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The Apennine foredeep (Italy) during the latest Messinian: Lago Mare reflects competing brackish and marine conditions based on calcareous nannofossils and dinoflagellate cysts

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Abstract

Sediments deposited after the peak of the Messinian Salinity Crisis (MSC) in the Apennine foredeep of Italy embody a topic debated on both chronostratigraphic and palaeoenvironmental grounds. We performed micropalaeontological (calcareous nannofossil and dinoflagellate cyst) analyses on four stratigraphic sections (Monticino, Civitella del Tronto, Fonte dei Pulcini, Fonte la Casa) and reused those from Maccarone. All sections belong to the p-ev$_2$ Formation that includes the Colombacci deposits, usually considered emblematic of the Lago Mare in the area. Marine microfossils recorded in previous studies have often been neglected or considered reworked and hence discarded. We propose the occurrence of at least four marine inflows between 5.36 and 5.33 Ma, the first of which is reflected in the Apennine foredeep by marine dinoflagellates that are then replaced by Paratethyan (brackish) ones. Paratethyan species occupied favourable environments during intervals separating marine inflows while the marine species survived elsewhere. From this perspective, the Apennine foredeep was an isolated perched basin during most of the peak of the MSC (5.60–5.36 Ma), and was progressively and repeatedly invaded by marine waters overflowing a palaeo-sill before the beginning of the Zanclean (5.33 Ma) which itself reflects a continuing eustatic rise. The Gargano Peninsula and, offshore, the present-day Pelagosa sill may be regarded as the remnants of such a Messinian sill. This interpretation provides new possibilities for ecostratigraphically correlating the sections with Lago Mare biofacies, the deposition of which unquestionably started prior to the deposition of Colombacci sediments and continued just into the earliest Zanclean. The results of this study show that the Lago Mare facies cannot be restricted to a single brackish palaeoenvironment but included competing marine and brackish waters controlled by geographic and chronological factors. Deposits overlying the unconformity separating the regional p-ev$_1$ and p-ev$_2$ formations are considered to represent the first marine incursion into the Apennine foredeep. These results allow us to refine the palaeogeographic reconstruction of the Apennine foredeep during the peak of the MSC. Although this basin was deep, its history during the peak of the MSC did not parallel that of the central Mediterranean basins.

1. Introduction

The Apennine foredeep (Fig. 1) is a sedimentary basin filled mostly by thick Neogene sediments, including Messinian deposits of the turbiditic Laga succession and a wide array of evaporites, overlain by the Zanclean Argille Azzurre (Fig. 2; Crescenti, 1975; Milli et al., 2007). This foredeep has been considered a perched basin during the peak of the Messinian Salinity Crisis (MSC) (Corselli and Grecchi, 1984; Clauzon et al., 1997, 2005), isolated from the almost completely desiccated Mediterranean Basin by a palaeo-sill, most probably in the area of the present-day Pelagosa sill (Figs. 1, 2; Bache et al., 2012). The Messinian post-evaporitic deposits are subdivided into two formations, p-ev$_1$ and p-ev$_2$ (Fig. 2; Roveri et al., 2001). The p-ev$_1$ Formation is devoid of fossils and mainly comprises thin-bedded siliciclastic turbidites considered to have been deposited in deep, fresh water conditions (Roveri et al., 2001). The p-ev$_2$ Formation (5.36–5.33 Ma: Bache et al., 2012; 5.42–5.33 Ma: Roveri et al., 2014) includes in its upper part the "Colombacci Formation" (Selli, 1952, 1954; Roveri et al., 1998), which is characterized by prevalent clays alternating with thin micritic limestones and is known for its Paratethyan fossils (Lago Mare biofacies: Selli, 1973; Colalongo et al., 1976; Corradini and Biffi, 1988). A brackish faunal association based on molluscs (dreissenids, limnocardiids) and ostracods (mostly *Cyprideis*, loxoconchids) is generally considered characteristic of this unit (Gillet, 1968; Colalongo et al., 1976; Bellagamba, 1978; Esu and Taviani, 1989; Faranda et al., 2007; Gliozzi et al., 2007; Esu and Girotti, 2008). However, marine organisms have long been reported from this unit: foraminifers(f), calcareous nannofossils(n), dinoflagellate cysts(d), and fishes(fi) (Cremonini et al., 1973[f]; Carloni et al., 1974[f]; Casati et al., 1976[f]; Colalongo et al., 1976[f]; Crescenti et al., 2002[f,n]; Bassetti et al., 2003[f]; Bertini, 2006[d]; Carnevale et al., 2006a[fi]; Popescu et al., 2007[f,n,d]; Trenkwalder et al., 2008[f,n]; Cosentino et al., 2012[n,d]; Luchetti in Brozzetti et al., in press[n]). Such fossils have largely been dismissed as reworked (Casati et al., 1976; Bassetti et al., 2003; Trenkwalder et al., 2008) or simply neglected because of the difficulty in explaining the co-occurrence of marine and brackish microplankton (Bertini, 2006; Cosentino et al., 2012). Microfossils can often be established as reworked if they are broken and/or abraded. If the microfossils are well preserved, it is still possible to invoke reworking but only for species that existed before the MSC. *Ceratolithus acutus* (Gartner and Bukry, 1974) [= *C. armatus* (Müller, 1974)] is a short-lived calcareous nannofossil which first appeared at 5.35 Ma (Raffi et al., 2006; Anthonissen and Ogg, 2012), i.e. just before the initial deposition of the Colombacci sediments. The lowest occurrence of this species is the first biostratigraphic event after the Mediterranean marine reflooding which is estimated at 5.46 Ma (Bache et al., 2012), prior to the Zanclean GSSP (Global boundary Stratotype Section and Point) at 5.33 Ma (Hilgen et al., 2012). Accordingly, the presence of *C. acutus* in the Colombacci deposits, as shown at Maccarone (Popescu et al., 2007) and Civitella del Tronto (Luchetti in Brozzetti et al., in press), is a robust indicator of marine conditions beneath the lowermost Zanclean Argille Azzurre ("Blue Clays").

This work aims to verify and better constrain the suggested marine conditions of the Colombacci sediments by integrating dinoflagellate cyst and calcareous nannoplankton analyses from five sections along the Apennine foredeep. From north to south, the studied sections are (Fig. 2): Monticino in a marginal position; Maccarone in the wedge-top basin, which provides useful data (Popescu et al., 2007) for comparison; Civitella del Tronto in the deepest part of the foredeep; and Fonte dei Pulcini and Fonte la Casa in the outer foredeep.

In this study, we pay special attention to the detection of reworked specimanes. Reworking is a common phenomenon in the Mediterranean Basin, particularly at the end of the MSC when increased fluvial flows and then marine inflows resulted in significant erosion and redeposition. The debate surrounding this problem is vigorous (Corbi et al., 2016) and the Lago Mare biofacies from the Apennine foredeep is not spared from contention, as illustrated by opposing interpretations of the Maccarone section (Popescu et al., 2007, 2008; vs. Roveri et al., 2008).

2. Methods

A few grams of sediment were used to prepare smear slides for microscopic examination of the calcareous nannofossils under bright light and polarized light at x1600 magnification. Their taxonomic identification followed Perch-Nielsen (1985) and Young (1998). Each sample was carefully analysed, with more than fifty fields of view being examined in order to find rare specimens (Fig. 3). In general, reworked calcareous nannofossil taxa may appear moderately well preserved, as with the in-situ specimens. Understandably, this can be problematic for nannofossil biostratigraphy for any succession of any age. In the studied sections, reworked taxa from older deposits, i.e. Paleogene and Cretaceous, have been identified but their abundance never exceeds 15–20%. The nannofossil assemblages in general are moderately preserved and show no erratic fluctuations in composition so we assume that their original composition is maintained. Concerning the presence of *Ceratolithus acutus* below the base of the Zanclean, we contend that specimens are in-situ and their low abundance, i.e., always below 1%, is similar to that recorded from the basal Zanclean by various nannofossil workers (Di Stefano and Sturiale, 2010). Similarly, the nannofossils *Triquetrorhabdulus rugosus* and *Amaurolithus* spp., markers of the Messinian–early Zanclean interval, are always recorded in very low numbers in the Mediterranean (Castradori, 1998). However, some species encountered in our study have been discarded as incompatible with the age of the p-ev$_2$ Formation, such as *Discoaster quinqueramus* (see sections 4A, 4C, 4D). Some of the considered calcareous nannofossils are shown in Figure S1.

For the analysis of dinoflagellate cysts, samples weighing 10–15 grams were processed as follows: acid treatments using HCl, HF, and HCl again, followed by concentration in $ZnCl_2$ at density 2.0, and sieving at 10 µm; a 50 µl volume of residue was mounted in glycerine and examined under a light microscope (magnification: x1000). Microscope slides were also examined using fluorescence microscopy to help with the identification of reworked specimens (Van Gijzel, 1967; Doláková and Burešová, 2007). Dinoflagellate cyst taxa were grouped according to their ecological tolerance, nutritional strategy, and geographical provenance based on Warny and Wrenn (2002), Londeix et al. (2007) and Popescu et al. (2009) (Table S1). Because their motile stage lives in surface waters, dinoflagellates are sensitive to changes in salinity and thus to water incursions, such as freshwater inflows, and influxes of marine and/or brackish (notably Paratethyan) water masses that potentially affected the Apennine foredeep during the late Messinian. Accordingly, dinoflagellate cysts were grouped into two associations: “marine” (including euryaline and stenohaline) reflecting the influence of Mediteranean waters, and “Paratethyan” comprising endemic species associated with more brackish conditions (Table S1). Counts provided in Table S1 indicate abundant reworked dinoflagellate cysts in some samples: under fluorescence microscopy, they exhibit a yellowish to orange colour with low intensity that makes them recognizable from the in-situ specimens, the latter displaying a greenish to yellowish colour with high intensity (brightness). Most reworked specimens belong to species that disappeared before the Late Miocene (Fig. S2).

3. Studied sections

A. Monticino

Forty-five kilometres southeast of Bologna, near Brighella (Faenza), the Monticino quarry is now a geopark (44°13’32” N; 11°45’53” E; Figs. 2a, 4a; Vai and Ricci Lucchi, 1977). It shows Colombacci deposits sandwiched between the Messinian Primary Lower Gypsums and the Zanclean Argille Azzurre (Figs. 2b, 4a–b) (Marabini and Vai, 1989). The thin (2–3 m) Colombacci deposits unconformably overlie the gypsums (Figs. 2b, 4b). Usually known as the intra-Messinian unconformity and being interpreted as exclusively tectonic in origin (Marabini and Vai, 1985; Roveri et al., 2005), this unconformity was called the Messinian Erosional Surface (MES) by Clauzon et al. (1996) who observed it in a fluvial erosional context relative to the Messinian sea-level drop. Only six or seven lower gypsum beds are visible at Monticino instead of the 16 beds forming what is known in the area as the Vena del Gesso that extends some 20 kilometres northwestwards (Vai and Ricci Lucchi, 1977; Roveri et al., 2008a). The overlying Colombacci sediments mostly comprise dark-grey to green, brown and black brackish clays with Paratethyan molluscs (*Dreissena simplex*, *Melanopsis marzolina*, *Adacna simplex*, some limnocardids, etc.; Taviani, 1988) and ostracods (*Cyprideis* gr. *pannonica*; Colalongo, 1988). This succession is conformably overlain by the Argille Azzurre. The Colombacci sediments also fill karstic fissures that were cut during the erosional phase. These infilling sediments have yielded a late Messinian vertebrate fauna mainly composed of mammals (De Giuli et al., 1988; Rook et al., 2015).

The Colombacci deposits contain some marine molluscs such as *Chlamys*, and also some planktonic marine microfossils including foraminifers (Colalongo, 1988) and dinoflagellate cysts (Bertini, 2006) that have been considered reworked or contaminants from the overlying Argille Azzurre, or simply disregarded. Allowing for the prospect of marine fossils occurring within the Colombacci deposits at Monticino, we deemed it necessary to clarify this matter. Eight samples were taken and analysed for calcareous nannofossils and dinoflagellate cysts: five from the stratified Colombacci deposits on the northern edge of the quarry (Figs. 4b–c), and three from a Colombacci-filled karstic fissure (n° 8bis) on the southern edge of the quarry (Figs. 4d–e).

B. Maccarone

Near the town of Apiro in the Marche region, the Maccarone section (43°24’20” N; 0°39’00” E; Fig. 2) is characterized by ca. 100 m of p-ev$_1$ Fm. overlying the Resedimented Messinian Lower Gypsums (Fig. 5a). The turbiditic p-ev$_1$ Formation includes an ash bed (Fig. 5b) present fully along the Apennine foredeep (Fig. 2b; Roveri et al., 2005) and dated at 5.53200 ± 0.00046 Ma (Cosentino et al., 2013). The pe-v$_1$ Fm. is overlain by the pe-v$_2$ Fm. (62 m thick) that includes the Colombacci deposits (23 m) which are in turn overlain by the Zanclean Argille Azzurre (Fig. 5c). An angular (erosional) discontinuity separating the p-ev$_1$ and p-ev$_2$ formations was indicated by Bassetti (2000) and Roveri et al. (2001), who referred it to a major reduction in accommodation space linked to the intra-Messinian tectonic phase.

Carloni et al. (1974) recorded planktonic foraminifers from 15 m below the base of the Colombacci deposits and within them. Casati et al. (1976) performed an oxygen and carbon isotope study on the uppermost 10 m of the Colombacci Fm. and concluded that salinity was highly variable but that the few foraminifers were allochthonous. Bertini (2006) recorded marine dinoflagellate cysts from the lowermost p-ev$_2$ Fm., some 40 m below the base of the Colombacci deposits. All these authors emphasized the ambiguous environmental character of the Colombacci unit. For this reason, the section was re-visited and new samples analysed (Figs. 5b–c; Popescu et al., 2007). The rare specimens of foraminifers, calcareous nannofossils and dinoflagellate cysts recorded in the upper part of the pe-v$_2$ Fm. (Popescu et al., 2007) were suspected of being reworked because of the assumed inconsistency of brackish ostracods and marine micro-organisms occurring in the same beds (Roveri et al., 2008b). Yet, the unquestionable calcareous nannofossil *Ceratolithus acutus* recorded in nine samples from the upper p-ev$_2$ Fm. (i.e. 38 m below the base of Argille Azzurre) cannot be reworked because the species's first appearance is in the latest Messinian (5.35 Ma; Raffi et al., 2006; Anthonissen and Ogg, 2012). As a consequence, the other planktonic microfossils should be reconsidered. In doing so, Popescu et al. (2007) concluded that these marine proxies indicate that the first influxes of marine waters entered the Apennine foredeep before the beginning of the Zanclean. Bache et al. (2012) defined this marine ingression at 5.36 Ma. Gennari et al. (2008) focussed their study on the Zanclean deposits in which they did not find *Ceratolithus acutus*, even though this species was continuously recorded in the three lowermost Zanclean samples analysed by Popescu et al. (2007). Analyzing calcareous nannoplankton takes longer than usual when recording rare species, particularly at the Messinian–Zanclean transition (Popescu et al., 2008, 2016a).

