Chapter 3

Palaeoecology of the Arda biota

Fossil specimens collected in the Arda marine succession are identified and illustrated in this chapter (Crippa & Raineri submitted). Their ecology and palaeoecology is here discussed, focusing the attention on *Glycymeris, Aequipecten* and *Arctica*, as they represent the genera whose species have been used for the isotopic analyses; an in depth palaeoecological investigation is in fact important for interpreting the data resulting from the geochemical study. A discussion on the palaeoecological significance of the overall Arda fauna is also reported (Crippa et al., in prep.).

3.1 Faunal composition

The fauna is composed by 159 taxa (Table 3.1; Pl. 1-11 at the end of this chapter) coming from 218 fossil beds, of which bivalves are dominant with 105 taxa, followed by gastropods (44 taxa) and a few corals (3 taxa) and serpulids (2 taxa); brachiopods, echinoids, barnacles, bryozoans and scaphopods do also occur in the fauna but they are left in open nomenclature due to their poor state of preservation.

Bivalve taxonomy is a complicated topic in constant evolution; as Bieler & Mikkelsen (2006) observed "much of the taxonomic instability in bivalve research is not a result of conflicting hypotheses of relationships, but one of an overabundance of available names" and this is the main problem I dealt with the bivalve identification of the Arda assemblages. According to Jimenez et al. (2009) the status of many genera is still uncertain and species are assigned to different genera depending on the authors; nonetheless, there is certain stability in the species concept that allows adequate classification at the species levels.

List of taxa occurring in the Arda marine succession

Bivalves
Nucula placentina (Lamarck, 1819)
Nucula sulcata Bronn, 1831
Nucula sp.
Nuculana pella (Linnaeus, 1758)
Saccella commutata (Philippi, 1844)
Arcoidea indet.
Arca noae Linnaeus, 1758
Arca tetragona Poli, 1795
Arca sp.
Barbatia mytiloides (Brocchi, 1814)
Anadara cf. *A.diluvii* (Lamarck, 1805)
Bathyarca sp.
Glycymeris glycymeris (Linnaeus, 1758)
Glycymeris inflata (Brocchi, 1814)
Glycymeris insubrica (Brocchi, 1814)
Glycymeris sp.
Mytilus edulis Linnaeus, 1758
Mytilus galloprovincialis Lamarck, 1819
Mytilus sp.
Pinna sp.
Amusium cristatum (Bronn, 1827)
Pseudamussium septemradiatum (O.F. Müller, 1776)
Aequipecten opercularis (Linnaeus, 1758)
Aequipecten scabrella (Lamarck, 1819)
Mimachlamys varia (Linnaeus, 1758)
Talochlamys cf. *T.multistriata* (Poli, 1795)
Flexopecten flexuosus (Poli, 1795)
Flexopecten glaber (Linnaeus, 1758)
Pecten flabelliformis (Brocchi, 1814)
Pecten jacobaeus (Linnaeus, 1758)
Anomia ephippium Linnaeus, 1758
Anomia sp.
Monia patelliformis (Linnaeus, 1761)
Loripes lacteus (Linnaeus, 1758)
Lucinoma borealis (Linnaeus, 1767)
Loripinus fragilis (Philippi, 1836)
Lucinella divaricata (Linnaeus, 1758)
Chama gryphoides Linnaeus, 1758
Chama placentina (Defrance, 1817)
Carditidae indet.
Venericardia sp.
Cardites antiquatus (Linnaeus, 1758)
Astarte fusca (Poli, 1791)
Astarte sp.
Cardium indicum Lamarck, 1819
Acanthocardia aculeata (Linnaeus, 1758)
Acanthocardia echinata (Linnaeus, 1758)
Acanthocardia paucicostata (G. B. Sowerby II, 1834)
Acanthocardia tubercolata (Linnaeus, 1758)
Acanthocardia sp.
Papillicardium papillosum (Poli, 1791)
Papillicardium sp.
Laevicardium crassum (Gmelin, 1791)
Laevicardium oblongum (Gmelin, 1791)
Laevicardium sp.
Mactra stultorum (Linnaeus, 1758)
Spisula subtruncata (da Costa, 1778)
Lutraria angustior Philippi, 1844
Lutraria oblonga (Gmelin, 1791)
Lutraria sp.
Ensis ensis (Linnaeus, 1758)
Tellina nitida Poli, 1791
Tellina corbis Sowerby, 1867
Tellina distorta Poli, 1791
Tellina incarnata Linnaeus, 1758
Tellina pulchella Lamarck, 1818
Tellina serrata Brocchi, 1814
Tellina tenuis da Costa, 1778
Tellina sp.
Donax cf. *D.trunculus* Linnaeus, 1758
Donax cf. *D.venustus* Poli, 1795
Donax sp.
Solecurtidae indet.
Solecurtus scopula (Turton, 1822)
Azorinus chamasolen (da Costa, 1778)
Arctica islandica (Linnaeus, 1767)
Glossus humanus (Linnaeus, 1758)
Venus multilamella (Lamarck, 1818)
Venus sp.
Pitar rudis (Poli, 1795)
Callista chione (Linnaeus, 1758)
Pelecyora brocchi (Deshayes, 1836)
Chamelea gallina (Linnaeus, 1758)
Clausinella fasciata (da Costa, 1778)
Clausinella sp.
Dosinia lupinus (Linnaeus, 1758)
Dosinia sp.
Polititapes cf. *P.rhomboides* (Pennant, 1777)
Polititapes rhomboides (Pennant, 1777)
Polititapes senescens (Cocconi, 1873)
Polititapes sp.
Timoclea ovata (Pennant, 1777)
Corbula gibba (Olivi, 1792)
Hiatella rugosa (Linnaeus, 1767)
Panopea glycymeris (Born, 1778)
Panopea sp.
Pholas dactylus Linnaeus, 1758
Teredo sp.
Pandora inaequivalvis (Linnaeus, 1758)
Thracia pubescens (Pulteney, 1799)
Thracia sp.
Clavagella sp.
Ostrea edulis Linnaeus, 1758
Ostrea sp.
Saccostrea cf. *S.cucullata* (Born, 1778)

Gastropods
Diodora graeca (Linnaeus, 1758)
Trochidae indet.
Calliostoma cf. *C.conulus* (Linnaeus, 1758)
Jujubinus striatus (Linnaeus, 1758)
Jujubinus sp.
Diloma patulum (Brocchi, 1814)
Turritella tricarinata (Brocchi, 1814)
Turritella sp.
Turridae indet.
Aporrhais uttingeriana (Risso, 1826)
Aporrhais pespelecani (Linnaeus, 1758)
Aporrhais sp.
Calyptraea chinensis (Linnaeus, 1758)
Calyptraea sp.
Capulus ungaricus (Linnaeus, 1758)
Xenophora crispa (König, 1825)
Naticarius stercusmuscarum (Gmelin, 1791)
Naticarius sp.
Euspira sp.
Neverita josephinia Risso, 1826
Neverita sp.
Galeodea echinophora (Linnaeus, 1758)
Epitonium tiberii (de Boury, 1890)
Epitonium turtonis (Turton, 1819)
Bolinus sp.
Murex sp.
Nassarius cf. *N.gibbosulus* (Linnaeus, 1758)
Nassarius cf. *N.conoidalis* (Deshayes, 1832)
Nassarius musivus (Brocchi, 1814)
Nassarius mutabilis (Linnaeus, 1758)
Nassarius obliquatus (Brocchi, 1814)
Nassarius prysmaticus (Brocchi, 1814)
Nassarius semistriatus (Brocchi, 1814)
Nassarius sp.
Mitra sp.
Acteon semistriatus Glibert, 1952
Acteon sp.
Ringicula auriculata (Ménard de la Groye, 1811)
Ringicula sp.
Cylichna cylindracea (Pennant, 1777)
Conus ventricosus Gmelin, 1791
Conus sp.
Pyramidella sp.
Helicidae indet.

Other macroinvertebrates
Cladocora sp.
Flabellum sp.
Corals indet.
Terebratula sp.
Echinoids indet.
Dentalium sp.
Serpulorbis sp.
Ditrupa sp.
Barnacle indet.
Bryozoa indet.

Table 3.1. List of taxa occurring in the Arda marine succession.

The Treatise on Invertebrate Paleontology – Mollusca, part N (Cox et al., 1969, 1971) has always been used has a starting point for bivalve systematics, but it is now outdated and hence do not include recent findings.

In the last few years new bivalve workers are increasingly involved in larger-scale phylogenetic analyses, using combinations of morphological, palaeontological and molecular data sources to investigate evolutionary patterns and refine classifications for various parts of the bivalve tree. In the meantime a revised volume of Treatise on Invertebrate Paleontology – Mollusca, part N is in preparation (Lawrence, University of Kansas, Paleontological institute).

For the classification of the fauna under study I made reference to past literature on Pliocene-Pleistocene faunas, to web sites concerning fossil and recent faunas and only occasionally to Treatise on Invertebrate Paleontology, Mollusca Part N for the reasons explained above. Dr. G. Raineri from 'Riserva Naturale Geologica del Piacenziano' also gave an important contribution in providing information for the identifications.

The World Register of Marine Species (WoRMS) has been consulted for resolving critical issues of nomenclature (valid name and so on). In some cases, however, I preferred to maintain the specific name used for fossil specimens as: 1) the link with the modern species is not always verified and the modern species may differ a lot from the fossil one [*Tellina corbis* (fossil) rather than *Tellina carnicolor* (recent); *Acteon semistriatus* (fossil) instead of *Acteon tornatilis* (recent)]; 2) the community of palaeontologists prefer to retain the name introduced for the fossils for clarity and tradition [*Pseudamussium septemradiatum* (fossil) rather than *Pseudamussium peslutrae* (recent); *Venus multilamella* (fossil) instead of *Venus nux* (recent); *Glycymeris insubrica* (fossil) instead of *Glycymeris nummaria* or *Glycymeris violacescens* (recent); *Tellina distorta* (fossil) rather than *Moerella distorta* (recent); *Tellina nitida* (fossil) instead of *Tellina albicans* (recent)].

3.2 Palaeoecology of selected genera

3.2.1 Genus *Glycymeris* Da Costa, 1778

The opportunistic genus *Glycymeris* has a cosmopolitan distribution and its species are known to be poor burrowers (Thomas, 1976), often found lying on the surface of the seabed or slightly buried in the sediments; they are protected from wave action and predators by their heavy and thick shell. They usually live at shallow water depths or in the middle part of the continental platform, but they are absent from polar and deep-sea regions (Oliver & Holmes in Bieler & Mikkelsen, 2006). *Glycymeris* has a very long life-span of as much as 21-100yrs, reaching up to ~200 years in populations of *Glycymeris glycymeris* off the west coast of Scotland (Brocas et al., 2013).

In the Arda section four species of *Glycymeris* have been found: *Glycymeris glycymeris* (Linnaeus, 1758) and *Glycymeris insubrica* (Brocchi, 1814), both living nowadays in the Mediterranean sea, *Glycymeris inflata* (Brocchi, 1814), an extinct species, and *Glycymeris* sp. ind.

a) *Glycymeris glycymeris* is a common bivalve inhabiting coarse sand and gravel substrata at depths of up to 100m, in area with strong bottom currents of the continental shelves of Europe and North Africa (Hayward & Ryland, 1990; Royer et al., 2013) (Fig. 3.1A). In sands, *G. glycymeris* is not deeply buried and the posterior valve and mantle margins are visible just above the surface, whereas in gravels they bury deeper, but always remaining a shallow burrower (Ramsay, 2000).

b) *Glycymeris insubrica* is a species abundant in medium-fine sand or shale deposits of the infralittoral zone (from 2.5 m to 40 m of depth) and from lagoonal settings of the Mediterranean Sea and the Atlantic Ocean (Malatesta, 1974; Domenech, 1986; Lozano Francisco et al., 1993; Raineri, 2007) (Fig. 3.1B).

c) *Glycymeris inflata* according to Raineri (2007) lived in gravel-sand deposits up to 70 m of depth; Malatesta (1974) on the other hand observed that it lived in shale deposits of the deep sea, although he did not specified the depth; there are not many information about the palaeoecology of this extinct species, but the findings in the Arda section support palaeoenvironmental interpretation of Raineri (2007). As said above, *Glycymeris inflata* is known only as a fossil species but recently Altaba et al. (2006) found along the northwestern coast of Mallorca (Spain) at 40 m of depth some shells that they identified as *Glycymeris inflata*. The authors did not clarify if the specimens were collected alive or if they found only shells without the organism, so it remains still unknown if this species is still alive nowadays.

3.2.2 Genus *Aequipecten* Fischer, 1886

The genus *Aequipecten* belongs to the family Pectinidae, which is the largest of the pectinoidean families. The family has a very broad ecological spread, in fact it ranges from the intertidal to depths around 7000 m, the greatest depth known for any living pectinoidean [*Hyalopecten*, reported by Knudsen (1970)].

They are active swimmer: *Amusium* is consider the "swimming star" of the scallop world; its smooth and streamlined shell and enlarged, centralized adductor muscle allows rapid swimming, clocked by Morton (1980) at up to 73 cm/s (Waller in Bieler & Mikkelsen, 2006). At the family level all of the genera share the presence of a true ctenolium, a structure that strengthens the byssal attachment by avoiding twisting of the threads where they cross the edge of the shell (Waller, 1984).

Species of *Aequipecten* are epifaunal bivalves and suspension feeders. Young specimens live attached to the substrate by byssus, while adult ones are free and able swimmer (Raffi, 1970).

In the Arda section two species of the genus *Aequipecten* have been found: *Aequipecten opercularis* (Linnaeus, 1758) and *Aequipecten scabrella* (Lamarck, 1819).

a) *Aequipecten opercularis*, commonly called the Queen scallop, is abundant in medium to fine grained sands, silts and shell gravels, from few meters up to 180 m of depth (Jimenez et al., 2009; Johnson et al., 2009). Nowadays it has a wide geographical range, with the northern, southern, eastern and western boundaries of its occurrence being, respectively, northern Norway, the Mediterranean Sea, the Adriatic Sea and the Atlantic to the west of Ireland (Waller, 1991) (Fig. 3.1C). It occupies waters ranging in temperature from an average winter minimum of c. 5.0°C to an average summer maximum of c. 24.0°C (Johnson et al., 2009). It requires current flow and tolerates only little change of marine salinity.

b) *Aequipecten scabrella,* although it was among the most common and representative species of the Mediterranean Pliocene and early Lower Pleistocene, has a poorly known palaeoecology; according to Jimenez et al. (2009) it is commonly found in different lithologies, allowing to infer that *A. scabrella* is a very generalist species. According to Monegatti & Raffi (2001) it becomes extinct in the Gelasian (c. 2.15 Ma ago).

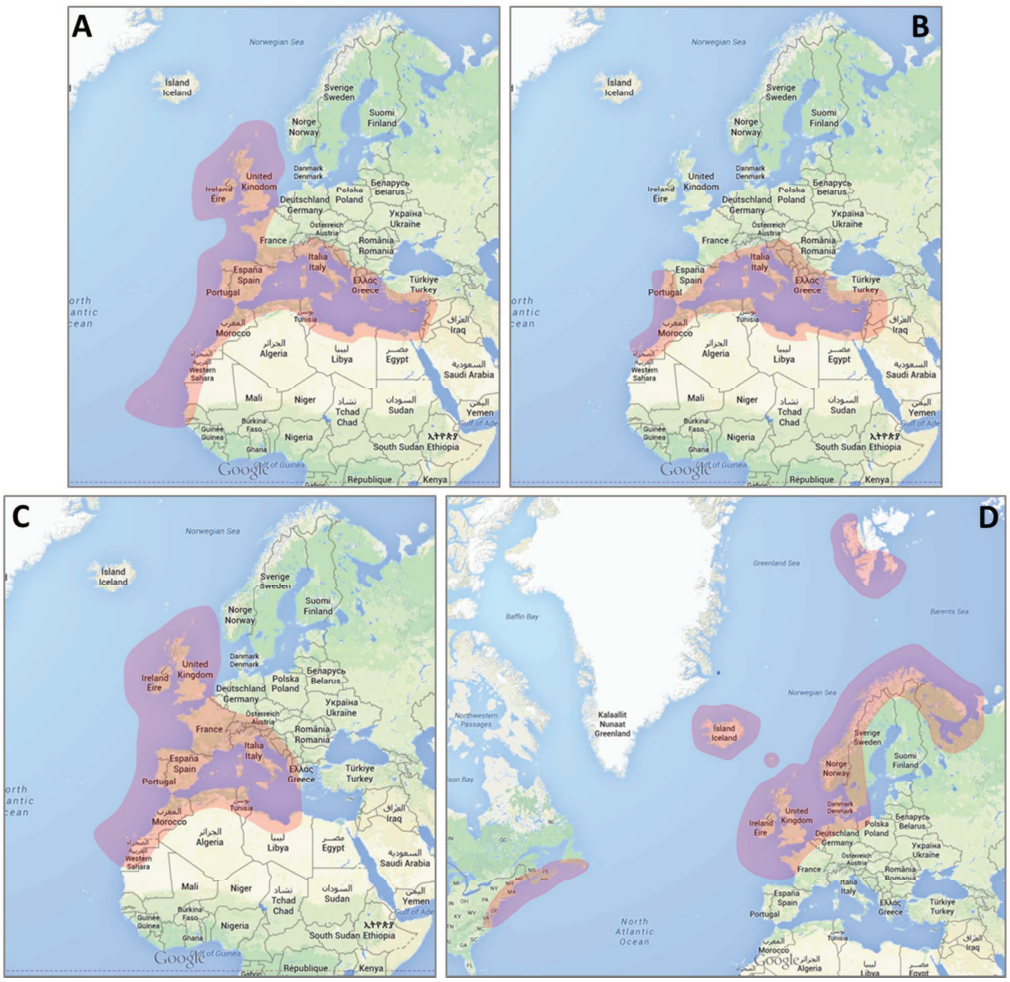

Fig. 3.1. Present-day distribution of: A) *Glycymeris glycymeris*. Data from Domenech, 1986; Brocas et al., 2013; Royer et al., 2013; WoRMS. B) *Glycymeris insubrica*. Data from Domenech, 1986; WoRMS. C) *Aequipecten opercularis*. Data from Hickson, 1999; WoRMS. D) *Arctica islandica*. Data from Cargnelli et al., 1999; Dahlgren et al., 2000; WoRMS.

3.2.3 Genus *Arctica* Schumacher, 1817

Arctica islandica is the only extant species of a bivalve genus which has its roots in the early Cretaceous. During this period, the genus only occurred in marine waters from temperate and boreal regions (Lutz et al., 1982). Nowadays *Arctica* is found on the continental shelves on both sides of the North Atlantic in Europe and North America (e.g. Witbaard, 1997) (Fig. 3.1D). Normally it lives buried in muddy, sandy and gravely sediments with its short siphons just at the sediment-water interface, but sometimes it may bury itself several cm beneath the surface (Lutz et al., 1981; Witbaard, 1997). It lives in water depth from 5 to more than 500 meters (Nicol, 1951; Schöne et al., 2013) with a

temperature tolerance that ranges between 0.0 to 20.0°C and it is capable of surviving with low dissolved oxygen levels (Cargnelli et al., 1999).

Arctica islandica is a very long-living species; with ages exceeding 500 years it is a record-holder of longevity among solitary animals (Butler et al., 2013).

In the Arda section the first occurrence of *Arctica islandica* is at 103.70 m from the base of the section.

3.3 Palaeoecological significance of the Arda biota

3.3.1 Fossil associations

The Mediterranean Neogene communities are similar to those of the present day Mediterranean Sea in terms of taxonomy, trophic structure and substrate requirement; in fact at least the 80% of the Mediterranean present-day species were already thriving in the early Pliocene (Dominici, 2001; Monegatti et al., 2001). I can thus use the taxonomic uniformitarianism (sensu Dodd & Stanton, 1990) to understand the ecological role of each species (still living nowadays) identified in the Arda succession, and recognize in some cases the Mediterranean communities described by the Endoume School (Peres & Picard, 1958, 1964).

The fossil assemblage is clearly different from the original biocoenosis because of the normally meagre preservation of the original biota. In palaeoecology an *organism community* is defined as a partial representation of the biocoenosis, which comprised the total preservable part of the biocoenosis (skeleton bearing and readily preserved organisms). If the fossil assemblage is analyzed as an organism community it is comparable to the community studied by ecologists (Dodd & Stanton, 1990).

As the majority of the Arda river biota is still living nowadays, it is possible to correlate the associations identified in the succession with the ones of Peres & Picard (1958, 1964). Three are the main fossil associations recognized:

1) 'Biocoenose des sables fins bien calibrés' (SFBC): the fauna belonging to this association, thriving in infralittoral settings, is found in sands (homogeneous or with sedimentary structures) without algae; it has a high biodiversity, it can tolerate minor salinity variation (as for example the nearness of a river) and it reaches a maximum depth of 25m, but usually it thrives in shallower water. Characteristic species found in the Arda association are: *Glycymeris insubrica, Chamelea gallina, Tellina pulchella, Tellina incarnata, Tellina nitida, Ensis ensis, Acanthocardia tubercolata, Spisula subtruncata, Flexopecten glaber, Mactra stultorum, Donax* cf. *D. venustus, Donax* cf. *D. trunculus, Lucinella divaricata, Neverita josephinia, Acteon semistriatus* and *Nassarius mutabilis*.

2) 'Biocoenose des fonds detritiques cotiers' (DC): typical of the circalittoral environment, slightly below the boundary with the infralittoral zone. This fauna lives on massive sands or shell debris

substrates. Characteristic species among the Arda biota are: *Aequipecten opercularis, Acanthocardia aculeata, Arca* cf. *A. diluvii, Tellina serrata, Pecten jacobaeus, Flexopecten flexuosus, Polititapes rhomboides, Polititapes* cf. *P. rhomboides, Laevicardium oblongum* and *Aporrhais pespelecani*.

