The end of the Lago-Mare time in the SE Valdelsa Basin (Central Italy): interference between local tectonism and regional sea-level rise

Laura ABBAZZI
Dipartimento di Scienze della Terra, Università di Firenze,
via G. La Pira 4, I-50121 Firenze (Italy)

Marco BENVENUTI
Dipartimento di Scienze della Terra, Università di Firenze,
and Istituto di Geoscienze e Georisorse, C.N.R,
c/o Dipartimento di Scienze della Terra, Università di Firenze,
via G. La Pira 4, I-50121 Firenze (Italy)

Maria Elena CECI
Dipartimento di Scienze Geologiche, Università di Roma Tre,
Largo San Leonardo Murialdo 1, I-00146 Roma (Italy)

Daniela ESU
Dipartimento di Scienze della Terra, Università di Roma "La Sapienza",
Piazzale Aldo Moro 5, I-00185 Roma (Italy)

Costanza FARANDA
Dipartimento di Scienze Geologiche, Università di Roma Tre,
Largo San Leonardo Murialdo 1, I-00146 Roma (Italy)

Lorenzo ROOK
Francesca TANGOCCI
Dipartimento di Scienze della Terra, Università di Firenze,
via G. La Pira 4, I-50121 Firenze (Italy)

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ABSTRACT

A multi-disciplinary study has been carried out on a Late Neogene succession exposed in the SE portion of the Valdelsa Basin (Strolla Creek, Central Italy). The succession consists of upper Tortonian-Messinian sediments, unconformably overlain by uppermost Messinian-Pliocene deposits, accumulated in alluvial, lacustrine and marine environments. Previous studies on this succession hypothesized a sudden marine flooding of the upper Messinian Lago-Mare realm in the earliest Zanclean in apparent agreement with the Mio-Pliocene transition recorded elsewhere in the Mediterrranean Basin. Data from this study suggest a more complex stratigraphy recording a local depositional evolution possibly driven by interference between uplift, relief denudation and eustacy. The sediments encompassing the Mio-Pliocene transition have been included into the Borro Strolla synthem, furtherly subdivided into three sub-synthems. The Borro Strolla synthem has been dated as uppermost Messinian-earliest Zanclean based on the integration of physical stratigraphy, facies analysis and biochronology of non-marine fossil assemblages in part documented for the first time. The occurrence in the lower Borro Strolla Synthem of the gerbil *Debruijnimys* sp. and the murid *Stephanomys* aff. *S. donnezani* (Depéret, 1890) with Pliocene affinity represents the most important novelty in the composition of a mammal fauna otherwise similar to other Italian late Messinian sites. The co-occurrence of terrestrial molluscs from the same sediments gives further biochronologic constrains supporting the calibration of the Borro Strolla synthem to the latest Messinian-earliest Zanclean. The Borro Strolla stratigraphic section then is discussed in the framework of local to regional events which marked the transition from the Messinian to Pliocene.

KEY WORDS
Late Messinian,
early Zanclean,
Lago-Mare,
non-marine fossil assemblages,
facies analysis,
Valdelsa Basin,
Central Italy.

RÉSUMÉ

La fin du Lago-Mare dans la partie SE du bassin de Valdelsa (Italie centrale) entre tectonique locale et remontée du niveau marin régional.

Une étude multidisciplinaire a été réalisée sur les dépôts néogènes (alluviaux, lacustres et marins) du sud-est du bassin de Valdelsa (Italie centrale). Ces sédiments, datés du Tortonien supérieur-Messinien inférieur, sont surmontés, en discontinuité, par des sédiments du Messinien supérieur-Pliocène. Cette étude suggère que ces dépôts résultent de l'interaction de phénomènes locaux tels que la surrection et la dénudation des reliefs ainsi que l'eustasie plutôt que du changement drastique dû à la transgression du Zancléen inférieur sur le Lago-Mare, enregistrée en Méditerranée. Ces sédiments, déposés à la transition du Mio-Pliocène correspondent au synthème de Borro Strolla (qui comprend trois sub-synthèmes). Il a été daté Messinien supérieur-Zancléen inférieur grâce à l'analyses de coupes, d'études sédimentologiques (étude de faciès), et de la biochronologie établie sur les associations de faunes non-marines, montrant elles-mêmes de nouveaux éléments. La découverte, dans la partie inférieure du synthème de Borro Strolla, du gerbillidé *Debruijnimys* sp. et du muridé *Stephanomys* aff. *S. donnezani* (Depéret, 1890) à affinité pliocène est un élément nouveau dans cette association faunistique qui correspond par ailleurs à celle observée en Italie dans les sites du Messinien supérieur. D'autre part, la présence de mollusques terrestres dans ces mêmes sédiments permet aussi d'attribuer le synthème de Borro Strolla au Messinien supérieur-Zancléen inférieur. Les attributions stratigraphiques établies pour le synthème de Borro Strolla sont corrélées aux événements locaux et régionaux enregistrés à la limite Messinien-Pliocène.

MOTS CLÉS
Messinien supérieur,
Zancléen inférieur,
Lago-Mare,
associations fossiles non-marines,
analyses de faciès,
Bassin de Valdelsa,
Italie centrale.

INTRODUCTION

The period encompassing the latest Miocene-earliest Pliocene was marked in the Mediterranean region by a well-known sequence of dramatic palaeoenvironmental changes though not unanimously interpreted in terms of sedimentary successions, including thick evaporites, chronology and forcing factors (see recent review in Rouchy & Caruso 2006). A late Messinian catastrophic sea-level fall affecting the whole Mediterranean Basin is generally accepted following the seminal papers on the Messinian Salinity Crisis (MSC) (Hsü *et al.* 1973, 1975, 1978; Cita *et al.* 1978). Nevertheless, in the last 15 years such a dramatic sea-level fall has been considered to have occurred either diachronically or synchronously in marginal and deeper areas, in a time-span ranging from about 7 to 5.6 Ma (see review of alternative time and facies models for the MSC in Rouchy & Caruso 2006 and Manzi *et al.* 2007). At the end of the Messinian, between 5.59 and 5.33 Ma (Krijgsman *et al.* 1999), a dilution of a hyperaline Mediterranean Basin determined the formation of a low-salinity sea known as the "Lago-Mare" realm (Ruggieri 1962, 1967a, b). The sedimentary successions referred to this latest Messinian setting, widely recognized in many circum-mediterranean basins and including resedimented and primary evaporites and clastic deposits, bear a typical palaeontological signature characterized by molluscs, ostracods and dynocysts with a marked Paratethyan affinity (for a review see Orszag-Sperber 2006). This feature has fed a debate which is still in large part open, around the latest Messinian connections among the Paratethys, the Mediterranean and the Atlantic basins (Orszag-Sperber 2006). Finally, the restored connection between the Atlantic Ocean and the Mediterranean Basin, at the beginning of the Pliocene, determined the sudden replacement of the Lago-Mare realm with open and deep marine conditions. These events had a great impact on the structure and composition of the circum-mediterranean biotas forcing large-scale faunal exchanges, local extinction, palaeobiogeographic isolation, etc. (Benson 1976, 1984).

Such a sequence of events was mostly controlled by tectonically-driven sea-level changes, related to the temporary closure and re-opening of the Gibraltar Strait, and by high-frequency climatic fluctuations (Bertini 1994, 2006; Butler *et al.* 1995; Orszag-Sperber *et al.* 2000; Rouchy *et al.* 2001; Griffin 2002). The latter determined cyclothemic development of the Messinian successions exposed in the Mediterranean area. The active tectonic setting related to the late collision between the Africa and Europe plates, was also affecting at local scales the circumediterranean margins with consequent control on the depositional patterns in several Messinian basins (Boccaletti *et al.* 1990b). The basins developed on the western side of the Northern Apennines (Central Italy) bear the sedimentary record of these events outlining the interference between local tectonism and sea-level changes occurred in the late Messinian. Angular unconformities within the evaporite-bearing successions and resedimented evaporites, in fact, record the active uplift and erosion of the basin margins across and following to the Salinity Crisis (Testa & Lugli 2000). The Mio-Pliocene transition has been described in many Tuscan basins as stratigraphically concordant (Bossio *et al.* 1993) equating the local Lago-Mare replacement by normal marine condition to the sudden, catastrophic, refilling of the Mediterranean Basin. Nevertheless, locally this transition may be stratigraphically more complex hinting to interplay of eustacy and tectonism on the depositional dynamics.

This paper summarizes a case study in which a previously reported concordant contact between Lago-Mare and open marine sediments is only apparent. Specifically, data from integrated stratigraphic and palaeontological analyses carried out in the SE Valdelsa Basin (Strolla Creek area, central Tuscany), indicate complex stratigraphic relations among marine and non-marine deposits which escape the picture of the Mio-Pliocene transition recorded elsewhere in the Mediterranean area.

GEOLOGICAL SETTING OF THE VALDELSA BASIN

The study area is located in the southeastern end of the Valdelsa Basin (Fig. 1), a 25 km wide and 60 km long NW-SE trending depression, bounded by the Monte Pisano-Poggio del Comune ridge to the SW, and the Monte Albano-Monti del Chianti ridge to the NE and SE and filled with more than 2000 m thick Neogene and Quaternary sediments (Ghelardoni *et al.* 1968).

The substratum of these deposits (Fig. 1B) is composed on the SW of Late Paleozoic-Jurassic phyllites, quartzites, evaporites and carbonates (Adria basement and Tuscan units) thrusted by sandstones, limestones and claystones, Late Cretaceous-Paleogene in age (Ligurid units). Oligocene Macigno sandstones (Tuscan units) dominate on the NE side, whereas limestones and claystones of Ligurid units form the eastern and southeastern margins of the basin.

The tectonic origin of the Valdelsa Basin, as well as of the several basins west of the Northern Apennines, feeds a debate between supporters of "extensional" (Trevisan 1952; Sestini 1970; Martini & Sagri 1993; Carmignani *et al.* 1994; Elter & Sandrelli 1994) and "compressional" (Bernini *et al.* 1990; Boccaletti *et al.* 1990a, 1995; Boccaletti & Sani 1998; Bonini & Sani 2002) models. These basins (Fig. 1A), filled with upper Miocene-Pliocene fluvio-lacustrine and shallow-marine deposits (central basins *sensu* Martini & Sagri 1993) or exclusively with middle Pliocene-Pleistocene fluvio-lacustrine and fluvial deposits (peripheral basins *sensu* Martini & Sagri 1993) a few hundreds meters up to 2500 m thick, are, in fact, alternatively interpreted as grabens/half-grabens or thrust-top basins.

The basin-fill development during the Messinian was regulated by a major regional relief, the Mid Tuscan Ridge (Fig. 1A), representing a significant physiographic divide. Several basins developed on the east of this ridge, such as the Valdelsa Basin, did not experience evaporitic deposition during the Salinity Crisis maintaining fully terrestrial environments up to the early Pliocene. On the contrary, west of this ridge, marine ingression since early Messinian favoured accumulation of gypsum and salts.

From a stratigraphic point of view the Neogene sediments exposed in the Valdelsa Basin, mostly of Pliocene age, have been recently (Benvenuti & Degli Innocenti 2001) included in a stratigraphic framework based on five main unconformity-bounded units (synthems: International Subcommission on Stratigraphic Classification 1994).

In the Strolla Creek valley a succession including the Miocene-Pliocene transition has been described by Bossio *et al.* (1993, 2001; Fig. 2). The basal term of this succession consists of non-marine clays ("unit A" or "Casino clays" respectively by Bossio *et al.* 1993 and 2001) ascribed to the uppermost Messinian on the base of the non-marine ostracod and mollusc assemblages. According to Bossio *et al.* (1993, 2001) this unit is conformably overlain by marine clays ("unit B" or "*Argille Azzurre*-lower part") referred to the lowermost Pliocene *Discoaster variabilis-Sphaeroidinellopsis* biozones. This unit is in turn unconformably capped by paralic gravels passing upward to shallow marine sands ("units C-D" or "*Conglomerati di Casa Stieri*") and clays ("unit E" or "*Argille Azzurre*-upper part") referred to the middle Pliocene. The local succession is topped by shallow marine sands ("unit F" or "*Sabbie di Talciona*"), in erosive contact with "unit E", ascribed to the middle Pliocene as well on the basis of the fossiliferous content.