C. Civitella del Tronto

Between Ascoli Piceno and Teramo, a very thick section of Messinian post-evaporitic deposits can be observed near Civitella del Tronto (Fig. 6a). Located at the foot of the Montagna dei Fiori (Mattei, 1987), the Neogene series mostly comprises the Messinian Laga succession (Fig. 6a), the upper part of which (i.e. the Laga 3) includes the resedimented evaporites (gypsum-arenites) overlain by the p-ev$_1$ and p-ev$_2$ formations (Bigi et al., 2009). The Laga 3 Member can be traced along the ancient road (Strada Provinciale Fondovalle–Salinello) from Civitella del Tronto to Ponzano (Fig. 6a). It includes the ash layer present along the entire Apennine foredeep (Fig. 2b; Roveri et al., 2008a) and dated at Maccarone (see above). The Civitella del Tronto series constitutes the thickest Messinian succession in the deepest part of the Apennine foredeep. The p-ev$_2$ Fm. is exposed along three segments, respectively 5 m, 18 m and 91 m thick, separated by covered intervals along the roadcut (Fig. 6b). The upper part of the p-ev$_2$ Fm. comprises 61 m of thin carbonate beds (the so-called "Colombacci") alternating with sandstone (lower segments I and II and topmost unit of segment III: Fig. 6b) and mudrock, dipping at a high angle (Figs. 6c–d). The occurrence of *Ceratolithus acutus* was reported in a calcareous nannoflora found close to the Crocetta Chapel, i.e. in segment III (Luchetti in Brozzetti et al., in press: p. 55). The p-ev$_2$ Fm. is overlain by the Argille Azzurre Fm. (Fig. 6a). The occurrence of *Ceratolithus acutus* in the Colombacci deposits led L. Luchetti, who performed the nannoplankton analysis, to conclude that the return to normal marine conditions preceded the Zanclean (Luchetti, in press: fig. 6, p. 48).

The sampled section, which begins approximately 800 m above the ash layer and some 550 m below the lowermost Colombacci carbonate bed, runs from 42°46'30.10"N; 13°41'32.50"E to 42°46'41.90"N; 13°42'4.10"E (Fig. 6a). We analysed the clays in the three segments, mainly in segment III located below the Crocetta Chapel: two samples came from segment I, five samples from segment II, and 62 samples from segment III.

D. Fonte dei Pulcini

Near Lama dei Peligni, the Fonte dei Pulcini section (42°01'51.20"N; 14°10'50.90"E) is located southeast of the Majella mountains (Fig. 2a). Here, Primary Lower Gypsums of the Gessoso-Solfifera Fm. are overlain by (1) p-ev$_2$ clays (thickness 240 m) designated as Lago Mare deposits on the basis of a rich ostracod fauna (Cosentino et al., 2005) and the occurrence of Paratethyan dinoflagellate cysts including *Galeacysta etrusca*, and (2) Zanclean clays (the Taranta Peligna clays equivalent to the Argille Azzurre) including at their base a conglomerate (thickness 7 m) with the foraminifer *Sphaeroidinellopsis* (Fig. 7a–b; Cosentino et al., 2012). At Colle di Votta, on the northern side of the Majella mountains, a thick Gessoso-Solfifera Fm. is cut by the Messinian Erosional Surface and overlain by the usual ash (Sampalmieri et al., 2010), there dated at 5.5320 ± 0.0074 Ma (Cosentino et al., 2013). Frequent to abundant calcareous nannofossils and 11 taxa of marine dinoflagellate cysts were found in the p-ev$_2$ clays from Fonte dei Pulcini (including *Ceratolithus* sp.) by Cosentino et al. (2012). These authors interpreted the nannofossils as reworked; the dinoflagellates while not being explicitly judged to be reworked, were not taken into account in the palaeoenvironmental interpretation. Considering the co-occurrence of Paratethyan (brackish) and marine microfossils, we re-visited section A of Cosentino et al. (2005) at the Fonte dei Pulcini locality (i.e. the upper 50 m of the p-ev$_2$ Fm.) and took five samples from its uppermost part (Fig. 7b–c).

E. Fonte la Casa

On the northern edge of the Pelagosa palaeo-sill (including the present-day Gargano Peninsula), which probably isolated the Apennine foredeep during the peak of the MSC (Bache et al., 2012), vertical Primary Lower Gypsum and unconformably overlying resedimented gypsum can be observed in several quarries (Fig. 2b). Patches of grey clays and yellowish sands lie on top of the Miocene series. They are particularly abundant in the Larino sheet of the 1:100,000 scale geological map of Italy where they are marked "MP" with a Miocene–Pliocene age, thus possibly suggesting a gradual transition from Miocene to Pliocene (Balboni, 1968a). These deposits contain marine macrofossils including the molluscs *Pecten*, *Dentalium*, and *Cardium* (Balboni, 1968b).

In order to clarify the chronostratigraphic position of these 'MP' deposits, we studied two outcrops at the Fonte la Casa hamlet, located between Palmoli and San Buono (Fig. 8a), where grey silts rich in mollusc shells (Fig. 8b–d) are overlain by yellow sands including some clayey beds (Fig. 8e–g). Three samples were taken: one in the grey silts, and two in intercalated clays within the yellowish sands (Fig. 8b, c–g).

4. Results

The results of the analyses of calcareous nannofossils and dinoflagellate cysts are provided in Figure 3 and Table S1, respectively. Selected taxa are shown in Figures S1 and S2.

A. Monticino

The calcareous nannofossil association from the two sets of samples is taxonomically diverse (Fig. 3). Our record of *Discoaster quinqueramus* (last appearance datum at 5.59 Ma; Raffi et al., 2006; Anthonissen and Ogg, 2012) in sample 1 has not been considered for dating because it is inconsistent with the age of the base of the p-ev$_2$ Formation (5.42 Ma: Roveri et al., 2014; 5.36 Ma: Bache et al., 2012). The dinoflagellate cyst content is rich, largely dominated by the stenohaline species *Impagidinium patulum* and *Nematosphaeropsis labyrinthus*, and subordinately by the euryhaline species *Lingulodinium machaerophorum* (Fig. 9; Table S1). No Paratethyan species were recorded.

B. Maccarone

The following is a summary of the results of Popescu et al. (2007). The reader is referred to that publication for a more thorough presentation and discussion of the dataset. Calcareous nannofossils are present in sample 1 in the p-ev$_2$ Fm., i.e. some 20 m below the base of the Colombacci deposits (Fig. 9). The biostratigraphic marker *Ceratolithus acutus* was recorded from sample 5, i.e. in the p-ev$_2$ Fm. about 16 m below the base of the Colombacci deposits (Fig. 10).

The lowest occurrence of marine dinoflagellate cysts is at the boundary between the p-ev$_1$ and p-ev$_2$ formations, about 38 m below the base of the Colombacci deposits (Fig. 10; Popescu et al., 2007). Assemblages are dominated by eurhyaline species such as *Achomosphaera andalousiensis*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and selected *Spiniferites* species (*S. bentorii*, *S. bulloideus*, *S. ramosus*) in the Messinian deposits (p-ev$_2$ Fm.), whereas stenohaline species such as *Impagidinium patulum* and *Spiniferites mirabilis* prevail in the Zanclean sediments (Argille Azzurre Fm.) (Table S1). A diverse group of Paratethyan dinoflagellate cysts is dominated by *Galeacysta etrusca*, *Impagidinium globosum*, *Pyxidinopsis psilata*, *Spiniferites sagittarius* and *S. cruciformis* (Table S1). A preponderance of marine species in the dinoflagellate cyst record is observed in the Messinian samples 1–5, 12, and 34–35, and in the Zanclean samples 43–45 (Fig. 10). In the other samples a Paratethyan species association prevails (Fig. 10).

C. Civitella del Tronto

Fifteen samples were analysed for calcareous nannofossils (one in segment I, one in segment II, thirteen in segment III); 13 of them provided a nannoflora (Fig. 3). The biostratigraphic marker *Ceratolithus acutus* was recorded in three samples (48, 62, and 65) (Figs. 3, 11). *Discoaster quinqueramus* was recorded in samples 9, 11, 13, 17 and 20 (Fig. 3). As this species disappeared (at 5.59 Ma) significantly before the first appearance datum of *C. acutus* at 5.35 Ma (Raffi et al., 2006; Anthonissen and Ogg, 2012), first recorded here 19 m higher in sample 48 (Figs. 3, 11), we consider the specimens of *D. quinqueramus* to be probably reworked. This option is supported by the age of the ash (5.532 Ma; Cosentino et al., 2013) at the base of the underlying p-ev$_1$ Formation, i.e. some 1350 m below our highest record of *D. quinqueramus*.

A total of 69 samples were analysed for dinoflagellate cysts (two in segment I, six in segment II, 61 in segment III), (Fig. 11). Marine dinoflagellate cysts are dominated by the euryhaline species *Lingulodinium machaerophorum*, *Melitasphaeridium choanophorum*, *Operculodinium centrocarpum* and *Homotryblioum* sp., and by the stenohaline species *Spiniferites hyperacanthus* (Table S1). *Galeacysta etrusca*, *Impagidinium globosum*, *Pyxidinopsis psilata*, *Pontadinium* spp., *Spiniferites bentorii oblongus*, *S. cruciformis* and *Spiniferites* spp. are prevalent among the Paratethyan dinoflagellate cysts (Table S1). The dinoflagellate cyst assemblages are alternately dominated by marine species and Paratethyan species, with secondary fluctuations (Fig. 11).

D. Fonte dei Pulcini

The five samples from the Colombacci deposits yielded a diverse calcareous nannoflora, including the biostratigraphic marker *Ceratolithus acutus* in sample 5 (Figs. 3, 12). This sample also contains specimens of *Discoaster quinqueramus* that are probably reworked, as also suggested above for Civitella del Tronto.

Marine dinoflagellate cysts (mainly the euryhaline *Lingulodinium machaerophorum* and the stenohaline *Nematosphaeropsis labyrinthus*) dominate sample 1 whereas Paratethyan elements (mainly *Galeacysta etrusca*, *Impagidinium globosum*, with subordinate *Spiniferites bentorii oblongus*, and *Spiniferites* spp.) dominate samples 2–5 (Fig. 12; Table S1).

E. Fonte la Casa

Sample 1 provided a relatively diverse calcareous nannoflora, although the other two samples were barren (Fig. 3).

The three samples yielded a dinoflagellate cyst association dominated by marine species (euryhaline: *Achomosphaera andalousensis*, *Homotryblium* sp., *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Spiniferites bulloideus*; open marine: *S. hyperacanthus*). Some Paratethyan species were also recorded (*Galeacysta etrusca*, *Impagidinium globosum*, *Pyxidinopsis psilata*, *Spiniferites bentorii oblongus*) (Fig. 13; Table S1).

5. Discussion

The studied sections provide a fairly wide and diverse micropalaeontological survey of Lago Mare (i.e. Colombacci) deposits in different contexts of the Apennine foredeep: the Maccarone section provides a complete record of the Colombacci deposits; and the Civitella del Tronto section yields a more or less continuous (in part at very high resolution) record of an expanded sedimentary succession. The three other localities give a more limited view of distinct settings within the Apennine foredeep (northern shoreline: Monticino; southern shoreline: Fonte dei Pulcini, Fonte la Casa).

Our palaeoenvironmental data draw attention to the significance of the Lago Mare biofacies in the Apennine foredeep and place it within a precise chronological framework. They show the successive brief incursions of marine waters into the Apennine foredeep, supporting the presence of a structural palaeo-sill which momentarily isolated this basin, as discussed with the help of the offshore seismic profiles. This evidence allows us to propose a new integrated palaeoenvironmental scenario for the Apennine foredeep during the MSC.

A. The Lago Mare, a biofacies horizon

Paratethyan dinoflagellate cysts are common below the Colombacci deposits. Bertini (2006) first recorded them some 10 m below the base of the Colombacci deposits at Maccarone, an interval extended to at least 20 m by Popescu et al. (2007) (Fig. 10). At Civitella del Tronto, Paratethyan dinoflagellate cysts can be found more than 650 m below the base of the Colombacci deposits. This seriously questions the a-priori accepted equivalence between the Lago Mare and Colombacci deposits (i.e. the “Congerie marls” in the Piedmont Basin; Roveri et al., 2008a). Popescu et al. (2009, 2015) and Do Couto et al. (2014) emphasized the importance of Paratethyan dinoflagellate cysts as actual indicators of Lago Mare episodes, their occurrence often preceding the Lago Mare biofacies as defined traditionally by ostracods and molluscs. The dinoflagellate cyst record from Maccarone documents the occurrence of the Lago Mare biofacies exclusively within the p-ev$_2$ Fm. (Bertini, 2006; Popescu et al., 2007) (Fig. 14). Some “Paratethyan” molluscs from the Po Valley (Esu and Popov, 2012; Harzhauser et al., 2015) and the Sicilian Basin (Harzhauser et al., 2013) have been re-visited and are now interpreted by these specialists as being possibly endemic to the Mediterranean Sea. However, we consider that several disseminations from the Central and Eastern Paratethys may have occurred through the Balkan corridor long before the peak of the MSC (Popescu et al., 2009). Molluscs introduced by successive invasions may have persisted in some ecologically favourable areas as suggested by Do Couto et al. (2014).

Beyond the Apennine foredeep–Po Basin realm, several Mediterranean deposits have both marine and Paratethyan fossils: the Cava Serredi in Toscana (Carnevale et al., 2006b; Popescu et al., 2009), Arenazzolo deposits at Eraclea Minoa in Sicily (Londeix et al., 2007; Popescu et al., 2009), Casabianda in Corsica (Popescu et al., 2009), Río Mendelín near Malaga in southern Spain (Do Couto et al., 2014), Níjar in southern Spain (Aguirre and Sánchez-

Almazo, 2004; Do Couto et al., 2014), Lower Rhône Valley (Théziers, Saint-Marcel d'Ardèche, Saint-Restitut, Allex) (Do Couto et al., 2014), DSDP Hole 134B, and ODP Holes 976B and 978A (Popescu et al., 2015). Such interplay of marine and Paratethyan conditions affects the three Lago Mare episodes proposed by Clauzon et al. (2005), Popescu et al. (2009), Do Couto et al. (2014) and Popescu et al. (2015). This interplay can also be extended to several localities from the Paratethys where the permanent regional "Lago Mare" biofacies was interrupted by episodic incursions of Mediterranean marine waters: eastern Pannonian Basin (Central Paratethys) (Krašić, Malunje and Krajačići: Popescu et al., 2009), Dacic Basin (Eastern Paratethys) (Valea Vacii: Snel et al., 2006; Popescu et al., 2009; Cernat, Hinova: Popescu et al., 2009; Suc et al., 2011; Ticleni: Drivaliari et al., 1999; Badislava: Snel et al., 2006; Stoica et al., 2007), and the Black Sea (Eastern Paratethys) (DSDP Site 380: Popescu, 2006; Popescu et al., 2010; Suc et al., 2015; Popescu et al., 2016b).

We emphasize the non-reworked nature of the micro-organisms used in developing our interpretations:

- the robustness of the calcareous nannofossil association is corroborated by the presence of *Ceratolithus acutus*, the lowest occurrence of which is consistent with the temporal context of the examined deposits. As explained by Popescu et al. (2016), this species cannot result from reworking when it occurs in deposits just preceding the Miocene–Pliocene boundary.
- the non-reworked status of the dinoflagellate cyst record is supported by the bright greenish–yellowish colour of specimens when observed in fluorescence light.

As to the debate about the significance of marine microfossils within the Lago Mare deposits, particularly in the Apennine foredeep, our study establishes definitively their status as in-situ elements of the surface microplankton.

Our reconstruction of the Lago Mare biofacies in the Apennine foredeep will hopefully stimulate a re-interpretation of the isotopic record for the Colombacci carbonates: despite values of $\delta^{18}O$ ranging from fresh/brackish to marine conditions, the conclusion reached from these records was that the limestones were deposited in a uniformly brackish palaeoenvironment (Casati et al., 1976; Molenaar and De Feyter, 1985; Bassetti et al., 2004).

