Quaternary Research
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doi:10.1017/qua.2019.20

Bio- and lithostratigraphy of lower Pleistocene marine successions in western Emilia (Italy) and their implications for the first occurrence of *Arctica islandica* in the Mediterranean Sea

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(Received November 9, 2018; Accepted March 28, 2019)

Abstract

The Arda and Stirone marine successions (Italy) represent key sections for the early Pleistocene; they were deposited continuously within a frame of climate change, recording the Calabrian cooling as testified by the occurrence of the "northern guests," such as the bivalve *Arctica islandica*. In addition, although the first occurrence of *A. islandica* in the Mediterranean Sea was used as the main criterion to mark the former Pliocene-Pleistocene boundary, the age of this bioevent was never well constrained. Here, we describe the Stirone depositional environment and constrain for the first time the section age using calcareous nannofossil and foraminifera biostratigraphy. We also correlate the Arda and Stirone sections using complementary biostratigraphic and magnetostratigraphic data. Our results indicate that *A. islandica* first occurred in both the successions slightly below the top of the CNPL7 biozone (dated at 1.71 Ma). Comparisons with other lower Pleistocene Mediterranean marine successions indicate that the stratigraphically lowest level where *A. islandica* first occurred in the Mediterranean Sea is in the Arda and Stirone sections; these environments satisfied the ecological requirements for the establishment and the proliferation of the species, which only subsequently (late Calabrian) has been retrieved in southern Italy and other areas of the Mediterranean Sea.

Keywords: Northern guests; Facies analysis; Calcareous nannofossils; Foraminifera; early Pleistocene

INTRODUCTION

The late Cenozoic marine successions of western Emilia (northern Italy) represent an unparalleled sedimentary archive for defining the role of climate and tectonic dynamics in shaping sediment flux, landscape, and biotic interactions (e.g., Dominici, 2001, 2004; Gunderson et al., 2012; Crippa and Raineri, 2015; Crippa et al., 2016, 2018; Russo et al., 2017; Cau et al., 2019). In this respect, the successions cropping out along the banks of the Arda and Stirone Rivers represent a historical landmark for these kinds of studies. Indeed, studying the fossils from these successions, Lyell (1833) confirmed his concept of the Pliocene, and Mayer-Eymar (1858) coined the term "Piacenzische Stufe" ("Piacenzian Stage") to indicate the "blue shales" ("Argille azzurre") so widespread in this area. Since then, the rich and well-preserved invertebrate fossil fauna from both the Arda and Stirone River beds has been the focus of numerous studies that promoted the development of the late Cenozoic geologic timescale, especially during the last century (e.g., Barbieri, 1958; Papani and Pelosio, 1962; Raffi, 1970; Caprotti, 1972, 1973, 1974, 1976; Pelosio and Raffi, 1974, 1977). Although several of these studies were performed on the Pliocene part of these successions, only a few were recently undertaken on the Pleistocene deposits (e.g., Dominici, 2001, 2004; Monegatti et al., 2001; Pervesler et al., 2011; Crippa, 2013; Crippa and Raineri, 2015; Crippa et al., 2016, 2018). Bio- and magnetostratigraphic analyses to constrain the age of the Arda and Stirone River sections were carried out nearly exclusively on Pliocene sediments (e.g., Barbieri, 1958, 1967; Mary et al.,1993; Channell et al., 1994; Gunderson et al., 2012; Cau et al., 2015). Recently, Crippa et al. (2016) provided

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Cite this article: Crippa, G. *et al* 2019. Bio- and lithostratigraphy of lower Pleistocene marine successions in western Emilia (Italy) and their implications for the first occurrence of *Arctica islandica* in the Mediterranean Sea. *Quaternary Research* 92, 549–569. https://doi.org/10.1017/qua.2019.20

an integrated biostratigraphy (calcareous nannofossils and foraminifera) of the Pleistocene part of the Arda River section that led to the identification of three nannofossil (CNPL7, CNPL8, and CNPL9) and one foraminiferal (*Globigerina cariacoensis*) biozones, all of Calabrian age. Monesi et al. (2016) confirmed the Calabrian age of the Arda section based on magnetostratigraphy. Conversely, the Pleistocene succession cropping out along the Stirone River lacks a robust biostratigraphic framework.

Marine successions of western Emilia are also important because of the occurrence of the "northern guest" bivalve *Arctica islandica* (Fig. 1). The term "northern guest" was first used by Suess (1883–1888) to define organisms, such as *A. islandica*, which are thriving nowadays at higher latitudes in the Northern Hemisphere; they migrated into the Mediterranean Sea through the Strait of Gibraltar because of the onset of the cooling in the Calabrian (Malatesta and Zarlenga, 1986; Raffi, 1986; Martínez-García et al., 2015). The first occurrence of the "northern guests" in the Mediterranean Sea has a historical importance; this biotic event was one of the main criteria used to mark the Pliocene-Pleistocene boundary (Pelosio and Raffi, 1974; Aguirre and Pasini, 1985; Raffi, 1986), when placed at the former Global Stratotype Section and Point (GSSP) at Vrica (Calabria, Italy). The Pliocene-Pleistocene boundary was then revised and lowered to 2.58 Ma at the base of the Gelasian Stage (e.g., Gibbard et al., 2010; Cohen et al., 2018). According to Raffi (1986) and Rio et al. (1997), the lowest stratigraphic level where *A. islandica* occurred is reportedly in the Arda and Stirone River sections (see Table 1 reporting Pleistocene Mediterranean distribution of *A. islandica*); however, these authors did not report a detailed biostratigraphic analysis of these successions. Raffi (1986) dated the first occurrence of *A. islandica* into the Mediterranean Sea at the top of the Olduvai magnetic subchron at 1.67 Ma. This age determination changed after 1995, when a new astronomically tuned timescale was proposed to define the magnetostratigraphic boundaries (Van Couvering, 1997). The new age for the top of the Olduvai subchron and the corresponding first occurrence of *A. islandica* in the Mediterranean Sea is 1.77 Ma (Van Couvering, 1997). In order to thoroughly understand the timing and the processes of the climatic changes (i.e., cooling) occurring during the early Pleistocene, and in particular from the Calabrian onward, it is important to accurately constrain the timing of the first occurrence of *A. islandica* in the Mediterranean Sea. Up to now, a detailed study on this topic has been lacking.

The goals of this article are threefold: (1) to better describe the stratigraphic setting, particularly for the Stirone section, in order to correlate the marine successions of western Emilia by means of an integrated approach relying on facies analysis, calcareous nannofossils, and foraminifera biostratigraphy fitted into the magnetostratigraphic framework available from the literature; (2) to calibrate the first occurrence of *A. islandica* in the Mediterranean Sea; and (3) to map the occurrence of the species in the area during the early Pleistocene.

GEOLOGIC SETTING

The investigated successions crop out in northern Italy near the town of Castell'Arquato (Arda River section) and 3 km northwest of Salsomaggiore Terme (Stirone River section). These deposits belong to the Castell'Arquato wedge-top basin (CAB), which developed from the late Messinian (~6 Ma; upper Miocene) to the Pleistocene after the northeastward migration and fragmentation of the Po Plain–Adriatic foredeep (Roveri and Taviani, 2003; Ghielmi et al., 2013; Fig. 2A). The CAB is located at the foothills of the northwestern sector of the Apennines; it is bounded to the south by the emerged front of Ligurian units (Monegatti et al., 2001) and to the north by the Salsomaggiore structure, one of the outermost thrust fronts of the Apennine orogenic wedge (Artoni et al., 2004, 2010).

The basal part of the CAB succession comprises deep-sea sediments deposited when marine conditions were restored in the Mediterranean Sea after the end of the Messinian salinity crisis (Ceregato et al., 2007; Calabrese and Di Dio, 2009); upward they pass to epibathyal to shelf-related facies (Pliocene to early Pleistocene in age). Then, through a strong regressive upward trend, alluvial deposits of the middle Pleistocene record the establishment of a continental environment with vertebrate faunas and freshwater mollusks (Cigala Fulgosi, 1976; Pelosio and Raffi, 1977; Ciangherotti et al., 1997; Esu, 2008; Esu and Girotti, 2015). The late Messinian to Pleistocene sedimentary infill of the CAB is represented by a depositional sequence controlled by tectonics; beds form a regular monocline dipping toward the north/northeast, and no major faults are present in the area, allowing a good correlation of the cropping out stratigraphic units (Monegatti et al., 2001; Cau et al., 2019). This sequence can be further subdivided into four lower rank unconformity bounded units, which are related to well-known Pliocene-Pleistocene tectonic phases of compressional deformation and depocenter migration toward the foreland of the Apennine thrust-fold belt (Roveri and Taviani, 2003; Artoni et al., 2010). In turn, these tectono-bounded stratigraphic units are subdivided into smaller-scale (higher-frequency) sequences.

The well-exposed Stirone succession crops out along the incised banks of the Stirone River (Fig. 2B), and it extends downstream the Pieve di San Nicomede locality (base at 44°50′38.87″N, 9°58′38.37″E; top at 44°50′46.96″N, 9°59′28.00″E). A detailed sedimentologic and biostratigraphic analysis of this section is presented in this article. For the sedimentologic, paleontological, and biostratigraphic reconstruction of the Arda River section, we refer to Crippa et al. (2016, 2018). For taphonomy and paleoecology of both sections, see Dominici (2001, 2004).

MATERIALS AND METHODS

Facies analysis

The Stirone succession (Figs. 2 and 3) is 138 m thick; a detailed stratigraphic section has been measured with a