3) 'Biocoenose des vases terrigenes cotieres' (VTC): typical of circalittoral settings in muddy-silty lithologies. Characteristic species identified in the Arda fauna are: *Acanthocardia echinata, Acanthocardia paucicostata, Nucula placentina, Venus multilamella, Glossus humanus* and *Turritella tricarinata*.

In addition to these characteristic associations, other three fossil assemblages have been found: 1) a mixed fauna composed of SFBC and DC species, indicating an infralittoral setting; 2) a mixed fauna composed of DC and VTC species, suggesting a circalittoral setting; 3) a transported fauna, where it is not possible to identify a precise association as it is composed of taxa coming from different environmental settings; this fauna is usually found in infralittoral settings, mainly according to the sedimentary structures present in these beds, but also in deeper ones as in Units A and D in the basal part or in Units N and T in the upper part of the section (see next paragraph).

It is worthy to observe that the fine massive lithologies (mudstones, siltstones and sandstones), lacking sedimentary structures, contain different faunal associations, from shallower (SFBC) to deeper ones (VTC) according to the granulometry of the sediment (coarser in SFBC, finer in VTC). The same SFBC association is found in different facies: 1) fine massive sandstones, 2) sandstones and siltstones with hummocky cross stratification, 3) sandstones and siltstones with plano-parallel laminations; the analysis of the sedimentary structures in this case can help to unravel if the same association of SFBC (usually living up to 25 m depth, shallower in the Northern Adriatic) lives under the fair weather wave base or storm wave base (shallow or deep infralittoral), giving further information about the depth of the succession.

The Arda fauna comprises infaunal, semi-infaunal and epifaunal species; infaunal taxa are slightly more numerous than epifaunal ones (Fig. 3.2A). SFBC assemblages (16 characteristic species) are mainly composed by infaunal taxa; species of the VTC assemblage (6 characteristic species) are all infaunal, whereas DC assemblage (9 characteristic species) is more diversified in terms of epifaunal and infaunal species (Fig. 3.2B-D).

The fossil preservation is generally good, often articulated specimens are present but usually the associations are dominated by disarticulated ones. Species belonging to VTC assemblages present a higher number of articulated specimens in comparison to SFBC and DC associations. Notwithstanding the disarticulation, shells preserve the fragile spiny ornamentation and the color pattern, indicating in situ disarticulation (by bioturbation) or short-distance transport. Shell debris is present mainly in beds

with accumulation of transported mollusk shells. Traces of bioerosion made by *Clionia* sponges are present both on bivalves and gastropods.

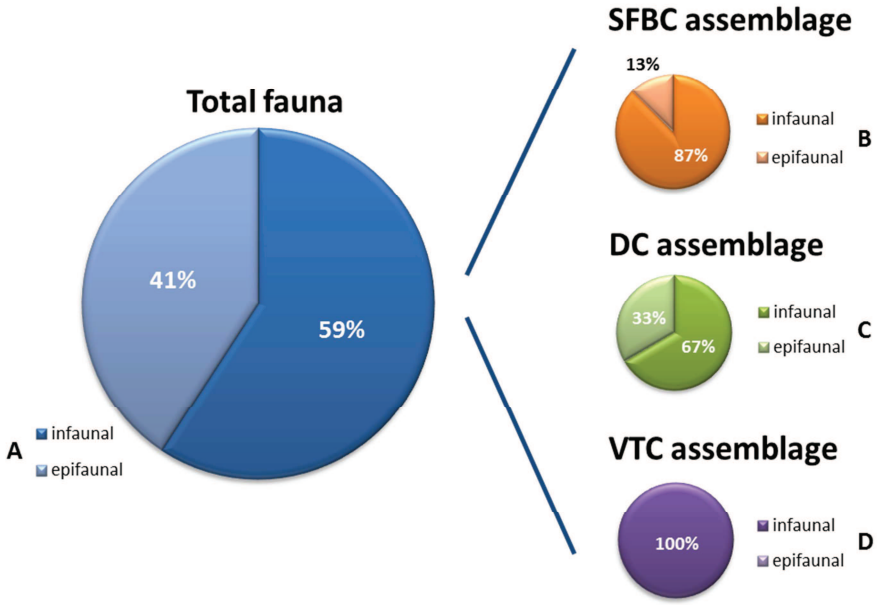

Fig. 3.2.Epifaunal/infaunal ratio: A) total fauna (103 species among bivalves and gastropods); B) 16 species belonging to SFBC assemblage; C) 9 species belonging to DC assemblage; D) 6 species belonging to VTC assemblage.

3.3.2 Palaeoecological classification of the Arda section

In this paragraph the marine succession is described and divided in units based on lithology and faunal composition (characteristic species of SFBC, DC and VTC assemblages are listed above). It should be taken into account that, even if the presence of macrofossil samples is nearly continuous, there are parts where specimens have not been found. From the base to the top of the section the following units have been identified:

Unit A (0-1.20 m). Yellowish cemented sandstones, frequently bioturbated. In the lower part the faunal association is composed by disarticulated specimens with rheophilous behavior (e.g. *Pecten flabelliformis, Astarte fusca*); toward the top the amount of clay increases and also the faunal association is affected by minor changes (e.g. *Glycymeris inflata, Amusium cristatum, Venus multilamella*). Circalittoral.

Unit B (1.20-24 m). Massive siltstones interbedded with fine-medium sandstones. Beds with fossils are very rare and when present have a low biodiversity and a low biomass. Small sized mollusks are mainly present, but also one larger specimen of *Ostrea edulis* and some echinoids in life position. A bed at 2.90 m from the base contains a monospecific assemblage of articulated specimens (occasionally unfilled) of *Corbula gibba*. Circalittoral.

24-36 m. Covered.

Unit C (36-45 m). Fine massive sandstones. The fauna is characterized by a high biodiversity and by the presence of many species, both articulated and disarticulated, typical of DC association, sometimes mixed with transported shallower water taxa. At 41.35 m from the base specimens of

Ostrea edulis, Loripinus fragilis, Capulus ungaricus and *Conus ventricosus* occur; numerous plant remains are also present. At 42 m in fine massive sandstones, *Glycymeris inflata* with disarticulated and articulated valves is the dominant species in terms of number of specimens. Toward the top of the interval corals, echinoids, brachiopods and non rheophilous mollusks occur in silty-clayey lithologies. Circalittoral.

Unit D (45-46.60 m). Yellowish cemented sandstones, frequently bioturbated. The fauna has a low diversity with rare specimens of *Aequipecten opercularis, Aequipecten scabrella* and *Ostrea edulis*, often poorly preserved, disarticulated, fragmented or abraded. Circalittoral.

Unit E (46.60-54 m). Fine massive siltstones and mudstones with a mixed fauna of DC-VTC species. *Pelecyora brocchi*, often in life position (Fig. 3.3A), represents the dominant taxon with articulated and very fragile shells with empty valves. Circalittoral.

Unit F (54-71 m). Fine massive siltstones and sandstones; at 54 m there are three closely set fossiliferous beds clearly observable along both river shores, containing a very diversified fauna mainly composed of DC disarticulated specimens together with transported SFBC species and plant remains. The highest of these beds contains *Ostrea edulis, Pinna* sp. and echinoids in numerous specimens (Fig. 3.3B,C). Above these beds *Pelecyora brocchi*, in life position, returns to be the dominant species together with echinoids. At the top of the interval there is a typical association of SFBC with articulated and disarticulated specimens (Fig. 3.3D). Deep infralittoral.

71-80 m. Covered.

Unit G (80-91.40 m). Fine massive siltstones and sandstones containing species belonging to DC assemblage. In the lower and upper part of the interval large specimens of articulated *Pinna* sp. together with VTC species are present. Frequent are also oxidized nodules containing plant remains. Circalittoral.

Unit H (91.40-98.30 m). Fine sandstones. The fauna is poor and ubiquitous, with *Venus multilamella, Glycymeris insubrica, Turritella tricarinata, Spisula subtruncata, Pecten jacobaeus* and *Aequipecten opercularis,* sometimes articulated, suggesting a DC association mixed with SFBC taxa. Specimens are often fragmented and packed together, suggesting transport. Deep infralittoral.

Unit I (98.30-114.30 m). Fine massive siltstones and sandstones; the fauna at the base is characterized by mud lovers *Venus multilamella, Turritella tricarinata* (as in 80-91.40 m) and by the first occurrence at 103.70 m of the boreal guest *Arctica islandica*. Toward the top, the fauna is more typical of a DC association mixed with shallower water species of SFBC assemblage (both articulated and disarticulated specimens). Circalittoral to deep infralittoral.

Unit J (114.30-122 m). Sandstones lacking fossils. Shallow infralittoral.

Unit K (122-126.40 m). Fine massive mudstones and siltstones with mainly VTC species. Circalittoral.

Unit L (126.40-147 m). Alternation of fine massive beds and laminated sandstones. A mixed fauna is present, with SFBC association dominating, accompanied by few DC species, both containing several articulated specimens (Fig. 3.3E). Several horizons are composed entirely by specimens of *Ditrupa* sp. Toward the top I observe an increase in DC taxa. Shallow infralittoral

Unit M (147-171 m). Fine massive siltstones and mudstones with articulated specimens of species belonging to VTC association. Circalittoral.

Unit N (171-195 m). Sandstones with a very diversified and mixed fauna, in which it is not possible to identify a typical association. Specimens are generally well preserved, sometimes articulated. At the base, the fauna is more typical of DC but, shallow water species are also present. Deep to shallow infralittoral.

Unit O (195-208 m). Fine massive mudstones and siltstones dominated by articulated specimens of species belonging to VTC assemblage. Circalittoral.

Unit P (208-212.40 m). Sandstones containing a mixed fauna of species belonging to SFBC and DC assemblages. Shallow infralittoral.

Unit Q (212.40-217 m). Fine massive siltstones lacking fossils. Deep infralittoral.

Unit R (217-218 m). Poorly preserved, disarticulated and fragmented specimens of SFBC and DC associations are present within a level with well rounded extraclasts, intercalated in sandstones. Shallow infralittoral.

Unit S (218-223.80 m). Sandstones in the basal part containing a mixed fauna (e.g. *Glycymeris glycymeris, Arctica islandica, Chamelea gallina, Spisula subtruncata, Aequipecten opercularis, Tellina pulchella*) overlain by fine massive and laminated sandstones with a typical SFBC association. Shallow infralittoral.

Unit T (223.80-225 m). This unit is bounded by two beds with large extraclasts; in correspondence of these beds with extraclasts a mixed fauna with disarticulated specimens is present. Within these beds there is a fine massive clayey horizon containing several articulated specimens of *Arctica islandica* in life position associated to *Spisula subtruncata* and *Calyptraea chinensis*. Deep infralittoral.

Unit U (225-237.40 m). Alternation of fine sandstones and mudstones. The association found here is the typical association of SFBC with articulated and disarticulated specimens, often in life position (Figs. 3.3 F-H). In particular toward the top *Glycymeris insubrica* becomes quite dominant, with numerous specimens found in life position in muddy beds; trunks and plant remains are also found. The top of the interval is capped by the first continental conglomerates. Shallow infralittoral.

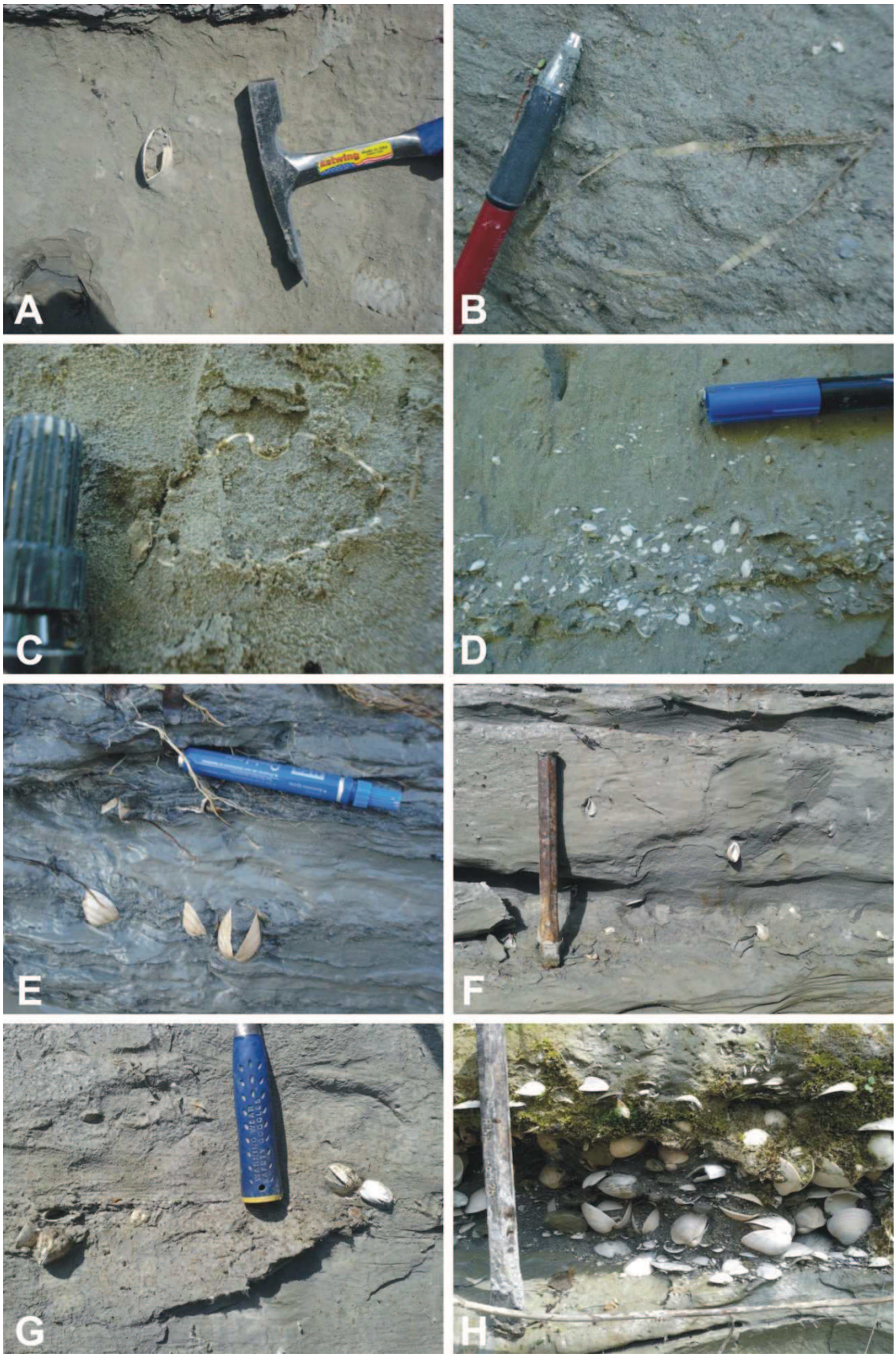

Fig. 3.3. Fossiliferous beds of the Arda succession. A) Articulated specimen of *Pelecyora brocchi* in fine massive siltstones/sandstones; B) Articulated specimen of *Pinna* sp.; C) Echinoid specimen; D) Fossil accumulation mainly composed by specimens of *Tellina* spp. E) Articulated specimens of *Glycymeris insubrica*; F) Specimens of *Chamelea gallina* with empty valves in life position at the top of the section; G) Articulated specimens of *Glycymeris insubrica* at the top of the section; H) Accumulation bed with articulated specimens of *Glycymeris insubrica* at the top of the succession.

3.4 Discussions

3.4.1 Palaeoecological interpretation

The Arda fauna comprises infaunal, semi-infaunal and epifaunal species, with infaunal taxa being slightly more numerous than epifaunal ones (Fig. 3.2A). SFBC assemblages are mainly composed by infaunal taxa; as this association occurs at shallow water depth and it is usually exposed to wave action, being infaunal can be a strategy to protect the organisms from strong currents. Also species of the VTC assemblage are all infaunal (Fig. 3.2B-D). The VTC assemblage is typical of muddy-silty lithologies; in finer sediments the substrate is not stable and thus it does not offer the possibility to organisms of anchorage or cementation, promoting the development of infaunal taxa.
Species belonging to VTC assemblages present a higher number of articulated specimens in comparison to SFBC and DC associations; this is due to the fact that species belonging to VTC thrive in a more quiet and with a low biodiversity environment, where neither currents or other organisms can contribute to the disarticulation process.

Some palaeoecological considerations can be deduced from the analysis of the fossil assemblages and of the sedimentary structures present in each bed of the succession:
1) Unit B (2-20 m): macrofossils are very rare, and usually have very small size. Inside Unit B at 2.90m from the base there is a bed containing exclusively articulated specimens of *Corbula gibba*; this bivalve tends to become dominant when oxygen levels decrease and it is common but not exclusive to hypoxia stressed areas; it is considered one of the most tolerant forms to oxygen depletion and it can also tolerate large quantities of suspended material (Dominici, 2001). This monospecific association can thus indicate the presence of a local hypoxic environment and/or of high suspended material where only *Corbula gibba* can thrive. Otherwise this interval only contains rare and small size disarticulated mollusks and several echinoids; these levels cannot be interpreted in the same way of the *Corbula gibba* bed as echinoids lives in normal salinity and oxygen conditions. They can thus be better indicators of a deeper water setting where only small mollusks are transported by weak currents which reach the bottom where echinoids live; this is also supported by the fact that these small mollusks are disarticulated and belong to shallow water taxa, which can be therefore transported from shallower settings.
2) Unit C: at 41.35 m from the base specimens of *Loripinus fragilis, Capulus ungaricus* and *Conus ventricosus* occur; these three species prefer algal beds and sea grass meadows, suggesting a shallow water depth.

3) Unit H: probably it records a channel which cuts obliquely the succession, as also indicated by the presence of plant remains, clay chips and flaser bedding. In fact, the fauna and the lithology of units G and I, preceding and following this unit, are the same, and they are different from the ones in unit H, confirming the presence of a channel in this part of the section.
4) Unit L: the presence of *Ophiomorpha* trace fossil indicates a high energy environment and a well oxygenated bottoms; it is also typical of very shallow settings, suggesting water depth less than 10 m. Furthermore in this unit several beds are composed entirely by specimens of *Ditrupa* sp.; this serpulid is considered an instability indicator, tolerant of high quantities of suspended inorganic matter and thriving in conditions of turbid waters (Dominici, 2001), also suggesting a shallow environment exposed to wave motion or currents.
5) Units S-U: SFBC assemblages are dominant, suggesting a shallow infralittoral setting; in particular shallow water species of the genus *Donax* (max 10 m of depth) occur only in the upper part of the section (Units N, P, T and U). At the very top *Glycymeris insubrica*, often associated with the very shallow water gastropod *Cylichna cylindracea*, is found in life position in clayey sandstones lithologies, possibly indicating a very shallow to lagoonal environment, subjected to salinity variation (Unit U). The presence of flaser bedding indicates the influence of tidal currents, supporting a more shallow water environment for the upper part of the succession toward the conglomerates.

The Arda marine succession can be divided into two part according to the biota and the sedimentology:
1) Units A-I, representing the basal part of the section up to 114 m, shows rare transported levels with shell accumulations and lithologies with few sedimentary structures indicating quiet and deep water settings.
2) Units J-U (middle and upper part of the section, 114-237.40 m). Transported assemblages and evidence of density flows become more frequent; this means that there is more river discharge into the paleoAdriatic basin which could be linked to the interplay among different factors: 1) proximity to the coast (regressive trend through the section), 2) increase of tectonic uplift of the Apennines, 3) climatic deterioration: a) warmer summers (with increased precipitations) and colder winters; b) increased ice melting during summer and more extensive growth during winter. These shell beds with accumulation of shells transported from shallower settings and mixed with autochthonous taxa, found together with mud clasts and extra-clasts represent geological instantaneous events caused by density flows. In Units J-U also hummocky crossed stratification and plano-parallel lamination become more frequent, suggesting shallower settings than those recorded at the base (Units A-I).

3.4.2 Palaeodepth reconstruction of the Arda section

The general trend of the succession is a shallowing upward which culminates with the retreat of the sea and the establishment of continental conglomerates at the top of the section.

This trend is not linear, but several alternations of lower order transgressive and regressive cycles are present. Based on the faunal associations and on the sedimentary structures present in the succession (described in Chapter 2), eight lower order cycles with a shallowing upward trend have been recognized (Fig. 3.4). The base of each cycle is represented by a circalittoral or deep infralittoral environment, whereas at their top shallow or deep infralittoral settings are present.

The assemblage of SFBC is characteristic of an infralittoral environment. The discrimination between shallow and deep infralittoral settings is based on the sedimentary structures, which can help to unravel the depth of this association; in fact taxa belonging to SFBC found in sandstones with sedimentary structures (e.g. hummocky cross stratification, plano-parallel laminations) have been referred to a shallow infralittoral setting (max 10 m of depth), whereas the ones occurring in fine massive sandstones suggest a deep infralittoral environment (10-20 m of depth). DC and VTC assemblages are instead typical of a circalittoral environment (from 20 m). The analysis of the palaeoecology of the Arda river biota integrated with sedimentological data furnish thus important information about the palaeodepth of the succession.

As observed above the deposition of the Arda river succession occur in an infralittoral to a shallow circalittoral environment. Nowadays in the Northern Adriatic the maximum water depth is 80 m (Zavatarelli et al., 1998); river runoff is particularly strong in the northern basin and affects the ecosystems by introducing large amounts of nutrients. The depth of the infralittoral zone in the Mediterranean Sea is 40 m, but in the Northern Adriatic is usually less, being about 20-30 m. In the case of the Arda succession we are in the proximity of a river delta which, with river discharge, contributes to increase the turbidity of the system; the depth of the infralittoral zone in this case could have thus been around 15-20 m and the maximum depth of the succession should not have exceeded 40-50 m.

