

# Late Miocene fish otoliths from the Colombacci Formation (Northern Apennines, Italy): Implications for the Messinian ‘Lago-mare’ event

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A fish otolith assemblage from the Messinian ‘Lago-mare’ deposits of the Colombacci Formation cropping out in the Montecalvo in Foglia Syncline, Marche, central Italy, is described. The assemblage displays a low diversity and consists of seven taxa belonging to three families: the Gobiidae, Myctophidae and Sciaenidae. Sciaenid otoliths are the most abundant elements representing 88% of the entire assemblage. The palaeoecological analysis reveals a coastal shallow marine environment strongly influenced by continental outflow. The low diversity and high abundance of the euryecious sciaenids are indicative of a very simplified food web, which probably represented an ecological response to the fluctuating environmental parameters and available food resources. The fish remains documented here provide an unambiguous evidence that normal marine conditions were present in the Mediterranean, at least in the upper part of the ‘Lago-mare’ event, and unquestionably demonstrate that the marine refilling preceded the Mio-Pliocene boundary. These findings clearly demonstrate that fishes, because of their mobility and migratory behaviour, represent a useful tool for the large-scale interpretation of the environmental conditions of the Messinian Mediterranean water body. The necessity of a new scenario of palaeoenvironmental evolution for the post-evaporitic Messinian of the Mediterranean is also discussed. Copyright © 2006 John Wiley & Sons, Ltd.

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## 1. INTRODUCTION

The events related to the Mediterranean Messinian Salinity Crisis are among the most intriguing and well studied of Cenozoic history. In this period the marine basin of early Messinian (Late Miocene) times underwent a progressive desiccation so that its base level lay several kilometres below normal sea level (e.g. Hsü *et al.* 1973). As a consequence, the marine ecosystem was completely destroyed and thick and extensive evaporites were deposited in the entire basin, resulting in the removal of more than 5% of dissolved oceanic salts (Hsü *et al.* 1977; Rouchy 1982), with a relevant effect on world oceanographic and climatic patterns (Thunnell *et al.* 1987). The Mediterranean was refilled during the Zanclean (Early Pliocene) deluge and its faunal content and physico-chemical characters returned to normal. Summarizing, the Messinian Salinity Crisis can be defined as the interval of the Mediterranean history before the Pliocene flooding, characterized by evaporite deposition and by the subsequent fresh- to brackish-water sedimentation of the ‘Lago-mare’ facies. The desiccation of the basin was triggered by the progressive isolation of the Mediterranean Basin from the Atlantic Ocean during late Miocene time. Although

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glacio-eustatic sea-level lowering has often been proposed as the main reason for explaining the isolation of the Mediterranean from the open ocean (Adams *et al.* 1977; Hodell *et al.* 1986; Aharon *et al.* 1993), recent studies have demonstrated that tectonic uplift along the African and Iberian continental margins must be considered as the only cause for the closure of the two marine gateways in the Betic and Rifian areas (Garćes *et al.* 1998; Duggen *et al.* 2003; Krijgsman *et al.* 2004). Because of the evocated spectacular catastrophic scenario, the Messinian Salinity Crisis is one of the most discussed topics in Earth Sciences. The scientific debate about this event started early in the 1970s and has stimulated intense investigations in several fields of geological sciences (e.g. palaeontology, stratigraphy, sedimentology, geochemistry) for more than 30 years. Biologists also benefited of the hypothesised palaeogeographic framework in order to justify the present distribution of terrestrial and freshwater organisms in the peri-Mediterranean region (e.g. Bianco 1990). The concept that the Messinian Mediterranean Sea was at times completely desiccated received remarkable publicity through popular articles and books (e.g. Hsü 1984). As a consequence of this considerable attention, the Messinian desiccation of the Mediterranean has been widely accepted by the scientific community and has been included in scientific textbooks as a well-documented event of Cenozoic history (e.g. Stanley 1986). However, the understanding of the different aspects related to this event is not completely clear and many important questions remain unanswered. Several aspects of the palaeogeographical, climatological and palaeoenvironmental setting of the Mediterranean and the physico-chemical structure of the water column through the Messinian remain obscure and the results of the studies often contrasting. The recent stratigraphic advances obtained after the adoption of the astronomical cyclostratigraphy and modern physical stratigraphic concepts have greatly improved our knowledge about the progression of the Salinity Crisis, leading to the calibration of geomagnetic and biostratigraphic Neogene time scales that allowed a detailed and accurate tuning of certain Messinian events. Based on these studies the base of the Messinian (Tortonian–Messinian boundary) has been fixed at 7.25 Ma and its end (Messinian–Zanclean boundary) dated at 5.33 Ma (Lourens *et al.* 1996; Hilgen *et al.* 2000). The top of this stage corresponds to the so-called ‘Terminal Messinian Flooding’, a catastrophic return to fully marine conditions synchronous in the whole Mediterranean. The well developed and widely distributed cyclic arrangement of the Messinian deposits suggested the classical three phase subdivision (see Krijgsman *et al.* 1999b): (1) Pre-evaporitic phase, characterized by cyclic diatomite-sapropel sedimentation that affected the basin in response to the precessional forcing of ocean stratification (7.25–5.96 Ma); (2) Evaporitic phase (=Lower Evaporites; 5.96–5.59 Ma); (3) Post-evaporitic phase (5.52–5.33 Ma). The second and the third phases correspond to the Salinity Crisis event. Astronomical cyclostratigraphic considerations indicate that the onset of these phases can be interpreted as synchronous throughout the Mediterranean, implying a marked climatic and/or geodynamic control. The cyclostratigraphic calibration of evaporite and post-evaporite cycles suggested the existence of a small hiatus between 5.59 and 5.52 Ma, the so-called ‘Messinian gap’, which was probably caused by the definitive isolation from the world-wide network of oceans (Krijgsman *et al.* 1999b) and the subsequent desiccation and associated isostatic rebound processes (Norman and Chase 1986). The stratigraphic resolution within the three phases is very different, mainly because of the lack of biostratigraphic control in the evaporitic and post-evaporitic phases, classically included in the so-called ‘Non Distinctive Zone’. The lack of biostratigraphic control limits the possibility to obtain a detailed stratigraphic framework for this interval. Moreover, the scarcity of fossils and the heterogeneity of sedimentary products that characterizes the Salinity Crisis-related deposits makes difficult the understanding of the physico-chemical and palaeoenvironmental conditions of the water body during the span of this event and the resulting palaeogeographical setting of the Mediterranean (see Cita and Corselli 1990). According to the original hypotheses of Messinian palaeoenvironmental evolution the isolated Mediterranean was affected, during the evaporitic phase (Lower Evaporites), by a cyclic evaporative draw down of the sea level that shallowed up to the complete desiccation. As a consequence of the cyclic progressive desiccation, an increased concentration of the brines culminating in the deposition of sulphate-rich evaporites widely occurred in the basin. The evaporitic phase was followed by a short time interval characterized by non-deposition and erosion (Messinian gap), and by the subsequent deposition of the non-marine sediments of the ‘Lago-mare’ event (Krijgsman *et al.* 1999b). The progressive sea-level drop and the successive desiccation of the basin were responsible for the drastic change of the drainage pattern in the peri-Mediterranean region, resulting in the partial refill with fresh and brackish waters of Paratethyan origin (e.g. Cita *et al.* 1978; McCulloch and De Dekker 1989). Thus, the desiccation model

implies that during the Salinity Crisis the Mediterranean water body was characterized by dramatic and rapid environmental changes, from hypersaline to completely dried out, to hyposaline. In this paper we report the occurrence of fish otoliths in the 'Lago-mare' deposits of the Colombacci Formation, Montecalvo in Foglia Syncline, Northern Apennines, Italy. The palaeoenvironmental interpretation of the fossil assemblage described herein suggests that normal marine rather than hyposaline conditions were present in the Mediterranean at least in the upper portion of the post-evaporitic 'Lago-mare' phase, thereby implying that the marine refilling of the basin occurred before the Messinian–Zanclean boundary. Our findings reinforce the hypothesis of Mediterranean palaeoenvironmental evolution derived from the analysis of the upper Messinian fish assemblages from Tuscany (Carnevale *et al.* 2006b). We also discuss the importance of fish remains in the large-scale interpretation of the environmental conditions of the Messinian Mediterranean water body.