According to Benvenuti & Degli Innocenti (2001) the middle Pliocene units C-F correspond to the Certaldo ("units C-E") and Ponte a Elsa ("unit F") synthems whereas unit B may represent part of an older synthem (Borro Strolla synthem, see below) within the Valdelsa Basin Pliocene succession.

LOCATION AND STRATIGRAPHY OF THE STROLLA CREEK AREA (SE VALDELSA BASIN)

The study area is located near Poggibonsi, 45 km SE to Florence (Fig. 3). This is a hilly area stretching along the western side of the Chianti Mounts, drained by two small tributaries of the Elsa river, the Carfini and Strolla creeks respectively. Along the Strolla Creek, good exposures of the Neogene deposits are available thanks to extensive quarrying of gravel and sand.

On the NNE of the study area the Mio-Pliocene deposits rest unconformably on the pre-Neogene substratum forming the Chianti Ridge. Upper Miocene sediments, unconformably overlain by the Pliocene succession, crop out to a limited extent in the study area but they are widely exposed in the nearby Casino Basin (Lazzarotto & Sandrelli 1977; Bossio *et al.* 2001). The field recognition of unconformities or inferences on unconformable transitions supported by facies relations and biochronologic considerations allowed to subdivide uppermost Messinian-earliest Zanclean deposits into three unconformity-bounded units consisting of various lithofacies associations (see Benvenuti & Degli Innocenti 2001 for a similar approach) indicative of different paleoenvironments developed in this area.

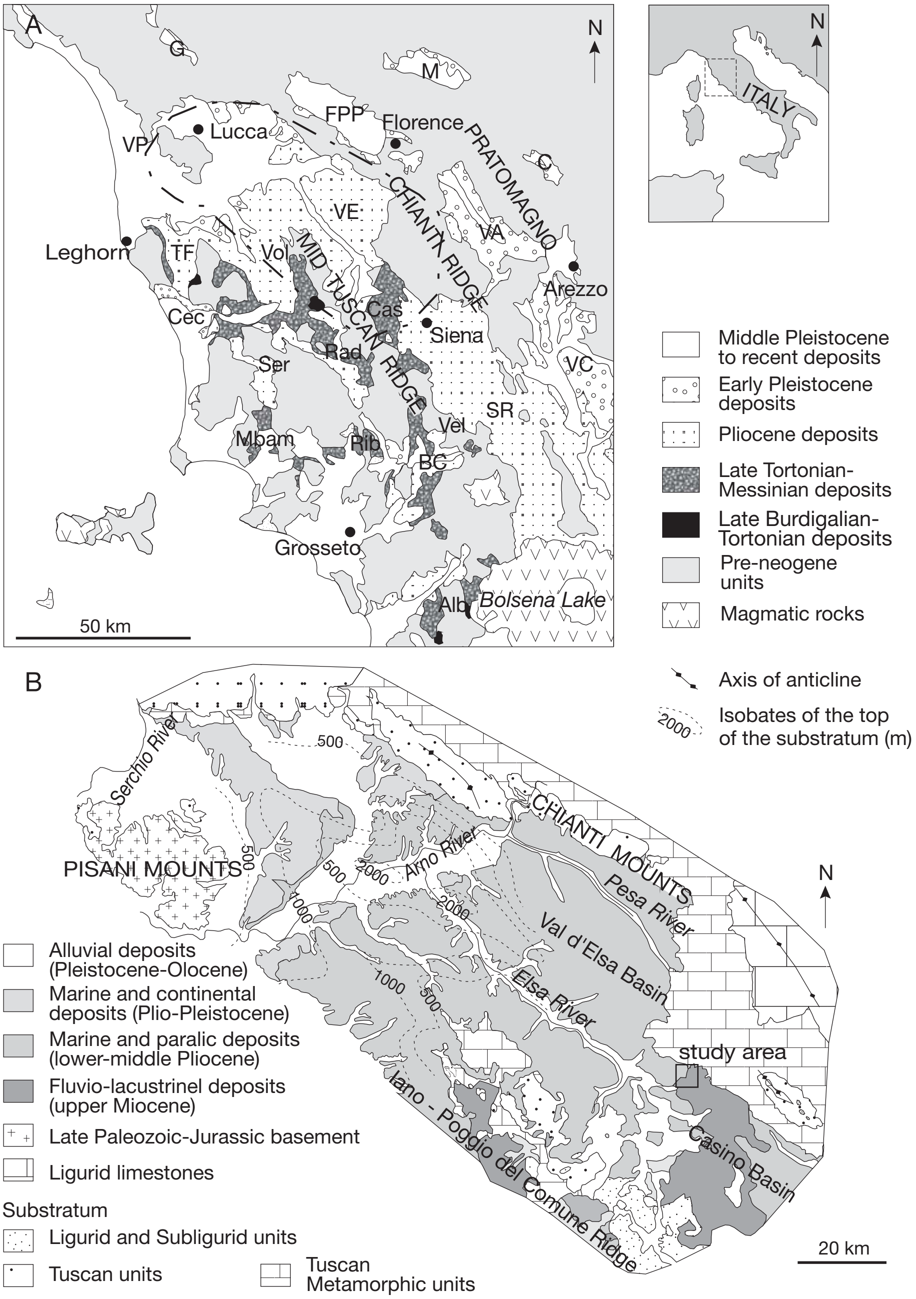

FIG. 1. — **A**, Schematic distribution of Neogene-Quaternary basins west of the Northern Apennines (dotted line borders area in B); **B**, schematic geology of a portion of central Tuscany including the Valdelsa and the Casino basins (after Benvenuti & Degli Innocenti 2001). Isobates of the top substratum after Ghelaroni *et al.* (1968). Abbreviations: Plio-Quaternary basins: **C**, Casentino Basin; **FPP**, Firenze-Prato-Pistoia Basin; **G**, Garfagnana Basin; **M**, Mugello Basin; **VA**, Upper Valdarno Basin; **VC**, Valdichiana Basin; Mio-Quaternary basins: **Alb**, Albegna Basin; **BC**, Baccinello-Cinigiano Basin; **Cec**, Cecina Basin; **Cas**, Casino Basino; **Mbam**, Montebamboli Basin; **Rad**, Radicondoli Basin; **Rib**, Ribolla Basin; **Ser**, Terrazzano Basin; **SR**, Siena-Radicondoli Basin; **TF**, Tora-Fine Basin; **VE**, Valdelsa Basin; **Vel**, Velona Basin; **Vol**, Volterra Basin; **VP**, Viareggio-Pisa Basin.

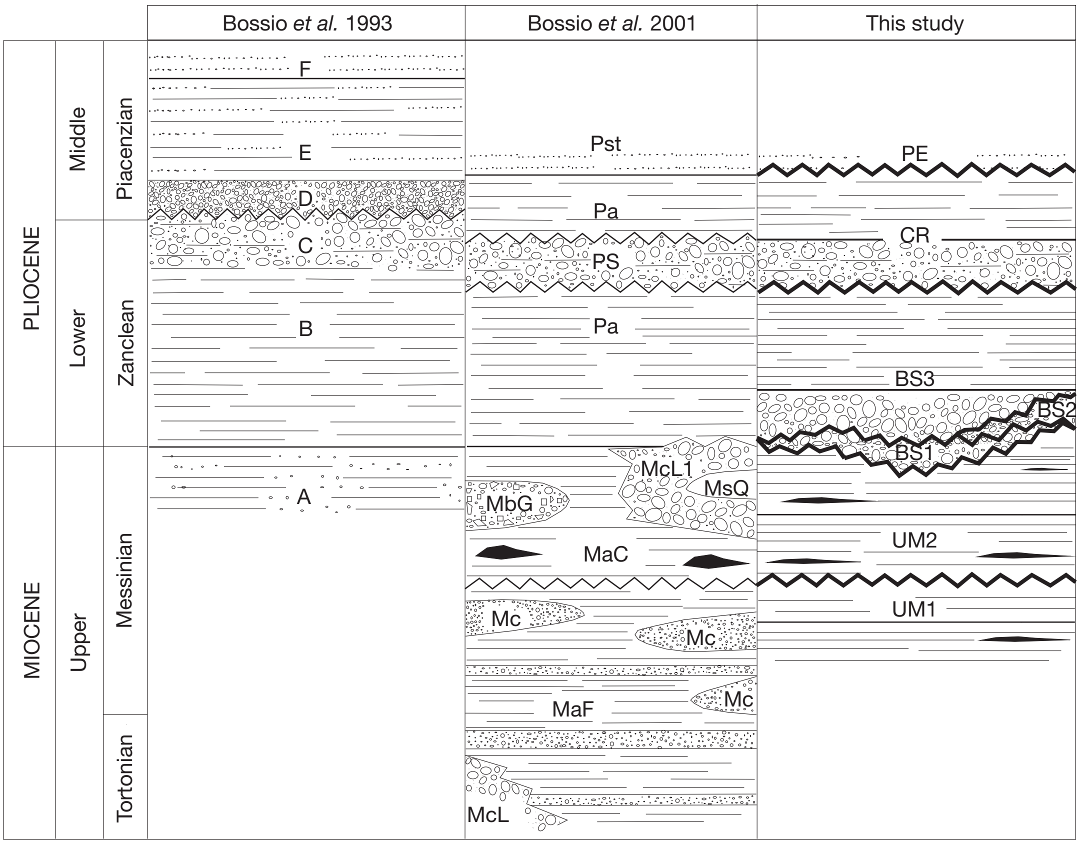

FIG. 2. — Comparison among different stratigraphic framework established for the Neogene deposits in the Strolla Creek area. Legend for codes: **A-F**, see text. Abbreviations: **BS1-3**, sub-synthems within the Strolla Creek synthem; **CR**, Certaldo synthem; **MaC**, Casino Clays; **MaF**, Torrente Fosci Clays; **MbG**, Grotti Breccias; **Mc**, Caprareccia Sandstones; **McL**, Podere Luppiano Conglomerates; **McL1**, Lilliano Conglomerates; **MsQ**, Quercegrossa Sandstones; **Pa**, *Argille Azzurre*; **PE**, Ponte a Elsa synthem; **PS**, Casa Stieri Conglomerates; **Pst**, Talciona Sand; **UM1**, upper Tortonian-lower Messinian lacustrine deposits; **UM2**, Messinian Lago-Mare deposits.

UPPER MIOCENE DEPOSITS (UPPER TORTONIAN-MESSINIAN)

The upper Miocene deposits are visible in small outcrops along and around the Strolla Creek (Fig. 3) and are represented by muddy sediments included within two units (UM1 and UM2). Despite stratigraphic transition is not directly visible, an unconformable contact between the two units is here suggested (see below):

– UM1: light brown-grey mostly massive silty clays bearing calcareous nodules, vegetal debris, ostracod valves and scanty mollusc remains. These deposits, observed exclusively in limited outcrops NE and SE of the Strolla Creek, are correlatable with those ascribed by various authors to the first lacustrine event in the Casino Basin ("lower lacustrine cycle", Lazzarotto & Sandrelli 1977; "Argille del Torrente Fosci", Bossio *et al.* 2001). Ostracod assemblages (see below), in fact, point to a late Tortonian-early Messinian age, in agreement with the biostratigraphic calibration provided by these authors;

– UM2: greenish-grey clays and silty clays with abundant organic matter, vegetal debris, calcareous nodules and rich oligohaline mollusc and ostracod assemblages (see below). These muddy deposits, in the outcrop 1.5 m thick, are prevalently massive although thin lamination has been locally observed. The mollusc fauna is either sparse in the sediment or