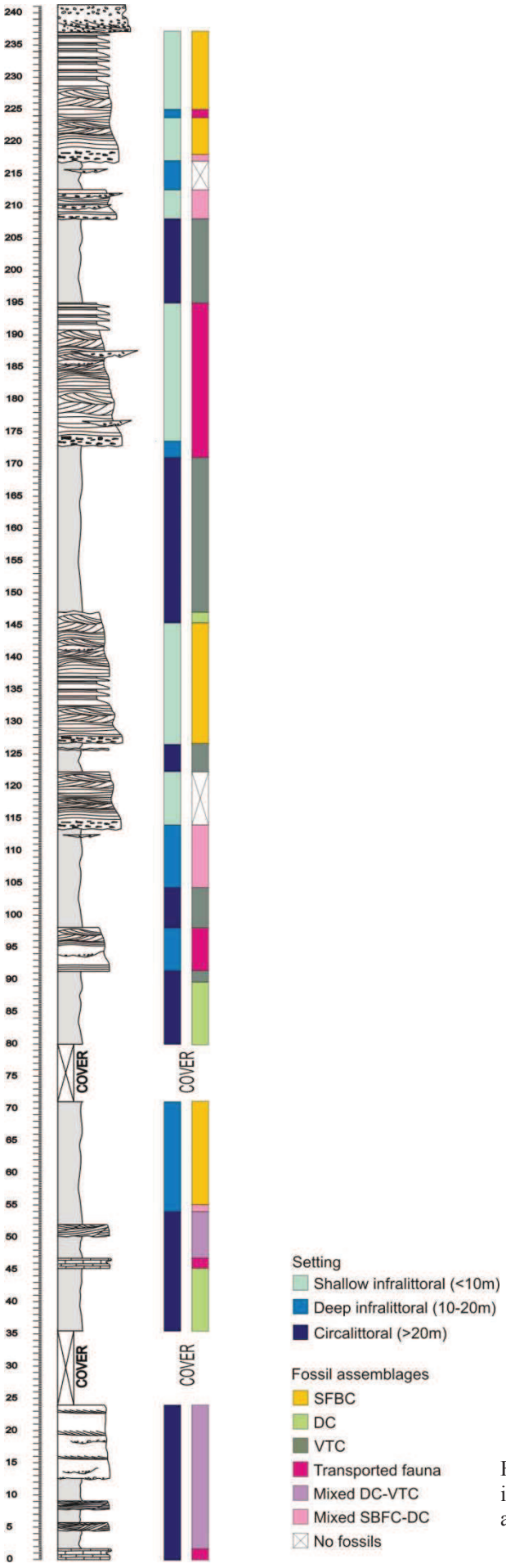

Fig. 3.4. Simplified log of the Arda section illustrating the sedimentology, the fossil assemblages and their corresponding palaeodepths.

3.4.3 Other palaeoecological observations

Here follow some observations on single species deduced from the faunal analysis:

1) *Pinna* sp. is often found together with echinoids in silty homogeneous lithology.

2) *Venus multilamella* lives nowadays in the Mediterranean Sea on muddy bottom from 70 m to deeper setting; Pelosio & Raffi (1977) observed that in the Stirone Section (10 km SE from the Arda section) it is present in shallower water often associated to *Arctica islandica* in transported assemblages. In the Arda section it is also found in association with elements belonging to DC biocoenosis, thus at shallower depth that it is usually found, confirming the finding of Pelosio & Raffi (1977).

3) The occurrence of the bivalve *Polititapes senescens* follows the first appearance of *Arctica islandica* in the Arda section; according to Papani & Pelosio (1962) this species does not appear before in the Western Emilia successions.

4) *Arctica islandica* is present in the succession from 103.70 to 224.30 m, then it disappears probably due to the decrease of the water depth, which become too shallow for its surviving, and due to the decrease in salinity. In the lower beds of its distribution is quite rare and often found with disarticulated valves associated with quite deep water fauna (e.g. *Turritella tricarinata*); towards the top (in particular from 174 m) specimens become more numerous with levels where it is dominant with both disarticulated and articulated valves, often associated with shallow water biota. This behavior is probably linked to the palaeoclimatic evolution of the succession: when *Arctica islandica* migrated in the Mediterranean Sea it was not enough cold so it was restricted to deeper settings, when climate becomes colder it could move to shallower depth; this is also supported by a slight decreasing trend in the $\delta^{18}O$ recorded by the shells in the upper part of its range (see Chapter 8).

5) *Mytilus edulis* is considered a boreal guests notwithstanding the difficulty to be distinguished from *Mytilus galloprovincialis* (see Chapter 6). It is interesting to observe that in the Arda section it is found in levels with VTC species, usually living in quite deep water environment. *Mytilus galloprovincialis* is, on the other hand, the common mollusk found in shallow water in our seas (Mediterranean Sea); the fact that I found *M. edulis* associated with deep water fauna support the correct identification of the species; in fact, in being a boreal guest, *M. edulis* usually lives in colder water; when it arrived in the Mediterranean Sea it began to colonize deep water setting, where temperatures were colder.

6) *Aequipecten opercularis* disappears in the succession at 224.50 m slightly after *Arctica islandica*. In this very upper part of the section the water depth is very shallow with possible salinity variation. *A. opercularis* tolerates only slightly salinity variation; the palaeoecological conditions thus do not allow its survival in these conditions.

3.5 Conclusions

The analysis of the Arda River biota and lithofacies have led to the following conclusions:

- The fauna is composed by 159 taxa, of which bivalves are dominant with 105 taxa, followed by gastropods (44 taxa) and a few corals (3 taxa) and serpulids (2 taxa); brachiopods, echinoids, barnacles, bryozoans and scaphopods do also occur in the fauna.
- The fauna is very diversified; it is characterized by both infaunal and epifaunal species, of shallow and deep infralittoral and circalittoral environments. Three are the main fossil associations recognized: 1) SFBC in sandstones with or without sedimentary structures; 2) DC in sandstones and siltstones lacking sedimentary structures (excepting the ones caused by high-density flows triggered by river floods) and 3) VTC in siltstones and mudstones without sedimentary structures.
- The higher biodiversity has been recorded in fine sandstones, which contain the typical shallow water association of SFBC; a lower biodiversity has been instead recorded in siltstones barren of sedimentary structures and characterized by a deeper water fauna of VTC assemblage.
- The palaeoecological analysis of the fauna confirms the general regressive trend of the marine succession; eight alternations of lower order transgressive and regressive cycles are present, but no event of emersion or shift to very deep water setting has been recorded.
- The Arda marine succession was deposited in an infralittoral to a shallow circalittoral environment; the proximity of a river delta contributes, with river discharge, to increase the turbidity of the system; the depth of the infralittoral zone could have thus been around 15-20 m and the maximum depth of the succession should not have exceeded 40-50 m.

PLATES

PLATE 1

All specimens are x1, except when indicated; (a) external view, (b) internal view, except when indicated.

(1a-b) *Nucula placentina*, right valve (ACG10-2);

(2a-b) *Nucula sulcata*, left valve (ACG90-13);

(3a-b) *Nuculana pella*, right valve, x2 (ACG197-13);

(4a-b) *Saccella commutata*, left valve, x2 (ACG104-6);

(5a-b) Arcoidea indet., right valve, x3 (ACG23-1);

(6a-b) *Arca tetragona*, right valve, x2 (ACG197-14);

(7a-b) *Arca noae*, left valve (ACG235-7);

(8a-b) *Arca* sp., left valve, x2 (ACG252-7);

(9a-b) *Anadara* cf. *A.diluvii*, left valve (ACG12-7);

(10a-b) Articulated specimen of *Barbatia mytiloides*, right (a) and left (b) valves (ACG62-1);

(11a-b) *Bathyarca* sp., left valve, x2 (ACG13-12);

(12a-b) *Amusium cristatum*, left valve (ACG6-1);

(13) Fragment of *Pinna* sp. (ACG200-16);

(14) Fragment of *Mytilus edulis* (ACG117-1);

(15a-b) *Mimachlamys varia*, right valve (ACG119-1);

(16a-b) *Talochlamys* cf. *T. multistriata*, left valve, x2 (ACG14-18);

(17a-b) *Pseudamussium septemradiatum*, left valve (ACG219-1);

(18) Unidentified valve of *Amusium cristatum* (ACG2-1).


Pl.1
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17b
18

PLATE 2

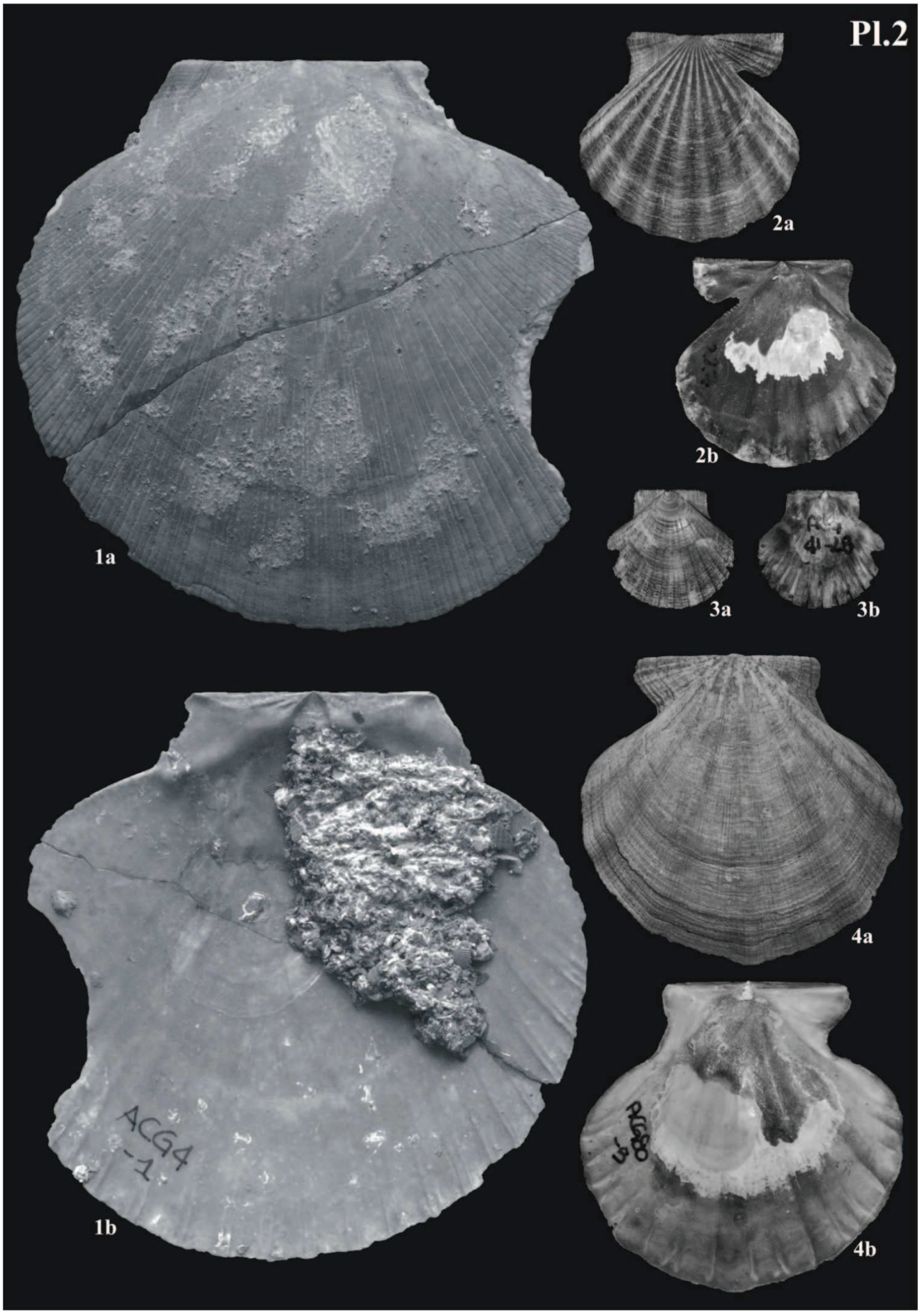
All specimens are x1; (a) external view, (b) internal view.

(1a-b) *Pecten flabelliformis*, left valve (ACG4-1);

(2a-b) *Flexopecten glaber*, right valve (ACG227-1);

(3a-b) *Pecten jacobaeus*, left valve (ACG41-28);

(4a-b) *Flexopecten flexuosus*, left valve (ACG80-5).


Pl.2
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ACG4
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PLATE 3

All specimens are x1.

(1a-b) *Glycymeris glycymeris*, left valve (ACG14-3);

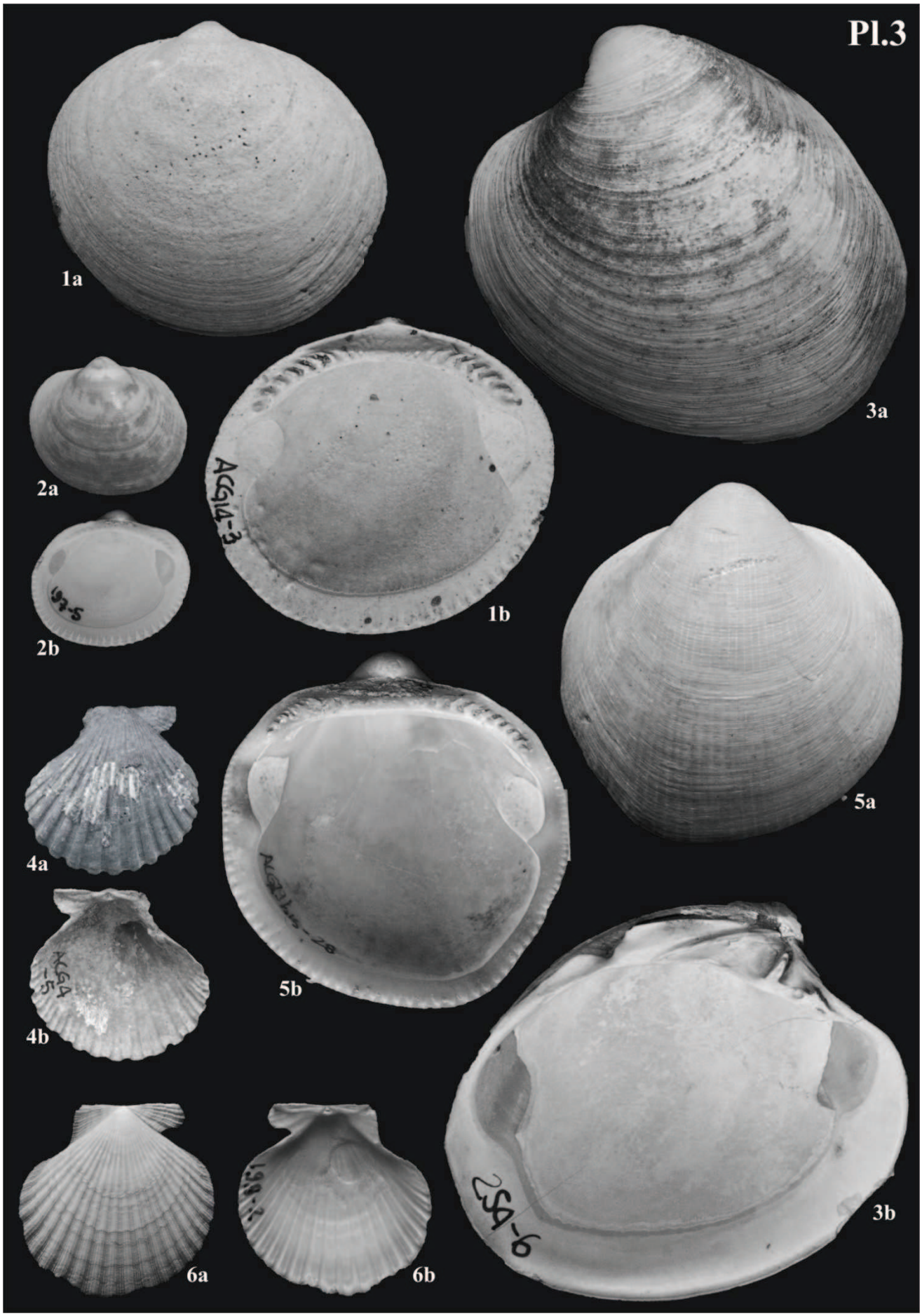
(2a-b) *Glycymeris insubrica*, left valve. Note the well preserved color pattern (ACG197-5);

(3a-b) *Arctica islandica*, left valve (ACG254-6);

(4a-b) *Aequipecten scabrella*, right valve (ACG4-5);

(5a-b) *Glycymeris inflata*, right valve (ACG29bis-28);

(6a-b) *Aequipecten opercularis*, right valve (ACG198-2).


Pl.3
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5b
6a
6b

PLATE 4

All specimens are x1, except when indicated; (a) external view, (b) internal view, except when indicated.

(1a-b) *Anomia* sp., left valve (ACG197-15);

(2a-b) *Pecten jacobaeus*, left valve (ACG29bis-38);

(3a-b) *Anomia ephippium*, left valve (ACG42-26);

(4a-b) *Anomia ephippium*, left valve (ACG41-30);

(5a-b) *Monia patelliformis*, left valves (ACG118-1);

(6a-b) *Loripes lacteus*, left valve (ACG259-6);

(7a-b) Articulated specimen of *Loripinus fragilis*, right (a) and left (b) valve (ACG28-3);

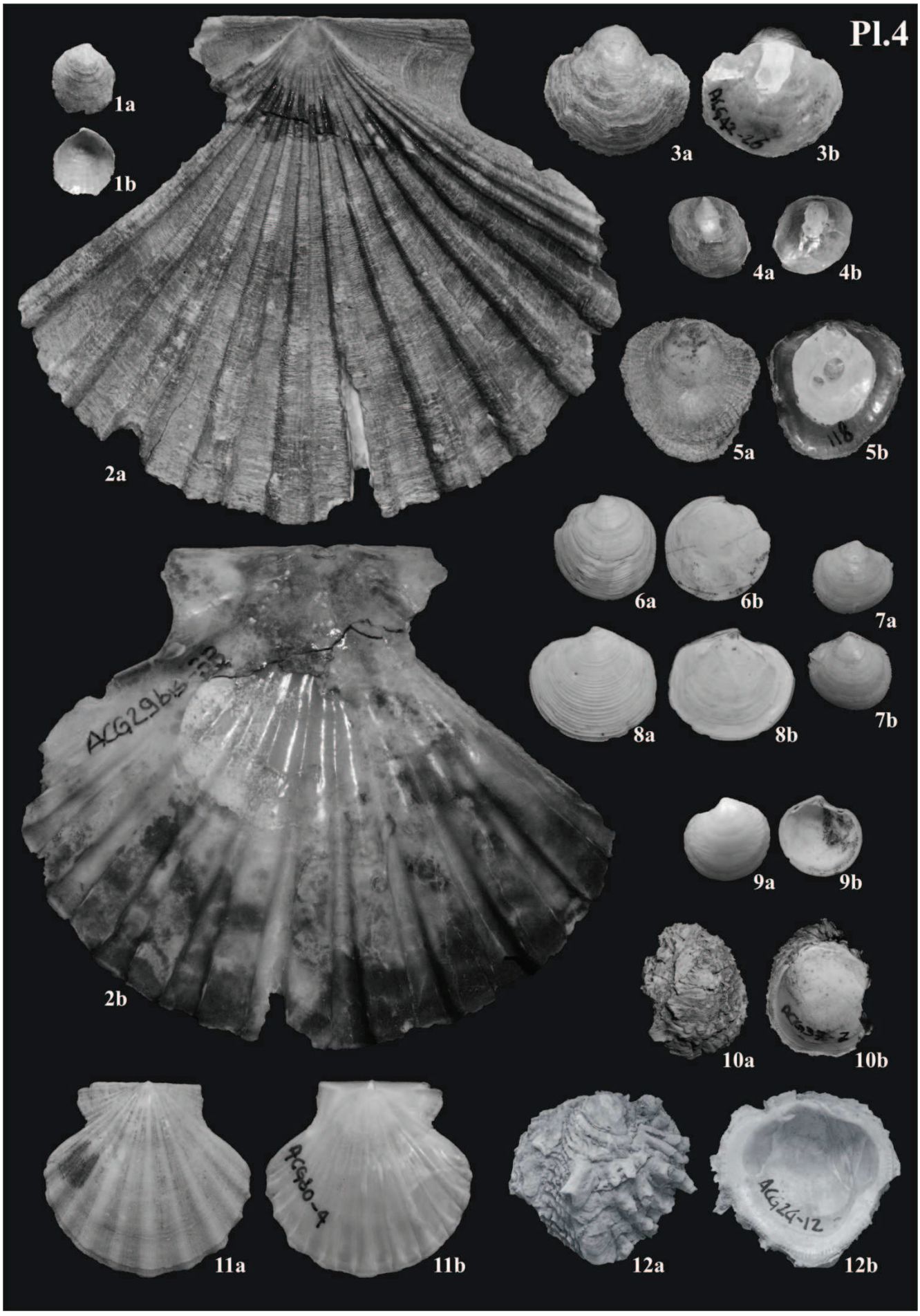
(8a-b) *Lucinoma borealis*, left valve, x2 (ACG41-32);

(9a-b) *Lucinella divaricata*, left valve, x5 (ACG259-7);

(10a-b) *Chama gryphoides*, left valve (ACG37-7);

(11a-b) *Flexopecten glaber*, left valve (ACG80-4);

(12a-b) *Chama placentina*, right valve (ACG24-12).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12a
12b

PLATE 5

All specimens are x1, except when indicated; (a) external view, (b) internal view.