B. Attempt in dating marine incursions into the Apennine foredeep at the end of the MSC

The Colombacci deposits are bio-chronostratigraphically constrained by the occurrence of the calcareous nannofossil marker *Ceratolithus acutus*, already indicated at Maccarone by Popescu et al. (2007) (Figs. 3, 10) and at Civitella del Tronto by Luchetti (in Brozzetti et al., in press). At Civitella, we specifically searched for this calcareous nannofossil in samples rich in marine dinoflagellate cysts. This resulted in the documentation of *C. acutus* in three samples within the Colombacci deposits (Figs. 3, 11). *Ceratolithus acutus* is a biostratigraphically useful species with a short range between 5.35 and 5.04 Ma (Raffi et al., 2006; Anthonissen and Ogg, 2012), i.e. appearing somewhat before the Messinian–Zanclean boundary at 5.33 Ma (Popescu et al., 2016a). Despite the absence of studied samples in the lowermost part of the p-ev$_2$ Fm. and hence uncertainty about a possible occurrence of *C. acutus* within this segment, Bache et al. (2012) tentatively regarded the lowest record of *C. acutus* in sample 5 from Maccarone (Figs. 3, 5b–c, 10) as its lowest occurrence. This constituted potentially a third chronological point (in addition to the ash dated at 5.53200 ± 0.00046 Ma and the base of Argille Azzurre at 5.33 Ma) in establishing a cyclostratigraphy for the section based on the pollen record. This approach pointed to an age of 5.36 Ma for the first influx of marine waters into the Apennine foredeep after the peak of the MSC (Bache et al., 2012). At Maccarone, this event marking the boundary between the formations p-ev$_1$ and p-ev$_2$ is observed some 36 m below the base of the Colombacci deposits (Fig. 10; Popescu et al., 2007). At Civitella, the lowest record of *C. acutus* is observed 17 m above the base of the Colombacci deposits (Fig. 11). Because we searched for calcareous nannofossils in just 13 among 69 samples (Fig. 3), selected for their rich marine dinoflagellate cyst content, it is quite possible that we missed the lowest occurrence of *C. acutus*, all the more likely as the lower part of the section (segments I and II) has long observation gaps and is dominated by sands unsuitable for nannofossil preservation (Fig. 11). We therefore assume that the records of *C. acutus* at Civitella del Tronto are younger than its first appearance datum at 5.35 Ma. At Fonte dei Pulcini Cosentino et al. (2005) used the ostracod record to correlate the uppermost 60 m of Messinian sediments (Fig. 7) with the p-ev$_2$ Formation within the 410 m of deposits overlying the Gessoso-Solfifera Fm. As a consequence, the record of *C. acutus* in the uppermost studied sample (Figs. 3, 12) cannot represent the lowest occurrence of this species in the Apennine foredeep, and we suggest correlating it with its uppermost record at Civitella del Tronto. The Maccarone section, owing to its high-resolution micropalaeontological records (Bertini, 2006; Popescu et al., 2007) and robust chronology (Bache et al., 2012), serves as the reference framework for Messinian post-evaporitic deposits in the Apennine foredeep (Fig. 14).

The occurrence of marine dinoflagellate cysts within the Colombacci deposits has been shown for several localities including Fonte dei Pulcini (Cosentino et al., 2014), Monticino and Maccarone (Bertini, 2006), but the consequences of such important occurrences have not been adequately emphasized (see Table S1 for comparison). In recent years growing evidence has pointed to a return to normal marine conditions in the Apennine foredeep before deposition of the earliest Zanclean sediments (Crescenti et al., 2002; Luchetti, fig. 6, in Brozzetti et al., in press; Crescenti and Raffi, fig. 12, in Crescenti, in press). The presence of marine fish otoliths in a Colombacci deposit from the Ca' Ciuccio section, north of Ancona (Carnevale et al., 2006a) provides further support for a pre-Zanclean sea-level highstand.

At Maccarone, the lowest occurrence of *Ceratolithus acutus* is significantly below the Colombacci deposits but within the p-ev$_2$ Formation (Popescu et al., 2007). The first evidence of reliable marine dinoflagellate cysts (marked by a sudden improvement in preservation and increase in diversity) including *Impagidinium* spp., *I. aculeatum*, *Spiniferites ramosus* and *Lingulodinium machaerophorum* (Bertini, 1992), and thus of marine water influx, occurs at the boundary between the p-ev$_1$ and p-ev$_2$ formations (Fig. 10; Popescu et al., 2007). Thereafter, palaeoenvironments alternated between marine and brackish based on the successive predominance of marine dinoflagellate cysts and Paratethyan ones. Figures 10–11 present a glimpse of such fluctuations along relatively long records, and Figures 9, 12–13 give a snapshot from short records. Several peaks in the abundance of marine dinoflagellate cysts are observed and numbered from 1 to 4 in the Maccarone section (Fig. 10): peak number 1 marks their lowest occurrence at the boundary between the p-ev$_1$ and p-ev$_2$ formations (see above); peak number 2 just follows the lowest occurrence of calcareous nannofossils and precedes the lowest occurrence of *Ceratolithus acutus* 18 m below the base of the Colombacci deposits; peak number 3 is less prominent and recorded 7 m below the base of the Argille Azzurre; and peak number 4 begins just below the base of the Argille Azzurre. These peaks of marine dinoflagellate cysts appear to result from at least four marine influxes: the first one shown by Popescu et al. (2007) is dated at 5.36 Ma by Bache et al. (2012); the second one, coeval with the first record of *C. acutus*, is dated at 5.35 Ma (Raffi et al., 2006; Anthonissen and Ogg, 2012); the third one, just below the base of the Argille Azzurre, is estimated a little before 5.33 Ma based on correlation of a pollen curve with eccentricity (Bache et al., 2012); and the last one (peak number 4) is dated near the earliest Zanclean at 5.33 Ma (Fig. 14).

Several peaks of marine dinoflagellate cysts are also recorded in the Civitella del Tronto section, the most prominent ones belonging to its segment III (Fig. 11). The lowermost peak is located 16 m below the base of the Colombacci deposits. At this state of knowledge, without neglecting the possibility of more marine influxes in the southern Apennine foredeep, we propose the correlation of this lowermost peak with peak number 2 of Maccarone because this is not the first influx of marine dinoflagellate cysts as shown by Figure 11 and thus cannot be correlated with peak number 1 of Maccarone. At Civitella del Tronto, the proposed peak number 2 is quite far below our lowest record of *C. acutus* (33 m) but it has been discussed above that this record of *C. acutus* probably does not correspond to its lowest occurrence within the Apennine foredeep. We tentatively correlate the overlying peak of marine dinoflagellate cysts with peak number 3 at Maccarone. At Civitella del Tronto, this peak is 45–30 m below the base of the Argille Azzurre whereas this distance is only 7 m at Maccarone. This is not surprising because the Civitella del Tronto section is expanded, as shown by the difference in thickness of the Colombacci deposits, 58 m here against 23 m at Maccarone.

Despite the relatively low number of counted individuals (Table S1), an unquestionably prominent peak of marine dinoflagellate cysts is recorded in sample 1 from Fonte dei Pulcini (Fig. 12). This peak underlies by 12 m our record of *Ceratolithus acutus* which cannot correspond to the lowest appearance datum of the species because it is located only 1.5 m below the Zanclean clays (Fig. 12). Accordingly, this peak could correspond to peak numbers 3 or 4. Considering the distance of 13.5 m between it and the base of the Zanclean clays, we tentatively correlate with peak number 3 (Fig. 12) because peak number 4 occurs within the Zanclean clays (not sampled here) as identified at Maccarone (Fig. 10). At Maccarone, peak number 3 is not strongly expressed (Fig. 10) but its increasing representation at Civitella del Tronto (Fig. 11) and then at Fonte dei Pulcini (Fig. 12) can be explained by its being progressively closer to the source of marine waters.

Sample 1 from Fonte la Casa shows a high percentage of marine dinoflagellate cysts (Fig. 13). Samples 2 and 3 are very poor but show the same tendency (Fig. 13). Sample 1 and the cluster of samples 2–3 could belong to the same peak of marine dinoflagellate cysts or to two successive peaks, as they are separated by a stratigraphic distance of 22 m. In the absence of any biostratigraphic assignment based on the calcareous nannofossils (Fig. 3), their correlation to a specific peak is left undetermined (Fig. 13).

Finally, at Monticino, the exclusive presence of marine dinoflagellate cysts in all samples (Table S1) contrasts with the poor record of dinoflagellate cysts (while mostly marine) indicated for these sediments by Bertini (1992, 2006) (Fig. 9). As the calcareous nannoflora is not discriminating (Fig. 3), we cannot easily correlate this optimum in marine dinoflagellate cysts to any specific peak recorded at Maccarone or Civitella del Tronto (Figs. 10–11). This in particular holds for samples 6–8 from deep mudstones filling a karstic fissure. However, the dinoflagellate cyst assemblages of samples 1–5 (Table S1) from sediments immediately below the Argille Azzurre might be tentatively attributable to peak number 4 considering its strong expression (Fig. 9). As almost the same dinoflagellate cyst assemblages are recorded within the karstic fissure n° 8bis (Table S1, samples 6–8), this sedimentary infilling could therefore belong to the same incursion of marine waters (Fig. 9), which would imply a wider geographic extent for this incursion than for previous ones.

The oldest of these influxes of marine waters reached the northern Apennine foredeep significantly before the beginning of the Zanclean (5.33 Ma). Its timing has been estimated at 5.36 Ma from the Maccarone section by Bache et al. (2012) (Fig. 14), i.e. some 100 kyrs later than the catastrophic reflooding of the Mediterranean Basin proposed at 5.46 Ma by the same authors. These arguments lead us to consider that the Apeninne foredeep was disconnected from the Ionian Sea (i.e. from the entire Mediterranean Sea) between 5.46 and 5.36 Ma.

C. Existence of a composite palaeo-sill in the Gargano–Pelagosa region

Miljush (1973), Corselli and Grecchi (1984), and then Clauzon et al. (1997) considered the presence of a palaeo-sill isolating the Apennine foredeep from the Ionian Basin during the second step of the MSC (5.60–5.46 Ma) as being essential to explain the deposition of the deep freshwater deposits of the p-ev$_1$ Formation. Such freshwater conditions are particularly evidenced in the Maccarone section by the absence of marine micro-organisms (Carloni et al., 1974; Popescu et al. 2007; Sampalmieri et al., 2010) and by ^{87}Sr/^{86}Sr data in the southern Apennine foredeep (Matano et al., 2005).

The location and origin of this palaeo-sill are debated, with a location first proposed in the area of the Gargano Peninsula (Miljush, 1973; Corselli and Grecchi, 1984), then at the present-day Otranto sill (Clauzon et al., 2005), and finally in the area of the present-day Pelagosa sill (Bache et al., 2012) (Fig. 16). Palinspastic reconstructions published by Vai (2016) also consider the occurrence of a Messinian sill in this area. However, no seismic profile from the Adriatic Sea was shown to support the hypothesis of a palaeo-sill. In fact, the palaeo-sill location is the result of different processes inherited from the Mesozoic sedimentary evolution and post-Mesozoic geodynamic history of the Adria plate. This morphological high is proposed to have existed since the mid-Oligocene and to have emerged at each significant sea-level fall from this time, hence serving periodically as a land bridge for mammal migration (Patacca et al., 2008).

For the offshore part of the Gargano–Pelagosa region illustrated by line drawings of interpreted seismic profiles (Fig. 15), some dissymmetry is observed between the Central and South Adriatic domains. The latter is associated with the development of Oligocene–Miocene and Pliocene–Quaternary sedimentary sequences in the Mesozoic Ionian basin. Conversely, along the Dinarid chain and in the Central Adriatic domain, the top of the Mesozoic platform and Paleogene structures show few if any Miocene and Pliocene–Quaternary sedimentary sequences. The Messinian surfaces and sedimentary units are no exception to these observations. The region of the Apulian platform – of which most of the Gargano Peninsula is made – is thus the best candidate for the location of the barrier responsible for the relative isolation of the Apennine foredeep during Neogene time.

Some onshore lines of evidence also support this hypothesis. Southeast of the Gargano–Apulian platform along the Apennine chain, a strong dissymmetry can be observed for the Messinian deposits overlying the Resedimented Lower Gypsums: p-ev$_1$ and p-ev$_2$ formations on the northern side, and the Messinian Laga Basin and deltaic deposits on the southern side (Fig. 2b). Both domains are overlain by Zanclean marine clayey sediments (Roveri et al., 2008a; Matano, 2007). The processes related to this difference are clearly of geodynamic nature, in which sedimentary and subsidence dynamics are linked, and bound either by the successive compressive phases along the chain (Bertotti et al., 2001; Vezzani, 2010) and/or by possible tearing of the plunging panel (Ascione et al., 2012). Whatever the dominant processes, the Messinian event has also been linked to a major regional compressive phase along the Apennine chain (Ricchi Lucchi, 1986; Bigi et al., 1999; Roveri et al., 2001; Roveri and Manzi, 2006). This phase controlled the development and accommodation of the Messinian Apennine foredeep north of the Gargano Peninsula and uplift around the Gargano Peninsula and in the south Apennine region, as observed by seismic profiles (Bertotti et al., 2001) and field studies along the South Apennine chain (Matano et al., 2005; Vezzani et al., 2010). This uplift is also seen in the field with tilting of the Primary Lower Gypsums (Marabini and Vai, 1985) to verticality near the Gargano Peninsula (Ciaranfi et al., 1976; Matano, 2007; Senatore et al., 2012) (Fig. 2b).

D. Towards an integrated MSC palaeoenvironmental model for the Apennine foredeep

The Lago Mare biofacies (including Paratethyan dinoflagellate cysts) documented in the Apennine foredeep refers to Lago Mare 3, i.e. the youngest of the three Lago Mare episodes distinguished by Clauzon et al. (2005), Do Couto et al. (2014), and Popescu et al. (2015), having occurred after the marine reflooding of the Mediterranean Basin at 5.46 Ma (Bache et al., 2012). Lago Mare 3 is known from many places in the Mediterranean (Do Couto et al., 2014). A reasonable possibility exists therefore that the first inflow of marine waters into the Apennine foredeep at 5.36 Ma seeded this basin with Paratethyan organisms (dinoflagellates, larvae of ostracods and molluscs, i.e. dreissenids and limnocardiids) transported by surface waters. They could have developed in several favourable areas where salinity was lower than that of the Mediterranean (Fig. 14). In such places, the Paratethyan organisms documented by several researchers (Gillet, 1968; Colalongo et al., 1976; Bellagamba, 1978; Esu and Taviani, 1989; Bassetti et al., 2003; Bertini, 2006; Faranda et al., 2007; Gliozzi et al., 2007; Popescu et al., 2007; Esu and Girotti, 2008) could have proliferated during intervals of time separating the successive brief inflows of marine waters, and they finally disappeared after the fourth (Fig. 14).

Our data obtained from the localities of Monticino, Civitella del Tronto, Fonte dei Pulcini and Fonte la Casa are compatible with those previously acquired along the thicker Maccarone stratigraphic section (Popescu et al., 2007). By integrating all available information on the Apennine foredeep and Po Basin, it is now possible to reconstruct the palaeogeographic evolution of the region and its relationships with the Ionian Basin (Fig. 16c), which completes and clarifies the reconstruction proposed by Scarselli et al. (2007). A palaeo-cross-section CD is drawn from the northern Po Basin to the Ionian Basin (Fig. 16a) on the basis of palaeo-topography drawn in Figure 2b that can be compared to the present-day cross-section AB (Fig. 16b).

