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Geochemical and sclerochronological analyses of the Lower Pleistocene macrofauna of Western Emilia (Northern Italy): palaeoenvironmental and palaeoclimatic implications

Ph.D. Thesis

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Abstract

The Early Pleistocene is a time interval characterized by several climatic oscillations which has its lower and upper boundaries coinciding respectively with the beginning of the Northern Hemisphere Glaciation and the Middle Pleistocene Transition. The Mediterranean area was strongly affected by the Early Pleistocene climatic changes. One of the most important biotic event is here represented by the appearance of the boreal guests (e.g. the bivalve *Arctica islandica* and the foraminifer *Hyalinea balthica*) at the beginning of the Calabrian Stage, suggesting significant cooling of the Mediterranean Sea, which is also confirmed by a change in the pollen flora indicating cold climatic conditions.

The Arda River marine succession, cropping out in Western Emilia, Northern Italy, is very rich in macrofossils and it covers without significant gaps the Early Pleistocene. It thus represents an ideal setting where to study the climatic oscillations of this time interval.

This study, combining sedimentology, taxonomy, palaeoecology, biostratigraphy and geochemistry and sclerochemistry of bivalve shells, provides an integrated investigation of the palaeoenvironmental and palaeoclimatic conditions accompanying these major climatic changes in the Arda section.

The Arda marine succession is 237.40 m-thick and consists of sandstones, siltstones and mudstones deposited in a tectonically active setting during phases of advance of fan deltas; it is bounded at the top by continental conglomerates indicating a major sea level drop and the establishment of a continental environment with vertebrate faunas and fresh water mollusks.

The taxonomic analysis of the macrofauna allows to identify 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. The comparative sedimentological and palaeoecological analysis shows that the Arda marine succession deposited in an infralittoral to a shallow circalittoral environment, where the maximum depth of the succession should not have exceeded 40-50 m. This comparative analysis confirms also the general regressive trend of the studied marine succession, punctuated by eight lower order transgressive and regressive cycles; however, no evidence of subaerial exposure or shift to water depths exceeding 50 m has been recorded, framing the depositional depth through the transgressive and regressive cycles between 5 m and 50 m of depth.

According to mollusk and nannofossil biostratigraphy the Arda River section has a late Gelasian-Calabrian (Early Pleistocene) age. The main mollusk bioevents comprise the last occurrences of *Chama placentina, Glycymeris inflata* and *Aequipecten scabrella* in the basal part of the section, the first occurrence of *Arctica islandica* at 103.70 m from the base and the last occurrence of the gastropods *Nassarius prysmaticus* and *Turritella tricarinata* in the upper part of the section. The identified nannofossil zones range from Zone CNPL7 to the lower part of Zone CNPL9.

The palaeoclimatic significance of the Arda biota has been investigated at two different levels: first the analyses of its mollusk fauna and of its pollen content and then a more detailed research involving geochemistry and sclerochemistry of the bivalve shells.
The occurrence of boreal guests, such as *Arctica islandica, Pseudamussium septemradiatum* and possibly also *Mytilus edulis*, from 103 m upward, suggests that a climatic change occurred in the Arda marine succession with a shift to colder seawater temperatures. However, aside from the occurrence of boreal guests, the fauna is mainly dominated by eurythermal species having a cosmopolitan distribution, lacking the strictly arctic or tropical ones. Preliminary data from pollen analysis suggest that a climatic change occurs also in the Arda flora; 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 shift.

To examine in detail the palaeoclimatic evolution of the Arda section, 249 fossil specimens from 141 stratigraphic beds belonging to *Glycymeris glycymeris*, *Glycymeris insubrica*, *Glycymeris inflata*, *Glycymeris* sp., *Aequipecten opercularis*, *Aequipecten scabrella* and *Arctica islandica* have been analyzed for carbon and oxygen isotope analyses. In addition, ten shells collected in seven distinct stratigraphic beds and belonging to the species *Glycymeris insubrica*, *Glycymeris inflata* and *Arctica islandica* have been analyzed for sclerochemistry in order to examine if and how seasonality varies along the section.
The geochemical and isotopic composition of calcareous skeletons has long been recognized to record past and present environmental conditions. As bivalves record in their calcium carbonate shells the primary seawater isotope composition, with little or no vital effect, the geochemical signature registered in bivalve shells can be thus used as an archive of global change in seawater composition and temperature. The equation used here to obtain palaeotemperatures from oxygen data from *Arctica* and *Glycymeris* aragonitic shells is that of Grossman & Ku (1986); the equation for the *Aequipecten* calcitic shell is that of O'Neil et al. (1969).
As diagenetic processes may alter fossil bivalve shell geochemical composition, I have undertaken four different screening tests (SEM microstructural examination, Cathodoluminescence, X-ray Powder Diffraction and Feigl's solution) to check if the shell is pristine, and thus effectively suitable to a

correct interpretation of isotope analyses. All these tests indicate that bivalve shells of the Arda River marine succession are very well preserved.

