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Palaeoclimatic and palaeoenvironmental evolution of the Lower Pleistocene Arda River succession

8th International Brachiopod Congress – Milano, 11-14 September 2018
XX Congress of the Italian Palaeontological Society – Bologna, 19-21 May 2020

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Cover page Figure: Outcrops along the Lower Pleistocene Arda River section.

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Abstract

The Arda River marine succession, cropping out in western Emilia (northern Italy) represents an excellent site to study past ecosystems dynamics in the frame of Early Pleistocene climate change and tectonic activity. This one-day excursion leads the participants to discover the palaeoclimatic and palaeoenvironmental evolution of the Lower Pleistocene Arda River marine section, unraveled through an integrated use of sedimentological, palaeoecological (molluscs and trace fossils) and geochemical tools. Upsection, the succession was deposited in progressively shallower water and colder climate during phases of advance of fan deltas affected by hyperpycnal flows. It culminates at the top with clast supported alluvial conglomerates and freshwater/terrestrial biota indicating a sea level drop and the establishment of a continental environment. It is very rich in fossils: in the marine part molluscs, brachiopods, corals and echinoderms, besides well preserved trace fossils, are abundant; whereas in the continental part a mammal fauna and freshwater/terrestrial molluscs are occasionally found. Sclerochemical analyses undertaken on bivalve shells indicate that seawater temperature seasonality was the main variable of climate change within the study area during the Early Pleistocene. In particular, strong seasonality and low winter palaeotemperatures were assumed to be the main drivers for the widespread establishment of *Arctica islandica* populations in the palaeo-Adriatic Sea around 1.80 Ma. During the excursion not only fossils are shown, but also interesting biocalcarenitic bodies with a complex geometry cropping out in the town of Castell'Arquato. The excursion is complemented by the visit to the Giuseppe Cortesi geological and palaeontological museum, housing vertebrate and invertebrate fossil collections.

Key words
Molluscs, Brachiopods, Facies analysis, palaeo-Adriatic, Calabrian, climate change

Program summary

The medieval town of Castell'Arquato is located in northern Italy and it is easily reachable by car from Milan (1h 30) or Bologna (1h 40) (Fig. 1A). All the stops of this one-day field trip are within walking distance from the Castell'Arquato town centre. A free parking lot for cars and buses is available at the entrance of the town. The field trip consists of a half-day visit to river outcrops (Stops 1-3 in Fig. 1B), complemented by the visit to the Giuseppe Cortesi Geological Museum (Stop 5 in Fig. 1B). On the walk to the Geological Museum there

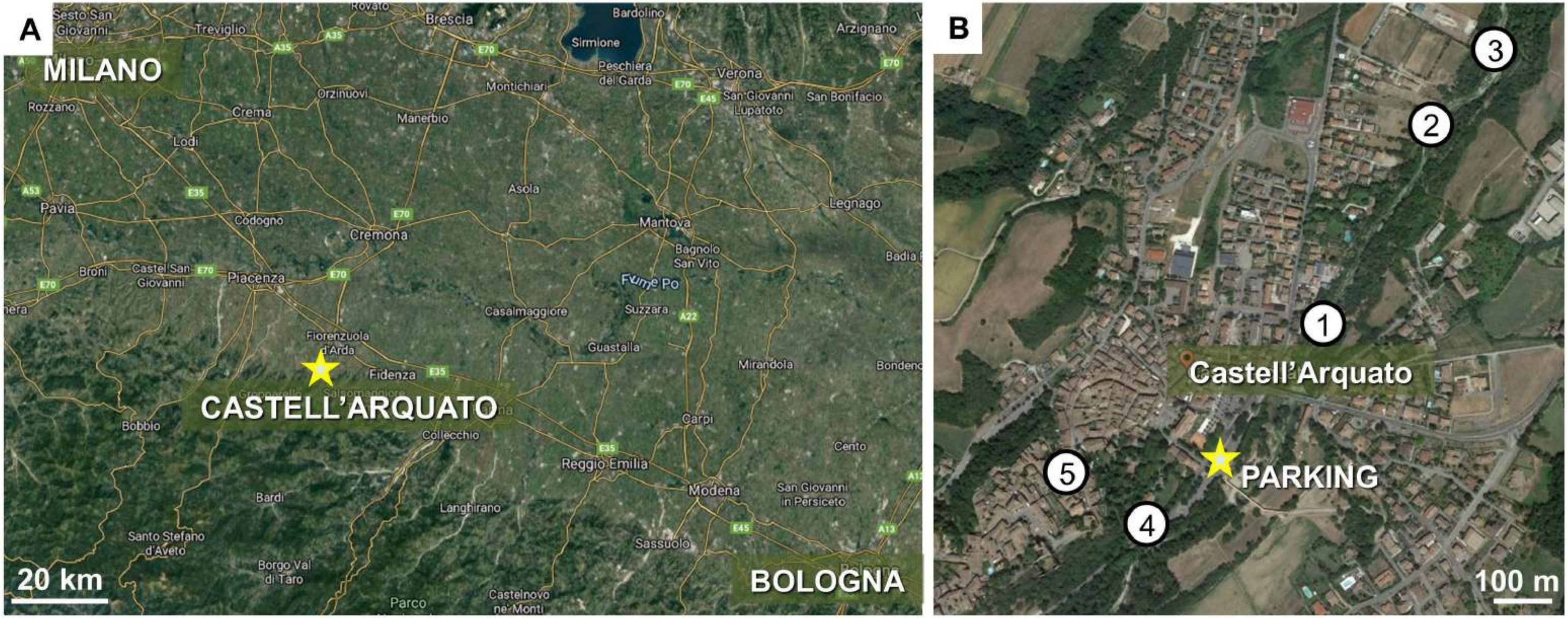

Fig. 1 - A) Location of the Castell'Arquato town with respect to Milano and Bologna. B) Main stops of the field trip.

is a stop to observe an additional outcrop, representing the bedrock on which Castell'Arquato was erected in medieval times (Stop 4 in Fig. 1B).

STOPS 1-3 – Participants walk along the Arda River looking at the Pleistocene marine succession exposed along its banks, which preserve fossiliferous beds deposited in progressively shallower water and colder climate, culminating with continental conglomerates and biota.

STOP 4 – The Viale Rimembranze outcrop shows a characteristic biocalcarenitic clinoform unit, cyclically recurrent in the Castell'Arquato basin. Here, its tripartite geometry is clearly observable.

STOP 5 – Participants visit the Giuseppe Cortesi Geological Museum and its rich palaeontological collections (macroinvertebrates, cetaceans and mammals).

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Safety

Participants walk on the riverbed for a short distance in a low-level water and this may be a slippery and rough path. Wellington boots or, alternatively, sport shoes (best if with ankle-support and good grip) are strongly recommended. An extra pair of shoes to be worn before and after the walk along the river is highly advised. There are also few outcrops with overhangs, in this case it is recommended to wear a helmet. For the visit to the Geological Museum participants walk up a steep path for about 15 minutes, stopping in the vicinity of a rocky cliff where you are advised to wear a helmet.
The best seasons for the visit are spring and autumn, winter and summer can be very cold or very hot, respectively. Sunscreen, sunglasses and a broad-brimmed hat but also something warm and light such as a fleece jacket are recommended; a lightweight waterproof jacket is also suggested in case of showers. The air might be dry, so beware of dehydration and bring at least a water bottle. Avoid scheduling the field trip after periods of heavy rain, as when the river level is high, the current is very strong.
The outcrops are located inside a regional natural park, therefore collecting fossils is forbidden. This also implies there is no need for hammering and bringing protective equipment (e.g., safety glasses and gloves etc.).
Emergency telephone number in Italy is 112 (all services).

Cultural notes

Castell'Arquato is a medieval town with numerous buildings which have remained the same since the 14th Century; two examples of historical architectures are the Giuseppe Cortesi Geological Museum and the medieval fortress of the Rocca Viscontea.
The Giuseppe Cortesi Geological Museum is housed in the sixteenth-century Ospitale Santo Spirito, an ancient hospice for pilgrims travelling to Rome in the Middle Ages (see Stop 5). Standing within the original town boundaries, the building is important not only for its architecture, but also because it has preserved the only example of porticoes connected to the street that survive in Castell'Arquato. The complex of the hospital is characterised by a loggia that overlooks the valley offering an impressive panoramic view of the plain extending as far as the Po River. The interior contains interesting frescoes in one vault of the main hall, which has retained its original configuration and a fine coffered sixteenth-century polychrome wooden ceiling that adorns the room with the fireplace.

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Fig. 2 - The Rocca Viscontea and the Castell'Arquato town.

The Rocca Viscontea dominates the Castell'Arquato town and the Arda valley, with its tower entirely made of laterizio brick (Fig. 2). Built under the domination of Luchino Visconti between 1342 and 1349, the fortress was then given to Scotti's family in 1404, and subsequently to Filippo Visconti. In 1466, it becomes a property of the Sforza's family until 1707, when it became part of the Duchy of Parma and Piacenza. The Rocca Viscontea is located on a formerly Roman military settlement (called *Castrum Quadratum*). It is an imposing building, composed by two connected structures and is dominated by the *mastio* (i.e. fortified tower). The high tower, an excellent observation point, was built for defensive and military purposes and has never become a noble residence. Soaring on the village square it had the double function of defence against external enemies, with a strategically dominant position on the surrounding valley, and of control over the inhabitants.

The fortress is surrounded by a double row of walls: the lowest, which is also wider, covers two levels, where soldiers usually lived and where, in case of danger, the citizens could be sheltered; the highest wall, perpendicular to the other, was reserved for the garrison's command. Today the external perimeter structure and the four defensive towers remain.

The main entrance with a bridge, once a drawbridge, is located at the base of the great *mastio*. The *mastio* contains rooms connected to each other by a partly wooden and partly masonry staircase leading visitors to the top from which they can enjoy a fantastic and incomparable view from the Po valley to the Alps to the north, up to the Apennine ridge to the south, towards the sea.
In the nineteenth and twentieth centuries, up until the ‘60s, the Rocca Viscontea was used as a jail. In 1985 the Rocca Viscontea and the centre of Castell’Arquato were used as a movie set for “Ladyhawke” with Michelle Pfeiffer, Rutger Hauer and Mattew Broderick. Nowadays it is a museum of medieval history and culture.

Hospitals

Ospedale di Fiorenzuola d’Arda, Viale Roma 29, 29017 Fiorenzuola d’Arda (PC); Tel: 0523 301111
Ospedale di Vaio Fidenza, Via Don Enrico Tincati 5, 43036 Vaio (PR); Tel: 0524 515111

Other useful addresses

Museo Geologico Giuseppe Cortesi, Via Sforza Caolzio 57, 29014 Castell’Arquato, Italy; https://www.museogeologico.it/
Parco dello Stirone e del Piacenziano, Loc. Millepioppi, 43039 Salsomaggiore Terme, Italy; http://www.parchidelducato.it/parco.stirone.piacenziano/pagina.php?id=75
IAT Ufficio Informazioni e Accoglienza Turistica, Piazza del Municipio, 29014 Castell’Arquato, Italy; http://castellarquatoturismo.it/

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Geological setting

The Arda River stratigraphic section is located in northern Italy near the town of Castell'Arquato, at the foothills of the northern Apennines to the south of the Po Plain (Fig. 3). The northern Apennines are an orogenic wedge formed since the Oligocene as a result of the westward subduction of the Mesozoic Ligurian-Piedmont Ocean (Carminati and Doglioni, 2012) beneath the Corsica-Sardinia microplate and the collision with the Adria promontory. The formation of the orogenic wedge was accompanied with the establishment of a complex foreland basin system, which migrated towards the east and was filled by thick siliciclastic successions including foredeep turbidites sourced from the Alps (Cau et al., 2015).

