to the combined effect of abrasion and dissolution (Brett and Baird, 1986); c) external and/or internal bioerosion, produced by predators, necrophages or by the presence of domichnia; d) internal and/or external encrustations, caused by episkeletobionts (sensu Taylor and Wilson, 2003); e) ornamentation, which is usually fragile and can be lost during post-mortem processes and f) original color and pattern of the shell/fragment surface (see Appendix A2 and Table A1 in the Supplementary information online). Based on the analysis of these features, we identified the associations defined by Brenchley and Harper (1998): 1) life assemblages, 2) neighborhood assemblages and 3) transported assemblages.

A qualitative palaeoecological analysis was then performed, where the assemblages of the Arda River section have been tentatively compared to the recent Mediterranean biocoenoses. As the majority of the retrieved taxa is represented by living species, the fossil associations recovered were grouped in biofacies and attributed to the present day depositional environments based on the occurrence of characteristic taxa described by Pérès and Picard (1964). The abbreviation used are: SFBC: biocoenosis of fine-grained well sorted sands; SFS: biocoenosis of shallow water fine-grained sands; DC: biocoenosis of coastal detritic bottoms; VTC: biocoenosis of terrigenous mud.

Trace fossils

Sedimentology and body fossil palaeontology have been integrated with ichnological analysis, using the workflow for integrated facies analysis (McIlroy, 2008). Because of the predominantly vertical outcrops and the high bioturbation intensity, the ichnofabric approach has been used. The ichnofabric analysis method considers the overall texture of a bioturbated sediment and as such it is the ichnological equivalent of facies analysis (Taylor et al., 2003; McIlroy, 2004, 2008).

Data collection consisted of recording the ichnofabric attributes of the Arda River section in the field at regularly spaced intervals (‘samples’). Each of the studied samples was approximately 25 cm thick and the spacing between successive samples was 1 m. The recorded ichnofabric attributes are: 1) primary sedimentology (Taylor et al., 2003), 2) degree of bioturbation, quantified by the ichnofabric index (ii) methodology (Bottjer and Droser, 1991), 3) components of the ichnofabric, including either distinct trace fossils or biodeformational structures with indistinct outlines (Schäfer 1956; Wetzel and Uchman, 1998; Taylor et al., 2003). Relative abundance, burrow size, tiering, trace fossil frequency and distribution at the sample scale have also been observed (Bromley, 1996; Taylor et al., 2003; Gingras et al., 2011).

Visual analysis of each sample included observation of 1) the weathered surface of the outcrop; 2) the fresh surface of the outcrop, exposed with a trowel; a minimum of three fresh surfaces of about 25x25 cm have been observed and 3) the enhanced fresh surface, obtained by dropping water on the fresh surface to enhance colour contrast and to differentiate weathered traces from the surrounding sediment. Each sample has been attributed to an ichnofabric class that has been distinguished on the basis of the degree of bioturbation, bioturbation distribution (Gingras et al., 2011), diversity (i.e., the number of ichnotaxa present; Bromley, 1996) and components of the ichnofabric.

RESULTS AND INTERPRETATIONS

Facies analysis

Facies analysis was carried out in marine sediments deposited during phases of advance of fan deltas when Apennine tectonic uplift renewed sediment dispersal and provided the basin with a steeper margin. Following the genetic classification scheme proposed by Zavala et al. (2011) for flood-generated delta-front lobes, the deposits of the Arda section (Fig. 2) have been grouped in three main facies categories related to the three main processes that characterise sustained hyperpycnal discharges (i.e., *hyperpycnal flows*; Mutti et al., 2000; Tinterri, 2007) in marine settings: 1) *bed load* (Facies B: bed-load related sedimentary facies), 2) *turbulent suspension* (Facies S: suspended-load-related sedimentary facies), and 3) *lofting* (Facies L: lofting-related sedimentary facies). Facies code and relative description are shown in Table 1.

Facies related to bed-load processes (Facies category B)

Facies category B is composed of massive (GmE; Fig. 3 A) and cross-stratified (or crudely stratified) conglomerates (Gp; Fig. 3 D) with abundant coarse- to fine-grained sandstone matrix (matrix supported). Large clasts in this facies appear to float in a medium- to coarse-grained sandstone matrix. Individual sets of crossbedding commonly show thicknesses between 0.1 and 0.5 m. The foreset inclination in general does not exceed 15°. Bounding surfaces between bedsets can be erosional. Lag deposits (Lag; Fig. 3 E, F) represented by gravel carpets with bioclastic and sandy (very coarse) matrix are frequent. This facies category also includes mud clast-supported conglomerate (GmM; clay-chips; Fig. 3 A, B, C). Mudstone intraclast diameter ranges from 0.5 up to 20 cm and their shapes range accordingly from rounded sub-spherical to rounded tabular.

Interpretation: this facies category includes different coarse-grained deposits related to shear/drag forces exerted by the overpassing long-lived turbulent (hyperpycnal) flow over coarse-grained materials lying on the flow bottom (Fig. 3). High-density flows triggered by river floods can mix and deposit skeletal remains from different shallow-water communities. Regardless, accumulations of shells are rare features in this bed-load related sedimentary facies.

Facies related to the collapse of suspended load (facies category S)

Facies category S (Fig. 4) are mostly fine-grained sandstone strata ranging from a few millimetres thick lamina-sets, to several tens of decimetres thick beds and bedsets, with massive stratification (Sm; Fig. 3 E, F), horizontal (Sh; Fig. 4 A, D) or hummocky cross stratification (HCS; Fig. 4 E), tabular and oblique cross stratification (Sp, Sx; Fig. 4 B), and small-scale cross lamination (Sr, St; Fig. 4 A, C). Many beds are sharp based and fine upward, with structures ranging from horizontal or large-scale wavy lamination to small scale cross lamination (wavy, sigmoidal, and/or climbing ripple structures).

Small floating clay chips are common and are dispersed within the sandstone body or grouped toward the top.

Accumulations of shells are common features in the sandstone intervals, where they form thick, sharp-based, sometimes normally graded lags at the base of massive (Sm; Fig. 3 E. F) or laminated strata (Sp, Sx, Sr; Fig. 4 A, B. C). Shell-bed geometry ranges from tabular to lenticular; shells are always closely packed, mostly concave-down, and sometimes imbricated. In many cases, tabular, sharp-based shell beds (that are 10–50 cm thick and broadly lenticular) are found at the base of horizontal or hummocky cross-stratified (HCS) beds. Carbonaceous remains and wood fragments (commonly leaves with exceptional preservation) are also common within massive sands. Sedimentary structures are rarely disrupted by bioturbation, but bedtops may be 100% bioturbated. Flasers and massive mudstone beds (HeB), from a few millimetres to several centimetres thick, are often intercalated with the sandstones.

Interpretation: this facies is mostly composed of fine-grained sediments transported as suspended load, forming thick and commonly complex intervals that can be massive or display traction plus fallout sedimentary structures.

Facies related to flow lofting (facies category L)

Facies category L (Fig. 5) is characterised by thin couplets of massive to laminated siltstones and mudstones (Fm; Fig. 5 A). The individual levels commonly display a variable thickness from a few millimetres up to 100 cm. Marine bivalves in life position are present in the lower part of the stratigraphic section.

Interpretation: this facies is composed of the finest materials transported by the hyperpycnal flow, which accumulated by normal settling when the flow completely stopped.

Facies association

On the basis of high-resolution stratigraphic framework, the marine sedimentary succession up to 217 m is characterised by at least six (labeled I–VI in Fig. 2), 5–25 m-thick fining upward cycles deposited by high-density turbidite flows (hyperpycnal flow, *sensu* Mutti et al., 2000) that grade into hemipelagic siltstones and mudstones (Fig. 2). These cycles are often very complex, showing internal erosional surfaces and gradual facies recurrences.

Each cycle usually starts with massive to cross-bedded conglomerates (GmE, GmM, Gp, Lag; Table 1) with abundant bioclastic and sandy matrix. Intraclasts and accumulations of shallow-water skeletal remains are also present. Bedset-bounding surfaces can be erosional (Fig. 5 C). Above follow sandstones that are either massive or with horizontal, hummocky, tabular or oblique cross stratification (Sp, Sx, HCS, St, Sr, Sh, Sm; Table 1). Sharp based, normally graded, tabular to lenticular lags of concave-down shells may occur at the base of the strata. Carbonaceous remains and wood fragments are also common within massive sands. Flasers, wavy and lenticular bedding (Heb; Table 1), from a few mm- to several cm-thick, are often intercalated with these sandstones. Finally, above the sandstones follow massive to laminated siltstones and mudstones arranged in thin couplets (Fm; Table 1), ranging in thickness from a few mm up to 1 m and accumulated by normal settling when the flow completely stopped.

Each cycle shows a complicated internal arrangement. The vertical and lateral facies anisotropy and the relatively rapid accumulation result in the common occurrence of water-escape features such as load cast and flame structures (Fig. 5 D). Field observations suggest a close association of this facies with channel fill deposits.

At 45 m from the base of the succession a biocalcarenite body occurs (Fig. 5 E, F). It forms basinward-prograding wedges composed of alternating well or poorly cemented layers with dense accumulations of reworked shells. It typically displays a tripartite geometry, whose topset horizontal strata are intensely bioturbated, and may contain abundant articulated bivalves and fragmented calcareous algae, whilst foresets and bottomsets are characterised by dense accumulations of reworked shells.

From 130 to 132 m, very fine-grained limestones form lenticular or pinching and swelling beds, up to 0.25 m thick (Fig. 5 B). The beds have sharp bases and tops and may be laminated. The thin section analysis reveals that these beds are predominately composed of a fine-grained calcareous matrix including calcareous microspheroids and organic matter.

From 217 to 237 m, the sequence is characterised by coarse-grained sands and pebbly sandstones with low-angle cross-stratification (Sx, Sh, St, Sm, HCS, Heb; Table 1). Large clasts appear floating in a medium- to coarse-grained sandstone matrix. Individual sets of cross-beds (Sx, St) commonly show thicknesses between 0.3 and 1 m and asymptotic relationships with top and base. The foreset inclinations do not usually exceed 20°. This facies association is attributed to littoral (transitional) environments.

From 237 to 300 m, the sequence comprises continental sediments arranged in four main cycles, each characterised by massive or crudely stratified, partially cemented, fluvial gravel beds (from 1 m to 4 m-thick; GmE, Gp; Fig. 2, Table 1), passing rapidly upward to sands, silts and muds packed in beds from few metres up to 15 m thick. In situ root systems and tree trunks, together with $CaCO_3$ nodules and typical terrestrial gastropods [e.g., *Pomatias elegans, Carychium tridentatum, Retinella (Retinella) olivetorum*] are abundant in fine grained beds, suggesting continental swamp environments.

Interpretation: Deposits of the Arda section display a complicated vertical arrangement of different lithofacies reflecting cyclic depositional changes between suspended-load and bed-load-dominated facies associated with different velocity and fallout rates. These cyclical and gradual changes between different facies are the result of near-continuous deposition from a quasi-steady turbulent flow (Zavala et al., 2011). Distinctive features observed in the studied deposits are: i) the sharp based and normally graded beds containing HCS, ii) gradual and sharp facies transitions without a definite and predictable internal arrangement, iii) the abundant rip-up mudstone clasts and shells, iv) internal and laterally discontinuous erosional surfaces, v) scarce burrows, and vi) a basal coarsening-upward interval (Mutti et al., 2000; Zavala et al., 2006, 2011). The studied deposits evolve laterally into packages of lofting rhythmites. These features are most likely related to bed-load processes developed at the base of a hyperpycnal flow (i.e., long-lived turbulent flow) and tend to dominate the proximal to medial parts of a river-delta system.

The biocalcarenite body occurring at 45 m from the base of the succession shows an internal geometry suggesting that biocalcarenitic deposits are formed during periods of decreased input of fine-grained terrigenous sediments (or sediment starved conditions) whose fossiliferous content indicates high-energy levels in the shelf environments. Different physical conditions can be assumed for their formation such as reduced terrigenous input or strong bottom reworking by currents. Massari and Chiocci (2006) describe the formation of very similar Pliocene-Quaternary basinward-prograding biocalcarenite wedges (detached from the shore and below the storm-wave base) along the submerged margins of the Mediterranean area by means of processes of sediment reworking from a nearshore by pass zone and of storm-driven down-welling flow. The cyclical nature of these biocalcarenites, observed in the Castell'Arquato basin (Stirone section, Cau et al., 2013, 2017), has been hypothesised to be orbitally-controlled by obliquity and/or precession cyclicity.

According to Mutti et al. (2003), the Arda River succession can be interpreted as a flood-dominated fan-delta system accumulated in roughly tabular lobes extending from alluvial conglomerates to shelfal siltstone and mudstone. The associate deposits (hyperpycnites; Mulder et al., 2003) are closely related to direct fluvial discharge. Observed facies associations clearly show as flood-generated dense flows enter seawaters as catastrophic and inertia-dominated relatively unconfined flows. Coarser materials tend to accumulate at the front of the flow, giving way to a horizontally negative grain-size gradient. Sedimentation occurs mainly in a mouth bar (characterised by sigmoidal bedding) and in associated flood-generated delta-front sandstone lobes.

This study suggests that the Arda River succession corresponds to the subaqueous extension of a fluvial system. It originated when the river in flood directly discharged a sustained (Carruba et al., 2004; Felletti et al., 2009) and relatively denser turbulent mixture of fresh water and sediments (hyperpycnal flows; Bates, 1953) into the receiving standing body of water. This system extended for kilometres away from the river mouth and developed a predictable path of genetically related facies (Browne and Naish, 2003;Mancini et al., 2013; Marini et al., 2013; Milli et al., 2016; Bruno et al., 2017) during its travel basinward.

Body Fossils

The fossil associations of the Arda River succession contain a very diversified fauna composed mainly of several species of bivalves and gastropods; brachiopods, corals, serpulids, echinoderms, scaphopods and barnacles do also occur. The associations have been grouped into 11 biofacies, based on the presence of key species, taphonomic evaluation (A2 and Table A1 in the Supplementary information online) and (palaeo)ecology of the fossils recovered (Figs. 6 A-F, 7 A-F; 8.1-14).

Biofacies 1

This biofacies occurs in fine-grained massive siltstones and sandstones (Facies L) at the base of the section (37.05-43.25 m). It is composed mainly of seminfaunal/infaunal organisms and by cemented/byssate epifaunal taxa; many rheophilous taxa (e.g., *Astarte fusca*, *Glycymeris inflata, Glycymeris glycymeris, Clausinella fasciata*) are present (Figs. 6 A; 8.1, 3, 4). The taphonomic preservation is generally good (A2 and Table A1 in the Supplementary information online).