The oxygen isotope bulk data obtained from species of the genera *Glycymeris, Aequipecten* and *Arctica* have been used to construct a mean oxygen curve, which was then compared to the Mediterranean and Atlantic stacks, in order to make a correlation with the Marine Isotope Stages.
The main outcome of the bulk isotope analysis is that seasurface palaeotemperatures seem to remain rather constant during the deposition of the Arda marine succession and they do not suggest any significant cooling during Gelasian and Calabrian (Early Pleistocene). Sclerochemical analyses give further detail on the palaeoclimatic evolution of the section. In the stratigraphic interval from the base of the section to 103.70 m, bivalve shells record a low seasonality (5.7°C), suggesting that probably the Northern Hemisphere Glaciation exerted a minor control on the Mediterranean climate in this moment. In the interval between 103.70 m and 110 m, which corresponds to the arrival of the boreal guests, the shells record a high seasonality (16.0° of winter-summer difference) and low palaeotemperatures (winter palaeotemperatures of 0.8-1.7°C), as also supported by other proxies in the Mediterranean region. This may be due to cold currents from the North Atlantic entering the Mediterranean Sea with annual-interannual variability causing a progressively cooling of the seawater, particularly during winter; a cooling threshold was reached and crossed, acting as a trigger factor for the arrival and successful recruitment of the boreal guests. This cold episode is followed by an interval (110 m - top of the section) in which bivalve shells record a clear increase in seasonality toward the top of the Arda section (from 9.2 to 19.0°C of seasonal change). However, they registered higher palaeotemperatures compared to the interval of the arrival of boreal guests described above, and in the case of *Arctica islandica* also a lower, but still increasing upward, seasonality. At this time the Apennine chain was rapidly uplifting, as suggested by a change in the pollen content, increase in sedimentation rates and terrigenous input, causing a perturbation in the Mediterranean climate system. The Apennine uplift may have acted as a shield for cold and dry continental air masses coming from the Northern Hemisphere, locally obscuring the impact of the climatic variations linked to the Northern Hemisphere Glaciation dynamics.

The complex palaeoclimatic and palaeoenvironmental evolution of the Arda River succession points out that the Mediterranean region was affected by the Northern Hemisphere Glaciation dynamics, which exerted a strong control on the Mediterranean climate during most of the Early Pleistocene. The significantly cold event recorded at 103.70 m, indicates that the arrival of the boreal guests in the

Mediterranean Sea was accompanied by a high seasonality and by particularly cold winters, as suggested by both sclerochemistry and pollen analyses.

Seasonality increases approaching the Middle Pleistocene Transition and the beginning of the continental glaciations in the Northern Hemisphere, representing thus a clear signal of climatic deterioration in the Mediterranean Sea during the Early Pleistocene. However, no cooling trend in the average seawater temperatures has been observed both in sclerochemical and bulk shells oxygen isotope data during this interval.

The changes in seasonality may well have amplified and propagated the signal of climate change toward the Middle Pleistocene Transition, representing thus a very important component in abrupt climate switches.

Chapter 1

Introduction and aim

The Early Pleistocene is a time interval characterized by several climatic oscillations; its lower and upper boundaries coincide respectively with the beginning of the Northern Hemisphere Glaciation and the Middle Pleistocene Transition. The Mediterranean area was strongly affected by the Early Pleistocene climatic changes. One of the most important biotic events is here represented by the appearance of the boreal guests (e.g. the bivalve *Arctica islandica* and the foraminifer *Hyalinea balthica*) at the beginning of the Calabrian Stage, suggesting significant cooling of the Mediterranean Sea, which is confirmed also by a change in the pollen flora indicating cold climatic conditions (Lona & Bertoldi, 1972).

The Arda River marine succession, cropping out in Western Emilia, Northern Italy, continuously covers this time interval and it is very rich in macrofossils. It is composed mainly of sandstones, siltstones and mudstones deposited in a tectonically active setting during phases of advance of fan deltas and it is bounded at its top by continental conglomerates; these represent a major sea level drop and the establishment of a continental environment with vertebrate faunas and fresh water mollusks.

As this succession is very rich in macrofossils and it covers without significant gaps the Early Pleistocene, it represents an ideal setting where to study the climatic oscillations of the Early Pleistocene using bivalve shells and their isotopic signature. The geochemical and isotopic composition of calcareous skeletons has long been recognized as records of past and present environmental conditions and thus allows reconstruction of the environmental history. The geochemical signature registered in bivalve shells can be thus used as an archive of global change in seawater composition and temperature, as these organisms record in their calcium carbonate shells the primary seawater isotope composition, with little or no vital effect.