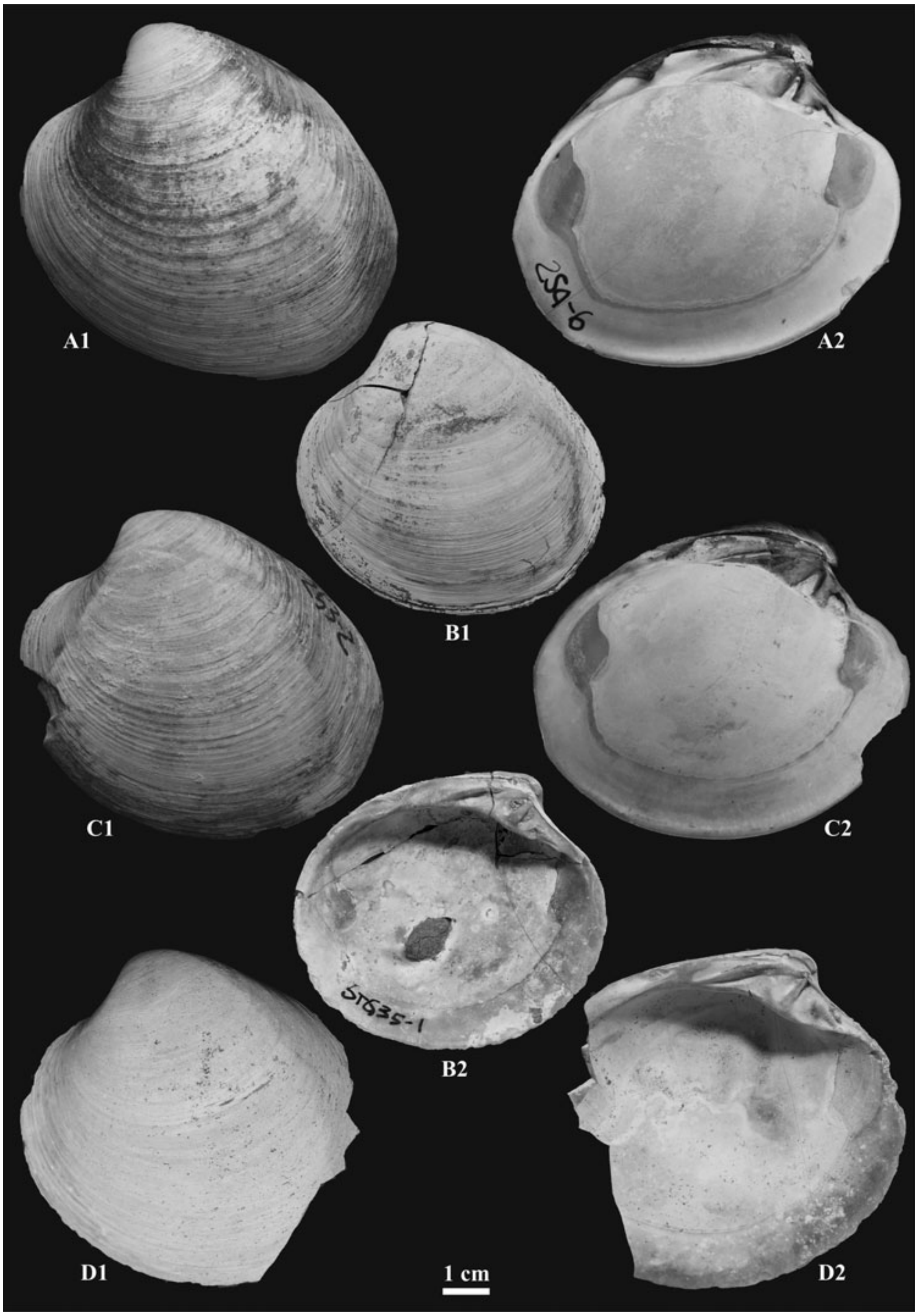

Figure 1. External (A1, B1, C1, D1) and internal (A2, B2, C2, D2) parts of left valves of specimens of *Arctica islandica* collected from the Arda River (A1, A2; C1, C2) and Stirone River (B1, B2; D1, D2) marine successions.

resolution of 1 cm. Thickness of beds and depositional intervals, geometry of bed-bounding surfaces, presence of mud clasts, sedimentary structures, and paleocurrent indicators were all recorded. Bed amalgamation is frequent in the studied succession, and thus individual layers were measured through detecting the subtle grain-size breaks associated with amalgamation surfaces. Grain-size measurements were made using a hand lens and grain-size comparator. Bed thickness measurement was performed mainly with a Jacob's staff (e.g., a 1.5-m-high rod provided with a clinometer and a flat disc on top).

Calcareous nannofossils

A total of 30 samples from the Stirone section were analyzed for calcareous nannofossils (Supplementary Table 1). The study was performed on smear slides under polarizing light, at 1250× magnification. Smear slides were prepared

Table 1. Occurrence of *Arctica islandica* in the lower Pleistocene of the Mediterranean Sea. Subdivision of the Calabrian (early Pleistocene) into three substages (Santernian [lower Calabrian], Emilian [middle Calabrian], and Sicilian [upper Calabrian]) according to Ruggieri and Sprovieri (1975, 1977). This subdivision, which refers to Italian marine stages, is not formally used yet, but several old and even recently published papers adopt it; here, it is used together with the formally accepted one (Cohen et al., 2018). Age in Ma reported only when explicitly cited in the literature.

	Locality	Age	Dating method	Reference
ITALY	Santerno Valley (Bologna, northern Italy)	~2 Ma	Magnetostratographic evidence and radiometric age (helium/uranium method) obtained on corals	Kukla et al. (1979)
	Arda and Stirone Rivers (Piacenza and Parma, northern Italy)	Rare specimens within the CNPL7 (1.93–1.71 Ma), more frequent during the CNPL8 calcareous nannofossil biozone (1.71–1.25 Ma; Backman et al., 2012)	Nannofossils and foraminifera biostratigraphy; magnetostratigraphy	Rio et al. in Van Couvering (1997); Gunderson et al. (2012); Crippa and Raineri (2015); Crippa et al. (2016, 2018); Monesi et al. (2016); this study
	Collesalvetti (Pisa, northern Italy)	≥2 Ma	Magnetostratigraphy	Bedini et al. (1981)
	Val Cecina (Livorno, northern Italy)	Santernian	Nannofossil and foraminifera biostratigraphy, macrofossil association	Gianelli et al. (1981); Sarti et al. (2007)
	Pisa hills (Valdarno, Pisa, northern Italy)	Santernian	Nannofossil and foraminifera biostratigraphy	Nencini (1983); Sarti et al. (2008)
	Monte Mario (Rome, central Italy)	Middle–late Santernian (1.66–1.59 Ma)	Nannofossils and foraminifera biostratigraphy; magnetostratigraphy	Faranda et al. (2007); Cosentino et al. (2009)
	Tacconi quarry (Rome, central Italy)	Emilian, 1.6–1.2 Ma	Nannofossil biostratigraphy	Malatesta and Zarlenga (1994); Von Leesen et al. (2017)
	Cutrofiano quarry (Lecce, southern Italy)	Sicilian, 1.2–0.8 Ma	Nannofossils and foraminifera biostratigraphy	Margiotta and Varola (2007); Von Leesen et al. (2017)
	Santa Maria di Catanzaro (Catanzaro, southern Italy)	Emilian	Nannofossils and foraminifera biostratigraphy	Azzaroli et al. in Van Couvering (1997 and reference therein)
	Valle di Manche (Crotone, southern Italy)	Sicilian	Nannofossils and foraminifera biostratigraphy	Capraro et al. (2015)
	Monasterace (Reggio Calabria, southern Italy)	Late Emilian-Sicilian	Nannofossils and foraminifera biostratigraphy	Azzaroli et al. in Van Couvering (1997)
	Ogliastro quarry (Siracusa, southern Italy)	Sicilian-"Ionian," 0.9–0.6 Ma	Nannofossil biostratigraphy	Di Geronimo et al. (2000); Von Leesen et al. (2017)
	Capo Rossello (Agrigento, southern Italy)	Emilian	Nannofossils and foraminifera biostratigraphy	Azzaroli et al. in Van Couvering (1997 and references therein); Caruso (2004)
	Belice Valley (Agrigento, southern Italy)	Sicilian	Nannofossils and foraminifera biostratigraphy	Di Geronimo et al. (1994); Garilli (2001)
	Puleo Quarry (Palermo, southern Italy)	Sicilian	Nannofossils and foraminifera biostratigraphy	Ruggieri et al. (1976, 1984); Buccheri (1984)
OTHER MEDITERRANEAN SITES	Rhodes (Greece)	Calabrian	Foraminifera biostratigraphy	Zaccaria (1968)
	Mallorca (Spain)	Sicilian	–	Pomar Gomá and Cuerda Barceló (1979)

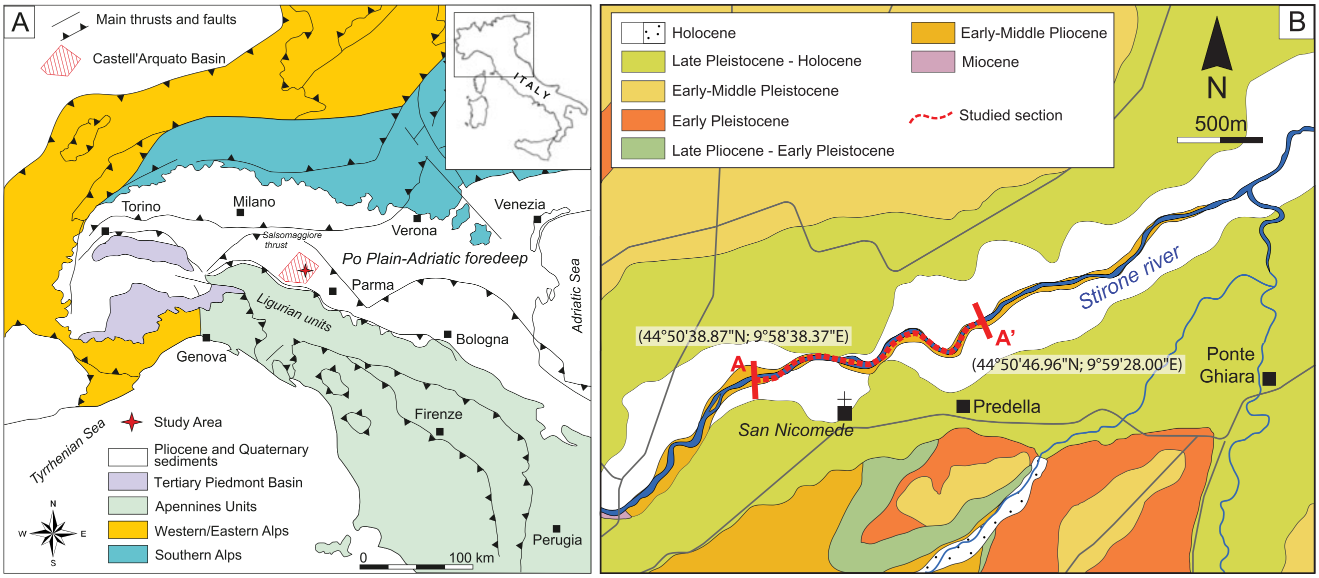

Figure 2. (color online) (A) Geologic sketch map of northern Italy showing the study area (modified after Crippa et al., 2016, 2018). (B) Enlarged geologic map showing the position of the Stirone River section (A-A').

