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Geobios (2002) Mémoire spécial n° 24

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Palaeoenvironmental changes in the Pliocene Intra-Apenninic Basin, near Bologna (Northern Italy)

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Received 21 November 2001; accepted 18 February 2002

Abstract

Combined palaeoecologic and sedimentologic studies reveal remarkable palaeoenvironmental changes in the Pliocene Intra-Apenninic Basin (PIB) of the Bologna Apennines (Northern Italy). At the northern margin of PIB, the stratigraphic succession is approximately 1000 m thick, and displays an overall coarsening-upward trend, including a lower mudstone-dominated succession (Argille Azzurre Formation) of Zanclean age, overlain by a sandstone-rich unit (M. Adone Formation), assigned to the Zanclean-Piacenzian. The vertical succession of biofacies within the Argille Azzurre Fm. indicates an obvious shallowing-upward tendency, from slope/outer-shelf (150–300 m water depths) to inner-shelf (30–50 m) environments. A vertical cyclic pattern of facies, with alternating sandy siltstones and sandstone bodies, characterizes M. Adone Formation. Each elementary cycle, about 30–50 m thick, includes a couple of siltstone-dominated inner-shelf and prodelta deposits, passing upwards into progradational delta front, tabular sand bodies. These high-rank cycles, spanning an interval of time in the order of magnitude of 40 ky, are separated by flooding surfaces, clearly recognizable on the basis of palaeoecologic analysis, and reflect an aggradational stacking pattern of parasequences superposed to the general shallowing-upward trend.

Keywords: Palaeoecology; Depositional cycles; Northern Apennines; Pliocene

1. Introduction

The development of integrated models of depositional environment and fossil data has always been a primary need intrinsic to taphonomy and palaeoecology. The present challenge is the integration of the palaeoecologic approach within sequence stratigraphy and its predictive models. In this respect, the Pliocene Intra-Apenninic Basin of the Bologna Apennines (Northern Italy) may constitute an interesting ground to constrain the palaeoecologic approach within a detailed stratigraphic and sedimentologic framework.

The Intra-Apenninic Basin (PIB of Ricci Lucchi et al., 1981) is located at the Northern Apennine foothills, just a few kilometres south of Bologna (Fig. 1). Despite its name, PIB was not a real intramontane basin, but developed during the Pliocene as an embayment or gulf, open to the Po-Adriatic Sea, in direct connection with the Periadriatic Apennines (Ricci Lucchi et al., 1981). Coarse-grained, laterally coalescent fan-delta systems were present in the proximal part of the basin (southern margin of PIB), and made transition, in the distal (northern) sector of the basin, to mudstone-dominated, open-marine successions, with intervening sandstone bodies.

The first attempt at establishing a stratigraphic and sedimentologic framework for PIB was carried out by Ricci Lucchi et al. (1981), who identified two major depositional cycles at the basin scale, providing the basis for sequence stratigraphic interpretation of the study succession. These studies, however, were concentrated almost entirely on the southern margin of PIB. As a consequence, the fine-grained stratigraphic succession cropping out in the northern part of the basin has received scant attention, with the exception of very local studies (Fregni and Panini, 1996; Panini and Fregni, 2000; Scarponi and Di Stefano, 2000).

The aim of this paper is to provide detailed documentation of stratigraphic architecture and palaeogeographic evolution at the northern margin of PIB, based upon combined sedimentologic and palaeoecologic data, in order to make a