The aim of this PhD research is to analyze the stable isotope record of pristine bivalve shells in order to reconstruct the palaeoecological and palaeoclimatic evolution of the Lower Pleistocene Arda marine succession, seeking for change in seasonality occurring during this time interval, through the use of bulk shell isotope composition and sclerochemical analyses. A robust palaeoclimatic interpretation of the Arda section would have not been possible without a stratigraphical, taxonomic and palaeoecological background. Sedimentology, taxonomy, palaeoecology, biostratigraphy, geo- and sclerochemistry are all the tools that were here used to reconstruct the palaeoenvironmental conditions and the palaeoclimatic evolution of the Arda section during the Early Pleistocene, in order to understand if and how the Mediterranean region respond to the climatic oscillation of this time interval.

The present thesis is divided in two parts and comprises an appendix:

1)"Palaeontological and stratigraphical framework". Palaeoenvironmental reconstruction depends on three ingredients: a well-established stratigraphic framework, good taxonomy and a comprehensive ecological background. The basic data for palaeoecology are the fossils, adequately identified and correctly positioned within the stratigraphic framework. Part 1 focuses on the sedimentological analysis of the Arda section and on the taxonomic and the palaeoecological studies of its biota in order to construct a robust background for the palaeoenviromental and palaeoclimatic reconstructions. In addition, the temporal context in which the Arda section deposited is also analyzed, based on biostratigraphy and dating of its fossil biota.

2)"Palaeoclimatic significance of the Arda biota". This part focuses on the palaeoclimatic significance of the Arda biota, through the analysis of the mollusk fauna and, in part, the pollen content; however, the major contribute to the understanding of the palaeoclimatic evolution of the Arda section is given by the bulk shell isotope and sclerochemical analyses of its bivalve shells. In fact, the isotopic signature recorded in these shells provides a useful tools to reconstruct the climatic oscillations of the Early Pleistocene. However, as diagenetic processes may alter fossil bivalve shell geochemical composition, it becomes important to check, by screening tests, if the shell is pristine, and thus effectively suitable to a correct interpretation of isotope analyses. Four different screening tests have been used for this purpose and are illustrated in this part.

Appendix: it is focused on the systematic descriptions of the species of the three genera used for the bulk shell isotope and sclerochemical analyses: *Glycymeris, Aequipecten* and *Arctica*. It contains also a detailed analysis of their shell ultrastructure.

PALAEONTOLOGICAL AND STRATIGRAPHICAL FRAMEWORK

Chapter 2

The sedimentary succession of the Arda section

The geological setting and the sedimentology of the Arda section are described in this chapter. Facies and facies associations identified in the section allow to reconstruct the depositional environment and the mechanisms which affected the sedimentation of the succession and have an important bearing in the palaeoecological and palaeoclimatic interpretations of the section.

The Arda River section crops out in Northern Italy along the Arda River at Castell'Arquato; the marine part, which is the subject of the present thesis, is 237.40 m thick and it is bounded at its top by continental conglomerates, representing the establishment of a continental setting. The stratigraphically lower part of the succession (Zanclean-Piacenzian in age), cropping out between the town of Lugagnano Val d'Arda and Castell'Arquato (Pc, Northern Italy), was the subject of several researches; in fact its fossiliferous sediments were soon adopted as the boundary stratotype for the Piacenzian Stage (e.g. Pareto, 1865; Barbieri, 1967). Subsequently an integrated calcareous plankton biostratigraphic analysis carried out by Rio et al. (1988) and by Raffi et al. (1989) clearly demonstrated that a hiatus was present right at the base of the stratotype, making thus this area unsuitable to define the Piacenzian Stage. Although numerous studies have been performed on this part of the Arda River section, less has been done on the upper part of the succession, apart from the studies of Dominici (2001, 2004) and Monegatti et al. (2001). This, extends downstream the bridge located at the entrance of the town of Castell'Arquato and is the subject of this thesis.

The section was measured in detail meter per meter; to make the measure of the section reproducible and available also for other analyses a labeled nail was fixed every meter from the base to the top of the section, according to the attitude of the bedding. The detailed sedimentological analysis of the succession was performed by Dr. F. Felletti and his student Dr. C. Frigerio from Dipartimento di Scienze della Terra 'A.Desio', Università di Milano.

I collected samples for macrofossils, palynology, nannofossils and foraminifers along the overall section. The results of the analyses undertaken on these samples are reported in the different chapters of this thesis.

2.1 Geological setting

The Apennine orogeny developed through several tectonic phases beginning in the Upper Cretaceous, as a results of the collision between the paleo-european plate and the apulo-adriatic microplate, which was part of the African plate (Plesi, 1997). Four are the main phases detected in the Northern Apennines: 1) Ligurian (Middle Eocene), 2) Subligurian (Upper Oligocene-Lower Miocene), 3) Tuscan (Tortonian) and 4) Padano-Adriatic (Messinian-Pleistocene), which represents the last important phase of formation of the Apennine chain and gave to the Emilian Apennines the actual aspect (Calabrese & Di Dio, 2009).

The studied marine succession belongs to the upper part of the Castell'Arquato Formation (Gelasian-Calabrian), which crops out in the Northern Apennines along the Arda River at Castell'Arquato (Western Emilia, Northern Italy) (Fig. 2.1 A,B); the studied section extends downstream the bridge present at the entrance of the town toward N-NE for nearly 2 km (base at 44°51'12.5''N; 9°52'22.4''E).