## 2. GEOLOGICAL FRAMEWORK

### 2.1. Structural and palaeogeographical setting

The Apennines formed since the Oligocene in response to crustal shortening caused by plate convergence after the main phase of collision between Europe and Africa (Kligfield 1979). This chain represents the northwest-trending portion of an arcuate thrust belt that continues southward through Calabria and into Sicily. Thrusting occurred in response to westward subduction of the Adriatic lithosphere beneath the Apennines (Royden *et al.* 1987). Since late Tortonian times, the migration of the thrust belt toward the foreland was accompanied by back-arc type extension and basin formation west of the chain in relation to the opening of the Tyrrhenian basin (see e.g. Malinverno and Ryan 1986; Patacca *et al.* 1990; Doglioni 1991). The orogeny occurred in two distinct tectonostratigraphic realms, the Northern and the Southern Apennines, which are separated by a tectonic line (Patacca *et al.* 1990; van der Meulen *et al.* 1998) representing the final result of a differential passive sinking of the foreland lithosphere during the Neogene and Quaternary convergence between Africa and Europe (Patacca and Scandone 1989).

During the main phases of uplift of the chain, the Northern Apenninic foreland basin system was characterized by intense compressional tectonic activity. Based on seismic profile analysis, Bally *et al.* (1986) separated the foreland basin system (foredeep *sensu stricto*) from a more marginal setting that was deeply involved in compressional fronts during the uplift of the chain, resulting in the development of satellite basins (=minor basins; see e.g. Centamore *et al.* 1978; Cantalamessa *et al.* 1982). As pointed out by Ricci Lucchi (1986), the term 'satellite basin' indicates a wide category of palaeogeographic units smaller in size than the coeval foredeep, characterized by localized and highly differentiated depocentres with subsidence phenomena synchronous with those of the foredeep.

The Marche Apennine represents the outer part of the northeast-verging northern Apenninic chain. This sector of the chain is bounded to the north by the Val Marecchia gravity sheet (Ligurids *sensu* Ruggieri 1958), a giant body of allochthonous terranes emplaced by gravity sliding into a depression created by convergence of compressional fronts (De Feyter 1991), and is also comprized between several transversal tectonic structures. Such structures played a relevant role in the tectono-sedimentary evolution of the chain by influencing basin topography, and therefore by creating differential subsidence between contiguous areas and by acting as entry points and preferential corridors for turbidites (Ricci Lucchi 1986). During the Messinian, the syndimentary tectonic activity produced a basin-and-swell morphology with a series of distinct satellite basins longitudinal with respect to the chain (Savelli and Wezel 1978). These basins, which represent embryonic structures of the compression affecting the Miocene foredeep, are coincident with the present-day synclines and are separated from each other by anticlines that acted as passive structural highs or sills during the Messinian (Savelli and Wezel 1978; De Feyter and Molenaar 1984; Molenaar and De Feyter 1985; Roveri *et al.* 1998).

The Montecalvo in Foglia Syncline is one of the satellite basins with NW-SE direction running parallel to the chain on the Adriatic side of the Apennines (Figure 1A and B). It is located SE of the Val Marecchia gravity sheet and is bounded by the Macerata Feltria structural high to the west, which separates it from the Pietrarubbia Syncline

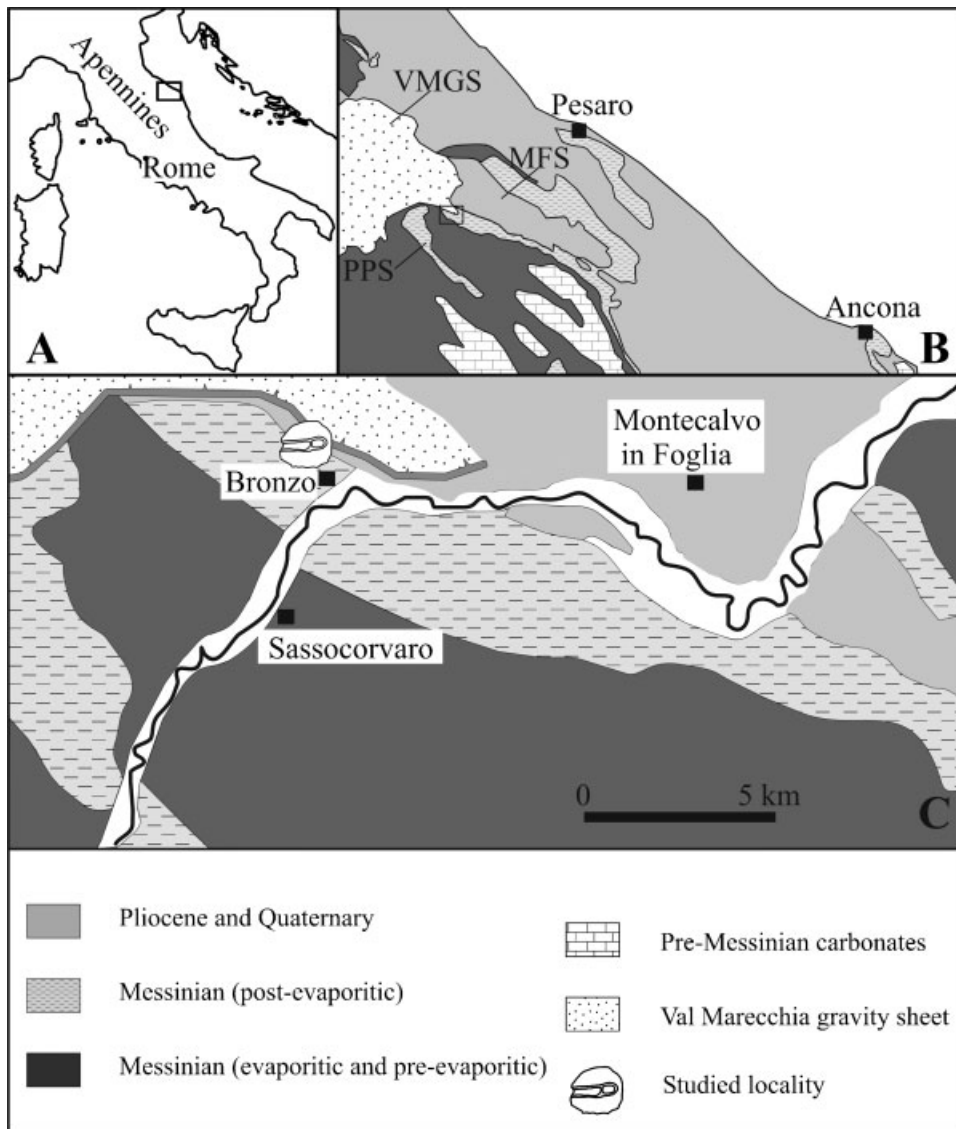


Figure 1. Schematic geological maps of the northern part of the Marche Apennine region (B), and of the investigated area of the Montecalvo in Foglia Syncline (C). MFS, Montecalvo in Foglia Syncline. PPS, Peglio-Pietrarubbia Syncline. VMGS, Val Marecchia gravity sheet.