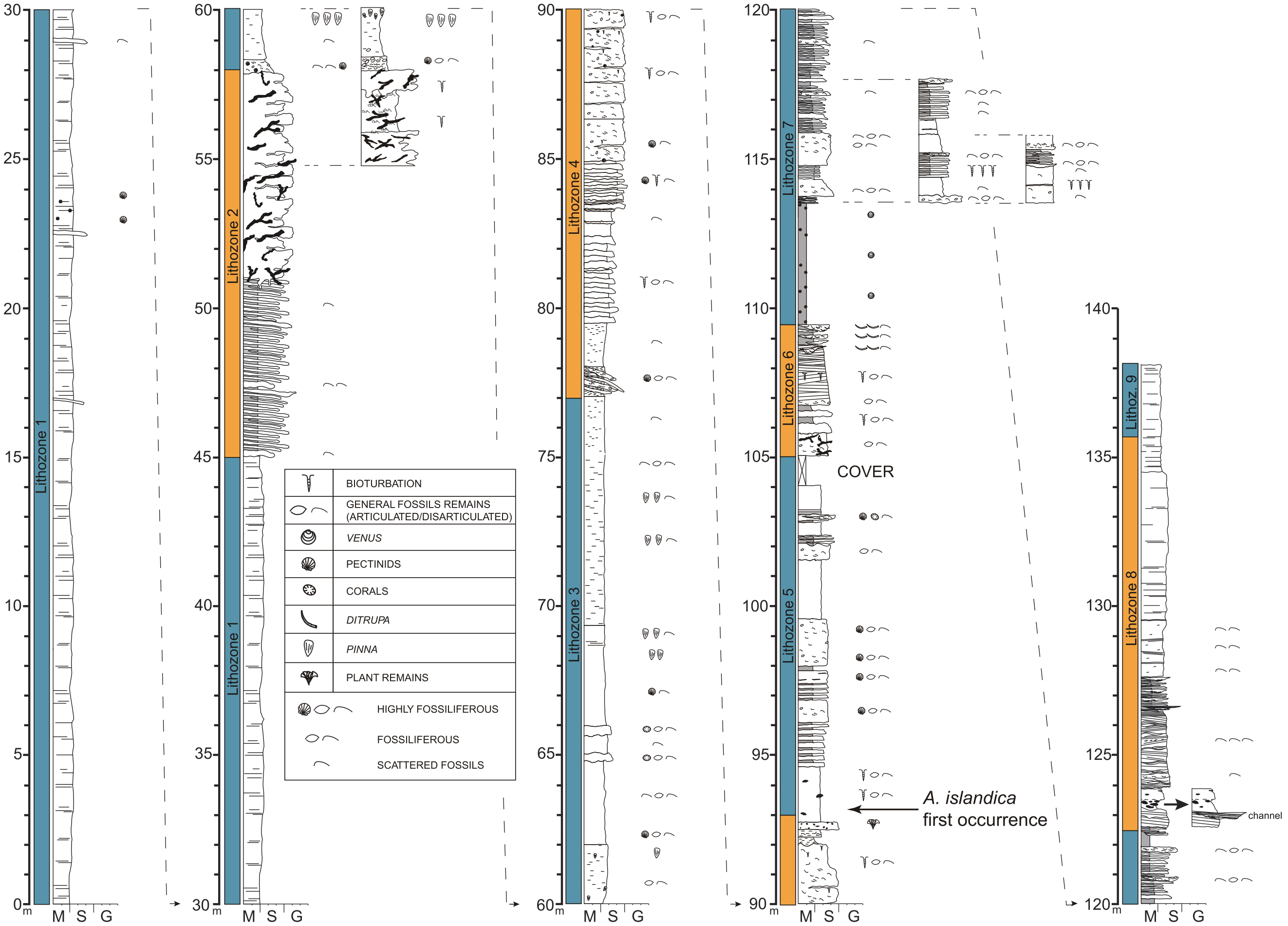

Figure 3. (color online) Detailed stratigraphic log of the Stirone River section. The nine lithozones identified in the succession are shown. M, mud; S, sand; G, gravel.

following the methodology described by Monechi and Thierstein (1985). For each sample, nannofossils were quantitatively characterized by counting at least 300 specimens. In addition, two random traverses were studied to detect rare and/or marker species. Specimen preservation is moderate throughout the entire studied interval (Supplementary Table 1). We applied the biozonation scheme by Backman et al. (2012) and the identification of *Gephyrocapsa* specimens based on the informal taxonomic concepts established by Raffi et al. (1993): "small" *Gephyrocapsa* refers to specimens <4.0 µm in size, "medium" *Gephyrocapsa* refers to specimens ≥4.0 µm, and "large" *Gephyrocapsa* refers to specimens >5.5 µm.

Foraminifera

A total of 21 samples were analyzed for planktonic and benthic foraminifera. Samples were processed using standard laboratory procedures for soft sediments and washed under water through >63 µm, >125 µm, and >250 µm sieves and then dried. Residues contain a variable amount of quartz, mica, ostracods, mollusk and echinoid fragments, vegetable debris, iron oxides, and aggregated grains. Foraminifera are generally common in all samples, with benthic taxa occurring in greater specimen abundance than planktonic ones; both groups decrease in number in the upper part of the stratigraphic section. Taxonomic concepts for foraminifera identification applied in this study follow Colalongo and Sartoni (1977), Agip (1982), Kennett and Srinivasan (1983), Iaccarino (1985), Iaccarino et al. (2007), and Holbourn et al. (2013). Foraminiferal biozonation follows Iaccarino et al. (2007) and Cita et al. (2012). The most significant taxa for biostratigraphy were photographed using a Cambridge S-360 Scanning Electron Microscope (SEM) with lanthanum hexaboride (LaB_6) cathodes at the University of Milan (Milan, Italy).

Calabrian Stage subdivision in the Mediterranean

The subdivision of the Calabrian Stage (early Pleistocene) into three Italian marine substages—Santernian (lower Calabrian), Emilian (middle Calabrian), and Sicilian (upper Calabrian)—was first proposed by Ruggieri and Sprovieri (1975, 1977) and then modified by Cita et al. (2006). Ruggieri and Sprovieri (1979) and Ruggieri et al. (1984) subsequently introduced the stage/age Selinuntian as a replacement for the Calabrian, which included the three abovementioned substages (Van Couvering, 1997; Cita, 2008). However, the Selinuntian was not defined following the procedures prescribed by the International Commission on Stratigraphy (ICS), so it was considered a *nomen nudum* (Vai, 1996; Cita, 2008; Cita et al., 2008). At the end of 2007, the Calabrian Stage was redefined with the Vrica section as type-section (Cita, 2008); for historical background and a deep review on Italian marine stages, see Cita (2008) and Cita et al. (2006, 2008, 2012).

The definition of the Santernian, Emilian, and Sicilian was essentially based on invertebrate paleontology, initially from the study of mollusks, but also of corals, ostracods, foraminifera, and calcareous nannofossils (Cita, 2008). This subdivision of the Calabrian corresponds in part to the three successive migration floods of "northern guests" and to the gradual extinction of taxa of tropical affinity in the Mediterranean Sea (Ruggieri et al., 1984; Raffi, 1986). According to Ruggieri and Sprovieri (1975, 1977), the lower boundary of the Santernian, Emilian, and Sicilian corresponds respectively to the first occurrence of *Arctica islandica*, *Hyalinea balthica*, and *Truncorotalia truncatulinoides excelsa*. This subdivision is not formally used yet (Cohen and Gibbard, 2016), but it is still widely adopted in the Italian literature on the marine Quaternary (see references in Table 1); here, in order to give clear and precise indications of the age of the sections described, we use it together with the formally accepted one (Cohen et al., 2018).

RESULTS

Facies analysis and interpretation of the Stirone section

The study of facies associations of the Stirone section allowed us to define nine lithozones (Fig. 3), each representing a different depositional environment. The vertical and lateral arrangement of different lithofacies reflects cyclic depositional changes between suspended-load- and bed-load-dominated facies associated with different velocity and fallout rates. Sedimentary characteristics and process interpretation, complemented with macroinvertebrate assemblages, are provided subsequently.

Lithozone 1 (0–45 m) is composed of massive to laminated mudstones forming ungraded to normally graded beds of a few millimeters up to 100 cm in thickness and containing marine shelf-related bivalves (e.g., *Amusium cristatum*, *Aequipecten opercularis*, *Corbula gibba*, *Glossus humanus*, *Pelecyora brocchi*, and *Venus nux*), commonly in life position. The biosedimentary features observed suggest sedimentation under low hydrodynamic energy and low accumulation rates, such those typical of an offshore transition environment, dominated by suspension settling. In turn, graded beds suggest deposition by traction plus fallout by waning-waxing hyperpycnal flows generated in nearby flood-dominated fan-delta systems.

Lithozone 2 (45–58 m) is initiated by 6 m of alternating massive to laminated very fine-grained bioclastic limestones and mudstones. Typically, limestone beds are up to 20 cm thick and show either lenticular or pinch-and-swell geometry with a sharp base and top. Above follows 7 m of intensely burrowed (*Thalassinoides* ichnofabric) silty sandstones organized in meter-thick beds (Fig. 4A and B). Macrobenthic remains are sparse and mostly represented by fragments of pectinids (e.g., *A. opercularis*). The lower part of lithozone 2 is interpreted as the product of deposition in an offshore

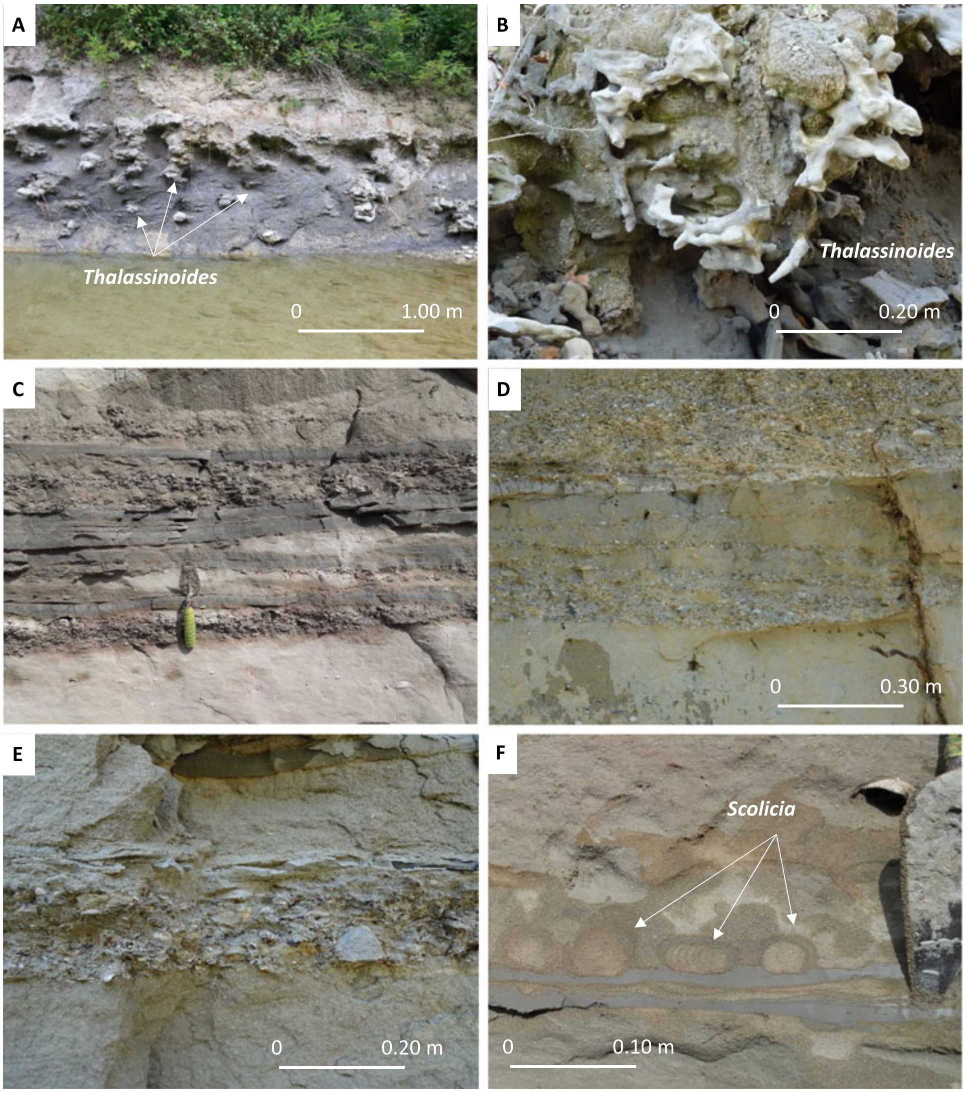

Figure 4. (color online) (A, B) Intensely burrowed silty sandstones: *Thalassinoides* ichnofabric dominated by vertical burrows filled by bioclastic sands. (C) Normally graded beds of fine sandstone and mudstone intercalated with accumulations of shells. (D, E) Normally graded beds of medium and coarse sandstone with large-scale lamination to small-scale cross lamination. Accumulations of shells and small floating clay chips are commonly found dispersed within the sandstone. (F) *Scolicia* ichnofabric overlying sand/mud couplets and reworking a mud layer.

transition environment cyclically receiving fine-grained bioclastic materials. Although bioturbation has obliterated any sedimentary structure, the dominant grain size of the upper half of lithozone 2 suggests deposition in a shoreface environment.