(1) *Pecten jacobaeus*, right valve (ACG24-1);

(2a-b) *Venericardia* sp., left valve (ACG14-8);

(3a-b) *Cardites antiquatus*, right valve (ACG29-1);

(4a-b) *Astarte fusca*, right valve (ACG29-6);

(5a-b) *Astarte fusca*, left valve (ACG25-12);

(6a-b) *Astarte* sp., left valve, x2 (ACG13-9);

(7a-b) *Acanthocardia aculeata*, left valve (ACG217-7);

(8a-b) *Acanthocardia paucicostata*, right valve (ACG223-6);

(9a-b) *Acanthocardia echinata*, right valve (ACG232-1);

(10a-b) *Acanthocardia aculeata,* right valve (ACG207-5).

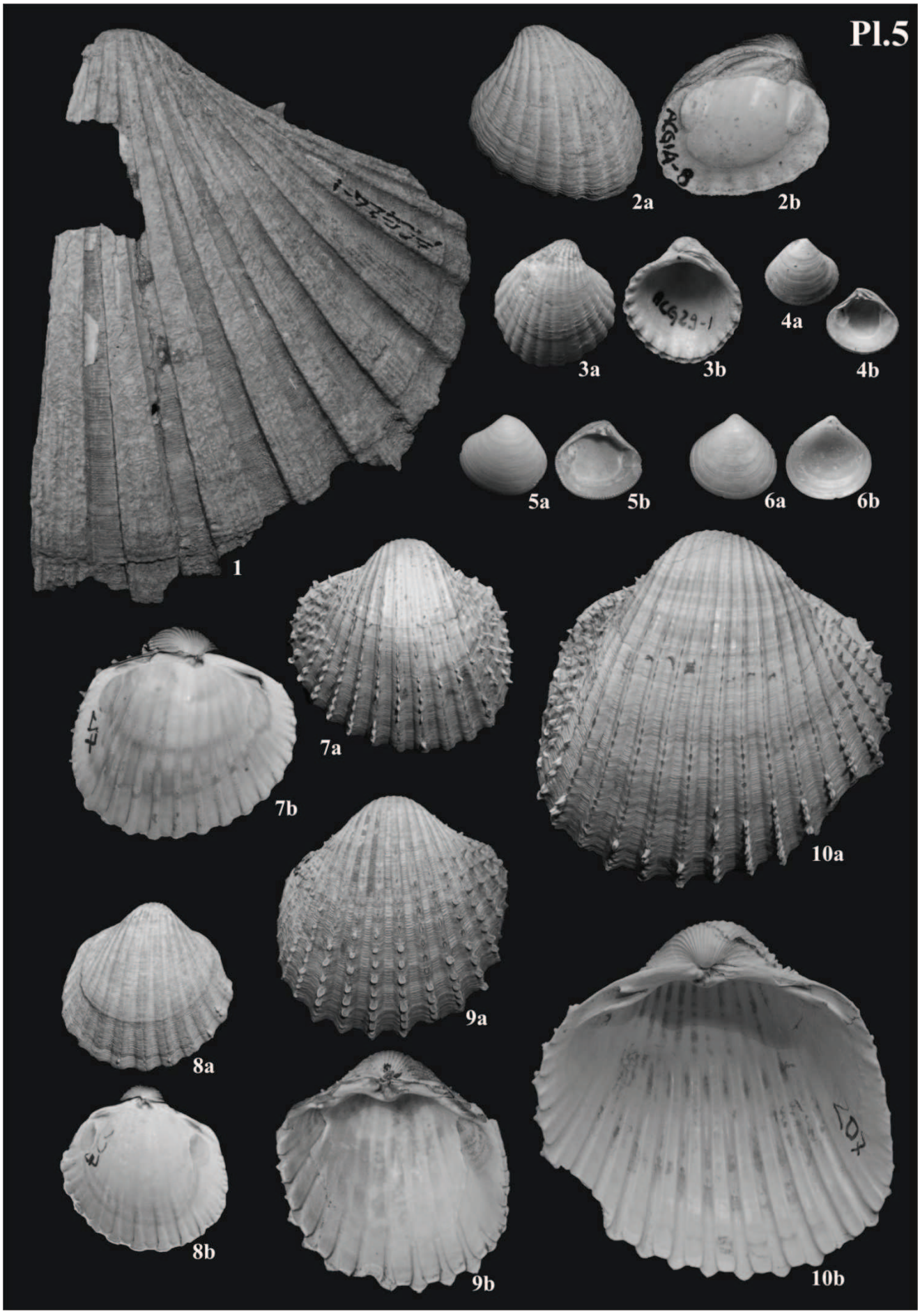
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PLATE 6

All specimens are x1, except when indicated; (a) external view, (b) internal view, except when indicated.

(1a-b) *Acanthocardia tubercolata*, left valve (ACG253-5);

(2a-b) Articulated specimen of *Acanthocardia tubercolata*, left (a) valve and anterior view (b) (ACG251-1);

(3a-b) *Laevicardium crassum*, left valve (ACG197-16);

(4a-b) *Laevicardium oblongum*, right valve (ACG197-17);

(5a-b) *Papillicardium papillosum*, right valve, x2 (ACG197-18);

(6a-b) *Papillicardium papillosum*, left valve, x2 (ACG198-8);

(7a-b) *Mactra stultorum*, left valve (ACG205-4);

(8a-b) *Papillicardium* sp., right valve, x2 (ACG256bis-3);

(9a-b) *Laevicardium* sp., left valve (ACG198-9);

(10a-b) *Spisula subtruncata*, right valve (ACG236-7);

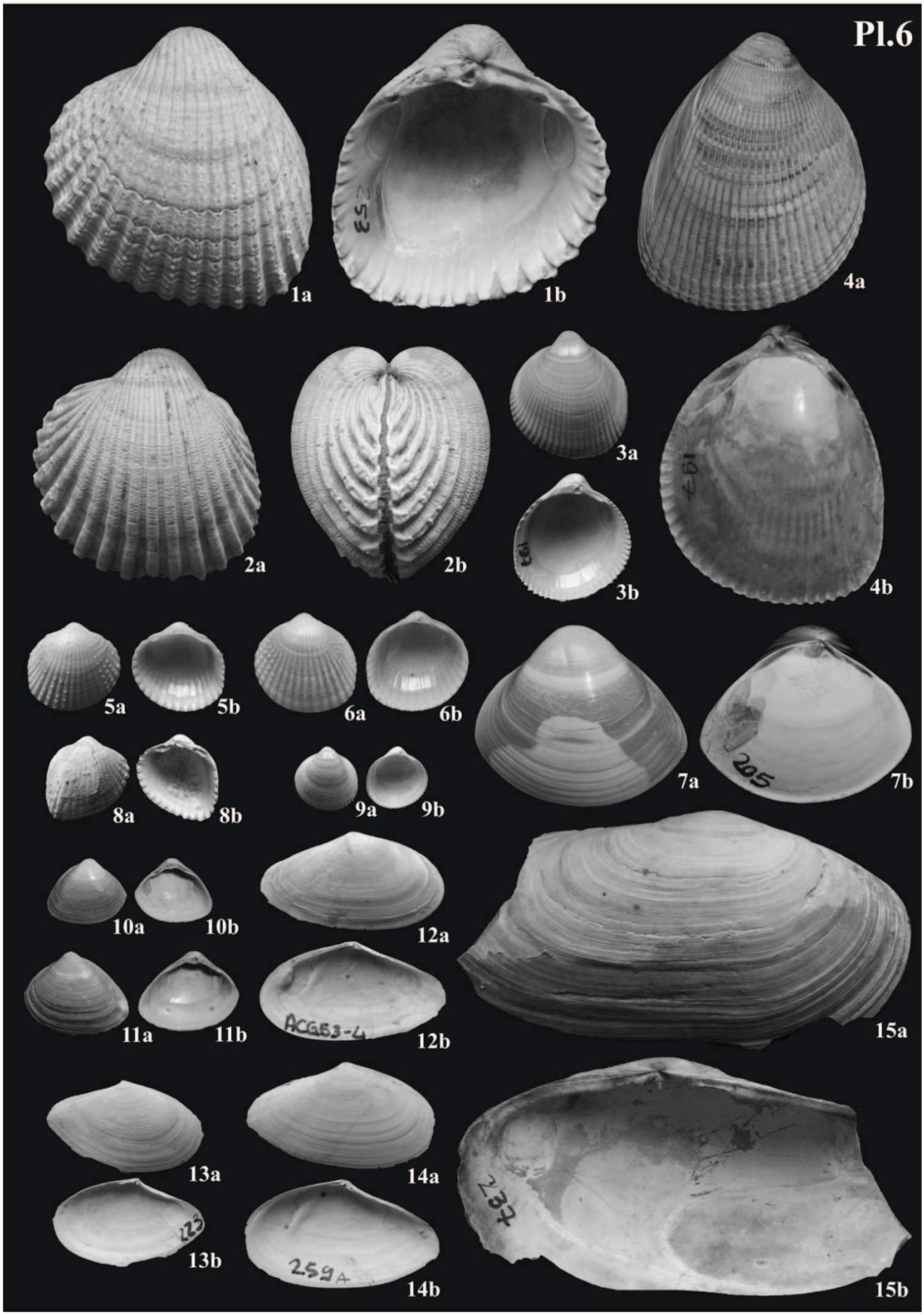
(11a-b) *Spisula subtruncata*, left valve (ACG236-8);

(12a-b) *Tellina nitida*, right valve (ACG53-4);

(13a-b) *Tellina incarnata*, right valve (ACG223-7);

(14a-b) *Tellina incarnata*, right valve (ACG259-8);

(15a-b) *Lutraria angustior*, right valve (ACG237-5).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15b

PLATE 7

All specimens are x1, except when indicated; (a) external view, (b) internal view, except when indicated.

(1a-b) *Lutraria oblonga*, left valve (ACG9-1);

(2a-b) *Tellina distorta*, right valve, x2 (ACG259-9);

(3a-b) *Tellina pulchella*, left valve (ACG207-5);

(4a-b) *Tellina pulchella*, right valve (ACG265-5);

(5a-b) *Tellina serrata*, right valve (ACG41bis-7);

(6a-b) *Donax* cf. *D. trunculus,* left valve (ACG219-2) ;

(7a-b) *Donax* cf. *D. venustus*, left valve (ACG213bis-4);

(8a-b) Articulated specimen of *Solecurtus scopula*, right (a) and left (b) valves (ACG131-1);

(9a-b) *Azorinus chamasolen*, right valve (ACG10-1);

(10a-b) *Tellina tenuis*, right (a) and left (b) valve, x2 (respectively ACG17-6 and ACG17-7);

(11) *Glossus humanus*, right valve (ACG200-15);

(12) *Venus multilamella,* dorsal view (ACG130-1);

(13a-b) *Venus multilamella*, left valve (ACG130-2);

(14a-b) *Pitar rudis*, left valve (ACG82-8);

(15a-b) *Pitar rudis*, right valve (ACG80-7);

(16a-b) *Callista chione,* right valve (ACG197-19).

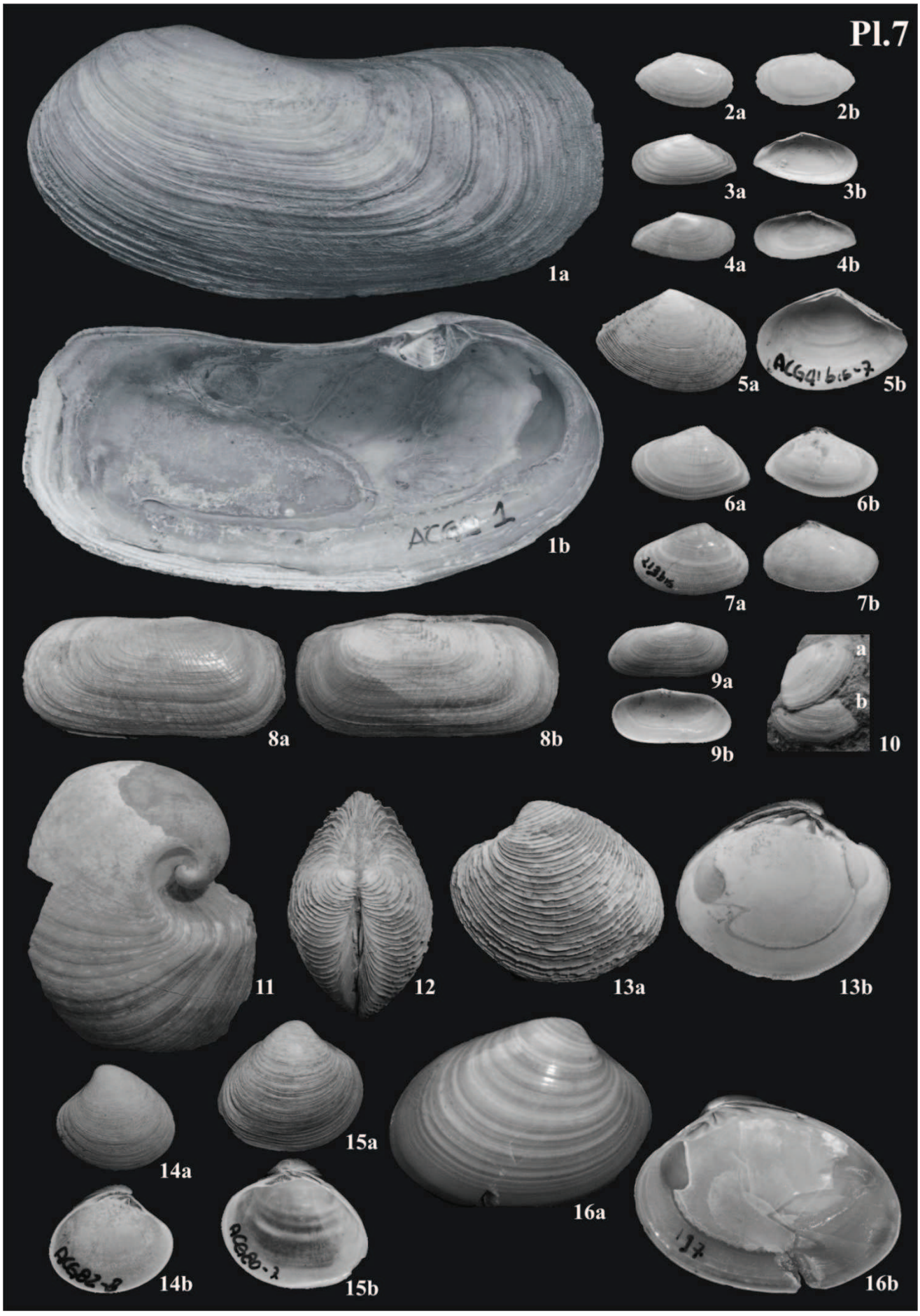
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PLATE 8

All specimens are x1, except when indicated; (a) external view, (b) internal view.

(1) *Pelecyora brocchi*, left valve (ACG37-4);

(2a-b) *Chamelea gallina*, left valve (ACG207-6);

(3a-b) *Dosinia lupinus*, left valve (ACG248-1);

(4a-b) *Chamelea gallina*, left valve (ACG90-15);

(5a-b) *Clausinella fasciata*, right valve, x2 (ACG25-10);

(6a-b) *Clausinella* sp., right valve, x2 (ACG23-8);

(7a-b) *Dosinia lupinus*, right valve (ACG235-8);

(8a-b) *Polititapes senescens*, left valve (ACG242bis-1);

(9a-b) *Polititapes rhomboides*, left valve (ACG200-16);

(10a-b) *Polititapes* cf. *P. rhomboides*, left valve (ACG237-6);

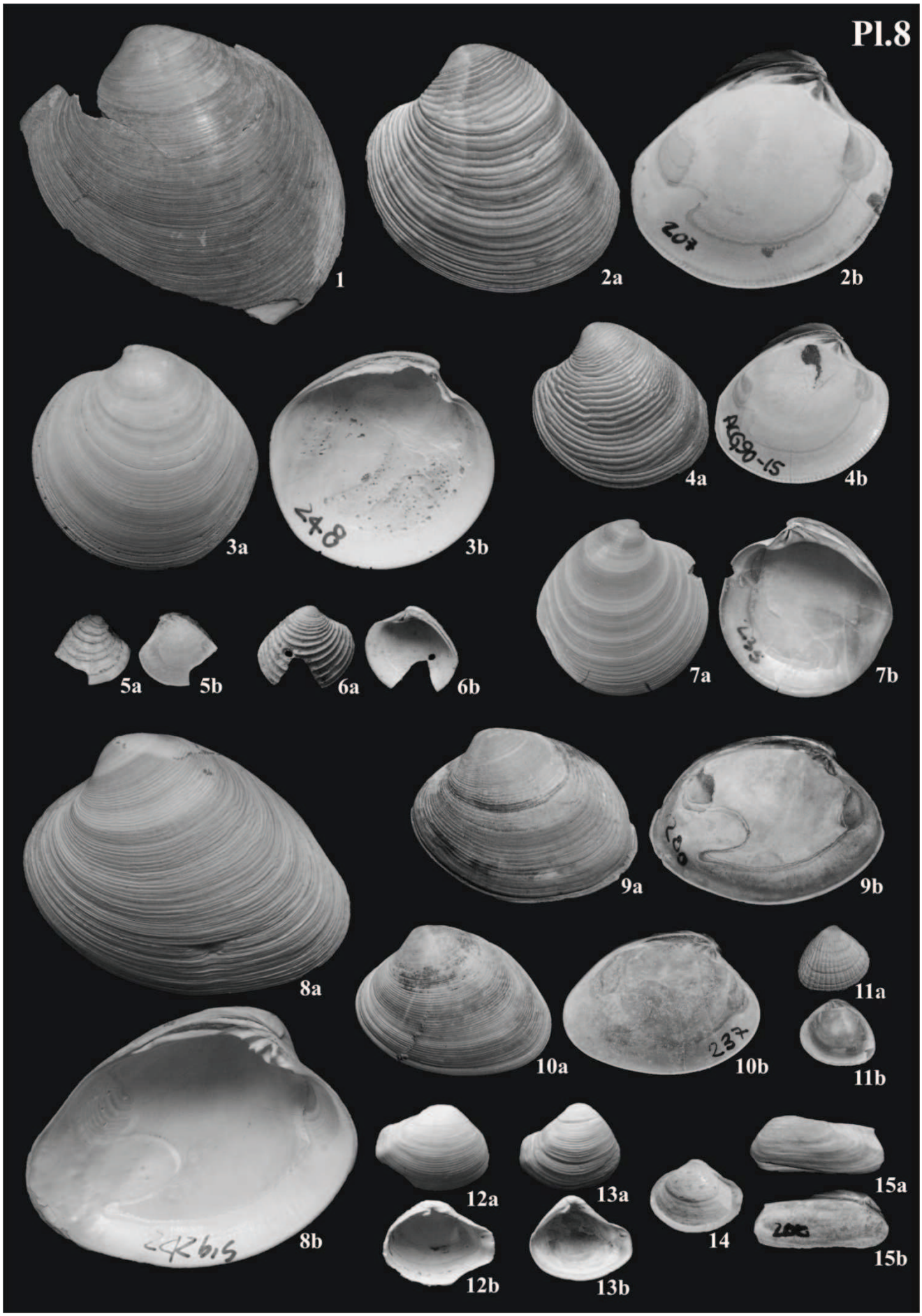
(11a-b) *Timoclea ovata*, right valve (ACG200-17);

(12a-b) *Corbula gibba*, right valve, x3 (ACG194-8);

(13a-b) *Corbula gibba*, right valve, x2 (ACG253-6);

(14) Articulated specimen of *Corbula gibba*, left valve view, x3 (ACG14-20);

(15a-b) *Hiatella rugosa*, left valve (ACG200-18).


Pl.8
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13b
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15a
15b

PLATE 9

All specimens are x1, except when indicated.

(1) *Panopea glycymeris*, right valve (ACG111-1);

(2a-b) *Pholas dactylus*, right valve, external view (a), internal view (b), x2 (ACG259-10);

(3) Fragment of *Pandora inaequivalvis* (ACG236-9);

(4) *Thracia* sp., right valve (ACG9-11);

(5a-b) *Thracia pubescens*, right valve, external view (a), internal view (b), x2, (ACG259-11);

(6) Tubular structure of *Clavagella* sp. (ACG195-8);

(7a-b) *Ostrea edulis*, right valve, external view (a), internal view (b) (ACG235-9);

(8a-b) *Ostrea* sp., right valve, external view (a), internal view (b) (ACG80-9);

(9a-b) *Diodora graeca*, apical (a) and lateral (b) views, x2 (ACG32-3);

(10a-b) *Calliostoma* cf. *C. conulus*, abapertural (a) and apertural (b) views, x2 (ACG56-13a);

(11a-b) *Jujubinus striatus*, abapertural (a) and apertural (b) views, x2 (ACG194-9);

(12a-b) *Jujubinus* sp., abapertural (a) and apertural (b) views, x2 (ACG194-10);

(13a-b) *Turritella tricarinata*, abapertural (a) and apertural (b) views (109-1);

(14a-c) *Diloma patulum*, apical (a), umbilical (b) and apertural (c) views (ACG53-23).


Pl.9
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14b
14c

PLATE 10

All specimens are x1, except when indicated; (a) abapertural, (b) apertural view, except when indicated.