(Bassetti 2000). More generally, in this area of the Marche Apennines, the Macerata Feltria structural high separates the so-called Inner Marche Basin from the Outer Marche Basin (Centamore and Micarelli 1991).

## 2.2. Stratigraphy and locality

Messinian post-evaporitic deposits are preserved in the core of the Montecalvo in Foglia Syncline (Figure 1C). As in other sectors of the Apenninic foredeep, the post-evaporitic succession of this basin can be subdivided into two separated allostratigraphic units ( $p\text{-ev}_1$  and  $p\text{-ev}_2$ ; e.g. Roveri *et al.* 1998, 2001, 2003) that together with the lower portion of the Pliocene Argille Azzurre Formation constitute a large-scale synthem recording a regional-scale phase

of tectonic deformation of the Apenninic chain (Roveri *et al.* 1998, 2003). The two units are characterized mostly by terrigenous facies and correspond respectively to the Terreni di Tetto and Colombacci formations. The Colombacci Formation continuously and conformably underlies the Argille Azzurre Formation. Although not formally defined, the Colombacci Formation (=p-ev<sub>2</sub>) seems to record the 'Lago-mare' phase of the Mediterranean Messinian history in the Apennine foredeep. According to the recent lithostratigraphic analysis provided by Bassetti (2000), in the Montecalvo in Foglia Syncline the di Tetto Formation (p-ev<sub>1</sub> unit) reaches 500–600 m in thickness and consists of grey-blue silty marls interbedded with thin sandstone (turbiditic) beds. In this basin the Colombacci Formation consists of more than 500 m of clays interbedded with coarse-grained sand bodies, and five well bedded and laminated 'Colombacci' layers. The clays show a characteristic mineralogical composition with a sharp predominance of illite and montmorillonite, and a minor portion of chlorite, kaolinite and attapulgite (Colalongo *et al.* 1976). The analysis of the whole clay mineral association in the Colombacci Formation suggests a limited alkaline depositional environment, represented by a coastal lagoon characterized by a continuous input of continental ions and sporadically flooded by marine waters (Colalongo *et al.* 1976). The coarse-grained units are mainly arenaceous representing channelized sand-bodies of prodelta shelf to upper submarine fan sedimented by immature turbidites and hyperpycnal flows. The composition of these deposits suggests the emergence of the Apenninic chain and the subsequent development of a drainage system that eroded the so-called 'ligurid' terrains. The 'Colombacci' consist of whitish or yellowish micritic or laminated limestone horizons recognizable as a single well-laminated bed or as thin layers interbedded with varved pelites or calcareous marls. The origin of these limestones have been discussed by several authors (e.g. Casati *et al.* 1976; Colalongo *et al.* 1976, 1978; Cremonini and Farabegoli 1977; Savelli and Wezel 1978; Molenaar and De Feyter 1985) and a recent multidisciplinary study performed by Bassetti *et al.* (2004) concluded that they were precipitated inorganically in an anoxic environment during periods of eustatic maxima.

The Colombacci Formation succession cropping out in the Montecalvo in Foglia Syncline, likewise to that of other basins of the Apenninic foredeep, is characterized by a cyclical architecture superimposed on an overall transgressive trend (see e.g. Bassetti *et al.* 2004). The cyclicity of the succession is exemplified by the vertical repetition of coarse- to fine-grained couplets characterized by thin-bedded 'Colombacci' horizons, which represent the depositional product of the periods of eustatic maximum and decrease of terrigenous input into the basin.

The studied section is located close to the village of Bronzo, in the northern part of the Montecalvo in Foglia Syncline (Figure 1). The section was described in detail by Carloni *et al.* (1974) and Borsetti *et al.* (1975) who considered it as one of the most representative of the Colombacci Formation (more than 500 m thick) in the northern sector of the Marche Apennines (Ca' Ciuccio section; Figure 2). The fossiliferous layer occurs 1 m below the Mio-Pliocene boundary, approximately 40 cm below a sandstone body characterized by low-angle cross-stratification (Figure 2). The fossil assemblage is included in a dark grey, organic-rich layer and mostly consists of thin-shelled gastropods, bivalves and fish otoliths. The analysis of the microfauna has revealed the presence of a moderately abundant ostracod fauna (*Cyprideis*, loxoconchids) which is interpreted as autochthonous based on the co-occurrence of specimens corresponding to different ontogenetic stages. Foraminiferans are represented by a mixture of reworked (e.g. *Uvigerina*) and autochthonous (*Ammonia*) benthic forms. The mollusc fauna was briefly described by Bellagamba (1978) who recognized 15 taxa belonging to the genera *Dreissena*, *Euxinocardium*, *Limnocardium*, *Plagiodacna*, *Prosodacna*, *Hydrobia*, *Melanopsis* and *Melanoides*. The age of the fossil assemblage can be interpreted based on its stratigraphic position that is placed between the uppermost 'Colombacci' layer and the Mio-Pliocene boundary. Since this boundary has been dated at 5.33 Ma (Lourens *et al.* 1996) and each 'Colombacci' cycle probably had an average duration of 20 kyr (e.g. Vai 1997; Roveri *et al.* 1998), the age of fossils described herein can be included in the time interval between 5.35 and 5.33 Ma.

### 3. MATERIALS AND METHODS

Otoliths are calcareous structures associated with the ear in teleost fishes that are considered to be involved in both auditory and vestibular functions (Popper and Fay 1993). There are three pairs of otoliths in the labyrinths of the