The section belongs to the Castell'Arquato piggy back basin, which developed after the fragmentation of the Po Plain foredeep in the late Messinian. The basin is filled by a sedimentary succession of late Messinian to Holocene age, organized in a large scale transgressive-regressive cycle controlled by tectonics (Fig. 2.2). Beds form a regular monocline dipping towards the N-NE and no major faults occur in this area (Monegatti et al., 2001).

The basal part of the succession comprises deep sea sediments deposited after the end of the Messinian salinity crisis (Calabrese & Di Dio, 2009), when marine conditions were restored in the Mediterranean sea; upward they pass to slope and platform facies and then through a regressive trend to the Middle Pleistocene alluvial continental deposits, which represent the final retreat of the sea in this area and the establishment of a continental environment with vertebrate faunas and fresh water mollusks (Cigala Fulgosi, 1976; Pelosio & Raffi, 1977; Ciangherotti et al., 1997).

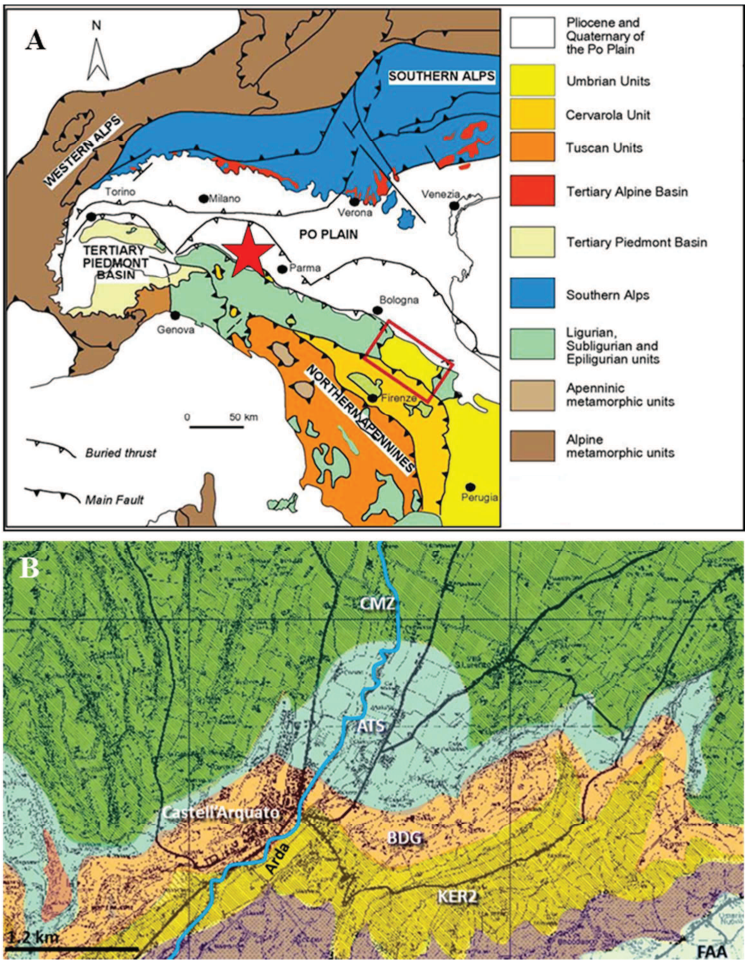

Fig. 2.1. A) Location of the Arda River section in Northern Italy (red star) (from Tinterri et al., 2012); B) Sketch map showing the synthems cropping out in the Castell'Arquato area (geologic map 1:10.000); see the text for the explanation of the terms CMZ, ATS, BDG and KER2.

According to the geological map 1:50.000 (Foglio 180, Salsomaggiore Terme; Calabrese & Di Dio, 2009) the Castell'Arquato Formation belongs to the post-evaporitic succession of the Padano-Adriatic margin, which represent a large transgressive-regressive sedimentary cycle. This succession is divided in two supersynthems: Val d'Arda supersynthem and Quaternario marino supersynthem, both entirely covering the deposition time of the Castell'Arquato Formation (Figs. 2.1B, 2.2):

1) Val d'Arda supersynthem. It is divided in two synthems:

a) Torrente Chero synthem (KER): it corresponds to the upper part of the Argille di Lugagnano Formation and to the lower part of the Castell'Arquato Formation. It is formed by shelf deposits with a sharp boundary with the underlying deep sea shale. Age: Zanclean-Piacenzian. It is subdivided in: 1. Montezago subsynthem (KER1): grey-blue clayey-marly basinal deposits and silty-sandy shelf deposits. 2. Monte Giogo subsynthem (KER2): bioturbated pelitic and siltitic sediments in which are intercalated three calcarenitic bodies.

b) Badagnano synthem (BDG): it corresponds to the middle-upper part of the Castell'Arquato Formation. It is formed by sandy deposits of delta front-marine marginal environment and of fine prodelta deposits. Age: Piacenzian-Gelasian.