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PII: S0016-6995(02)00044-X

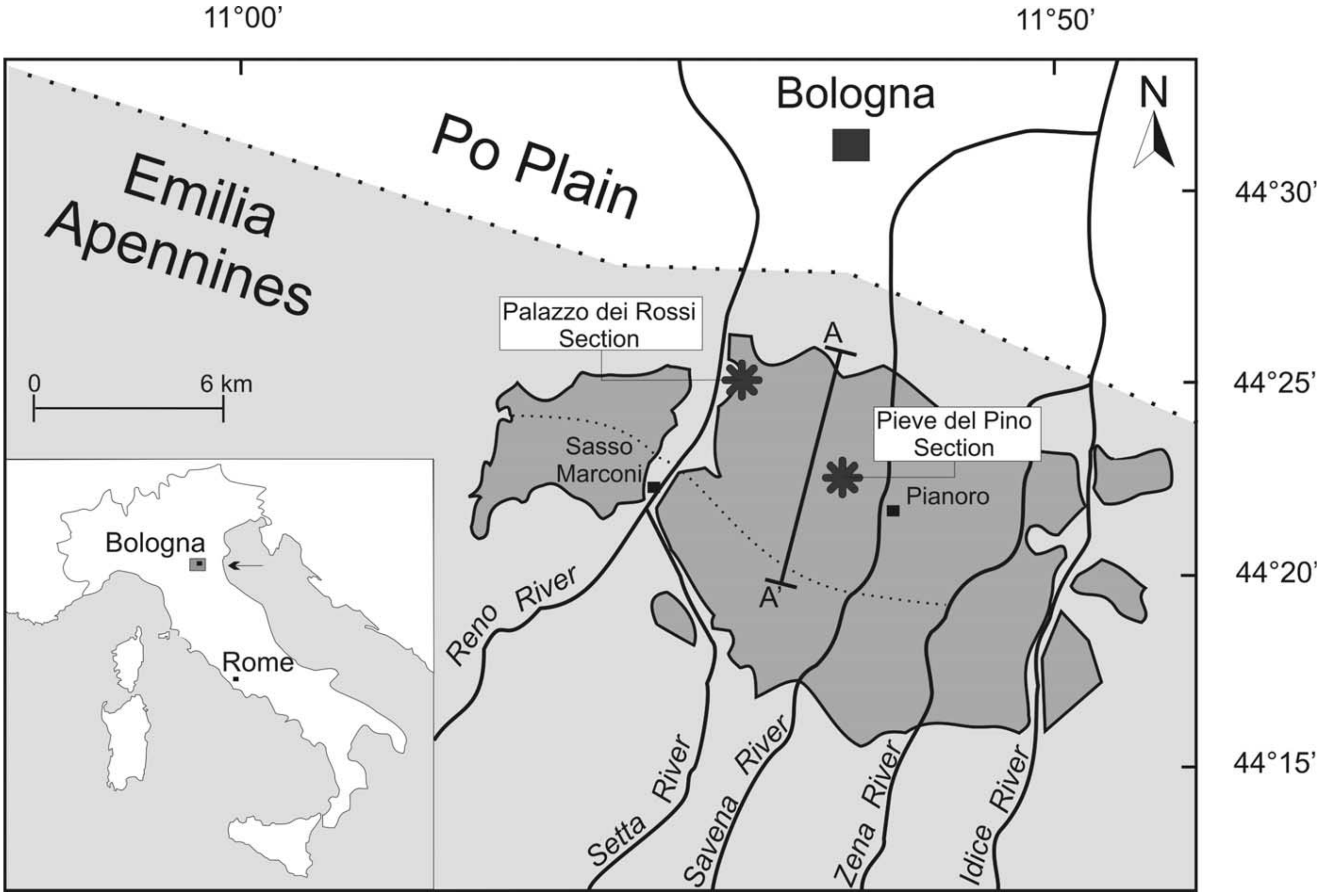

Fig. 1. Location map of the Pliocene Intra-Apenninic Basin (dark grey), with indication of the two study sections (Figs. 3–5) and section trace of Fig. 2. The dotted line marks the synclinal axis.

preliminary comparison with the well-known stratigraphic succession at the southern margin of the basin. Specific objective of this work is to document how palaeoecologic studies can play a fundamental role in reconstructing the depositional history of sedimentary basins, resulting in refined facies characterization of mudstone-prone successions.

2. Geologic and stratigraphic background

2.1. The Northern Apennines

The Apennines are a thrust and fold belt, the building of which started in the late Cretaceous, with the consumption of the Ligurian-Piedmont oceanic basin (Oceanic Phase) along a west-dipping subduction beneath the European plate (Boccaletti et al., 1980; Sestini et al., 1986; Bortolotti et al., 2001). The modern framework of the Northern Apennines originated from the subsequent continental collision (Ensialic Phase) between the Corsica-Sardinian block to the west, and the sinking Adria promontory (African plate) to the east. This collision took place through successive evolutionary stages, starting from the late Oligocene (Abbate et al., 1970; Gasperi et al., 1986; Ricci Lucchi, 1986; Laubscher, 1988; Boccaletti et al., 1990a, b; Conti and Gelmini, 1994; Mariucci et al., 1999). The inner part of the Northern Apennine arc was subjected to deformation and metamorphism during the late Oligocene-Tortonian; deformation extended to the outer part of the chain between the late Messinian and the middle Pleistocene (Vai, 2001).

The evolution of the Northern Apennines during the Neogene was marked by a characteristic NNE-migrating pattern, of compressional regime in the front of the chain and extension in the hinterland area. The compressional regime was marked by the east-northeastward migration of the thrust systems and related foreland basins, which originated ahead of the thrust fronts. These were progressively incorporated into the thrust systems (Ricci Lucchi, 1986). The thrust front reached its outermost position at the end of the early Pliocene (Vai, 1987), when filling of the Pliocene Intra-Apenninic Basin took place.