Interpretation: The occurrence of disarticulated rheophilous shelf related taxa indicates neighborhood assemblages of a high-energy environment winnowed by currents in an offshore transition setting. The negligible presence of shoreface key taxa (*Chamelea gallina, Spisula subtruncata* and *Acanthocardia tuberculata*) showing high taphonomic degradation suggests a transport from shallower settings.

Biofacies 2

This biofacies occurs in fine-grained massive silty to muddy lithologies (Facies L) below and above the biocalcarenitic body (44.90 m; 47.35-49 m; 56.35-58.35 m); it is mainly represented by few specimens of seminfaunal/infaunal species typical of muddy-detritic and muddy shelf substrates (e.g., *Venus nux, Turritella tricarinata pliorecens, Naticarius stercusmuscarum, Pelecyora brocchii*), showing an excellent preservation (Fig. 6 C, D. A2 and Table A1 in the Supplementary information online). Corals, echinoids, brachiopods and non-rheophilous molluscs are also present.

Interpretation: The sparse presence of *V. nux* and *P. brocchii* along with echinoids, brachiopods and corals suggest a low-energy lower offshore transition setting, characterised by normal marine salinity and oxygen conditions

Biofacies 3

This biofacies occurs in biocalcarenite (45.65-46.05 m; Facies S) and is represented by sparse and poorly preserved valves of epifaunal molluscs: *Aequipecten opercularis, Aequipecten scabrella* and *Ostrea edulis* (A2 and Table A1 in the Supplementary information online).

Interpretation: The sparse mollusc content associated with poor taphonomic preservation within coarse-grained deposits allows only a generic interpretation of a transported assemblage from relatively high-energy settings.

Biofacies 4

This biofacies occurs in fine-grained massive siltstones (59-70.02 m; 106.50-111.60 m; Facies L). Several key infaunal shoreface to offshore transition well preserved taxa typical of muddy sands are found, specifically *Glycymeris insubrica, A. tuberculata, C. gallina, S. subtruncata, Neverita josephinia* (Figs. 6 E; 8.5, 6; A2 and Table A1 in the Supplementary information online).

Interpretation: The ecological and taphonomic signatures of this biofacies suggest life and neighborhood assemblages of shallow marine, high-energy offshore transition environments (Facies L);

the faunal composition can be compared to the recent Mediterranean biocoenosis of SFBC (Pérès and Picard, 1964).

Biofacies 5

This biofacies occurs in an alternation of fine-grained sandy to silty and muddy lithologies (217.90-223.20 m; 230.80-237 m; Facies S and B). It contains mainly seminfaunal/infaunal taxa living in shallow water muddy sands (e.g., *G. insubrica, A. tuberculata, C. gallina, Ensis ensis, Loripes orbiculatus, Cylichna cylindracea, Atlantella pulchella, N. josephinia*), together with species of upper shoreface (*Donax* spp.) and of wave-protected environments (*Lucinella divaricata*) (Figs. 7 C-F; 8.12). Toward the top, *G. insubrica* becomes the most abundant species (Fig. 7 E, F), with numerous articulated specimens found in life position in muddy beds; trunks and plant remains are also found. All the specimens are well preserved (A2 and Table A1 in the Supplementary information online).

Interpretation: Biofacies 5 indicates life and neighborhood assemblages of upper shoreface setting, due to the presence of key taxa *Ensis ensis* and *Donax* spp.; the faunal composition is comparable to the SFBC and SFS biocoenoses of the recent Mediterranean Sea (Pérès and Picard, 1964). Seminfaunal/infaunal taxa are dominant, suggesting a high-energy shallow water environment, which may prevent the colonization by epifaunal species; however, the presence of species living in wave-protected environments suggests a more heterogeneous substrate with quieter areas. Also, toward the top of the section, the disappearance of stenohaline species and the increase of euryhaline taxa, suggests settings affected by river discharge. Indeed, *G. insubrica*, which can also thrive in low salinity settings (e.g., Malatesta, 1974; Raineri, 2007; Crnčević et al., 2013) becomes the dominant species in this upper part. Biofacies 5 differs from Biofacies 4 by the presence of shallower water taxa (e.g., *Donax* spp.), which are absent in Biofacies 4.

Biofacies 6

This biofacies is found in fine-grained massive clayey horizon (224.20-224.30 m; Facies L), hosting several articulated specimens of *Arctica islandica* in life position and lacking sediment filling inside the valves (Fig. 7 B), associated to the shallow water *S. subtruncata,* (average preferred depth: 6.60 m, standard deviation: 7.3 m; Wittmer et al., 2014) both showing an excellent preservation (A2 and Table A1 in the Supplementary information online).

Interpretation: The co-occurrence of lower shoreface *S. subtruncata* and of the "northern guest" *A. islandica* suggests a lower shoreface/offshore transition setting.

Biofacies 7

This biofacies occurs in fine-grained massive silts and clays (Facies L) (146.55-167.90 m, 196-207 m). Seminfaunal/infaunal taxa living in muddy to silty lithologies are dominant. *V. nux* is the most abundant species in this interval, together with *Turritella tricarinata pliorecens*, *Glossus humanus*, *Aporrhais pespelecani, Acanthocardia paucicostata* and *Saccella commutata,* all showing an excellent preservation (Fig. 8.2, 8; A2 and Table A1 in the Supplementary information online).

Interpretation: The abundance of *V. nux* suggests a low-energy offshore transition setting which can be compared to the recent VTC biocoenosis of the Mediterranean Sea (Pérès and Picard, 1964). According to Taviani et al. (1997) and Dominici (2001) the *Venus nux* assemblage lived at water depths of 20–40 m.

Biofacies 8

This biofacies (80.30-91.40 m; 101-104.10 m; 122.90-125.50 m; Facies L) comprises well preserved epifaunal species of mainly muddy/sandy-detritic settings (e.g., *Pecten jacobaeus, Aequipecten opercularis, Flexopecten flexuosus, Pitar rudis*), occurring together with mud-loving infaunal species (as *V. nux* and *T. tricarinata pliorecens)* where the mud content increases (A2 and Table A1 in the Supplementary information online).

Interpretation: This biofacies is characterised by many key species (e.g., *P. rudis, F. flexuosus, P. jacobaeus*) belonging nowadays to the recent DC biocoenosis (Pérès and Picard, 1964) together with VTC species where the mud content increases, all indicating life or neighborhood assemblages of offshore transition environments.

Biofacies 9

This biofacies is found in an alternation of fossil rich fine-grained sands/silts and mud barren of fossils (127.95-146.45 m; Facies S and B). The fauna consists of well preserved seminfaunal/infaunal species together with few epifaunal ones; taxa of shallow water muddy sands are abundant (e.g., *G. insubrica, C. gallina, A. tuberculata, E. ensis, Tritia mutabilis*) together with few sandy/muddy-detritic species (*A. opercularis, Laevicardium oblongum, P. rudis*) (Figs. 6 F, 7 A; 8.7; A2 and Table A1 in the Supplementary information online). Occasionally *Ditrupa* sp. horizons are retrieved (e.g., ACG95; Table A1 in the Supplementary information online).

Interpretation: This biofacies suggests neighborhood assemblages of shoreface settings, which thank to the presence of *G. insubrica, C. gallina, A. tuberculata, E. ensis* and *T. mutabilis* can be compared to SFBC biocoenosis of the recent Mediterranean Sea (Pérès and Picard, 1964), although few DC taxa (e.g., *L. oblongum, P. rudis*) are also found. Biofacies 9 is similar to Biofacies 5, although very shallow water taxa have not been identified here. The occasional presence of monotaxic beds of *Ditrupa* sp., usually thriving in turbid waters conditions (Dominici, 2001), suggests unstable and loose substrates.

Biofacies 10

This biofacies occurs in several sandstones beds of the succession within Facies S and B (54-54.20 m; 92.50-98.30 m; 170-194.10 m; 208.40-210.40 m) and is characterised by containing ecologically mixed and generally poorly preserved taxa (Fig. 8.9-11, 13, 14; A2 and Table A1 in the Supplementary information online), often associated to clay chips and vegetal debris; an exception is given by well preserved, articulated specimens of *Pinna* sp. and infaunal echinoids. Seminfaunal/infaunal and epifaunal species of shelf muddy/sandy-detritic settings (e.g., *L. oblongum, Timoclea ovata, P. rudis, P. jacobaeus*) are associated to shallower water species (e.g., *A. pulchella, C. gallina, G. insubrica, S. subtruncata*) and mud loving taxa (e.g., *Nucula placentina, T. tricarinata pliorecens, V. nux*).

Interpretation: This biofacies, characterised by an ecologically mixed poorly preserved fauna of shoreface to offshore transition settings, represents mainly transported assemblages finally buried in an offshore transition setting as testified by articulated *Pinna* sp. and infaunal echinoids in life position (Fig. 6 B); this suggests a high-energy setting as indicated also by the facies analysis (Facies S and B).

Biofacies 11

This biofacies groups species poorly preserved and ecologically mixed (e.g., *A. tuberculata, A. opercularis, V. nux*) found within conglomerate beds (217.20 m; 223.80 m; Facies B; A2 and Table A1 in the Supplementary information online).

Interpretation: The high taphonomic degradation along the different ecology of the species recovered reflects transport/reworking in a high-energy, coarse-grained shallow marine settings.

Trace Fossils

The samples of the Arda River section have been attributed to 15 ichnofabric classes, that are grouped in 4 ichnofabric groups based on bioturbation intensity, distribution and diversity (Table 2). Ichnofabric groups have been named according to the dominant feature, and ichnofabric classes have been named according to the dominant traces. Ichnotaxa have been identified at the ichnogenus level and open nomenclature has been used for difficultly identifiable traces. Readers are addressed to Table A2 in the Supplementary information online for details on ichnotaxa.

Ichnofabric group 1 - low-moderate bioturbation, homogeneous distribution of traces, low diversity

The ichnofabric classes of group 1 typically present low to moderate bioturbation intensity, homogeneous distribution of traces at the scale of the sampling unit and low diversity of traces:

(1) Unbioturbated ichnofabric. Unbioturbated conglomerates (Facies GmE, Gp);

(2) Low bioturbation ichnofabric. Unbioturbated or sparsely bioturbated (ii 1-2) sands with monogeneric assemblages of *Planolites, Palaeophycus*. Cryptobioturbation locally present;

(3) *Skolithos* ichnofabric. *Skolithos* occurring in massive sands (Facies Sm);

(4) *Ophiomorpha* ichnofabric (Fig. 9 A-C). *Ophiomorpha* preserved as full-reliefs in planar- or cross-laminated sands (Facies Sh);

(5) *Macaronichnus* ichnofabric (Fig. 9 D-F). *Macaronichnus* preserved in faintly laminated sands with rare shell debris (Facies Sm).

Interpretation: The low to moderate bioturbation intensity is interpreted as the result of a stress factor that prevented total bioturbation of the sediment (Bromley, 1996; Taylor et al., 2003). The homogeneous distribution of traces indicates that the stress factors were persistent, at least at the scale of the observation unit (Gingras et al., 2011). Specifically, the ichnofabric classes are interpreted as follows:

(1) Unbioturbated ichnofabric. The lack of bioturbation suggests the original lack of endobenthic activity or the non-preservation of biogenic structures (Bromley, 1996). Because this ichnofabric is characterised by bed load related facies, it is likely that physical stress, represented by high hydrodynamics and shifting substrates, prevented endobenthic colonization of these units.

(2) Low bioturbation ichnofabric. This ichnofabric reflects the work of trophic generalists (the producers of *Planolites* and *Palaeophycus;* see Gingras et al., 2011). Brackish setting is suggested by low ichnodiversity, simple structures produced by trophic generalists, monospecific associations and small size (Pemberton et al., 2001; Buatois et al., 2005; Hauck et al., 2009; Buatois and Mángano, 2011). These features are consistent with a foreshore to middle shoreface environment.

(3) *Skolithos* ichnofabric. Based on the distribution of both animal and plant *Skolithos* (Bromley, 1996; Gregory et al., 2006; Knaust, 2017), this ichnofabric is interpreted to reflect marine (foreshore to upper shoreface) or, at least, marine-influenced (backshore) settings. A more precise environmental interpretation of this ichnofabric is difficult, also because plant ichnology is an understudied field (Baucon et al., 2012).

(4) *Ophiomorpha* ichnofabric. This ichnofabric represents the work of a deep-tier community of trophic generalists (the producers of *Ophiomorpha*). The constructional lining of *Ophiomorpha* is a strategy to cope with high-energy and shifting substrates (Frey et al., 1978; Coelho and Rodrigues, 2001; Pemberton et al., 2001; Taylor et al., 2003; Buatois and Mángano, 2011; Gingras et al., 2011). These features are consistent with a high-energy foreshore to shoreface environments (see Pemberton et al., 2001; Baucon et al., 2014; Leaman et al., 2015). Based on the palaeoclimatic significance of *Ophiomorpha* (Goldring et al., 2004, 2007), this ichnofabric is regarded as a warm water indicator.

(5) *Macaronichnus* ichnofabric. This ichnofabric represents the work of a deep-tier community of selective deposit feeders, well-adapted to soft substrates with very high hydrodynamics at the water-sediment interface. These environmental parameters are compatible to foreshores and shorefaces, as also suggested by the environmental preferences of *Macaronichnus* (high-energy foreshores and shallow shorefaces: Clifton and Thompson, 1978; Pemberton et al., 2001; Savrda and Uddin, 2005; Seike et al., 2011; Pearson et al., 2013). *Macaronichnus* has been proposed as an indicator of temperate to cold waters (Quiroz et al., 2010).

Ichnofabric group 2 - low-moderate bioturbation, heterogeneous distribution of traces, moderate diversity

The ichnofabric classes of group 2 are characterized by regular heterogeneous distribution of traces. Traces are preserved in heterolithic facies (Fig. 10 A) consisting of alternating sand and mud layers (Facies HeB). Mud layers commonly present biogenic structures with poorly defined wall (e.g., *Planolites* and mantle and swirl structures) (homogeneous suite; Fig. 10 B) and “sharp walled burrows” (sharp burrows suite; Fig. 10 C-E). Sand layers are typically bioturbated by lined burrows (e.g., morphotype A of *Schaubcylindrichnus*?; Fig. 10 F) and/or smooth-walled traces (e.g., *Scolicia*; Fig. 10 G, H). This ichnofabric group comprises three ichnofabric classes, distinguished on the basis of the paucity of “sharp walled burrows” (few sharp burrows – smooth burrows ichnofabric), the dominance of scolicids (Sharp burrows – Scolicids ichnofabric) and the abundance of “sharp walled burrows” (Sharp burrows – smooth burrows ichnofabric).