Lithozone 3 (58–77 m) is similar to lithozone 1 apart from the lowermost 0.4 m, which consists of a closely packed unit of macrobenthic invertebrate shells, and from the macroinvertebrate content, which is more abundant and diversified with respect to lithozone 1. Within this lithozone, faunal assemblages are categorized as neighborhood and life assemblages (sensu Brenchley and Harper, 1998), and the most common mollusks are *Pinna* sp., *Nucula placentina*, *Glycymeris inflata*, *Anomia ephippium*, *Lembulus pella*, *Acanthocardia echinata*, *Loripinus fragilis*, *Azorinus chamasolen*, and *Serratina serrata*. Less abundant brachiopods (e.g., *Terebratula terebratula* and *Aphelesia bipartita*) and corals (e.g., *Flabellum* sp.) are also present.

The sedimentary features of this lithozone suggest an offshore transition environment characterized by low hydrodynamic energy and low accumulation rates, dominated by suspension settling; this is also confirmed by the fossil assemblages represented by taxa commonly retrieved in offshore transition to inner shelf settings.

Lithozone 4 (77–93 m) mostly consists of variously cemented biocalcarenitic beds organized into a tripartite facies association. The lower unit is composed of horizontal strata (i.e., bottomsets) containing locally abundant articulated bivalves (such as *G. inflata*, *Glycymeris glycymeris*, *Pecten jacobaeus*, *A. opercularis*). The middle unit shows clinostratified geometries (i.e., foresets) with mainly reworked shells. The upper unit has flat-laying bedding (i.e., bedsets), showing shell pavements mainly represented by concave-down pectinids (e.g., *P. jacobaeus* and *A. opercularis*). In some places, planar lamination and thin horizons made of densely packed anomiid valves are also encountered.

The internal bedding geometry of this unit (i.e., superimposition of bottomset, foreset, and topset) suggests a basinward-prograding body developed in a relatively high-energy shelf environment. The reduced amount of siliciclastic component may reflect either low clastic input or winnowing by bottom currents. Similar Pliocene-Quaternary deposits from the CAB (Cau et al., 2013, 2017, 2019) and other Mediterranean sites (Massari and Chiocci, 2006) have been interpreted likewise.

Lithozone 5 (93–105 m) is mainly composed of normally graded beds of fine sandstone (Fig. 4C–E), with structures ranging from horizontal or large-scale wavy lamination to small-scale cross lamination (wavy, sigmoidal, and/or climbing ripple structures). Bioturbations are frequent (Fig. 4F) and can obliterate any primary sedimentary structure. Locally, flaser, wavy, and lenticular beds with thickness in the range of a few millimeters to several centimeters are intercalated in the sandstones. Small floating clay chips are commonly found homogenously dispersed within the sandstone or clustered in the topmost part of beds. Accumulations of closely packed and mostly concave-down shells are also common and may form thick, sharp-based, and normally graded lags highlighting the base of sandstone beds and showing tabular to lenticular bed geometry. At the base of lithozone 5 (93.15 m), *Arctica islandica* first occurs in the section.

This lithozone is mostly composed of fine-grained sediments transported as suspended load, which form thick and complex intervals that can be massive or displaying traction plus fallout sedimentary structures. The lithofacies' vertical arrangement reflects cyclical and gradual changes between suspended-load- and bed-load-dominated facies, which are the result of near-continuous deposition from a quasi-steady hyperpycnal flow (i.e., long-lived turbulent flow; Zavala et al., 2011; Marini et al., 2016) that tends to dominate the medial parts of a river-delta system. Closely packed and mostly concave-down shells suggest that these lags most likely represent transported assemblages (sensu Brenchley and Harper, 1998).

Lithozone 6 (105–109.5 m) is represented by very thin to thick beds (0.3–1 m) of coarse sandstones internally displaying low-angle (less than 20°) tabular cross stratification with asymptotic relationships with bed top and base. A shallow-water macroinvertebrate fauna of neighborhood assemblage (sensu Brenchley and Harper, 1998) is present here (e.g., *Glycymeris insubrica*, *Dosinia lupinus*, *Chamelea gallina*, and *Ensis ensis*). The diagnostic sedimentary structures along with a stock of nearshore bivalves point toward a high-energy littoral environment (shoreface settings).

Lithozone 7 (109.5–122.5 m) is initiated by 4.5 m of mudstones with abundant marine bivalves in life assemblages (sensu Brenchley and Harper, 1998) in which *Venus nux*, *Acanthocardia paucicostata*, and *Ostrea edulis* are the most abundant species, followed upward by 8.5 m of structureless to laminated sandstones (horizontal, hummocky, tabular, or oblique cross laminations) locally interbedded with flaser, wavy, and lenticular beds (millimeters to centimeters thick). Floating clay chips and accumulations of shells are common features in the sandstone intervals, where they form thick lags at the base of massive or laminated strata. Internal erosional surfaces are frequent; carbonaceous remains and wood fragments are also common within sandstones. Soft-sediment deformation diapir-like structures (Fig. 5A and B) made of fine material (argillaceous fine sands and silts), which intrudes and deforms the overlying beds, have been observed at 116 m. In a few cases, plastic intrusions reach the surface and the sweeping of mud and sand produces the "sand volcanoes" (centimeter scale) set out as flattened cones along fissures. At 117 m, a small block of chemoherms is found containing the typical lucinid fauna. At the top of the interval, *A. islandica* is abundant with articulated valves in life position (Fig. 6).

Lithozone 7 is mostly composed of fine-grained sediments transported as suspended load deposited in the medial parts of a river-delta system. The abundance of *Venus nux* at the base of the lithozone suggests a low-energy offshore transition setting; according to Taviani et al. (1997) and Dominici (2001), the *Venus nux* assemblage is indicative of water depths in the range of 20–40 m. Today, this species is commonly reported from deeper-water settings in the Mediterranean Sea (70–80 m; Raffi and Serpagli, 1993). The observed soft-sediment deformation structures formed in loose, unconsolidated to semiconsolidated fine-grained, water-saturated muddy and sandy deposits and were induced chiefly by liquefaction and/or fluidization processes. These ductile deformation structures can be related to seismic shocks on water-saturated sediments (Berra and Felletti, 2011). The presence of chemoherms is here recorded for the first time in this part of the section, whereas they are well documented in Pliocene sediments of western Emilia (Monegatti et al., 2001; Cau et al., 2015). These chemoherms were interpreted, by Monegatti et al. (2001) and Cau et al. (2015), to have formed in a deep-water environment affected by expulsion of hydrocarbon-rich fluids generated by the tectonic pulses of the Salsomaggiore structure.

Lithozone 8 (122.5–134.5 m) is represented by coarse-grained sands with intercalated massive and cross-stratified conglomerates with abundant coarse- to fine-grained sandstone matrix, especially in the lower part of the lithozone (Fig. 5C and D). Individual sets of cross beds commonly show thicknesses between 0.5 and 1.5 m and asymptotic relationships with top and base. Bounding surfaces between bedsets are erosional, and the foreset inclinations do not usually exceed 15°. Flaser and massive mudstone beds up to several centimeters thick are intercalated within these sandstones (Fig. 5E and F), as well as large mud clasts floating in a medium- to coarse-grained sandstone matrix.

This lithozone documents a foreshore to upper shoreface environment characterized by high hydrodynamic energy and high sedimentation rate. Simultaneously, the presence of massive and cross-stratified conglomerates suggests the

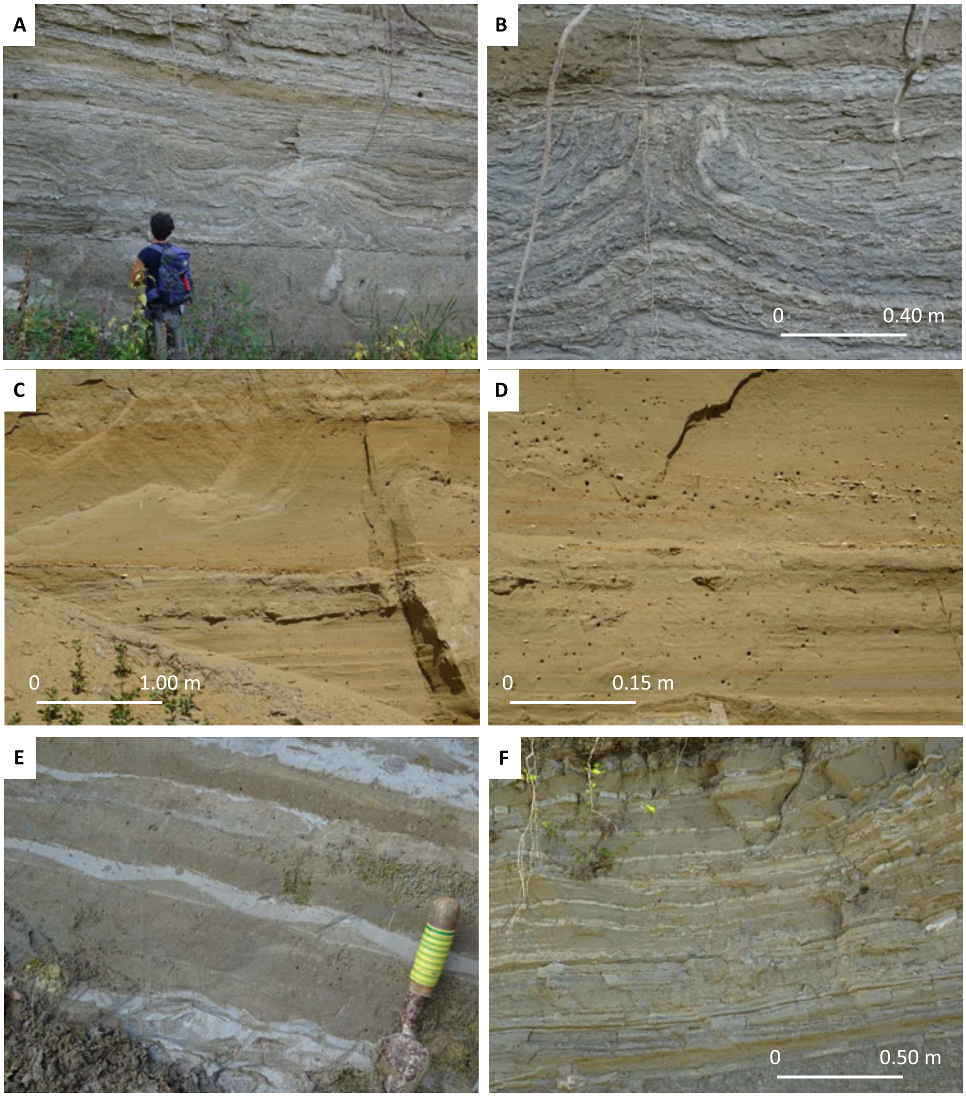

Figure 5. (color online) (A, B) Soft-sediment deformation structures. These ductile deformation structures can be related to seismic shocks on water-saturated sediments. (C, D) Medium-grained sands with low-angle cross stratification, documenting a foreshore to upper-shoreface environment. (E, F) Flasers, wavy and lenticular bedding, from a few millimeters to several centimeters thick, intercalated with sandstones.

existence of high-density flows that occur mainly in a flood-generated delta-front sandstone lobe (mouth bar).