2.2. Stratigraphy of the Bologna Apennines

The two major palaeogeographic-structural elements forming the Northern Apennine arc in the Bologna area are: the Ligurian nappe, including Jurassic ophiolites of the ancient Ligurian-Piedmont oceanic basin, and Jurassic to Eocene thrust sheets, made up of pelagic successions, capped by turbidites. The Ligurian nappe was obducted over both the African (Insubric) and European (Corsica) continental margins during the Eocene and then underwent compressional reactivation and eastward transport (Bettelli et al., 1987; Bettelli and Panini, 1987; Pini, 1999 and references therein; Vai, 2001). In the Bologna area, the Ligurian nappe consists predominantly of rock units characterized in outcrop by variably disrupted strata or blocks of diverse sizes disposed in a clay-rich matrix (Pini, 1999). These units have been subdivided into tectonosomes, originated by in situ tectonic deformation, and olistostromes, originated by gravitational mass movements (Cowan and Pini, 2001).

The Epiligurian sequences, which include mostly terrigenous, diachronous deposits of late Eocene to early Pleistocene age, unconformably overlie the Ligurian nappe. The Epiligurian successions were deposited within satellite, thrust-top (or piggy-back) basins on top of the Ligurian nappe, during its NE migration (Ricci Lucchi, 1986; Bettelli et al., 1987). For this reason, the term “semi-allochthonous” (Ricci Lucchi, 1987) has been used to define these units. The Epiligurian successions, which are separated by major unconformities marking significant depositional/erosional hiatuses, are characterized by a lesser degree of deformation with respect to the underlying Ligurian nappe, and reflect a progressive decrease of tectonic migration through time. The Pliocene Intra-Apenninic Basin represents the youngest of the Epiligurian units.

2.3. The Pliocene Intra-Apenninic Basin

The Pliocene Intra-Apenninic Basin (PIB) forms an isolated, floating slab, which unconformably overlies either the Ligurian nappe (see “Argille Scagliose” in Fig. 2) or the Epiligurian (Bismantova Group and Termina Formation) sequences (Lucchetti et al., 1962; Ricci Lucchi et al., 1981). A recent paper by Panini and Fregni (2000) shows that PIB may locally overlie lacustrine muddy-marly deposits of late Messinian age, assigned to post-evaporitic Colombacci Formation.

During the last important Apennine orogenic phase, of late Pliocene age, the sedimentary fill of PIB was slightly deformed in a broad asymmetrical syncline, with WNW-ESE axis, and segmented by transversal faults. The depocentral area, showing a maximum thickness of approximately 1.000 m, has a broadly pentangle shape, comprised between the Reno and Idice rivers valleys (Fig. 1). West of the Reno transversal fault and east of the Idice tectonic line, the overall thickness of PIB is dramatically reduced to about 100 m (Ricci Lucchi et al., 1981).

A basinwide unconformity enables identification of two distinct depositional cycles (1 and 2), especially at the southern margin of PIB (Ricci Lucchi et al., 1981). In this area, the stratigraphic architecture consists of a complex pattern of fan-delta/fluvial conglomerates, freshwater/lagoonal mudstones, and littoral sandstones. The unconformity separating the two depositional cycles is replaced at seaward locations (northern margin of PIB) by a correlative conformable surface, with continental and coastal units showing transition to shallow-marine and open-marine deposits. In this part of the basin, the lower part of the succession, tentatively correlated to cycle 1, is made up of monotonous and structureless, grey-blue mudstones, 450 m thick, whereas the upper part (cycle 2), about 500 m thick, shows a vertical stacking pattern of facies, made up of progradational sandstone bodies.

Literature data (Ricci Lucchi et al., 1981) suggest an early Pliocene age (*Globorotalia puncticulata* zone) for cycle 1, and a middle-late Pliocene age for cycle 2. A similar age attribution is the one by Vai and Castellarin (1992), who indicate lack of *Globorotalia margaritae* zone in PIB.

Following the criteria adopted by Geological Survey of Regione Emilia-Romagna in its geological maps, the stratigraphic succession cropping out at the northern margin of PIB is here provisionally included into a lithostratigraphic framework, and subdivided into two formations: Argille Azzurre (= blue clays) Formation and M. Adone Formation (Fig. 2). These broadly correspond to cycles 1 and 2 of Ricci Lucchi et al. (1981), respectively. A stratigraphic subdivision into allostratigraphic units is in progress.