Before 5.97 Ma, i.e. before the onset of the MSC (Manzi et al., 2013), all the basins were connected and filled by marine waters up to the southwestern margin of the Po Basin, i.e. the Piedmont Basin (Sturani, 1973; Dela Pierre et al., 2011, 2012) (Fig. 16c).

From 5.97 to 5.60 Ma, the minor fall in sea level that affected the Mediterranean Sea (Clauzon et al., 2015a) caused deposition of the Primary Lower Gypsums in the shallow marginal basins (e.g., Po Basin, outer Apennine foredeep; Fig. 2) (Selli, 1973; Roveri et al., 2008a; Lugli et al., 2010; Manzi et al., 2013). This episode is the first step of the MSC as defined by Clauzon et al. (1996). Evaporitic deposits of this episode were interrupted by clay intercalations indicating marine incursions into the shallow basins and high sea level reconnection at the Mediterranean scale, as mainly evidenced by fish remains (Sturani, 1973; Fontes et al., 1987; Carnevale et al., 2008) and dinoflagellate cysts (Bertini, 2006).

The huge Mediterranean sea-level drawdown that characterized the second (paroxysmal) step of the MSC occurred **at 5.60 Ma** (Clauzon et al., 1996). Bache et al. (2012, 2016) proposed a succession of events in the central Mediterranean basins during the time interval covering the peak of the crisis and the marine reflooding of the Mediterranean Basin up to the earliest Zanclean (i.e. 5.60–5.33 Ma). In the Adriatic domain, several coeval and brief events occurred at the beginning of this time-interval, probably consistently with other peri-Mediterranean areas. Basin-floor uplift caused by sudden isostatic rebound at 5.60 Ma has been estimated at ca. 1,000 m in the Ionian Sea facing southern Calabria (DeCelles and Cavazza, 1995), a value not contradicted by field data in the Eastern Pyrenees (Clauzon et al., 2015b). The Gargano–Pelagosa palaeo-sill, as we call it, may have been significantly uplifted thus turning the Apennine and Po basins into an isolated perched area as proposed by Corselli and Grecchi (1985) and Cita and Corselli (1990) (Fig. 16c). Subaerial erosion took place simultaneously, forced by both the sea-level drop, active also in the margins of the Apennine foredeep, and the isostatically-driven land uplift (Fauquette et al., 2015b). The resulting Messinian Erosional Surface is obvious offshore on both sides of the palaeo-sill (Fig. 15) and off the Po Plain (Rossi et al., 2015). Subaerial erosion caused changes in the drainage network and/or its entrenchment (Scarselli et al., 2007), the formation of karstic cavities within the Primary Lower Gypsums (De Waele and Pasini, 2013), and is hypothesized to be at the origin of the lakes in the northern Po Plain (Bini et al., 1978; Cita and Corselli, 1990). At Monticino, the Messinian Erosional Surface is particularly well exposed through its two aerial (Fig. 4b, d) and karstic (Fig. 4e–g) expressions. The occurrence of a land bridge during the peak of the MSC is evoked to explain the distribution of fossil micromammals (De Giuli et al., 1987) and living plants (Musacchio et al., 2006; Bellusci et al., 2010) on both sides of the Adriatic Sea and northern Ionian Sea.

Freshwater, probably supplied in abundance by the surrounding uplands (Alps: Fauquette et al., 2015a; Apennines: Fauquette et al., 2015b), filled the Apennine foredeep and Po Basin where high levels persisted during the lowered Mediterranean Sea level (**5.60–5.46 Ma**). During this phase, the Resedimented Lower Gypsums (resulting from the erosion of the Primary Lower Gypsums) were deposited in subaqueous environments as coarse material in marginal areas (Corselli and Grecchi, 1984; Dela Pierre et al., 2007) or as gypsarenites in turbiditic contexts in the foredeep (Bigi et al., 1999; Manzi et al., 2005) (Fig. 2b).

Bache et al. (2012) proposed an age of **5.46 Ma** for the marine reflooding of the Mediterranean, which probably occurred significantly before the beginning of the Zanclean Stage (5.33 Ma) based on many lines of evidence (Cavazza and DeCelles, 1998; Cornée et al., 2006; Bache et al., 2012; Popescu et al., 2015). However, marine waters did not immediately enter the Apeninne foredeep as observed at Maccarone where their arrival, located at the boundary between the p-ev$_1$ and p-ev$_2$ formations (Popescu et al., 2007), has been precisely dated at **5.36 Ma** (Bache et al., 2012).

From 5.36 Ma, marine waters overflowed the palaeo-sill and penetrated the Apennine foredeep, transporting in after a short delay the Paratethyan elements (dinoflagellate cysts, larvae of molluscs and ostracods; Fig. 14; Popescu et al., 2007). At least four overflows of marine waters are potentially identified in this work (Fig. 14), which possibly later invaded the Po Basin (Channell et al., 1994; Mary et al., 1999; Sprovieri et al., 2007; Violanti et al., 2011). This process was probably forced first by the isostatic response of the palaeo-sill linked to the Apennine deformation phase and/or to the reflooding of the Mediterranean Basin, then by the continuous global sea-level rise **after 5.33 Ma** (Gorini et al., 2014). Bassetti (2000) and Roveri et al. (2001) defined an unconformity separating the p-ev$_1$ and p-ev$_2$ formations. They described the marine transgression following this erosional event as being "driven by a generalized subsidence following the acme of the intra-Messinian tectonic phase" (Roveri et al., 2001). At Maccarone, this transgression is marked by a sudden increase in *Pinus* within the pollen record (Bertini, 2006). Because *Pinus* produces bisaccate pollen favoured by water transport (Beaudouin et al., 2007), its increased abundance is interpretable as resulting from a retreating palaeo-shoreline during sea-level rise (Popescu et al., 2007).

Despite its depth, the Apennine foredeep evolved differently from the central Mediterranean basins during the peak of the MSC and thus cannot be proposed as a reference for the entire Mediterranean during this event, contrary to the assertion of Roveri et al. (2001, 2014).

Lastly, the transition from the Colombacci deposits to the Argille Azzurre, as that from the Arenazzolo to Trubi in Sicily (Bache et al., 2012), must be regarded as a significant step in the continuous global sea-level rise after the late Messinian glacial period in the Antarctic (Gorini et al., 2014).

6. Conclusion

This study provides new evidence that the Lago Mare deposits, particularly those from the Apennine foredeep and probably the entire Po Basin, are more complex than usually considered. They are not characterized merely by brackish conditions but by alternating brief marine and longer brackish episodes. The first inflow carried marine dinoflagellates followed by Paratethyan ones over the Gargano–Pelagosa palaeo-sill into the isolated Apennine and Po basins. There, the marine species survived briefly and the brackish Paratethyan species persisted until the following marine influx. Four comparable marine phases have been identified between 5.36 and 5.33 Ma. Their recognition, based on both calcareous nannofossil and dinoflagellate cyst contents, constitutes (1) an efficient way to discriminate between the p-ev$_1$ and p-ev$_2$ formations, as well as (2) a potential tool for stratigraphic correlation within the latter. The idea of a strict one-to-one correlation between the Colombacci deposits and the Lago Mare facies in the Piedmont Basin must be seriously re-evaluated.

In addition to providing an innovative way of correlating stratigraphically the Messinian post-evaporitic sections within the Apennine foredeep, this integrated study of calcareous nannofossils and dinoflagellate cysts results in a refined palaeogeographic reconstruction of the region at the end of the MSC. The specific evolution of the Apennine foredeep as an isolated perched basin during most of the second step of the MSC disqualifies this area as reference for the peak of the crisis for the entire Mediterranean Basin. On the contrary, this work gives substance to the scenario postulated by Corselli and Grecchi (1984) and Cita and Corselli (1990). Integrated micropalaeontological analyses and offshore–onshore field investigations support the notion of a palaeo-sill in the area of the Gargano Peninsula and, offshore, of the present-day Pelagosa sill as hypothesized by Miljush (1973).

Finally, this work provides additional evidence that the marine reflooding of the Mediterranean Basin after the MSC significantly preceded the beginning of the Zanclean.

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Illustrations

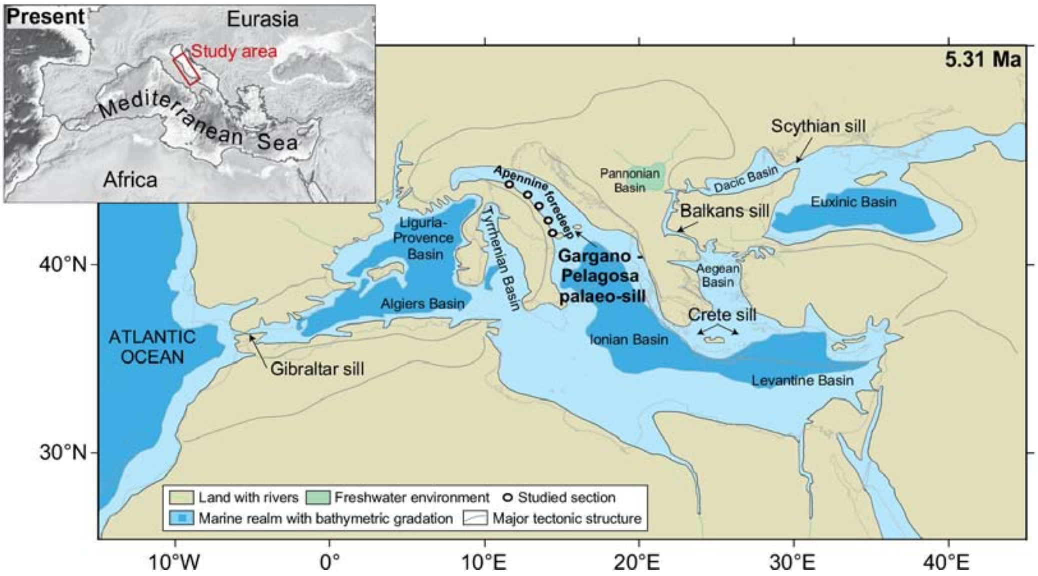

Fig. 1. Present-day Mediterranean region compared to reconstruction just after the Messinian Salinity Crisis (Bache et al., 2012), with location of the studied sections in the Apennine foredeep.

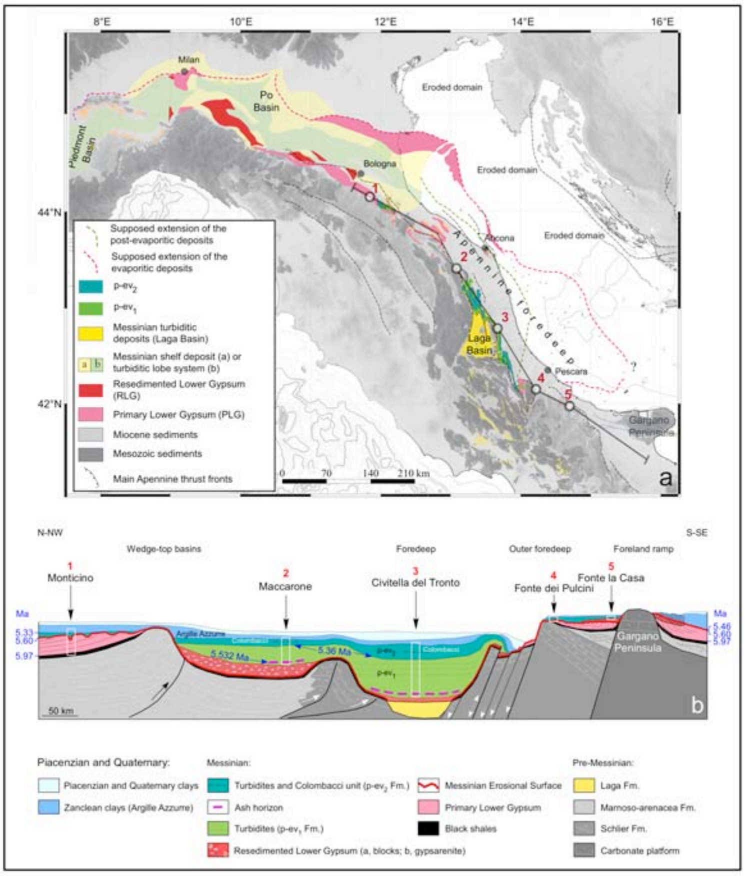

Fig. 2. The Apennine foredeep.

a, Simplified geological map (from Compagnoni et al., 2005; Roveri et al., 2005; Ghielmi et al., 2010; Vezzani, 2010; Artoni, 2013) with location of the studied sections shown in b.

b, Schematic geological section from Romagna to Apulia focussing on Messinian and Zanclean deposits (modified from Roveri et al., 2008a) with correlation between the studied successions. Sediment thickness is not to scale.

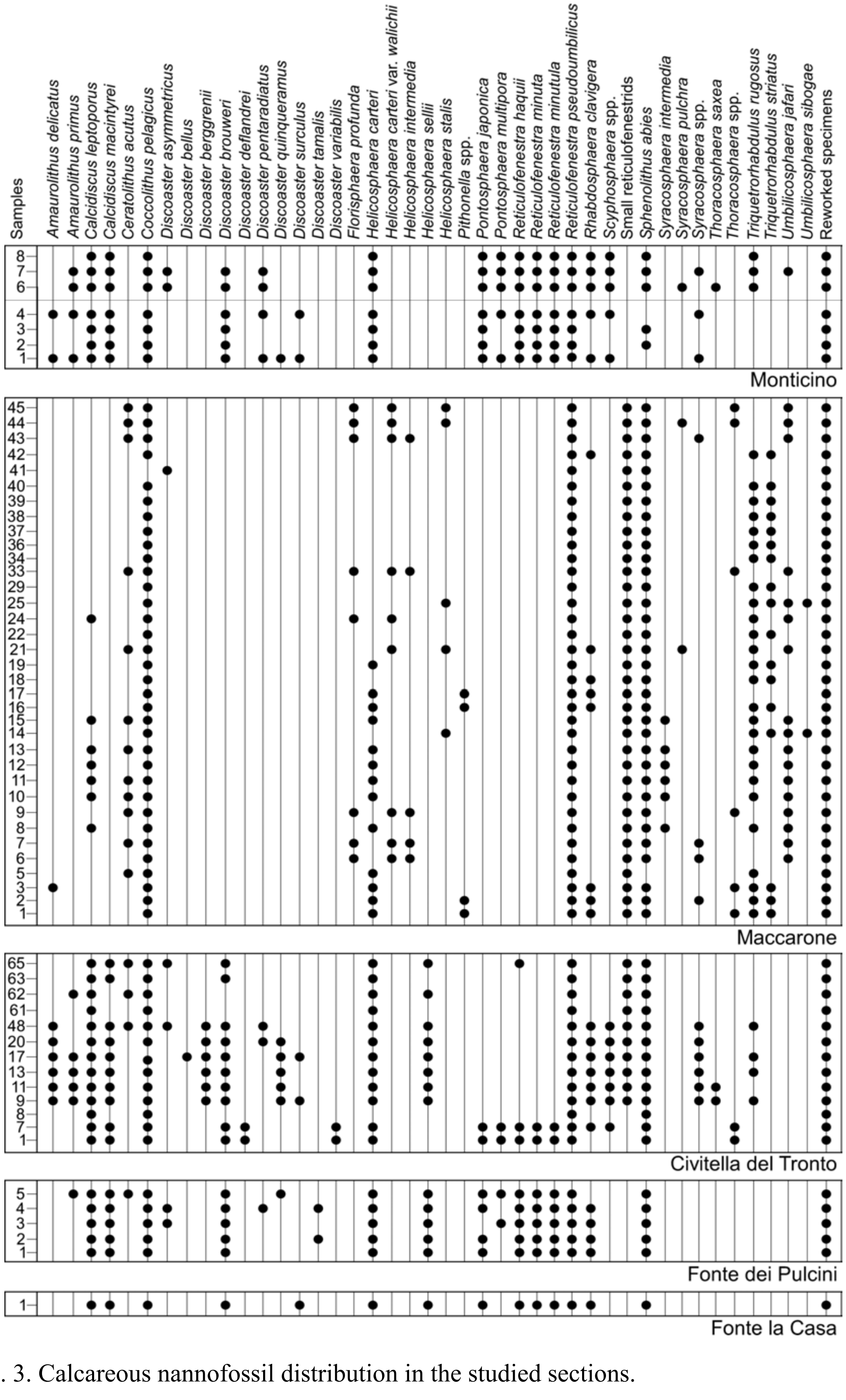

Fig. 3. Calcareous nannofossil distribution in the studied sections.