(1) *Ostrea edulis*, articulated specimen (ACG133-5);

(2) *Capulus ungaricus*, lateral view of, x3 (ACG194-11);

(3a-b) *Aporrhais pespelecani* (ACG236-10);

(4a-b) *Calyptraea chinensis*, apical (a) and lateral views (b) (ACG41bis-10);

(5a-b) *Aporrhais uttingeriana* (ACG197-20);

(6a-c) *Calyptraea chinensis*, apical (a), umbilical (b) and lateral (c) views, x2 (ACG253-7);

(7a-c) *Calyptraea* sp., apical (a), umbilical (b) and lateral (c) views (ACG59-9);

(8a-c) *Xenophora crispa*, apical (a), umbilical (b) and lateral (c) views (ACG199-6);

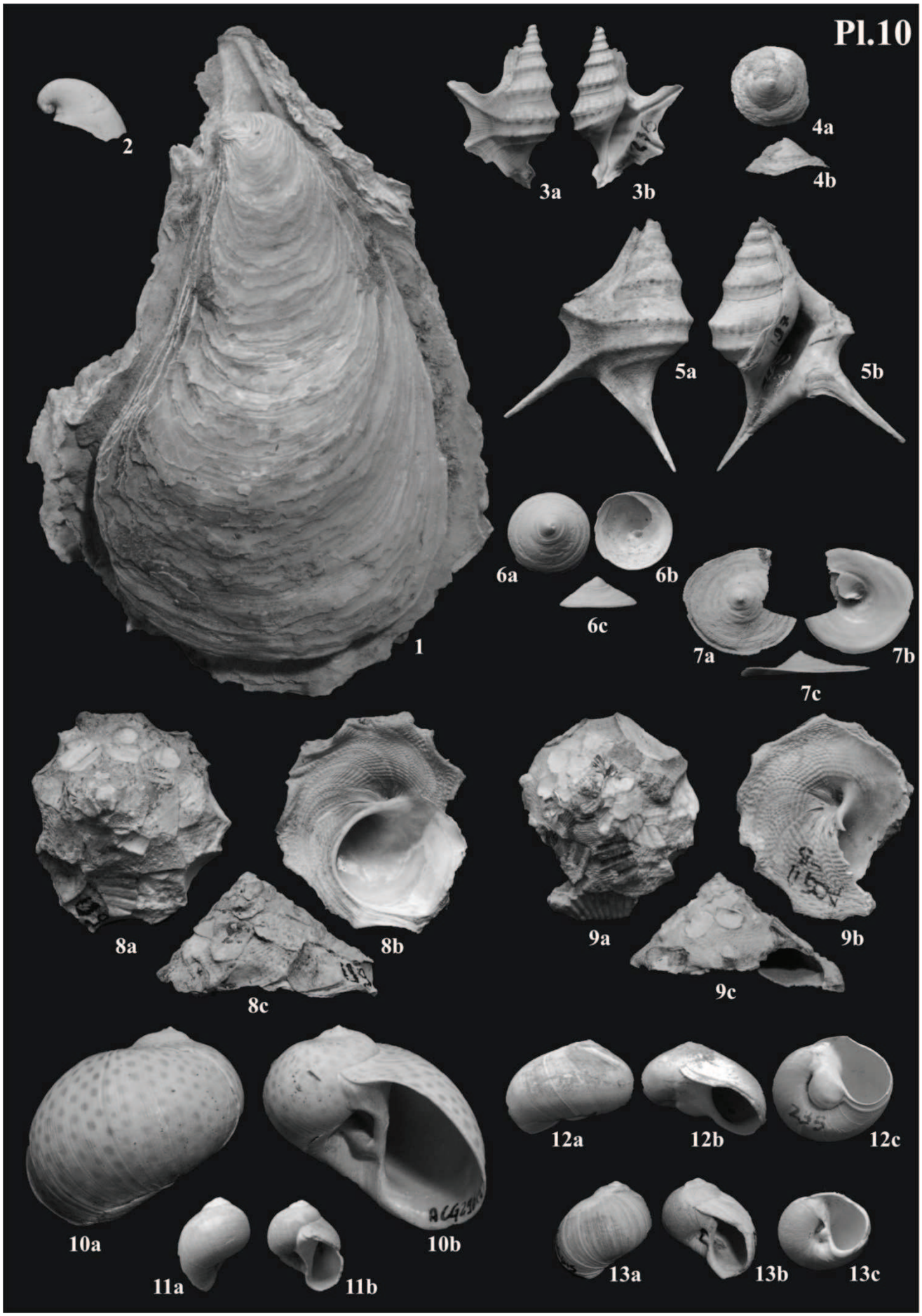
(9a-c) *Xenophora crispa*, apical (a), umbilical (b) and lateral (c) views (ACG11-5);

(10a-b) *Naticarius stercusmuscarum* (ACG29bis-20);

(11a-b) *Euspira* sp., x2 (ACG261-3);

(12a-c) *Neverita josephinia*, umbilical view (c) (ACG235-10);

(13a-c) *Naticarius* sp., umbilical view (c) (ACG256bis-4).


Pl.10
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8c
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9c
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10b
11a
11b
12a
12b
12c
13a
13b
13c

PLATE 11

All specimens are x1, except when indicated; (a) abapertural, (b) apertural view, except when indicated.

(1a-b) *Galeodea echinophora* (ACG200-19);

(2a-b) *Epitonium tiberii* (ACG220-1);

(3a-b) *Epitonium turtonis* (ACG198-10);

(4a-b) *Nassarius* cf. *N. gibbosulus* (ACG258-1);

(5) *Bolinus* sp. (ACG133-6);

(6a-c) *Neverita josephinia*, umbilical view (c), x2 (ACG251-2);

(7a-b) *Nassarius musivus* (ACG258-2);

(8a-b; 9a-b) *Nassarius mutabilis* (235-11; 235-12);

(10a-b) *Nassarius obliquatus* (ACG53-21);

(11a-b) *Nassarius prysmaticus*, x2 (ACG56-13b);

(12a-b) *Nassarius* cf. *N. conoidalis* (ACG10-3);

(13a-b; 14a-b) *Nassarius semistriatus*, x 2 (ACG41bis-8a, ACG41bis-8b);

(15a-b) *Nassarius* sp. (ACG43-6);

(16a-b) *Mitra* sp., x2 (ACG207-7);

(17a-b) *Acteon semistriatus* (ACG235-13);

(18a-b) *Ringicula auriculata*, x3 (ACG198-11);

(19a-b) *Cylichna cylindracea*, x3 (ACG263-6);

(20a-b) *Conus ventricosus* (ACG28-5);

(21a-b) *Conus* sp., x2 (ACG29bis-43);

(22) *Pyramidella* sp. (ACG102-4);

(23a-b) Echinoids indet., apical (a) and oral (b) views, x3 (ACG26-10);

(24) *Cladocora* sp. (ACG200-20);

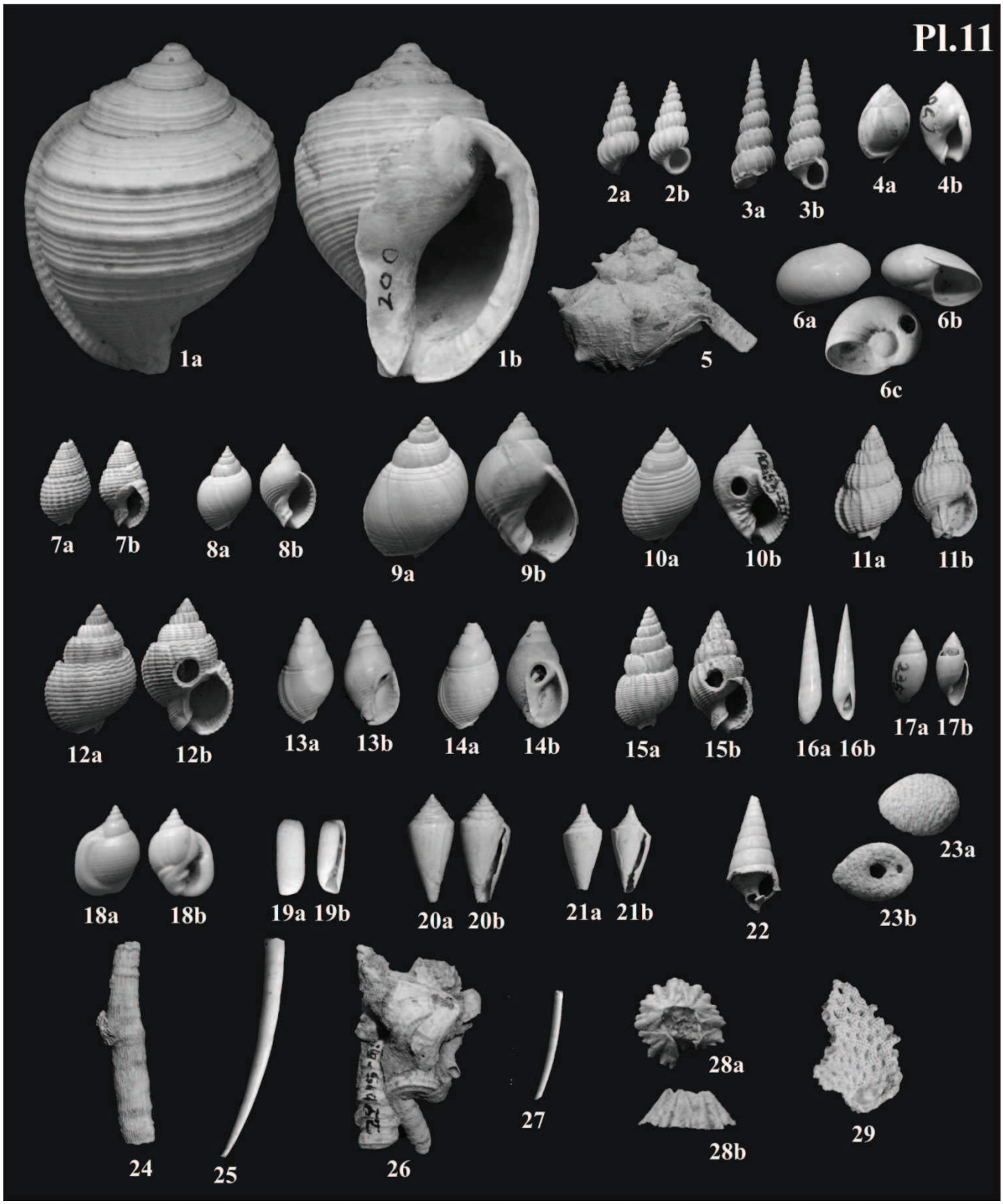
(25) *Dentalium* sp. (ACG29-4);

(26) *Serpulorbis* sp. (ACG29bis-41);

(27) *Ditrupa* sp. (ACG95-4);

(28) Barnacle indet., top (a) and lateral (b) views (ACG25-17);

(29) Bryozoa indet. (ACG199-7).


Pl.11
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Chapter 4

Biostratigraphy and dating of the Arda section

Previous works (e.g. Dominici, 2001; Monegatti et al., 2001) inferred an Early Pleistocene age for the biota of the Arda section, mostly based on the comparison with the more famous and studied Stirone River Section (Dominici, 2001; Gunderson et al., 2012), cropping out 10 km SE, which has very similar biota. In this chapter an integrative biostratigraphic analysis is presented based on mollusks and nannofossils from the Arda succession.

The analysis of the mollusk fauna was carried on by the writer (Crippa & Raineri submitted); nannofossil analysis was undertaken by Dr. C. Bottini and Prof. E. Erba from Dipartimento di Scienze della Terra 'A. Desio', Università di Milano and by Prof. I. Raffi from DiGAT-CeRS Geo, Università di Chieti-Pescara. An attempt to date the bivalve shells and coral skeletons with Uranium-Lead method was done by Prof. R. Parrish and Dr. N. Roberts from NIGL (NERC Isotope Geoscience Laboratory) of British Geological Survey, Keyworth, UK. In the meantime, magnetostratigraphic analyses are in progress by Prof. G. Muttoni and Dr. E. Monesi from Dipartimento di Scienze della Terra 'A. Desio', Università di Milano.

4.1 Mollusk fauna

The Arda mollusk fauna is mainly composed of species which make their first appearance in the Miocene (Tortonian) or in the Early Pliocene (Raffi et al., 1985); this fauna established in the Mediterranean Sea after the Messinian salinity crisis when normal marine waters invaded the basin

from the Atlantic (Raffi et al., 1985). The majority of the species found in the Arda River succession belongs to the modern mollusk fauna currently thriving in our seas. Among the Arda biota there are, however, species which make their first appearance or become extinct during the time of deposition of the section, and these represent a useful tool to better constrain the age of the marine succession.

The analysis of the biostratigraphic significance of the range of the species of the Arda fauna is made difficult by two main problems: 1. Available literature, as data on ranges of extinct species are very fragmentary and confusing as often several authors give a different time of disappearance for the same species (often referring to local extinction); see for example the case of the bivalves *Chama placentina* and *Glycymeris inflata* described below. 2. Sampling bias, as macrofossils are discontinuously occurring along the section; when rare they may have not been found during sample collection (Signor-Lipps effect) (Signor & Lipps, 1982).

4.1.1 Bioevents and age determination

It has been possible to identify fifteen species of bivalves and gastropods disappearing along the section; the most significant ones are illustrated in Fig. 4.1.

Pecten flabelliformis and *Aequipecten scabrella* disappear in the succession respectively at 0.15[1] m and at 45.65 m; according to Monegatti & Raffi (2001) they become extinct at 2.1 Ma.

Chama placentina, Glycymeris inflata and *Amusium cristatum* disappear in the section well before the FO of *A. islandica* (respectively at 0.15 m, 37.05 m and 42 m). This is in agreement with the findings of Raffi (1986) and Monegatti & Raffi (2001) who suggested that these species get extinct in the Mediterranean Sea at 1.8 Ma; however, some authors observed that they survive also after this time interval and they probably die out at the end of the Early Pleistocene (Greco, 1970; Caprotti, 1972).

The bivalves *Barbatia mytiloides* and *Nucula placentina* disappear in the Arda section respectively at 132.25 m and 185.70 m, while the gastropods *Diloma patulum, Nassarius obliquatus, Aporrhais uttingeriana* and *Nassarius prysmaticus* disappear in the section respectively at 70.02 m, 133.25 m, 172.70 m and 221.40 m; according to several authors (Caprotti, 1972; Marasti, 1973; Malatesta, 1974; Raffi, 1986; Taviani et al., 1997; Monegatti & Raffi, 2001) these taxa get extinct at the end of the Early Pleistocene and this seem to be in agreement with my findings.

Turritella tricarinata disappears at 224.20 m in the section. This species has three sub-species: *T. tricarinata tricarinata, T. tricarinata pliorecens* and *T. tricarinata communis*, which differ by few characters in the ornamentation and by the outline of the aperture (see Borghi & Vecchi, 2005).

1. 0.15 m from the base of the section. From this point on, all the metres values are referred from the base of the section.

The Arda specimens are most similar to *T. tricarinata tricarinata* and *T. tricarinata pliorecens* rather than to *T. tricarinata communis*, although it is not possible to discern between the former two species. In particular, the latter is considered a Recent subspecies, whereas the former are mainly Miocene-Pliocene and Lower Pleistocene subspecies. For these reasons I consider *T. tricarinata* as a species which gets extinct at the end of the Early Pleistocene.

Pelecyora brocchi, Polititapes senescens and *Nassarius musivus,* disappearing in the Arda section respectively at 58.35 m, 218 m and 231.90 m, probably disappear after the Early Pleistocene, but no exhaustive information is available for these species (Buccheri, 1970; Monegatti & Raffi, 2001; Garilli, 2011).

The same holds true for *Nassarius semistriatus,* disappearing at 54.10 m, as Bouchet (2011) in WoRMS (www.marinespecies.org, *N. semistriatus* corresponding page) observed that "the name *Nassarius semistriatus* has been misapplied during much of the 19th and 20th century to several Recent species from the North-East Atlantic and Mediterranean, while the true *Nassarius semistriatus* (Brocchi, 1814) is strictly fossil", but no data about the time of extinction is given.

A very important biotic event in the Arda succession is represented by the first occurrence of the bivalve *Arctica islandica* at 103.70 m from the base of the section, which until 2010 has been used to mark the Pliocene-Pleistocene boundary (Pelosio & Raffi, 1974; Raffi, 1986).

Raffi (1986) dated the first appearance of *Arctica islandica* into the Mediterranean Sea at the top of the Olduvai magnetic subchron at 1.67 Ma; however, this age has to be corrected as, after 1995, a new astronomically tuned time scale began to be used to define the magnetostratigraphic boundaries (Van Couvering, 1997); the new age for the top of the Olduvai subchron and the corresponding first appearance datum for *A. islandica* in the Mediterranean Sea is thus 1.77 Ma. According to Kukla et al. (1979) *A. islandica* first appears about 2.00 Ma ago in the Santerno Valley (Northern Italy), based on magnetostratigraphic evidence and radiometric age obtained by corals.

According to Rio et al. in Van Couvering (1997), the stratigraphically lowest level where *A. islandica* occurs seems to be right in the Arda and the Stirone sections; the first appearance of *A. islandica* in the Arda section should thus be bracketed between 1.77 and 2.00 Ma depending on the different interpretations discussed above. This species become extinct in the Mediterranean Sea around 9.8 ka (Dahlgren et al., 2000) but it is still living nowadays in the Atlantic Ocean along the American coast and in Europe along the coasts of Iceland, Great Britain and the Scandinavian peninsula (Dahlgren et al., 2000).

The presence of mollusks disappearing at the end of the Early Pleistocene in the upper part of the section and the lack of taxa of Middle Pleistocene age, allow to exclude a younger age for the Arda section cropping out downstream the bridge of Castell'Arquato. The stratigraphic ranges of the

bivalves and gastropods confirm a late Gelasian-Calabrian age (Early Pleistocene), for the Arda marine section.

4.2 Calcareous nannofossils

A total of 106 samples from the Arda section have been sampled by the writer and analyzed for nannofossil biostratigraphy (Crippa et al. in prep.) covering the interval comprised between 40 and 245 m. The analyses were performed by Dr. C. Bottini and Prof. E. Erba from Università di Milano and by Prof. I. Raffi from Università di Chieti-Pescara, on smear slides under polarizing light microscope (cross polarized, transmitted light and quartz lamina), at 1250X magnification. For each sample, nannofossils were semi-quantitatively characterized by examining at least 200 fields of view of the smear slide. A total of 4 samples (40, 75, 95, 206) were also studied at the SEM.

4.2.1 Preservation, abundance and assemblage composition

Calcareous nannofossil preservation is moderate to good throughout the entire studied interval. Nannofossil abundance increases upwards in the section, starting from rare to rare/frequent in the interval 40–110 m, and reaching common to common/abundant in the upper part of the section from 111 to 245 m.

The assemblages are characterized by the presence of small placoliths (e.g reticulofenestrids and gephyrocapsids <4 μm in size), *Pseudoemiliania lacunosa, Calcidiscus macintyrei, Helicosphaera sellii* and, in some intervals, by *Gephyrocapsa* ≥4 μm, and/or *Gephyrocapsa* >5 μm (see the description below). All these taxa are considered to be in situ. In addition, reworked Cretaceous and Cenozoic species have been detected in relatively high abundance. Among Cretaceous species we found for example *Amuhellerella octoradiata, Corollithion kennedyi, Eprolithus floralis, Prediscosphaera columnata, Lucianorhabdus cayeuxii, Eiffellithus turriseiffelii, Eiffellithus eximius, Micula decussata, Tranolithus orionatus, Arkhangelskiella cymbiformis, Reinhardtites levis, Nannoconus steinmannii, Biscutum constans, Discorhabdus rotatorius*, and many others. Reworked Cenozoic species consist of several species ranging from the Paleocene to Miocene as for example *Reticulofenestra bisecta, Reticulofenestra lockeri, Reticulofenestra minuta, Reticulofenestra pseudoumbilicus, Calcidiscus premacintyrei, Cyclicargolithus floridanus, Discoaster* sp. (6 to 11 rays), *Sphenolithus* sp., *Cruciplacolithus* sp., *Chiasmolithus grandis, Pontosphaera multipora, Fasciculithes* sp., *Calcidiscus leptoporus, Coccolithus pelagicus*.

The presence of reworked species in the assemblage was likely supplied to the Pleistocene Palaeoadriatic basin from the erosion of the Apennine chain.

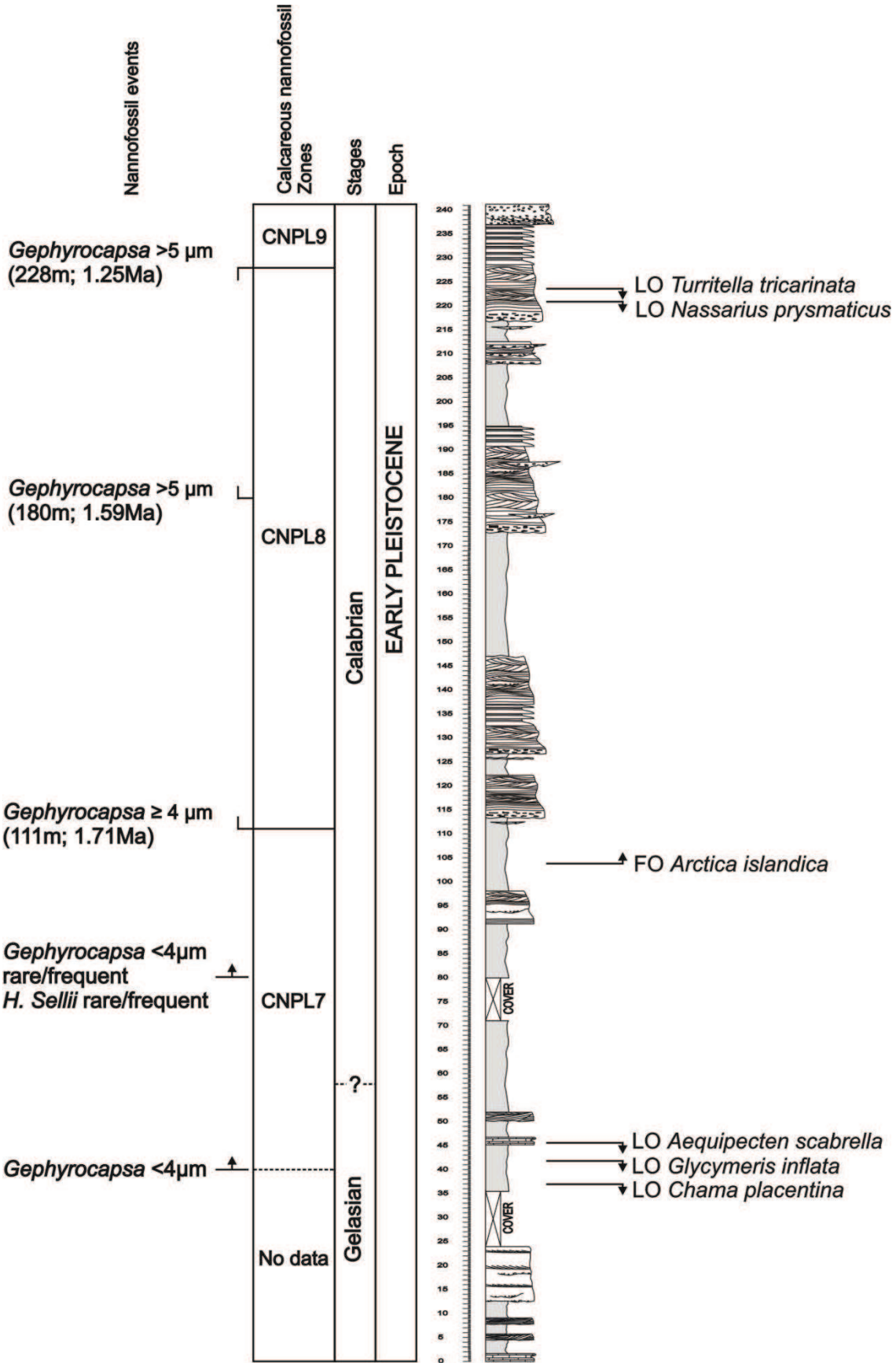

Fig. 4.1. Stratigraphic log of the Arda section showing the position of the most important bioevents based on nannofossil and mollusk biostratigraphy.