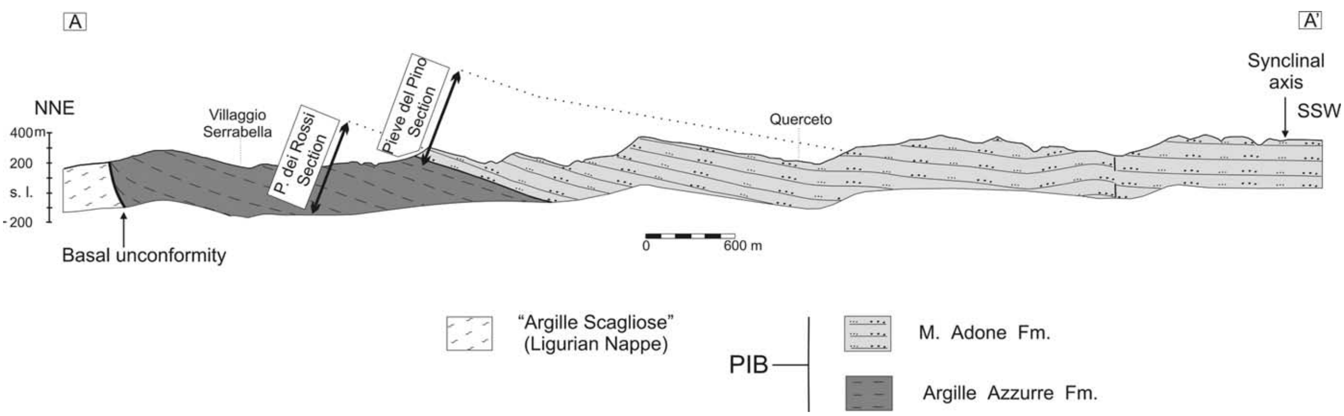

Fig. 2. Geologic cross-section across the northern limb of the Pliocene Intra-Apenninic syncline.

2.4. Methods

Following close field inspection, a total of 46 bulk samples (Bks), including in situ (living position) or little-transported fossils, were collected in coincidence of selected stratigraphic intervals. Where strata include homogeneous fossils assemblages, bulk samples are locally representative of up to 10 m of section.

Single bulk samples were subdivided into several block units. Block units were soaked in H_2O_2 solution, and molluscs were isolated using 1 and 5 mm sieves. The fossils were then taxonomically identified and counted, following methods suggested by Di Geronimo and Robba (1976). In order to get representative samples, counting procedure was repeated until the percentage of new species in the considered block-unit was < 10% number of species recovered.

Blue, homogeneous or poorly stratified mudstones with scanty sedimentary structures characterize the lower 340 m of Pliocene deposits, where 19 bulk samples were recovered. Despite remarkably high bulk sample volumes ($10 < Bk < 25$ l), a small number of specimens (N) were recovered ($15 < N < 40$), with the exception of Bk 19 ($N = 90$). This did not allow the statistic treatment of data. However, following methods by Robba (1990), based upon the presence/absence and relative abundance of species, six stratigraphic intervals characterized by distinctive molluscan biofacies were recognized. Within each biofacies, the mean abundance and mean dominance (Dm) of species were calculated. Only taxa with Dm > 3% were considered in this paper, except for key species regarded as environmental indicators.

The upper part of the study succession, dominated by sandstone–mudstone alternations, was investigated mostly on the basis of a sedimentological approach. Through reconnaissance surveys followed by stepwise refinements, facies associations were recognized and interpreted in terms of processes, environments, and depositional cycles. The fossil assemblages found in each facies association are discussed on the basis of bathymetric zonation and palaeoecologic significance. A statistical treatment of mollusc database is in progress.

Palaeoecologic interpretation of molluscs was based upon papers by Vatova (1949), Thorson (1957), Pérès and Picard (1964), Picard (1965), Carpine (1970), Massé (1971), Robba (1981, 1990), Catellani (1989), Cauquil (1992), Bernasconi and Robba (1993), Diaz and Rosenberg (1995), Aguirre et al. (1996), and Monegatti et al. (1997).

3. Lithostratigraphy, sedimentology and palaeoecology at the northern margin of PIB

An almost complete section across the northern margin of PIB (Fig. 2) is exposed between the Reno River and Savena River valleys (Fig. 1), where two sections (Palazzo dei Rossi— Fig. 3 and Pieve del Pino— Fig. 4) were measured and sampled for sedimentologic and palaeoecologic analyses, for a total thickness of 821 m (Fig. 5). The uppermost 150 m of PIB are discontinuously exposed, and for this reason are not reported in this work (Scarponi, 2002).

3.1. Argille Azzurre Formation

One of the best exposures of the Argille Azzurre Formation in PIB is the Palazzo dei Rossi section (Figs. 3 and 5). This section, approximately 450 m thick, is located 10 km SW of Bologna and 3.5 km NE of Sasso Marconi (Fig. 1).

Fig. 3. The Palazzo dei Rossi section (see Fig. 1, for location). The clayey unit below the Argille Azzurre Fm. includes the “Argille Scagliose” and the overlying Tortonian Termina Fm.