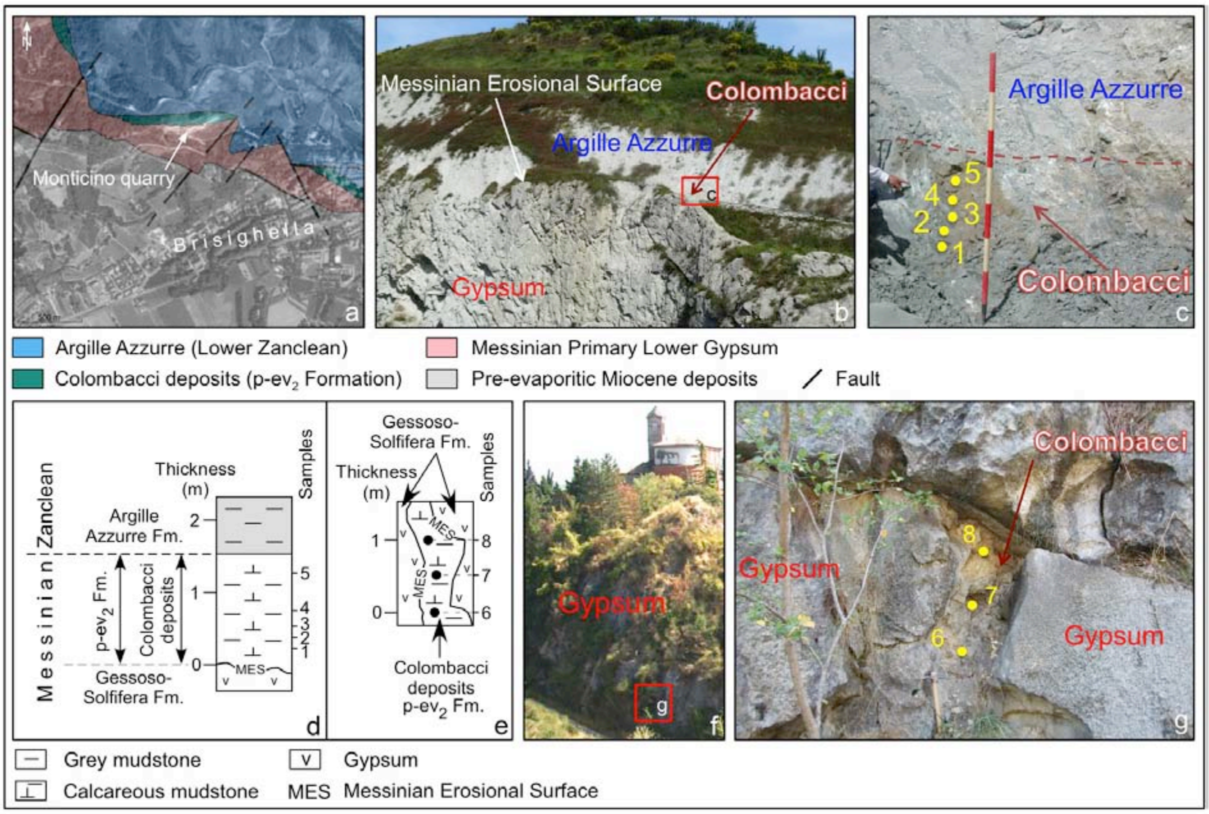

Fig. 4. The Monticino section near Brisighella.

a, Monticino quarry located on a Google Earth image, with geology after Marabini and Vai (1988).

b, Overview of the Primary Lower Gypsum beds (Gessoso-Solfifera Formation) cut by the Messinian erosion and overlain by thin Colombacci deposits and the Zanclean Argille Azzurre. Rectangle c: first sampling site on the northern margin of the quarry.

c, Detailed position of samples 1–5.

d, Sedimentary log of the section overlying the Messinian Erosional Surface.

e, Sedimentary log of the section within the the karstic fissure n° 8bis.

f, Sampling site (e) of the the karstic fissure n° 8bis on the southern margin of the quarry.

g, Detailed position of samples 6–8 within the karstic fissure n° 8bis.

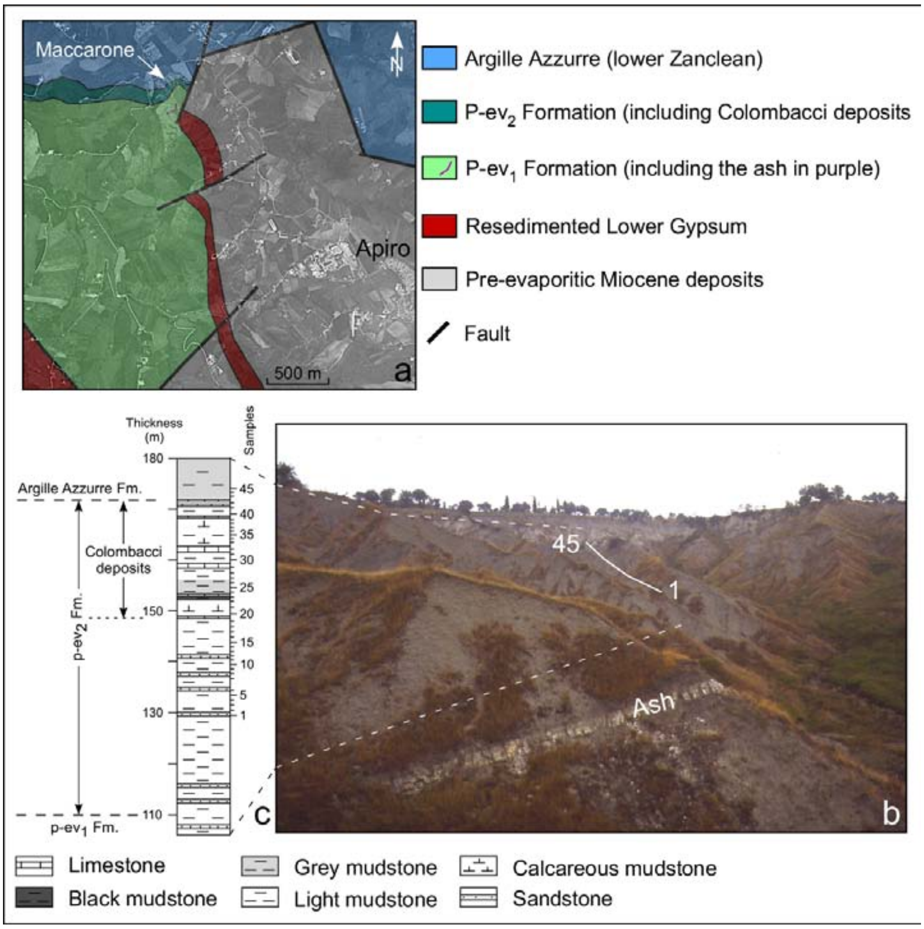

Fig. 5. The Maccarone section near Apiro.

a, Maccarone section located on a Google Earth image, with geology after Centamore et al. (1991).

b, The Maccarone section with position of the studied samples.

c, Lithology and sample location of the studied part of the section.

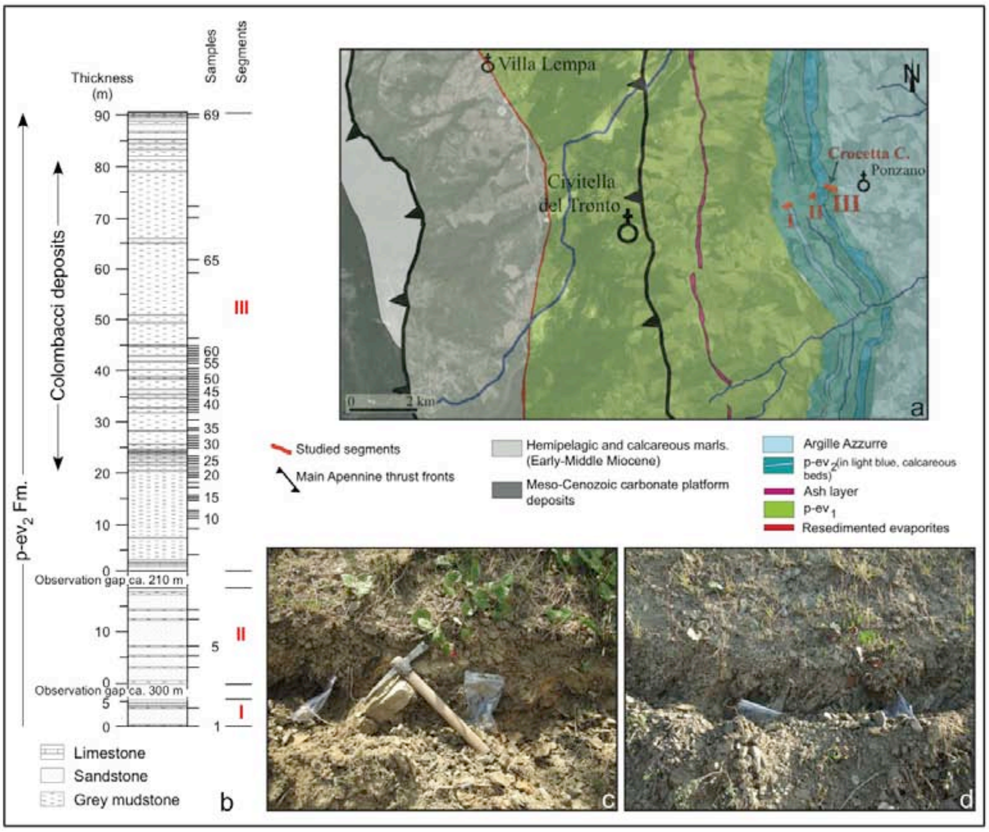

Fig. 6. The upper Messinian succession at Civitella del Tronto.

a, Studied segments of the section located on a Google Earth image, with geology after Del Sordo et al. (in press) and Albouy et al. (2002). The segments are within the p-ev_2 Formation.

b, Sedimentary log of the studied section and position of the analysed samples.

c, Photograph of samples 50 and 51 bordering a Colombacci carbonate bed.

d, Photograph of samples 30 and 31 from a mudstone interval.

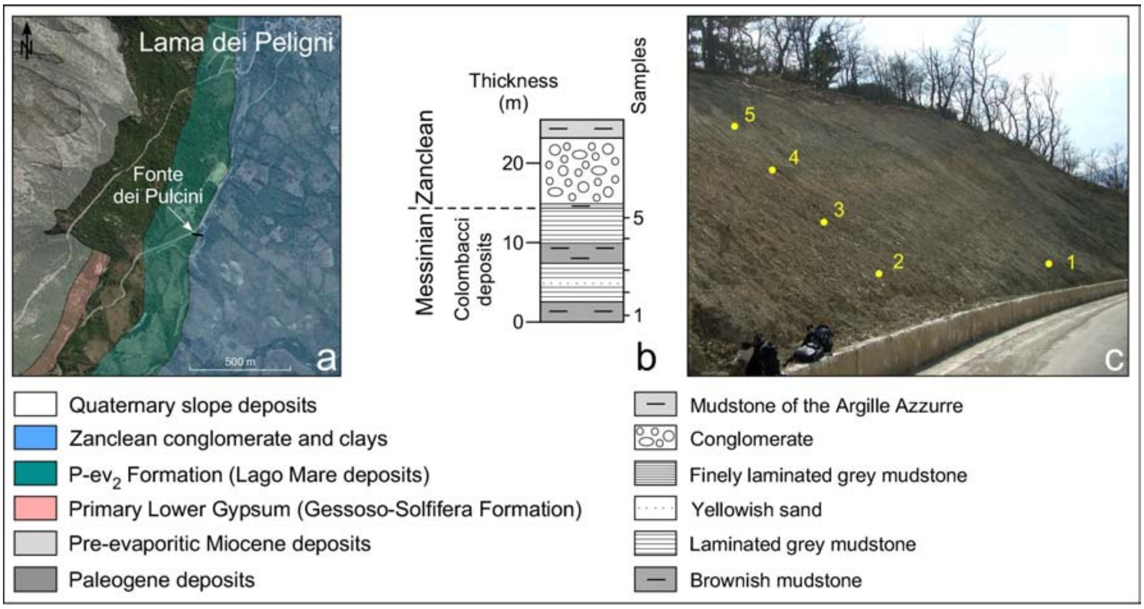

Fig. 7. The Fonte dei Pulcini section near Lama dei Peligni.

a, Fonte dei Pulcini section located on a Google Earth image, with geology after Cosentino et al. (2005).

b, Sedimentary log of the studied section and position of the analysed samples.

c, Position of samples in the upper part of the Fonte dei Pulcini section A of Cosentino et al. (2005).