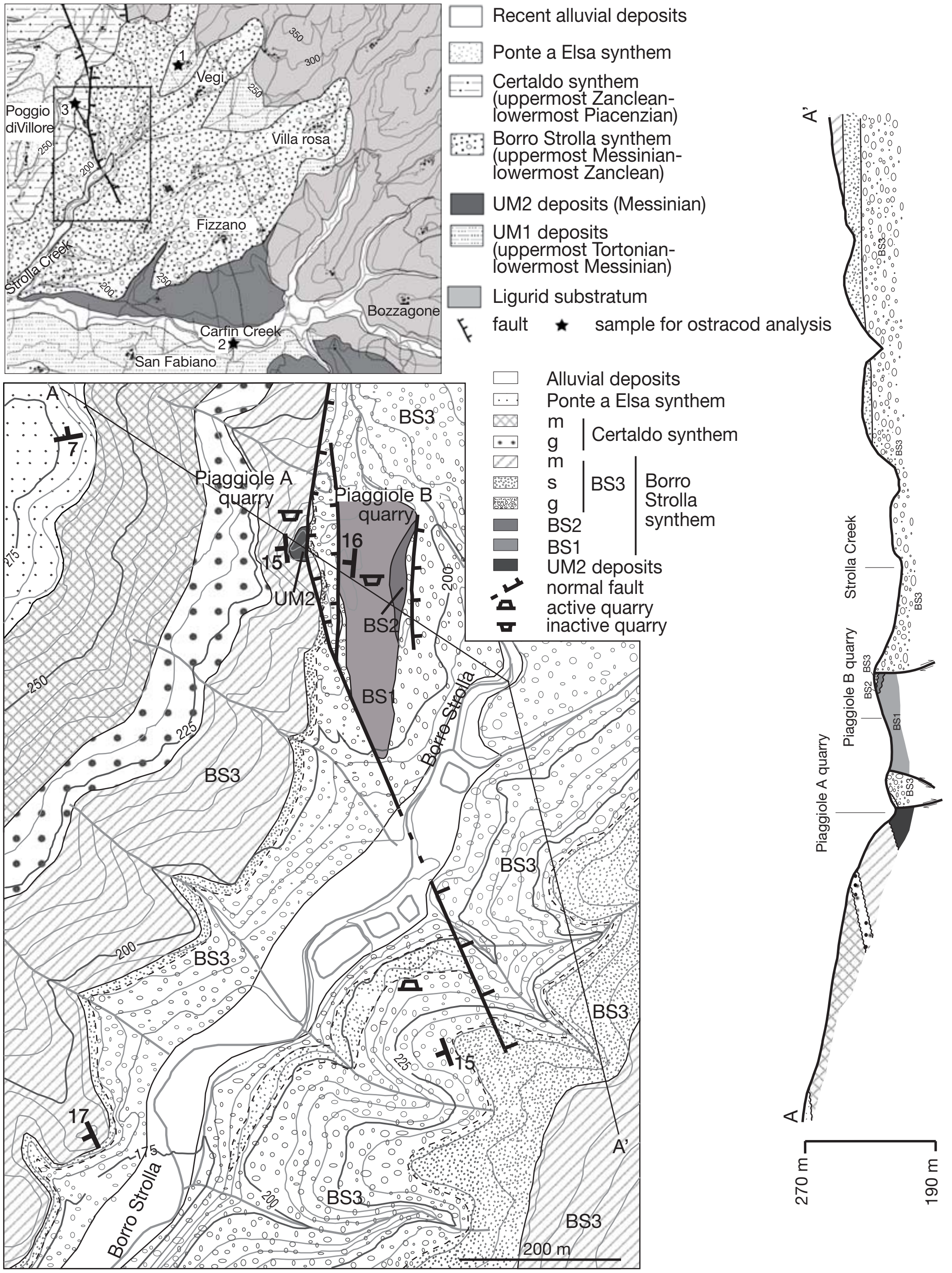

FIG. 3. — Schematic geological maps and cross-section of the Strolla Creek area. Abbreviations: **g**, gravelly lithofacies; **m**, muddy lithofacies; **s**, sandy lithofacies.

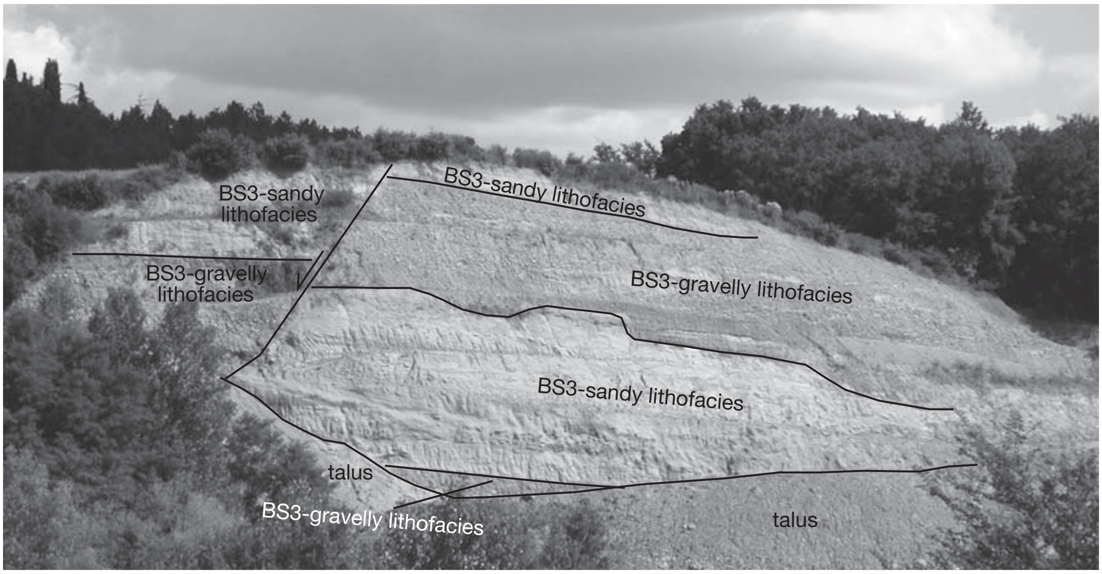

FIG. 4. — Panoramic view of the sub-synthem BS3 showing the cyclic stacking pattern of fluvial gravely-sandy lithofacies associations. The outcrop, the Sefi Quarry face affected by a normal fault, is about 45 m high.

concentrated in thin horizons. Ostracods are present even if scanty. The uppermost part of the deposit is composed of blackish clays lacking molluscs, rich in organic matter and sulphur concretions. This lithofacies is sharply overlain by Zanclean marine clays of sub-synthem BS3 (see below).

The UM2 unit has been observed exclusively in the Piaggiole A quarry (Fig. 3), coinciding with the Bossio *et al.* (1993) "unit A". Successively this unit was ascribed to the "*Argille del Casino*" (Bossio *et al.* 2001), considered to record a second lacustrine episode ("upper lacustrine cycle", Lazzarotto & Sandrelli 1977) in the adjacent Casino Basin. Renewed lacustrine condition established in the latter basin following the deformation and erosional truncation of UM1 deposits. Angular unconformity within the lacustrine succession of the Casino Basin represents an "intramessinian" unconformity of regional significance (see below).

New survey of the Casino Basin's upper Miocene succession (Benvenuti pers. comm.), indicated that the UM2 deposits in the Strolla Creek are at least partially separated from such lithologically equivalent deposits in the Casino Basin, by a substratum high. Thus the UM2 lithofacies is considered to be accumulated in the southeastern end of the Valdelsa Basin simultaneously to similar deposition in the second Casino's lake. Deposits lithologically and paleontologically equivalent to UM2, in fact, have been drilled in the central part (San Miniato area) of this basin (Ghelardoni *et al.* 1968) suggesting that a Lago-Mare-like setting occurred on a large portion of the Valdelsa Basin during the latest Miocene. We consider, therefore that the transition bewteen UM1 and UM2, though not visible, is marked by an unconformity related to the tectonically-driven transition from the early Casino Basin to the early Valdelsa-late Casino Basin system (see Discussion).

BORRO STROLLA SYNTHEM (UPPERMOST MESSINIAN-LOWERMOST ZANCLEAN)

The deposits included in this study in the Borro Strolla synthem (BS) were referred by Bossio *et al.* (1993) to the upper Miocene continental gravels ("Conglomerati di Lilliano"in Bossio *et al.* 2001) and to "unit B" ("*Argille Azzurre*-lower part" in Bossio *et al.* 2001). These deposits are overlain by uppermost Zanclean-Piacenzian Certaldo synthem in

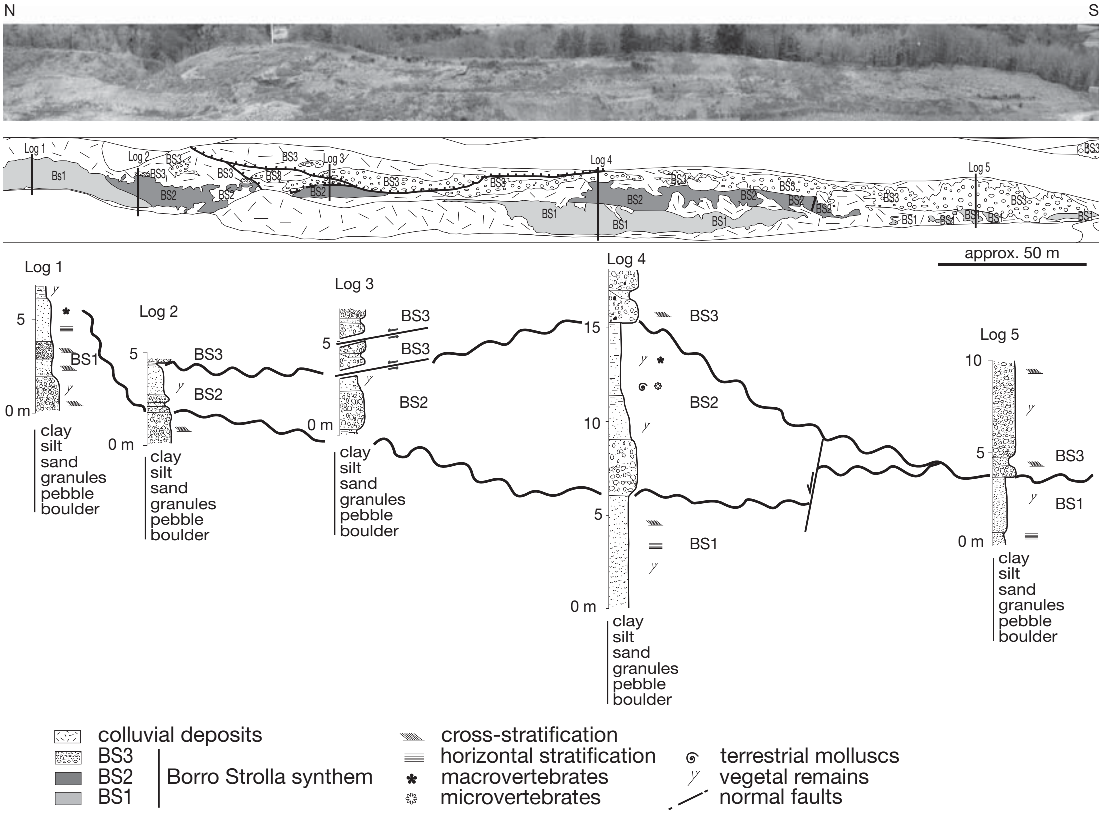

FIG. 5. — Photographic sketch, line drawing and correlation of logged sections in the lower-mid portion of the Borro Strolla synthem exposed in the Piaggiole B quarry face (see text).

turn capped by the Piacenzian Ponte a Elsa synthem which are not discussed in this paper. BS unconformably overlies UM1 deposits whereas the stratigraphic contact with UM2 has not been observed. Nevertheless, we favour an unconformable transition as well, basing on the following considerations:

– UM2 and the Borro Strolla synthem crop out at very short distance respectively in the Piaggiole A and B quarries (Fig. 3). Due to the significant thickness of the gravelly-sandy portion of BS, well-exposed on the left bank of the Strolla Creek (Fig. 4), a stratigraphic onlap of UM2 on these deposits seems highly improbable being, in fact, never documented (see also Bossio *et al.* 1993, 2001). Furthermore a lateral transition from alluvial gravels and sand into lacustrine muds in a so short distance, appears sedimentologically inconsistent;

– despite BS is affected by normal faults (Fig. 3), offset doesn't prevent the recognition of its internal architecture proving limited tectonic displacement. Nevertheless, a normal fault, visible in the Piaggiole A quarry area, downthrows the BS deposits indicating an original position over the UM2 deposits;

– lowermost Zanclean marine clays (Bossio *et al.* 1993, 2001) onlapping UM2 at the Piaggiole A quarry and the fluvial, gravelly-sandy portion of the BS elsewhere (Fig. 3 see geologic section), represent in fact, the uppermost portion of this synthem.

We suggest therefore that UM1-UM2 and BS deposits are separated by an high-relief erosional contact recording a NW-SE trending deeply incised fluvial valley (see discussion). The recognition of low-rank erosional surfaces within the BS deposits allowed to establish three sub-synthems (Figs 3; 5).