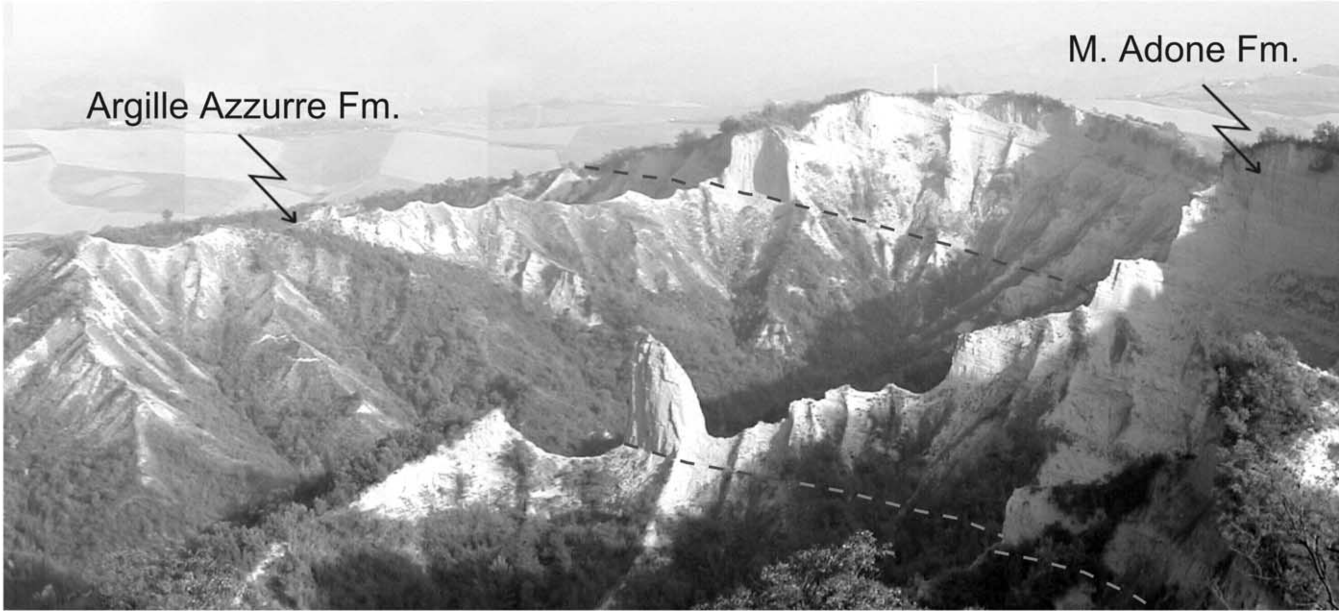

Fig. 4. Lower part of Pieve del Pino section (see Fig. 1, for location).

The Pliocene deposits crop out along the banks of Reno River, between the Reno Quarry and the old and fashionable Palazzo dei Rossi Castle. The Palazzo dei Rossi section is apparently continuous, and with no appreciable tectonic disturbances.

A recent paper by Scarponi and Di Stefano (2000) has shown that the Pliocene succession in the Palazzo dei Rossi section unconformably overlies an alternation of dark-green clayey marls and thin (< 10 cm) sandstone beds, of early Tortonian age (zone MNN8a sensu Fornaciari et al., 1996), which have been assigned to Termina Formation (Fig. 5). The boundary between the Argille Azzurre and M. Adone Formations, covered by a small artificial lake along Reno River (see Fig. 5), can be easily seen on the eastern side of Reno River (Fig. 3).

On the basis of preliminary micropalaeontological data from the Palazzo dei Rossi section, the Argille Azzurre Formation can be attributed to the lower part of the early Pliocene (Zanclean), as indicated by the first recovering in PIB of *G. margaritae* across most (60–200 m) of the section (M.L. Colalongo and S.C. Vaiani, pers. com. 2001). This age assignment, which is fully consistent with data from calcareous nannofossil biostratigraphy (Scarponi and Di Stefano, 2000; A. Di Stefano, pers. com. 2001), suggesting an attribution of the lower 250 m to zone MNN12 of Rio et al. (1990), indicates a slightly older age than reported by previous work (see Ricci Lucchi et al., 1981; Vai and Castellarin, 1992).

3.1.1. Description

Grey-blue, massive or poorly stratified mudstones (clay content around 35%, and sand < 5%) characterize the lower-middle part of the Argille Azzurre Formation (between 0 and 265 m). Mudstones are structureless, owing to pervasive burrowing. A slight upward increase in silt proportion is recorded in this part of the unit. The uppermost 80 m record a transitional lithological change to sandy mudstones and then sandy siltstones, displaying a lower proportion of clay (around 20%) and a higher amount of sand (10–30%). This allows a general coarsening-upward tendency to be identified (Fig. 5). Very thin, centimetre-thick, sand layers, with sharp base and occasional normal grading, are recognized at places.

A biofacies dominated by *Korobkovia oblonga* (Dm 22%), with abundant *Limea strigilata* (Dm 9.9%), *Nassarius cabrierensis* (Dm 7%) and *Mitrella thiara* (Dm 4.2%), is present in the lower 95 m of Palazzo dei Rossi section (Bks 1–7 in Fig. 5). This stratigraphic interval also records lack of eulamellibranchs filter feeders and relatively high cumulative Dm 22% of protobranchs deposit-detritus feeders, such as *Nucula sulcata*, *Jupiteria concava*, *Pseudomalletia caterinii*, *Neilo isseli*, and other deposit-detritus feeders, such as *Gadilina triquetra* (Dm 5%).