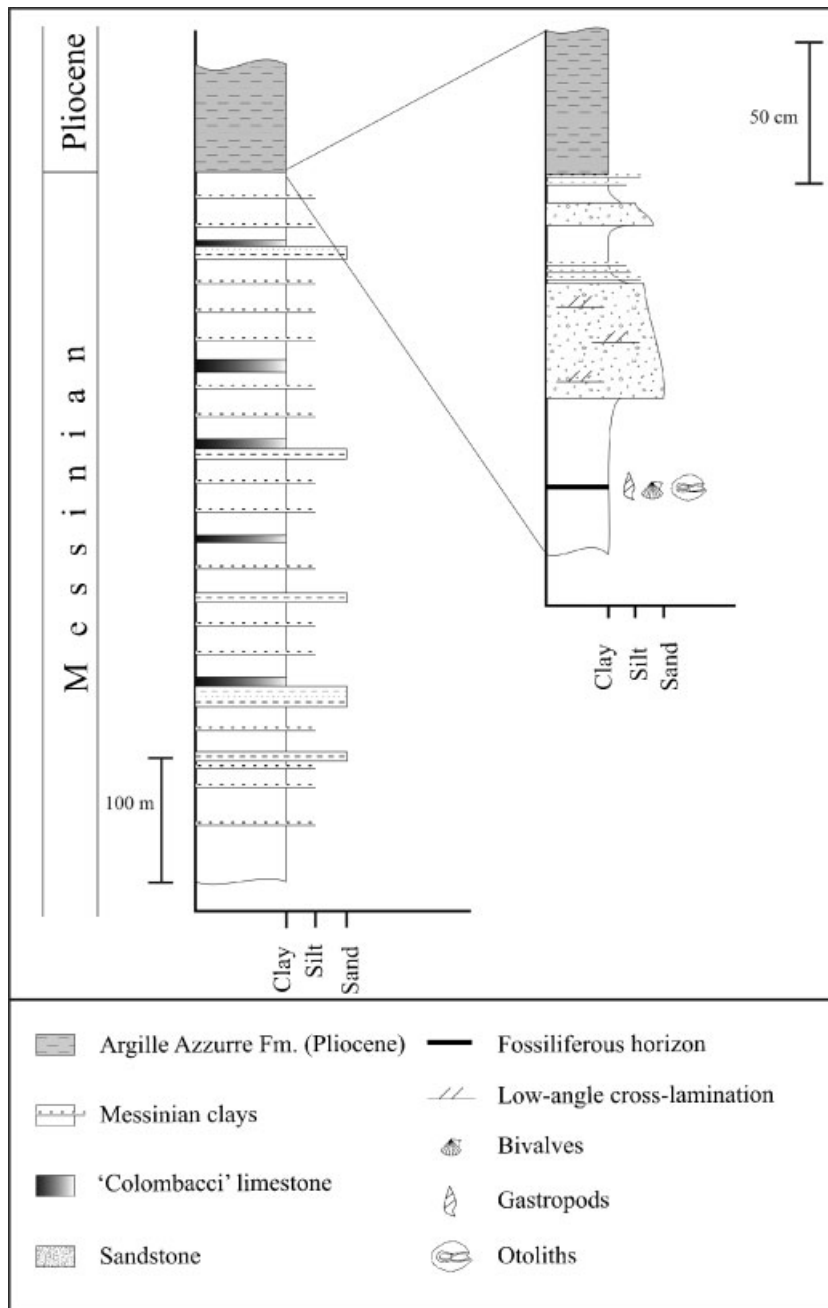


Figure 2. Columnar log of the Ca' Ciuccio section, Montecalvo in Foglia Syncline (modified from Borsetti *et al.* 1975), with an enlargement of the upper portion showing the position of the fossiliferous horizon containing fish otoliths (modified from Bellagamba 1978).

neurocranium of the teleost fishes. The saccular otolith, the Sagitta, is the largest in most fishes and, because of its broad interspecific morphological variation it is currently used in species-level taxonomic studies (e.g. Nafpaktitis and Paxton 1969; Trewavas 1977). The saccular otolith can be considered as a sort of 'black box' that records the age, as well as seasonal or annual events occurring during the lifecycle of fishes (Lecomte-Finiger 1999). Otoliths are very common fossils in a wide spectrum of marine sedimentary environments, representing the most common

way in which teleost fishes fossilize (Nolf 1995). For this reason, the study of fossil otoliths has largely contributed to our knowledge of the palaeontological history of fishes, providing the opportunity to infer the palaeobathymetry, palaeotemperatures and other environmental conditions in which assemblages originated (Nolf 1995). The taxonomical identification of fossil otoliths is based on comparative studies with the sagittae of the closest recent relatives (Nolf 1985).

The presence of otoliths in a fossiliferous layer of the Ca' Ciuccio section, in the Montecalvo in Foglia Syncline, was first reported by Bellagamba (1978). In the course of a project on the analysis of the macropalaeontological record of Messinian post-evaporitic deposits of Italy the entire section has been re-examined, including the productive layer described by Bellagamba (1978). The otoliths were extracted from a 200 kg sample after processing with hydrogen peroxide, drying and sieving (smallest screen 0.5 mm). These are well preserved and fine structures necessary for taxonomic diagnosis are usually clearly discernible. Because of the good preservation of the fish otoliths, we conclude that the fossil assemblage from the Colombacci Formation described herein reflects autochthonous embedding, thereby excluding the possibilities of reworking from older rocks and contamination from younger deposits. This is also supported by the mollusc shell preservation and by the mutual occurrence of juvenile and adult ostracod valves.

All the studied otoliths are sagittae. The morphological terminology followed is that of Nolf (1985). Measurements of the otoliths belonging to the family Sciaenidae follow the method proposed by Schwarzhans (1993). All the described material is deposited in the Dipartimento di Scienze della Terra, Università di Pisa.

#### 4. SYSTEMATIC DESCRIPTIONS

Subdivision Teleostei *sensu* Patterson and Rosen, 1977

Order Myctophiformes Regan, 1911

Family Myctophidae Gill, 1893

*Diaphus* sp.

Figure 3A

*Material.* 2 specimens

*Measurements.* Ratio length/height (L/H) = 1.14–1.21.

*Description.* The otoliths are almost quadrangular in outline. The ventral rim is moderately curved and bears 5–7 irregularly disposed obtuse spines. The posterior rim is nearly vertically oriented. The dorsal rim is gently curved but slightly truncated in correspondence to the posterodorsal angle. The rostrum is more prominent than the antirostrum and both are separated by a poorly incised excissura. The shallow dorsal area is moderately developed. The inner face is flat. The outer face is smoothly convex.

*Remarks.* The overall morphology of the specimens strongly supports their placement within the genus *Diaphus* (see Brzobohaty and Nolf 1995, 2000). More precisely, the nearly vertical posterior rim and the general structure of the rostrum, antirostrum and excissura are shared with those of the group of species composed by *Diaphus debilis* (Koken), *Diaphus kokeni* (Prochazka) and *Diaphus taaningi* Norman (see Nolf 1977; Steurbaut 1979; Brzobohaty and Nolf 2000). Among these taxa, the otoliths reported herein are the nearest to those of *D. taaningi*, from which they slightly differ in having a much more developed rostrum.

Order Perciformes *sensu* Johnson and Patterson, 1993

Family Sciaenidae Cuvier, 1829

“*Sciaenidarum*” sp. nov.

Figure 3C-I

*Material.* 230 specimens

*Measurements.* L/H = 1.55–1.70; L/T = 2.80–3.25; H/T = 1.84–2.03; cl/ol = 1.07–1.50; ol/oh = 1.36–1.66; cci (x/y) = 3–5.75.