The stratigraphic succession exposed along the Arda River belongs to the sedimentary fill of the Castell'Arquato basin,

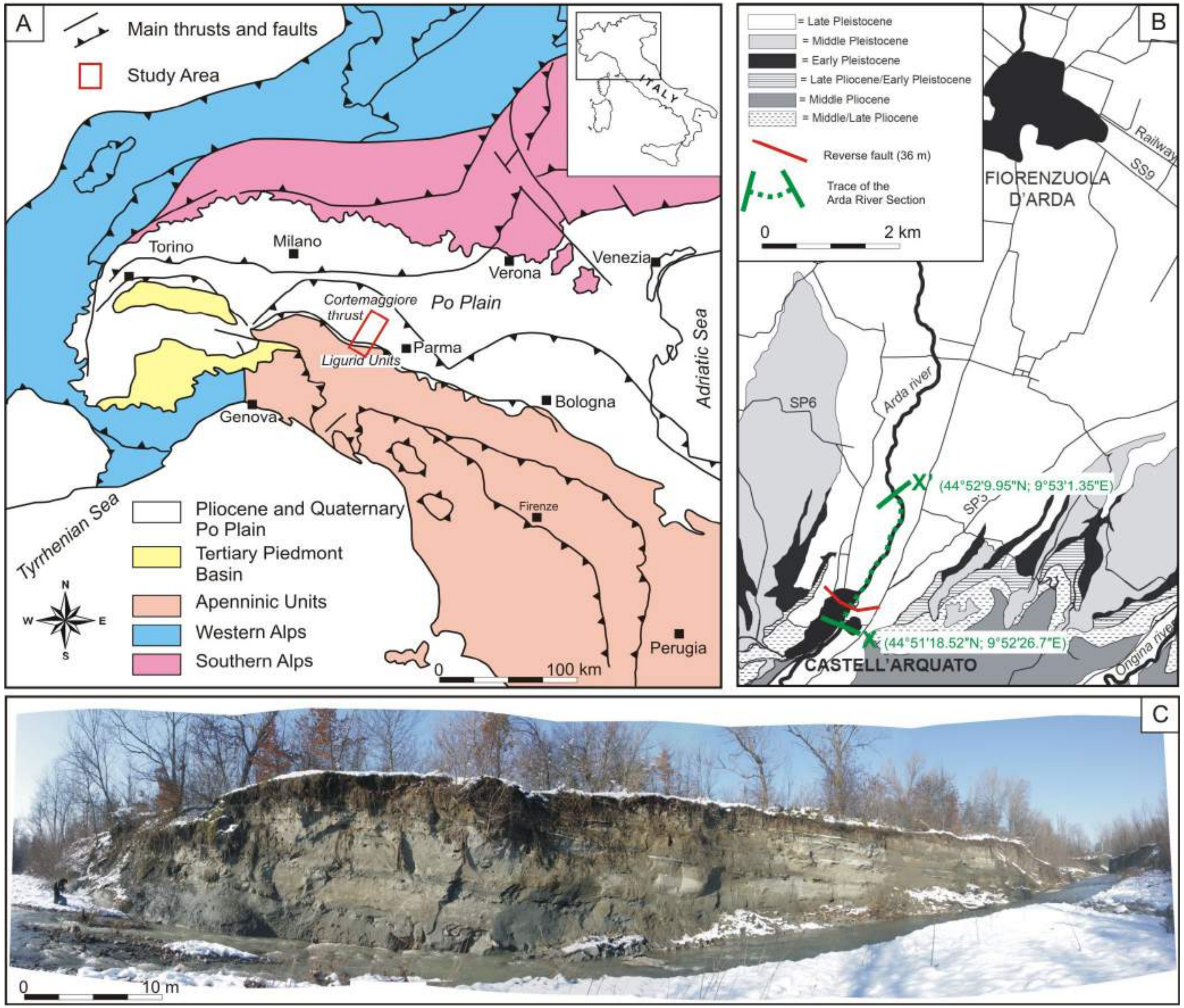

Fig. 3 - A) Geological sketch map of northern Italy showing the study area (red rectangle). B) Enlarged geological map of the Castell'Arquato basin showing the measured Arda River section. C) Photograph of a part of the outcrop along the Arda River. Crippa et al. (2018), reproduced with permission.

developed since the Messinian (late Miocene) within the wedge-top depozone of the northern Apennine orogenic wedge, following the tectonic fragmentation of the Po Plain axial foredeep (Roveri and Taviani, 2003; Artoni et al., 2010; Fig. 3). Geographically, the Castell'Arquato basin represented the north-western continuation of the palaeo-Adriatic Sea, bounded to the north by the Salsomaggiore structure (one of the outermost thrust fronts of the Apennine orogenic wedge; Artoni et al., 2004, 2010) and to the south by the obducted units of the Ligurian-Piedmont Ocean (the Ligurides; Monegatti et al., 2001; Fig. 3A).

The Castell'Arquato sedimentary succession forms a monocline gently dipping towards the north-northeast (Monegatti et al., 2001) with only minor tectonic deformation, which allows the correlation of distant outcrops and subsurface equivalents with confidence (Monegatti et al., 2001; Cau et al., 2019; Crippa et al., 2019). The fill of the basin constitutes a large-scale transgressive regressive cycle of late Messinian to Holocene age, amenable to subdivision into four lower rank unconformity bounded units controlled by tectonics (Roveri and Taviani, 2003; Artoni et al., 2010), exposed at outcrop and recognized in the subsurface of the Po Plain and the central Adriatic Sea (Pieri, 1983; Ori et al., 1986; Ricci Lucchi, 1986). The basal part of the fill of the Castell'Arquato basin comprises deep sea sediments postdating the Messinian salinity crisis (Ceregato et al., 2007; Calabrese and Di Dio, 2009) which shallow upward, making transition to slope and shelfal facies deposits of the Pliocene-Early Pleistocene. In the Middle Pleistocene, this regressive trend culminated with the final retreat of the sea and the establishment of a continental environment with vertebrate faunas, freshwater/terrestrial molluscs and alluvial deposition (Cigala Fulgosi, 1976; Pelosio and Raffi, 1977; Ciangherotti et al., 1997; Esu, 2008; Esu and Girotti, 2015).

Palaeoclimatic setting

The Early Pleistocene was a time interval characterised by climatic oscillations related to glacial/interglacial cycles (Fig. 4), causing several cooling events; these produced an increase in the ice cap thickness and large sea level drops (e.g., Clark et al., 2006; Sosdian and Rosenthal, 2009; Elderfield et al., 2012). The beginning and the end of this time interval correspond to two important palaeoclimatic events, respectively:

a) The intensification of the Northern Hemisphere Glaciation ~2.6-2.7 Ma ago (Sosdian and Rosenthal, 2009; Hodell and Channell, 2016) which marks the onset of major glaciations in the Northern Hemisphere, with

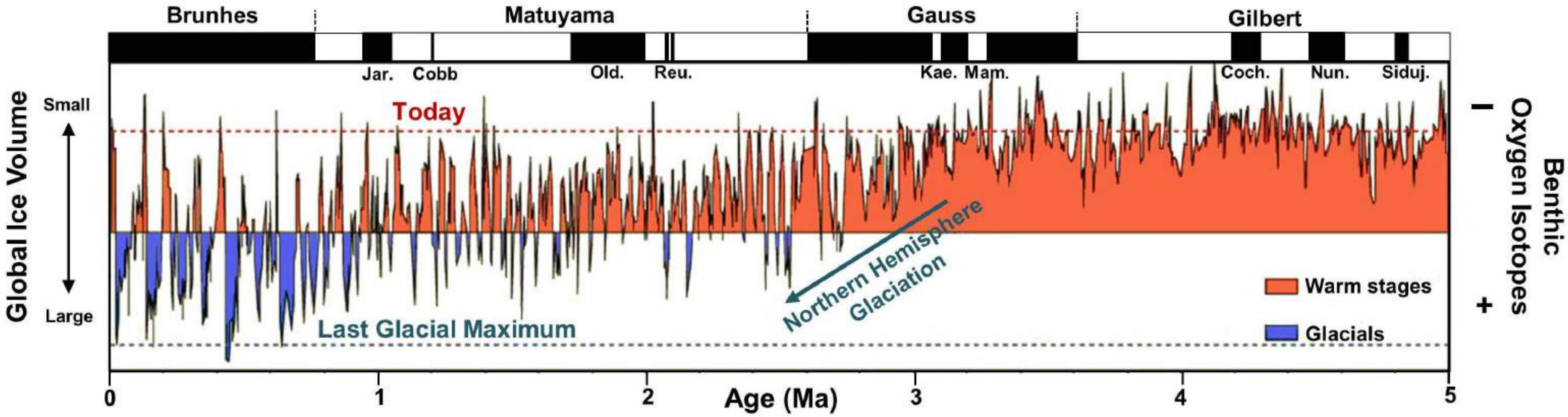

Fig. 4 - Climatic oscillations during the last 5 Ma. Jar: Jaramillo; Old: Olduvai; Reu: Reunion; Kae: Kaena; Mam: Mammoth; Coch: Cochiti; Nun: Nunivak; Siduj: Sidujfall. Modified from Tiedermann et al. (1994).

expansion of ice sheets recorded by an increase of ice rafted debris in the Atlantic Ocean and by a cooling of deep waters in the Atlantic Ocean (Shackleton et al., 1984) and the Mediterranean Sea (Thunell, 1979). However, according to Ghinassi et al. (2004), the Pliocene-Pleistocene deposits of the northern Apennine intermontane basins generally do not record clear signs of these climatic variations. The location and north-south configuration of Italy, surrounded by warm seas, and the tectonic activity with rapid uplifts of parts of the Apennines may have contributed to a mitigation of these global climatic changes.

b) The Early-Middle Pleistocene Transition (1.4–0.4 Ma; Head and Gibbard, 2015) marking the onset of precession-driven Quaternary-style glacial–interglacial cycles (e.g., Clark et al., 2006; Ehlers and Gibbard, 2007; Sarnthein et al., 2009; Elderfield et al., 2012; Head and Gibbard, 2015). Its onset was accompanied by a decrease in sea surface temperatures in the North Atlantic (up to 9°C) and tropical-ocean upwelling regions, a decrease in CO_2 content in the atmosphere (Clark et al., 2006) and an increase in long-term average ice volume up to 50 m sea-level equivalent (Dwyer et al., 1995). The acme of the cooling is in correspondence of Marine Isotope Stage 22 (~0.9 Ma), which records the first large continental glaciation

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in the Northern Hemisphere, characterised by a prominent and an unprecedented sea level fall of 120–140 m, similar in magnitude to that of the last glacial maximum (e.g., Muttoni et al., 2007; Head and Gibbard, 2015; Monesi et al., 2016).

The Mediterranean area was affected by these Pleistocene climate 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., 2016a; Capraro et al., 2017; von Leesen et al., 2017). In the marine environment the most significant biotic events are represented by the disappearance of taxa of subtropical affinity and the occurrence of "northern guests". The latter are represented by taxa presently thriving at higher latitudes in the Northern Hemisphere, such as the bivalve *Arctica islandica*, which migrated into the Mediterranean Sea during glacial periods since the Calabrian (Early Pleistocene; Suess, 1883–1888; Raffi, 1986; Martínez-García et al., 2015). Major changes occurred also in the vegetation and in the vertebrate faunas of the Italian Peninsula (e.g., Azzaroli, 1995; Bertini, 2001; Fusco, 2010; Combourieu-Nebout et al., 2015). The Early Pleistocene is in fact characterised by floral alternations reflecting glacial and interglacial cycles (Bertini, 2003): arid and cool climatic conditions with open vegetation with herbaceous taxa indicative of steppe-like conditions and coniferous forests alternate with humid and warm-temperate climatic conditions with forest expansion of mesophilous deciduous taxa.
All these modifications in climate and vegetation affected large mammal assemblages with important turnovers in the Villafranchian mammal faunal communities (Palombo, 2007; Bona and Sala, 2016).