TABLE. 1. — Checklist of micro- and macromammal taxa found in the BS1 and subordinately BS2 sub-synthems.

Artiodactyla	Bovidae: *Protoryx-Paleorix* group
	Cervidae: cf. *Paracervulus*
	Giraffidae: gen. et sp. indet.
Insectivora	Erinaceidae: *Galerix* cf. *depereti*
Rodentia	Cricetidae: *Apocricetus barrierei*
	Gerbillidae: *Debruijnimys* sp.
	Muridae: *Apodemus gudrunae*
	Centralomys benericettii
	Stephanomys aff. *donnezani*
	Sciuridae: gen. et sp. indet.
Lagomorpha	Ochotonidae: *Prolagus sorbinii*
	Leporidae: gen. et sp. indet.

Sub-synthem BS1

It is composed of sands and subordinate gravels observed exclusively in the Strolla Creek valley at the base of the Piaggiole B quarry face (Fig. 5). The lithofacies association, 1.5-9 m thick, is represented by an alternation of greyish-purple coarse-grained sands, silty sands, and subordinate gravels. Sands range from normal graded, horizontal planar and high-angle cross laminated, to massive in places. The high-angle cross lamination indicates palaeocurrent from S-SE. Gravels are polymodal, clast-supported with abundant sandy-silty interstitial matrix in dm-m thick lenticular beds interbedded with sands. Clast composition is mostly represented by limestones deriving from the Ligurid unit that occurs on the northeastern margin, and subordinately by sandstones, limestones and scanty quartzites supplied from the Tuscan unit (*Macigno* Fm., *Calcare Cavernoso*, *Verrucano*). Sands and silty sands bear non-marine mollusc and vertebrate fossil fauna (see below). This unit is unconformably overlain by the sub-synthem BS2 deposits.

Sub-synthem BS2

The lithofacies association included in this sub-synthem is exposed exclusively in the Piaggiole B quarry (Fig. 5) and consists of gravels grading upward to coarse-grained sands, silty sands and silty clays. Gravels are polymodal, clast-supported with abundant grey sandy matrix and showing a clast composition similar to sub-synthem BS1. Clast imbrication indicates a provenance from SE. The sands are massive fining upward to silty sands and dark grey silty clays. The latter are characterised by dispersed organic matter, root traces, land and subordinate freshwater molluscs and scanty vertebrate remains (see below). These deposits are unconformably overlain by sub-synthem BS3 deposits.

Sub-synthem BS3

This sub-synthem consists of two vertically stacked lithofacies assemblages well-exposed on the Piaggiole B and Sefi quarry faces (Figs 4; 5):

– the lower lithofacies assemblage is mostly represented by gravely and subordinate sandy deposits arranged in two main fining-upward bedsets separated by an erosive surface. Gravels are polymodal, well to moderately, clast-supported with abundant coarse grained sandy matrix. Locally gravels are characterised by trough and planar cross-bedding indicating paleocurrent to W-SW. The sands are coarse-medium grained showing horizontal and trough cross-stratification;

– the upper lithofacies assemblage rests on the previous one through a sharp surface marked by oxidized iron encrustations, gypsum crystals and concretions. Furthermore it sharply overlies the UM2 just at the Piaggiole A quarry (see also Bossio *et al.* 1993, 2001). The lithofacies assemblage, up to 40 m thick, is represented by massive grey silty clays and silts becoming dominant toward the top. These deposits are characterised by dispersed organic matter and vegetal debris and by a rich fossil marine invertebrate fauna including molluscs, ostracods (see below) forams and nannofloras (Bossio *et al.* 1993, 2001). Bossio *et al.* (1993, 2001) reported the results of a biostratigraphic analysis of this deposit ("unit B" = *Argille Azzurre*-lower part) suggesting an earliest Pliocene age (*Discoaster variabilis-Spaeroidinellopsis seminulina* s.l. biozones).

PALEONTOLOGICAL ANALYSES

The material is house in the Science Department of the University of Firenze.

MAMMALS

A not abundant mammal assemblage has been recovered at Strolla Creek, with at least 12 taxa

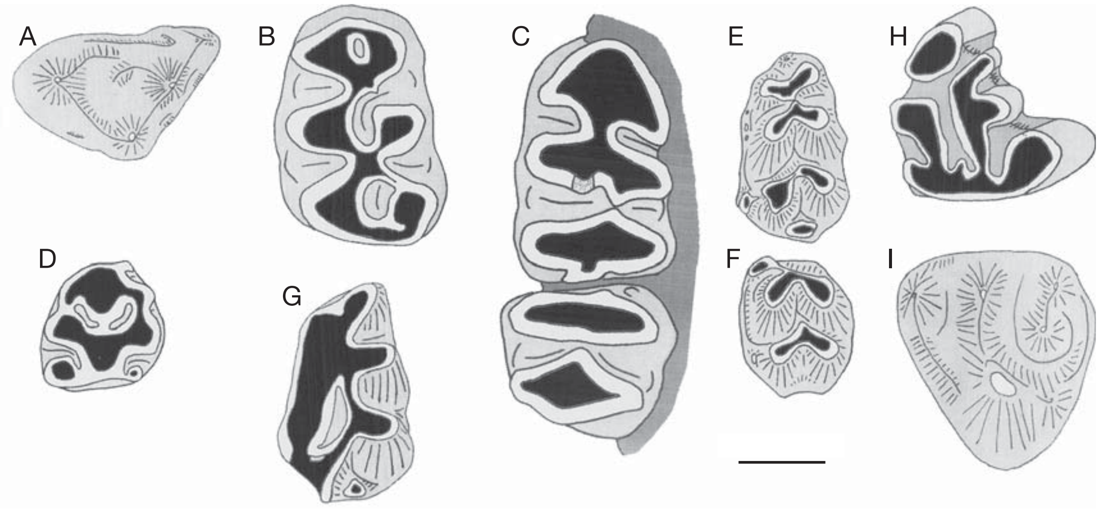

FIG. 6. — Small mammals recovered from Borro Strolla synthem: **A**, *Galerix* cf. *depereti* Crochet, 1986, left M3 (DST-BS-07); **B**, *Apocricetus barrierei* Mein & Michaux, 1970, left M1 (DST-BS-05); **C**, *Debruijnimys* sp. right mandible with M1-M2 (DST-BS-08); **D**, *Apodemus* cf. *gudrunae* van de Weerd, 1976, right M2 (DST-BS-09); **E**, **F**, *Centralomys benericettii* De Giuli, 1989, left M1 and M2 (DST-BS-10); **G**, *Stephanomys* aff. *donnezani* Depéret, 1890, left M1 (DST-BS-11); **H**, *Prolagus sorbinii* Masini, 1989, right P3 (DST-BS-06); **I**, Sciuridae indet., M3 (DST-BS-12). Scale bar: 1 mm.

documented (Table 1). Fossils, on the whole collected in the Piaggiole B quarry, come mostly from deposits of the BS1 sub-synthem (from sediments of the BS2 sub-synthem, only remains of the ochotonid *Prolagus* Pomel, 1853 are occurring).

The greater part of fossils belongs to micromammals (Fig. 6) with an insectivore, six rodents and two lagomorphs; the ochotonid *Prolagus sorbinii* Masini, 1989 (Fig. 6H) is the best represented taxon.

The completeness of the mammal fossil record is low and both the large and small mammal samples cannot be considered fully representative of the original assemblage. The contribution of mammals to the palaeoclimatic and palaeoenvironmental reconstructions is therefore of limited value, taking also into account that some taxa are not completely located in a precise systematic scheme; on the other hand more significant are the biochronological setting and the paleobiogeographic considerations deriving from the mammal remains.

The Strolla Creek mammal assemblage, suggests palaeobiogeographic connections with western Europe, fitting the general aspect of a fauna at the Mio-Pliocene boundary. Indeed, the cervid *Paracervulus* Teilhard de Chardin & Trassaert, 1937 (Fig. 7A), one of the younger representatives of the Muntiacinae group in Europe and one of the better known cervids in France during the Ruscinian Mammal Age (Dong 1990, 1996; cf. Azanza 2000), occurs in some Italian localities referred to the latest Turolian (e.g., Baccinello V-3, Abbazzi 2001; Monticino quarry and Casino Basin, Abbazzi & Azanza 2000; Gallai 2002). The bovids *Palaeoryx* Gaudry, 1861 and *Protoryx* Forsyth Major, 1891 (Fig. 7B, C) well-known from Greek and Turkish localities during the middle and late Miocene (Solounias 1981; Köhler 1987), are also reported in Spain (Alcalà 1994) during the latest Miocene and early Pliocene.

The occurrence of a very large giraffe (Fig. 7D, E), comparable in size to *Helladotherium* Gaudry, 1860 from Greece, is an interesting new datum because this group of ruminants is not known from not endemic Neogene Italian sites. However, it does not allow any biochrological conclusion. In fact, large sized giraffes, widespread during the late Miocene, are still present in the Pleistocene in eastern Europe (cf. Geraads 1998a), while the occurrence of a dubious sivatheriine is reported from France in the early Pliocene (Montpellier, MN14 unit; Guerin 1986).

Also the micromammal fauna shows a transitional character (Rinaldi 2003) partially comparable with other latest Messinian mammal assemblages such as those from Monticino, in Central Italy (Marabini & Vai 1989). Indeed some of the taxa occurring in Strolla Creek are also present in the fillings of the karst fissures in the gypsum within the Monticino quarry (De Giuli 1989; Masini 1989; Rook 1992), correlated to the latest Messinian Colombacci Fm: *Galerix* aff. *depereti* Crochet, 1986 (Fig. 6A), *Apocricetus* cf. *barrierei* Mein & Michaux, 1970 (Fig. 6B), *Apodemus* cf. *gudrunae* van de Weerd, 1976 (Fig. 6D), *Centralomys benericettii* De Giuli, 1989 (Fig. 6E, F) and *Prolagus sorbinii* Masini, 1989 (Fig. 6H). However, the murid *Stephanomys* Schaub, 1938, which is documented at Monticino by the species *S. debruijni* De Giuli, 1989, is represented at Strolla Creek by remains (Fig. 6G) which are closer to the Pliocene species *S. donnezani* Depéret, 1890 (e.g., from the French site Sète; Adrover 1986), and another important difference is the occurrence of a representative of the Rodentia family Gerbillidae Gray, 1825 (Fig. 6C); the latter form needs a more extensive discussion. The dispersal of these rodents from Africa towards Spain is indeed one of the main events related to the Messinian Salinity Crisis (Wessel 1998, 1999; Agustí 1999).

The morphology of the gerbil remains from Strolla Creek is comparable to that of the genus *Debruijnimys* Castillo & Agustí, 1996. This genus has been defined by Castillo & Agustí (1996) on the material from the middle Pliocene locality Asta Regia (MN 15 biochronological unit), which has been referred to the species *D. julii* Castillo & Agustí, 1996. *Debruijnimys* occurs also as an indetermined species (*Debruijnimys* sp.) in other latest Miocene-early Pliocene Spanish localities (Bacochas 1, cf. Sesé 1989; Caravaca 1, cf. Bruijn 1974; Alcoy, cf. Castillo & Agustí 1996; Agustí 1999; Agustì & Casanovas-Vilar 2003). An origin of the European species of *Debruijnimys* by migration from North Africa during the late Messinian is further supported by the occurrence of *D. davidi* (Geraads, 1998) in the latest Miocene/early Pliocene locality Lissasfa (Morocco) (Geraads 1998b; Agustí & Casanovas-Vilar 2003).

The Strolla Creek gerbil shows a mosaic of characters which does not occur in the African sample, nor in the Spanish ones. As a matter of fact, the large size – the length of M_1 falls at the largest extreme of the range of the type sample of *D. julii* from Asta Regia and it is significantly larger than the African species – and the large anteroconid are associated to the well-developed posterolofid and to the very brachyodont dental crown (Fig. 6C). Taking into account the unknown morphological variability and the possibility of endemism, we refer the Strolla Creek gerbil to *Debruijnimys* sp.

The occurrence of gerbils in the Neogene of Italy is not, however, a novelty: Gerbillidae gen. et sp. indet. is firstly reported from the latest Messinian Ciabot Cagna site (Piedmont, Cavallo *et al.* 1993). However, the scarcity of the material – only a M_3 has been been found at Ciabót Cagna – prevents any comparison with our remains.