2) Quaternario marino supersynthem. It is formed by paralic and marine sediments, bounded at its top by a locally erosive discontinuity established by the advance of depositional system and the spreading of continental deposits. It correspond to the upper part of the Castell'Arquato Formation and it is divided in two synthems:

a) Torrente Stirone synthem (ATS): it is mainly composed of arenitic-conglomeratic fan delta and shore deposits. Age: Gelasian-Calabrian.

b) Costamezzana synthem (CMZ): shore and lagoonal-paralic facies with locally fan delta systems. Age: Calabrian.

The studied section belongs to the Quaternario marino supersynthem (Fig. 2.2).

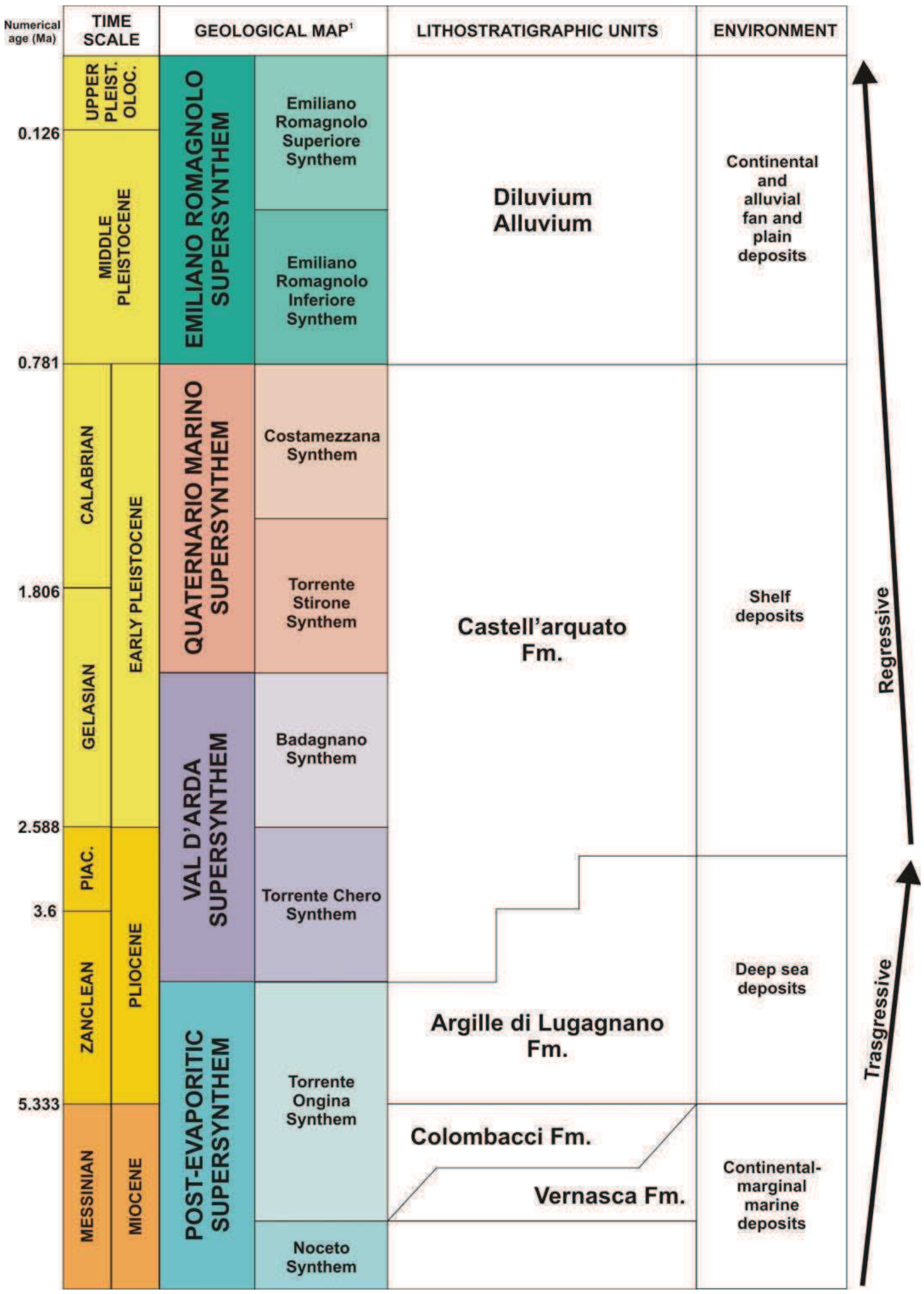

Fig. 2.2. Stratigraphic scheme of the Miocene-Holocene successions cropping out in Western Emilia;
1. Geological map from Calabrese & Di Dio, 2009 (Foglio 180, Salsomaggiore Terme).