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STOP 1 – Base of the section (44°51'18.52"N, 9°52'26.7"E)

A brief introduction to the geological setting of the northern Apennines and to the studied depositional system is given here. This stop focuses on the lower part of the measured stratigraphic succession (Fig. 5), cropping out along the Arda River and extending downstream of the bridge located at the entrance of the town of Castell'Arquato (northern Italy) towards north-northeast for nearly 2 km; the marine part, which is the subject of the present excursion, is 237 m thick and it is bounded at the top (44°52'9.95''N, 9°53'1.35''E) by continental conglomerates with vertebrate faunas (e.g., *Bison* sp., *Hippopotamus* sp., *Praemegaceros* sp., *Pseudodama farnetesis, Stephanorhinus hundsheimensis, Sus strozzii, Ursus dolinensis*; Bona and Sala, 2016) and freshwater/terrestrial molluscs (e.g., *Pomatias elegans, Carychium tridentatum, Retinella olivetorum, Valvata cristata, Acroloxus lacustris, Gyraulus albus, Acicula lineolata;* Bagattini, 2014). A fault is present in the lowermost portion of the section, causing the repetition of the first 36 m of the succession (base at 44°51'18.52"N, 9°52'26.7"E).

Magnetostratigraphic (Monesi et al., 2016) and integrated biostratigraphic (calcareous nannofossil and foraminifera; Crippa et al., 2016a) data assign a Calabrian (Early Pleistocene) age, ranging from ~1.8 to 1.2 Ma, to the marine Arda River section. The biostratigraphic analysis identifies three nannofossil (CNPL7, CNPL8, and CNPL9) and one foraminiferal (*Globigerina cariacoensis*) biozones (Crippa et al., 2016a).

The succession represents a subaqueous extension of a fluvial system (Crippa et al., 2018, 2019), which formed in a tectonically active setting during phases of advance of fan deltas affected by high-density (hyperpycnal) flows linked to river floods. The hydrodynamic energy and the sedimentation rate are not constant along the section, as they are influenced by hyperpycnal flows discharging terrigenous sediments in the basin mainly supplied by an increase in Apennine uplift and erosion, especially after 1.80 Ma (Crippa et al., 2018). Lithofacies associations, trace fossils and molluscs key-taxa document a fully marine and well oxygenated environment overlain by alluvial conglomerates, suggesting a relative sea level fall and the establishment of a continental setting (Crippa et al., 2018). An overall regressive trend is recorded through the section, passing from a prodelta (Cycles 0–II) to a delta front (Cycles III–IV) to an intertidal zone setting (Cycle VII) (Fig. 5). Lower order transgressive and regressive cycles record shifts from lower foreshore-shoreface to offshore transition environments, with inferred water depths ranging between 5 and 50 m (Crippa et al., 2018).

Thus the overall regressive trend recorded through the Arda section during the Calabrian is the result of climate deterioration (i.e., cooling; see afterwards Stops 2-3) coupled with regional tectonic activity.

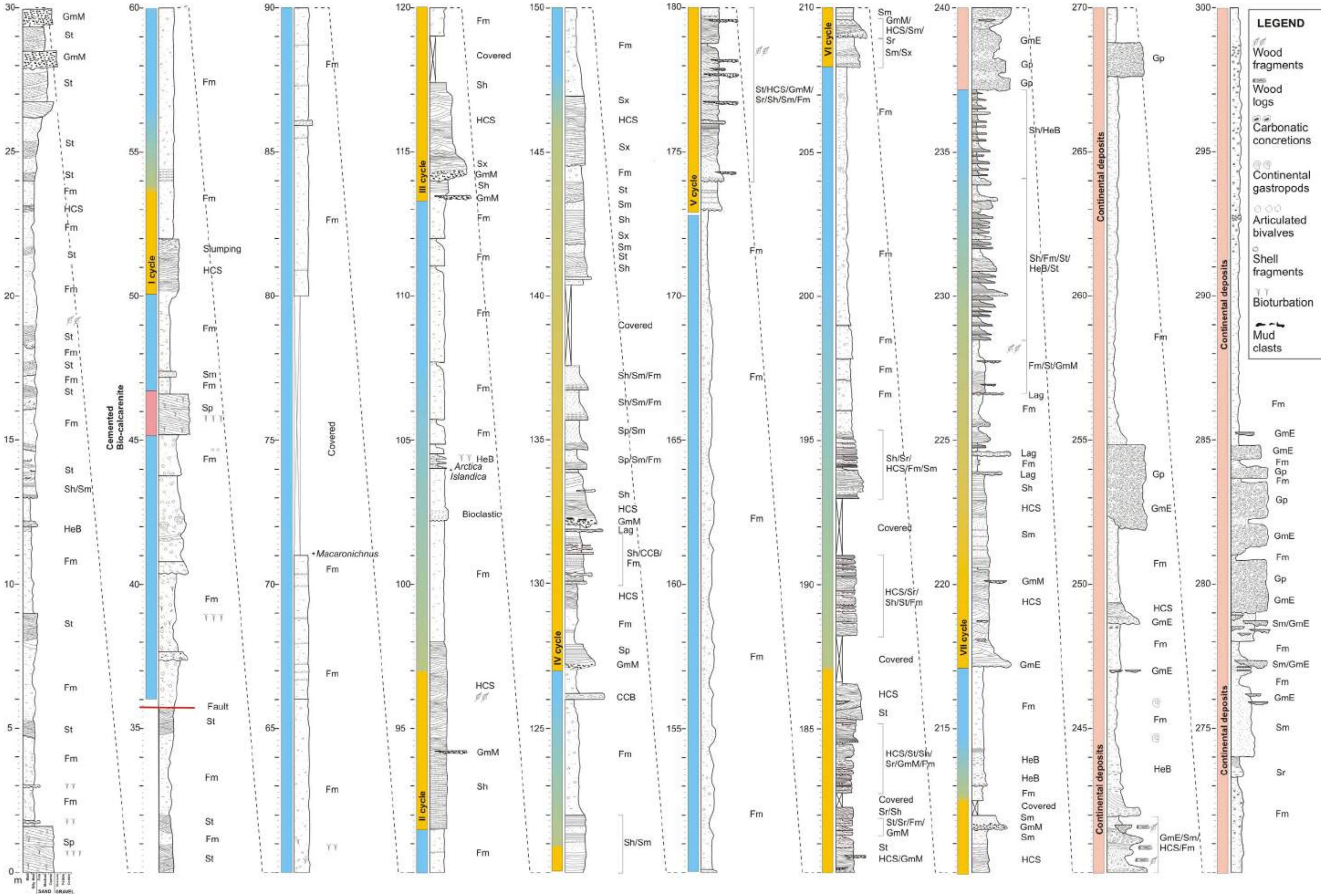

Fig. 5 - Stratigraphic log of the Arda River succession. Crippa et al. (2018), reproduced with permission.

The Arda River marine succession is thus an ideal setting where to study how seawater temperature seasonality varied during the Early Pleistocene using as a tool the fossil shells isotope composition. As observed in several studies (e.g., O'Neil et al., 1969; Schöne and Surge, 2012; Brocas et al., 2013; Schöne, 2013; Crippa et al., 2016a), bivalve and brachiopod shells are excellent archives for studies of past seawater conditions as they record the seasonal variations of the seawater in which they live with no or limited vital effect (e.g., Epstein et al., 1953; Grossman and Ku, 1986; Lécuyer et al., 2004; Brand et al., 2011; Royer et al., 2013; Brand et al., 2019). Bivalves and brachiopods form their calcium carbonate shells episodically, providing a sequential record of growth increments that can be analysed as an archive of geochemical proxies ($\delta^{18}O$, $\delta^{13}C$) and thus be used to reconstruct seasonal seawater temperature variations through sclerochemistry (Gröcke and Gillikin, 2008). However, it is important to check for any sign of possible diagenetic overprint that may alter the shell isotope composition. One of the most used and easily available screening method is the analysis of the shell microstructure at the Scanning Electron Microscope (e.g., Angiolini et al., 2009; Crippa, 2013; Crippa et al., 2016a, b; Ye et al., 2018; Crippa et al., 2020).
Based on this premise, a sclerochemical analysis was performed on a pristine specimen of *Glycymeris inflata* (Fig. 6), collected in the basal part of the section (42 m from the base) and predating the first occurrence of *Arctica islandica* (103.70 m) in the succession; the *G. inflata* shell records a low seasonality scenario in this part of the section (maximum seasonality excursion recorded by the shells: $\delta^{18}O$ = 1.1‰ corresponding to $T_{excursion}$ = 4.7 °C), documenting the background palaeoclimatic conditions before the successful establishment of the "northern guests" and the Apennine uplift (Crippa et al., 2016a).

Main features to observe:

- Fossiliferous beds in fine grained massive sands and silts containing bivalves (e.g., *Glycymeris inflata, Glycymeris glycymeris*, *Aequipecten opercularis, Astarte fusca, Clausinella fasciata*), gastropods (e.g., *Diodora graeca, Capulus ungaricus*), brachiopods (*Terebratula terebratula*), corals (mainly *Flabellum* sp. and *Cladocora* sp.), and bryozoans (Fig. 7). Specimens are often articulated and well preserved, but disarticulated shells occur as well, suggesting within-habitat transport. An offshore transition-inner shelf setting (around 40 m of depth) characterised by normal marine conditions and winnowed by currents is suggested, as testified also by the presence of rheophile molluscs (e.g., *Glycymeris glycymeris, Astarte fusca, Clausinella fasciata*). This is the only part of the succession where brachiopods occur. Brachiopods are not rare in the Emilian successions, although the palaeoenvironmental conditions of the basin during the Pliocene-

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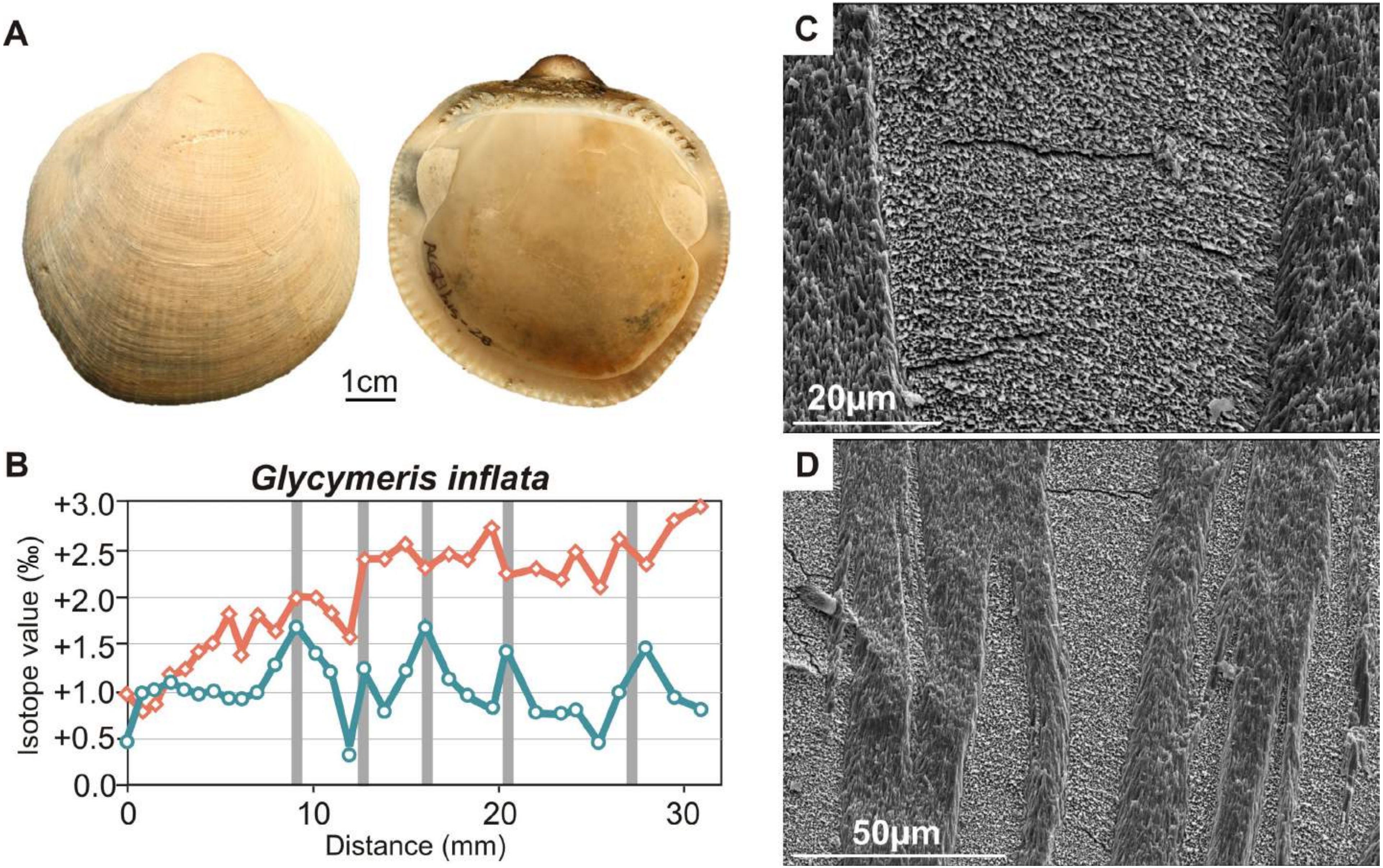