To sum up, we believe that the occurrence of gerbil attributable to the genus *Debruijnimys*, as well as its association with the murid *Stephanomys*, represented by a species (*Stephanomys* aff. *donnezani*) more evolved than the latest Messinian one, could be indicative of a latest Messinian-earliest Zanclean age for the BS1 sub-syntem.

Very general palaeoenvironmental inferences can be drawn from the mammalian assemblage, which are however in agreement with those derived from other sources of informations (e.g., molluscs, see below). Indeed an environment with wooded areas and more open spaces is suggested by the occurrence of the cervid on one hand, and of the large sized giraffid and *Debruijnimys* sp. on the other; modern gerbils are in fact widespread in the desertic and sub-desertic regions of Africa and central and western Asia (cf. Tong 1989).

MOLLUSCS

UM2 deposits

A significant rich oligo-mesohaline mollusc assemblage is recorded from unit UM2 sampled in the Piaggiole A quarry (Fig. 8). It is composed of aquatic prosobranch gastropods belonging to the families Neritidae Rafinesque, 1815, Melanopsidae H. & A. Adams, 1854 and Hydrobiidae Troschel, 1857 and bivalves belonging to the families Cardiidae Lamarck, 1809 (Lymnocardiinae Stoliczka, 1871) and Dreissenidae Gray *in* Turton, 1840.

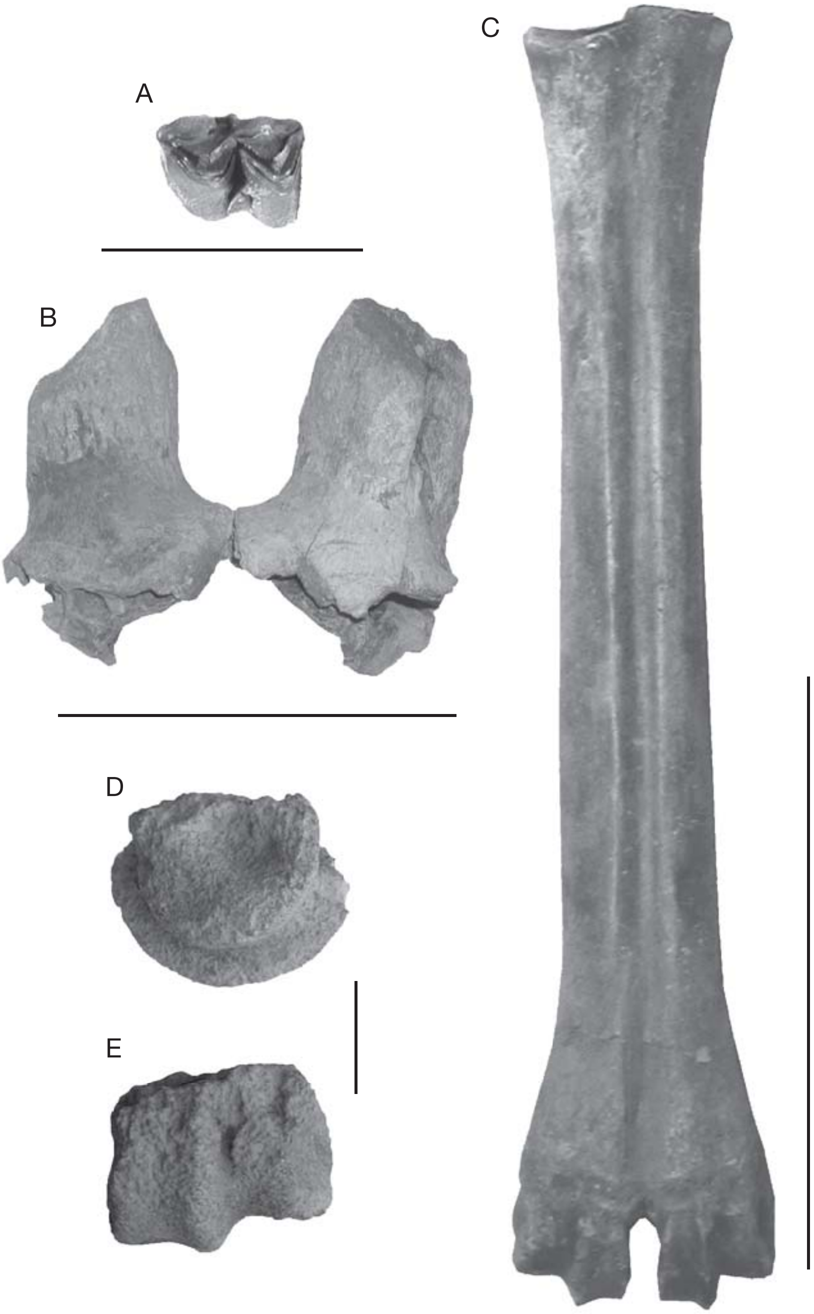

FIG. 7. — Large mammals recovered from Borro Strolla synthem: **A**, *Paracervulus* sp., left M1, occlusal view (DST-BS-02); **B**, **C**, *Protoryx-Paleoryx* group (DST-BS-03); **B**, frontals with horn cores; **C**, left metatarsus; **D**, **E**, Giraffidae indet., distal end of metapod (DST-BS-04). Scale bars: A, D, E, 2 cm;B, C, 10 cm.

The gastropods are represented by few species with a high number of specimens: *Theodoxus mutinensis* D'Ancona, 1869, *Saccoia etrusca* Capellini, 1880, *Saccoia fontannesi* Capellini, 1880 and *Melanopsis narzolina* D'Archiac, 1846. The bivalves are dominated by several species of Lymnocardiinae: *Euxinicardium subodessae* Sinzov, 1877, *Pseudocatillus* cf. *P. pseudocatillus* Barbot de Marny, 1869, *Pontalmyra partschi* Mayer, 1871, *Chartoconcha* sp., *Prosodacnomya sturi sabbae* Andreescu, 1975, *Psilodon* cf. *P. haueri* Cobalcescu, 1883, *Psilodon* cf. *P. munieri* Stefanescu, 1896 and other taxa in a fragmentary state of preservation. Dreissenidae are represented by one species: *Dreissena* ex gr. *D. rostriformis* Deshayes, 1832.

The gastropods *T. mutinensis*, *S. etrusca* and *S. fontannesi* are typical extinct endemic elements, occurring in hypo-oligohaline oxygenated shallow water enviroments of Italian basins from the late Tortonian-early Messinian to the latest Messinian (Ghetti *et al.* 2002 and references therein). *Melanopsis narzolina* is widespread in the hypo-oligohaline enviroments of several upper Miocene basins of the Mediterranean area and in Italy where it occurs in latest Messinian deposits; it seems to be also present in lower Pliocene deposits of eastern Europe (Romania and Slavonia) (Wenz 1929, 1942; Esu 1980).

The subfamily Lymnocardiinae is very important for palaeobiogeographic inference, being its numerous representatives widespread since the Oligocene in the western and eastern Paratethys (Nevesskaya *et al.* 2001). The genera and species belonging to this subfamilty recorded from Strolla Creek deposits are of particular palaeoecologic, chronostratigraphic and palaeobiogeographic interest. They characterize the latest Messinian Lago-Mare biofacies with low salinity (oligo-mesohaline) and shallow water occurring in several latest Messinian deposits (such as Colombacci Fm.) of the Italian peninsula and Sicily during the post-evaporitic phase (Esu 2002, 2007). Moreover close relations with the lower "Pontian" (Odessian) fauna of the Aegean area and strong affinity with Paratethyan assemblages of Pontian age from Dacian and/or Euxinian basin (Andreescu 1977; Popov & Nevesskaya 2000; Nevesskaya *et al.* 2001) are pointed out by several recorded Italian Lymnocardiinae taxa (Di Geronimo *et al.* 1989; Esu 2007). *Dreissena* ex gr. *D. rostriformis*, an upper Miocene species of Paratethyan origin (Archambault-Guezou 1976), also points to oligohaline oxygenated waterbody. The Paratethyan genera *Chartoconcha* Andrussov, 1908 and *Psilodon* Cobalcescu, 1883 are new for the Italian fauna. Since the ecology of Lymnocardiinae and Dreissenidae is linked to low salinity, spreading of suitable habitat in depositional systems of marginal settings characterized by increasing freshwater influx after the "salinity crisis" favoured their dispersal into the Mediterranean area from the Paratethyan realm. Indeed the well-preserved and diversified mollusc assemblage from the Strolla Creek UM2 deposits indicates the occurrence of a shallow water oligo-mesohaline environment characterized by a latest Messinian "Lago-Mare" biofacies in that area.

Sub-synthems BS1 and BS2

Sands of sub-synthem BS1 and the uppermost muds of BS2, both sampled in the Piaggiole B quarry, bear non-marine mollusc assemblages characterized by some pulmonate gastropods. The common recorded species are *Carychium tridentatum* Risso, 1826, *Physa* sp., *Acanthinula aculeata* O. F. Müller, 1774, *Cernuella* sp., whilst *Parmacella* sp., *Truncatellina callicratis* Scacchi, 1833, a fragment of the aquatic prosobranch *Melanopsis* sp., is exclusive of BS1, and *Oxychilus* sp. and *Cepaea* sp., have been found only in BS2.

On the whole this fauna is composed of species of different habitats with a medium degree of aridity and developed under temperate-warm conditions: *C. tridentatum* and *A. aculeata* occur commonly in damp and wooded places, whilst *T. callicratis*, *Parmacella* sp. and *Cernuella* sp. are elements living in open drier places (Kerney & Cameron 1979). *Physa* sp. and *Melanopsis* sp. require slow running-water. Such type of assemblage, in which the terrestrial taxa are dominant, points to mollusc reworking in an environment liable to flooding. The recorded species are known so far since the (early?) Pliocene to Recent (Esu & Ciangherotti 2004) except for the genus *Parmacella* Cuvier, 1804 which is known in Italy from Messinian to Early-Middle Pleistocene and is still living in warmer Mediterranean and Middle