Interpretation: The regular heterogeneous distribution of trace fossils indicates regular variability in the physico-chemical conditions and iterative colonization events (Gingras et al., 2011). Based on the idea that burrow boundary stores information about the sediment consistency (Uchman and Wetzel, 2011), these events are interpreted as follows:

(1) Colonization of soupground to softground mud. Traces of the homogeneous suite represent the work of organisms ‘swimming’ in soupgrounds (mantle and swirl traces) or deposit-feeding in firmer substrates (*Planolites*) (Lobza and Schieber, 1999). Settling of hypopycnal plumes or lofting of hyperpycnal flows are interpreted to be the major depositional processes because of sedimentological evidences and the ichnological similarity with other hyperpycnites (Bhattacharya and MacEachern, 2009);

(2) Dewatering and colonization of firmground mud. The unlined, passively filled burrows of the sharp burrows suite suggest that the sediment became firm enough to avoid collapse of unlined burrows themselves (see Uchman and Wetzel, 2011; Fürsich, 1978; Bromley, 1996);

(3) Erosion and event deposition. The passive fill of the sharp burrows suite suggests that, after colonization of firmground muds, an abrupt depositional event brought sand to the seafloor. Hyperpycnal flowing is interpreted to be the major depositional process (see Bhattacharya and MacEachern, 2009).

(4) Colonization of looseground sand. The smooth burrows suite represents the community that colonized sand brought to the seafloor by event deposits ('post-depositional suite'; Ksiazkiewicz, 1954; Seilacher, 1962; Uchman and Wetzel 2011). Lining indicates that the substrate was soft and unconsolidated (Bromley, 1996).

For these reasons, the ichnofabric classes of this group are interpreted to reflect bioturbation of muddy seafloors during low-energy conditions and colonization of sandy event (hyperpycnal) deposits. Based on bioturbation intensity, ichnodiversity and tiering complexity, the ichnofabric classes of this group are interpreted to reflect a stress gradient, including persistently stressed marine environments (few sharp burrows – smooth burrows ichnofabric), temporarily stressed environments (sharp burrows-scolicids ichnofabric) and stable environments (sharp burrows – smooth burrows ichnofabric).

According to the palaeoclimatic significance of *Scolicia* (Goldring et al., 2004, 2007), the sharp burrows-scolicids ichnofabric is interpreted to represent temperate to warm waters. It should be also noted that *Scolicia* is associated to normal marine salinity (Buatois and Mángano, 2011), well-oxygenated porewaters (Löwemark et al., 2006; de Gibert and Goldring, 2008; Uchman and Wetzel, 2011), restricted competition by organisms of deeper-burrowing tiers (Fu and Werner, 2000), at times being correlated with bottom currents and high sedimentation rates (Fu and Werner, 2000; Löwemark et al., 2006; Wetzel et al., 2011).

Ichnofabric group 3 - moderate-high bioturbation, homogeneous distribution of traces, low diversity

Ichnofabric group 3 includes a very heterogeneous set of ichnofabric classes with sharp-walled traces and/or passively filled burrows:

(1) *Lockeia* ichnofabric (Fig. 11 A, B). Cemented carbonatic beds (Facies CCB) with no distinct burrows, or predominantly monogeneric (e.g., *Lockeia, Ophiomorpha, Diplocraterion*) assemblages;

(2) *Thalassinoides* ichnofabric (Fig. 11 C, D). Horizontal *Thalassinoides* bioturbating plurimetrical layers of bioclastic sands (Facies Sp). “Y-shaped burrows” and bioerosion structures on shells (e.g., *Entobia*) are also present;

(3) Coarse-fill burrows ichnofabric (Fig. 11 E). Irregular mottles and circular sharp-walled burrows (*Thalassinoides*?) filled with coarse-grained sand or fine-grained conglomerate.

Interpretation: Low diversity and homogeneous distribution of traces suggest persistently stressed conditions or preservation of elite trace fossils by upward migration of deep tiers (Bromley, 1996):

(1) *Lockeia* ichnofabric. Cementation is a post colonization feature for the *Ophiomorpha*-dominated assemblages because a loose substrate is required by its tracemakers to manipulate the characteristic pellets of the burrow lining. Other assemblages show some of the characteristics of the substrate-controlled *Glossifungites* ichnofacies (i.e., presence of sharp-walled, unlined dwelling burrows of suspension feeders; dominance of robust, vertical to subvertical, simple and spreite U-shaped burrows; low ichnodiversity; high abundance; Buatois and Mángano, 2011). They could represent substrates that became stiff before of the colonization by shallow-tier suspension-feeding organisms. Presence of food in suspension and lack of deep-tier deposit feeders suggests an energetic environment, possibly a high-energy foreshore.

(2) *Thalassinoides* ichnofabric. This ichnofabric occurs in plurimetrical units bioturbated by *Thalassinoides*, implying that it results from the upward migration of a deep-tier. This feature and the passive bioclastic fill suggests that this ichnofabric is the result of repeated cycles of colonization, passive infilling and deposition. The tubular tempestite model, consisting of the repetitive excavation and storm infilling of burrow networks, could explain this pattern (Tedesco and Wanless, 1991).

(3) Coarse-fill burrows ichnofabric. Sharp wall and passive fill indicate that biogenic structures have been emplaced in firmground muds and maintained as open burrows (Buatois and Mángano, 2011; MacEachern et al., 2007, 2012). Because the burrow fill differs from surrounding and overlying

sediments, this ichnofabric class represents a trace-fossil omission suite that preserves a high-energy event that would otherwise have passed unnoticed (see MacEachern et al., 2012). These features are consistent with an environment dominated by sediment bypass, such as the margins of a submarine canyon, that is a typical depositional setting of the *Glossifungites* ichnofacies (Buatois and Mángano, 2011).

Ichnofabric group 4 - high bioturbation, homogeneous distribution of traces, moderate to high diversity

The ichnofabric classes of group 4 are typically characterized by intense bioturbation:

(1) Scolicids ichnofabric (Fig. 12 A-C). Scolicids (*Scolicia, Bichordites*) bioturbating sands (Facies Sm), silts and sandy muds (Facies Fm);

(2) *Palaeophycus* ichnofabric (Fig. 12 D-F). Numerous distinct burrows (e.g., *Planolites, Palaeophycus, Schaubcylindrichnus* – morphotype A) bioturbating sands, silts and sandy muds (Facies Sm, Fm);

(3) High bioturbation ichnofabric (Fig. 12 G-L). Homogeneous or mottled muds and silts (Facies Fm). Distinct burrows are not always present.

Interpretation: High bioturbation intensity and homogeneous bioturbation are interpreted to reflect slow sedimentation, stable, well oxygenated physico-chemical conditions (Taylor et al., 2003; Gingras et al., 2011; Uchman and Wetzel, 2011). The ichnofabric classes of this group have been interpreted as follows:

(1) Scolicids ichnofabric. The abundance in scolicids suggests oxic porewater with normal marine salinities (de Gibert and Goldring, 2008; Buatois and Mángano, 2011), the possible influence of bottom currents (Löwemark et al., 2006; Wetzel et al., 2011), restricted competition by organisms of deeper burrowing tiers (Fu and Werner, 2000) and a good quantity and quality of food (Wetzel, 2010). These environmental features are consistent with an upper shoreface to offshore depositional setting.

(2) *Palaeophycus* ichnofabric. This ichnofabric class presents similar features with respect to the previously discussed ichnofabric class, but the higher bioturbation intensity and diversity suggest a less stressed environment. This scenario suggests an offshore depositional environment influenced by hyperpycnal flows.

(3) High bioturbation ichnofabric. With respect to the other ichnofabrics of the same group, this ichnofabric presents the highest bioturbation intensity, probably indicating higher bioturbation rates, lower sedimentation rates and a higher availability of food (see Wetzel and Uchman, 1998). These features are interpreted to represent an oxic offshore environment.

DISCUSSION

Palaeoenvironment of the Arda section

In this section, the seven fining upward cycles (Fig. 2) have been interpreted in terms of palaeoenvironments, integrating the results of sedimentology, body fossil palaeontology and ichnology (Fig. 13).

Cycle 0

Cycle 0 does not constitutes a full cycle, as it lacks the complete facies sequence characterising cycles I-VII (see paragraph 'Facies Association'). The presence of brachiopods, corals and echinoids (Biofacies 3; 45.65-46.05 m) as well as the prevalence of high-bioturbation ichnofabric in this cycle would suggest an offshore transition environment characterised by low hydrodynamic energy and low sedimentation rate. However, oscillations to high-energy foreshore to shoreface settings with high sedimentation rate do also occur, as testified by the presence of rheophilous molluscs in Biofacies 1 (37.05-43.25 m). In addition, it is noteworthy the presence (45.20-46.60 m) of a characteristic body of cemented biocalcarenite with abundant burrows (*Thalassinoides* ichnofabric). Different physical conditions can be assumed for its formation such as reduced fine-grained terrigenous input or strong bottom reworking by currents. The upward reduction of winnowing events restores the initial low-energy conditions characterised by deposition of finer-grained sediments. Here, body fossils show, besides a diagenetic dissolution of aragonitic shells, a high degradation (Biofacies 2; 44.90 m, 47.35-49 m), suggesting a high-energy setting winnowed by currents. In this cycle oxygen isotope values of bivalve shells (Crippa et al., 2016) point at temperate-cold conditions, related to a mid-shelf environment (around 50 metres of depth).

Cycle I

Cycle I is interpreted to reflect environmental conditions similar to those of the previous cycle, i.e. prevailing offshore transition conditions. Specifically, with the exception of a thin sandstone bed in the basal part, most of Cycle I is represented by monotonous fine-grained to laminated siltstones (Facies L) deposited by suspension settling from decelerating hyperpycnal flows. Body and trace fossils record a change in the environment; the lower part of the cycle accounts for lower shoreface to offshore transition settings [Biofacies 2 (56.35-58.35 m) and high-bioturbation ichnofabric], whereas the middle part records a temporary shift to shallower and higher-energy foreshore to shoreface settings [Biofacies 4 (59-70.02 m) and presence of the *Macaronichnus* and scolicids ichnofabrics]. The topmost part testified a return to a deeper water setting [Biofacies 8 (80.30-91.40 m) and high-bioturbation ichnofabric]. Although only few palaeotemperature data are available from body fossils of this cycle, these suggest a temperate-cold water environment. Such interpretation is coherent with the presence of *Macaronichnus*, a typical temperate to cold water indicator (Quiroz et al., 2010), and *Scolicia*, which, though not exclusive, is common in temperate waters (Goldring et al., 2004, 2007).

Cycle II

Cycle II mainly documents offshore transition environments recording a cooling event. The basal part of the cycle documents a shoreface environment characterised by high to high-fluctuating energy and high sedimentation rate. This cycle includes coarse-grained deposits related to shear/drag forces exerted by the overpassing long-lived turbulent (hyperpycnal) flow over coarse-grained materials lying on the flow bottom. High-density flows triggered by river floods can mix and deposit skeletal remains from different shallow-water communities. The poor preservation of body fossils in Biofacies 10 (92.50-98.30 m), the abrupt changes in ichnofabric, the presence of mud clasts and of reworked vegetal debris, besides field observations, all indicate the presence in this interval (91.40-98 m) of a channel cutting obliquely (direction south-southwest – north-northeast) the main succession and discharging fresh water and sediments. Aside from this interval, sedimentology and trace fossils document offshore transition environments, whereas body fossils record a shallowing upward trend, passing from an offshore transition environment characterised by low-energy and low sedimentation rate (Biofacies 8; 101-104.10 m) to a shoreface setting with higher energy (Biofacies 4; 106.50-111.60 m). From a palaeoclimatic point of view the first occurrence of the "northern guest" *Arctica islandica* (103.70 m) and the abundant presence of *Macaronichnus* (94 m), mark the beginning of a climatic cooling in the area, which is further supported by bivalve shell oxygen isotope composition (Crippa et al., 2016).

Cycles III-VI

Cycles III to VI show a more regular organization; each cycle records a deepening upward trend (from foreshore-shoreface to offshore transition settings) and a likewise decrease in hydrodynamic energy and sedimentation rate. Each cycle frequently has an erosive base and starts with conglomerates or rip-up mud clasts (Facies B), followed above by sandstones either massive or stratified (Facies S). Here, low bioturbation ichnofabric indicates brackish conditions, possibly caused by direct fluvial discharge of fresh water and sediments by hyperpycnal flows. This is also supported by the presence of Biofacies 10 (170-194.10 m; 208.40-210.40 m) in Cycles V and VI; this biofacies contains an ecologically mixed fauna and specimens showing a poor preservation, both evidence indicating a high-energy environment affected by high density flows triggered by river floods which mix skeletal remains from different environments. In Cycles III-VI transported body fossil assemblages and evidence of density flows become more frequent; this means more river discharge and thus more terrigenous input into the Palaeo-Adriatic basin. The increase in the tectonic uplift and erosion of the Apennines after 1.80 Ma (e.g., Amorosi et al., 1996; Bartolini et al., 1996; Argnani et al., 1997, 2003; Dominici, 2001, 2004), the proximity to the coast and possibly the climatic deterioration (e.g., increased precipitations and/or increased ice melting during summer and more ice growth during winter) may account for the observed increment of hyperpycnal flows in these cycles. The top of each cycle records fully marine conditions with typical faunal associations/ichnofabrics of low-energy settings [Biofacies 7 (146.55-167.90 m, 196-207 m), high bioturbation ichnofabric)], reflecting the normal settling when the flow completely stops or the sedimentation in a distal portion of the delta system.

Cycle V is particularly rich in scolicid-dominated ichnofabrics. The sedimentological evidence for hyperpycnal flows may indicate that *Scolicia*-dominated ichnofabrics are a proxy for extrabasinal turbidites *sensu* Zavala and Arcuri (2016), such as those deposited by hyperpycnal flows. This hypothesis is plausible as *Scolicia* is correlated with the abundance of food (Wetzel, 2010) and extrabasinal turbidites are rich in phytodetritus because they originated from the continent (Zavala and Arcuri, 2016). By contrast, intrabasinal turbidites originated within the marine basin and are therefore less rich in phytodetritus (Zavala and Arcuri, 2016). Further case studies are required to test this hypothesis.