Lithozone 9 (134.50–138 m) consists of laminated silty mudstone with diagnostic freshwater/ipohaline mollusks, such as *Dreissena polymorpha*, *Theodoxus groyanus*, *Lithoglyphus* sp., *Melanopsis wilhelmi*, and *Tanousia stironensis* (see also Esu, 2008; Esu and Girotti, 2015).

The presence of such a large stock of freshwater mollusks points toward a coastal plain setting, characterized by a standing body of fresh to low-salinity water.

Biostratigraphy

Calcareous nannofossils

The nannofossil assemblages are composed of in situ specimens and reworked Cretaceous and Cenozoic species. The total nannofossil abundance (average number of specimens in one field of view, which is equal to 0.02 mm^2) is 5.7. Only one sample (86.25 m) was found to be barren of nannofossils. The interval between 75.70 m and 87.35 m is characterized by the lowest total abundance (lower than 3.5 specimens/field of view). The taxa considered to be in situ constitute between 20% and 45% of the assemblages and include relatively small placoliths (e.g., reticulofenestrids and "small" *Gephyrocapsa* <4.0 µm in size), *Pseudoemiliania lacunosa*, *Calcidiscus macintyrei*, *Helicosphaera sellii*, and, in some intervals, "medium" *Gephyrocapsa* ≥4.0 µm and/or "large" *Gephyrocapsa* >5.5 µm. Reworked Cretaceous species make up, on average, 30% of the assemblages (Supplementary Fig. 1). Reworked Cenozoic species are present throughout the section and constitute, on average, 35% of the total nannofossil assemblage. Some of the most representative and/or biostratigraphically important nannofossil taxa found in the studied samples are shown in Figure 7.

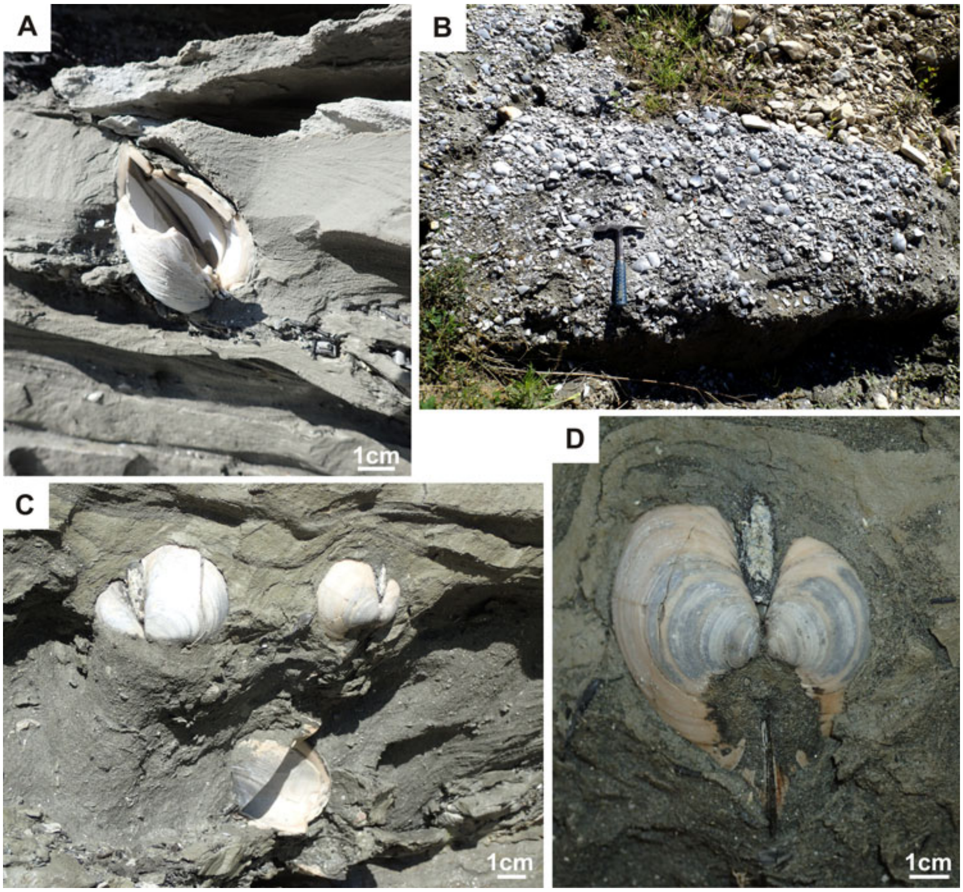

Figure 6. (color online) Specimens of *Arctica islandica* occurring in lithozone 7. (A, C, D) Articulated specimens in life position and not filled inside by the sediment; note the well-preserved organic ligament in panels C and D. (B) Accumulation bed with abundant disarticulated concave-down valves.

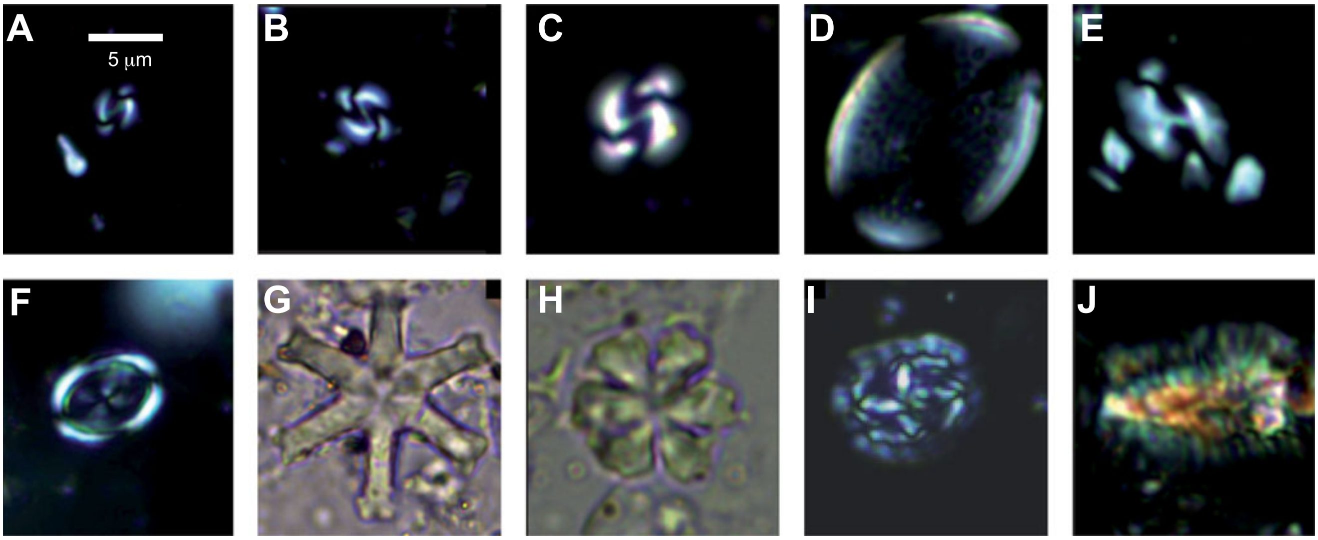

Figure 7. (color online) Calcareous nannofossils identified in the Stirone section under light microscope in smear slides. Scale bar is 5 µm. PL, plain light; XPL, cross-polarized light. (A) *Gephyrocapsa* "small," XPL (95.25 m). (B) *Gephyrocapsa* "medium," XPL (112.8 m). (C) *Gephyrocapsa* "large," XPL (113.5 m). (D) *Pontosphaera discopora*, XPL (64.75 m). (E) *Helicosphaera sellii*, XPL (57.65 m). (F) *Syracosphaera pulchra*, XPL (57.65 m). (G) *Discoaster* sp., PL (91.85 m). (H) *Discoaster* sp., PL (58.1 m). (I) *Prediscosphaera cretacea*, XPL (64.75 m). (J) *Nannoconus* sp., XPL (64.75 m).

The nannofossil analysis allowed the identification of the CNPL7 to CNPL9 zones described as follows (Fig. 8):

Zone CNPL7 (from 0 to 98.25 m) was determined by the presence of "small" *Gephyrocapsa* <4.0 µm and the absence of *Discoaster brouweri*. In this interval, the assemblage is characterized by specimens of *H. sellii*, *C. macintyrei,* and *P. lacunosa*.

Zone CNPL8 (from 98.25 to 121.50 m) was defined by the First Occurrence (FO) of *Gephyrocapsa* ≥4.0 µm at the base. "Large" *Gephyrocapsa* >5.5 µm (dated 1.59 Ma) was found from 112.80 m up to 121.50 m where its last occurrence (LO) marks the top of zone CNPL8.

Zone CNPL9 (from 121.50 to 138 m) was characterized by specimens of *Gephyrocapsa* (<4.0 µm) occurring concomitantly with specimens of *P. lacunosa* and *H. sellii*. The presence of *P. lacunosa* and *H. sellii* and the absence of *Reticulofenestra asanoi* suggests that the top of the Stirone section extends into the lowermost part of zone CNPL9 (below the LO of *H. sellii* and the FO of *R. asanoi*, dated at 1.14 Ma).

In this work, we used the biozonation scheme by Backman et al. (2012), which is a development of previous calcareous nannofossil biozonations of the Cenozoic (e.g., Martini, 1971; Bukry, 1973, 1975, 1978; Okada and Bukry, 1980). Based on the identified nannofossil zones, the age of the Stirone section is early Pleistocene (Gelasian-Calabrian).

Foraminifera

Benthic foraminifera are abundant, and preservation is moderate to good. However, assemblages show severe resedimentation being composed of mixed populations containing shoreface–upper offshore transition (i.e., infralittoral; Rotalidae, Elphididae, Astigerinidae, Nonionidae, and Miliolidae) and lower offshore transition-offshore taxa (i.e., circalittoral; Buliminidae, Bolivinidae, and Cassidulinidae) and more lagoon-brackish to nearshore species (i.e., *Ammonia beccarii*, *Elphidium crispum*, and *Elphidium aculeatum*). Planktonic foraminifera show their maximum abundance (35% of the total foraminifera) in the middle part of the section (from STF47, 39 m, to STF13, 75.75 m) with intercalated shoreface–upper offshore transition benthic taxa, whereas the freshwater influence increases upward as testified by the dominance of *Ammonia* spp. and *Elphidium* spp. (from STF33, 92.40 m, to STF54, 130.50 m). Selected species are illustrated in Figure 9.

In general, planktonic foraminifera are rare to frequent, small in size, and moderate to poorly preserved. The assemblages are composed of the common Pleistocene taxa *Globigerina bulloides*, *Globigerinoides elongatus*, *Globigerinoides obliquus extremus*, *Globigerinoides ruber*, *Globigerina falconensis*, and *Orbulina universa*. The presence of Miocene and Pliocene marker species such as *Globigerinoides parawoodi*, *Globigerina venezuelana*, *Globorotalia sphericomiozea*, *Globorotalia puncticulata*, and *Neogloboquadrina atlantica* indicates reworking from older stratigraphic levels.