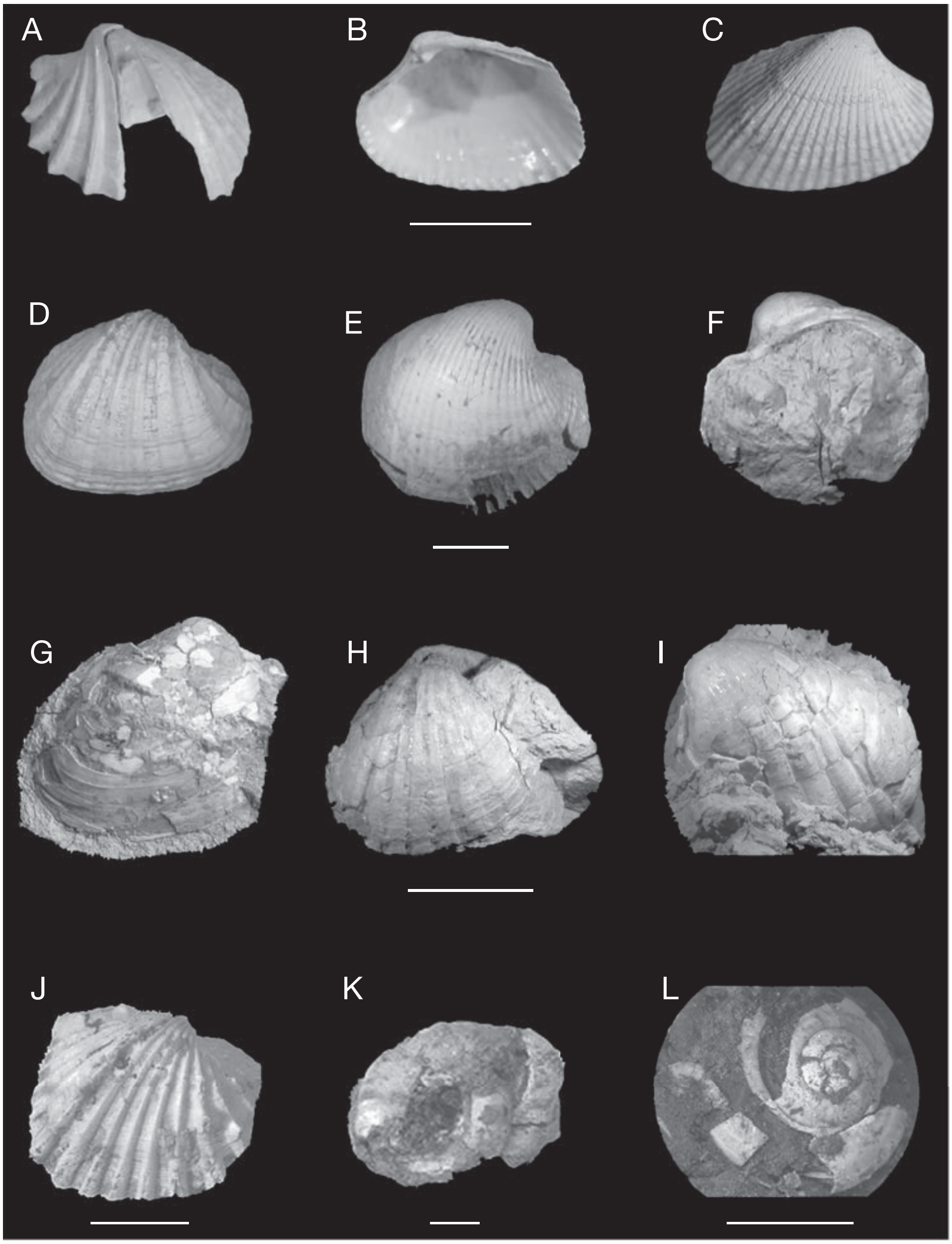

FIG. 8. — Non-marine molluscs from UM2 deposit: **A**, *Euxinicardium subodessae* Sinzov, 1877, left valve; **B**, **C**, *Pseudocatillus pseudocatillus* Barbot de Marny, 1869, right valve, interior and exterior view; **D**, *Pontalmyra partschi* Mayer, 1871, right valve; **E**, **F**, *Prosodacnomya sturi sabbae* Andreescu, 1975, right valve, exterior and interior view; **G**, *Chartoconcha* sp., right valve; **H**, *Psilodon* cf. *P. haueri* Cobalcescu, 1883, right valve; **I**, *Psilodon* cf. *P. munieri* Stefanescu, 1896, left valve; **J**, Lymnocardiinae indet., right valve. **K**, **L**, non-marine molluscs from BS2 deposit; **K**, *Oxychilus* sp., apical view; **L**, *Cepaea* sp., apical view. Scale bars: A-C, 3 mm; D-F, J, 4 mm; G-I, 15 mm; K, 1 mm; L, 7 mm.

East areas (Manganelli & Giusti 1990), as well as the genus *Melanopsis* Férussac, 1807, pointing to warm climate and a semi-arid environment. A probable trend from semi-arid and warm conditions to a more humid climate can be hypothesized for the time-span deposition of BS1 and BS2, taking into account the occurrence of the genera *Parmacella*, *Truncatellina* Lowe, 1852 and *Melanopsis* only in the first sub-synthem BS1.

OSTRACODS

Upper Miocene deposits

Three samples have been collected in very small outcrops referable to late Miocene, respectively located NE and SE of the Strolla Creek: two came from unit UM1 (samples 1 and 2, Fig. 3), whereas the third has been collected at Piaggiole A quarry within unit UM2.

UM1 deposits. UM1 samples bear well preserved and rather abundant ostracods (Fig. 9A-E), each species represented both by adults and instars, thus considered *in situ* species. The ostracod assemblage from sample 1 is made of brackish Cytheroidea Baird, 1908 such as *Cyprideis* sp. 1, *Cyprideis* sp. 2, *Cyprideis* sp. 6 and *Loxoconchissa* (*Loxocaspia*) sp. 1. The ostracod assemblage from sample 2 consists, on the contrary, mainly of Cypridoidea: Candoninae Kaufmann, 1900 (*Lineocypris* spp., *Candona* [*Neglecandona*] sp., *Fabaeformiscandona* sp., *Labiatocandona* sp. and *Pseudocandona* sp.), Cyclocypridinae Kaufmann, 1900, (*Cypria* sp. and *Physiocypria* sp.) while Cytheroidea are limited to *Cyprideis* sp. 6 and *Tavanicythere joachinoi* Bossio, Gliozzi & Tassone, 2004.

Despite the open nomenclature of some species, the recognized assemblages suggest the existence of a brackish waterbody characterized by slight fluctuation in salinity. *Cyprideis* Jones, 1857, *Tavanicythere* Bossio, 1980 and *Loxoconchissa* (*Loxocaspia*) Triebel & Malz, 1969, represent typical brackish water dwellers, whereas candonids such as *Lineocypris* Zalanyi, 1929, and *Labiatocandona* sp. (both typical of upper Miocene Paratethyan deposits) tolerate slightly saline waters. These ostracod assemblages are referable to the late Tortonian-early Messinian (Bossio *et al.* 2001) and confirm the correlation of UM1 with the deposits of the first lacustrine episode in the Casino Basin (Lazzarotto & Sandrelli 1977). They document that the first lake of the Casino Basin significantly extended to the NW. The UM1 ostracod assemblages are dominated by western European and Mediterranean species in full agreement with the late Tortonian-early Messianian ostracods recorded in other Tuscan basins. The occurrence of *Lineocypris* spp. and *Labiatocandona* sp., pertaining to the Paratethyan domain and not exclusive of UM1 (Belforte and Velona basins, Devoto 1968; Ghetti *et al.* 2002; Volterra-Radicondoli Basin, Bossio *et al.* 1981; Krstic & Bossio 1992; Testa 1995; Gliozzi *et al.* 2007), is tentatively explained by the passive dispersal via aquatic birds from the Paratethyan regions (Benson 1976; Benson & Rakic-El Bied 1991; Gliozzi *et al.* 2007).

UM2 deposits. The Piaggiole A quarry ostracod assemblage (sample 3, Fig. 3) is made of few valves of *Caspiocypris* cf. *C. pontica* Sokac, 1852, *Cyprideis* sp., *Loxocorniculina djafarovi* (Schneider *in* Suzin, 1906) and *Loxoconcha* sp. (Fig. 9F-J).

The species detected in this sample again point to a brackish (oligo- to mesohaline) waterbody, but the presence of two typical Pontian/Dacian Paratethyan species such as *Caspiocypris* cf. *C. pontica* and *L. djafarovi* indicates a very restrict time interval corresponding to the latest Messinian Lago-Mare biofacies, widespread almost all over the Mediterranean Basin (Carbonnel 1978; Cipollari *et al.* 1999a, b; Gliozzi 1999; Gliozzi *et al.* 2002, in press). In particular, the presence of *L. djafarovi* seems to constrain the age of the deposits to the last latest Messinian precessional cycle (Gliozzi *et al.* 2006). These results, in full agreement with those of Bossio *et al.* (1993), which reported a richer Paratethyan ostracod association from these deposits, suggest a palaeoenvironmental and chronological correlation with the *Argille del Casino* and confirm the development of the Lago-Mare realm east of the Mid Tuscan Ridge. Differently from the basins located to the west, where the Lago-Mare followed to pre-existing restricted marine environments (Volterra-Radicondoli Basin, Bossio *et al.* 1978; Bossio *et al.* 1981, 1996a, b; Sarti & Testa 1994;

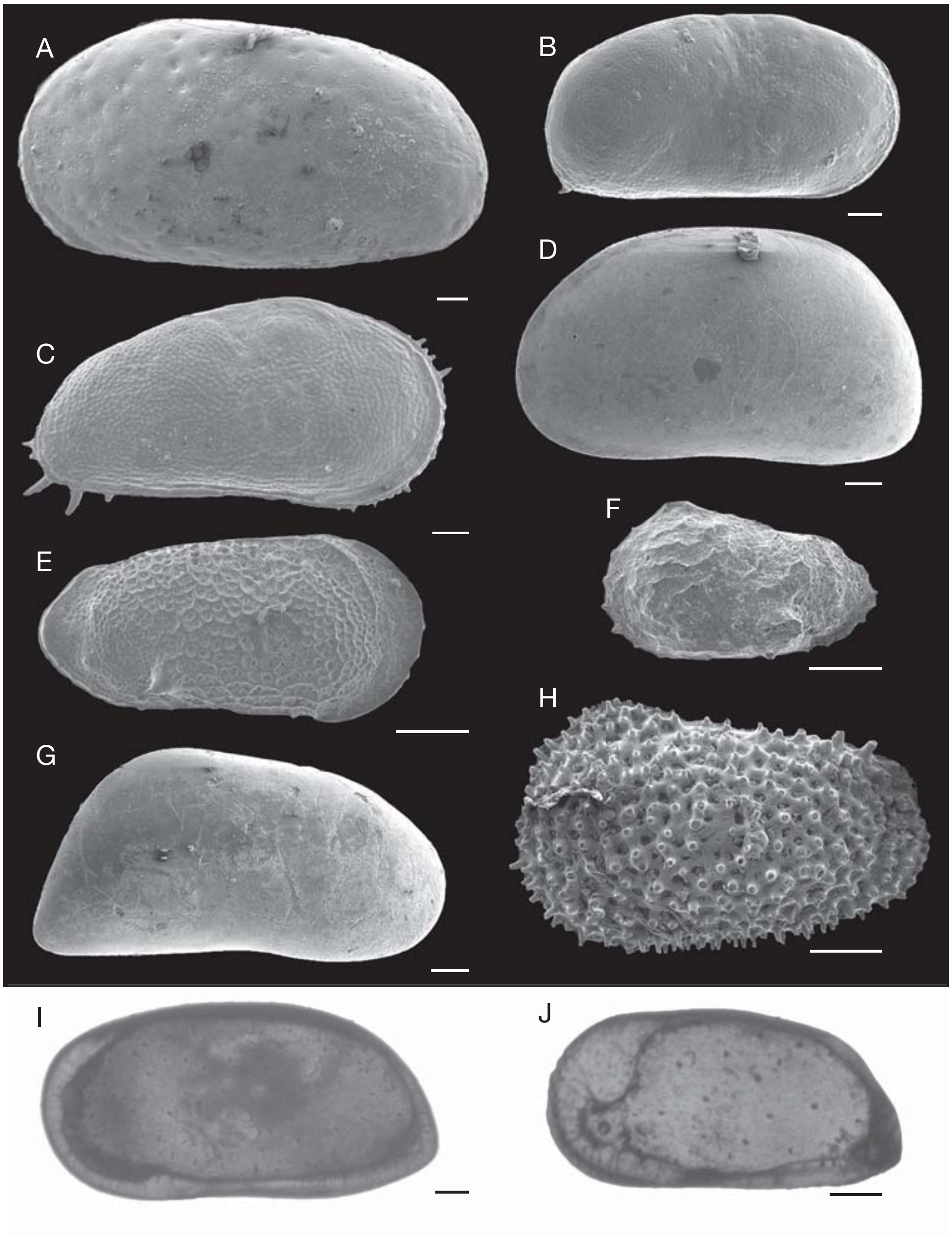

FIG. 9. — Ostracod valves from UM1 (samples 1, 2, Fig. 3A), UM2 and Borro Strolla synthem-upper part (samples Piaggiole A quarry, Fig. 3B): **A**-**C**, sample 1; **A**, *Cyprideis* sp. 1, male left valve in lateral external view; **B**, *Cyprideis* sp. 2, female right valve in lateral external view; **C**, *Cyprideis* sp. 6, male right valve in lateral external view; **D**-**F**, sample 2; **D**, *Labiatocandona* sp., carapace in left lateral view; **E**, *Tavanicythere joachinoi* Bossio, Gliozzi & Tassone, 2004, female right valve in lateral external view; **F**-**J**, sample Piaggiole A quarry; **F**, *Loxocorniculina djafarovi* Schneider *in* Suzin, 1906, female left valve in lateral external view; **G**, *Caspiocypris* cf. *C. pontica* Sokac, 1852, female right valve in lateral external view; **H**, *Henryhowella sarsi* Müller, 1894, left valve in lateral external view; **I**, *Bythocypris obtusata producta* Seguenza, 1880, left valve in lateral view, transmitted light; **J**, *Krithe padovani* Colalongo & Pasini, 1988, left valve in lateral view, transmitted light. Scale bars: 0.1 mm.

Fine Basin, Aldinucci *et al.* 2005), in the eastern basins, fully or partially isolated from the marine influence, brackish lakes may have been favoured by: 1) the inflow of saline water generated by the dissolution of the Triassic evaporites (isotopic studies by Anadón *et al.* 2002 in the lower Messinian of the Velona Basin); or 2) a partial connection with the Lago-Mare facies, in the specific case possibly existing in the western portion of the Valdelsa Basin as suggested by core data (Ghelardoni *et al.* 1968).