Fig. 6 - A) External and internal valve view of a right valve of a specimen of *Glycymeris inflata*. B) $\delta^{18}O$ (blue) and $\delta^{13}C$ (pink) data of a *Glycymeris inflata* shell from the base of the section. The position of the growth lines is represented by vertical grey bands (modified from Crippa et al., 2016a). C, D) SEM images of a pristine specimen of *Glycymeris inflata*, showing the outer shell layer made by crossed lamellae.

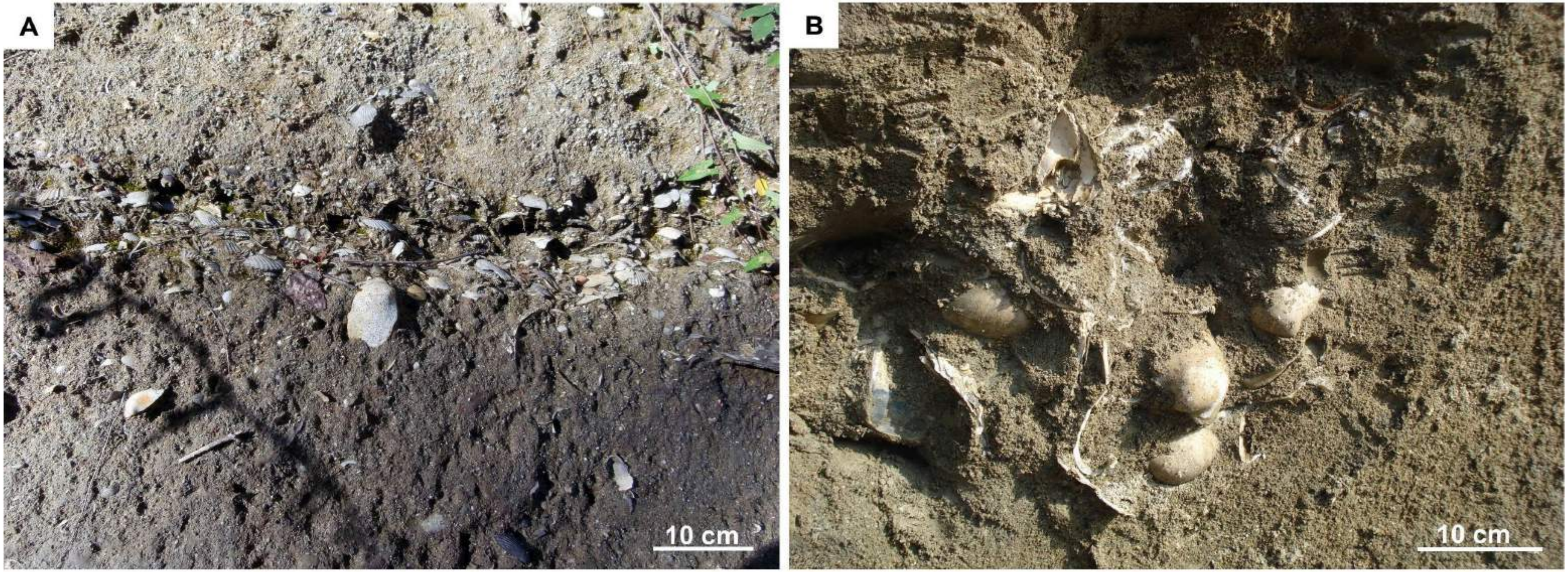
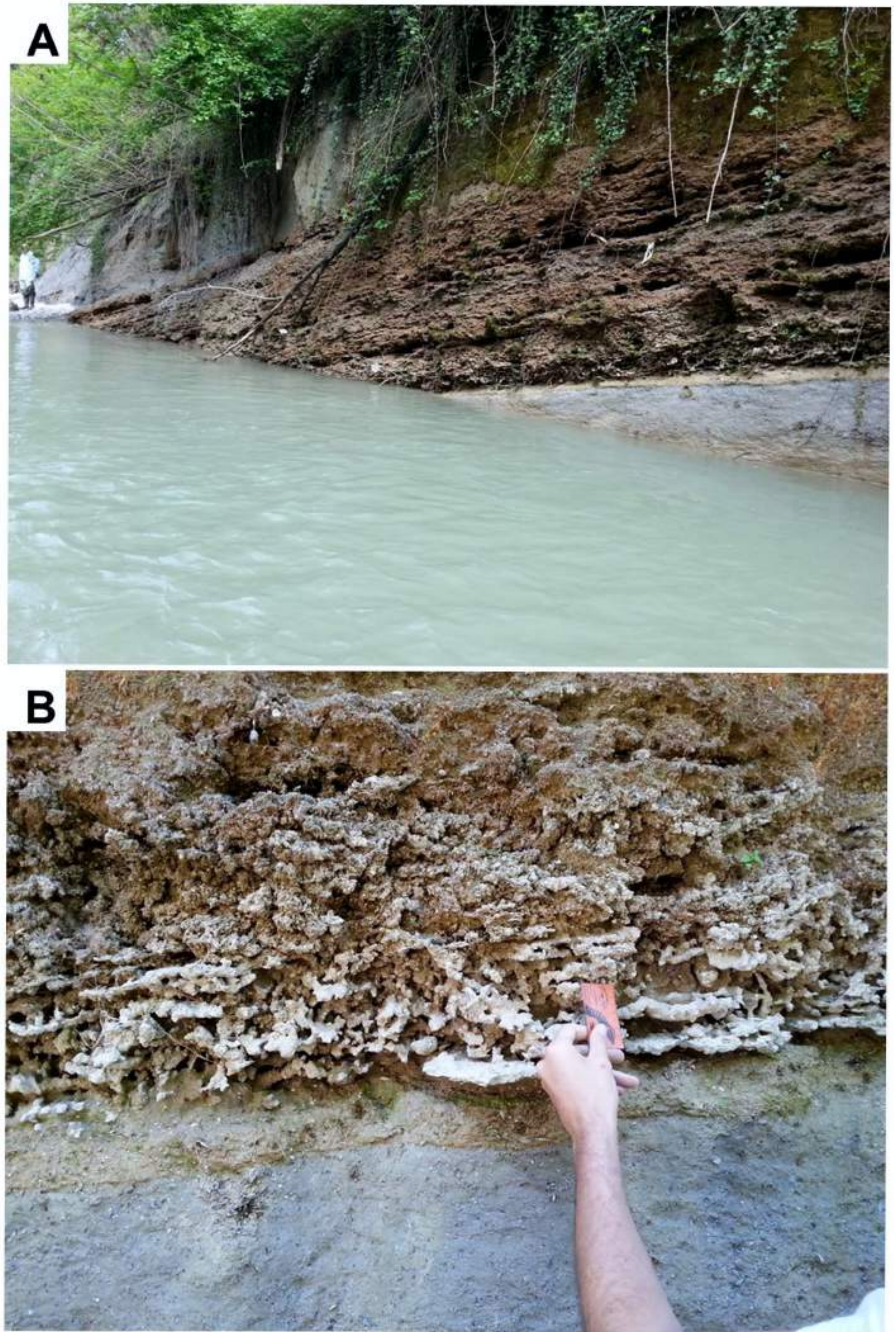


Fig. 7 - A, B) Fossiliferous beds occurring at the base of the section below the biocalcarenitic unit.

Pleistocene were not favorable to their proliferation. Neogene and Quaternary bathyal brachiopod species, which inhabited Southern Italian settings, are lacking in Western Emilian coeval marine successions. This is probably due to the less favorable environmental conditions of northern Italy (i.e., higher water turbidity, more fine-grained substrates respect to rocky settings; Gaetani and Saccà, 1984), but also to a different geological configuration of the study area lacking deep water settings during this time interval.

- A biocalcarenite body at the base of the succession (Fig. 8), forming basinward-prograding wedges composed of alternating well- or poorly cemented layers displaying intense bioturbation and dense accumulations of reworked shells (see Stop 4 for a detailed description and interpretation). Here, aragonitic shell remains show a high degree of degradation and diagenetic dissolution. The biocalcarenitic unit is embedded within fine grained massive silty to muddy beds with sparse malacological content typical of muddy-detritic and muddy substrates along the shelf. The most common species are *Venus nux, Turritella tricarinata*



pliorecens, Naticarius stercusmuscarum and *Pelecyora brocchii*, hence suggesting an offshore transition-inner shelf environment characterised by low hydrodynamic energy and episodic sedimentation.

- Facies related to flow lofting characterised by thin couplets of massive to laminated siltstones and mudstones with variable thickness from a few mm up to 100 cm, and marine bivalves in life position. This facies accumulated fine materials by normal settling when the hyperpycnal flow completely stopped.

STOP 2 – *Arctica islandica* first occurrence (44°51’29.2”N, 9°52’35.9’’)

The horizon recording the first occurrence of the “northern guest” bivalve *Arctica islandica* is situated at 103.70 m from the section base (Fig. 5). The first occurrence of the “northern guests” in the Mediterranean Sea has a historical importance, as this biotic event was considered one of the main criteria to define the Pliocene-Pleistocene boundary (Pelosio and Raffi, 1974; Aguirre and Pasini, 1985; Raffi, 1986), when placed at the former Global Stratotype Section and Point (GSSP) at Vrica (Calabria, Italy). Nowadays the Pliocene-Pleistocene boundary is set at 2.58 Ma at the base of the Gelasian Stage (e.g., Gibbard et al., 2010; Cohen et al., 2020).

Fig. 8 - A) Biocalcarenitic unit (46 m from the base of the section), displaying intense bioturbation. B) Detail of the biocalcarenitic unit.

According to Crippa et al. (2019) the oldest occurrence of *A. islandica* in the Mediterranean Sea is in the Arda and Stirone River successions (northern Italy), which based on biostratigraphic inferences is dated between 1.71 and 1.78 Ma. The authors, mapping the occurrence of *A. islandica* in Lower Pleistocene Mediterranean successions (Fig. 9), concluded that the lower Calabrian palaeoenvironmental conditions of the northern palaeo-Adriatic satisfied the ecological requirements for the establishment and the proliferation of the species such as a shallow water and sandy setting characterised by normal water salinity and high seawater seasonality; only subsequently (late Calabrian) this taxon successfully established also in southern Italy and in other areas of the Mediterranean Sea (Fig. 9).