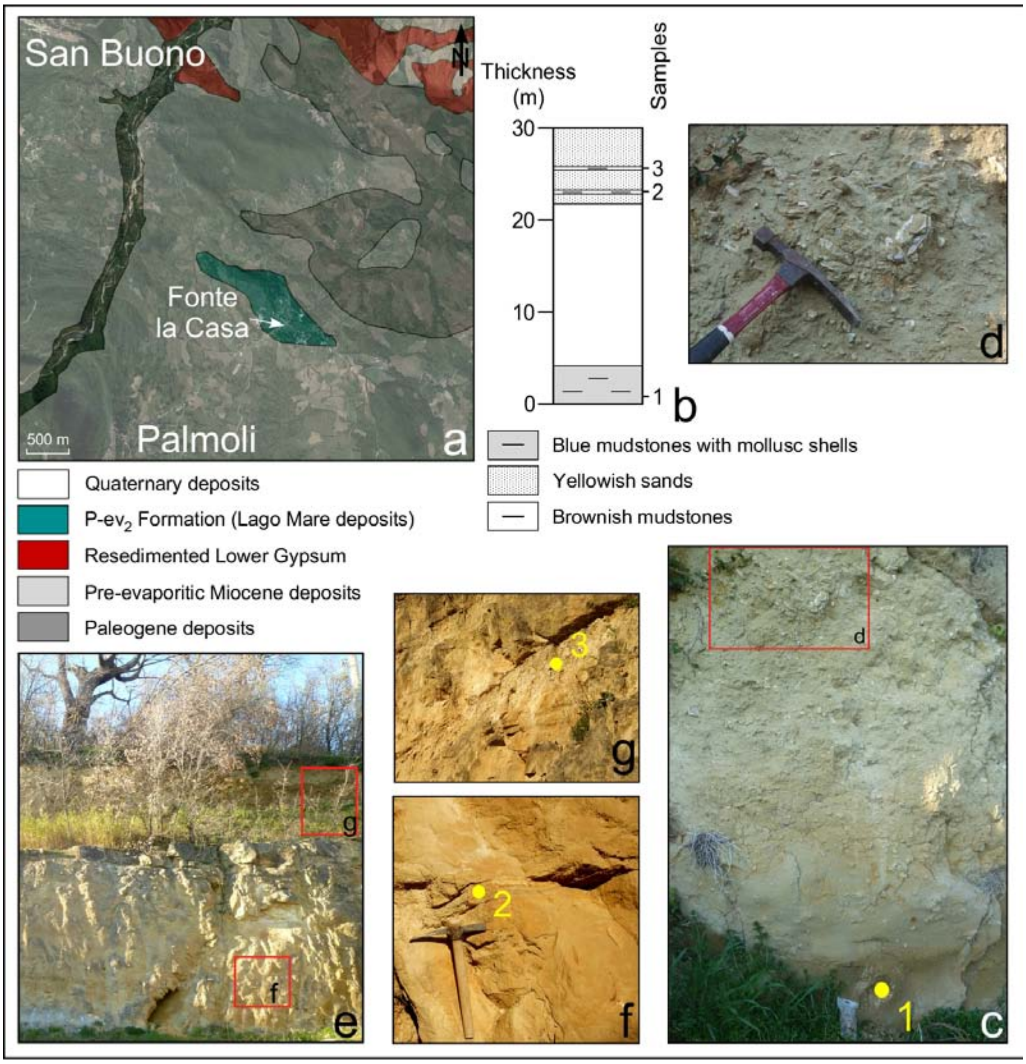

Fig. 8. The Fonte la Casa section near Palmoli.

a, Fonte la Casa section located on a Google Earth image, with geology after Balboni (1968).

b, Sedimentary log of the studied section and position of the analysed samples.

c, Photograph of the lower part of the section rich in mollusc shells where sample 1 was taken.

d, Detailed photograph of this section showing mollusc shells.

e, Photograph of the upper part of the section comprising yellow sands with intercalated clayey beds where samples 2 and 3 were taken.

f, Photograph of sample 2.

g, Photograph of sample 3.

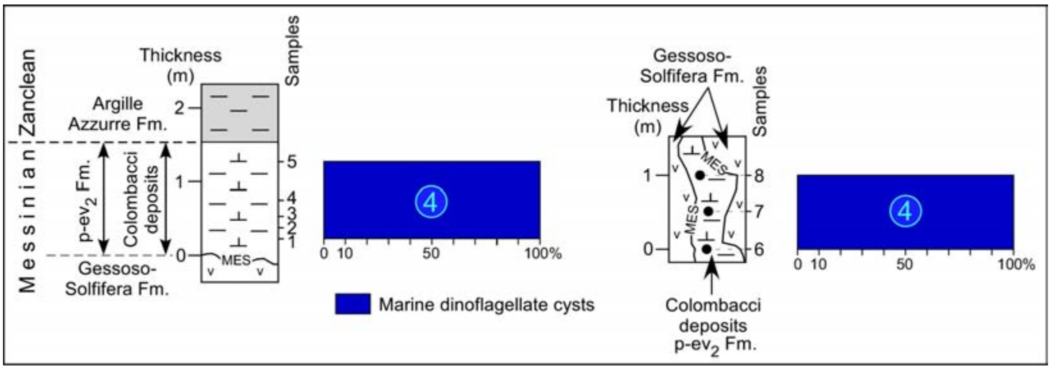

Fig. 9. Dinoflagellate cysts from the Monticino section: marine assemblages.
Lithology: see Figure 4.
4, Peak corresponding to marine influx (see text for details).

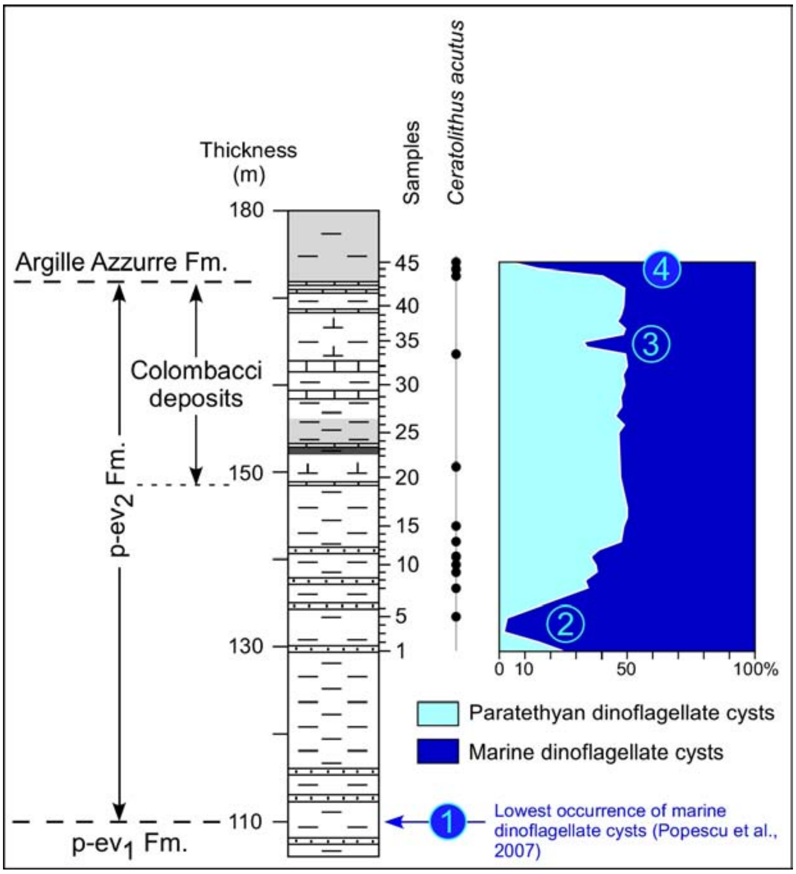

Fig. 10. Dinoflagellate cysts from the Maccarone section (Popescu et al., 2007): Paratethyan (brackish) vs. marine assemblages.
Lithology: see Fig. 5.
1 to 4, Peaks corresponding to successive marine influxes.

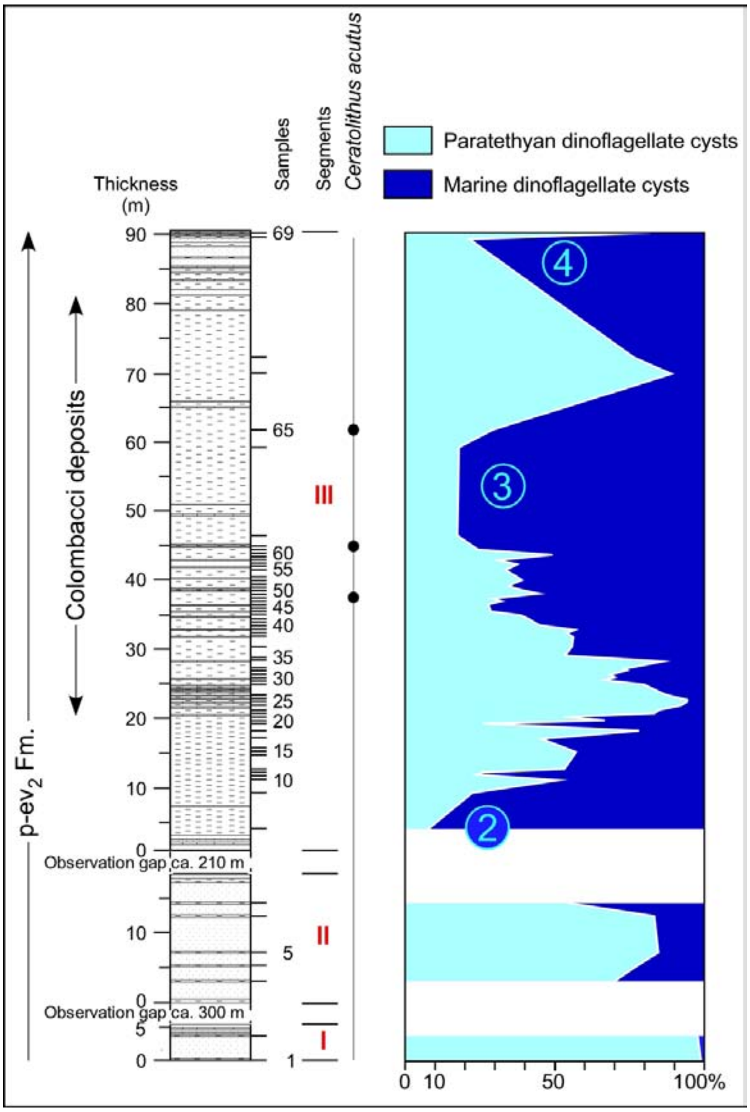

Fig. 11. Dinoflagellate cysts from the Civitella del Tronto section: Paratethyan (brackish) vs. marine assemblages.
Lithology: see Figure 6.
2 to 4, Peaks corresponding to successive marine influxes.

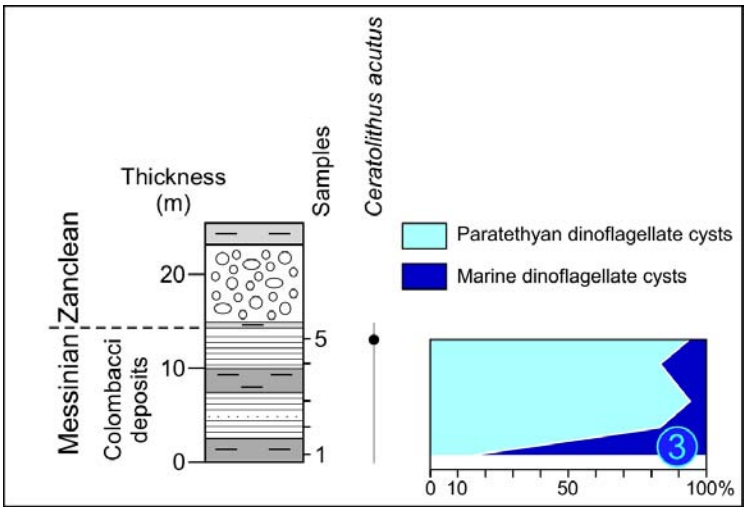

Fig. 12. Dinoflagellate cysts from the Fonte dei Pulcini section: Paratethyan (brackish) vs. marine assemblages.
Lithology: see Figure 7.
3, Peak corresponding to marine influx.

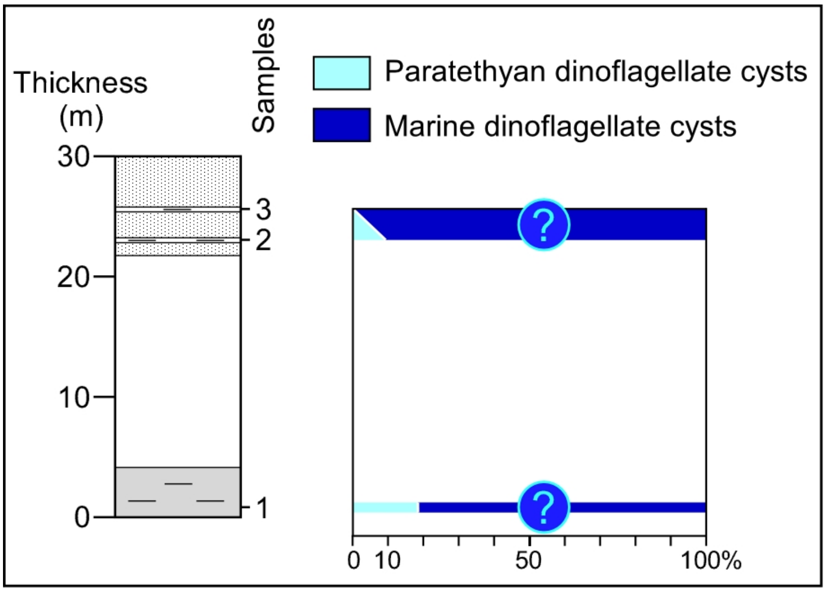

Fig. 13. Dinoflagellate cysts from the Fonte la Casa section: Paratethyan (brackish) vs. marine assemblages.
Lithology: see Figure 8.
Unnumbered peak(s) corresponding to marine influx(es).

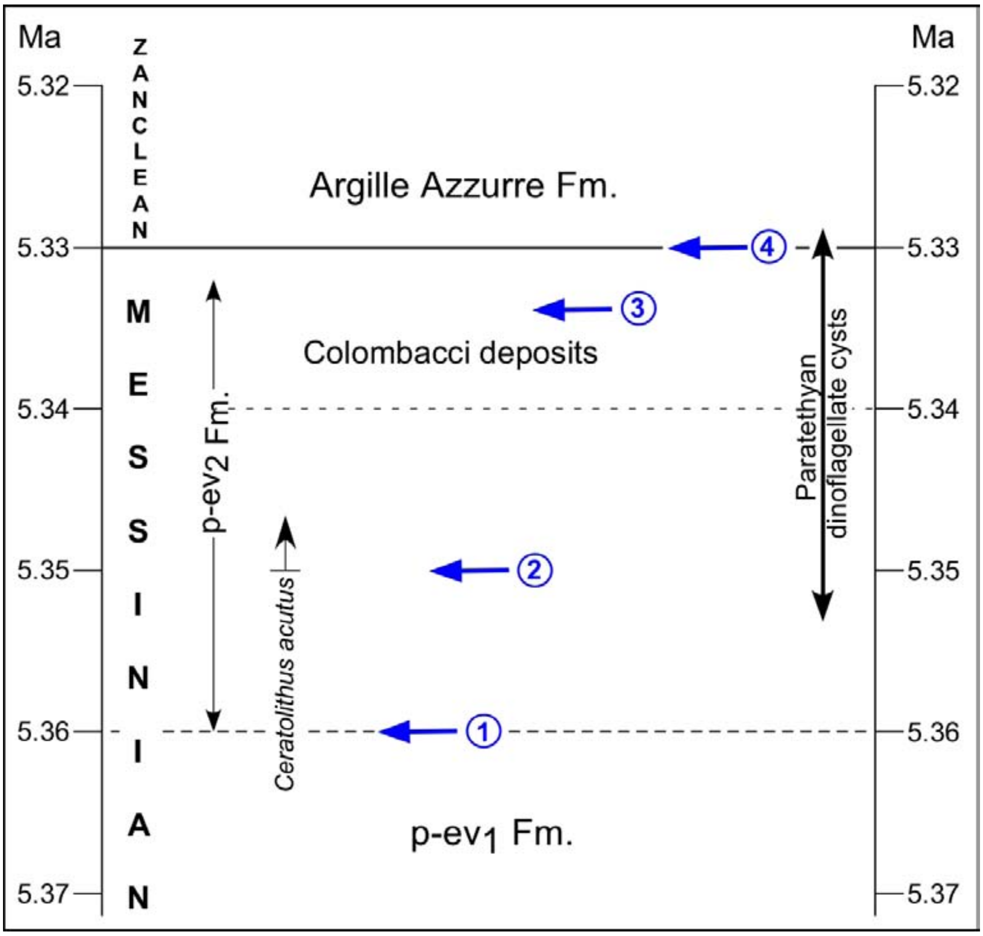

Fig. 14. Chronostratigraphic and palaeoenvironmental re-interpretation of the Messinian post-evaporitic deposits of the Apennine foredeep. Marine dinoflagellate cyst peaks 1–4 are shown.