Palaeoclimatic indicators mainly suggest temperate water, although in a few levels, oxygen isotopes from bivalve shells and evidence from trace fossils (*Macaronichnus*) indicate lower water temperatures, confirming the change towards cooler climates, affecting the Palaeo-Adriatic after the arrival of the “northern guests”. In Cycle III, trace fossils record high-frequency climate fluctuations; abundant *Ophiomorpha,* an ichnological indicator of warm climate, are present at little stratigraphic distance from *Macaronichnus*-dominated horizons.

Cycle VII

Cycle VII represents the last marine cycle of the Arda succession before the establishment of a continental environment with freshwater molluscs and vertebrate faunas (Bona and Sala, 2016; Monesi et al., 2016); it documents a foreshore to upper shoreface environment characterised by high hydrodynamic energy and high sedimentation rate, due to discharge by fluvial floods. This cycle is characterised by the dominance of ichnofabrics related to brackish water (low bioturbation ichnofabric, few sharp burrows-smooth burrows ichnofabrics). Increased freshwater input, and thus salinity dilution, is also indicated by the presence of Biofacies 5 (230.80-237 m), recording from 230.80 m to the top the only occurrence of *Glycymeris insubrica*, a species which tolerates salinity variations (e.g., Malatesta, 1974; Lozano Francisco et al., 1993; Raineri, 2007; Crnčević et al., 2013). At the top of the succession, Crippa et al. (2016) observed the presence of abundant brackish-water benthic foraminifera and low oxygen isotope ratios in bivalve shells, indicating salinity reduction due to freshwater river discharge. All these evidence, together with the presence of frequent bed-load deposits (Facies B), indicate a foreshore to upper shoreface environment for this part of the section.

Regional significance of the Arda section

The Arda sedimentary succession represents a valuable case study as it offers the rare opportunity to study depositional dynamics through phases of strong natural climate change within a tectonically active setting. The stratigraphic and palaeontological investigation presented for the Arda section highlights the importance of integrated studies to disentangle the effects of climate and tectonic processes acting in structuring sedimentary successions during the early Pleistocene. In this respect, the overall regressive trend of the marine part of Arda section, consisting of offshore/prodelta (Cycles 0-II) passing to prodelta/delta front (Cycles III-IV) and to intertidal/coastal (Cycle VII) stacked successions, can be directly related to deformation phases of the local fronts of Apennine mountains; this is represented by the change in the dip of the bedding from 20° in the stratigraphically lower part of the section up to <5° in the upper part. While tectonic and climatic forcings are acting simultaneously, regional studies (e.g., Gunderson et al., 2014) evidenced as the early Pleistocene (from about 1.60 till 1.10 Ma) structuring of this sector of the northern Apennines has been characterized by unsteady but rapid and intense deformation. This specified interval of time encompasses the entire marine sedimentation along the Arda section (see Geological Setting; Crippa et al., 2016). In addition, overall regressive trends were already documented for few other successions outcropping along the north-eastern margin of the Apennines, such as the Enza and Stirone River sections (e.g., Pelosio and Raffi, 1977; Dominici, 2001; Gunderson et al., 2014).

The cyclothemic nature of the sedimentary succession retains an expression of climatic changes that occurred during the early Pleistocene and was modulated by the morphology of the basin (see Dominici, 2001). Specifically, cyclic stacking pattern of fan-delta forestepping/backstepping episodes described here were produced primarily by the onset and disappearance of local climatic conditions favouring the development of catastrophic flooding through time (see other geologic examples in Weltje and de Boer, 1993; Mutti et al., 1996). Our results correlate well with regional changes at higher temporal frequencies, recording, besides the Apennine uplift, the same evolutionary history of coeval successions in the Castell'Arquato basin and the Palaeo-Adriatic region (e.g., Stirone and Enza River sections; Papani and Pelosio, 1962; Dominici, 2001, 2004; Gunderson et al., 2014). The analyses of the biota and of their traces record not only local but also global climate changes. The occurrence of the "northern guest" bivalve *A. islandica*, of *Macaronichnus* trace fossil, and of the "northern guests" foraminifera *Hyalinea balthica* and *Neogloboquadrina pachyderma* left coiling (Crippa et al., 2016) in the section, testified a climatic deterioration, i.e. cooling, which represents an expression of the climatic changes occurring during the early Pleistocene, leading to the onset and establishment of Middle and Upper Pleistocene continental glaciations.

The multidisciplinary method: advantages and disadvantages

The methodological significance of this study is to provide a multidisciplinary approach to palaeoenvironmental reconstructions. The ecosystem evolution is affected by many different factors; instead of just looking at one factor, we followed an integrated approach for the understanding of past environments, integrating three different tools (sedimentology, body and trace fossil palaeontology). The practical application of a multidisciplinary approach in palaeoenvironmental reconstructions revealed some methodological advantages and disadvantages. One of the main advantages in applying this method is the possibility to investigate, from different point of views, the ecosystems in detail, obtaining a more complete and reliable picture of past environments. The use of a single tool, besides giving a one side perspective, may be affected by biases specific to the tool itself, which can be avoided or compensated for when using two or more tools. However, in employing different tools, data may also disagree. Disagreements are generally due to different sampling strategies or to problems intrinsic to the tools themselves, for example the lack of continuity in the recorded data along the succession and thus a lower resolution scale of analysis, which does not allow to identify small variations. In the case of the Arda River section, data from sedimentology and body fossils have shown a lower resolution in the scale of analysis compared to trace fossils. For practical reasons, sedimentology, body fossil palaeontology and ichnology involve different sampling schemes, characterised by different resolutions, which also affect the results of the analysis. In some cases, this has led to possible misinterpretations and disagreements between the different tools used; on the other hand, the higher resolution shown by trace fossils has allowed to identify changes at a finer scale of analysis, highlighting also the smallest environmental variation. Generally, we noted that these three different approaches complement one another quite well and compensate for their respective defects, giving strength and robustness to the obtained results, besides a more complete and exhaustive picture of past ecosystems.

The geological record provides a number of different settings and locations within different time intervals, where this multidisciplinary approach can be applied. Elements required are well exposed, continuous and age constrained sedimentary successions rich of fossils (micro-, macro- and/or trace fossils) and two, although three or more are preferred, different tools on which to base the palaeoenvironmental reconstruction. The use of a multidisciplinary approach would greatly improve the resolution of past environment reconstructions and should be applied more frequently for these purposes, taking advantages of the numerous opportunities that the geological record provides.

CONCLUSION

The detailed multidisciplinary study presented here (sedimentology, body and trace fossils) has proved to be a powerful tool for resolving palaeonvironmental dynamics recorded in sedimentary succession from collisional margins during time intervals of climate change. The palaeoenvironmental evolution of the marine Arda River section has been interpreted taking into account the interplay between tectonics and climatic factors. Based upon sedimentology, body fossils and trace fossils, it corresponds to a subaqueous extension of a fluvial system, originated in a tectonically active setting during phases of advance of fan deltas affected by high-density flows triggered by river floods, which are an expression of early Pleistocene climate changes. It documents a fully marine and well oxygenated environment, bounded at the top by continental conglomerates indicating a major sea level drop and the establishment of a continental environment; indeed, a general regressive trend is observed through the section, passing from a prodelta (Cycles 0-II) to a delta front (Cycles III-IV) to an intertidal zone (Cycle VII) settings. Lower order transgressive and regressive cycles with shifts from lower foreshore-shoreface to offshore transition environments have been identified, with supposed water depths ranging between 5 and 50 m. The hydrodynamic energy and the sedimentation rate are not constant through the section, but they are influenced by hyperpycnal flows which caused an increase in terrigenous input linked to fluvial floods, whose sediments are mainly supplied by an increase in the Apennine uplift and erosion, especially after 1.80 Ma (e.g., Amorosi et al., 1996; Bartolini et al., 1996; Argnani et al., 1997, 2003; Dominici, 2001, 2004). The regressive trend and the climatic deterioration, i.e. cooling, recorded through the section are an expression of the climatic changes occurring during the early Pleistocene; our results correspond well with other studies of both global and local climatic/tectonic changes, recording the same evolutionary history of coeval successions in the Castell'Arquato basin and the Palaeo-Adriatic region.

The lower Pleistocene Arda River marine succession represents only one of the numerous case studies provided by the geological record where to apply a multidisciplinary approach to interpret past complex ecosystems in the frame of climate change and tectonic activity. A multi-approach analysis based on the integration of sedimentological data, body and trace fossils would greatly improve the resolution of palaeoenvironmental reconstructions and should be extended also to other geological sites.

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FIGURE CAPTIONS

Figure 1. A) Geological sketch map of northern Italy showing the study area (modified after Crippa et al., 2016); B) Enlarged geological map of the Castell'Arquato basin with indication of the measured Arda River section (modified after Monesi et al., 2016). C) Photograph of a part of the outcrop along the Arda River section (metric interval on the stratigraphic section, Fig. 2: 120-140 m).

Figure 2. Detailed stratigraphic log of the Arda River section. Facies codes are listed in Table 1.

Figure 3. A-F) Facies related to bed-load processes (Facies B). This category includes different coarse-grained deposits related to shear/drag forces exerted by the overpassing long-lived turbulent

(hyperpycnal) flow over coarse-grained material lying on the flow bottom. See Table 1 for facies codes and relative description. Corresponding metric intervals on the stratigraphic section (Fig. 2): A) 179.10 m; B) 114 m; C) 94.10 m; D) 28.20 m; E) 224.80 m; F) 131.90 m.

Figure 4. A-F) Facies related to the collapse of suspended load (Facies S). This category mostly includes fine-grained sediments transported as suspended load, forming thick and commonly complex intervals that can be massive or display traction plus fallout sedimentary structures. See Table 1 for facies codes and relative description. Corresponding metric intervals on the stratigraphic section (Fig. 2): A) 177.20 m; B) 134 m; C) 193.80 m; D) 230.60 m; E) 184.60 m; F) 194.20 m.

Figure 5. A) Facies related to flow lofting (Facies L). It is characterised by thin couplets of massive to laminated siltstones and mudstones (Fm), transported by the hyperpycnal flow, which accumulated by normal settling when the flow completely stopped (107.40 m). B) Cemented levels, rich in carbonate (CCB; 130.20 m). See Table 1 for facies codes and relative description. C) Erosional bedset-bounding surfaces (114 m). D) Rapid accumulation results in the common occurrence of water-escape features such as load cast and flame structures (184.60 m). E, F) Biocalcarenitic body (46 m). It forms prograding wedges typically displaying intense bioturbation. Foresets and bottomsets are characterised by dense accumulations of reworked shells.

Figure 6. Fossiliferous beds of the Arda succession. A) Articulated specimens of *Glycymeris inflata* (42 m, Biofacies 1, Cycle 0); B) Section of an articulated specimen of *Pinna* sp. (54.20 m, Biofacies 10, Cycle I); C) Articulated specimen of *Pelecyora brocchii* in life position (57.35 m, Biofacies 2, Cycle I); D) Echinoid specimen (58.35 m, Biofacies 2, Cycle I); E) Shell accumulation mainly

containing specimens of *Spisula subtruncata* (68.53 m, Biofacies 4, Cycle I); F) Life assemblage of articulated specimens of *Glycymeris insubrica* (133.90 m, Biofacies 9, Cycle IV).

Figure 7. Fossiliferous beds of the Arda succession. A) Bed with several specimens of *Aequipecten opercularis* (134.35 m, Biofacies 9, Cycle IV); B) Articulated specimen of *Arctica islandica* in life position and lacking internal sediment filling (224.30 m, Biofacies 6, Cycle VII); C) Specimens of *Chamelea gallina* with empty valves in life position (234 m, Biofacies 5, Cycle VI); D) Accumulation bed with mainly disarticulated bivalves (234.40 m, Biofacies 5, Cycle VII); E) Articulated specimens of *Glycymeris insubrica* (235.70 m, Biofacies 5, Cycle VII); F) Accumulation bed with articulated specimens of *Glycymeris insubrica*, representing the most abundant species at the top of the section (236.80 m, Biofacies 5, Cycle VII).

Figure 8. Taphonomic conditions of the body fossils; a: external or abapertural view, b: internal or apertural view. 1a,b) *Glycymeris inflata*, left valve; note the encrustation made by bryozoans and serpulids (ACG29bis-3, Biofacies 1, Cycle 0); 2a,b) *Pitar rudis*, right valve; note the hole of a bioerosion reaching the internal part of the valve (ACG106, Biofacies 7, Cycle IV); 3a,b) *Aequipecten opercularis*, right valve; the valve is encrusted by serpulids only in the external part (ACG27bis-6, Biofacies 1, Cycle 0); 4a,b) *Naticarius stercusmuscarum,* the original color pattern is preserved (ACG29bis-20, Biofacies 1, Cycle 0); 5a,b) *Peronidia albicans*, right valve; the finer ornamentation and the color pattern are preserved (ACG53-4, Biofacies 4, Cycle I); 6a,b) *Flexopecten glaber*, left valve; the finer ornamentation is preserved (ACG80-4, Biofacies 4, Cycle II); 7a,b) *Acanthocardia tuberculata*, right valve; note the attempt of a bioeroding organism to perforate the shell (ACG94, Biofacies 9, Cycle IV); 8a,b) *Aequipecten opercularis*, right valve; the finer ornamentation is well preserved (ACG104-2, Biofacies 7, Cycle IV); 9a,b) *Dosinia lupinus*, right valve; note the original

color pattern (ACG235, Biofacies 10, Cycle VI); 10a,b) *Aequipecten opercularis*, left valve; the shell is encrusted by bryozoans both in the internal and external part (ACG238, Biofacies 10, Cycle VI); 11a,b) *Glycymeris insubrica*, left valve; the original color pattern is preserved (ACG197-5, Biofacies 10, Cycle V); 12a,b) *Flexopecten glaber*, right valve; the bioerosion does not perforate the entire thickness of the shell (ACG250, Biofacies 5, Cycle VII); 13a,b) *Dosinia lupinus*, right valve; hole made by bioeroding organisms (ACG201, Biofacies 10, Cycle V); 14a,b) *Callista chione*, right valve; note the preservation of the glossy periostracum (ACG197, Biofacies 10, Cycle V).