Sclerochemical isotope analysis (Fig. 10) was performed on two specimens of *A. islandica* collected from the first occurrence bed of this taxa in the Arda succession (Crippa et al., 2016a). The results of the analysis suggest that the palaeo-Adriatic Sea was characterised by high seasonality (maximum seasonality excursion recorded by the shells: $\delta^{18}O$=3.3-3.7‰ corresponding to $T_{excursion}$=14.4–16.0 °C) and low winter palaeotemperatures (0.8–1.6 °C) at this time. The measured values are not comparable with those of the present day shallow northern Adriatic Sea, where the seasonal variation at 20–25 m depth is 7 °C and the minimum winter temperature is 9 °C (Fig. 3 in Zavatarelli et al., 1998). Indeed, the seasonal variation is higher and winter palaeotemperatures are lower than today for the *A. islandica* specimens collected at 103.70 m where water depth was inferred to be 20–25 m (Crippa et al., 2016a). The high seasonality recorded by these shells is mostly due to strong winter cooling, while summer temperatures remained relatively stable (Crippa et al., 2016a).

The cold and high seasonality event which triggered the recruitment, reproduction and the successful establishment of *A. islandica* in the Mediterranean Sea around 1.7-1.8 Ma represents a turning point in the palaeoclimatic regime of the region; this is also confirmed by Herbert et al. (2015) based on alkenone unsaturation. The authors observed a pronounced cooling at 2.09–2.05 Ma in the Mediterranean Sea, followed by an onset of multiple cold events starting from ~1.84 Ma. The climatic cooling along the Arda succession is also supported by the presence of *Macaronichnus* trace fossil at 94 m, considered a cold indicator (Crippa et al., 2018).

<u>Main features to observe:</u>

- Bed with the first occurrence of the “northern guest” bivalve *A. islandica* with disarticulated valves in silty to muddy lithologies, indicating an offshore transition environment characterised by low-energy and low sedimentation rate (Fig. 11).

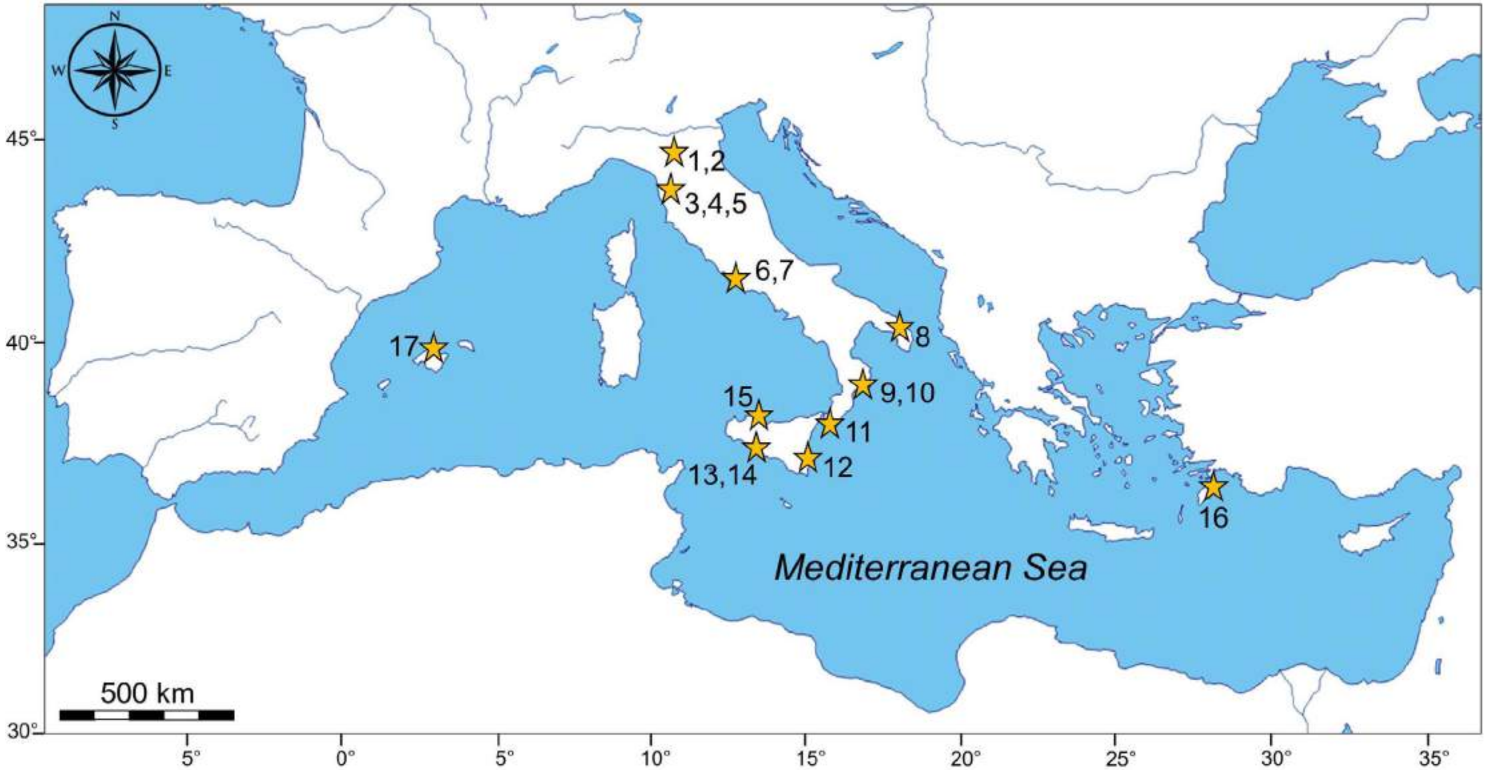


Fig. 9 - Map showing the Lower Pleistocene outcrops with *Arctica islandica* in the Mediterranean Sea. Subdivision of the Calabrian (Early Pleistocene) into three substages (Santernian [lower Calabrian], Emilian [middle Calabrian], and Sicilian [upper Calabrian]) according to Ruggieri and Sprovieri (1975, 1977). 1, Santerno Valley, Bologna, Santernian (Kukla et al., 1979); 2, Arda and Stirone Rivers, Piacenza and Parma, Santernian (Gunderson et al., 2012; Crippa and Raineri, 2015; Crippa et al., 2016a, 2018, 2019; Monesi et al., 2016); 3, Collesalvetti, Pisa, Santernian (Bedini et al., 1981); 4, Val Cecina, Livorno, Santernian (Gianelli et al., 1981; Sarti et al., 2007); 5, Pisa hills, Valdarno, Pisa, Santernian (Nencini, 1983; Sarti et al., 2008); 6, Monte Mario, Rome, middle-late Santernian (Faranda et al., 2007; Cosentino et al., 2009); 7, Tacconi quarry, Rome, Emilian (Malatesta and Zarlenga, 1994; Von Leesen et al., 2017); 8, Cutrofiano quarry, Lecce, Sicilian (Margiotta and Varola, 2007; Von Leesen et al., 2017); 9, Santa Maria di Catanzaro, Catanzaro, Emilian (Azzaroli et al., 1997 and reference therein); 10, Valle di Manche, Crotone, Sicilian (Capraro et al., 2015); 11, Monasterace, Reggio Calabria, late Emilian-Sicilian (Azzaroli et al., 1997); 12, Ogliastro quarry, Siracusa, Sicilian (Di Geronimo et al., 2000; Von Leesen et al., 2017); 13, Capo Rossello, Agrigento, Emilian (Azzaroli et al., 1997 and references therein; Caruso, 2004); 14, Belice Valley, Agrigento, Sicilian (Di Geronimo et al., 1994; Garilli, 2001); 15, Puleo Quarry, Palermo, Sicilian (Ruggieri et al., 1975, 1984; Buccheri, 1984); 16, Rhodes, Greece, Calabrian (Zaccaria, 1968); 17, Mallorca, Spain, Sicilian (Pomar Gomá and Cuerda Barceló, 1979). Crippa et al. (2019), reproduced with permission.

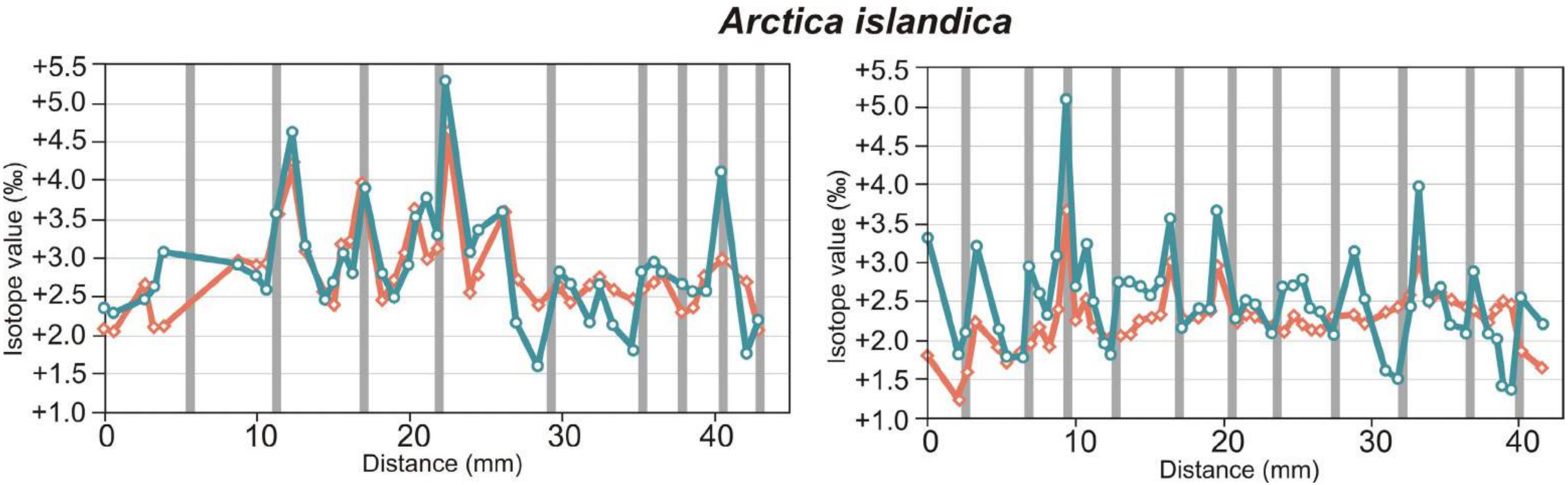


Fig. 10 - δ^{18}O (blue) and δ^{13}C (pink) data of two *Arctica islandica* shells from the first occurrence bed (103.70 m). The position of the growth lines is represented by vertical grey bands. Modified from Crippa et al. (2016a).

- Channel cutting (south-southwest to north-northeast) the main succession (92.50–98.30m) obliquely and discharging fresh water and sediments. This is supported by reworked fossil specimens, the abrupt changes in ichnofabric, the presence of mud clasts and of transported vegetal debris.

STOP 3 – Palaeoclimatic and palaeoenvironmental change (44°51’33.0”N, 9°52’39.3”E)

A change in the palaeoclimate, palaeoenvironment and in the tectonic activity is observed in the Arda section starting from about 110 m upward (Cycles III–VII). In particular, as indicative of the ongoing tectonic activity, Crippa et al. (2016a, 2018) described an increase in terrigenous input and in nannofossil total abundance and composition. Specifically, the authors reported an increase in mean abundance of reworked Lower Cretaceous species from 135 m, likely deriving from the erosion of older sediments uplifted with the Apennine chain. Transported fossil assemblages, containing an ecologically mixed fauna with specimens showing poor preservation, become more frequent from 110 m upward, suggesting a high-energy environment where high density flows triggered by river floods

Fig. 11 - Bed with the first occurrence of *Arctica islandica*.

transport and mix skeletal remains from different environments. Also, low bioturbation ichnofabric indicates low salinity conditions in some beds, pointing to an increase in river discharge and thus an increase in water turbidity in 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 cooling of the Early Pleistocene may account for the observed increase of hyperpycnal flows in these cycles.