However, the presence of rare specimens of *Globigerina cariacoensis* and *Neogloboquadrina pachyderma* left-coiled, and the benthic foraminifera *Uvigerina mediterranea*, *Uvigerina bradyana*, and *Bulimina elegans marginata* from the base of the section (STF43, 18 m), allow assignment of the Stirone section to the early Pleistocene (Calabrian Stage) *Globigerina cariacoensis* zone (Cita et al., 2012 and references therein) (Fig. 8). The highest occurrence of *Globigerinoides obliquus extremus* is placed at 113.50 m (STF38), whereas only one specimen resembling the benthic foraminifera *Hyalinea balthica* is recorded at 121.50 m (STF52). The top of the section cannot be constrained using foraminifera because of the rarity of both benthic and planktonic foraminifera and the absence of marker bioevents (e.g., temporary disappearance of *N. pachyderma* left-coiled and lowest occurrence of *Truncorotalia truncatulinoides excelsa*). Nevertheless, our findings are in agreement with previous studies from the Arda section (Crippa et al., 2016) and other stratigraphic sections in the Mediterranean area (e.g., Colalongo and Sartoni 1979; Ragaini et al., 2006; Cosentino et al., 2009; Di Bella, 2010, Maiorano et al., 2010; Baldanza et al., 2011, among many others). Therefore, based on foraminiferal biostratigraphy and geochronology data from the Vrica section (Calabrian GSSP; Cita et al., 2012 and references therein), the age of the studied stratigraphic interval is likely between 1.78 Ma and about 1.1 Ma (see Cita et al., 2012; Gradstein et al., 2012).

DISCUSSION

Correlation of the Arda and Stirone River sections

Lithostratigraphic correlation

A large-scale lithostratigraphic correlation between the Arda and Stirone River sections has been previously attempted by Channell et al. (1994) and Monegatti et al. (2001), with a specific focus on the Pliocene part of the successions. In this regard, Channell et al. (1994) observed that during the lower Zanclean, both sections were prone to mud deposition in a slope setting (i.e., "Argille azzurre"), whereas a change in the sedimentary regime is recorded from the upper Zanclean through the Gelasian with the establishment of an outer shelf environment in the Castell'Arquato area. Such differentiation in the study area into a slope environment (Stirone) and an adjacent shelf (Arda) during the late Pliocene is further substantiated by Monegatti et al. (2001).

The large-scale lithostratigraphic correlation framework resulting from the present study suggests this configuration lasted through the Calabrian (1.78–1.14 Ma) even if less pronounced. Indeed, the Arda River section records biosedimentary dynamics developed closer to the basin margin with respect to the Stirone River section and to previous time intervals. However, both sections developed within a strongly fluvio-influenced marginal marine setting, recording improvised and strong changes in the depositional style.

All lithofacies/lithozones identified along the Arda (see Crippa et al., 2018) and Stirone Rivers (except for lithozone 4) represent the sedimentary product of—and are strongly influenced by—a high-gradient fluvial network, originated when

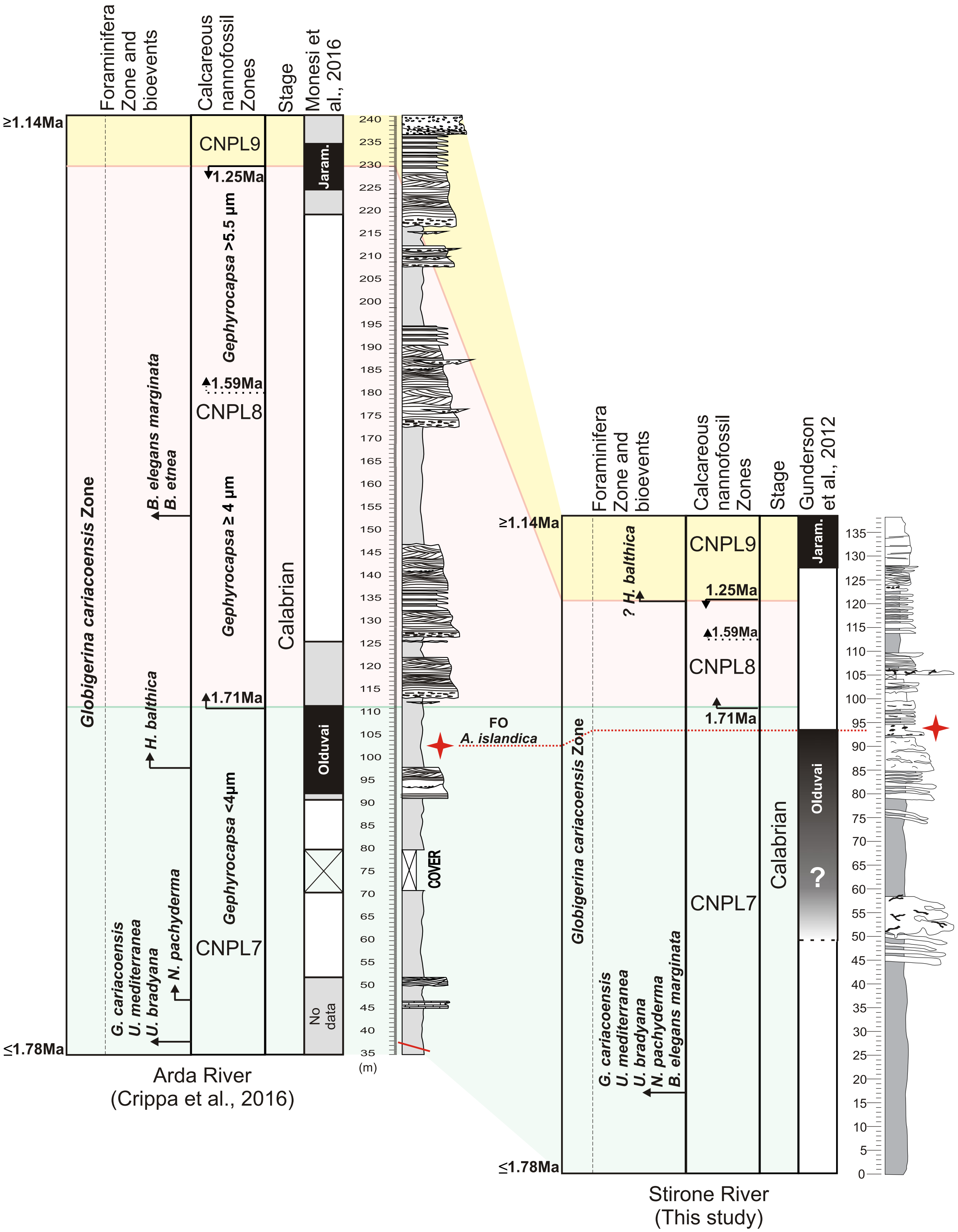

Figure 8. (color online) Biostratigraphic correlation between the Arda and Stirone River sections and main biovents. For both sections, the foraminiferal and calcareous nannofossil biozones, the magnetostratigraphic data available from the literature (Gunderson et al., 2012; Monesi et al., 2016), and the stratigraphic logs are shown. The boundaries between calcareous nannofossil biozones are taken as tie points between the two sections. Main bioevents are the first occurrences of *Arctica islandica*, *Globigerina cariacoensis*, *Uvigerina mediterranea*, *Uvigerina bradyana*, *Neogloboquadrina pachyderma*, *Hyalinea balthica*, *Bulimina elegans marginata*, *Bulimina etnea*, and "small", "medium" and "large" *Gephyrocapsa.*

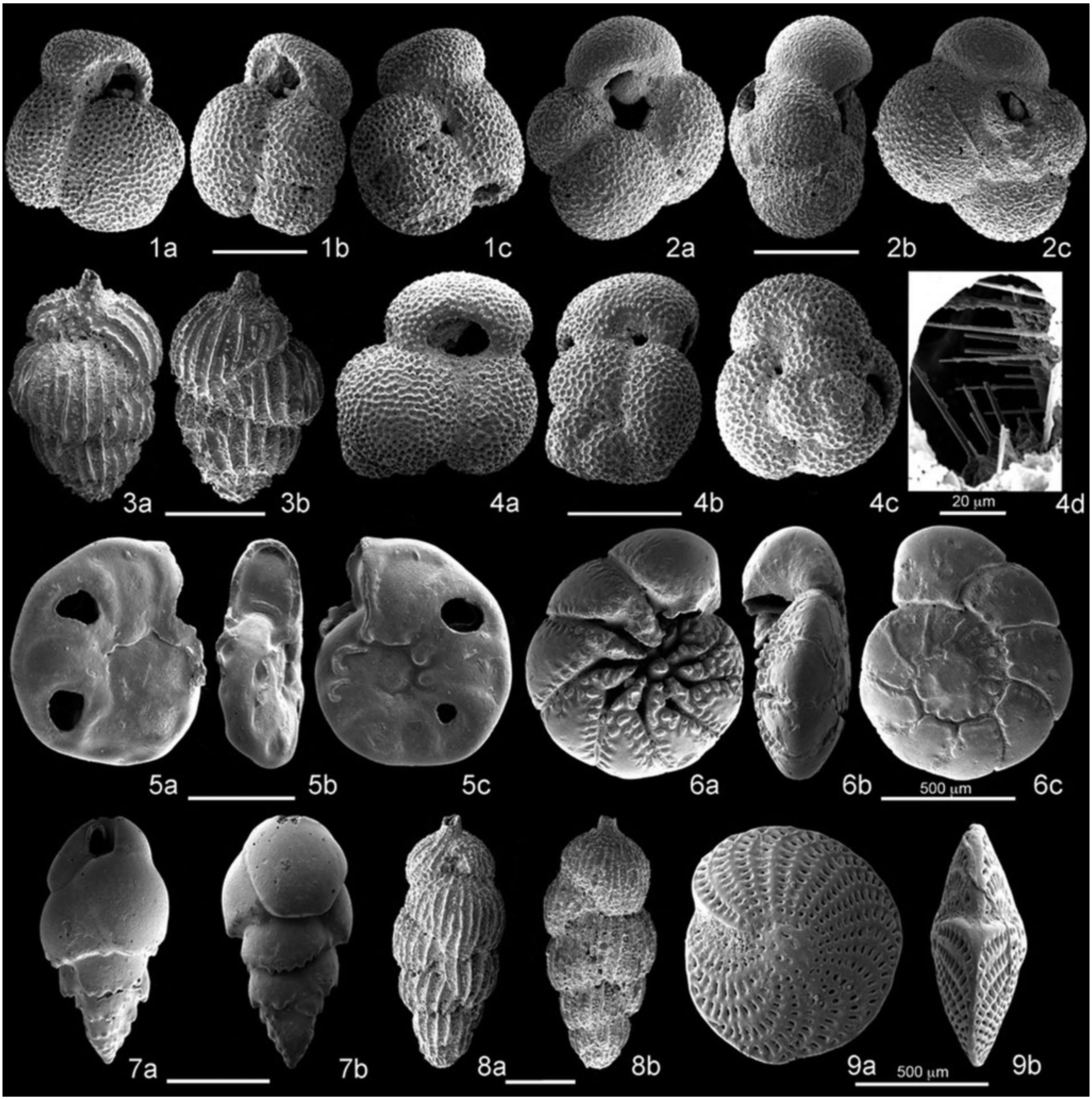

Figure 9. (1a–c) *Globigerinoides obliquus extremus*, sample STF9. (2a–c) *Globigerina cariacoensis*, sample STF9. (3a–b) *Uvigerina mediterranea*, sample STF13. (4a–d) *Globigerinoides elongatus*, sample STF13. (5a–c) *Hyalinea* cf. *H. balthica*, sample STF52. (6a–c) *Ammonia beccarii*, sample STF7. (7a–b) *Bulimina elegans marginata*, sample STF9. (8a–b) *Uvigerina bradyana*, sample STF9. (9a–b) *Elphidium crispum*, sample STF7. Scale bars 200 µm except where otherwise stated.

the rivers discharged a sustained and relatively dense turbulent mixture of freshwater and sediments (i.e., hyperpycnal flows; Bates, 1953) into the receiving standing body of seawater; this is in agreement with the findings of Dominici (2001, 2004). The influence of the fluvial systems extended for kilometers away from the rivers' mouths. The fossil assemblages are mainly represented by sets of oligotypic to low-diversity macrobenthic remains, commonly represented by life assemblages (e.g., lithozone 1, lithozone 7), or lenticular-shaped, hydraulically sorted, or chaotically mixed fossils (e.g., lower most part of lithozone 3, lithozone 5).