Figure 9. Ichnofabric group 1. A) *Ophiomorpha* ichnofabric. B) Close-up of A showing a specimen of *Ophiomorpha*, parallel lamination and concave-up shells. C) *Ophiomorpha* with a robust constructional lining, indicating high-energy conditions. D) *Macaronichnus* ichnofabric. E) *Macaronichnus* ichnofabric cross-cut by “Lined light filled burrows” (*Ophiomorpha*?). F) Intensely bioturbated *Macaronichnus* ichnofabric with a significant contribution from other undetermined ichnotaxa.

Figure 10. Ichnofabric group 2. A) Few sharp burrows-smooth burrows ichnofabric. B) Homogeneous suite represented by biogenic structures with poorly defined wall bioturbating a mud layer. C) Sharp burrows suite represented by a sharp-walled trace that bioturbated a mud layer. D) Sharp burrows-smooth burrows ichnofabric. E) Close-up of E showing several “sharp-walled traces”. F) *Schaubcylindrichnus*? (morphotype A). G) Scolicid-sharp burrows ichnofabric. H) Close-up of G showing a scolicid and abundant vegetal debris.

Figure 11. Ichnofabric group 3. A) *Lockeia* ichnofabric represented by numerous specimens of *Lockeia*; bedding plane view. B) *Ophiomorpha* preserved in cemented layers. C) *Thalassinoides*

ichnofabric dominated by horizontal burrows filled by bioclastic sands. D) "Columnar burrow set". E) Coarse-fill burrows ichnofabric overlain by sand-mud couplets pertaining to the ichnofabric group 2.

Figure 12. A) Scolicids ichnofabric overlying the sand/mud couplets typical of the ichnofabric group 2. B) Close-up of A showing a specimen of *Scolicia* reworking a mud layer. *Palaeophycus* and *Planolites* are present in the sand layer, whereas "sharp-walled traces" bioturbates the mud layer. C) Scolicid. D) *Palaeophycus* ichnofabric with a large specimen of *Teichichnus* (morphotype A) and *Palaeophycus*. E) *Palaeophycus*. F) *Rosselia*? G) High bioturbation ichnofabric. H) Close-up of G showing a probable specimen of *Asterosoma*. I) High bioturbation ichnofabric with a distinct *Teichichnus* (morphotype B). L) High bioturbation ichnofabric with distinct lined vertical burrows (*Schaubcylindrichnus*?)

Figure 13. Environmental evolution of the Arda Section. A simplified stratigraphic log (sed. log) with the age of the section, based on calcareous nannofossil (CNZ) and foraminifera (FZ) biostratigraphy, is illustrated (Crippa et al., 2016). For each tool used (Sed: sedimentology; Body: body fossils; Trace: trace fossils) it was analysed: *Water depth*: 1. Foreshore (region between high tide water level and the low tide water level), 2. Shoreface (low tide water level-fair weather wave base), 3. Offshore transition and deeper (wave base-shelf edge break; Nichols, 2009). In the modern Adriatic Sea, these regions are respectively at depths of <0 m, 0-10 m, >10 m. *Energy*: 1. Low (nutrients in deposition), 2. High and fluctuating (hyperpycnal flows), 3. High (nutrients in suspension). *Sedimentation rate*: 1. Low, 2. High. *Oxygenation*: 1. Disoxic (2-0.2 ml O_2/l H_2O), 2. Oxic (8.0-2.0 ml O_2/l H_2O) (Tyson and Pearson, 1991; Buatois and Mangano, 2011, p.104). *Salinity*: 1. Brackish (0.5-30 ‰), 2. Seawater (30-40 ‰) (Buatois and Mangano, 2011, p. 107). *Water temperature*: 1. Cold, 2. Temperate, 3. Warm. For body fossils, water temperature was based on oxygen isotope composition of bivalve shells, considering cold: > 2.5 ‰, temperate: 0-2.5 ‰, warm: < 0 ‰ (data from Crippa et al., 2016). For trace fossils, climate is

defined as following: cold (climate at modern artic to temperate latitudes), temperate (climate at modern temperate to tropical and subtropical latitudes) and warm (climate at modern tropical and subtropical latitudes). Arctic latitudes are between 66° and 90°, temperate latitudes are between 35° and 66°, tropical and subtropical latitudes are between 0° and 35° (Goldring et al., 2004, 2007).

TABLE CAPTIONS

Table 1. Facies classification scheme utilised for the Arda section following the genetic classification proposed by Zavala et al. (2011). All these facies categories are genetically related and occupy a definite position within the hyperpycnal system. The B facies is diagnostic of proximal areas and progressively disappears as the flow enters the area of lobe deposition. The S facies is the consequence of the loss of flow capacity and is typical of the medium to distal parts of the system. The L facies results from the flow inversion, which is diagnostic of flow-margin areas (both down the depositional axis and laterally along the axis).

Table 2. Ichnofabrics of the Arda river. Ichnotaxa are described in Table A2 in the Supplementary information online. The degree of bioturbation is quantified by the ichnofabric index (ii) (Bottjer and Droser, 1991). Firm substrates indicate stiffgrounds (Wetzel and Uchman, 1998) and firmgrounds (Fürsich, 1978; Bromley, 1996). Diversity refers to the typical number of distinct burrows per sampling unit. All ichnofabrics indicate oxic settings.

Figure 1

Click here to download Figure Fig_01 revised.jpg

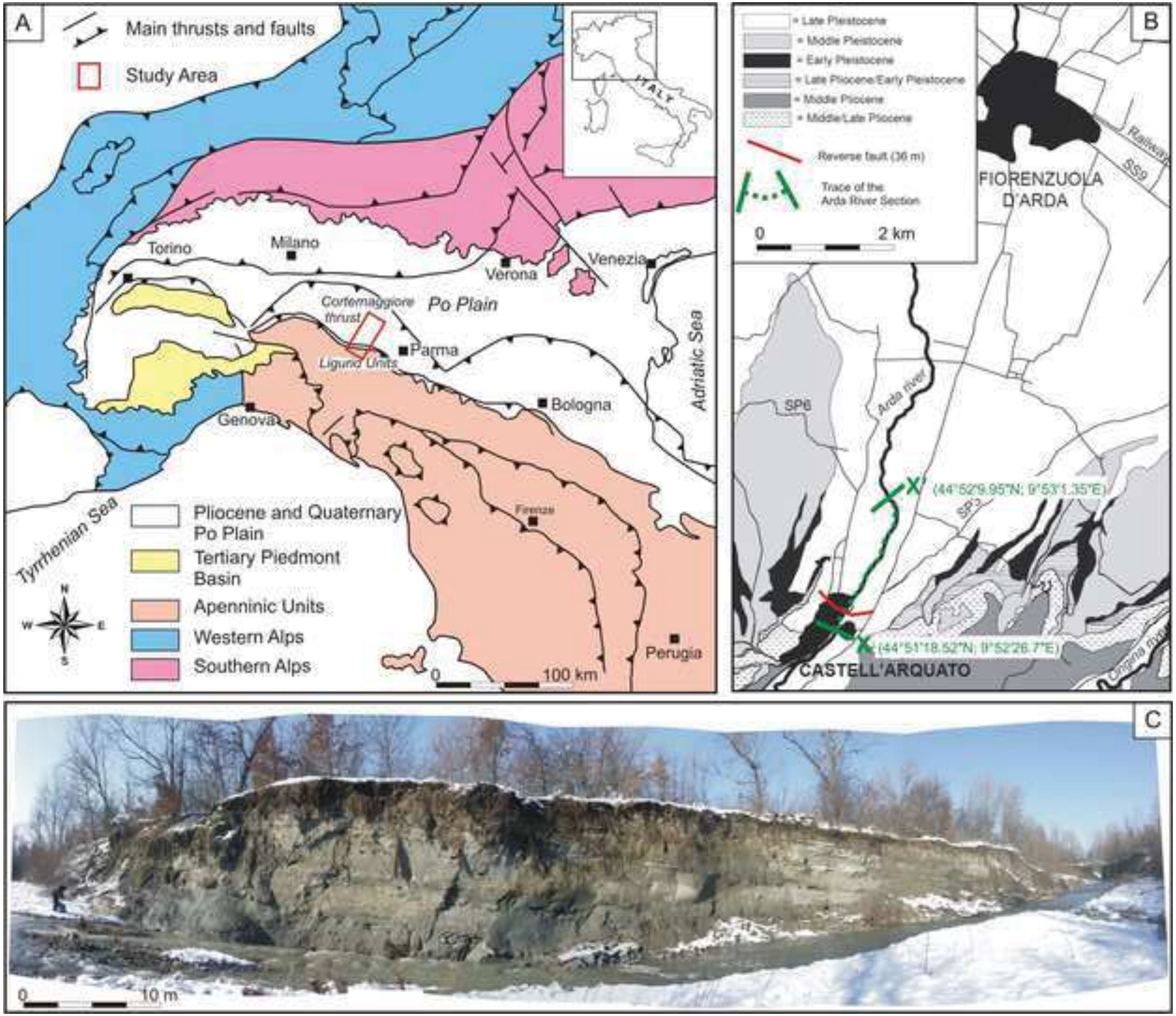

Figure 2

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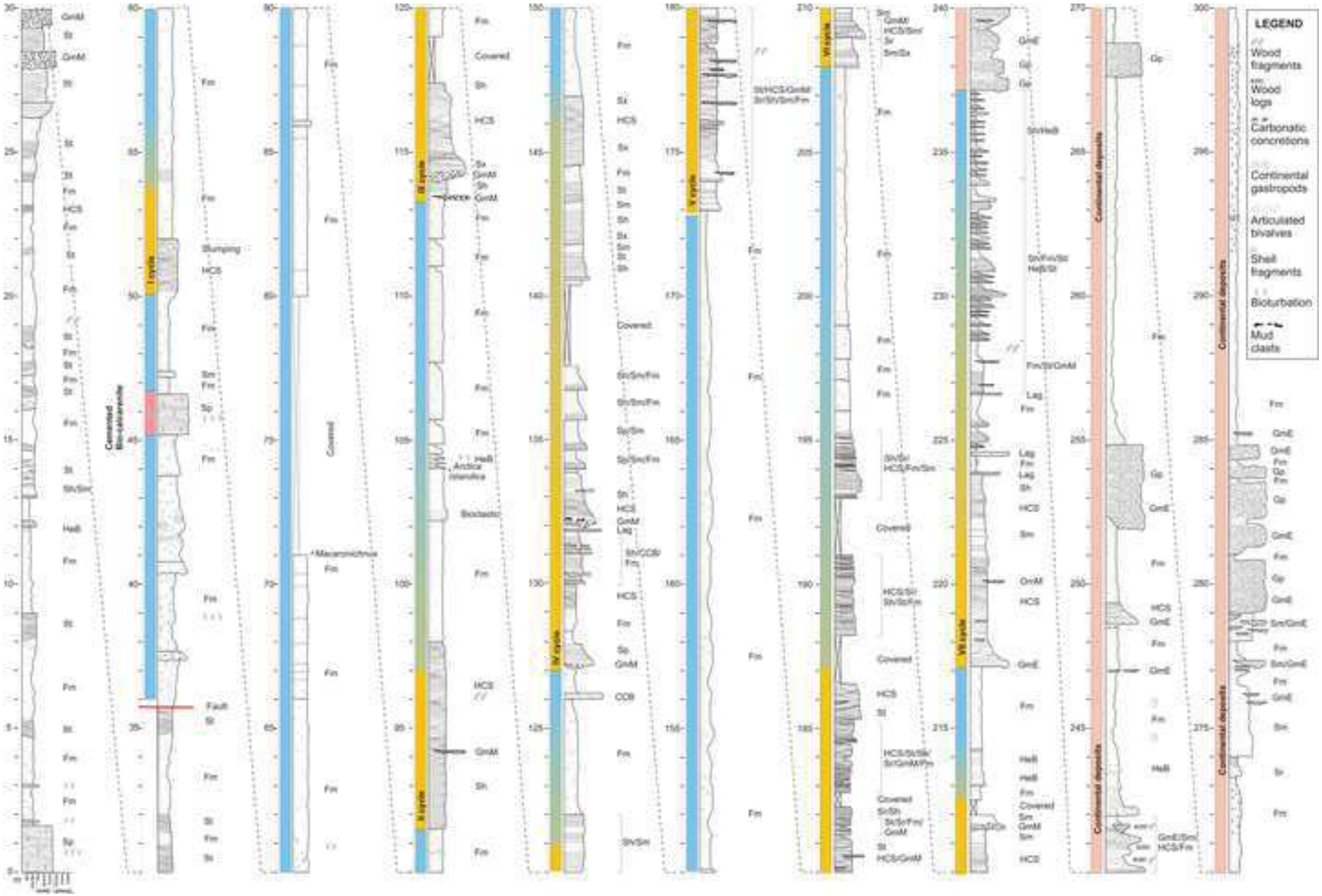