4.2.2 Bioevents and age determination

Calcareous nannofossil biozonations for the Cenozoic were developed by Martini (1971), Bukry (1973, 1975, 1978), Okada and Bukry (1980), and Backman et al. (2012). The scheme used in this work is the one proposed by Backman et al. (2012) although modified for the Pliocene/Pleistocene boundary that we placed at 2.58 Ma as indicated in the time scale of the International Commission on Stratigraphy (2014) (Fig. 4.2).

Gephyrocapsa specimens were classified following the informal taxonomic concepts established by Raffi et al. (1993), who divided Gephyrocapsids into: "small" *Gephyrocapsa* <4 μm, "medium" *Gephyrocapsa* ≥ 4 μm, and "large" *Gephyrocapsa* >5 μm.

The nannofossil events (First Occurrence - FOs, and Last Occurrence - LOs) recognized in the Arda section, allowed the identification of some of the biozones defined by Backman et al. (2012) and, consequently, the age determination of the studied part of the section (Fig. 4.1). The zones identified are ranging from Zone CNPL7 to the lower part of Zone CNPL9 corresponding to the early Pleistocene:

- The interval from 40 to 111 m is assigned to Zone CNPL7 due to the presence of *Gephyrocapsa* < 4 μm, but absent specimens of *Discoaster brouweri*. In this interval, the assemblages are also characterized by specimens of *H. sellii, C. macintyrei* and *P. lacunosa*.
- The interval from 111 to 228 m is assigned to Zone CNPL8 (1.71–1.25 Ma). Specifically, from 111 m specimens of *Gephyrocapsa* ≥ 4 μm are identified defining the base of the CNPL8 Zone. At 180 m, specimens of *Gephyrocapsa* >5 μm make their FO (dated 1.59 Ma). "Large" gephyrocapsids are found up to 228 m where they have their LO marking the top of Zone CNPL8.
- The interval from 228 to 245 m is assigned to the lower part of Zone CNPL9. The base of the Zone is marked by the LO of *Gephyrocapsa* >5 μm. From this level upwards specimens of *Gephyrocapsa* (< 4 μm) are accompanied by relatively abundant *P. lacunosa* and specimens of *H. sellii* thus suggesting that the section extends in the lowermost part of Zone CNPL9 below the LO of *H. sellii* and the FO of *Reticulofenestra asanoi* which has never been detected in the studied samples. The absence of *R. asanoi*, which FO has been dated as 1.14 Ma, indicates that the studied part of the Arda section is older than 1.14 Ma.

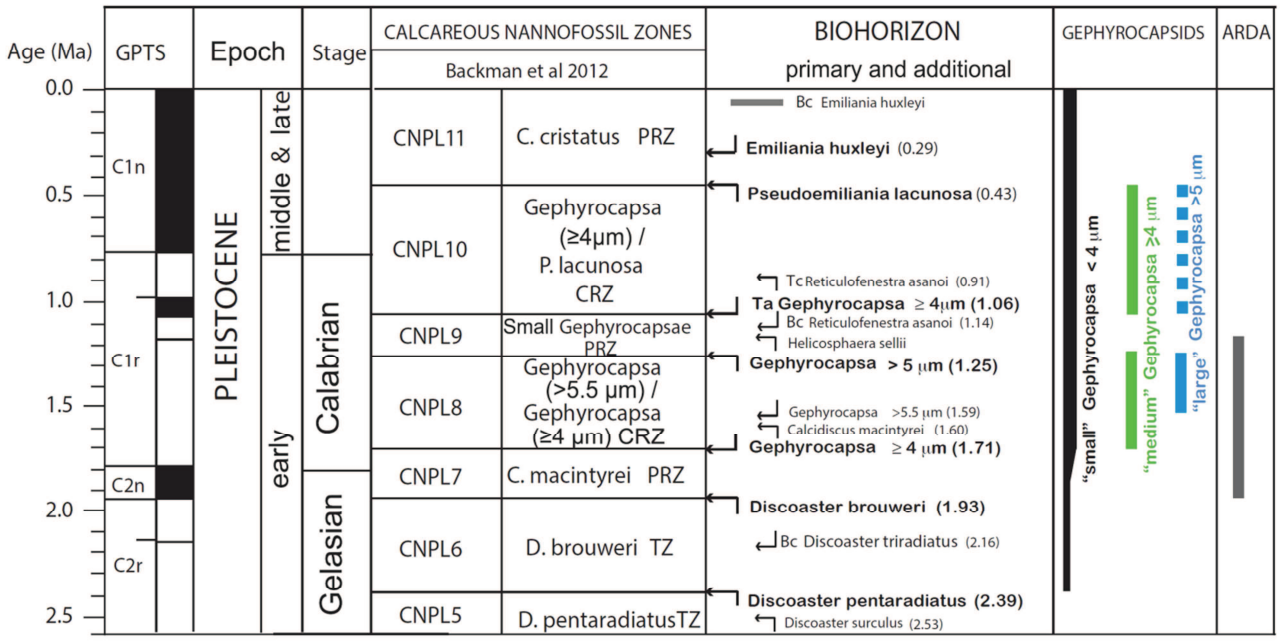

Fig. 4.2. Biostratigraphic scheme with calcareous nannofossil biozonations for the Pleistocene showing the bioevents and the biostratigraphic range of the Arda section according to its nannofossil content (modified after Backman et al., 2012).

4.3 Uranium-Lead dating

In addition to mollusks and nannofossils biostratigraphy an attempt to obtain a radiometric age has been made using the Uranium-Lead (U-Pb) dating method on aragonitic bivalves and corals of the Arda section. For this purpose, I selected three bivalves belonging to *Glycymeris inflata* (ACG14-25, 1.20 m) and *Arctica islandica* (ACG78-1, 103.70 m; ACG254-4, 224.30 m) and four corals belonging to *Flabellum* sp. (ACG9-18, 0.20 m; ACG9-16, 0.20 m) and *Cladocora* sp. (ACG200-19, 174m; ACG219-3, 187m) coming from different beds of the succession. Before doing the U-Pb dating analysis I performed several screening tests (SEM, Cathodoluminescence and X-ray Powder Diffraction) in order to check the preservation of the material (see Chapter 7).

4.3.1 Results and discussions

Screening tests confirm the good preservation of the specimens from the Arda succession. The results of each test are here briefly summarized (see Chapter 7 for details on the screening tests):

1) SEM: both bivalves and corals show a well preserved fabric with no trace of diagenetic alteration. One bivalve shell belonging to *Glycymeris inflata* (ACG14-25), although characterized by a well preserved ultrastructure, shows tubula perforations probably caused by bioturbation; for this reason I exclude this specimen from the analysis (Chapter 7, Fig. 7.1 P-R).

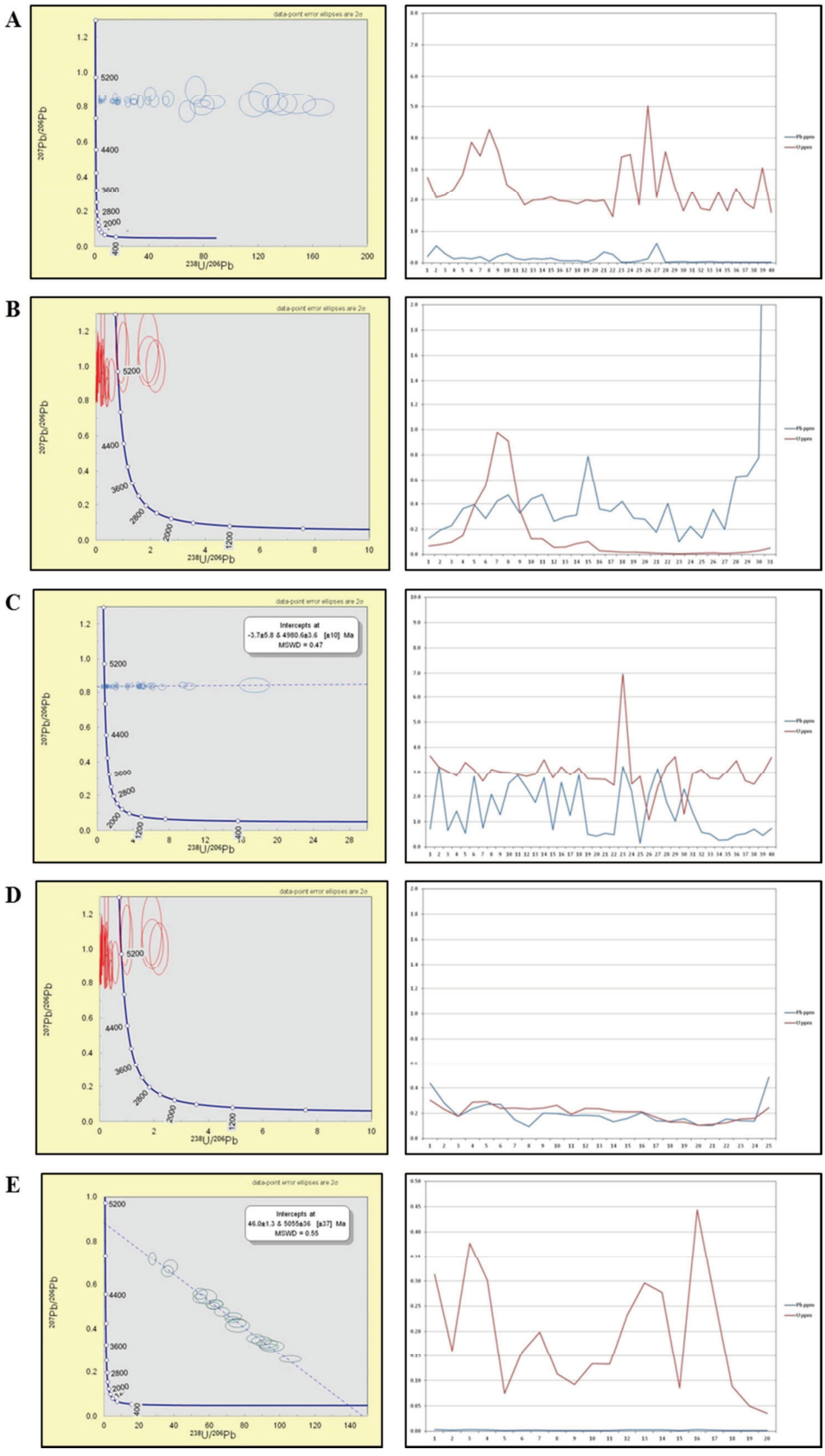

Fig. 4.3. These graphics show the Uranium (in red) and Lead (in blue) content in the Arda fossil skeletons (A-D) and an example of how it should be a material suitable for U-Pb dating coming from a calcite vein from the Faroe Islands (E). A) Moderate U content, but high initial Pb; *Flabellum* sp. (ACG9-16); B) Low U and comparably high initial Pb, *A. islandica* (ACG78-1); C) Moderate U content, but high initial Pb, *Cladocora* sp. (ACG200-19); D) Low U, and comparably high initial Pb, *A. islandica* (ACG254-4).

2) Cathodoluminescence: bivalve shells and coral sections are completely non luminescent; this means that the original structure is preserved and not altered by diagenetic processes (Chapter 7, Fig. 7.2 H, I).

3) X-ray Powder Diffraction: three bivalve shells (*G. inflata*, ACG14-25; *A. islandica*, ACG78-1; *A. islandica,* ACG254-4) and two corals (*Flabellum* sp., ACG9-16; *Cladocora* sp., ACG200-19) are all composed of original aragonite, with no trace of calcite or other elements. However, the other two corals (*Flabellum* sp., ACG9-18; *Cladocora* sp., ACG219-3) have aragonite in their skeletons, but with a small percentage of calcite and of other elements (probably coming from contamination with the matrix within the coral septa). To be sure and avoid contamination, I have analyzed for U-Pb dating only the three bivalves and the two corals composed of original aragonite.

All these analyses confirm that the specimens from the Arda succession have pristine aragonitic shells/walls. The next step for U-Pb dating is to test if the selected material has the favourable conditions for U-Pb dating, i.e. Uranium >0.30 ppm and very low common Pb. This test was made at NIGL (NERC Isotope Geoscience Laboratory) of British Geological Survey, Keyworth, UK by Prof. R. Parrish and Dr. N. Roberts. Unfortunately, despite the excellent preservation of the Arda material, this screening test highlight that the skeletons do not have the favourable conditions for the dating as they contain high Pb and usually low U (Fig. 4.3).

4.4 Conclusions

According to mollusk and nannofossil biostratigraphy the Arda River marine succession has an Early Pleistocene age. In particular:

- Mollusk fauna analysis gives a late Gelasian-Calabrian age, based on the last occurrence of the bivalves *Chama placentina, Glycymeris inflata* and *Aequipecten scabrella* in the basal part of the section, the first occurrence of *Arctica islandica* and the last occurrence of the gastropods *Nassarius prysmaticus* and *Turritella tricarinata.*
- Calcareous nannofossil analysis gives an entirely Calabrian age based on the recognition of the CNPL7, CNPL8 and CNPL9 zones.

This small incongruity in the age of the basal part of the section may be explained in two ways: a) a slightly longer persistence of the mollusk taxa in the Arda section; b) the difficulty in detecting the last occurrence of *Discoaster brouweri,* which define the basal boundary of the CNPL7. In fact, the highest stratigraphic range of this species is difficult to detect in deep water sections and it is almost impossible to document in the Apennine successions (Prof. I. Raffi pers. comm.). For these reasons the dating of the basal part of the section is not easy to define; taking into account these data the base of

Arda River succession may be older than 1.90 (based on nannofossils) - 2.10 (based on mollusks) Ma, while the top is not younger than 1.14 Ma.

Although unfortunately U-Pb dating gave no results, magnetostratigraphic analyses are in progress by Prof. G. Muttoni and Dr. E. Monesi from Dipartimento di Scienze della Terra ‘A. Desio’, Università di Milano, which may provide other chronologic data for the Arda succession.

PALAEOCLIMATIC SIGNIFICANCE OF THE ARDA BIOTA

Chapter 5

The climate during the Early Pleistocene: state of the art

The Early Pleistocene (2.58 – 0.78 Ma; ICS, 2014) was an interval characterized by several climatic oscillations related to glacial/interglacial cycles with obliquity as the dominant forcing parameter.

These climatic perturbations caused several cooling events, producing an increase in the ice cap thickness and significant sea level drops; evidence from the main positive excursions of the marine oxygen isotope curve and from sediments and fossils of different localities in the world confirm these climatic oscillations (e.g. Ghinassi et al., 2004; Clark et al., 2006).

The lower and upper boundaries of this time interval coincide with two important climatic events (Fig. 5.1):

1) the Northern Hemisphere Glaciation (NHG), which marks the Pliocene-Pleistocene boundary (2.58 Ma); it represents a global climatic change marking the onset of major glaciations in the Northern Hemisphere, recorded by the oxygen isotope shift in the oceans (Marine Isotope Stage 103) (Raymo et al., 1992; Shackleton et al., 1995). During this interval, expansion of ice sheets in the Northern Hemisphere is recorded by an increase of ice rafted debris in the Atlantic Ocean (Kennett, 1982; Warnke et al., 1992). Also, stable isotopes indicates cooling of deep water in the North Atlantic (Shackleton et al., 1984), South Atlantic and Mediterranean Sea (Thunell, 1979) and a progressive decrease of temperatures began also in the Southern Hemisphere (Hornibrook, 1992). Furthermore, shifts toward more arid conditions in Africa are recorded by an increase of eolian dust in the Atlantic and Arabian sea sediments (de Menocal, 1995) and by a strong degradation in tree cover (Bonnefille, 1995); tundra spread over north and central Europe (Martini et al., 2001) and loess began to be

deposited in northern China (Kukla & An, 1989). 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.

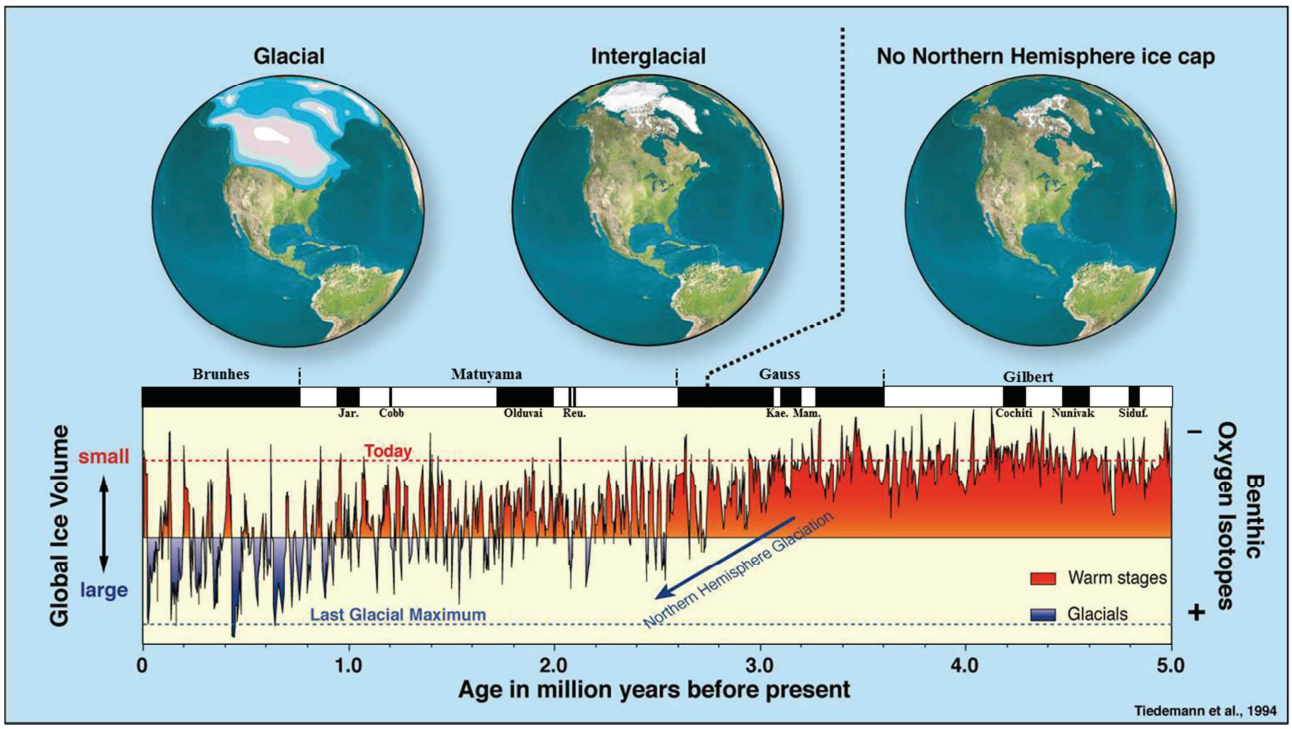

Fig. 5.1. Palaeoclimatic oscillations from the Miocene to the recent. Modified after Capotondi, 2011 and Tiedermann et al., 1994.

2) the Middle Pleistocene Transition (MPT) (1.25-0.70 Ma), marking a world in which the dominant periodicity of climate cycles changed from 41.000 (obliquity dominated) to 100.000 years (eccentricity dominated). Its onset was accompanied by a decrease in sea surface temperatures in the North Atlantic (up to 9°C) (Ruddiman et al., 1989) and tropical-ocean upwelling regions (McClymont & Rossel-Mele, 2005), and by an increase in African (Tiedermann et al., 1994) and Asian aridity and monsoonal intensity (Clark et al., 2006). During the MPT, long-term average ice volume gradually increased by 50 m sea-level equivalent (Dwyer et al., 1995) and deep oceanic circulation and CO_2 content in the atmosphere decreased (Clark et al., 2006). The acme of the cooling is in correspondence of Marine Isotope Stage 22, which identify the first large continental glaciation of the Pleistocene in the Northern Hemisphere, characterized by an increase of global ice volume and by the first most prominent glacioeustatic lowstand of the Pleistocene with an unprecedented sea level fall of 120–140 m, similar in magnitude to that of the last glacial maximum (Muttoni et al., 2007).