The difference in sediment thickness observed between the two sections (CNPL8 biozone: 120 m in the Arda section, 23 m in the Stirone section) may be explained considering a lateral position, and for its lower part, a slightly deeper-water setting of the Stirone section with respect to the river mouth, with a consequent lower sedimentation rate. Indeed, the Arda River succession is characterized by an overall aggradational (cycles 0 to 2) to progradational stacking pattern (cycles 3 to top section), developed within offshore transition to alluvial depositional settings (Crippa et al., 2018). Along the Stirone River section, lithozone 4, with its pectinid rich, bioclastic deposits (i.e., biocalcarenites), represents a prolonged phase of low clastic input or winnowing by bottom currents indicative of offshore transition settings; it constitutes the turning point from a slightly deepening upward (lithozones 1 to 4) to an overall progradational stacking pattern that led to emplacement of a thick marginal marine to coastal plain succession along the Stirone River section (lithozones 5 to 9). The onset of the progradational stacking pattern (i.e., Stirone lithozone 5 and Arda unit 2 in Crippa et al. [2018]) in both sections is highlighted by the first occurrence of *Arctica islandica*, an indicator of climate deterioration in the Mediterranean region during the Calabrian (Raffi, 1986).

The overall regressive trend of the Arda and Stirone River sections can be directly related to deformation phases of the local fronts of the Apennines. As underlined by Dominici (2001, 2004), the sedimentary dynamics along both sections are controlled by recurring tectonic pulses on which, at smaller scale, climatic fluctuations are superimposed. Comparable sedimentary dynamics were already documented for a few other sedimentary successions outcropping along the northeastern margin of the Apennines, such as the Enza River section (e.g., Gunderson et al., 2014). However, correlation at the scale of genetically related packages of strata (high-frequency cycles) between the two sections is very complex within such highly dynamic depositional settings represented by the sedimentary staking of meter-thick layers of hyperpycnal flows associated with widespread erosional features.

Biostratigraphic correlation

The integrated biostratigraphic analysis of calcareous nannofossils and foraminifera in the Arda (Crippa et al., 2016) and Stirone sections allows us to identify three nannofossil zones (CNPL7, CNPL8, and CNPL9) and one foraminiferal zone (*Globigerina cariacoensis*), suggesting that the age of the studied stratigraphic intervals is Calabrian (early Pleistocene) (Fig. 8). Calcareous nannofossils suggest that the base of these sections is between 1.93 Ma (LO of *D. brouweri*) and 1.71 Ma (first common occurrence of "small" *Gephyrocapsa*). Foraminifera analysis further constrains the age of the base of the sections; the presence of rare specimens of *Globigerina cariacoensis* and *Neogloboquadrina pachyderma* left-coiled and of the benthic foraminifera *Uvigerina mediterranea* and *Uvigerina bradyana* indicates that both the Arda and Stirone River successions deposited during the early Pleistocene (Calabrian Stage) *Globigerina cariacoensis* zone (base at 1.78 Ma). The overlap of these biozones suggests that the base of the sections should be dated between 1.78 and 1.71 Ma. The top of the sections is here interpreted to be limited to the lowermost part of the nannofossil zone CNPL9; thus it is not younger than 1.14 Ma (FO of *R. asanoi*).

Other important bioevents are recorded in the two sections. *A. islandica* first occurs in both sections in the upper part of the CNPL7 biozone (a few meters below the top of this biozone), after the first occurrence of *N. pachyderma* left-coiled. *H. balthica* occurs before the first occurrence of *A. islandica* in the Arda section, but after in the Stirone one, where only one specimen resembling this benthic foraminifer has been found. Generally, in lower Pleistocene successions, the first occurrence of *H. balthica* is recorded after that of *A. islandica* (e.g., Rio et al., 1997), but in the Arda section, we observe the opposite. To explain this, we need to consider the discontinuity of the benthic fossil record through the section, which is not complete and may be controlled by the Signor-Lipps and Jaanusson effects (Jaanusson, 1976; Signor and Lipps, 1982). Indeed, here we refer to the first occurrence of both species and not to their first appearance. The occurrence of *H. balthica* before *A. islandica* in the CNPL7 biozone in the Arda section—and not in the upper part of the CNPL8 biozone (~Emilian substage) as generally accepted—suggests that the Calabrian substages cannot be used in their original significance based on the successive occurrence of *A. islandica*, *H. balthica*, and *T. truncatulinoides excelsa.*

The calcareous nannofossil and foraminiferal biostratigraphic data are not perfectly tuned with magnetostratigraphic data available from the literature (Gunderson et al., 2012; Monesi et al., 2016). Both Gunderson et al. (2012) and Monesi et al. (2016) indicated a Calabrian age for the Arda and Stirone sections, and this is in general agreement with our biostratigraphic data. However, looking at this in more detail, we observe that in both sections the lower boundary of the Olduvai subchron (1.94–1.77 Ma) does not fit with biostratigraphic data (Fig. 8). In fact, the lower boundary of this magnetic subchron (1.94 Ma) is recorded several meters stratigraphically above the bases of both sections, which, based on calcareous nannofossil and foraminiferal biostratigraphy, should be younger than 1.78 Ma. The top of the Olduvai (1.77 Ma) occurs stratigraphically below the top of the CNPL7 (1.71 Ma) in the Stirone section and thus fits quite well with both the age of the top of the CNPL7 biozone and the other bioevents (e.g., *Arctica islandica* first occurrence). However, this is not the case for the Arda section, where the top of the Olduvai subchron coincides with the top of the CNPL7 biozone. Magnetostratigraphic analysis thus assigned an older age to the base of the sections compared with biostratigraphy (i.e., 1.94 vs. 1.78 Ma). At the top of the Stirone succession, the position of the Jaramillo subchron (base at 1.07 Ma, top at 0.99 Ma) is in agreement with our biostratigraphic data, as it occurs stratigraphically above the base of the CNPL9 biozone (dated at 1.25 Ma); on the other hand, in the Arda section this magnetostratigraphic interval corresponds to the boundary between CNPL8 and CNPL9 nannofossil biozones (1.25 Ma; Fig. 8), thus suggesting a younger age for the upper part of the section.

One possible explanation of these discrepancies can be found in the different measurement of the thickness of the sections reported by different authors; this could be the case for the Stirone River succession (Gunderson et al., 2012 and this study), where different authors produced different stratigraphic logs, but not for the Arda River section, where the log used by Crippa et al. (2016) and Monesi et al. (2016) was the same. In the first case, it is difficult to precisely locate the base of the Olduvai of Gunderson et al. (2012) in the Stirone section, mainly because of the different recorded thicknesses and the lack of a detailed figured stratigraphic log in Gunderson et al. (2012, their fig. 2b), which may have been helpful to correlate the two logs using lithologic markers. In the case of the Arda section, this discrepancy may be explained by making reference to the short reversed polarity interval found in the Vrica section at the top of the Olduvai subchron (the ß interval in Zijderveld et al., 1991; Roberts et al., 2010; Cita et al., 2012), which may be tentatively correlated with the reversed interval occurring between 50 and 90 m in the Arda section (Monesi et al., 2016). Another possibility to consider would be microfossil reworking; this can be taken into account to explain the discrepancies at the top of the Arda section, but not the ones concerning the base of the Olduvai subchron. Reworked samples would result in a younger age for the base of the section, enhancing even more the lack of correspondence between magneto- and biostratigraphic data; however, reworking as the only cause should be excluded, as otherwise we would not have recorded such a complete sequence of bioevents and biozones, which strengthens our biostratigraphic data.

Although some of the discrepancies between bio- and magnetostratigraphic data can be considered irrelevant for the age determination of these sections (i.e., those regarding the part of the sections containing the Jaramillo subchron and the top of the Olduvai subchron), the ones concerning the base of the sections are difficult to reconcile. They suggest an age for the base of the sections that differs by about 200 ka (>1.94 Ma according to magnetostratigraphy vs. ≤1.78 Ma according to biostratigraphy). Unless considering the possibility of correlating the base of the sections with the above-mentioned short reversed polarity interval (ß interval) at the top of the Olduvai subchron at Vrica, this issue remains unsolved.

Arctica islandica in the early Pleistocene of the Mediterranean Sea

The ocean quahog *Arctica islandica* is a shallow infaunal bivalve that today is found on both sides of the North Atlantic in temperate and boreal waters (e.g., Witbaard, 1997; Dahlgren et al., 2000). However, fossil evidence indicates that its paleobiogeographic range extended southward during phases of climate deterioration—that is, cooling starting in the Calabrian (ca. 1.8 Ma; Raffi, 1986; Table 1)—colonizing the Bay of Biscay and the Mediterranean Sea. In a revision of the available information, complemented with data from this study, on the first occurrence of *A. islandica* in the early Pleistocene of the Mediterranean Sea (Table 1, Fig. 10), two important outcomes are immediately observable and worthy of note: (1) nearly all lower Pleistocene marine on-land successions recording the widespread occurrence of *A. islandica* are located in Italy, with the exception of Rhodes, Greece (Zaccaria, 1968), and Mallorca, Spain (Pomar Gomà and Cuerda Barceló, 1979); and (2) the oldest outcrops are located in northern Italy.

These two considerations can be explained taking into account the present ecological range and the biology of the species and assuming that it has not changed since the Pleistocene (see Table 2). Unlike other areas in the Mediterranean Sea, at the beginning of the Calabrian the shallow marine settings of the northern paleo-Adriatic (northern Italy) satisfied the ecological requirements (type of substratum, salinity and oxygenation levels, temperature and water depth; Table 2) for the establishment of widespread populations of *A. islandica*. During the Santernian (lower Calabrian), northern Italy was a wide gulf wedging out westward, mainly characterized by terrigenous shallow-water settings, with fully marine and well-oxygenated conditions, apart from occasional events of salinity dilution (Kukla et al., 1979; Bedini et al., 1981; Sarti et al., 2007, 2008; Crippa et al., 2016, 2018; this study). These settings were characterized by strong seawater seasonality and low winter paleotemperatures conditions (Crippa et al., 2016), satisfying those required for the successful establishment and settlement of the first populations of *A. islandica* (Raffi, 1986).