The results of sclerochemical stable isotope analyses (Fig. 12), performed on shells of species of *Glycymeris nummaria* and *Arctica islandica*, highlight also palaeoclimatic changes (Crippa et al., 2016a). The shells postdating the arrival of the "northern guests" record a return to lower seasonal variations and higher seawater palaeotemperatures, similar to the background conditions recorded by *G. inflata* at the base of the section (Figs. 6 B; 12 D). Furthermore, an increasing trend in seasonality is recorded by both *A. islandica* and *G. nummaria* shells approaching the Early-Middle Pleistocene Transition and the beginning of continental glaciations in the Northern Hemisphere, but without a corresponding

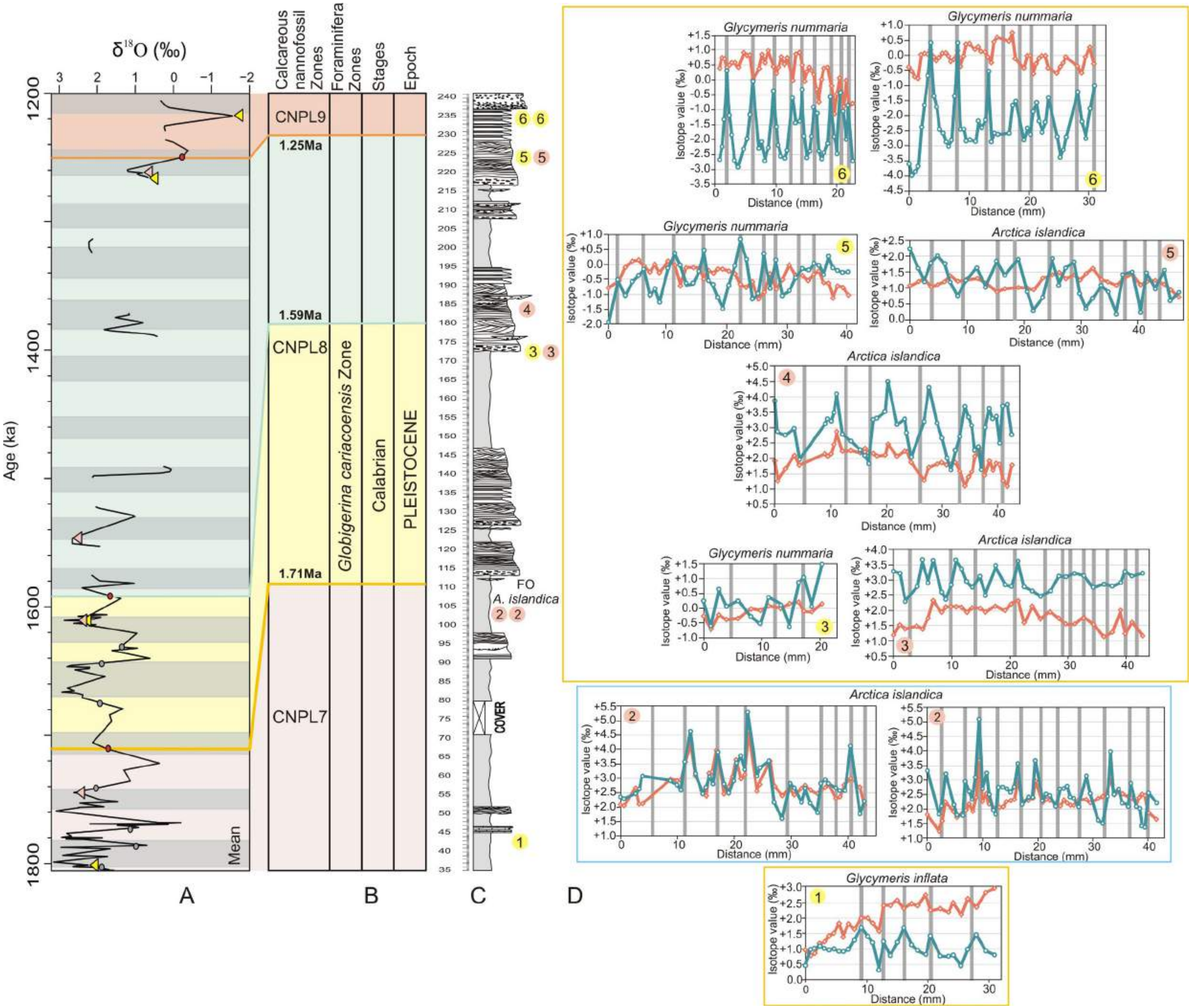


Fig. 12 - A) Mean $\delta^{18}O$ curve obtained from whole shells oxygen isotope analyses performed on species of *Glycymeris*, *Aequipecten* and *Arctica*. Triangles represent the position of the shells sclerochemically analysed: *Glycymeris* in yellow, *Arctica* in pink. B) Calcareous nannofossil (following Backman et al., 2012) and foraminifera biostratigraphy of the Arda section. C) Simplified stratigraphic log of the section. D) $\delta^{18}O$ (blue) and $\delta^{13}C$ (pink) sclerochemical data of *Glycymeris inflata*, *Arctica islandica* and *Glycymeris nummaria* shells from the base to the top of the section. The position of the growth lines is represented by vertical grey bands. Modified from Crippa et al. (2016a).

cooling of the mean seawater palaeotemperatures (Fig. 12 A). The influence of the Northern Hemisphere Glaciation on the Mediterranean climate, in particular on mean seawater palaeotemperatures, may have been locally mitigated by the Apennine uplift. Based on these data, Crippa et al. (2016a) concluded that the variation in seasonality represents a clear signal of progressive climate change in the Mediterranean Sea. An intensification of seasonality with constant mean palaeotemperatures has been recorded also in other time intervals (e.g., Ivany et al., 2000; Eldrett et al., 2009), promoting seasonality as an important variable during climate change. Also, the increase in seasonality is often associated with cold, rather than with warm climate conditions, as observed also in several studies spanning from the Cretaceous to the Holocene (e.g., Ivany et al., 2000; Pross and Klotz, 2002; Steuber et al., 2005; Ferguson et al., 2011; Hennissen et al., 2015); indeed, a large seasonal variability is needed for the existence and maintenance of polar ice sheets (Steuber et al., 2005). The observed increasing seasonality recorded by Arda River shells may have prepared the ground for the onset and establishment of eccentricity-controlled waxing and waning of the Middle and Late Pleistocene continental glaciations (Crippa et al., 2016a).

Main features to observe:

- Fossiliferous beds; the Arda river succession contains a diversified fauna composed by 159 taxa (Crippa and Raineri, 2015), where bivalves are dominant, followed by gastropods, brachiopods, corals, serpulids, echinoderms, scaphopods and barnacles (Fig. 13). Mainly life or neighborhood assemblages are present, although transported assemblages become more frequent from 110 m towards the top of the section. Trace fossils are also very abundant and well preserved (Fig. 14).
- Facies related to bed-load processes (Fig. 15) characterised by massive and cross-stratified (or crudely stratified) conglomerates supported by abundant coarse- to fine-grained sandstone matrix and mud clast-supported conglomerates. Lag deposits are represented by gravel carpets with bioclastic and coarse sandy matrix. This facies category includes coarse-grained sediments linked to shear/drag forces exerted by the overpassing hyperpycnal flow over coarse-grained materials present on the flow bottom.
- Facies related to the collapse of suspended load composed of fine-grained sandstone strata with massive stratification, horizontal or hummocky cross stratification, tabular and oblique cross stratification and small-scale cross lamination, often intercalated with flasers and massive mudstone beds (Fig. 16). Although sedimentary structures are rarely disrupted by bioturbation, bedtops may be 100% bioturbated. This facies is characterised by fine grained sediments transported as suspended load, which form thick and complex intervals that can be massive or display traction plus fallout sedimentary structures.

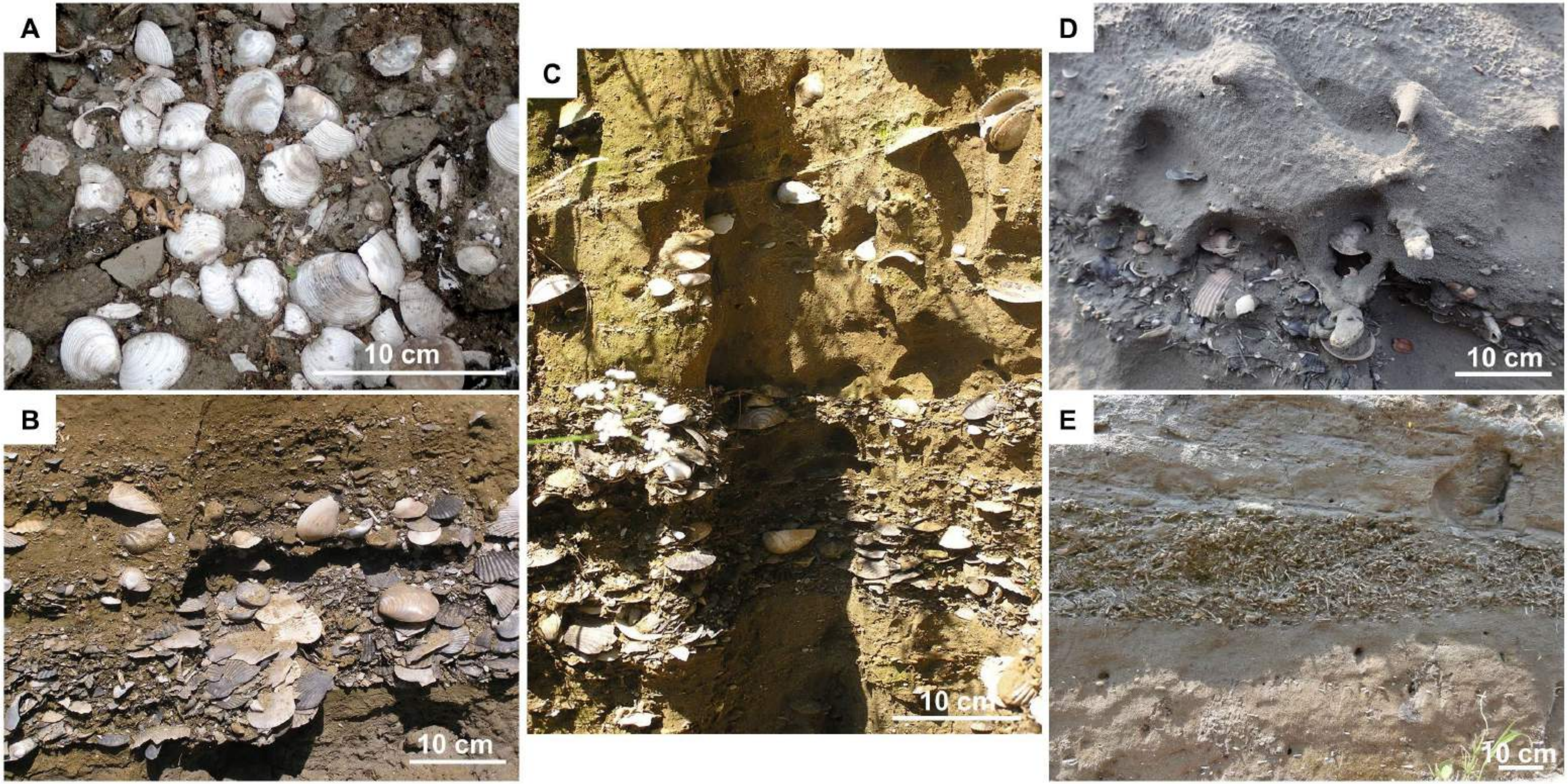
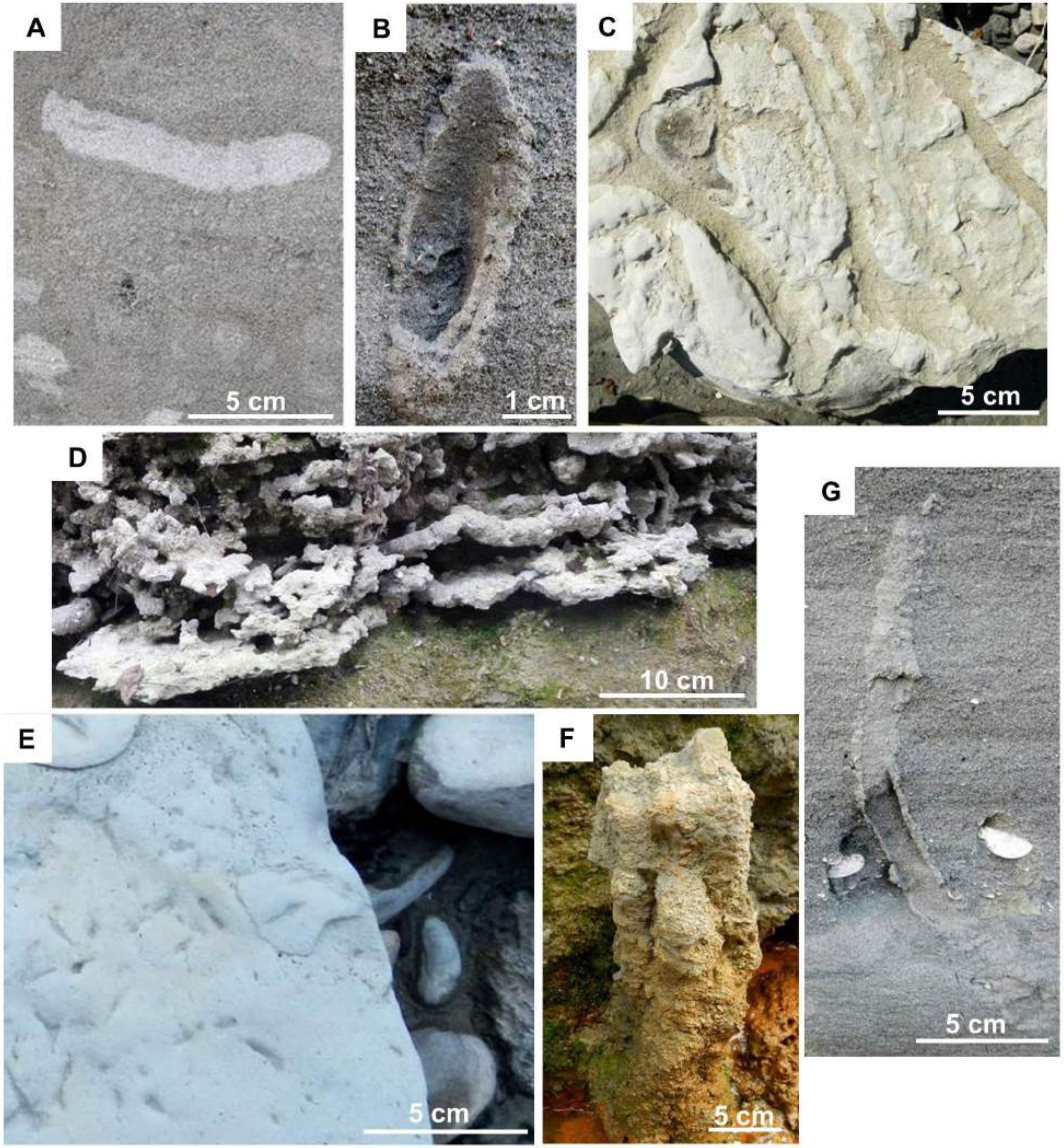