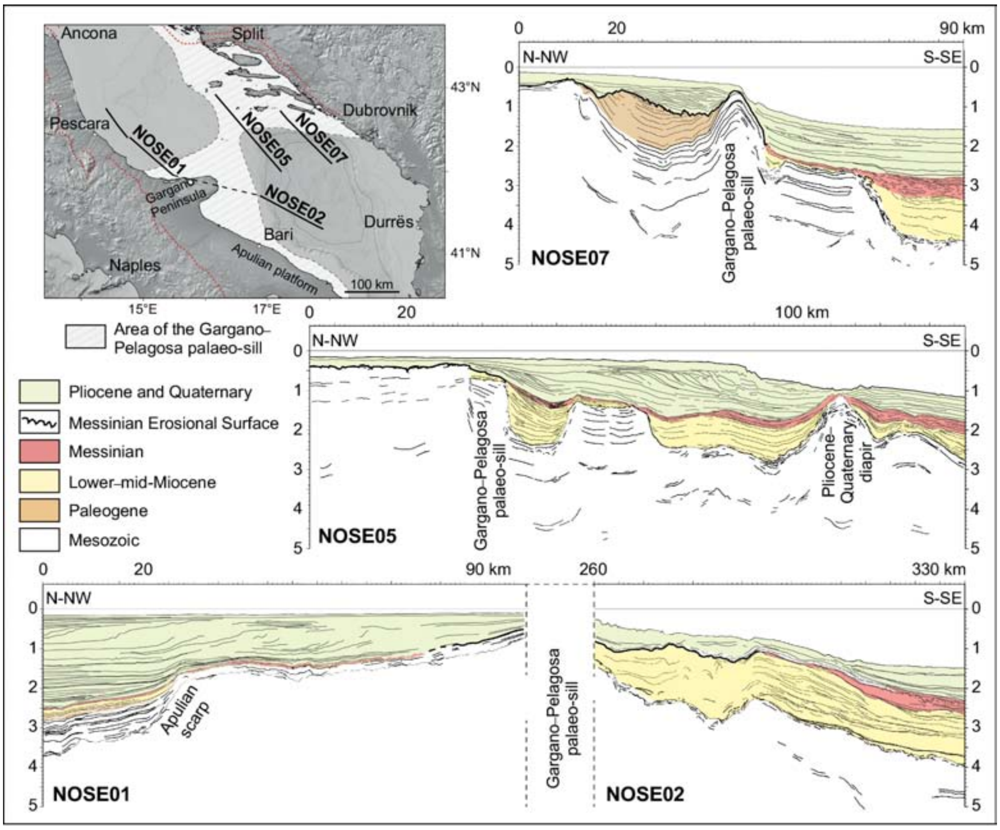

Fig. 15. Line drawings of interpreted seismic profiles in the Adriatic Sea showing the Messinian Gargano–Pelagosa palaeo-sill.

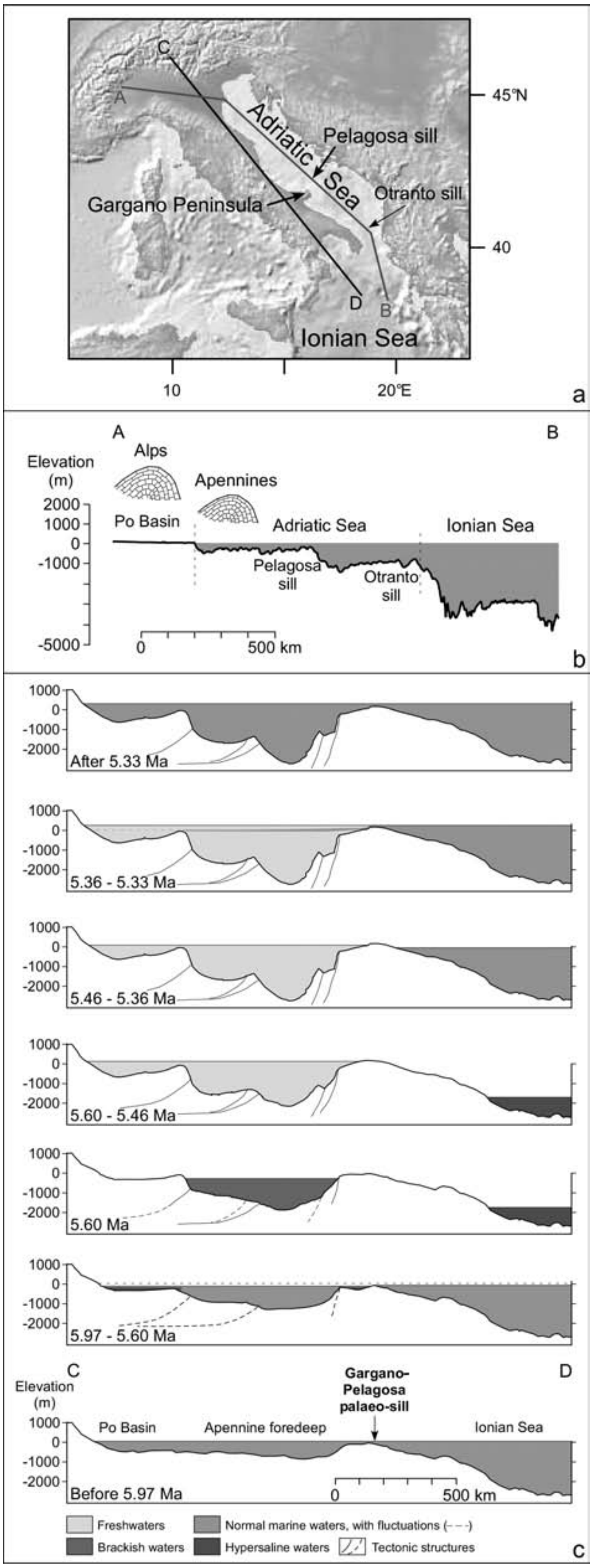

Fig. 16. Mediterranean–Adriatic (vs. Apennine foredeep) connections since 6 Ma. a, Location of the cross-sections; b, Present-day cross-section; c, Successive reconstructed cross-sections from 5.97 to 5.33 Ma, highlighting the role of the Gargano–Pelagosa palaeo-sill and Messinian Apennine deformation phase.

Supplementary illustrations

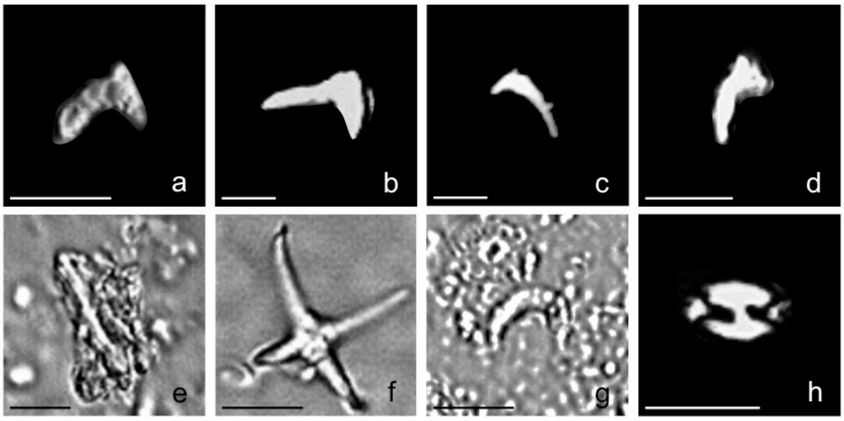

Fig. S1. Photographs in polarized light of selected specimens of calcareous nannofossils. Scale bar = 10 μm for all views.

a, *Ceratolithus acutus* (Gartner and Bukry, 1974), Civitella del Tronto (sample 48), crossed nicols;

b, *Ceratolithus acutus* (Gartner and Bukry, 1974), Fonte dei Pulcini (sample 5), crossed nicols;

c, *Ceratolithus acutus* (Gartner and Bukry, 1974), Maccarone (sample 5), crossed nicols;

d, *Ceratolithus acutus* (Gartner and Bukry, 1974), Maccarone (another specimen, sample 5), crossed nicols;

e, *Triquetrorhabdulus rugosus* (Bramlette and Wilcoxon, 1967), Civitella del Tronto (sample 13), parallel nicols;

f, *Discoaster tamalis* (Kamptner, 1967), Fonte dei Pulcini (sample 2), parallel nicols;

g, *Amaurolithus primus* (Bukry and Percival, 1971), Civitella del Tronto (sample 62), parallel nicols;

h, *Helicosphaera sellii* (Bukry and bramlette, 1969), Civitella del Tronto (sample 9), crossed nicols.

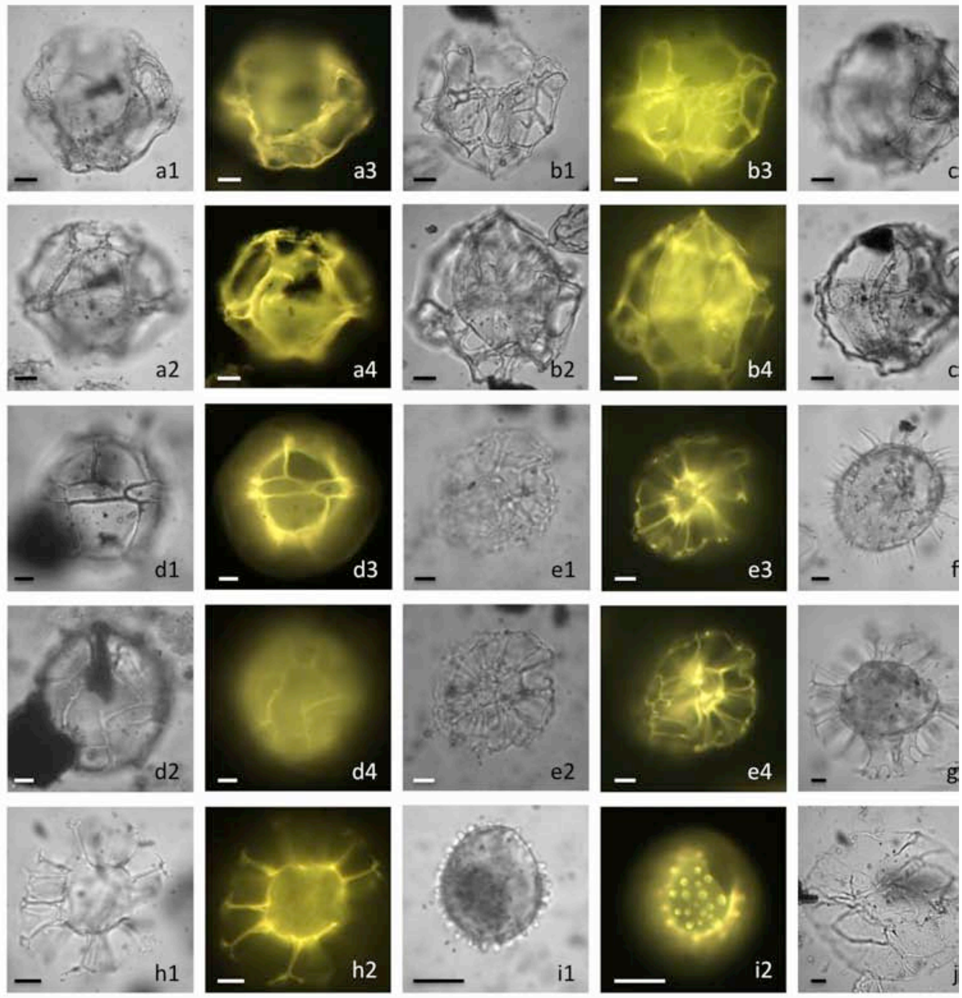

Fig. S2. Photographs of selected dinoflagellate cysts. Scale bar = 10 μm for all views.

a–c, Paratethyan dinoflagellate cysts:

a1–a4, *Galeacysta etrusca* (Corradini and Biffi, 1988), Fonte dei Pulcini (sample 3): a1–a2, in light microscopy; a3–a4, in fluorescence microscopy;

b1–b4, *Galeacysta etrusca* (Corradini and Biffi, 1988), Civitella del Tronto (sample 10): b1–b2, in light microscopy; b3–b4, in fluorescence microscopy;

c1–c4, *Galeacysta etrusca* (Corradini and Biffi, 1988), Fonte dei Pulcini (sample 4): c1–c2, in light microscopy; c3–c4, in fluorescence microscopy;

d–j, Marine dinoflagellate cysts:

d1–d4, *Impagidinium patulum* [(Wall, 1967) Stover and Evitt, 1978], Monticino (sample 2): d1–d2, in light microscopy; d3–d4, in fluorescence microscopy;

e1–e4, *Nematosphaeropsis labyrinthus* [(Ostenfeld, 1903) Reid, 1974], Monticino (sample 2): e1–e2, in light microscopy; e3–e4, in fluorescence microscopy;

f1–f2, *Lingulodinium machaerophorum* [(Deflandre and Cookson, 1955) Wall, 1967], Monticino (sample 4): f1, in light microscopy; f2, in fluorescence microscopy;

g1–g2, *Spiniferites mirabilis* [(Rossignol, 1964) Sarjeant, 1970], Monticino (sample 4): g1, in light microscopy; g2, in fluorescence microscopy;

h1–h2, *Reticulatosphaera actinocoronata* (Benedek, 1972), Monticino (sample 4): h1, in light microscopy; h2, in fluorescence microscopy;

i1–i2, *Operculodinium janduchenei* (Head et al., 1989), Monticino (sample 4): i1, in light microscopy; i2, in fluorescence microscopy;

j1–j2, *Invertocysta tabulata* (Edwards, 1984), Monticino (sample 3): j1, in light microscopy; j2, in fluorescence microscopy.