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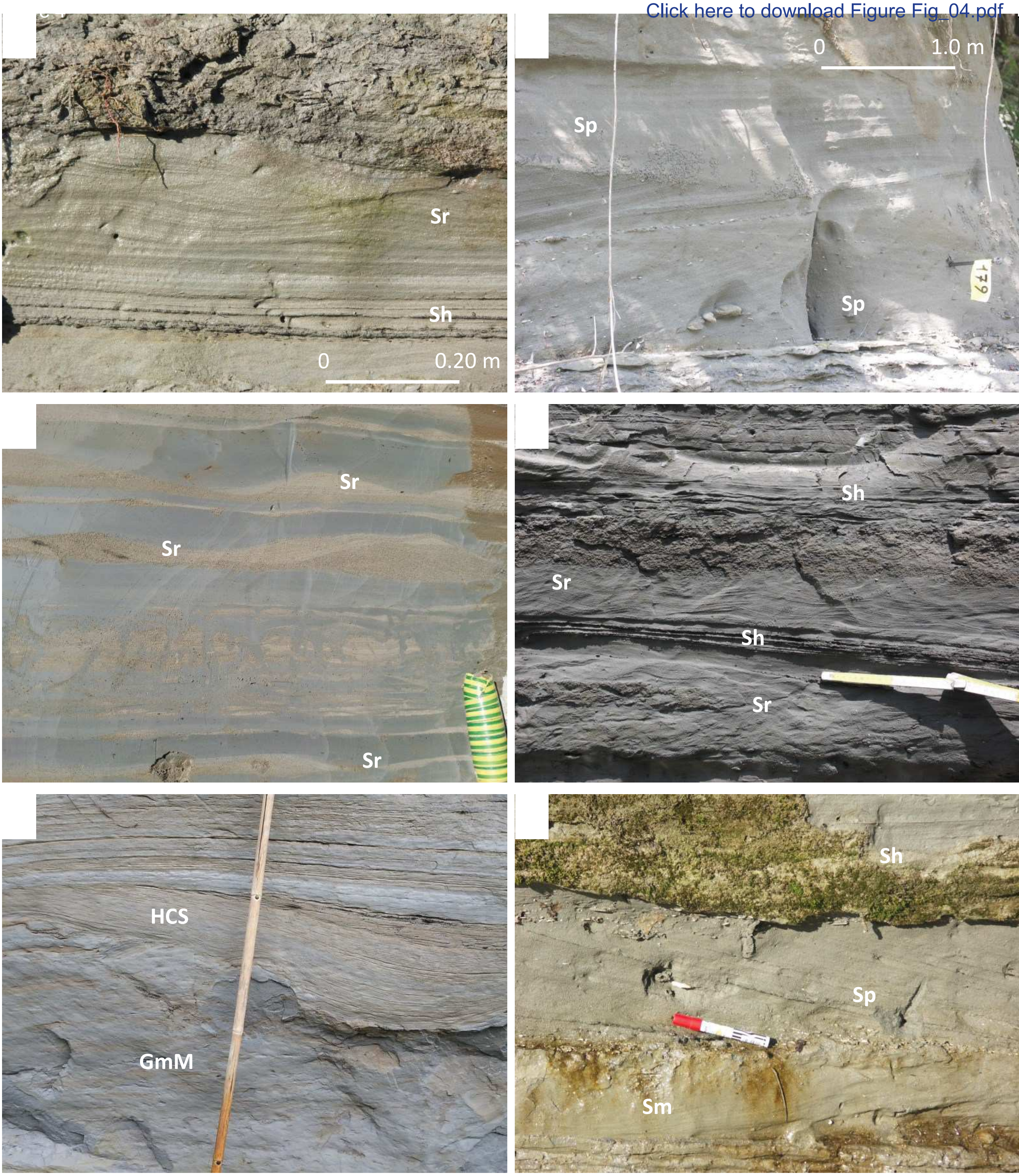
Sr
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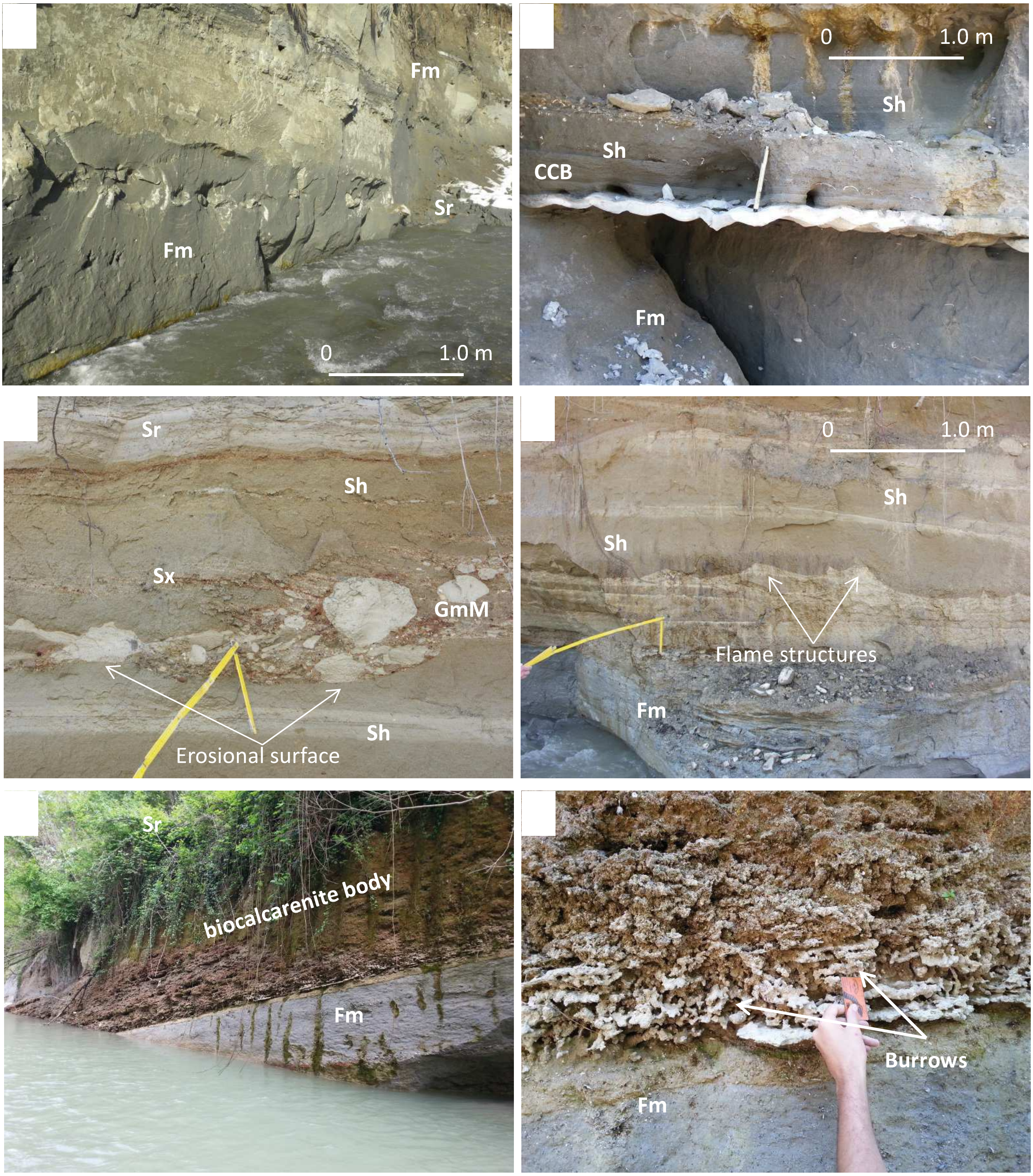
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Erosional surface
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Flame structures
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biocalcarenite body
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Burrows
Fm

Figure 6

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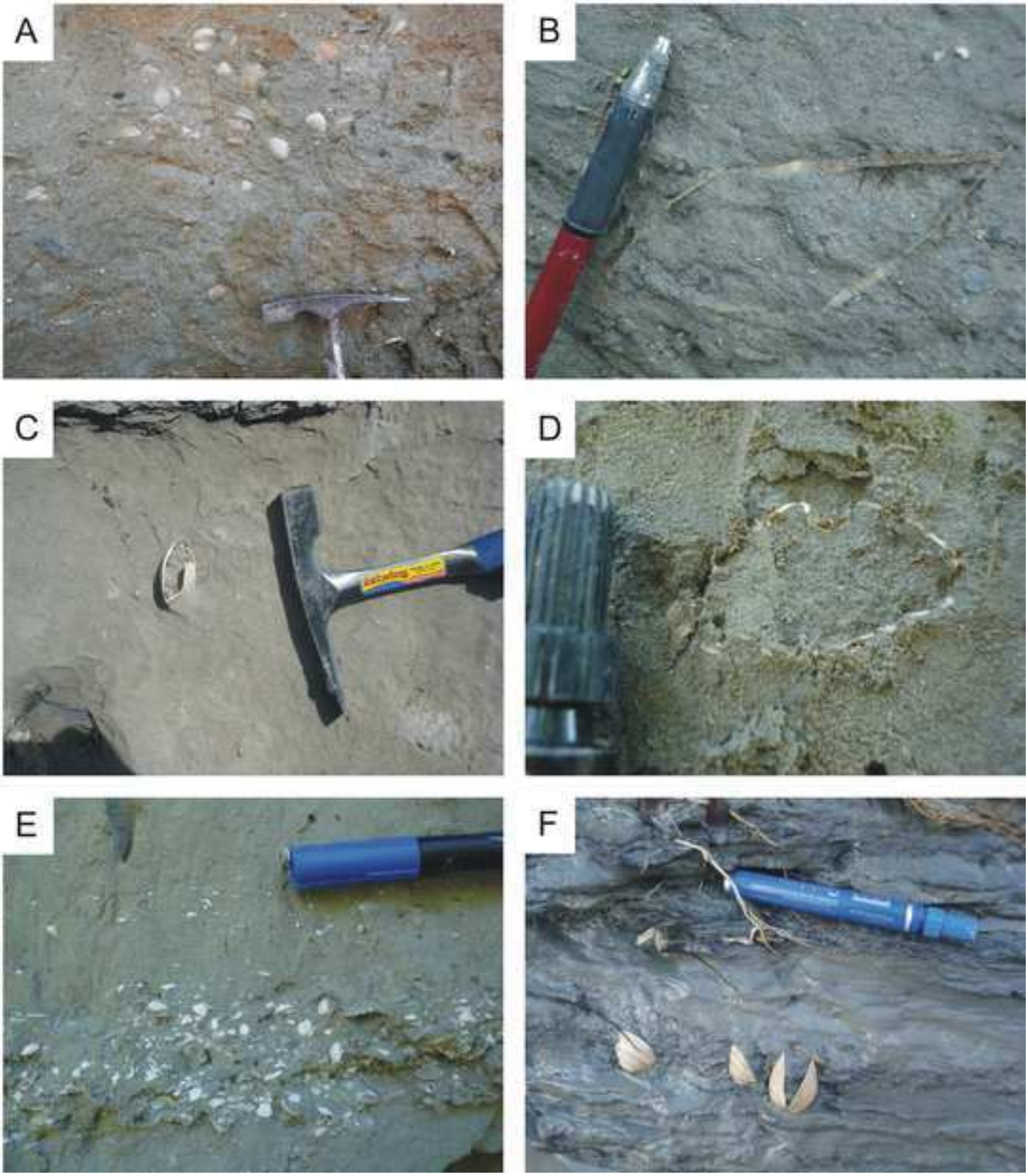

Figure 7

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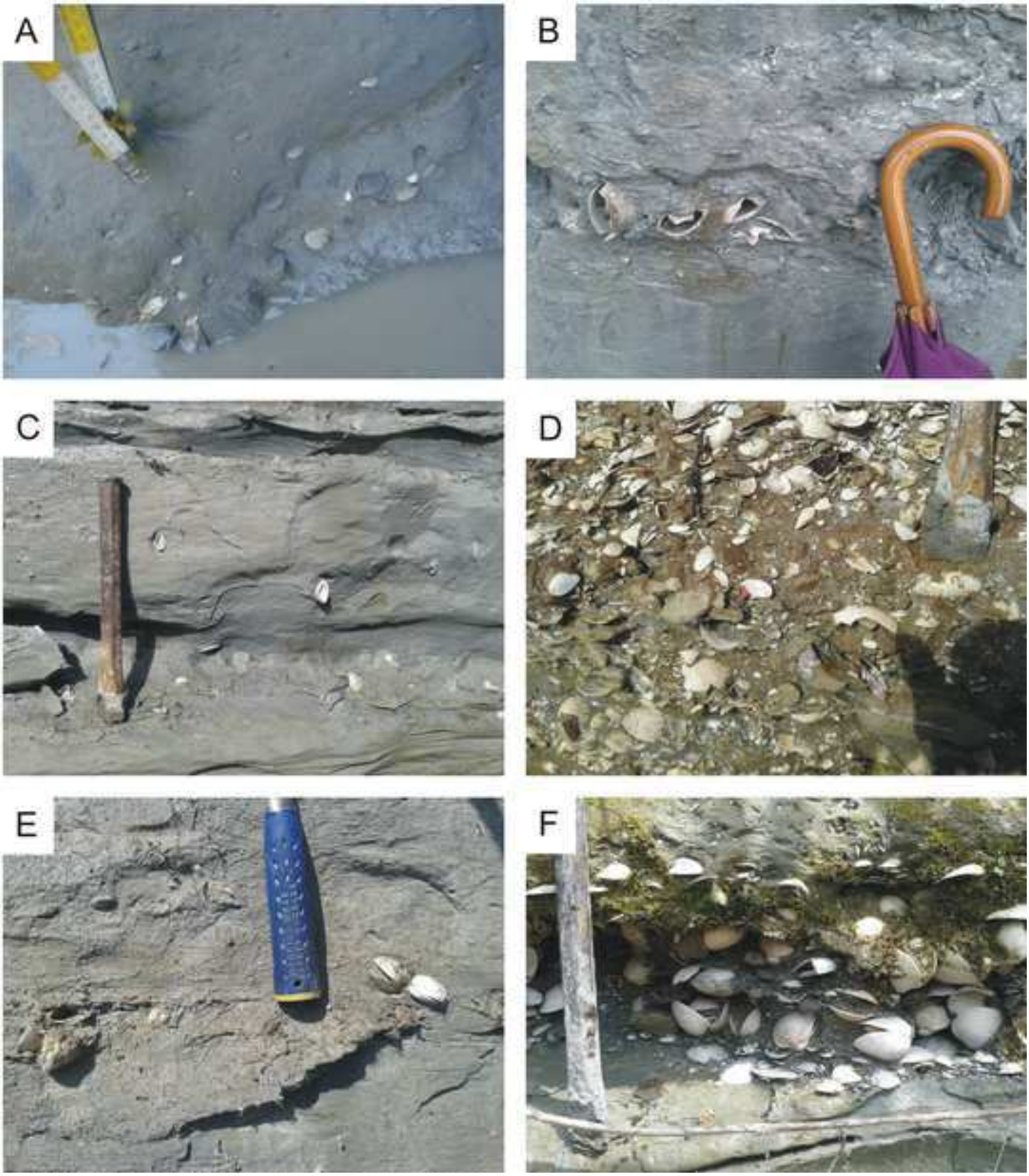