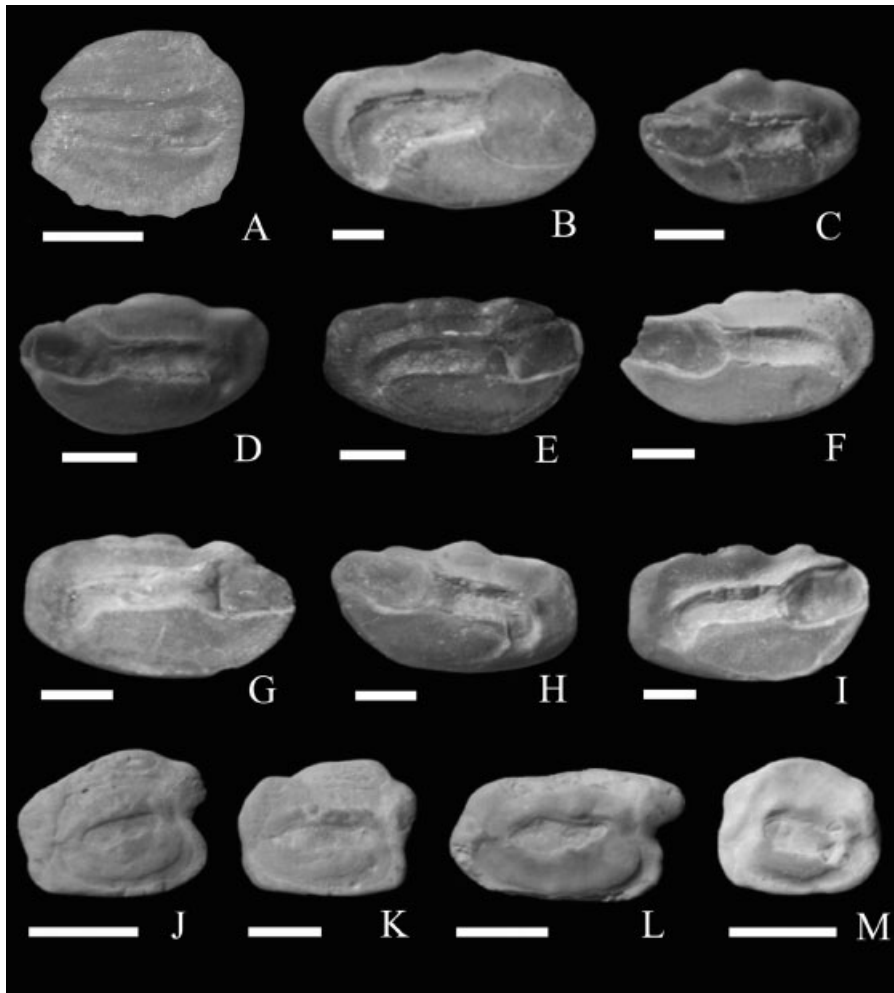


Figure 3. Fish otoliths from the Colombacci Formation, Ca' Ciuccio section, Montecalvo in Foglia Syncline. A: *Diaphus* sp., B: *Umbrina* sp., C–I: different growth stages of *Sciaenidarum* sp. nov., J: *Gobius* aff. *truncatus* Schwarzahans, 1979, K: *Gobius* sp., L: *Gobiidarum* aff. *weileri* Bauza Rullan, 1955, M: Gobiidae indet. Scale bars 1 mm.

**Description.** The otoliths are moderately elongate and moderately thick. The outer surface is generally convex whereas the inner surface is flat. The ventral margin is gently curved and rounded. The dorsal rim is irregular, with a sharp posterodorsal angle. The anterior tip is slightly rounded and progressively narrow, often terminating in a distinct and well-recognisable rostrum. A small excissura can be observed in selected specimens. The posterior rim is slightly rounded to angular. The ostium is short, narrow and ovoid, with a slightly concave and sometimes irregularly sculptured surface; the midventral notch is slightly marked and the postostial lobe usually present in fossil and recent sciaenid otoliths is absent. A small precaudal depression is often present. The precaudal joint is vertical to slightly oblique. The cauda is moderately elongate and clearly incised; it is rather wide and extends close to the posteroventral margin of the otolith. The downturned portion of the cauda is short and very slightly bent. The posterior end of the cauda is poorly distinct. The dorsal depression is large and extends parallel to the cauda towards its posterior end. A ventral furrow is also absent in certain specimens.

**Remarks.** The overall morphology of the otoliths justifies their placement in the family Sciaenidae, among which they show an unusual combination of plesiomorphic features such as the short, narrow and ovoid (with a slightly marked midventral notch and devoid of a postostial lobe) ostium with an often differentiated rostrum and excissura



ostii, and the slightly bent downward cauda. They show some general resemblance with the otoliths of the living species *Seriphus politus* Ayres and *Cynoscion striatus* (Cuvier) (see Schwarzhans 1993) and the fossil *Sciaenidarum teutonicus* Weiler (see Huyghebaert and Nolf 1979) from which they differ by their overall morphology, and presence of a shorter and narrower ostium, less developed cauda, and larger dorsal depression. The primitive nature of the otolith morphology is also evidenced by their remarkable similarity with those characteristic of the juvenile stages of several other sciaenids (e.g. *Sciaenops ocellatus* Linnaeus; Nolf and Aguilera 1998). Although the specimens examined show a unique combination of features and may belong to a new, not yet described species, we prefer to postpone the formal description of a new taxon awaiting better-preserved material.

*Umbrina* sp.  
Figure 3B

*Material.* 3 specimens

*Measurements.* L/H = 1.5–1.7; L/T = 3–3.4; H/T = 1.9–2; cl/ol = 1.06–1.07; ol/oh = 1.10–1.11; cci (x/y) = 0.97–1.02.

*Description.* The otoliths are moderately elongate, more or less oval in outline. The ventral rim is regularly convex. The dorsal rim is irregular or crenulate, and slightly concave in its posterior sector. The posterior rim is curved. The inner face is smoothly convex. The outer face is flat or irregularly convex. The sulcus occupies a relevant portion of the inner face of the otolith. The ostium is strongly enlarged, characterized by a scarcely developed postostial lobe. The midventral notch appears to be absent. The surface of the ostium is smooth or slightly sculptured. The precaudal depression is usually well recognisable. The cauda is remarkably large and moderately deep. The downturned portion of the cauda is shorter than the horizontal one. The dorsal area is moderately depressed.

*Remarks.* The overall morphology of the specimens suggests their alignment with the so-called *Sciaena* morphological pattern defined by Chao (1978), and in particular with those genera belonging to the tribe Sciaenini. This tribe (see Trewavas 1977) includes the extant species of the genera *Sciaena* and *Umbrina* plus a number of fossil taxa, most of which were referred by Schwarzhans (1993) to the genus *Trewasciaena*. A detailed comparative morphological and morphometrical analysis of the otoliths examined herein has revealed a marked resemblance with those of *Umbrina kokeni* (Schubert) from the Miocene of Paratethys, from which they differ by having a larger and wider cauda and for the absence of a prominent posterodorsal projection (see Schubert 1901; Nolf 1981; Schwarzhans 1993). Although the specimens show several autapomorphic features that support their placement in a new undescribed taxon, they are left unnamed within the genus *Umbrina*, awaiting a more complete series, in order to properly define their morphologic and ontogenetic variability (see Chaine 1938).

Family Gobiidae Bonaparte, 1832  
*Gobius* aff. *truncatus* Schwarzhans, 1979  
Figure 3J

*Material.* 7 specimens

*Measurements.* L/H = 1.14–1.33.

*Description.* The otoliths are moderately thick, roughly subrectangular with a well-developed posterodorsal corner. The dorsal rim is irregular, asymmetrically convex. The anterior and posterior margins are slightly concave at their midheights. Both the inner and outer faces are convex. The outer surface lacks any ornamentation. The sulcus is relatively narrow, irregular or roughly ovoid in outline. The area depressa is often well developed. The ventral furrow is deeply incised.