Samples	*Galeacysta etrusca*	*Gonyaulax apiculata*	*Gonyaulax digitalis*	*Gonyaulax* spp.	*Impagidinium caspienense*	*Impagidinium globosum*	*Millioudodinium dektense*	*Millioudodinium punctatum*	*Millioudodinium* sp.	*Pontiadinium inequicornutum*	*Pontiadinium obesum*	*Pontiadinium pecsvaradense*	*Pontiadinium* spp.	*Pyxidinopsis psilata*	*Romanodinium areolatum*	*Seriliodinium explicatum*	*Spiniferites balcanicus*	*Spiniferites bentorii budajenoensis*	*Spiniferites bentorii coniunctus*	*Spiniferites bentorii oblongus*	*Spiniferites bentorii pannonicus*	*Spiniferites cruciformis*	*Spiniferites galeaformis*	*Spiniferites inaequalis*	*Spiniferites maisensis*	*Spiniferites sagittarius*	*Spiniferites tihanyensis*	*Spiniferites validus*	*Spiniferites virgulaeformis*	*Spiniferites* spp.	*Virgodinium asymmetricum*	**Total**	*Achomosphaera alcicornu*	*Achomosphaera andalousiensis*	*Achomosphaera argesiensis*	*Achomosphaera ramulifera*	*Ataxiodinium choane*	*Bitectatodinium tepikiense*	*Brigantedinium cariacoense*	*Brigantedinium simplex*	*Capisocysta lata*	Cysts of *Pentapharsodinium dalei*	*Echinidinium* spp.	*Edwardsiella sexispinosa*	*Homotryblium* sp.	*Hystrichokolpoma rigaudiae*	*Hystrichokolpoma* sp.	*Hystrichosphaeropsis obscura*	*Impagidinium aculeatum*	*Impagidinium patulum*	*Impagidinium paradoxum*	*Impagidinium sphaericum*	*Impagidinium strialatum*	*Impagidinium* sp.	*Invertocysta lacrymosa*	*Invertocysta tabulata*	*Lejeunecysta oliva*	*Lejeunecysta* sp.	*Lingulodinium machaerophorum*	*Melitasphaeridium choanophorum*	*Nematosphaeropsis labyrinthus*	*Nematosphaeropsis lativittatus*	*Nematosphaeropsis lemniscata*	*Operculodinium centrocarpum*	*Operculodinium eirikianum*	*Operculodinium israelianum*	*Operculodinium janduchenei*	*Operculodinium* sp.	*Pyxidinopsis* spp.	*Polysphaeridium zoharyi*	*Reticulatosphaera actinocoronata*	*Selenopemphix brevispinosa*	*Selenopemphix quanta*	*Selenopemphix* sp.	*Spiniferites bentorii*	*Spiniferites bentorii truncata*	*Spiniferites bulloideus*	*Spiniferites delicatus*	*Spiniferites falcipedius*	*Spiniferites granulatus*	*Spiniferites hyperacanthus*	*Spiniferites membranaceus*	*Spiniferites mirabilis*	*Spiniferites pseudofurcatus*	*Spiniferites ramosus*	*Spiniferites* spp.	*Tectatodinium pellitum*	*Trinovantedinium applanatum*	*Trinovantedinium* sp.	*Tuberculodinium vancampoae*	*Xandarodinium* sp.	Unidentified round brown cysts	**Total**	Unidentified dinoflagellate cysts	Indéterminable dinoflagellate cysts	*Botryococcus*	*Cymatiosphaera* spp.	*Concentricystes*	*Pediastrum* spp.	Reworked dinoflagellate cysts
8																																										1			1				3	110		4			1	1			9		5			1			2		9		1	1			2		4				3		2	2		4				1			167							3
7																																						2							2				3	93					1	4			13		19	1					2		11		1						1				2		4	1	3	10							173							1
6																																						6										1	8	69		4			4				5	1	34			2			1		16								3				2		3			4							163				1			2
5																																												2	1			1	1	3				1		1			4		7			2			1				2															5							31				1			2
4																																		3				2											5	44		2				8			12	3	24	5		4			1		2		11						6				3		7		5	5							152				2			3
3																																		2					1			3			1				7	24						9			14	5	33	4		6			2		4		5						9				4	1	4		2	12							152							4
2																																		3			1					1			1				4	110				2		1			4	2	8	4		4			5														3		3			4							160							12
1																																		3					1			2				4			11	36						8			11	1	38			8			4		6								5				3		1		4	10							156							4
Monticino																																																																																																				
45	2											1										2										5				1				3									12	2	1								5		55		5											1	3		1				2		4		9								104				2			19
44	4					3								2												11						20		1												2			10	12									8		35			1			1										3				7		10										90							16
43	36					11								3	2											16						68								2										7	4			1					4		2			2															1			1	1		2							5	32				1			
42	30					65									2							4				7						108		1	1																																																											2							
41	25					57																				15						97			4																																																										4							
40	56					8								1	1							1				27						94			2																								1					1																		1											5							
39	47					20																10				23						100																																2											1					1	1				1							3	9							
38	42					25								2	1							1				11						82								2										1									2		1			5			1													1	2					2							17							10
37	3					100																				3						106																																																													0							
36	25					59																5				4						93		1																									3																				1											1			6							6
35	10					16								18								2				1						47								18																																																				35	53							
34	13					14								24												3						54																																			1																									49	50							
33	25					51								5								5				12						98																											2																																	1	3							5
32	3					71								15								3				7						99																																																													0							
31	24					86								9								9				22						150								3									1																										1																	5	10							1
30	10					77								31			1					5				8						132		1	1					3																																																					5							
29	1					83								2								3				7						96		4																									1					5																													10							7
28						70								17								1				5						93		3															1										4					3																												1	12							2
27	1					55								2								5				14						77		7	3															1									3					2													1				1					1							19							3
26						62								23								2				10						97		1																																																											1							3
25						58								4								2				24						88									7								2										1																1																	1	12							2
20						54								23								6				15						98		1															1	1									2		2			3																1													11						3	
17	43	1				28					2	11	1				5			1		11										103																																																													0							12
16	63					11					5						4		3		16				1	2		5			110																																																													0		2				1	12
15	26	1				16					4						11	1		5	1	28				4						97																											3					1													1																5							14
13	1	11				20					4		2				1	1		1		25					1					67																											1																		4																5							55
12		1				8					1	14								1		3	10		2				1			41		4																									5											1							5				5				3								23		3					39
11						38				29			13									5		1								86															1												7	5				2																						4							19						1	16
10	3					20					49	6	8									3		2								91		1																											1			4																													6		4				2	15
9						39					60		11									1										111																	1										2		2																																5						6	7
8			3			3				2	11	15							1	1		12	17		6	2	3					76		2		2											1											1	4		2			2													3				1	1			2	3			1				25		2				90	19
7			11			4	2				20	17							3	4		4	11		1				4			81																											4	1	1			4													1								4								15		5				98	22
5	2																															2	1	13		4	2								3		2			2									19	3	3			8			1										9				7	1	1		2	14							95			1				71
4																																0																																																													0							
3				1							1																					2		11		2										2		1	1									2	17	5	3		2	12			1				1			1			14				3				10	9							97					1	2	85
2				2		2												1										3	1			9		1															2										11				1	7			2			2							4				1					9							40			1				109
1				5									6																			11		4																									6					4																	3	2				3							22							12
Maccarone																																																																																																				
69	8						5	1				1	1	1		1		18										13		49		1															2	1								1						1									1		1		1									2							11							
68	1																													1		2																		1				1				1		3				1							1																						8							1
67	14					4		3					1	10						1										5		38		1																				6										1													3								1								12							
66	55					18		13	1				5	8						3										7		110																						7					1	1																	2																11		5					
65	11					1				1										4										7		24		2								1			4		1		1	7				1					9	4	2			6			2			1							3				6		1	1	1	5							58		1				4	3
64	6																			5										14		25					2					1		1	18	2	3	2		5						1			16	17	9			11						1							9				7		1			8							114						4	40
63	5					4							1							1										12		23		4			1					1			27		4			3				3					28	3	1			15			3										5				2					5							105		4	2			1	12
62	4					1			0						1					5										23	1	35		1			2					2			3		1		4	1				1					26	9	6			7	1					4					4						7	2	5		5	14							105	2	9					30
61	2								3				6	3						2								3		29		48										2			5		2				4								8	4	2			1	2												2				2				5	8						4	51		4					13
60	2					1			5				7	1						4								3		73		96													13		3		2	1									25	2				8	3					2					7		3				7	2			4	7		2					91	4	5					31
59	1					3			5				7	1						4	1									25		47		1								1			13						2			1				3	40	6	8			3	7	2	2						1	1	5		2				16	4	3		2	2						2	127	1	15					51
58									6				2	4	1					1										15		29													9		1		2										12		2			4						1							1				5	1	1		1	5							45	1	8					14
57	4					1			3				5		1					2					1					41		58		4											10		1		2	1				1					18	6	8			12	1	1									2		1		2		7	3	3		8	13							104	1	4					27
56	6					1			2				2	1	1		1		4										38	1	57		3								3	2		18		2		2	1				2					27	2	4			10	2	2				1			2		3		3				7	3	2		6	11						1	119	3	10					28
55						3			5				5	4						1										13		31		1											6					1								3	16	6	1			2	2					1		1			3						2	2			2	6		1				1	57		5					24
54	1		4			3			1				4							1										27		41										1			8									1					10	5	1			4	2		1								2						8	1			3	14							61							
53	3					2			2				6							3										37		53													7		3												26	7	4			8	1	1						3			1		6				5	3	2		8	5							90	1	2					48
52	1								1				4		1					4	1									29		41													7		1			1	1			2					24	1	2			5	3	3	1			1					1						5	2			5	13		2				1	81		5					44
51	1		4			2			1				4							1										27		40										1			8									2					10	5	1			4	2		1								2						8	1			3	14							62							
50	1					2			2				4	2						6										26		43													6														11	3				3	2									3	2						3	1	1		1	5							41	2	6					22
49	1					1			1				6	3						2										8	1	23													11		1		3	1				1					13	5	1			3	2										2						6	2			3	11		2				1	68		4					43
48	3								1				5	1						9										43		62										1			15		3		3										18	6	8			14	4					2							3		1		8	1	3		9	14		2					115	2	6					46
47	1								3				3							4										22		33		1											5		1				1			1					24	5	1			3	2		2						1	1	4		1				9	1	1		5	11		2				2	84		4					47
46	0					1			1											3	1				3					41		50										2			12					1	1	1							34	4	6			5	3	2				3				1	2		2				12	3	2		7	20						2	125	1	4					57
45	3								4				2							6										26	3	44										1			6						1								24	10	5			8	1	1				3					8		3				11	3	2		2	18						1	108		5					58
44	0					1			1				1	2						3										17	2	27										1			3						1							1	10	2				2	1										1		2				7				3	8						1	43		2					39
43	7								3					5	1					1										25		42		0								1			4					1	2							2	10	8	2				1					1				2	2		5				4	1	1		4	7		2				2	62	1	6					37
42	1								2				3	2	1					2			1						3	57	2	74		1								3			8		1		1		1								21	8	1			3	4		1			1					3		7				6	2	2		6	14		3				2	99		6					44
41	1					3			1				3	3						2			2							30		45													5														13	5	1			2	2	1								1	1		1				4	2	2		1	9		3				3	56		10					37
40	1		1						3				7	7						1										59		79		1								1			7		4				2								23	5	2			3	3		4			2					2		1				8	2	2		4	11		2				4	93		10					40
39									2				3	1						1										15		22										1			1						1								4	2							1								1										2	2							15		2					13
38			1						6				7	6						12										56		88										1			6														13	9	4			2	5		4			3					2		3				9	2			6	8		1					78		11					47
37	1								3				8	4			1		7										41		65													5					1								1	9	6					3		2			1				1			3				5	2	1		2	6		1					49		5					32
36									3				1	3						3										9		19													1					1									4		1			1											1						1	1				3						1	15		3					15
35	1								2					1						3										11	3	21													1														6	1	1				2												1				2				1	3		1					19	1	2					19
34	12					1			4				37	19	3		2		18										114		210										2							3										3		2			1													4				1		1		2								19	1	2					12
33	9		2			1			4				6	9			1		26			1							37	4	100													3						1	1							7	1				3	1		1								2						4				3	9		1				3	40	1	4					55
32	14								4				6	9	2		3		38										52		128										1			2		1												10	5	3			1	2										1		1				6	2	1		4								40		2					53
31	29		3			3			6				7	10	4		2		18	1								1	30		114													6		2				1								9	3	1			2	2		1			2			1	1	5						4	1	1		3	8		2				1	56	1	7					58
30	13		1						7				9	10	8					25										37		110															1		1	4				1					10	1				7						1					2						3		1		1	10							43		5					12
29	7								4				3	4	3					5										11		37											1		3				1										3	2										1				1	1		1				3	2	2			1							22		2					24
28	24					4			8				10	12	4					30										60		152													5		1												3	3	2			2			1								2		4				1	1	2		2	8							37		5					54
27	28								1				4	15	6		1		24										52		131										1																1	3					2											1		2					2			2	4							18		2					39
26	10		1						11				25	13		1	2		45	4				2					108		222										1	1																2		1														3						1					2							11		1					20
25	24					1			3				16	24	4					11										97		180										1								1									5																		1						2			1							11		4					12
24	14					10		3					1							16	1				1					3		49													2									1													1																										4						1	7
23	9					2		1	3				1							20	6									10		52		2													1		1					1					1	1				2																													9							18
22	17					1		13	4											7										3		45													3							1		2					1					2																													9							9
21	1				1	4			3				3								1									2		15													5									1					2					1			3				1																						13							3
20	32					7			1											5										5		50		2											6														4	1	1			3							2				1		2				2			1									25							3
19	2					3								1							2											8										1			9					1				1					4					3																	1					2							22							28
18	93								2					1						11										8		115							1						7	1								6					3	2				2													6				2		1			1							32							3
17	43					2								1						4	1									6		57		1								1			15	1			2	4				1					11	1	1	1		8		1	1		1		1	2					3				8		3		5	2	2						76							16
16	75																			3										5		83		1						1				1	11	1			1	1									13	9	5			8			3										3				5			2	2	4							71							26
15	37					3		2	1					1						1										19		64												1	6			2								1			9	2	1			4							5						4				4		2		2	2	1			1			47							11
14	65					1		2												1										7		76													7			1											9	3	2			5			1										18				7		1		1	2							57							16
13	32					1		4																						4		41		1											3					2				1					3	1	3			6							1						11						1		1	2							36		1				1	11
12	5																			1										7		13		1											6	2													4	1	1			5													3				3				3	7							36							9
11	20				1			1												1										6		29		2								1			22	4				1						1			20	5	5			9			1										6				12		3		6	17							115		1		3			19
10	50							2												7										25		84		1						1		2			12				1			1				1			4	2	1	1		5			2				1						8	1	1		8		1		2	5							61		3					19
9	23					1														1										8		33	1	2		1								2	17	6								1		1	1		23	2	3			18			1				1						12				8	1	4		1	10							116	1					1	20
8	3					1								7																1		12	4	2			1								54					5			1	1		2			10	5	4			15			1	1			1		4				6				5			4	1	14					1		142							7
7	19					2		4	1					3			5		20										38		92	1												19		1			1			1	1					16	4				10						1	1				1		6				4		1	1	1	4					1		75						2	8
6	37					6		6	8					1			1		17										41		117	1	1											7			1						1					3	1				3													1				1		1	1		1				1			24						1	4
5	28					6		1	2					2			2		14	8						1			62		126	1						2						3									8					1					1													3					1		1	1	1							23							3
4	20				3	14		5	11	1			2	3	1					10	4									35		109	2	2											2	1				1				7		1			3		1						1			1	1		2				3									4							32						1	4
3	10				1	9		6	4				2	5						26	1									30	1	95		2											7	2				1				1					10		1			3			3			5							2						1		1								39						1	5
2	1																													3		4	1				1					2			29	10		2		2			1	2					23	10	5			18			1			1	6	2	1				6		2		8		1	6	1	10							151						2	31
1	1																															1										3			35	10	5			4				2					25	6	3			25			2			1	2	2				3					8	1	4	8	2	14							165						2	9
Civitella del Tronto																																																																																																				
5	46					30		2	4	1			1	8					18											8	1	119		4																				3																							1																8							3
4	48					12		3	3				3						11			3								29		112		6					1						1	5								1					2					1							1						1									2							21						1	6
3	115				1	6		3					2	2					19			5								15		168																						7													1																			1							9							2
2	27					4			1				5						27											25		89		2											1									3					2	2				3			1				1						2								1								18							15
1	7																		1			1								3		12		2										1	5		3				1			2		1			17	4	6			2							4			2			5				1				1	6				1			64							42
Fonte dei Pulcini																																																																																																				
3																																3													6					2									9																		4		1		2				1	7							32							
2	1																										1			1		5				1									10														7	1				2			1										5				1					1							29							4
1						1								2						4										16		24		10								1			5				2	1									12	1	4			8							1						16				13	2	1		6	23	1						107				1		2	11
Fonte la Casa																																																																																																				

Table S1. Dinoflagellate cyst distribution in the studied sections.