The stratigraphic interval between 95 and 130 m (Bks 8–10) is characterized by the dominance of filter feeders, with *L. strigilata* as dominant species (Dm 13.2%), and by the first appearance of eulamellibranch filter feeder *Venus nux* (Dm 3%). This interval records a dramatic decrease (cumulative Dm 6.3%) in protobranchs detritus-deposit feeders (*N. isseli*, Dm 2.3%, is the best represented), concurrent with the disappearance of *K. oblonga* and *G. triquetra*, and appearance of *Yoldia nitida* (Dm 1.8%) and *Limopsis merklini* (Dm 12.1%). This interval is also characterized by remarkable percentages of *Nassarius italicus* (Dm 12.9%), *Dentalium sexangulum* (Dm 11.2%) and *Corbula gibba* (Dm 5.4%).

The middle portion of the Argille Azzurre, between 130 and 200 m (Bks 11–15), records a relative increase in

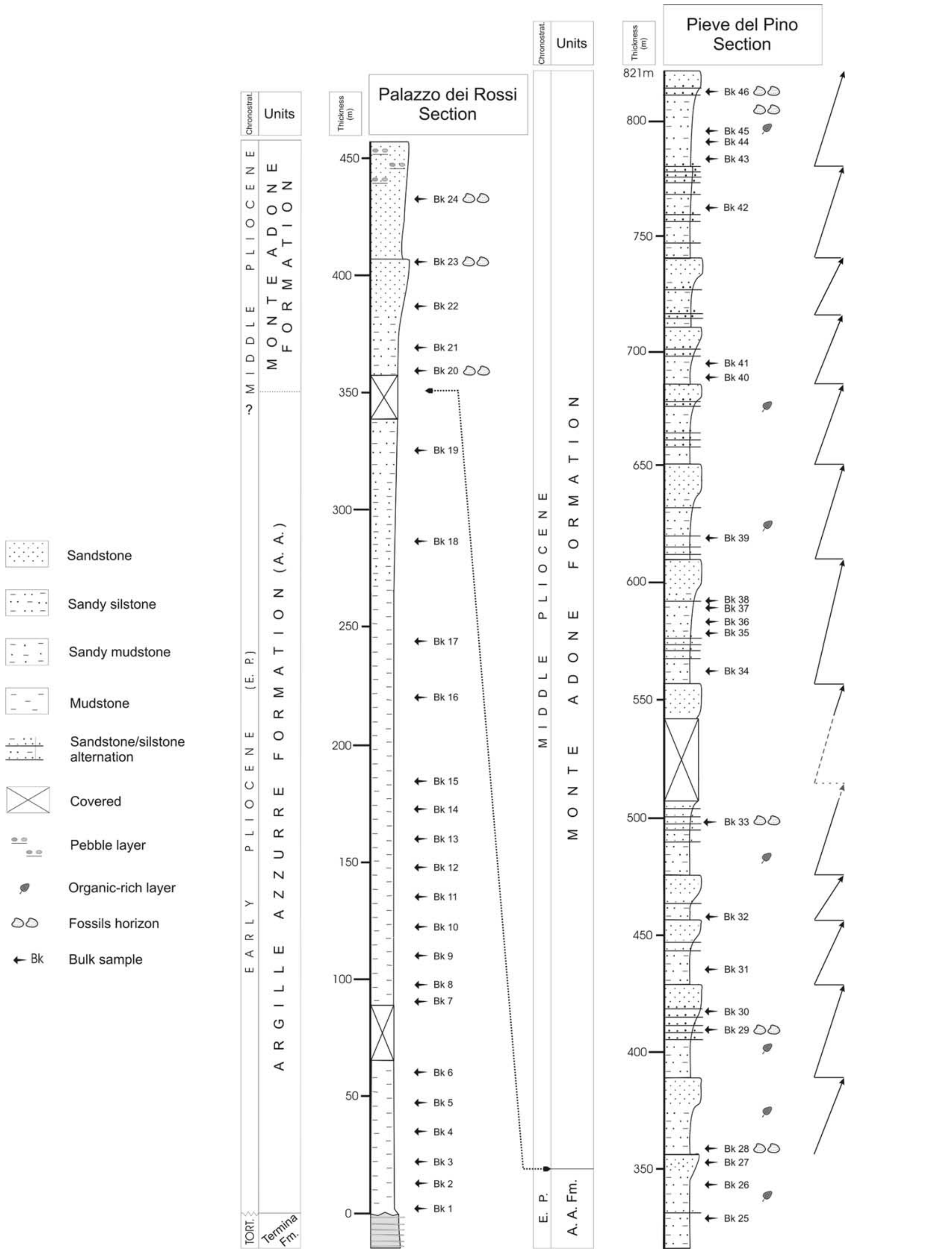

Fig. 5. Lithostratigraphy and stratigraphic correlation of the two study sections. The arrows mark the 13 parasequences identified within M. Adone Formation.

taxonomic diversity, associated to increasing *V. nux* (Dm 8.7%), and decrease in *L. strigilata* (Dm 8.7%), *L. merklini* (Dm 5.7%), *N. italicus* (Dm 3.3%) and *C. gibba* (Dm 3%). This stratigraphic interval, dominated by *Turritella spirata* (Dm 12.6%), records the disappearance of almost all protobranchs identified in the underlying deposits (with the exception of *Y. nitida*), and the appearance of protobranch *Saccella commutata* (Dm 6.8%), along with the appearance of *Amusium cristatum* (Dm 5.7%), *Tellina serrata* (Dm 4.4%), *Hiattella arctica* (Dm 3%) and *Myrtea spinifera* (Dm 2%).