*Remarks.* The overall morphology of the specimens examined strongly supports their inclusion within the genus *Gobius*. The placement at the species level is rather difficult, mostly because of the wide infraspecific variability and scarcity of autapomorphic features that characterize the otoliths of the species of this genus, and more generally of the family Gobiidae (see e.g. Nolf 1985; Nolf and Cappetta 1989). However, the otoliths are very close to those of

the extinct species *Gobius truncatus* Schwarzahns, known from the Mediterranean Neogene (Schwarzahns 1979, 1986; Nolf and Cappetta 1989; Nolf and Cavallo 1995; Nolf *et al.* 1998), from which they differ in their shorter and more regular outline of the sulcus.

*Gobius* sp.  
Figure 3K

*Material.* 12 specimens

*Measurements.* L/H = 1.06–1.18.

*Description.* The otoliths are subrectangular in outline. The dorsal rim is irregular, characterized by a central convex apophysis. The ventral rim is flat to slightly convex. The posterior rim has a small concavity at its midheight. The outer face is convex. The sulcus is relatively narrow. The area depressa is moderately large. The ventral furrow is well developed.

*Remarks.* The specimens are close to those of the species *Gobius niger* Linnaeus and *Gobius multipinnatus* (Von Meyer) and for this reason they are assigned to the genus *Gobius*; however, they differ from these species in their more regular outline and narrower sulcus.

“*Gobiidarum*” aff. *weileri* Bauza Rulan, 1955  
Figure 3L

*Material.* 12 specimens

*Measurements.* L/H = 1.50–1.53.

*Description.* The specimens are elongate, dorsoventrally depressed and characterized by a pronounced posterodorsal corner. The dorsal rim is irregularly convex. A delicate notch can be observed in the midheight of the anterior and posterior rims. The sulcus is relatively narrow. The ostium is slightly wider than the cauda.

*Remarks.* The general morphology of the otoliths is consistent with that of the material referred to *Gobiidarum weileri* (see Schwarzahns 1986; Nolf and Cappetta 1989; Nolf and Cavallo 1995; Nolf and Girone 2000). However, they differ from those of this taxon for their narrow and elongate rather than short and ovoid sulcus.

Gobiidae indet.  
Figure 3M

*Material.* A single juvenile specimen

*Measurements.* L/H = 1.13.

*Description.* The specimen is roughly rectangular, with rounded corners. The dorsal rim is irregularly convex. The ventral and anterior rims are convex, whereas the posterior rim has a concavity in its midheight. The outer face is convex. The sulcus is relatively wide, nearly ovoid in outline. The area depressa is rather large. The ventral furrow is well developed.

*Remarks.* The otolith is a clear representative of the family Gobiidae. Unfortunately, the juvenile nature of the material available does not allow a more precise taxonomic placement.

## 5. PALAEOENVIRONMENT

It is not possible to assume that the composition of a fossil otolith assemblage faithfully reflects the structure of the original fauna. The otoliths of some families (e.g. Gasterosteiformes, Scombroidei, Tetraodontiformes) do not fossilise well or at all, and taphonomic processes may otherwise alter the assemblage. More generally speaking, the diversity of a fossil biotic community must be regarded as an underestimate, even when dealing with organisms with a hard skeleton (e.g. Nebelsick 1996), and its interpretative analysis must be subject to several tests (e.g.

Bennington and Bambach 1996). Although the fossil record preserves neither entire original communities nor original proportions of different ecological categories, it can certainly reveal evidences of taxonomic composition, relative abundance, as well as of other synecologic features of ancient communities. The study of the taxonomic composition of a fossil assemblage can provide several well-documented information concerning the physical and chemical conditions of a determinate palaeoenvironment. Moreover, as evidenced by recent studies (see e.g. Nehm and Geary 1994; Kohn and Arua 1999), for later Cenozoic and Quaternary periods, the ecological knowledge of extant relatives can provide a large amount of data which are independent from those derived directly from the fossils and their matrices, but can be combined to better define the palaeobiology of extinct species and their role in ancient communities and palaeoenvironments.

The otolith assemblage examined herein displays a low diversity showing a marked oligotypic character. The taxonomic analysis of the assemblage suggests that at least seven taxa were present, representing three families. The most abundant fish family was the Sciaenidae, representing 88% of the 267 otoliths examined. Nearly all the sciaenids were represented by *Sciaenidarum* sp. nov. (87% of the whole assemblage). The Gobiidae comprised approximately 11% of individuals but was the most diverse family with four taxa. Myctophid otoliths were very rare, represented by two specimens (1% of the whole assemblage).

Fossil and Recent relatives of the taxa recognized in the assemblage are typical for marine-euryhaline (Sciaenidae, Gobiidae) and—stenohaline (Myctophidae) environments. Fishes of the family Sciaenidae (drums or croakers) commonly occur in temperate to tropical coastal waters and estuaries worldwide, where they are particularly abundant at the mouth of continental rivers (Sasaki 1989). Most sciaenids are large demersal carnivorous (piscivores, epipsammivores, infaunal feeders) species with a key role in estuarine ecosystems. In a recent categorisation of major fish groups utilising brackish environments (Whitfield 1999), these fishes have been placed in the marine stragglers guild, which includes marine species where only a small part of the overall population makes use of brackish biotopes. Gobies (family Gobiidae) are small benthic fishes that are very abundant in coastal marine and brackish environments, where they are cryptic bottom dwelling carnivores. The speciose group of euryhaline gobies consists of species of marine origin that usually reside in brackish environments as juveniles and/or adults but have a marine larval phase (estuarine migrants *sensu* Whitfield 1999). Myctophids (lanternfishes) are mesopelagic fishes that usually occur at depths between 300 and 1200 m, undergoing diurnal migration to the surface layers (Nafpaktitis *et al.* 1977). Lanternfishes are characterized by an opportunistic feeding behaviour and represent the most consumed preys of numerous piscivorous fishes. Lanternfishes of the genus *Diaphus* are small- to medium-sized fishes distributed in tropical, subtropical and temperate waters of all the oceans (Nafpaktitis *et al.* 1977). Several species of this genus are pseudoceanic (land-associated) and may appear irregularly in areas close to deltas or estuaries (marine adventitious visitors *sensu* Mathieson *et al.* 2000).

The fish assemblage documented herein points to a coastal shallow marine environment strongly influenced by freshwaters of continental origin. The data deriving from the otolith assemblage are consistent with the sedimentological interpretation of Bassetti (2000) who suggested a proximal to distal fan-delta front depositional environment affected by fluvial catastrophic floods. As reported above, the ostracod fauna is dominated by *Cyprideis* valves and articulated carapaces that are indicative of a delta or marine coastal environment (see Athersuch *et al.* 1989). Ostracods of the genus *Cyprideis* are generally found in NaCl-dominant (marine-derived) waters (Anadon *et al.* 1986), but they can also inhabit environments characterized by aberrant alkaline or hypersaline waters (Van Harten 1990). As far as concerns the mollusc fauna, it appears dominated by euryhaline taxa (hydrobiids, limnocardids) most of which are indicative of an estuarine or intertidal environment (e.g. Asmus and Asmus 1985; Bandel and Kowalke 1999; Barnes 1999) probably characterized by soft bottom and turbid waters. In conclusion, the geological and palaeontological data concur to indicate that the Messinian post-evaporitic sediments of the Montecalvo in Foglia Syncline record, at least in their upper portion, the final marine depositional zone of a flood-dominated fluvio-deltaic system (see Mutti *et al.* 1996).