Sub-synthem BS3

No ostracod valves have been recovered in sub-synthem BS1, BS2 and in the lower part of the sub-synthem BS3 deposits. One sample from the mudstone on top of sub-synthem BS3 collected in the Piaggiole A quarry, provided a scanty but well-preserved marine ostracod assemblage, made of *Bythocypris obtusata producta* (Seguenza, 1880), *Palmoconcha agilis* Ruggieri, 1967, *Krithe padovani* Colalongo & Pasini, 1988, *Henryhowella sarsi* Müller, 1894 and *Macrocypris* Brady, 1868. This association is very similar to that reported by Bossio *et al.* (1993, 2001) from the same deposits.

The lower diversity of this assemblage coupled with the presence of marine taxa such as *Krithe* Brady, Crosskey & Robertson, 1874, *Bythocypris* Brady, 1880 and *Henryhowella* Puri, 1957 suggest a rather deep (outer circalittoral/bathyal) marine environment. The co-presence of *P. agilis* (early Messinian [Ruggieri 1967b; Aruta 1982] to Zanclean [MPl 2 or *G. margaritae* zone] [Nachite 1993]), *Bythocypris obtusata producta* (middle Mliocene-early Pleistocene [Aiello *et al.* 2000]), *H. sarsi* (middle Miocene-Present [Bonaduce *et al.* 1999]) and *K. padovani* (Zanclean [MPl 2 or *G. margaritae* zone] [Ciampo 1992] to Santernian [MPl 6 or *G. inflata* zone] [Colalongo & Pasini 1988])point to the Early Zanclean. Due to the relatively low resolution of the Pliocene marine ostracod biostratigraphy, this age is considered to be in an overall agreement with that proposed by Bossio *et al.* (1993, 2001), based on the nannoplankton and planktic foraminifer assemblages.

Finally, the composition of this assemblage, made of a typical Mediterranean-Atlantic stock, attests to the completely restored connection between Atlantic and Mediterranean at the beginning of the Pliocene.

DISCUSSION

The stratigraphic revision of the succession encompassing the Mio-Pliocene transition in the Strolla Creek area allows to focus the discussion on two specific aspects.

LOCAL DEPOSITIONAL EVOLUTION: REGIONAL SEA-LEVEL RISE VS LOCAL TECTONISM

The stratigraphic relations among the different units recognized in this study illustrate a complex depositional dynamic. Non-marine, fluvial and marine conditions established in the Strolla Creek area in the following sequence (Fig. 10).

The late Tortonian-early Messinian deposition and the intramessinian tectonic event

Unit UM1, bearing scanty molluscs and meso-/oligohaline ostracod assemblages, accumulated during the first fluvio-lacustrine episode of the Casino Basin in the late Tortonian-early Messinian (Lazzarotto & Sandrelli 1977; Bossio *et al.* 2001; Fig. 10A). This evidence indicates that the first Casino expanded to NW flooding an area that successively will pertain to the Valdelsa Basin. The upper Messinian UM2 deposits record the development of a non-marine flooded environment (Fig. 10B) quite similar to those developing in the same time-span in other Tuscan basins. In particular such an environment occurred in the nearby Casino (e.g., during the second lacustrine episode), Siena basins (Lazzarotto & Sandrelli 1977; Bossio *et al.* 2001) and in the central part of the Valdelsa Basin (Ghelardoni *et al.* 1968). Deposition was characterised by sediment settling in quiet shallow waters populated by a diversified benthic invertebrate fauna. The mollusc and ostracod assemblages characterising these deposits show a marked Paratethyan affinity being referable to the latest Messinian Lago-Mare biofacies (Esu 2002 and references therein; Gliozzi *et al.* 2002 and references therein). The attribution of UM2 to the Valdelsa Basin rather than to the Casino Basin points to a physical separation established between the two areas after the deposition and deformation of UM1-"lower lacustrine cycle"/"*Argille del Torrente Fosci*". This "intramessinian" tectonic event (see below) caused the development of a second lacustrine setting in the Casino Basin and the possible activation of the SE Valdelsa Basin where "Lago-Mare" condition determined the deposition of UM2 and similar deposits drilled in the central portion of this basin. In particular the physical separation of the Casino from the Valdelsa Basin possibly testifies to an actively growing structural high tranversal to the basin's axes.

The combination of subsidence pulses and rapidly rising sea-level at the Messinian-Pliocene transition

In the latest Messinian a vigorous fluvial rejuvenation caused the deep incision of the UM1-UM2 deposits with the development of a N-S trending fluvial valley about 2 km wide (Fig. 10C). The western bank of this valley, although disturbed by faults, is located between Piaggiole A and B quarries whereas the eastern bank is approximately on the right side of the Carfini Creek around Fizzano (Fig. 3). The valley is filled by the Borro Strolla synthem accumulated throughout three major stages of alluvial deposition. Palaeocurrent data indicate the occurrence of tributaries which during the deposition of BS1 and BS2 supplied sediments from the SE to the main valley oriented NNE-SSW. The latter drained toward the SW (Colle Valdelsa area) as indicated by palaeocurrent in BS3.

The BS1, BS2 and part of BS3 sub-synthems record three periods of valley aggradation punctuated by erosion (Fig. 5). The internal lithofacies architecture in the three sub-synthems is characterised by fining upward trends related to significant change of sediment supply and base level.

BS1 sub-synthem records a transition from high to low-energy channels filled with gravels abruptly grading into sands and silty sands. The non-marine molluscs point to slow flowing water and to an environment liable to flooding. A similar conclusion can be drawn from the analysis of mammal fossils. The low abrasion showed by some bones and, in particular, the presence of articulated limb bones indicate that burial occurred soon after the death of specimens and that fluvial transport did not play significant role in the setting of mammal fossils. In BS2 the transition from a gravel-bed river to low-energy environment is outlined by organic matter-rich and terrestrial mollusc-bearing muds. These deposits are interpreted as accumulated in a floodplain marking the deactivation of the coarse-grained transport and deposition. In the thicker BS3 sub-synthem two gravel-sand depositional units record as many phases of decreasing bed-load grain size which reflect a cyclic shift of the fluvial style, from gravel- to sand-bed river, as a consequence of reduced sediment supply and/or reduced transport capacity, both phenomena compatible with a relative base-level rise (Shanley & McCabe 1994). In the studied case fining-upward trend of successive valley fills may reflect the fluvial response to uplift/denudation cycles (Blair & Bilodeau 1988; Paola *et al.* 1992; Mutti *et al.* 1996) interfering with a regional sea-level rise (see below). The uplift/denudation component determined coarse-grained sediment supply to the fluvial system during tectonic quiescence whereas sediment starving and fining derived from the coupled effect of active uplift of the Chianti Mounts and consequent subsidence of the Valdelsa Basin. The joined effect of subsidence pulses and rapidly rising sea-level at the Miocene-Pliocene transition determined periods of high relative base-level in the valley controlling the cyclic, fining-upward, filling pattern.

A similar, fluvial, succession occurs in the Casino Basin (Benvenuti *et al.* pers. comm.) attesting to the possible coeval development of a fluvial system draining the former Casino Basin and flowing to the ESE (i.e. toward the Siena Basin). It appears therefore that at the Miocene-Pliocene transition a watershed between the former Casino and the Valdelsa basins controlled a diverging drainage. Such a watershed formed as the consequence of the actively growing tranversal high which conditioned the Lago-Mare sedimentation in adjacent basins during the late Messinian.

The flooding of the Strolla Creek area at the early Zanclean maximum sea-level rise

The abrupt marine flooding marked by the mollusc-bearing mudstone sharply resting on UM1-UM2 and BS3 fluvial deposits effectively records the maximum Zanclean rise of the sea level that approached the Chianti Mounts (Fig. 10D). An inner shelf, dominated by sediment settling and populated by diversified benthic communities, replaced the fluvial environment. The lack of transitional environments between the fluvial and the inner shelf and the presence of a circalittoral/bathyal ostracod assemblage indicate a very rapid marine flooding.

The high sea level recorded by these deposits, reasonably related to the definitive re-filling of the Mediterranean Basin, may have been the last in a succession of flooding pulses which concurred to control the facies stacking pattern of the incised valley fill (see Discussion above). The physiography of the wide region including central Tuscany and the Northern Tyrrhenian Sea, was characterized in the Late Neogene by several basins separated by structural highs and located at elevations progressively higher toward the Northern Apennines divide. Zanclean sea flooding of the innermost portion of this region, thus, could have been delayed in respect with the flooding of the lowermost Northern Tyrrhenian Basin and adjoined coastal areas. Such a "threshold effect" on sea-level rise, hence on fluvial base level, may have represented a further controlling factor for the cyclic sedimentary filling of the Borro Strolla palaeovalley.

The Messinian and the Mio-Pliocene events: from a local to a regional perspective

The local stratigraphic architecture of the succession recording the Mio-Pliocene transition provides arguments for a comparison of events at wider scales. In general terms the Strolla Creek succession records a discontinuous transition from lacustrine to fluvial to open marine settings evidenced by two significant internal unconformities. The basal one separates UM1 from UM2 deposits whereas the upper unconformity subdivides UM1-UM2 from the Borro Strolla synthem.

Occurrence of unconformities in the Messinian successions of the Tuscan basins, documented on both sides of the Mid Tuscan Ridge, is discussed for comparison with the studied case (Fig. 11).

At least three major "intramessinian" unconformities are recognized in the Radicondoli-Volterra Basin (Fig. 1A) located west of the Mid Tuscan Ridge and bearing evaporites. Here, the pre-evaporitic terrestrial to shallow marine deposits, including primary evaporites pre-dating the Salinity Crisis (Benvenuti *et al.* 1999; Testa & Lugli 2000), are deformed (see Moratti & Bonini 1999 and Brogi & Liotta 2005 for alternative structural interpretations) and unconformably overlain, through unconformity Im$_a$, by clastics and resedimented evaporites. Angular unconformity Im$_b$ (Testa & Lugli 2000; Brogi *et al.* 2002, see also Pascucci *et al.* 2004 for a different interpretation of this stratigraphic transition) separates two gypsum units which are referred respectively to the lower (primary) and upper (resedimented) evaporites of Sicily and Spain (Testa & Lugli 2000). Finally unconformity Im$_c$ puts in contact the upper gypsum unit with a stratigraphically complex clastic succession including resedimented evaporites, gravels, sands, marls and clays (Montemamboli Group in Testa & Lugli 2000). On the whole the upper gypsum and overlying deposits are referred to the Lago-Mare realm (Testa & Lugli 2000; Pascucci *et al.* 2004).

East of the Mid Tuscan Ridge, where the Messinian is represented by fully terrestrial, evaporite-free, terrigenous successions, a prominent intramessinian unconformity is also documented. In the Velona Basin (Rook & Ghetti 1997; Bonini *et al.* 1999; Fig. 1B), strongly deformed fluvio-lacustrine deposits ascribed to the early Messinian (Ghetti *et al.* 2002) are angularly overlain by a further alluvial succession possibly of late Messinian age. As mentioned above a similar unconformity has been described in the Casino Basin (Lazzarotto & Sandrelli 1977; Bossio *et al.* 2001) separating the deformed upper Tortonian-lower Messinian fluvio-lacustrine deposits from the second fluvio-lacustrine succession encompassing the late Messinian. Due to the strong deformation of the underlying upper Tortonian-lower Messinian units, unconformities in these basins are tentatively correlated with the Im$_a$ of Volterra-Radicondoli Basin, thus pre-dating the Salinity Crisis. Similarly, we equate the inferred unconformable contact between UM1 and UM2 in the Strolla Creek area to unconformity Im$_a$.