Higher up in the stratigraphic column, between 200 and 270 m (Bks 16–17), a very low-diversity association, with dominance of *Nucula placentina* (Dm 28%) and abundant *A. cristatum* (Dm 11.7%), *V. nux* (Dm 8.5%), *Aporrhais uttingeriana* (Dm 8%), *N. sulcata* (Dm 7%) and *Conus antidiluvianus* (Dm 6%) is recorded. This stratigraphic interval, characterized by disappearance of *T. spirata*, *L. merklini*, *Y. nitida*, *T. serrata*, *M. spinifera*, *H. arctica*, and a further decrease in abundance of *L. strigilata* (Dm 3%), can be differentiated from the overlying and underlying deposits by the abundance of juvenile shells.

Shell abundance increases significantly between 270 and 310 m (Bk 18). In this stratigraphic interval, the dominance (D 13%) of *Timoclea ovata* with abundant *Y. nitida* (D 8.9%), *Odostomia conoidea* (D 7.8%), *Nassarius semistriatus* (D 7%) and *S. commutata* (D 6.7%) is recorded, along with the appearance of *Aequipecten seniensis* (D 8.3%), *Pelecyora brocchii* (D 4%) and *Turbonilla lanceae* (D 3.4%), and the decrease in mud-seeker taxa, such as *T. spirata* (D 3%) and *A. uttingeriana* (D 3%).

In the upper part of the Argille Azzurre, between 310 and 340 m (Bk 19), the macrofauna is characterized by the dominance (D 21.6%) of *Anadara diluvii*, extensive encrustation (mostly *Petaloconchus glomeratus* (D 12%), *Chama gryphoides* (D 5%) and appearance of *Turritella tricarinata* (D 4%) and *Acteon semistriatus* (D 3.3 %)). The sporadic presence of *Bolinus brandaris*, and some articulated specimens of *Glycymeris insubrica*, is also observed. The correlative deposits in the Pieve del Pino section (Fig. 5) display a relatively high-diversity fossil assemblage (Bk 26), characterized by high percentages of *Bela brachystoma*, *T. ovata* and *S. commutata*.

3.1.2. Interpretation

Due to homogeneous lithologic characteristics and lack or scarcity of sedimentary structures within the Argille Azzurre, sedimentologic criteria are hardly suitable for detailed palaeoenvironmental interpretation in this part of the succession, and palaeoecologic analysis constitutes the most powerful tool for palaeobathymetric inferences.

The vertical succession of biofacies identified at Palazzo dei Rossi section clearly indicates a general shallowing-upward trend within the Argille Azzurre Formation, from a slope-outer shelf transition to an inner-shelf environment. This trend, already suggested by Ricci Lucchi et al. (1981) on the basis of foraminifera and ostracod analysis, is consistent with the observed facies characteristics and grain-size variations, showing an overall coarsening-upward tendency.

Particularly, the dominance of *K. oblonga* recorded in the lower part of the unit, combined with abundance of *N. cabrierensis*, *M. thiara* and protobranchs detritus-deposit feeders, and the absence of eulamellibranchs, indicate an upper bathyal environment, with depths ranging between 150 and 300 m. Low diversity and high cumulative Dm of *K. oblonga*, *L. strigilata* and *G. triquetra*, suggest relatively high sedimentation rates (Pavia et al., 1989; Bernasconi, 1990, 1996). The *K. oblonga*–*L. strigilata* biofacies is included in the *K. oblonga*–*J. concava* type palaeocommunity of Ceregato and Raffi (2001), interpreted as typical of the upper bathyal muddy environment. This palaeocommunity, although labelled with different names in previous work, is very common in early and middle Pliocene deposits of Northern Italy (Raineri, 1986; Cauquil et al., 1992; Catellani, 1989; Monegatti et al., 2001).

The rapid transition to significantly shallower environments (palaeodepths between 90 and 180 m) is recorded by the dramatic decrease in protobranchs and the first appearance of *V. nux*, within the 95–130 m stratigraphic interval. A transition to a deep circalittoral environment is also strongly suggested in this instance by the presence of *Y. nitida*, *L. merklini* and remarkable mean dominance of *N. italicus* (Robba, 1990). In particular, the high mean percentages of opportunistic *L. strigilata* and *C. gibba* can be related to a muddy low-energy environment, with increased sedimentation rates with respect to underlying biofacies.