Fig. 13 - A-E) Fossiliferous beds of the Arda marine succession, showing different shell accumulations, some of them nearly monospecific as the bed with *Chamelea gallina* (A) or *Ditrupa arietina* (E).

- Carbonate cemented beds. Very fine-grained limestones forming lenticular or pinching and swelling and sometimes laminated beds up to 0.25 m thick, that have sharp bases and tops. These beds are predominately composed of a fine-grained matrix including calcareous microspheroids and organic matter, but their origin is currently not known.



- *Venus nux* beds. In these thick beds of fine-grained massive silts and clays *Venus nux* is the most abundant species, together with *Acanthocardia paucicostata, Aporrhais pespelecani, Glossus humanus, Saccella commutata* and *Turritella tricarinata pliorecens.* These beds also show a high bioturbation intensity, indicating low-energy settings with low or episodic sedimentation, reflecting the normal settling when the hyperpycnal flow completely stops or sedimentation in a distal portion of the delta system.

Fig. 14 - Well preserved trace fossils occurring in the Arda River succession. A) *Macaronichnus* ichnofabric. B) *Ophiomorpha* with a robust constructional lining, indicating high-energy conditions. C) *Ophiomorpha* preserved in cemented layers. D) *Thalassinoides* ichnofabric dominated by horizontal burrows filled by bioclastic sands. E) *Lockeia* ichnofabric. F) "Columnar burrow set". G) *Ophiomorpha* ichnofabric. Crippa et al. (2018), reproduced with permission.

STOP 4 – Biocalcarenites: Viale Rimembranze outcrop (44°51'03.5"N, 9°52'10.8"E)

The stop focuses on a biocalcarenitic body up to 10 m thick (MTP1 in Cau et al., 2019) that occurs at the base of the succession, near the town of Castell'Arquato. It reveals a complex internal architecture resulting from a polyphasic development of a basinward-prograding wedge (northward prograding clinoforms) composed of alternating well- or poorly-cemented layers with dense accumulations of reworked shells (Fig. 17). It typically displays a tripartite geometry (Fig. 17A) consisting of different (1) topset, (2) bottomset and (3) foreset facies associations. (1) Topset horizontal strata are intensely bioturbated, and may contain abundant disarticulated skeletal remains and fragmented calcareous algae without a preferential organisation. As reported by Cau et al. (2019), these deposits enclose rich macrofaunal associations, with abundant herbivorous (*Tricolia pullus, Diodora italica* and *Emarginula* spp.) and epifaunal detritivorous gastropods (in particular *Alvania* spp.). (2) Bottomsets are characterised by dense accumulations of reworked

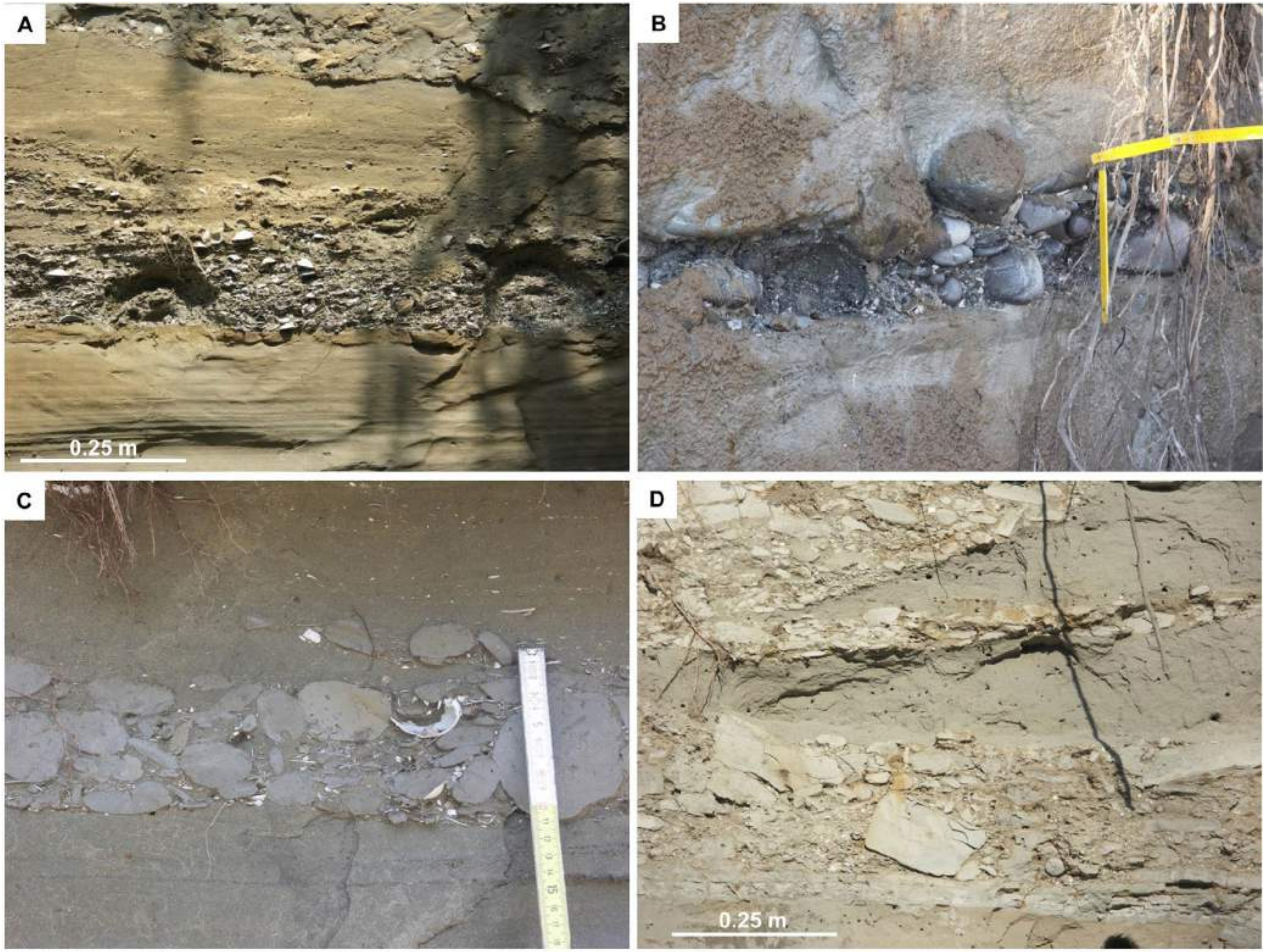


Fig. 15 - A-D) Facies related to bed-load processes including different coarse-grained deposits. From Crippa et al. (2018), reproduced with permission.

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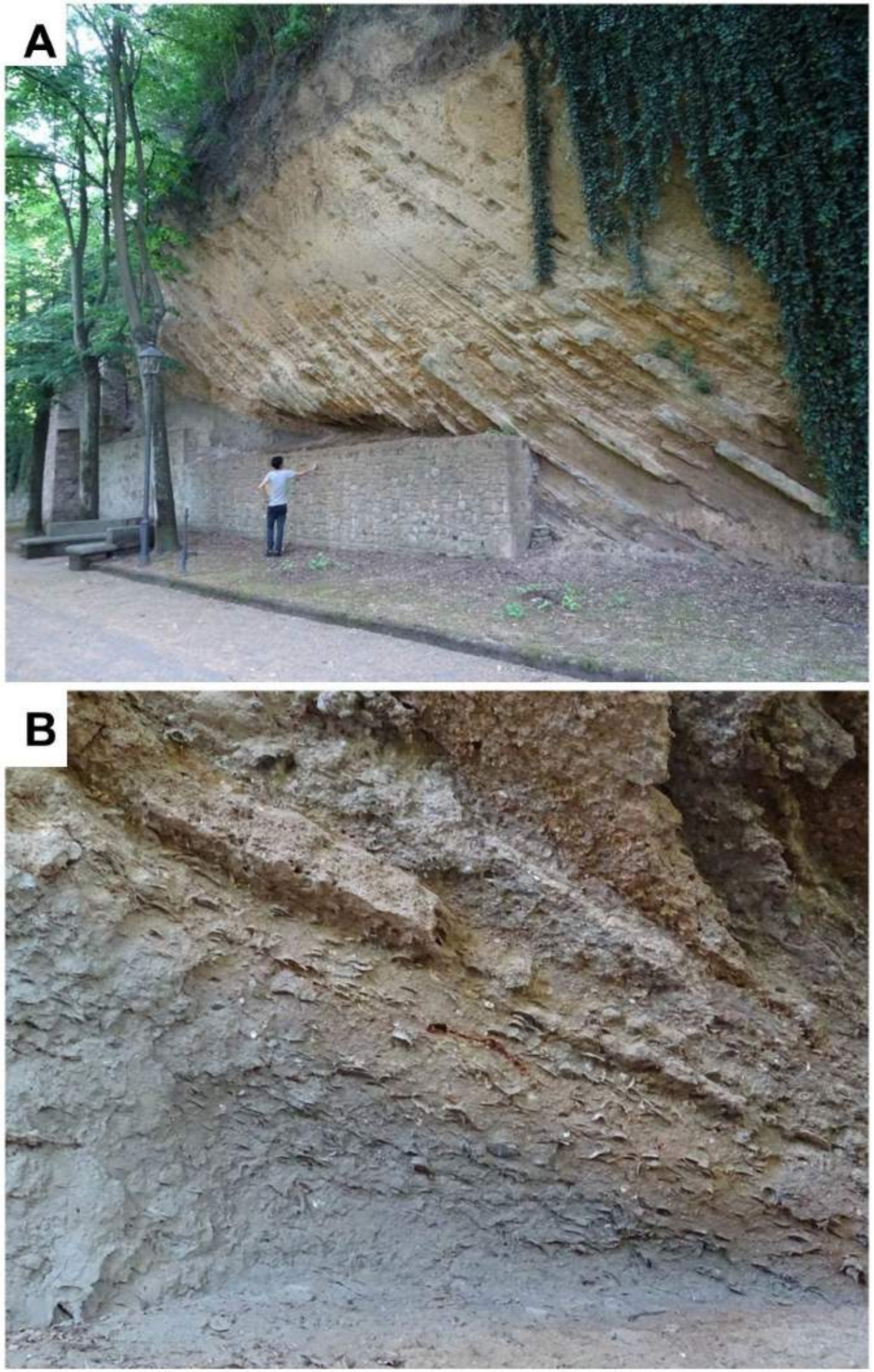
Fig. 16 - A-C) Facies related to collapse of suspended load including fine grained sediments. From Crippa et al. (2018), reproduced with permission.