The most abundant fish taxon, *Sciaenidarum* sp. nov., probably was the most important member of the original fauna. Aquatic environments affected by fluctuations of the salinity and/or other physical and chemical factors are typically characterized by a low ichthyofaunal diversity but high abundance of individual taxa, most of which

exhibit wide tolerance limits to the unstable conditions found within these systems (e.g. Day and Grindley 1981; Whitfield 1993; 1999). The synergistic effect of many interacting physical factors directly and indirectly determines the structure of fish populations in these environments (see Blaber 1997). Low ichthyofaunal diversity and high abundance of individual taxa are mainly associated to systems characterized by fluctuating salinity and highly turbid waters (e.g. Cyrus and Blaber 1987; Whitfield 1999). Turbidity is caused by suspended silt and detritus that reduce light penetration; when large quantities are deposited as a result of river flooding, they smother submerged plants and algae, thus reducing habitat diversity. The low diversity of turbid systems may therefore be linked to the indirect effect of silt deposition and sediment disturbance of aquatic plants and their associated invertebrates, rather than turbidity (see Day *et al.* 1981). For this reason, herbivorous fishes are uncommon in such systems. The sharp dominance of a single taxon is probably related to the strict dependence of fishes on the detrital food web, which represents the major supply of energy in these systems (Naiman and Sibert 1979), conferring ecological stability by extending the availability of fixed biomass. Abundant detritus is available in these systems throughout the year, whereas plankton biomass varies both spatially and seasonally. The detritus consists of a mixture of plant debris, amorphous organic matter and autotrophic and heterotrophic bacteria (see Bowen 1976) representing an important food source for many invertebrates which are in turn consumed by carnivorous fishes (Whitfield 1989). The abundance of available detritus and benthic invertebrates (molluscs) is the primary reason why fishes are attracted to these systems.

The asymmetric structure of the fish assemblage documented herein can be explained in terms of ecological response to the fluctuating environmental parameters and adaptation to the available food resources. From an ecological-energetic point of view, the low diversity and high abundance of an individual taxon reflect a very simplified food web, with the most successful species in the system, *Sciaenidarum* sp. nov., being that remarkably euryecious and with the broadest niche.

Although the assemblage is dominated by euryhaline fishes (99% of individuals), the occurrence of representatives of the marine stenohaline family Myctophidae, even if very rare (1% of individuals), is highly significant from a palaeoenvironmental and palaeogeographical point of view. The presence of the mesopelagic lanternfishes in a coastal marine environment influenced by fluvial outflow was probably related to their nightly migration to the surface over the continental shelf, or, alternatively, they were brought into this assemblage by piscivorous predators foraging in oceanic waters. Thus, their presence in the assemblage described herein does not modify the interpretation of the palaeoenvironmental conditions of the depositional setting. Nevertheless, they provide unquestionable information about the presence of open marine conditions very close to the depositional environment testified by the assemblage examined.

## 6. DISCUSSION

The palaeoenvironmental significance of the Messinian post-evaporitic deposits of the Apennine foredeep has been largely debated since the pioneering studies performed by Selli, who in the extensive monograph 'Il bacino del Metauro', divided for the first time the post-evaporitic succession into two lithostratigraphic units, the Terreni di Tetto and Colombacci formations, considering the presence or absence of limestone beds (Selli 1954). The Colombacci formation was named after the name used by the miners to designate the limestone layers that crop out in Messinian post-evaporitic successions in the Marche and Romagna regions. The increased interest around the Messinian Salinity Crisis event in the 1970s opened a season of multidisciplinary studies on the post-evaporitic deposits of the entire Mediterranean area, including those of the Apennine foredeep. However, despite the potentially high stratigraphic resolution offered by the Apenninic post-evaporitic sequences, only a few studies were realised, mostly focused on the understanding of the palaeoenvironmental significance of the deposits of the Colombacci Formation (e.g. Casati *et al.* 1976; Colalongo *et al.* 1976; Savelli and Wezel 1978) and of the events occurring at the Mio-Pliocene boundary. The renewed interest around the Messinian question in the last few years has led to the re-examination of the post-evaporitic successions of the Apennines which have been reinterpreted in detail from a physical-stratigraphic (Bassetti *et al.* 1994; Roveri *et al.* 1998, 2001, 2003; Bassetti 2000; Manzi *et al.*

2005), palaeomagnetic (Krijgsman *et al.* 1999a), and geochemical (Bassetti *et al.* 2004) point of view. These studies have greatly improved our knowledge of the Messinian stratigraphy and palaeogeography of this area of the Apennines providing innovative ideas about the mechanism of triggering and progression of the Salinity Crisis event in the whole Mediterranean. Both the litho- and magneto-stratigraphic attempts to quantitatively estimate the duration of the post-evaporitic phase recognized the existence of eight sedimentary cycles probably controlled by astronomical precession (Roveri *et al.* 1998; Krijgsman *et al.* 1999a). The possibility of an orbital (precessional) forcing for depositional cyclicity during the post-evaporitic phase of the Messinian is also suggested by the occurrence, in other areas of the Mediterranean, of sequences originated in the same time interval and characterized by a similar vertical organisation (see e.g. Ghibaudo *et al.* 1985; Krijgsman *et al.* 2001). The cyclic nature of the post-evaporitic sequences of the Apennines has also been recorded by palynological studies which recognized eight climatic oscillations expressed by vegetational changes (Bertini 1994, 2002). The Colombacci Formation consists of three sedimentary cycles that are well recognisable in the satellite basins of the Adriatic side of the Apennines. In this setting, the three 'Colombacci' horizons (each characterized by several limestone layers; see e.g. Bassetti *et al.* 2004) intercalated in the clastic sequence have been interpreted as the result of reduced terrigenous input to the basin during base-level maxima (Roveri *et al.* 1998; Bassetti *et al.* 2004). Although the chronological and stratigraphic framework of the Colombacci Formation has been defined in detail, there is still controversy about the chemical characteristics of the depositional environment. The interpretation of the composition of the water body during the deposition of the Colombacci Formation has been largely debated and several studies of isotope geochemistry, clay mineralogy and palaeontology (foraminiferans, ostracods, molluscs) have been produced, resulting in a rather confused scenario of fresh, brackish, oligohaline or mesohaline waters. The geochemical measurements have been carried out in marls and limestone from several localities where the Colombacci Formation is exposed (Casati *et al.* 1976; Molenaar and De Feyter 1985; Bassetti *et al.* 2004). The isotope composition (carbon and oxygen) of the two lower 'Colombacci' horizons is indicative of a marine-derived water characterized by a strong meteoric dilution, whereas the upper (third) 'Colombacci' horizon originated from a 'quasi-marine' water salinity (Bassetti *et al.* 2004). The isotope composition of the Colombacci Formation is consistent with those measured from coeval deposits of other regions of the Mediterranean Basin (Longinelli 1979; Rouchy *et al.* 2001). However, as pointed out by Molenaar and De Feyter (1985) and Bassetti *et al.* (2004), the isotope values are only relevant in a comparative sense and cannot be used to estimate absolute palaeosalinities. The strontium isotope composition of the 'Colombacci' carbonates (Bassetti *et al.* 2004) is in the range of the values measured from other 'Lago-mare' deposits (e.g. McCulloch and De Dekker 1989; Müller and Mueller 1991; Fortuin *et al.* 1995), suggesting an origin from diluted seawater by means of continental run-off. The interpretation of strontium isotopes is rather problematic because although their values do not preserve a normal seawater isotopic signature, they provide no evidence indicating that during this period the Mediterranean was isolated from the global ocean network (Flecker *et al.* 2002; Bassetti *et al.* 2004). The isotopic compositions of 'Lago-mare' deposits of the Colombacci Formation concur to indicate an enhanced meteoric inflow in the depositional environment. An increased run-off related to a humid phase (Griffin 2002) has also been suggested by the occurrence of floristic taxa (e.g. *Sciadopitys*; *Taxodium*) typical of moist forests (Bertolani Marchetti and Marzi 1988; Bertini 1994), and by the architecture of the sequence, which is characterized by the cyclic presence of coarse-grained terrigenous sediments deposited by flood-related mass flows (Bassetti 2000; Bassetti *et al.* 2004). The analysis of clay minerals suggested that their deposition occurred in an alkaline environment flooded by marine waters and characterized by a constant input of continental ions (Colalongo *et al.* 1976). An alkaline environment subject to salinity fluctuations was also hypothesized by other authors (Molenaar and De Feyter 1985). In summary, both geochemical and mineralogical analyses indicate a depositional environment with fluctuating salinities related to a massive supply of continental waters in the basin. Although the broad contribution of meteoric waters to the salinity fluctuations in the depositional environment of the Colombacci Formation has been demonstrated by means of different approaches, the real chemical nature (chemical pathway) of the original water body remains dubious. The water dilution, even considering the highly humid climate, was probably enhanced by the palaeophysiography of the basin which strongly influenced its hydrological balance. As pointed out by Roveri *et al.* (1998) the intricate tectonic movements which affected this region during the Late Miocene probably produced emergent or submerged sills,