Figure 8

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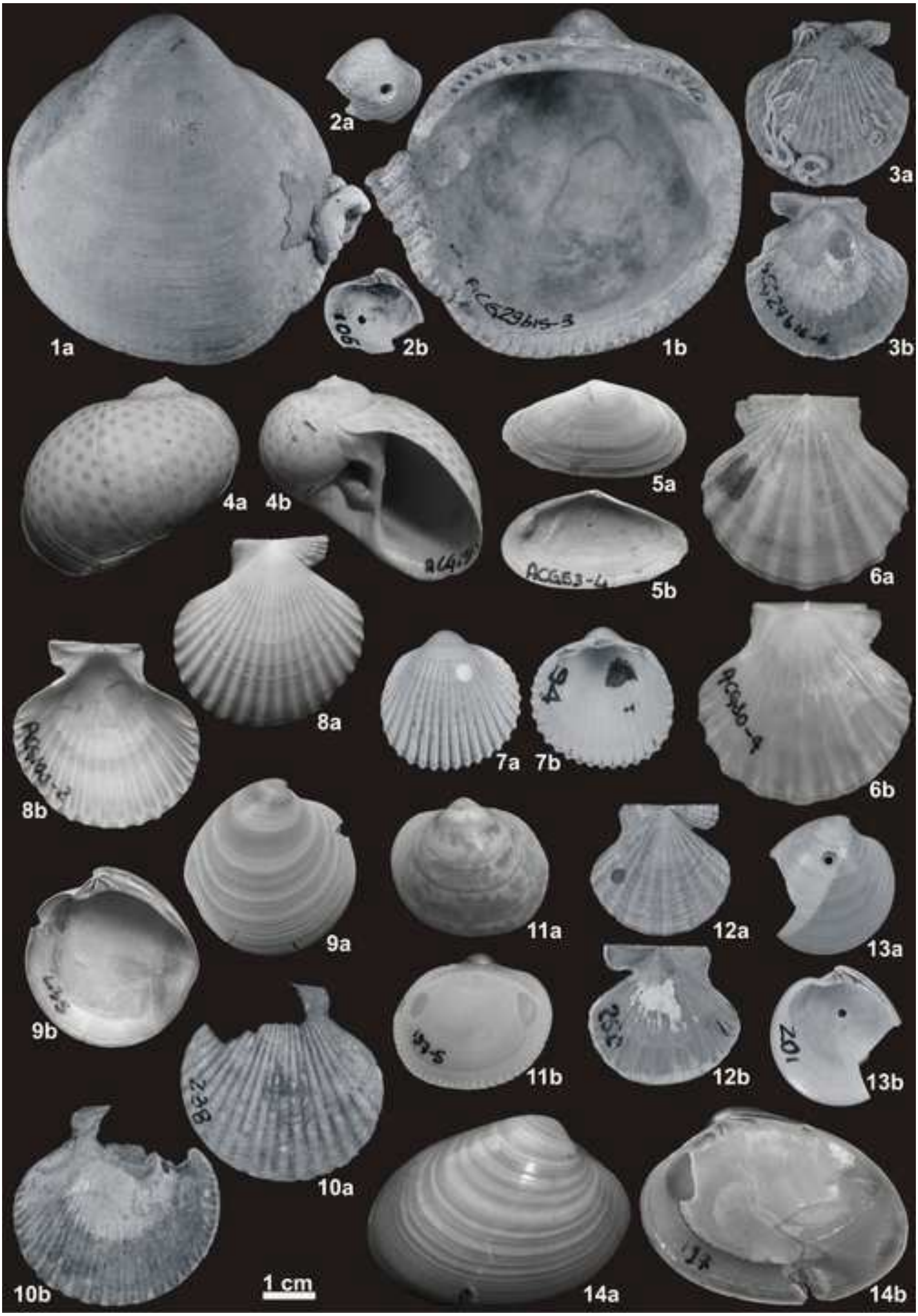

Figure 9

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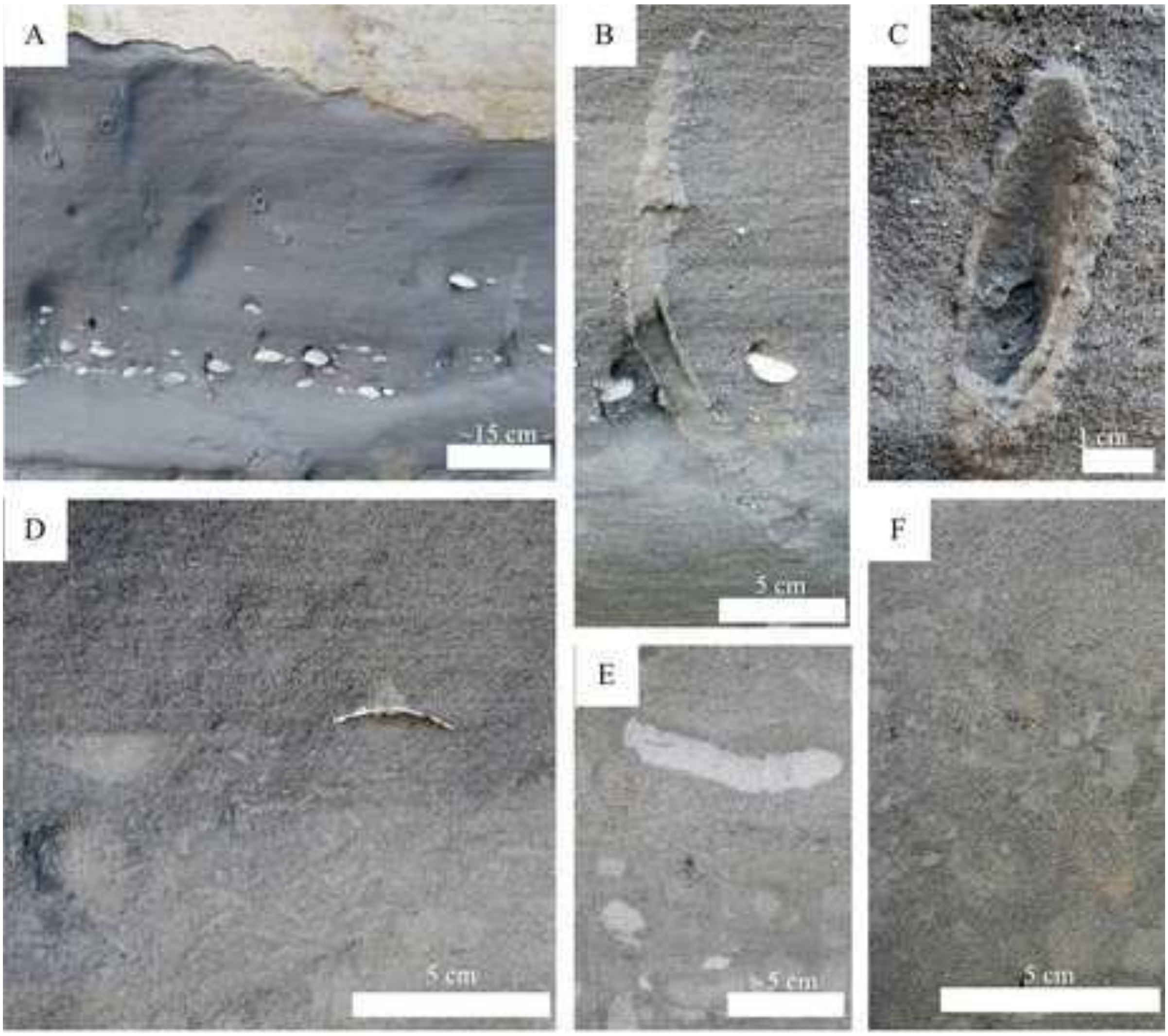

Figure 10

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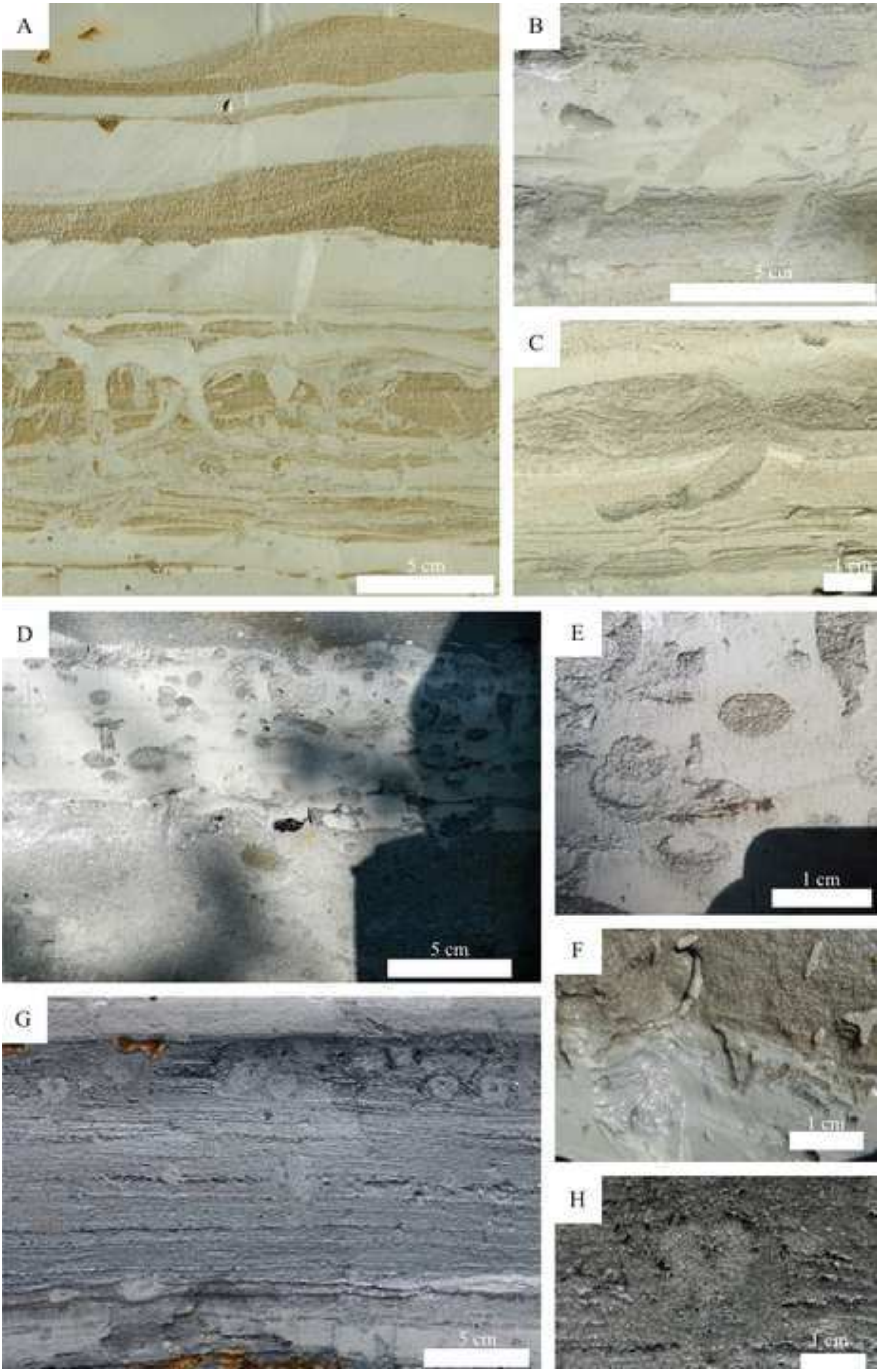

Figure 11

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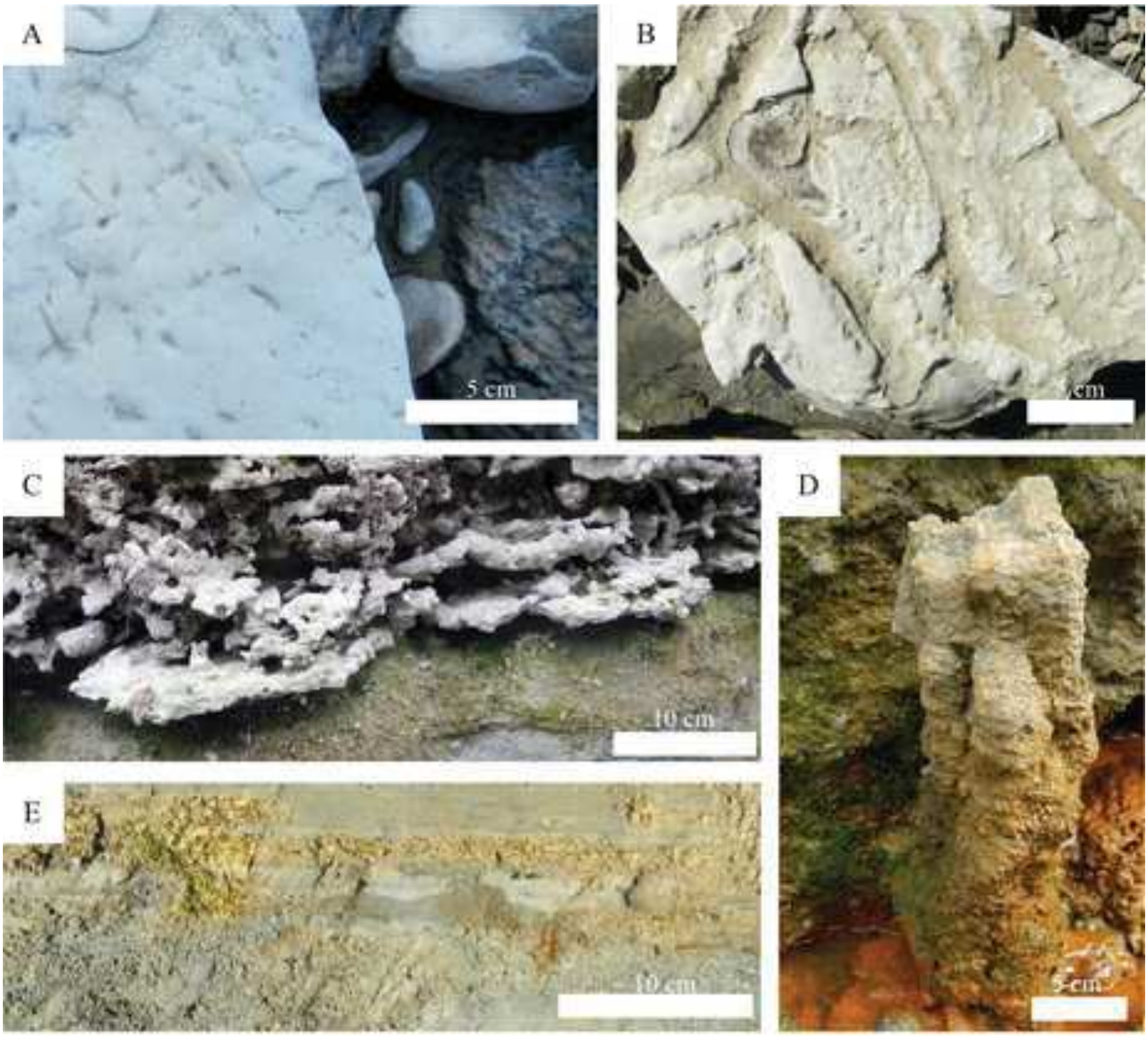