The unconformity separating UM1-UM2 from the Borro Strolla synthem documents a further

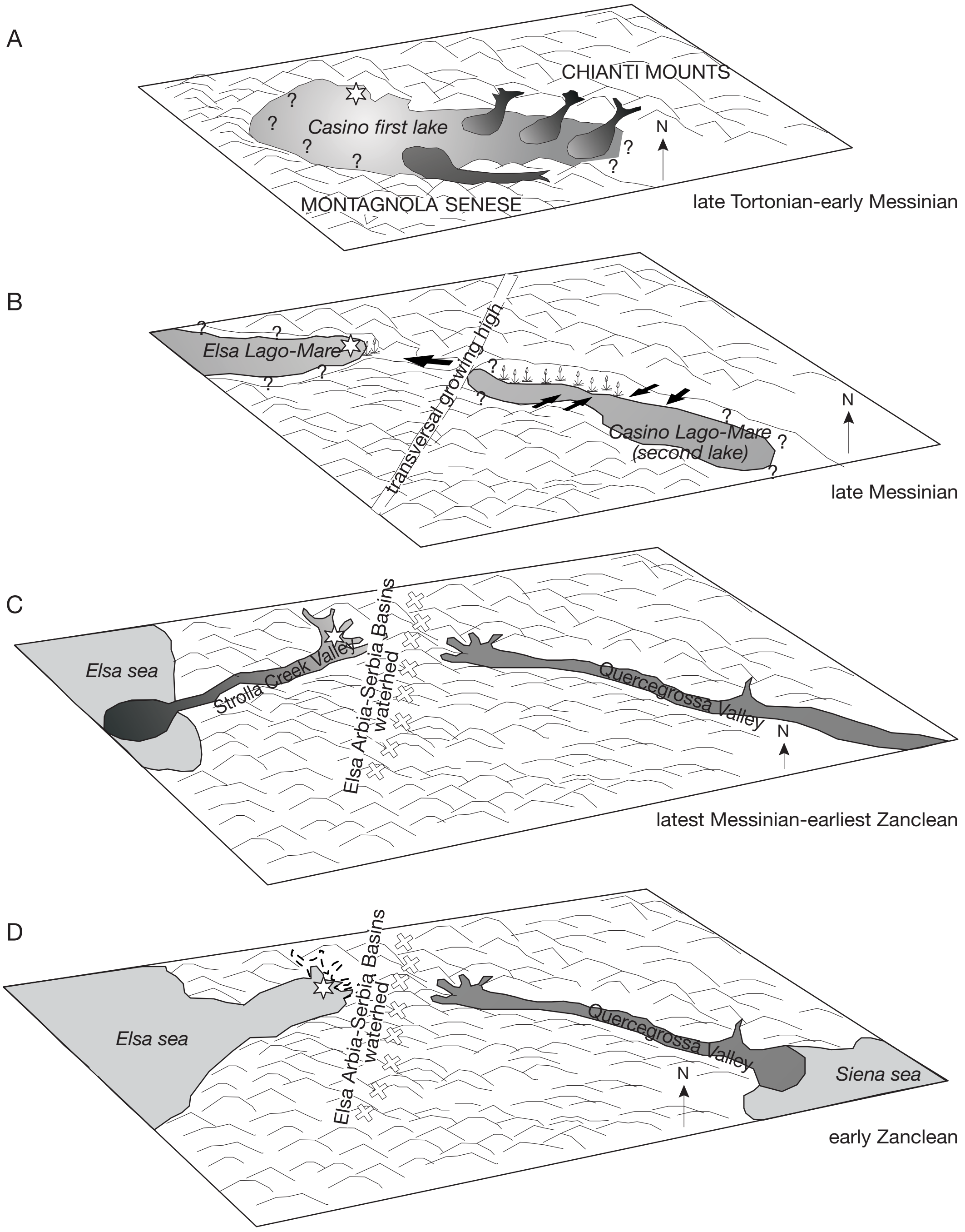

FIG.10. — **A**, The Strolla Creek area (✡) is included in the lacustrine Casino Basin; **B**, a NE-SW trending structural high separates the Casino from the Valdelsa basins, black arrows indicate major supply points; **C**, the NE-SW high is a watershed for drainage to the Valdelsa and Siena basins respectively; **D**, at the early Zanclean maximum of sea-level rise the Strolla Creek area is flooded.

event that characterized the end of the Messinian and that can be searched for in other Tuscan basins. The stratigraphically complex Montebamboli Group (*sensu* Testa & Lugli 2000), laying on top of several Messinian successions, has been frequently reported to be conformably overlain by lowermost Pliocene marine mudstones (Bossio *et al.* 1993). The basal unconformity of this succession may be related to the Im_c of the Volterra-Radicondoli Basin and, due to the occurrence of several coarse-grained alluvial units possibly separated by low-rank unconformities. On the northwestern margin of the Volterra Basin, for istance, alluvial gravels (i.e. "Conglomerati delle Volpaie", Lazzarotto *et al.* 2002), rest unconformably on the "Lago-Mare" deposits being in turn overlain by lowermost Pliocene marine mudstones. These alluvial deposits are ascribed to the lowermost Pliocene (Lazzarotto *et al.* 2002), though a latest Messinian age could be considered.

Similarly, in the Velona Basin Montebamboli-like alluvial deposits, resting unconformably on top of the Messinian succession (Rook & Ghetti 1997), may be reasonably referred to the Mio-Pliocene transition.

As already mentioned, a possibly equivalent unconformity occurs in the Casino Basin separating the Messinian fluvio-lacustrine deposits from fluvial gravels and sands possibly encompassing the Mio-Pliocene transition (Lazzarotto & Sandrelli 1977).

In conclusion we suggest that, despite lacking a precise chronostratigraphy, further low-rank unconformities punctuated the late Messinian in response to a generalised uplift of the basin's margins and that the youngest one, Im_d, could have marked a palaeogeographic transition from lacustrine to alluvial settings in some parts of central-southern Tuscany during the latest Messinian.

Two intramessinian unconformities (Im and Im_1), occur also in the evaporite-bearing deposits filling the Adriatic foredeep (Roveri *et al.* 2001, 2003; Fig. 11), and suggest a possible wider significance of tectonic events affecting the Northern Apennines during the latest Miocene. Specifically, in the foredeep basin, Im separates primary evaporites from post-evaporitic deposits similarly to the Im_b of the Tuscan basins. Unconformity Im_1 subdividing the post-evaporitic succession in two main units (P-ev1 and P-ev2), can be tentatively equated to Im_c-Im_d group of Tuscany. Major tectonic pulses in the Northern Apennines thrust belt and related deformation of the foredeep are suggested for the origin of these unconformities. Unconformity Im_1, in particular, marked the beginning of cyclic sedimentation recorded in the P-ev2 by fluvio-deltaic sandstone and mudstones. The cyclothemic arrangement, expressed by fining-upward trends within an overall backstepping fluvio-deltaic system, is interpreted as the effect of precession-dominated climatic cycles which controlled water and sediment discharge in the fluvial systems of the Northern Apennines during the latest Messinian (Roveri *et al.* 2001, 2003).

A latest Messinian unconformity, is recognized also in other Mediterranean marginal basins (Morocco, Spain, Sardinia, Sicily, Israel; Fortuin *et al.* 1995; Buchbinder & Zilberman 1997; Rouchy *et al.* 2003; Cornée *et al.* 2004; Soria *et al.* 2005) associated to non-marine or fully terrestrial deposits resting on the Lago-Mare deposits. This evidence suggests that at a regional scale the Mio-Pliocene transition may have been marked not only by rapid massive sea flooding as widely documented in relatively deep basins of eastern Mediterranean and Adriatic regions (Rouchy *et al.* 2001; Roveri *et al.* 2001, 2003) but also by base-level lowering and consequent fluvial incision caused by intense tectonic deformation of the circumediterranean margins and associated shallow basins.

CONCLUSIONS

The study of a clastic succession referred to the Late Neogene and exposed in the SE portion of the Valdelsa Basin has been carried out by the integration of physical stratigraphy, vertebrate and invertebrate (ostracods and continental molluscs) palaeontology. In particular attention has been focused on the sediments encompassing the Mio-Pliocene transition and included into the Borro Strolla synthem which represents a composite fill of a NE-SW trending fluvial valley, incised in upper Messinian Lago-Mare deposits, culminating with a marine flooding. The fluvial deposits characterizing the lower portion of this synthem bear scanty remains of the gerbil *Debruijnimys* sp. and the murid *Stephanomys* aff.

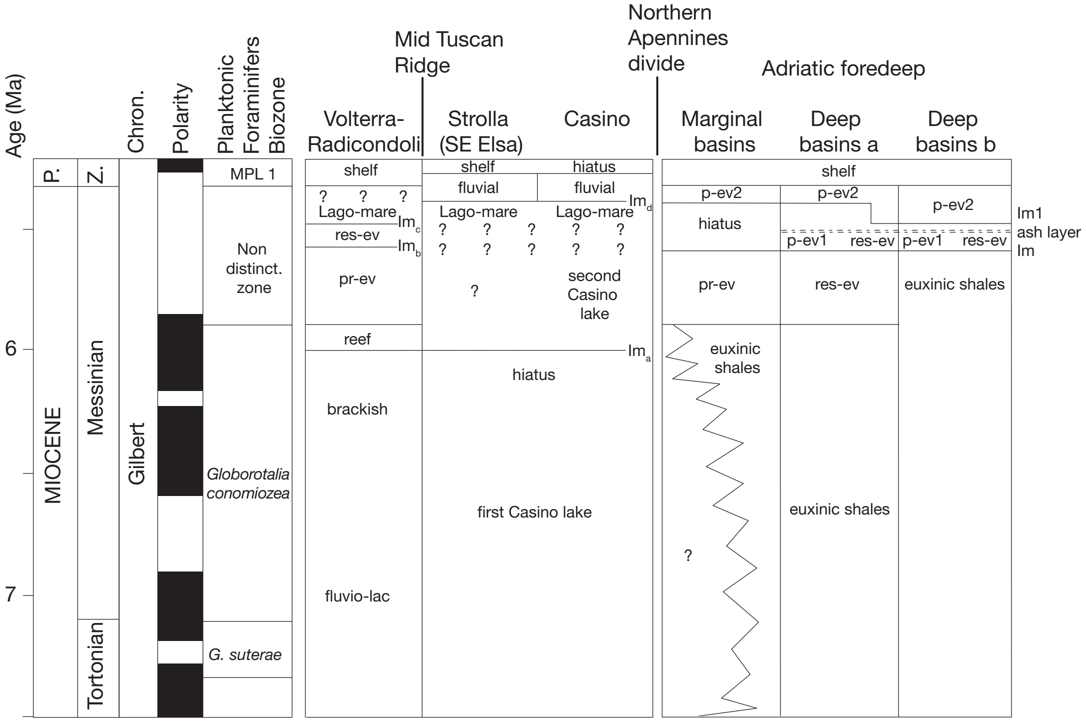

FIG. 11. — Tentative correlation of Tortonian-Messinian successions across the Northern Apennines region extending the scheme of Roveri *et al.* (2001) for the Adriatic margin and foredeep basins. Abbreviations: **Chron.**, chronology; **P.**, Pliocene; **Z.**, Zanclean.

S. donnezani (Depéret, 1890) (both rodents with Pliocene affinity) which represent significant novelties in regard to the latest Messinian mammal fauna Italian record. The co-occurrence of terrestrial molluscs from the same sediments with a Pliocene affinity, gives further biochronologic constrains supporting the calibration of the fluvial deposits to the latest Messinian-earliest Zanclean. Finally, the marine mudstone on top of the synthem were calibrated in previous studies to the early Zanclean. Besides the revised chronological calibration, the Borro Strolla synthem is characterized by a cyclic facies architecture which is interpreted in terms of interplay between variable sediment supply, depending on local, tectonically-controlled, relief uplift and denudation, and regional rise of sea-level. The latter was evidently driven by the earliest Pliocene refilling of the Mediterranean Basin following to the Salinity Crisis. The region between central Tuscany and the Northern Tyrrhenian Sea was characterized during the Late Neogene by several basins separated by structural highs determining a "threshold effect" on the earliest Pliocene sea-level rise which may have caused pulsatory variation of the fluvial base level. This effect may have concurred to the development of cyclic facies trends in the fluvial portion of the Borro Strolla synthem.

On the whole the Strolla Creek succession records a discontinuous transition from lacustrine to fluvial to open marine settings evidenced by two significant internal unconformities which may have some equivalents in the Northern Apennines region. In particular the occurrence of a latest Messinian unconformity allows to reconsider the local Messinian-Zanclean transition as not properly continuous, a conclusion having possible implications at a wider scale. The Mio-Pliocene transition may have been marked not only by rapid massive sea flooding as commonly documented in the Mediterranean deep basins. Tectonic uplift in the marginal areas may have locally subtracted accommodation space during the rapid refilling of the Mediterranean Basin, favouring erosional truncations and the development of terrestrial environments which, as in the studied area, may have locally persisted up to the earliest Pliocene.

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