which created small nearly independent basins each characterized by their own water circulation and chemical composition (see also Bassetti *et al.* 2004). The contribution of the humid phase to the water dilution of these satellite basins was clearly related to their relative position with respect to the main Mediterranean water body. Several geological evidences suggest that the Montecalvo in Foglia Basin was relatively distant from the emerging Apenninic chain and the fossils documented herein point to a marine environment influenced by continental outflow. Considering the complex palaeogeographic scenario of this area and the variable influences of the humidity and continental ions input to the water composition of the basins, it is reasonable to conclude that the structure of their benthic fauna (molluscs, ostracods, benthic foraminiferans) reflected their physical and chemical structure, thereby representing only a local indicator of palaeoenvironmental conditions. In this setting, it is possible to observe a trend of progressive increase of the oligo- meso-haline character of the fossil assemblages moving towards the inner and marginal basins (*sensu* Bassetti *et al.* 2004) of the Adriatic foredeep, as suggested by the ostracod faunas of the Giaggiolo-Cella (Colalongo *et al.* 1976) and Sapigno (Bassetti *et al.* 2003; Gliozzi and Grossi 2004) synclines, which are characterized by rich and diverse assemblages of taxa of Paratethyan affinity. Most of these taxa appeared in the Sarmatian of Central Paratethys (see Gliozzi 1999) and were probably adapted to the anomalous (marine) alkaline (Piller and Harzhauser 2005; Carnevale *et al.* 2006a) conditions that occurred in the Paratethyan realm since that period. The migration of Paratethyan ostracods in the Mediterranean probably preceded the post-evaporitic phase of the Messinian, since molluscs (Cipollari *et al.* 1999) and dinocysts (Kontopoulos *et al.* 1997) of Paratethyan affinity were already present in this area, at least during the first part of the Messinian. However, the dramatic radiation of the biota of Paratethyan affinity in the Mediterranean occurred later due to the combined effect of the wide development of marginal and satellite basins in coincidence with one of the strongest phase of geodynamic activity of the Neogene, with a major reorganisation of the African–Eurasian convergent plate boundary zone (see Meulenkam and Sissingh 2003), and of the humid conditions related to the northern displacement of the monsoonal system (Griffin 2002; Cosentino *et al.* 2005). The widespread development of marginal basins and the humid phase related to the onset of a monsoonal regime, created, in the entire Mediterranean region, optimal conditions for the rapid diffusion and demographic explosion of the taxa of Paratethyan affinity. The formation of nearly independent basins characterized by marine-derived waters with continuous salinity fluctuations and a strong continental input was superimposed on to a general transgressive trend (e.g. Bassetti *et al.* 2004), resulting in a progressive filling of inner basins and in a contemporaneous increased exposition of the external basins (e.g. Montecalvo in Foglia) to the influences of the main Mediterranean water body, as demonstrated by the fish remains described herein. The integrated palaeoecological analysis of the entire fossil assemblage (benthic foraminiferans, ostracods, molluscs, fishes) highlights the key role of fish remains as palaeoenvironmental indicators. Because of their mobility and frequent migratory behaviour, marine fishes can co-occur with fresh- or brackish-water organisms, and, at the same time, provide useful information for the interpretation of the palaeoenvironmental conditions of the areas surrounding those testified by the resident biota (Carnevale *et al.* 2006b). As discussed above, the assemblage consists of marine euryhaline fishes which are unable to complete their life cycle without normal marine conditions. The physiological homeostasis of these fishes in their ecosystem is determined by a number of complex biochemical and metabolic pathways that are very sensitive to permanent changes in water chemistry and ion balance (see Evans 1993). Moreover, the possibility of a physiological adaptation to the oligo- or meso-haline conditions traditionally postulated for the Mediterranean environment during the ‘Lago-mare’ phase must be completely excluded because of the presence in the assemblage of unquestionable marine stenohaline organisms such as the lanternfishes. The lanternfishes belong to a well-defined and diversified clade, the Myctophiformes, which exclusively inhabited the marine realm since their appearance in the Cretaceous (e.g. Goody 1969).

The results presented herein greatly reinforce those derived from the study of fish remains from the coeval deposits of Cava Serredi, in Tuscany, where nine fossiliferous horizons characterized by rather diversified fish assemblages have been recently investigated (Carnevale *et al.* 2006b). The analysis of fossil fish remains clearly indicates that a new palaeoenvironmental interpretation of the Messinian ‘Lago-mare’ event is necessary, and provides an unquestionable demonstration that the re-establishment of normal marine conditions in the Mediterranean preceded the Mio-Pliocene boundary. The possibility of an intra-Messinian marine reflooding has

been proposed by several authors (e.g. Butler *et al.* 1995; Riding *et al.* 1998, 1999; Pedley and Maniscalco 1999; Steffahn and Michalzik 2000a,b; Griffin 2002; Aguirre and Sánchez-Almazo 2004), and evidences of at least periodical marine influxes are rather common in the 'Lago-mare' sedimentary record (e.g. Iaccarino and Bossio 1999; Iaccarino *et al.* 1999; Rouchy *et al.* 2001; Crescenti *et al.* 2002; Clauzon *et al.* 2005). However, the hypothesis of pre-Pliocene reflooding has never been commonly accepted, as the proposed evidence has been considered weak or inadequate (e.g. Fortuin *et al.* 2000; Fortuin and Krijgsman 2003). Fossil fish remains indicate that the rapid and catastrophic Pliocene inundation from the Atlantic was preceded by a progressive transgression that re-established the marine biotic communities. Our findings are in agreement with the scenario postulated by Keogh and Butler (1999) who suggested that during the 'Lago-mare' phase the base-level of the Mediterranean was within the range of the world's oceans even though the water body probably had a different but internally homogeneous isotopic composition.

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