The Mediterranean area was strongly affected by the Early Pleistocene climatic changes both in marine and continental settings. In marine environment important biotic events are represented by the disappearance of warm water taxa and by the occurrence of boreal guests (such as the bivalve *Arctica islandica*, the benthonic foraminifer *Hyalinea balthica* and the planktonic one *Neogloboquadrina pachyderma*) indicating significant cooling of the Mediterranean Sea (Raffi et al., 1985; Thunell et al., 1990; Zachariasse et al., 1990). Major changes occurred also in the vegetation and in the vertebrate faunas of the Italian Peninsula (Azzaroli, 1995; Bertini, 2001; Fusco, 2010). The Early Pleistocene is in fact characterized by floral alternations reflecting glacial and interglacial cycles (Bertini, 2003): 1) arid and cool climatic conditions with open vegetation with herbaceous taxa indicative of steppe-like conditions and coniferous forests (glacial) and 2) humid and warm-temperate climatic conditions with forest expansion of mesophilous deciduous taxa (interglacial). All these modifications in climate and vegetation affected large mammal assemblages with important turnovers in the Villafranchian mammal faunal communities (Palombo, 2007).

Chapter 6

Palaeoclimatic significance of the Arda biota

In this chapter the palaeoclimatic significance of the Arda biota is inferred from the analyses of its mollusk fauna and of its pollen content. This prepares the ground for the discussion on the palaeoclimatic evolution of the Arda marine succession based on geo- and sclerochemistry of its bivalve shells which will be illustrated in the following Chapters 8 and 9.

6.1 Mollusk fauna

The evolution of the biota of the Mediterranean basin has been strongly affected by Pliocene-Pleistocene climatic changes (Raffi et al., 1985). In the Arda section the most important biotic event from a palaeoclimatic point of view is the appearance of the boreal (or northern) guests. These organisms, mainly mollusks, ostracods and foraminifers, usually living nowadays at higher northern latitudes, migrated into the Mediterranean Sea through the Strait of Gibraltar in consequence of the climatic cooling beginning in the Calabrian (Garilli, 2011). Malatesta & Zarlenga (1986) and Raffi (1986) make an exhaustive discussions on boreal guests, their arrival and their distribution in the Mediterranean fossil communities and in the present seas.

Arctica islandica is the most famous boreal guest, but other important climatic indicators have been found in the succession: *Mytilus edulis, Pseudamussium septemradiatum* and *Acanthocardia echinata*, all of them appearing stratigraphically above *A. islandica*, which first occurrence is at 103.70 m from the base of the section. The latter is found nowadays at high latitudes in the Atlantic Ocean along the American coast and in Europe along the coasts of Iceland, Great Britain and the Scandinavian peninsula (Dahlgren et al., 2000) (for a detail discussion of the temperature range tolerated by *A.*

islandica see Chapter 3); according to Malatesta (1974), *Mytilus edulis* has a similar geographic distribution to that of *A. islandica*, whereas *Pseudamussium septemradiatum* and *Acanthocardia echinata* are now widespread in the eastern part of the Atlantic ocean from Iceland to Morocco coasts. However, their interpretation as boreal guests is not always straightforward and in fact only the bivalves *Arctica islandica* and *Pseudamussium septemradiatum* can be considered good markers in this regard.

The so called boreal guest *Acanthocardia echinata* has been reported by some authors to have been present in the Mediterranean Sea already since the Pliocene (e.g. Monegatti & Raffi, 2001); it is not clear though if the authors here refer to the *A. echinata echinata* or to the *A. echinata mucronata* subspecies; in fact the first is the Atlantic restricted taxon (considered a boreal guest by Malatesta & Zarlenga, 1986 and Raffi, 1986), whereas the latter is the typical Mediterranean subspecies. Nowadays they are considered synonyms and this may add problems to their interpretation. La Perna & D'Abramo (2009) gave a clarifying discussion on this topic observing that also *Acanthocardia echinata echinata* was already present in the Pliocene as shown in several records (Palla, 1966; Cavallo & Repetto, 1992). Thus, according to La Perna & D'Abramo (2009) *Acanthocardia echinata* should not be considered as a boreal guest; here I follow this interpretation.

According to Malatesta & Zarlenga (1986) *Mytilus edulis* appears in the Mediterranean Sea in the Calabrian. However, it is often difficult to distinguish it from *Mytilus galloprovincialis*, which is the typical Mediterranean form and thus not a boreal guest, as they both show great variation in shell shape due to environmental conditions (Seed, 1992) and they can also be hybridized (Skibinski et al., 1978). Gosling (1992) and Seed (1992, 1995) underscored that not a single morphological characteristic can be used to distinguish these *Mytilus* species. For these reasons it has been very difficult to distinguish the two species in the Arda section. However, specimens which I identified as *M. edulis* are usually found in the Arda section in stratigraphic levels with VTC species, usually living in quite deep water environment (see Chapter 3 for details). *Mytilus galloprovincialis* is, on the other hand, the most common *Mytilus* species found in shallow water in our seas (Mediterranean Sea); the fact that I found *M. edulis* associated with deep water fauna may support the correct identification of the species; in fact, in being a boreal guest, *M. edulis* usually lives in colder water; when it arrived in the Mediterranean Sea it began to colonize deep water setting, where temperatures were colder.

Taking into consideration these problematics, it seems that the only true boreal guests are the bivalves *Arctica islandica* and *Pseudamussium septemradiatum* to which *Mytilus edulis* may be added, keeping in mind the problems of identification.

Aside from the occurrence of the boreal guests, which are important palaeoclimatic indicators, the analysis of the fauna does not allow to have more precise palaeoclimatic information; in fact it is

mainly dominated by eurythermal species having a cosmopolitan distribution, including boreal to warm-warm temperate water species; the strictly arctic or tropical ones are instead absent from the associations.

6.2 Pollen analysis

In addition to the analysis of the mollusk fauna, also pollen may add important information to the palaeoclimatic evolution of the Arda section during the Early Pleistocene. Previous studies on the Italian successions indicated that during this time interval floral alternations reflect glacial and interglacial cycles: arid and cool climatic conditions 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 (Bertini, 2003).

The onset of glacial/interglacial cycles during the Early Pleistocene and especially the occurrences of cold glacial periods has favored a rise in steppic taxa, that have continued their expansion throughout the Pleistocene until the present time, marking step-wise declines in humidity and winter temperature. At the same time, forest diversity has decreased as a result of the progressive decline and loss of sub-tropical taxa during the Early and Middle Pleistocene. In particular the temperature decrease is retained one of the causes of the disappearance of several species from the fossil record (Martinetto et al., 2014).

138 pollen samples have been collected by the writer from the Arda section; the analysis of the samples is still in progress by Dr. M. Pound from Northumbria University, Newcastle upon Tyne, UK. Preliminary data seem to indicate two shifts in the pollen content: 1) from 91 m from the base of the section is observed a definite increase in seasonality and colder winters, shown by the increase in xerophytic plant pollen and microthermal plant pollen (mainly *Picea*); 2) from 110 m from the base of the section is noted a proportional drop in microthermal plant pollens, i.e. those which like cold winters, and in conifers (e.g. *Picea, Pinus*); this drop is accompanied by an increase in mesothermal plant pollen, i.e. those which like mild winters (e.g. *Carpinus, Quercus* and *Ulmus/Zelkova*), combined with an increase in herbaceous plants, mainly grasses and *Plantago*. This preliminary data suggest thus the presence between 91 and 110 m of an interval characterized by a high seasonality with taxa preferring colder winters, followed by an interval in which taxa preferring milder winters are dominant. More will become clear with a more complete pollen record than what is available for the moment, but preliminary data seem to support the periodical shifts in climate from cold/arid to warm/humid and underline that increase in seasonality was mainly related to winter coolings.

6.3 Conclusions

The occurrence of boreal guests, such as *Arctica islandica, Pseudamussium septemradiatum* and possibly also *Mytilus edulis*, suggests that a climatic change occurred in the Arda marine succession with a shift to colder seawater temperatures. In fact, increasing seasonality mainly achieved through colder winter temperatures may be the leading factor in driving their arrival and colonization of the Mediterranean Sea. Aside from the occurrence of boreal guests the fauna is mainly dominated by eurythermal species having a cosmopolitan distribution, including boreal to warm-warm temperate water species; the strictly arctic or tropical ones are instead absent from the associations.

Preliminary data from pollen analysis suggest that climatic oscillations linked to glacial/interglacial cycles occur also in the Arda flora with seasonality increasing through the section; in particular pollen data suggest the presence between 91 and 110 m of an interval characterized by a high seasonality with taxa preferring colder winters, which is followed by an interval in which taxa preferring milder winters are dominant, thus possibly indicating a glacial/interglacial oscillation.

All these data indicate that a climatic deterioration occurred during the deposition time of the Arda marine succession; climatic oscillations are linked to the Northern Hemisphere Glaciation dynamics and they prepared the ground for the onset of the continental glaciation of the Middle and Late Pleistocene.

In the next chapters the palaeoclimatic evolution of the succession will be analyzed using another proxy, the stable isotope composition of the bivalve shells occurring in the Arda section, which will complement the data obtained in the present chapter.

Chapter 7
Screening tests

Bivalves are among the best tools for palaeoclimatic and palaeoenvironmental reconstructions because they are known to precipitate their shells in isotopic equilibrium with the seawater in which they live, based both on researches on extant species (e.g. Berthou et al., 1986; Goodwin et al., 2001; Schöne et al., 2004; Strom et al., 2004; Schöne et al., 2005a; Wanamaker et al., 2008; Butler et al., 2013) and fossil representatives (e.g. Ivany et al., 2004; Scourse et al., 2006; Johnson et al., 2009; Schöne & Fiebig, 2009; Ivany & Runnegar, 2010; Kim et al., 2010). In particular, species of the genera *Glycymeris, Aequipecten* and *Arctica* have been shown to be deprived of vital effect and thus to be very suitable for isotope analyses (e.g. Schöne et al., 2005a; Hickson et al., 1999, 2000; Brocas et al., 2013; Royer et al., 2013; Schöne, 2013; Bušelić et al., 2015). For an exhaustive discussion on this topic see Chapters 8 and 9.

However, diagenetic processes may alter fossil bivalve shell geochemical composition; so it becomes important to check, by screening tests, if the shell is pristine, and thus effectively suitable to a correct interpretation of isotope analyses. In particular, screening tests are essential in this study as most of the analyzed shells are mainly aragonitic; aragonite is a metastable form of calcium carbonate and when the shell undergoes diagenetic alteration it is usually replaced by calcite. To assess shell preservation and thus the reliability of the isotope data, four different screening techniques were used: Scanning Electron Microscopy, Catholuminescence, X-Ray Powder Diffraction and Feigl's solution.

7.1 Scanning Electron Microscopy

7.1.1 Material and methods

I prepared for SEM analysis 245 fossil specimens belonging to the species *Glycymeris glycymeris*, *Glycymeris insubrica*, *Glycymeris inflata*, *Glycymeris* sp., *Aequipecten opercularis*, *Aequipecten scabrella*, *Arctica islandica*, *Flabellum* sp. and *Cladocora* sp. collected from the Arda succession and 3 recent specimens belonging to *Glycymeris glycymeris* and *Arctica islandica* from Brittany, France (*G. glycymeris*) and from Iceland (*A. islandica*).

Fossil specimens were selected in order to have, when possible, two bivalve shells belonging to two different species from each stratigraphic bed. All the specimens were cut longitudinally along the axis of maximum growth (the axis perpendicular to the growth lines). The obtained sections were then embedded in epoxidic resin, forming blocks which contains several sections of different shells; every block was polished, ground smoothed and etched with 5% chloridric acid for 15-20 seconds in order to reveal the detail of the ultrastructure; finally each block was coated with gold and observed at the SEM Cambridge S-360 with lanthanum hexaboride (LaB_6) cathodes at Dipartimento di Scienze della Terra 'A. Desio', Università di Milano.

7.1.2 Results and discussions

SEM analysis of the shells is important in order to detect if the fabric is pristine or if there is evidence of diagenetic alteration, as dissolution or the presence of sparry calcite. For a detailed description of the observed fabrics, see Appendix A. Here, I discuss the SEM preservation test undertaken on *Glycymeris, Aequipecten* and *Arctica* shells and on several coral specimens which were considered suitable for uranium-lead dating.

Glycymeris. Species of *Glycymeris* have an aragonitic shell with an outer crossed lamellar layer, an inner irregular and cone complex crossed lamellar layer and an irregular simple prismatic pallial myostracum (see also Appendix A.2.1); all the layers are penetrated by cylindrical tubules (Fig. 7.1, A-E). The comparative analysis of fossil and recent fabrics of several species of *Glycymeris* showed a consistent pattern, with the recent and fossils shells being almost identical. No traces of diagenetic alteration, such as dissolution, recrystallization or replacing by sparry calcite, have been observed in the analyzed shells. This allows to conclude that fossil specimens of *Glycymeris* from the Arda River succession are pristine and suitable for geochemical and isotopic analyses.

Aequipecten. Specimens belonging to species of the genus *Aequipecten* have a very complex ultrastructure, sometimes difficult to interpret due to the numerous layers that composed it. The shell is formed both by low magnesium calcite and aragonite, with the right and left valves having the same

ultrastructure and mineralogy (Fig. 7.1 F-K). They have three main layers in addition to the pallial myostracum: a calcitic foliated inner and outer layers and an aragonitic prismatic and crossed lamellar middle layer (see Appendix A.2.2). The shell ultrastructure of almost all the specimens belonging to species of *Aequipecten* is very well preserved and shows no diagenetic alteration; however, nine specimens coming from two cemented, yellowish-reddish sandstones present in the basal part of the section (Units A and D, see Chapter 3), have the original aragonitic middle layer replaced by diagenetic calcite. In specimens affected by diagenetic alteration the middle layer is leached and filled with sparry calcite (Fig. 7.1 J, K), as observed also by Zamarreño et al. (1996) in specimens of *Amussiopecten baranensis* from the Miocene of Spain; sparry calcite is often composed by polygonal, anhedral crystals, but may also be prismatic, as in the present case. In carbonate shells it forms during diagenesis by neomorphism of aragonite. Diagenetic alteration has thus been detected in five specimens belonging to the species *Aequipecten scabrella* (ACG2-5, ACG3-4, ACG4-6, ACG5-3, ACG6-8) and in four shells of the species *Aequipecten opercularis* (ACG2-2, ACG33-1, ACG34-1, ACG34-3). The isotopic values obtained from these specimens have therefore not been considered as equilibrium values and have been excluded from subsequent interpretations.

Arctica. *A. islandica* has an aragonitic shell with an outer homogenous/crossed lamellar/crossed acicular layer, an inner fine complex crossed lamellar layer and an irregular simple prismatic pallial myostracum (Fig. 7.1 L-O). As for shells belonging to the genus *Glycymeris*, the analyzed specimens of *A. islandica* have a well preserved fabric (see Appendix A.2.3), showing the characteristic aragonitic structure without evidence of diagenetic alteration. The comparative analysis of fossil and recent fabrics of specimens of *A. islandica* shows that the two are nearly identical, allowing to conclude that fossil specimens of *A. islandica* from the Arda River succession are pristine and suitable for geochemical and isotopic analyses.

Corals. The colonial coral *Cladocora* sp. and the solitary coral *Flabellum* sp. have an ultrastructure composed by aragonitic fibers radiating from calcification centers, in a spherulitic arrangement (Fig. 7.1 P-R). The fabric observed at SEM does not show any sign of diagenetic alteration suggesting that the aragonitic wall is pristine. This is an important starting point for the U-Pb dating (see Chapter 4).

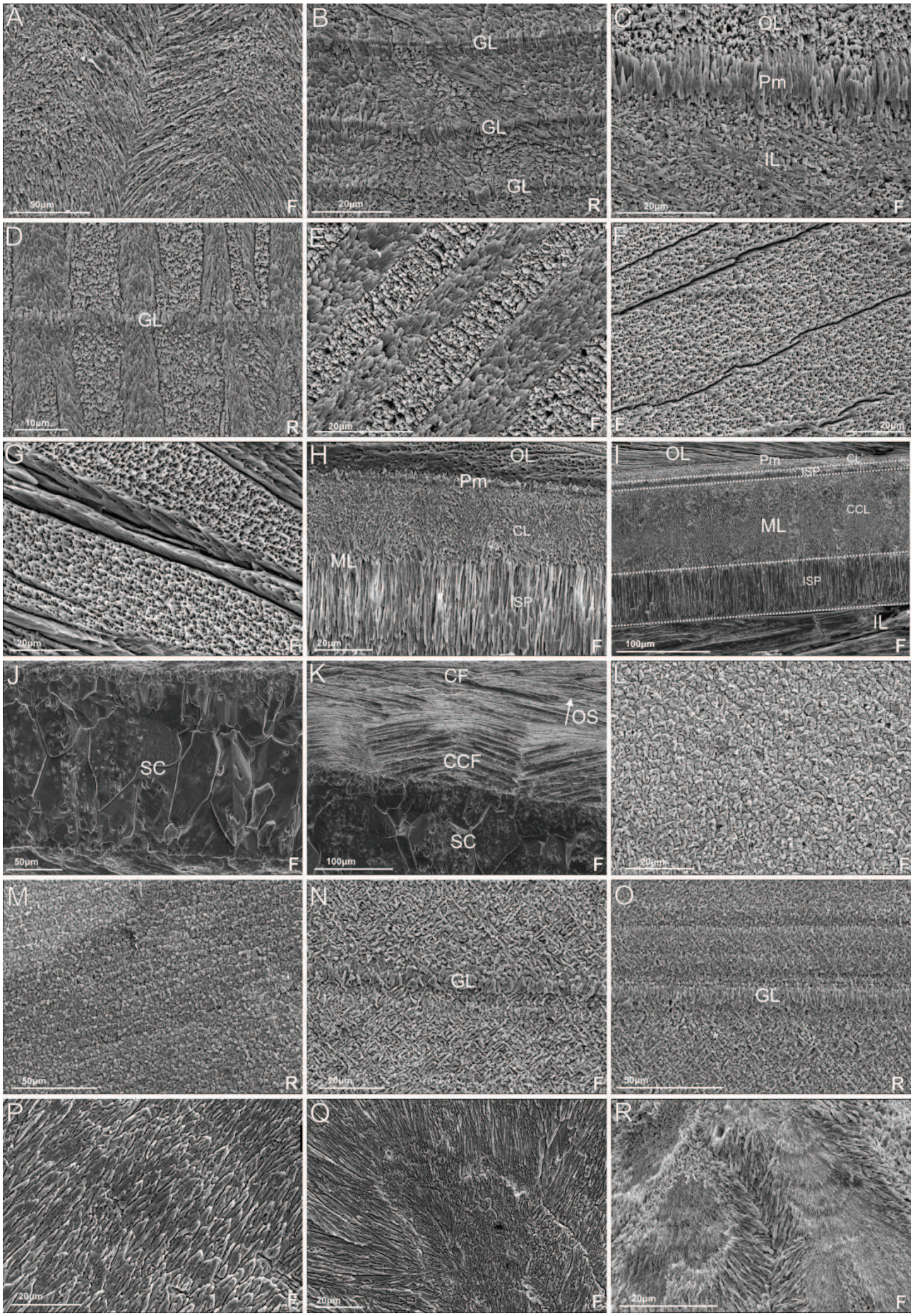
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Fig. 7.1 (previous page). Legend: CF: crossed foliated; CCF: complex crossed foliated; CL: crossed lamellar; CCL: complex crossed lamellar; GL: growth line; IL: inner layer; ISP: irregular simple prismatic; ML: middle layer; OL: outer layer; OS: outer surface; Pm: pallial myostracum; SC: sparry calcite. F: fossil specimen; R: recent specimen.
(A) Cone complex crossed lamellar inner layer. Fossil specimen of *Glycymeris insubrica* (ACG98-3). (B) Irregular complex crossed lamellar inner layer crossed by growth lines made of irregular simple prisms. Recent specimen of *Glycymeris glycymeris* (AG2). (C) Prismatic pallial myostracum. Fossil specimen of *Glycymeris insubrica* (ACG59-1). (D) First order lamellae of the outer layer crossed by a growth line. Recent specimen of *Glycymeris glycymeris* (AG1). (E) Well preserved crossed lamellae of the outer layer: first, second and third order elements are clearly observable. Fossil specimen of *Glycymeris glycymeris* (ACG14-4). (F) Regular foliated fabric of the inner layer. Right valve of *Aequipecten opercularis* (ACG70-3). (G) Crossed foliated fabric of the inner layer. Left valve of *Aequipecten opercularis* (ACG90-7). (H) Regular foliated outer layer, irregular simple prismatic pallial myostracum and, crossed lamellar and irregular simple prismatic pallial myostracum. Left valve of *Aequipecten opercularis* (ACG235-4). (I) Section showing the complex organization of the shell. The outer and inner layers are composed of a regular foliated fabric. The middle layer shows a double pattern of crossed lamellae (simple and complex) separated by a thin layer of irregular simple prisms; inward there is a thick layer of irregular simple prisms. Right valve of *Aequipecten opercularis* (ACG100-2). (J) Sparry calcite replacing the aragonitic middle layer in an altered shell. Left valve of *Aequipecten scabrella* (ACG6-8). (K) Middle and outer layer of an altered shell. Note the sparry calcite replacing the aragonitic crossed lamellae. Left valve of *Aequipecten scabrella* (ACG6-8). (L) Homogeneous outer layer. Fossil specimen of *Arctica islandica* (ACG228-1). (M) Homogeneous outer layer. Recent specimen of *Arctica islandica* (AG3). (N) Fine complex crossed lamellar inner layer crossed by an irregular prismatic growth line. Fossil specimen of *Arctica islandica* (ACG86-4). (O) Fine complex crossed lamellar inner layer crossed by an irregular prismatic growth line. Recent specimen of *Arctica islandica* (AG3). (P) Well preserved fibers. Fossil specimen of *Flabellum* sp. (ACG19-16). (Q) Well preserved fibers radiating from a calcification center. Fossil specimen of *Flabellum* sp. (ACG9-16). (R) Well preserved fibers radiating from calcification centers. Fossil specimen of *Cladocora* sp. (ACG200-10).