According to Kukla et al. (1979), *A. islandica* first occurred about 2.00 Ma ago in the Santerno Valley (northern Italy), based on magnetostratigraphic evidence and radiometric age (helium/uranium method) obtained on corals. The same or a slightly older age (≥2 Ma, based on magnetostratigraphy; Table 1) was suggested also by other authors (Arias et al., 1980; Bedini et al., 1981). However, Azzaroli et al. (1997) observed that the magnetostratigraphic interpretation of Kukla et al. (1979) was not in agreement with biostratigraphic data (see Azzaroli et al., 1997 for a detailed discussion). Also, Arias et al. (1980) did not record the occurrence of shells of *A. islandica* in their sections, but rather they estimated the age of its first occurrence through a comparison with other Italian successions, mainly based on magnetostratigraphic correlations without biostratigraphic data to support it. Crippa and Raineri (2015), Crippa et al. (2016, 2018), and this study recorded the first occurrence of rare specimens of *A. islandica* in the Arda and Stirone sections a few meters below the top of the CNPL7 biozone (dated at 1.71 Ma), but the species becomes more abundant in the CNPL8 calcareous nannofossil biozone (1.71–1.25 Ma; Backman et al., 2012). The same distribution pattern was also noted by other authors (e.g., Pelosio and Raffi, 1974; Kukla et al., 1979).

A. islandica is not present in outcrops of Santernian age of southern Italy, where this time interval is mainly represented by deep-water (bathyal) muddy/marly successions (e.g., Ruggieri and Sprovieri, 1975; Di Geronimo and La Perna, 1997 and references therein); as an example, the Vrica section, GSSP for the Calabrian Stage, recorded during the Santernian the deposition of epibathyal, silty marl claystone (Cita et al.,

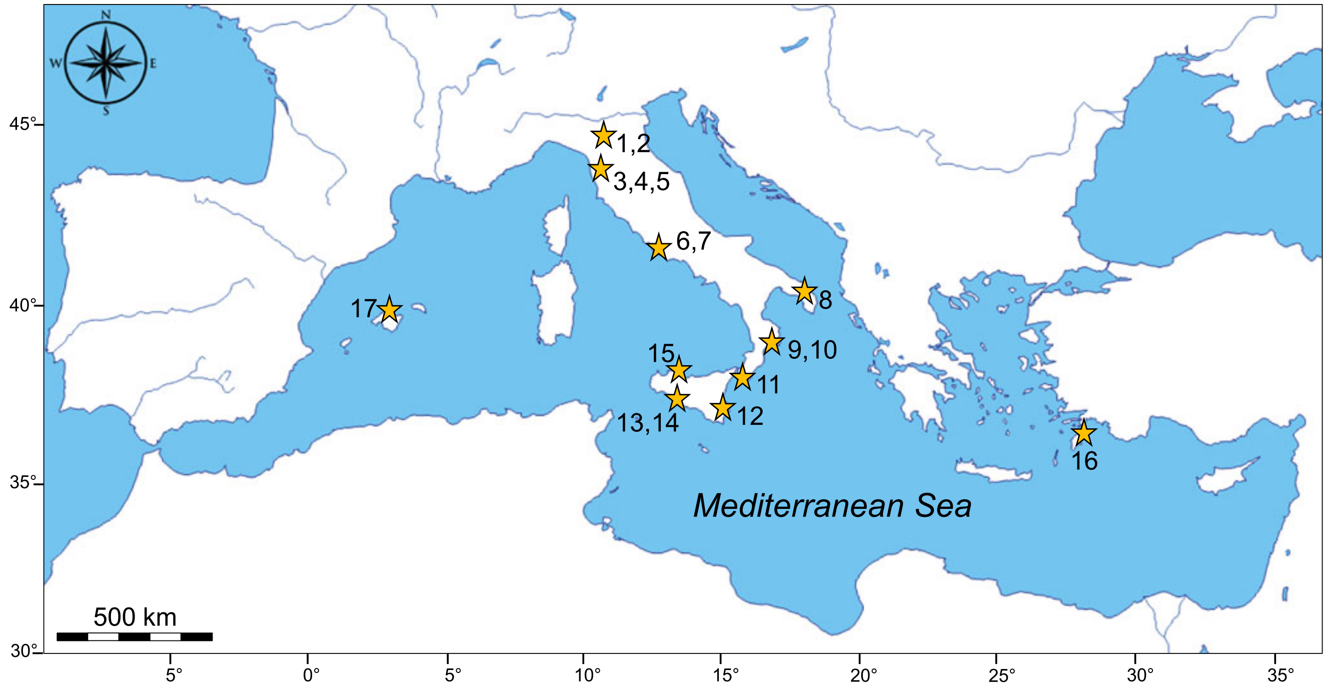

Figure 10. (color online) Map showing the lower Pleistocene outcrops with *Arctica islandica* in the Mediterranean Sea: 1, Santerno Valley, Bologna; 2, Arda and Stirone Rivers, Piacenza and Parma; 3, Collesalvetti, Pisa; 4, Val Cecina, Livorno; 5, Pisa hills, Valdarno, Pisa; 6, Monte Mario, Rome; 7, Tacconi quarry, Rome; 8, Cutrofiano quarry, Lecce; 9, Santa Maria di Catanzaro, Catanzaro; 10, Valle di Manche, Crotone; 11, Monasterace, Reggio Calabria; 12, Ogliastro quarry, Siracusa; 13, Capo Rossello, Agrigento; 14, Belice Valley, Agrigento; 15, Puleo Quarry, Palermo; 16, Rhodes, Greece; 17, Mallorca, Spain. See Table 1 for corresponding references for each locality.

Table 2. Summary of the main ecological and biological parameters for the ocean quahog *Arctica islandica.* Asterisk (*) indicates rare specimens have been reported up to 256 m, but the common occurrence is in less than 100 m. Nicol (1951) reported a water depth up to 500 m from commercial catches; however, according to Merrill and Ropes (1969), the author did not state whether the catch contained live organisms or only shells.

	Arctica islandica targeted species
Water depth	4–256* m (Merrill and Ropes, 1969). Highest densities and common occurrence in <100 m [e.g., 25–61 m (Serchuk et al., 1982); 50–100 m (Northeast Fisheries Science Center, 2000); 30–60 m (Dahlgren et al., 2000); 5–50 m (Thorarinsdóttir et al., 2009)].
Substratum	Siliciclastic substrates, highest densities on sandy bottoms (Lutz et al., 1981; Cargnelli et al., 1999; Thorarinsdóttir et al., 2009).
Water temperature	It prefers temperatures of 1–16°C, but tolerates up to 20°C (Golikov and Scarlato, 1973; Cargnelli et al., 1999; Schöne, 2013). The inshore limit distribution follows the 16°C sea-bottom isotherm during the summer (Mann, 1989).
Salinity and oxygen levels	It tolerates low dissolved oxygen levels and salinity fluctuation between 22 and 35 psu (Winter, 1969; Cargnelli et al., 1999). However, strong shifts in environmental parameters represent a stress for the organism that leaves peculiar traces in the shell growth pattern (i.e., growth lines; see Schöne, 2013).
Feeding strategy	Suspension feeder on phytoplankton by means of short siphons that are extended just above the sediment–water interface (Josefson et al., 1995; Cargnelli et al., 1999).
Larval development	Fastest rates at 10–16°C and 32 psu (Lutz et al., 1982).
Larval type	Planktotrophic (Cargnelli et al., 1999; Schöne, 2013).
Shell growth	It occurs at temperatures as low as 1°C, increases strongly between 1°C and 6°C, and shows a 10-fold increase between 1°C and 12°C (Witbaard et al., 1997).

2008). In these areas, *A. islandica* populations are found only in the Emilian-Sicilian (middle–upper Calabrian); from this time on, the widely preserved on-land marine successions of southern Italy deposited in shallow-water settings and showed the optimal conditions for the proliferation of the species (Tables 1 and 2). Indeed, *Arctica islandica* in nearly all southern Italy successions (Emilian or Sicilian in age) occurs in coarse to fine sands deposited at water depth ranging from

20 to 80 m (Table 1 and references therein); this is in agreement with the present day highest densities and common occurrence of the species (see Table 2).

Outside the Italian peninsula, there may be other areas satisfying the ecological requirements for the establishment of *A. islandica*, but, to our knowledge, lower Pleistocene outcrops recording the occurrence of this species are rarely cited (outcrops not studied/found yet or inaccessible). Pomar Gomá and Cuerda Barceló (1979) observed the presence of this species in the Sicilian (upper Calabrian) of Mallorca (Spain), whereas Zaccaria (1968) documented the occurrence of rare specimens in the Calabrian of Rhodes (Greece), but no information is given about which of the three Calabrian substages (sensu Ruggieri and Sprovieri, 1975, 1977) is represented. Also, submarine successions with *Arctica islandica* from France (Lyon Gulf; Gadel and Mongin, 1973) and Spain (Cap Creus; Mars, 1958, 1963) are all referred to the Würmian (upper Pleistocene).

Thus, our findings support the hypothesis that the lowest recorded occurrence of *A. islandica* in the Mediterranean Basin is in the Arda and the Stirone River sections (i.e., a few meters below the top of the CNPL7 biozone); here, this species successfully settled with widespread populations, subsequently establishing in southern Italy and in other Mediterranean sites, then becoming extinct in the Mediterranean Sea during the early Holocene (ca. 9.8 ka; Froget et al., 1972).

CONCLUSIONS

This study allows us to date and correlate the Arda and Stirone Rivers, two lower Pleistocene key sections in northern Italy, and to calibrate and map the first occurrence of the bivalve *Arctica islandica* in the Mediterranean Sea during the early Pleistocene. We conclude the following:

The Stirone River section is Calabrian in age (1.78–1.14 Ma) based on the identification of three nannofossil (CNPL7, CNPL8, and CNPL9) and one foraminiferal (*Globigerina cariacoensis*) biozones; the same age was recorded in the nearby Arda River section (Crippa et al., 2016). The biostratigraphic data do not fit perfectly with magnetostratigraphic data available in the literature.

The Stirone River succession corresponds to the subaqueous extension of a fluvial system affected by hyperpycnal flows; a lateral position with respect to the river mouth is suggested. A general regressive trend is observed through the section, which can be directly related to the tectonic activity and to early Pleistocene climatic change.

The occurrence in both the Arda and Stirone marine successions of the “northern guest” *A. islandica* indicates a climatic deterioration (i.e., cooling) from the Calabrian, which is an expression of the climatic change occurring during the early Pleistocene, leading to the onset and establishment of middle and upper Pleistocene continental glaciations.

The original data here presented complemented with previous findings seem to support that the stratigraphically lowest level where *A. islandica* first occurred in the Mediterranean was in the Arda and Stirone River successions (in both sections a few meters below the top of the CNPL7 calcareous nannofossil biozone). The paleoenvironmental conditions present in this region satisfy the ecological requirements for the establishment and the proliferation of the species (i.e., water depth up to 100 m, sandy substratum, normal water salinity, and high seawater seasonality); only subsequently did the species successfully become established also in southern Italy and in other areas of the Mediterranean Sea.

This and previous studies (e.g., Crippa et al., 2016) strengthen the importance of applying integrated biostratigraphic analyses to obtain robust and reliable data concerning the age of a section, especially in shallow-water settings, avoiding or compensating for biases specific to the use of only one tool. Also, it highlights the importance of using multidisciplinary approaches in past environmental and climatic reconstructions in different geologic contexts.

SUPPLEMENTARY MATERIAL

The supplementary material for this article can be found at https://doi.org/10.1017/qua.2019.20.

ACKNOWLEDGMENTS

We would like to thank A. Rizzi (University of Milan) for SEM analyses. “Parco dello Stirone e del Piacenziano” and “Museo Geologico G. Cortesi” (Castell’Arquato) are acknowledged for the permissions to enter the conservation areas. L. Angiolini is warmly thanked for constructive discussions and suggestions. Two anonymous reviewers are also thanked for their useful comments and suggestions, which improved the quality of this manuscript.

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