2.2 Facies and facies associations

A well exposed stratigraphical section (~ 300 m thick) has been measured and studied from the outcrops of the Arda valleys (Figs. 2.3 A,B; 2.4). Facies analysis was carried out in the shallow-marine deposits of sequence Qm1 (part of Quaternario marino supersynthem; Dominici, 2001, 2004) that is formed during phases of advance of fan deltas and deposited when Apennine tectonic uplift renewed sediment dispersal and provided the basin with a steeper margin. The deposits can be interpreted as flood-generated delta-front lobes recording the final sandy deposition of high-density flows (hyperpicnal flows) (Dominici, 2004). Distinctive features are the sharp based and normally graded beds containing hummocky cross stratified sands (HCS) (Table 2.1), and the abundant rip-up mudstone clasts and shells (see Mutti et al., 2000).

Recent advances in the understanding of this category of clastic depositional system (Mutti et al, 2000; Zavala, 2006; Tinterri, 2007; Zavala, 2011), termed "hyperpycnal system", have provided a new frontier for the understanding of clastic facies in shallow-marine environments. The hyperpycnal system is a relatively new category of depositional system that corresponds to the subaqueous extension of the fluvial system (in the sense of Schumm, 1977, 1981). A single hyperpycnal system can extend for hundreds of kilometers away from the river mouth and will develop a predictable path of genetically related facies during its travel basinward. It originates when a river in flood directly discharges a sustained and relatively more dense turbulent mixture of fresh water and sediments (hyperpycnal flows; Bates, 1953) into a receiving standing body of water.

A hyperpycnite (Mulder et al., 2003) is a particular type of turbidite having distinctive and at present poorly known facies characteristics (Mulder & Alexander, 2001). Its origin is closely related to a direct fluvial discharge and results in facies types and depositional features that commonly resemble those considered as typical of fluvial environments (bed load, meandering, etc.), but are commonly associated with clear marine and lacustrine indicators. Mutti et al. (2003) recognized the flood-generated delta-front sandstone lobes as the main depositional element associated with hyperpycnal flows. This provides a broad spectrum of relatively small intergradational and coarse-grained fluvial-deltaic systems ranging between two end members: 1) fan deltas and 2) river deltas. According to Mutti et al. (2003), fan-delta systems accumulate in roughly tabular lobes extending from alluvial conglomerates to shelfal siltstone and mudstone. In these systems, flood-generated dense flows enter seawaters as catastrophic and inertia-dominated relatively unconfined flows. Coarser materials tend to collect at the front of the flow, giving way to a horizontally negative grain-size gradient. In river-delta systems, sedimentation occurs mainly in a mouth bar (characterized by sigmoidal bedding) and in associated flood-generated delta-front sandstone lobes.