shells (Crippa et al., 2018) mainly consisting of pectinid-dominated shell pavements (Fig. 17B) mostly showing concave-down orientation in a coarse- to medium-grained sandy matrix with planar lamination (Cau et al., 2019). (3) The foreset facies is characterised by weakly to well cemented clinoform beds showing oligotypical and poorly preserved horizons composed of mainly imbricate valves of *Anomia ephippium*, pectinids and ostreids associated with *Ophiomorpha* and *Thalassinoides* ichnotaxa (Cau et al., 2019). Bioturbation is pervasive in topset and bottomset beds, whereas foreset beds appear bipartite, with a lower division displaying physical structures (planar lamination, hummocky and swaley cross stratification, and trough cross-bedding in sets 15 to 40 cm thick with dip matching, or slightly diverging from, the dip of the clinoforms), grading upwards into a thoroughly bioturbated division. In the down-ramp part of this segment, packages of sigmoidal clinoforms locally alternate with packages of oblique clinoforms.

The internal geometry suggests that biocalcarenitic deposits (and their biological component) 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. Cau et al. (2019) suggest the presence of strong bottom reworking by wind-driven shelf currents (presumably generated by storm events; see Massari and Chiocci, 2006) and affecting the shelf sea-bottom between 30 and 50 m water depth



during periods of reduced fluvial runoff and silting. These currents are responsible for winnowing of muddy deposits accumulated during previous periods of decrease in the intensity of bottom currents. Clinostratified (foreset) deposits record peak energy conditions (e.g., high-frequency storm events and/or winnowing by steady unidirectional currents) and indicate the full development of sandwave/dune fields in shelfal settings (Cau et al., 2019).
Massari and Chiocci (2006) describe the formation of very similar Pliocene-Quaternary basinward-prograding biocalcarenite wedges (detached from the shore and below the stormwave 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.

STOP 5 – Giuseppe Cortesi Geological Museum (44°51’05.2”N, 9°52’04.3”E)

The civic Giuseppe Cortesi Geological Museum of Castell’Arquato was formally established in 1961, but the first register of visitors bears the date of May 1927 (Fig. 18). The civic fossil collections formed in the early decades of the twentieth century and were initially placed in the thirteenth-century Palazzo Pretorio, in a room housing the municipal archives. The collections were reorganised in 1961 in the

Fig. 17 - A) Biocalcarenitic body cropping out in Viale Rimembranze. It forms prograding wedges typically displaying intense bioturbation. Note (B) the dense accumulations of reworked shells.

Fig. 18 - External and internal view of the Giuseppe Cortesi Geological Museum of Castell'Arquato.

Torrione Farnesiano, but with the acquisition of new cetaceans bones and macroinvertebrates discovered nearby, there was the need to find a more suitable location for the fossil materials. The museum was moved in 1991 in the historical building of the Ospitale Santo Spirito, which became its permanent home.
Although the museum is a local institution, it is also well known outside Italy because it preserves the remains of the abundant fossil fauna of the Piacenzian (Pliocene) stage. Since the late eighteenth century, the fossil record of the "Pliocene Sea" was brought to light in the clay and sandy sediments of the Apennines of Piacenza, and in particular along the steep walls of the calanchi and in incisions made by small streams such as the Nure, Chiavenna, Arda and Ongina Rivers. But already three centuries before, Leonardo da Vinci, who first recognised the organic origin of fossils, saw the shells collected in the Piacenza area while he was in Milan and his reference to these fossils, which he called *nicchi*, is shown in the celebrated Leicester Codex. Following Leonardo, many important

Fig. 19 - "The Gulf of the whales" room of the museum.

scientists were interested in the Pliocene sediments of the area, among which we can remember Giuseppe Cortesi, to whom the museum is dedicated, Giovanni Battista Brocchi, Georges Cuvier, Karl Mayer and Lorenzo Pareto.

The museum houses a rich documentation of the geological history of the Po basin. Outstanding among the collections are those of the local fossil molluscs and in particular the Vittorio Pighi collection, consisting of more than two thousand specimens of considerable interest both scientifically and aesthetically, and the historic Odoardo Bagatti collection. The latter includes a large number of species of bivalves and gastropods as well as numerous other invertebrates, collected by Bagatti, a lawyer from Cremona, in the Piacenza province, between the end of 1800 and the beginning of 1900.

The importance and great variety of fossil specimens, especially concerning malacology, on various occasions aroused the interest of scholars, including Giovanni Battista Brocchi who in his "*Conchiologia fossile subappennina*" (1814) presented one of the best known collections of the European Tertiary, now preserved in the Natural History Museum of Milan, comprising several specimens from the Castell'Arquato area.

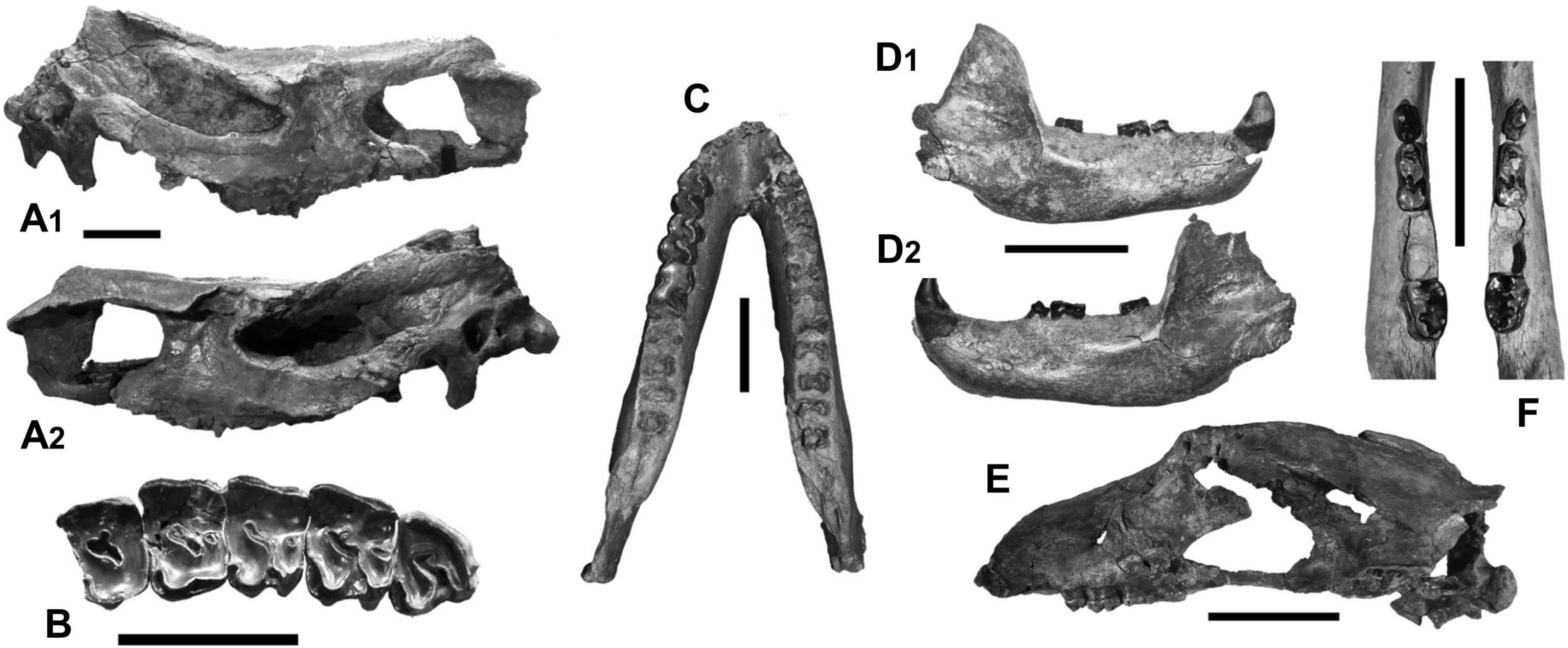


Fig. 20 - A-C) *Stephanorhinus hundsheimensis* from the Early Pleistocene of the Arda River; A) Skull, A1 right view; A2 left view; B) cheek teeth series; C) Mandible, occlusal view. D-F) *Ursus rodei* from the Early Pleistocene of the Arda River; D) Mandible in buccal view; E) Half skull, left view; F) Mandible in occlusal view. Scale bars: 10 cm. Modified from Bona and Sala (2016).

An important collection of brachiopods is also housed in the museum. The first studies on Neogene and Quaternary brachiopods in northern Italy date back to the 1800 and the beginning of the 1900. Sacco (1902) mainly analysed and described the fauna of the Ligurian Piedmont basin, whereas scarce information exists for the Emilian area, with the exceptions of the works of Brocchi (1814), Cocconi (1873) and Coppi (1881). The most recent and important research on Emilian brachiopods have been undertaken by Borghi (2001) and

Bertolaso et al. (2009), whose studied specimens are housed in the Giuseppe Cortesi Geological Museum in Castell'Arquato (Fig. 18). Also a taxonomic revision of species of *Terebratula*, housed in the museum, has been performed by Taddei Ruggiero et al. (2019).
Also, of great interest and importance are the fossil remains of Pliocene whales and dolphins, displayed in the central room of the museum and found in the surrounding area of Castell'Arquato from the end of the eighteenth century (Fig. 19). Certainly, the event that has attracted a lot of interest in the museum has been the recovery in 1983 of a nearly complete whale skull of *Balaenoptera acutorostrata* in the calanchi of Rio Carbonari near Tabiano di Lugagnano, in the Piacenza province. The last major discovery has been the skeleton of a dolphin, found in 2009 in Montezago.
Among continental faunas, skeletal parts of Quaternary vertebrates, such as rhinoceroses, bears, wild boars, deer, bovids and Proboscidea, discovered since 2009 along the Arda River, are displayed in the museum rooms (Fig. 20). The collection includes also the mammal fauna from Quaternary floods in the Piacenza countryside near the Po River, which is particularly rich in the remains of *Bison, Elephas, Bos, Cervus* and *Equus*.

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