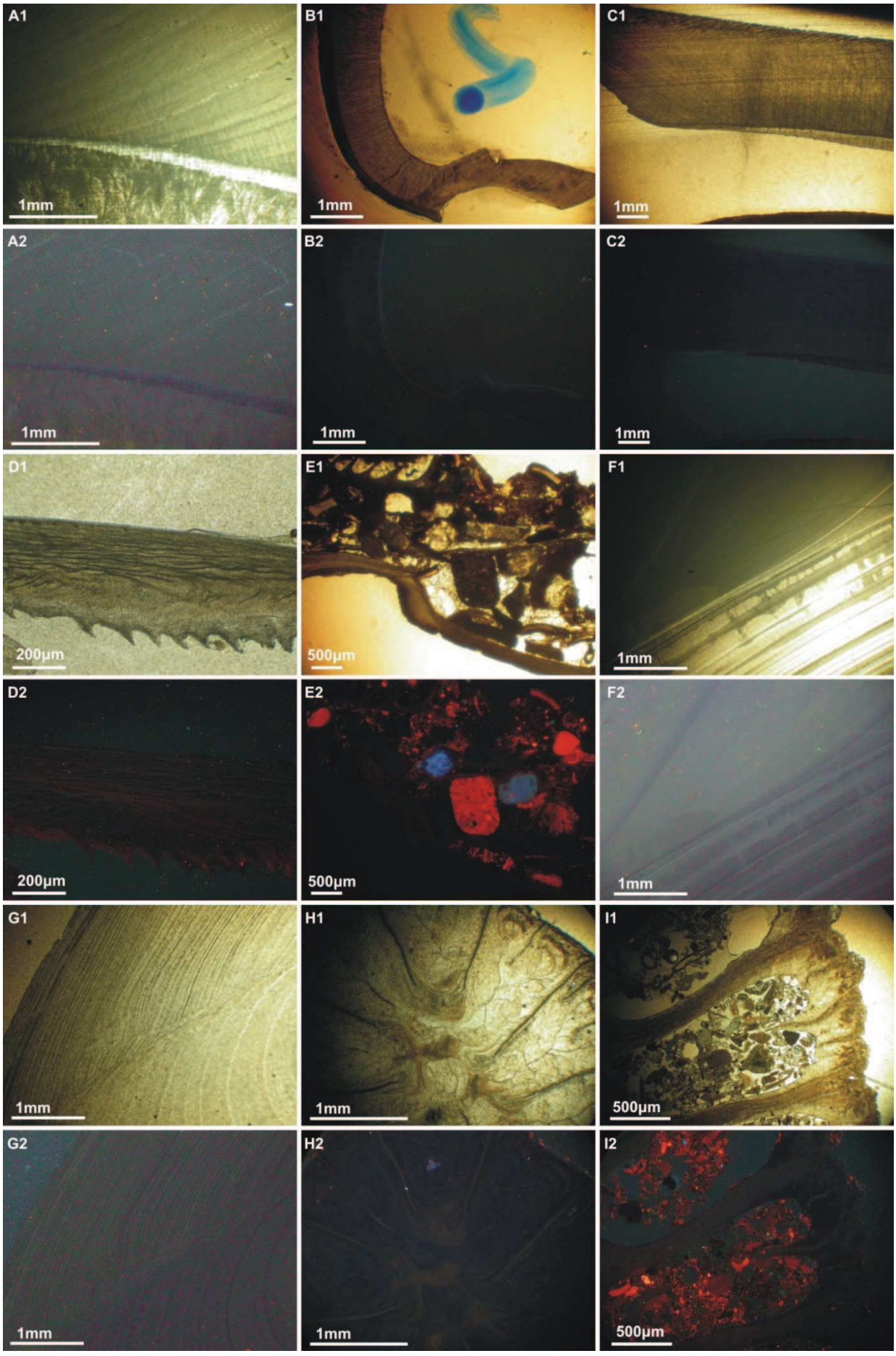
7.2 Cathodoluminescence

7.2.1 Material and methods

Ten thin sections, containing several bivalve shells and coral sections, were analyzed by cathodoluminescence by Prof. F. Jadoul at Dipartimento di Scienze della Terra 'A. Desio', Università di Milano. Cathodoluminescence was performed with a Nuclide ELM2 cold cathode luminoscope operating at 10 kV and a beam current of 5–7 mA. Electron beam exposure (before taking the photo) was on the order of 15–30 s for all specimens to minimize damage to the micro-fabric. Photographic exposure time was set to 2 s for consistency using a Nikon Coolpix 4500 operating at 400 ISO.

7.2.2 Results and discussions

This screening technique is widely used to assess the preservation of fossil shells as they commonly show no luminescence in the absence of significant geochemical alteration (Popp et al., 1986; Grossman et al., 1993; Elorza & Garcia-Garmilla, 1996; Angiolini et al., 2008). Manganese (Mn^{2+}) is the main activator of luminescence in carbonates, whereas Iron (Fe^{2+}) acts as a quencher (Elorza & Garcia-Garmilla, 1996); pristine shells are usually non-luminescent as Mn in natural environments is low. However, luminescence induced by natural levels of manganese derived from the ambient environment has been detected in both aragonitic and calcitic shells of mollusks (Barbin, 2000).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F2
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G1
1mm
H1
1mm
I1
500µm
G2
1mm
H2
1mm
I2
500µm

Fig. 7.2 (previous page). Transmitted light thin-section (1) and cathodoluminescence (2) photomicrographs. (A1-2) Non luminescent shell of *Glycymeris inflata* (ACG14-25); (B1-2) Non luminescent shell of *Glycymeris insubrica* (ACG31-1); (C1-2) Non luminescent shell of *Glycymeris glycymeris* (ACG27bis-8); (D1-2) Non luminescent shell of *Aequipecten opercularis* (ACG81-2); (E1-2) Non luminescent shell of *Aequipecten opercularis* (ACG34-1); note the luminescence of the matrix due to Mn-enriched diagenetic cements and recrystallized allochems; (F1-2) Non luminescent shell of *Arctica islandica* (ACG78-1); (G1-2) Non luminescent shell of *Arctica islandica* (ACG254-4); (H1-2) Non luminescent skeleton of *Flabellum* sp. (ACG9-16); (I1-2) Non luminescent skeleton of *Flabellum* sp. (ACG9-18); note the luminescence of the matrix within the coral septa caused by Mn-enriched diagenetic cements and recrystallized allochems.

Bivalve shells. They have a totally non luminescent shells, allowing to conclude that the original structure is preserved and not altered by diagenetic processes, and thus suitable for the subsequent geochemical analyses (Fig. 7.2 A-G).

Corals. They show completely a non luminescent skeleton, so their original structure is probably preserved and not altered by diagenetic processes, and thus suitable for the subsequent U-Pb dating (Fig. 7.2 H, I). Worthy of note is the contrast between the non luminescent coral skeleton and the high luminescence of the matrix within the coral septa (Fig. 7.2 I), caused by Mn-enriched diagenetic cements and recrystallized allochems.

7.3 X-Ray Powder Diffraction

7.3.1 Material and methods

Small amount of powders (~0.1 gr.) were collected from 65 bivalve shells, belonging to species of *Glycymeris* and *Arctica*, and from four corals (*Cladocora* sp. and *Flabellum* sp.) using a microdrill (Dremel 3000) equipped with a 300-μm tungsten carbide drill bit at Dipartimento di Scienze della Terra 'A. Desio', Università di Milano. The powders were then deposited on glass sample holders and fixed with acetone; finally, they were qualitatively analyzed at the X-ray powder diffractometer in the laboratory of Dr. M. Dapiaggi at Dipartimento di Scienze della Terra 'A. Desio', Università di Milano. Some analyses were also performed at the NERC Laboratory of British Geological Survey, Keyworth, England by P. Sayce during his Master Thesis under the supervision of Prof. M. Leng.

7.3.2 Results and discussions

The qualitative analysis at the X-ray powder diffractometer allows to distinguish between aragonite and calcite. In particular, as aragonite is a metastable form of calcium carbonate it is usually replaced by low magnesium calcite during fossil diagenesis; for these reasons I checked for preservation mainly specimens belonging to species of *Glycymeris* and *Arctica*, whose shells are entirely aragonitic, as well as the scleractinian corals.

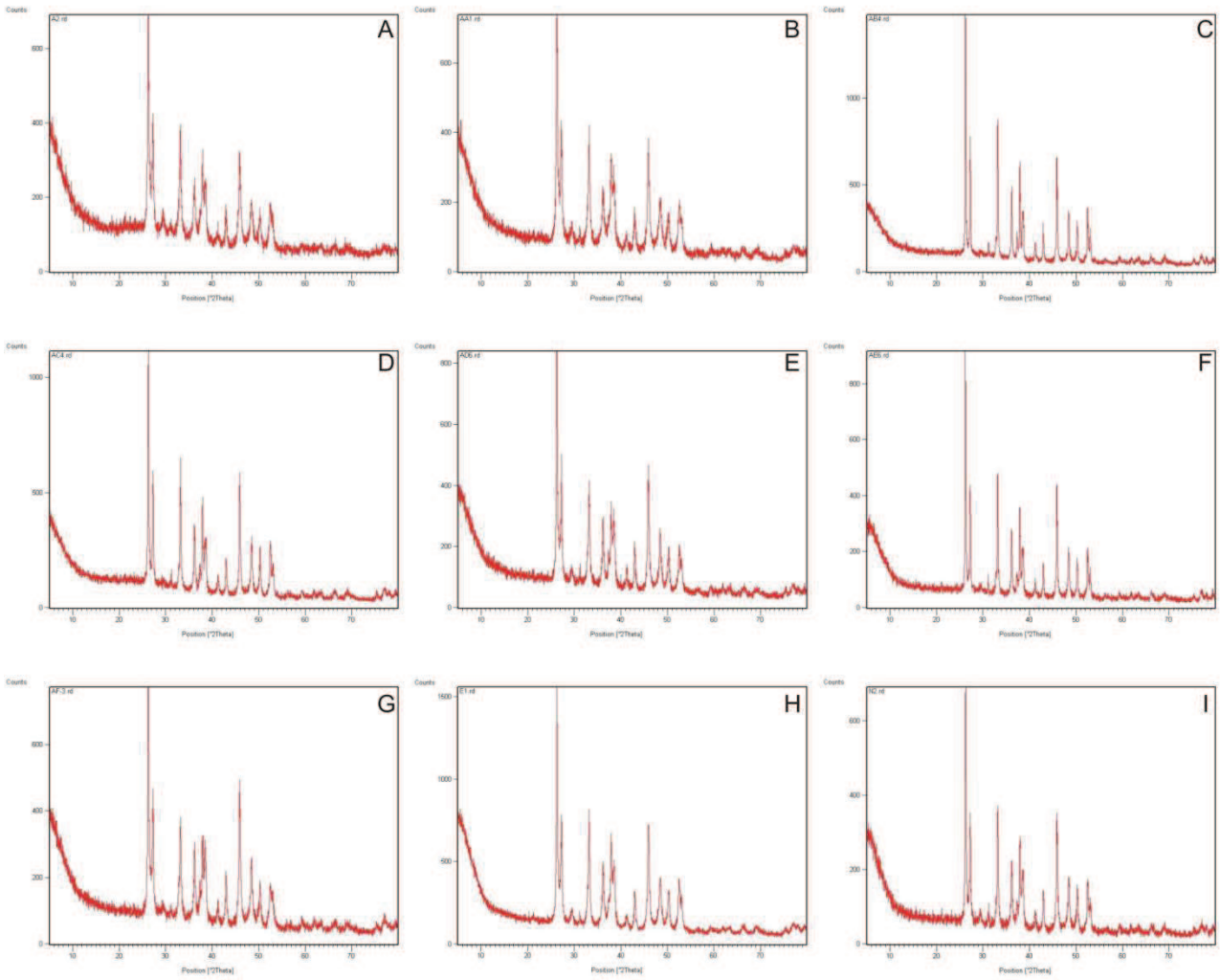

Fig. 7.3. Diffractograms of nine bivalve shells belonging to: one recent specimen of *Glycymeris glycymeris* (Fig. A), five fossil specimens of *Glycymeris insubrica* (Figs. B-D, F, I), one fossil specimen of *Glycymeris inflata* (Fig. H) and two fossil specimens of *Arctica islandica* (Fig. E, G). All these diffractograms indicate that the shells are entirely composed of 96-98% pure aragonite. Note the small peak present in quite all the specimens in correspondence of magnesium calcite (2Θ=29.452°), indicating the presence of very small impurities, which occur also in recent specimens.

Bivalve shells. All the shells analyzed show that they are composed of 96-98% pure aragonite. A small peak in correspondence of magnesium calcite (quantitatively less than 5%) is present in the diffractograms of almost all specimens, included the recent one (Fig. 7.3 A), indicating the presence of very small impurities, which however are not related to diagenetic processes (Fig. 7.3 A-I).

Corals. Two of the analyzed corals (ACG9-16, ACG200-19) are entirely made of aragonite. The other two (ACG9-18, ACG219-3), however, have aragonite in their skeletons, but with a small percentage of calcite and of other minerals (e.g. quartz, gypsum, lizardite), probably coming from the matrix within the coral septa. Although I collected the powders from the initial stage of growth of the corallite, it may be that some minerals from the matrix have contaminated the coral powders during the

sampling. The presence of trace of calcite in corals is, however, not unusual, as in fact it may be present in the initial framework on which the spherulitic clusters grow (Dodd & Stanton, 1990). However, to avoid problems of contamination, in the subsequent analyses I have selected for U-Pb dating only the two corals entirely consisting of original aragonite.

7.4 Feigl's solution

7.4.1 Material and methods

I followed the method of preparing the reagent described by Feigl (1937, p. 329) with the assistance of Dr. E. Ferrari from Dipartimento di Scienze della Terra 'A. Desio', Università di Milano, as follows: "1g of solid Ag_2SO_4[13] is placed in a solution of 11.8 grams $MnSO_4$ $7H_2O$ in 100 cc of distilled water, and boiled. On cooling, the mixture is filtered and one to two drops of dilute NaOH solution are added and the precipitate which forms is filtered after one to two hours. The solution should be kept in dark bottles." Nine bivalve shells were immersed in the solution for 30 minutes.

7.4.2 Results and discussions

This test has been arranged by Feigl (1937) and is based on the slightly different dissolution rates of calcite and aragonite in water, which produce differential etching between the two minerals. Aragonite stains black if immersed in this solution for less than 30 minutes (at room temperature), whereas calcite and dolomite remain unstained during limited exposure to Feigl's solution, as they take at least ten times as long to turn black. The black colour is due to a precipitate of manganese oxide and metallic silver. The analyzed specimens belonging to species of *Glycymeris* and *Arctica*, became all black (Fig. 7.4 J-M), confirming the aragonitic composition of their shells. Interesting results are obtained from shells of species of *Aequipecten,* which are composed by both aragonite and calcite; aragonite, which is present in the middle layer, around muscle attachment, and on the flanks of the resilifer, stains black, whereas the rest of the shell, which is calcitic, remains unstained (Fig. 7.4 A-I).
A poor preserved specimen of *Aequipecten scabrella* (Fig. 7.4 A) immersed in the solution did not become black in its aragonitic parts; this specimen was collected from cemented sandstones in the lower part of the section (Unit A, see Chapter 3), where also other specimens of species of *Aequipecten* show the middle aragonitic layer displaying diagenesis, in this case leached and replaced by sparry calcite (SEM observations, this chapter; Appendix A.2.2).

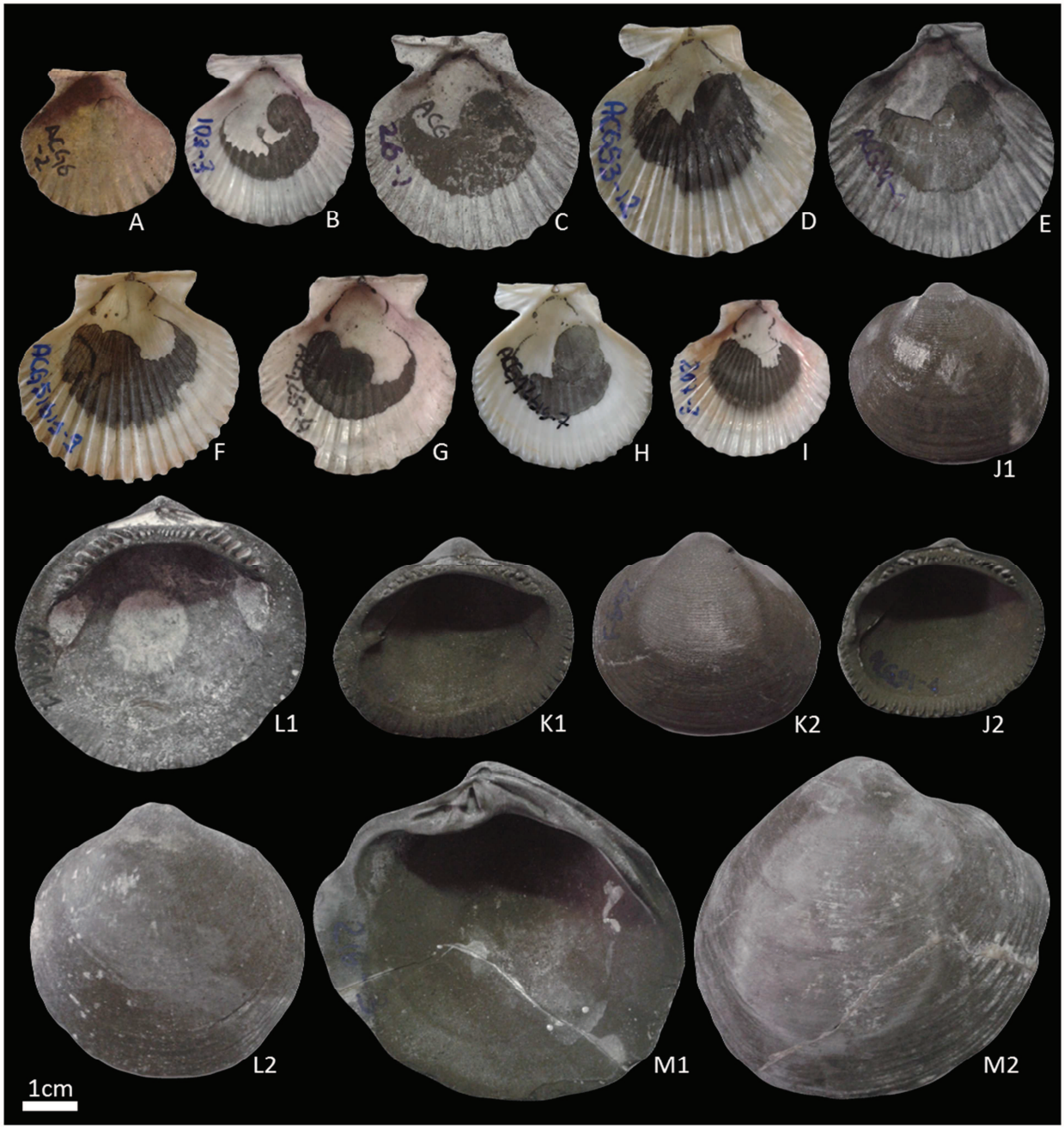

Fig. 7.4. *Aequipecten, Glycymeris* and *Arctica* specimens after the treatment in the Feigl's solution. All specimens are x1. (A) *Aequipecten scabrella* (ACG6-2), poorly preserved specimen, probably with aragonite not preserved in its middle layer as it does not stain black. (B-I) *Aequipecten opercularis* (ACG26-1, ACG103-3, ACG53-12, ACG84-4, ACG51bis-9, ACG25-4, ACG42bis-7, ACG207-3), all these specimens show that the aragonitic middle layer is preserved as indicated by the black staining. (J-K) *Glycymeris insubrica* (ACG91-4, ACG264-3), black shells indicating that aragonite is preserved. (L) *Glycymeris glycymeris* (ACG14-1), black shell indicating that aragonite is preserved. Muscle attachment and ligament area are grey or white; this is probably due to the presence of calcitic bioencrustation (e.g. bryozoan). (M) *Arctica islandica* (ACG216-3), black shell indicating that aragonite is preserved.

7.5 Conclusions

Crystal dissolution, sparry calcite and luminescent shells indicate that the shells underwent diagenetic changes through time, modifications which could not have been possible without geochemical changes of the original composition. Screening tests are thus essential before doing isotopic and geochemical analyses. As shown by Brand et al. (2011) for other proxies, the best way of assessing the degree of alteration of an individual specimen is to apply as many screening tests as possible. I have thus chosen to apply different screening tests in order to have more robust data on shells preservation.

The four different screening tests here undertaken (SEM microstructural examination, Cathodoluminescence, X-ray Powder Diffraction and Feigl's solution) indicate that bivalve shells and coral skeletons of the Arda River marine successions are very well preserved, except for a few specimens which are thus excluded from the geochemical and isotopic analyses. The excellent preservation is also shown by the well preserved color pattern and by the presence of the spiny fragile ornamentation; furthermore, in the majority of cases shells do not show the presence of microboring, which, in shallow water, usually indicates a prolonged exposure to biological or physical factors after the organisms death. This lack of microboring thus suggests a quick burial which has preserved the shells and their ornamentation (Parsons-Hubbard et al., 2014).

All these data allow to conclude that Arda shells are pristine and suitable for the subsequent geochemical and isotopic analyses and Uranium-Lead dating.