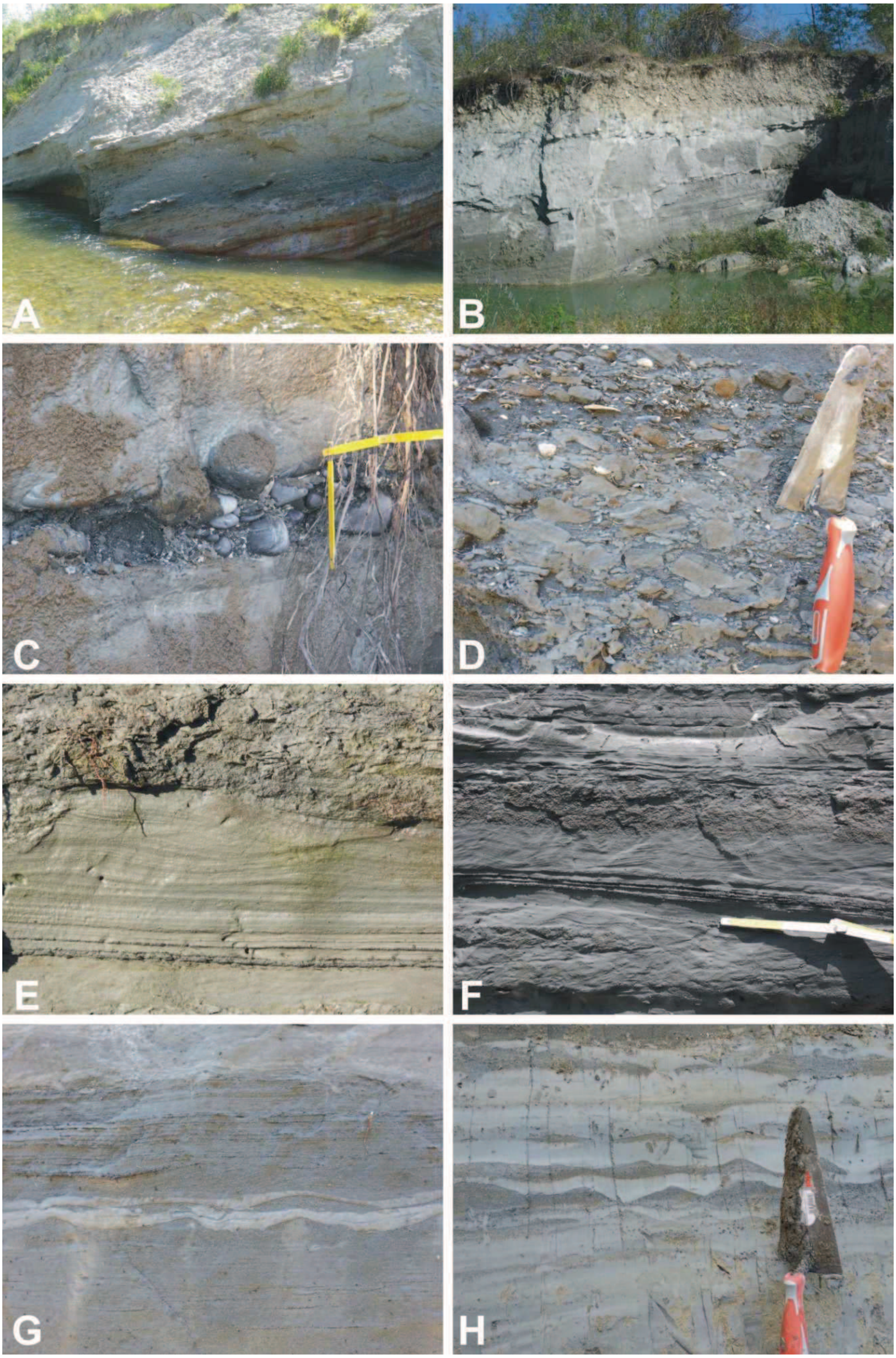

Fig. 2.3. A,B) Photos of the Arda River section; note the clear dip of the strata; C) Lag deposit (Facies B); D) Rip-up mud clasts (Facies B); E,F) Fine sandstones with climbing ripples (Facies S); G) Lenticular bedding (Facies S); H) Wavy and lenticular bedding (Facies S).

Following the genetic classification scheme proposed by Zavala (2011), the deposits of the Arda section can be grouped in three main facies categories related to the three main processes that characterize all sustained hyperpycnal discharges in marine settings: bed load, turbulent suspension, and lofting. These facies categories are here termed as B (bed-load related sedimentary facies), S (suspended-load-related sedimentary facies), and L (lofting-related sedimentary facies) (Table 2.1).

Facies Related to Bed-load Processes (Facies B)

Type B facies includes different coarse-grained deposits related to shear/drag forces exerted by the overpassing long-lived turbulent (hyperpycnal) flow over coarse-grained materials lying on the flow bottom.

This Facies is composed of massive (GmE) and cross-stratified (or crudely stratified) conglomerates (Gp) with abundant coarse- to fine-grained sandstone matrix (matrix supported). Large clasts in this facies appear floating in a medium- to coarse grained sandstone matrix. Individual sets of crossbedding commonly show thicknesses between 0.1 and 0.5 m. The foreset inclination in general does not exceed 15°. Bedset-bounding surfaces can be erosional. Lag deposits (Lag) represented by gravel carpets with bioclastic and sandy (very coarse) matrix are frequent (Fig. 2.3C). This facies category also include mud clast-supported conglomerate (GmM; clay-chips) (Fig. 2.3D). Mudstone intraclast diameter ranges from 0.5 up to 20 cm and their shapes range accordingly from rounded sub-spherical to rounded tabular.

High-density flows triggered by river floods can mix and deposit skeletal remains from different shallow-water communities. Anyway, accumulations of shells are rare features in this bed-load related sedimentary facies.

Facies Related to the Collapse of Suspended Load (Facies S)

Facies S are mostly fine grained and composed of sediments transported as suspended load, forming thick and commonly complex intervals that can be massive or display traction plus fallout sedimentary structures.

Sandstone strata range from a few millimeters thick laminasets, to several tens of decimeters thick beds and bedsets, with massive stratification (Sm), horizontal (Sh) or hummocky cross stratification (HCS), tabular and oblique cross stratification (Sp, Sx), and small-scale cross lamination (Sr, St). Many beds are sharp based and fine upward, with structures ranging from horizontal or large-scale wavy lamination to small scale cross lamination (wavy, sigmoidal, and/or climbing ripple structures) (Fig. 2.3 E,F). Small floating clay chips are common and could seem dispersed within the sandstone body or grouped toward the top.

Accumulations of shells are common features in the sandstone intervals, where they form thick, sharp-based, sometimes normally graded lags at the base of massive (mS) or laminated strata (Sp, Sx, Sr). Shell-bed geometry ranges from tabular to lenticular; shells are always closely packed, mostly concave-down, and sometimes imbricated. In many cases, tabular, sharp-based shell beds (that are 10–50 cm thick and broadly lenticular) are found at the base of horizontal or hummocky cross-stratified (HCS) beds. Carbonaceous remains and wood fragments are also common within massive sands, commonly displaying an exceptional preservation. Sedimentary structures are rarely disrupted by bioturbation, but bedtops may be 100% bioturbated. Flasers and massive mudstone beds (HeB), from a few millimeters to several centimeters thick, are often intercalated with the sandstones (Fig. 2.3 G,H).