Figure 12

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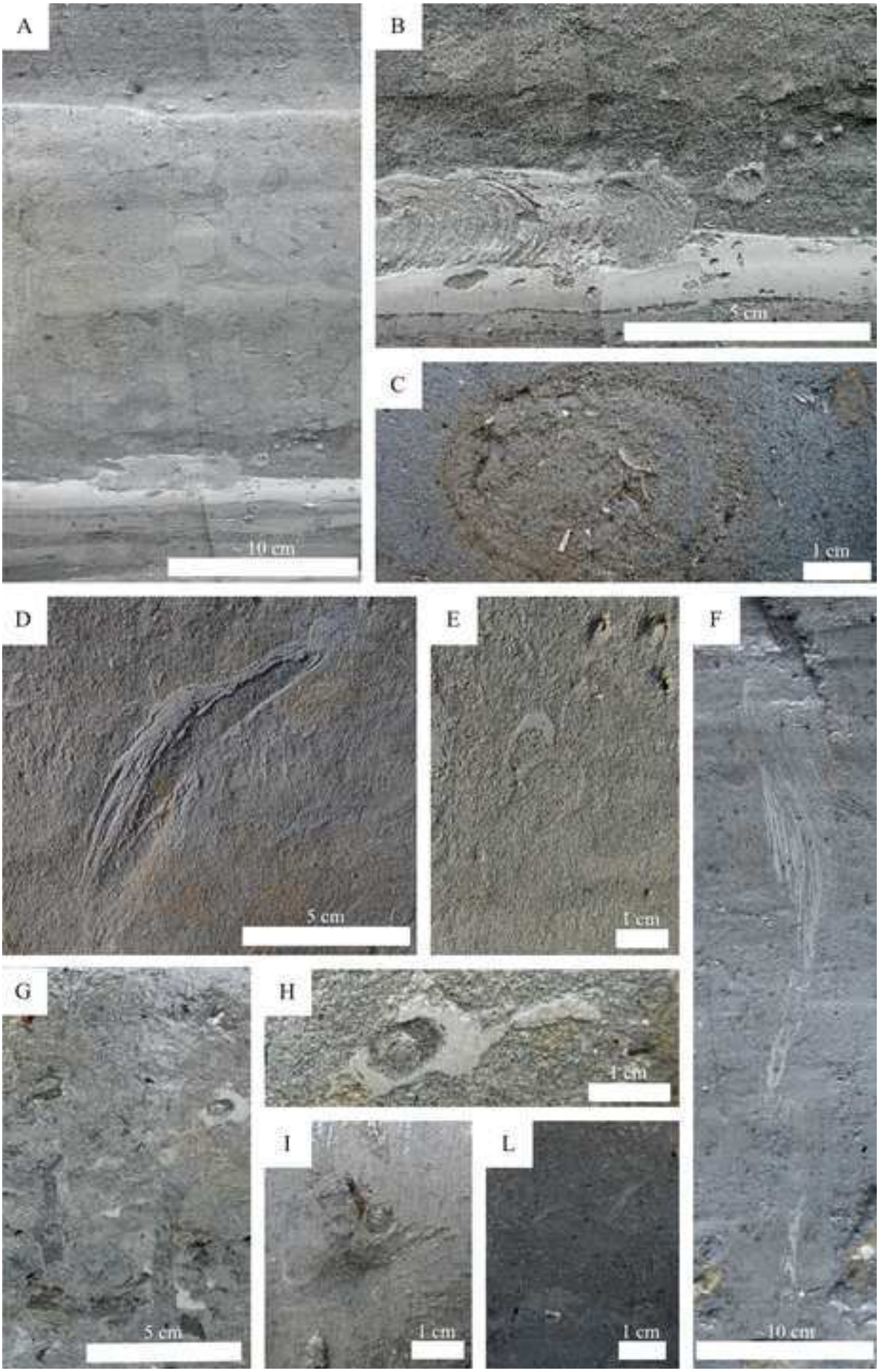

Figure 13

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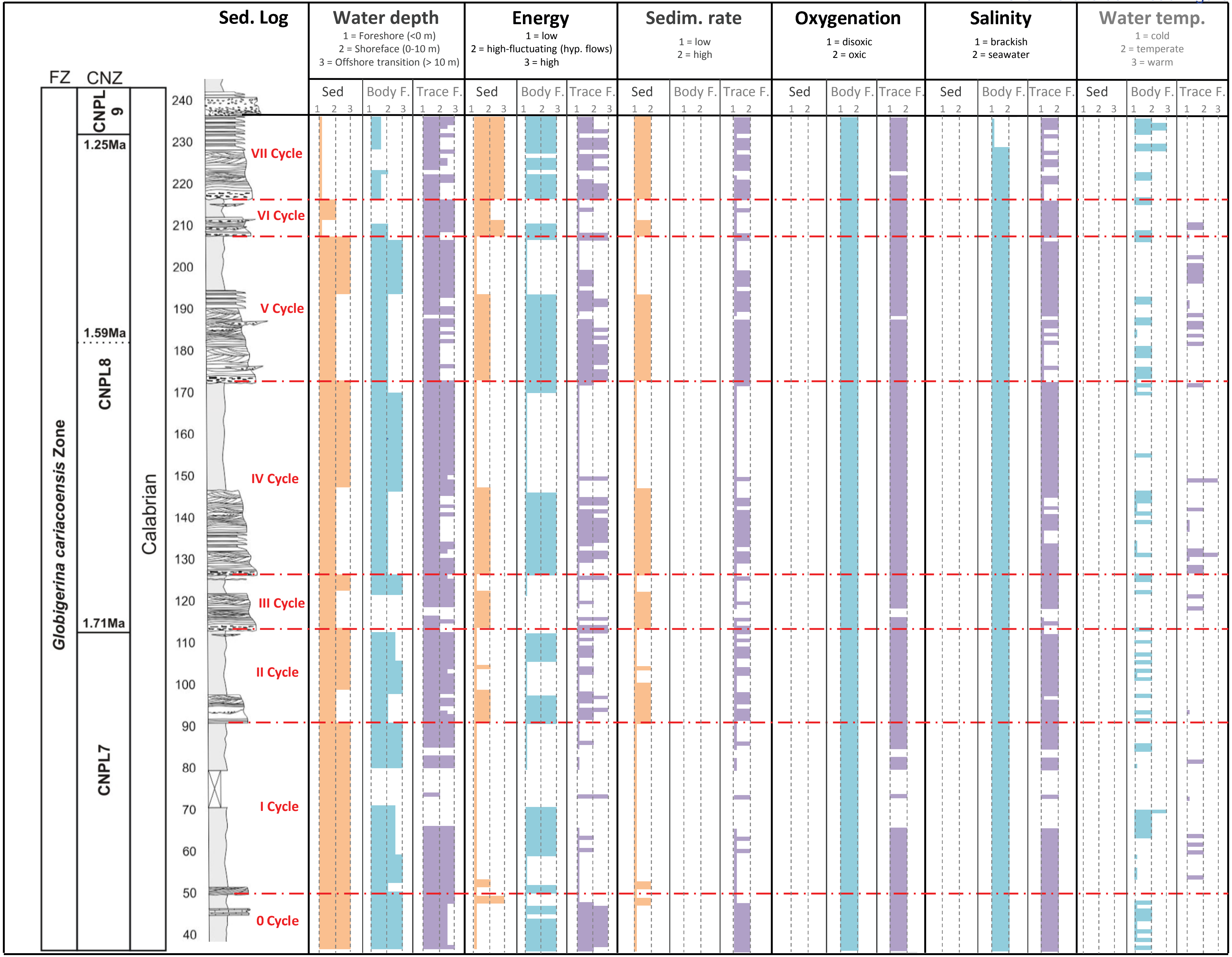

Table 1

Facies categories	Code	Facies	Sedimentary features
Facies B (bed-load related)	***GmE***	*Massive grain-supported gravels*	Massive, grain supported polygenic gravels. Beds have an erosive base and are usually heavily cemented (Fig. 3 A).
	GmM	*Massive mud clasts deposits*	Massive rip-up clasts deposits. Sandy matrix with abundant bioclasts (bivalves and gastropod shell fragments). Beds have an erosive base. Mud clasts are ripped from muddy layers (Fig. 3 A, B, D; Fig. 4 E; Fig. 5 C).
	Gp	*Planar stratified gravels*	Gravels with horizontal or oblique planar stratification. Clasts are usually embricated. Some of these beds are heavily cemented (Fig. 3 D).
	Lag	*Lag deposits*	Gravel carpets with bioclastic and sandy (very coarse) matrix (Fig. 3 E).
Facies S (suspended-load-related)	***Sp***	*Planar oblique stratified sands*	Mostly bioclastic, planar oblique stratified coarse grained sands. Beds are heavily cemented and bioturbated. Bioturbation is in the form of vertical tunnels (Fig. 4 B, F).
	Sx	*Planar cross stratified sands*	Fine to medium grained planar cross stratified sands. Bioturbation is apparently absent. (Fig. 5C).
	HCS	*Hummocky cross stratified sands*	Fine to coarse grained hummocky stratified sands. Beds are usually rich in bioclasts. Bioturbation is apparently absent. Occurrence of wood fragments and logs. (Fig. 4 E).
	St	*Trough cross stratified sands*	Fine to coarse grained trough cross stratified sands. Beds are usually rich in bioclasts. Bioturbation is apparently absent. Occurrence of wood fragments and logs (Fig. 3 C, B).
	Sr	*Ripple cross stratified sands*	Fine grained sands with wave or current ripples, sometimes with well-developed climbing ripples laminasets(current). No evidence of bioturbation (Fig. 4 A, B, D; Fig. 5 A, C).
	Sh	*Horizontally stratified sands and silts*	Horizontally stratified fine and very fine grained sands and silts usually rich in organic matter (small wood fragments) and mollusc fragments (Fig. 3 A, C, D; Fig. 4 A, D, F; Fig. 5 B, C, D).
	Sm	*Massive sands*	Very fine to medium grained massive sands. Beds are locally bioturbated (Fig. 3 A, E, F; Fig. 4 F; Fig. 5 C).
	HeB	*Heterolitic bedding*	Heterolitic fine grained sands to mud. Flaser, wavy and lenticular bedding.
Facies L (lofting-related)	***Fm***	*Massive fines*	Structureless silts and muds with minor very fine sands. Beds are locally heavily bioturbated. Presence of in-life position marine bivalves in the lower part of the stratigraphic section. In the upper part (continental deposits) frequent root systems and vertebrates (Fig. 5 A, B, E, F).
	CCB	*Carbonatic Cemented Beds*	Cemented levels, rich in carbonate. (Fig. 5 B)

Table

		Data						Interpretation		
Ichnofabric group	**Ichnofabric class**	**Degree of bioturbation (ii)**	**Characteristic ichnotaxa**	**Accessory components**	**Diversity (n)**	**Facies**	**Figures**	**Depositional environment**	**Major environmental features**	**Climate**
1	Unbioturbated ichnofabric	1	-	-	0	GmE, Gp	-	Fluvial	-	-
	Low bioturbation ichnofabric	1-2	*Planolites, Palaeophycus,* cryptobioturbation	-	0-1	Sx, St, Sr	-	Foreshore-middle shoreface	Brackish water	-
	Skolithos ichnofabric	2	*Skolithos*	-	1	Sm	-	Backshore?; Foreshore-upper shoreface	-	-
	Ophiomorpha ichnofabric	2	*Ophiomorpha*	*Macaronichnus*	1	Sh	9 A-C	Foreshore-shoreface	High energy	Warm
	Macaronichnus ichnofabric	4-5	*Macaronichnus*	"Lined light filled burrows", "unlined light filled burrows"	1	Sm	9 D-F	Foreshore-shoreface	High energy	Temperate-cold
2	Few sharp burrows – smooth burrows ichnofabric	1-2	*Bergaueria*	Fugichnia	0-1	HeB	10 A-C	Upper shoreface-offshore	Hyperpycnal-influenced, rhythmical development of firm substrates	-
	Sharp burrows – Scolicids ichnofabric	2-3	Scolicids (*Scolicia, Bichordites)*	*Palaeophycus, Planolites*?, *Thalassinoides*, oblique burrows, *Teichnichnus*-like, mantle and swirl structures	1-3	HeB	10 G-H	Upper shoreface-offshore	Hyperpycnal-influenced, rhythmical development of firm substrates	Warm
	Sharp burrows – smooth burrows ichnofabric	2-3	"sharp-walled burrows"	mottles, dark-filled *Planolites*, *Scolicia, Schaubcylindrichnus*? (morphotype A), *Planolites, Palaeophycus, Rosselia*?, *Teichichnus*	1-5	HeB	10 D-F	Offshore	Hyperpycnal-influenced, rhythmical development of firm substrates	-
3	*Lockeia* ichnofabric	2-3	*Lockeia, Ophiomorpha, Siphonichnus, Arenicolites, Diplocraterion, Skolithos*	"winding trails"	0-1	CCB	11 A, B	Foreshore?	Firm substrates	-
	Thalassinoides ichnofabric	3-5	*Thalassinoides*	"Y-shaped burrows", "columnar burrow sets"	1	Sp	11 C, D	Shoreface?	High energy	-
	Coarse-fill burrows ichnofabric	4-5	"Coarse-fill burrows"	-	1	Fm	11 E	Submarine canyon?	Firm substrates	-
4	*Scolicids* ichnofabric	4-5	*Scolicids (Scolicia, Bichordites)*	-	1-3	Sm, Fm	12 A-C	Lower shoreface - offshore	Hyperpycnal-influenced?	Warm
	Palaeophycus ichnofabric	5-6	*Planolites, Palaeophycus, Schaubcylindrychnus? (morphotype A), Scolicia, Rosselia?, Teichichnus (morphotype A).*	-	3	Sm, Fm	12 D-F	Offshore	-	-
	High bioturbation ichnofabric	5-6	Dark-*filled Planolites, Schaubcylindrichnus?* (morphotype A), *Palaeophycus , Teichichnus* (morphotype B), *Asterosoma.*	bioerosion traces (*Oichnus, Entobia*?), "shell filled burrows"	0-3	Fm	12 G-L	Offshore	-	-