Facies Related to Flow Lofting (Facies L)

Facies L is characterized by thin couplets of massive to laminated siltstones and mudstones (Fm). It is composed of the finest materials transported by the hyperpycnal flow, which accumulated by normal settling when the flow completely stopped. The individual levels commonly display a variable thickness from a few millimeters up to 100 cm. In-life position marine bivalves are present in this facies in the lower part of the stratigraphic section. In the upper part (continental deposits) frequent root systems and vertebrates are present.

2.3 Conclusions

The Arda River section is ~ 300 m thick; the marine part, which is the subject of the present thesis is 237.40 m-thick and mainly consists of sandstones, siltstones and mudstones bounded at the top by continental conglomerates indicating a major sea level drop.

The deposits are interpreted as flood-generated delta-front lobes recording the final sandy deposition of high-density flows (hyperpicnal flows). Three main facies categories related to the three main processes that characterize the hyperpycnal discharges in marine settings are identified in the Arda deposits: B (bed-load related sedimentary facies), S (suspended-load-related sedimentary facies), and L (lofting-related sedimentary facies).

The presence of these facies and facies associations suggest that the Arda River section formed during phases of advance of fan deltas affected by high-density flows triggered by river floods and deposited when Apennine tectonic uplift renewed sediment dispersal and provided the basin with a steeper margin.

Facies categories	Code	Facies	Sedimentary features
Facies B (bed-load related)	***GmE***	*Massive grain-supported gravels*	Massive, grain supported polygenic gravels. Beds have an erosive base and are usually heavily cemented.
	GmM	*Massive mud clasts deposits*	Massive rip-up clasts deposits. Sandy matrix with abundant bioclasts (bivalves and gastropod shell fragments). Beds have an erosive base. Mud clasts are ripped from muddy layers.
	Gp	*Planar stratified gravels*	Gravels with horizontal or oblique planar stratification. Clasts are usually embricated. Some of these beds are heavily cemented.
	Lag	*Lag deposits*	Gravel carpets with bioclastic and sandy (very coarse) matrix.
Facies S (suspended-load-related)	***Sp***	*Planar oblique stratified sands*	Mostly bioclastic, planar oblique stratified coarse grained sands. Beds are heavily cemented and bioturbated. Bioturbation is in the form of vertical tunnels.
	Sx	*Planar cross stratified sands*	Fine to medium grained planar cross stratified sands. Bioturbation is apparently absent.
	HCS	*Hummocky cross stratified sands*	Fine to coarse grained hummocky stratified sands. Beds are usually rich in bioclasts. Bioturbation is apparently absent. Occurrence of wood fragments and logs.
	St	*Trough cross stratified sands*	Fine to coarse grained trough cross stratified sands. Beds are usually rich in bioclasts. Bioturbation is apparently absent. Occurrence of wood fragments and logs.
	Sr	*Ripple cross stratified sands*	Fine grained sands with wave or current ripples, sometimes with well-developed climbing ripples laminasets (current). No evidence of bioturbation.
	Sh	*Horizontally stratified sands and silts*	Horizontally stratified fine and very fine grained sands and silts usually rich in organic matter (small wood fragments) and mollusk fragments.
	Sm	*Massive sands*	Very fine to medium grained massive sands. Beds are locally bioturbated.

	HeB	*Heterolitic bedding*	Heterolitic fine grained sands to mud. Flaser, wavy and lenticular bedding.
Facies L (lofting-related)	***Fm***	*Massive fines*	Structureless silts and muds with minor very fine sands. Beds are locally heavily bioturbated. Presence of in-life position marine bivalves in the lower part of the stratigraphic section. In the upper part (continental deposits) frequent root systems and vertebrates.
	CCB	*Carbonatic Cemented Beds*	Cemented levels, rich in carbonate.

Table 2.1. Facies and facies associations identified in the Arda section.

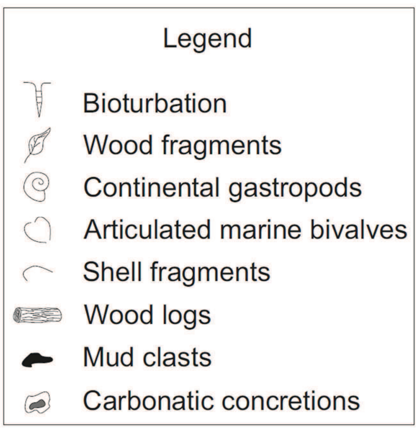

Fig. 2.4 (next page). Stratigraphic log of the marine and continental parts of the Arda section. Legend on the left. Courtesy of Dr. F. Felletti & Dr. C. Frigerio.

Sezione Stratigrafica T. Arda