The mollusc assemblage between 130 and 200 m provides evidence for a muddy circalittoral environment (open shelf). A similar biofacies has been commonly reported from the Pliocene deposits of the Northern Apennine foothills by Marasti and Raffi (1976, 1977), Monegatti and Raffi (1996), and Civis et al. (1999). Disappearance of the bathyal protobranchs, combined with increase in *V. nux* and appearance of *S. commutata*, *A. cristatum*, *T. serrata*, and *M. spinifera*, indicate shallower depositional environments, which can be related to the terrigenous-mud community (VTC) of Pérès and Picard (1964), typically developed between 50 and 120 m water depths.

The stratigraphic interval between 200 and 270 m records mostly changes in palaeoenvironmental conditions rather than in palaeodepth. The high cumulative mean percentage of *A. cristatum*, *V. nux*, *A. uttingeriana* and *C. antidiluvianus* suggests a muddy low-energy shelf environment. The occurrence of a low-diversity assemblage, combined with the high rates of juvenile mortality and the remarkable mean dominance of *N. sulcata*, suggests possible hypoxic conditions (Allen, 1978; Taylor et al., 1995). It is noteworthy that the overlying sediments are characterized by the re-appearance (although with lower dominance values) of some taxa of the underling stratigraphic interval.

An upward transition to a sandy–muddy circalittoral environment is suggested by fossil assemblage between 270 and 310 m, concurrent with the slight increase in grain size. Lower water depths seem to be suggested by higher shell abundance and high cumulative percentage of infralittoral/circalittoral taxa, such as *T. ovata*, *A. seniensis*, *P. brocchi*, and *T. lanceae*. This interpretation is also consistent with decrease of strictly mud-seeker taxa *T. spirata* and *A. uttingeriana*.

The uppermost part of the Argille Azzurre (interval between 310 and 340 m) records a further decrease in water depth, as documented by *T. tricarinata* and the presence (rare) of typical infralittoral taxa, such as *A. semistriatus*, *B. brandaris* and *G. insubrica*. These suggest an upper circalittoral-lower infralittoral (inner shelf) environment, with silty–sandy bottoms, and water depths possibly ranging between 30 and 50 m. The fossil assemblage dominated by *B. brachystoma* and *T. ovata*, recovered in Pieve del Pino section at the same stratigraphic level, is interpreted to reflect a slightly different depositional environment, with detritic muddy bottoms, but similar bathymetric significance (30–60 m).

3.2. M. Adone Formation

At the northern margin of PIB, the sandstone-rich M. Adone Formation is best exposed along the Reno River/Savena River divide (Fig. 4), where an almost complete section (Pieve del Pino— Figs. 4 and 5) has been measured, between Villaggio Serrabella and Pianoro. The Pieve del Pino section includes the boundary between the Argille Azzurre and M. Adone Formations and is about 500 m long.

The almost ubiquitous presence of *G. puncticulata* in the Pieve del Pino section suggests a late Zanclean (?)—early Piacenzian age for M. Adone Formation (M.L. Colalongo and S.C. Vaiani, pers. com. 2001), which is partly consistent with the middle Pliocene age suggested by Ricci Lucchi et al. (1981) for this part of PIB. The entire section, however, is attributed to the lower part of the middle Pliocene and there exists no microfaunal evidence of a possible younger (late Pliocene) age, even in the uppermost deposits of PIB (see Rio Caurinziano section in Scarponi, 2002).

3.2.1. Description

The rapid, vertical transition from the Argille Azzurre Formation to overlying M. Adone Formation is characterized by the remarkable increase in the sandstone/mudstone ratio, which readily enables identification of the two formations in the field (Figs. 3 and 4). The boundary between the Argille Azzurre and M. Adone Formations broadly corresponds to the boundary between cycles 1 and 2 of Ricci-Lucchi et al. (1981).

In the study area, M. Adone Formation is characterized by the distinctive cyclic alternation, from base to top, of sandy siltstones (similar to those recorded in upper part of the Argille Azzurre Formation), sandstone–siltstone alternations, and fine-grained sandstone bodies (Fig. 5). In the Pieve del Pino section, M. Adone Formation includes 13 depositional cycles (Fig. 5), about 30–50 m thick, showing a characteristic vertical cyclic pattern of facies. Each depositional cycle exhibits sharp lower and upper boundaries, and distinctive internal coarsening-upward trends. The fine-grained (sandy-siltstone) bodies wedge out in landward direction, and are replaced by amalgamated sandstone bodies. These lithologic changes result in lateral transition from Ganzole Member of M. Adone Formation (northern margin of PIB) to M. Mario Member (southern margin of PIB). The latter is dominated by amalgamated sandstone bodies, with common occurrence of conglomerate bodies.

The lower parts of the 13 cycles identified within M. Adone Formation include massive and extensively bioturbated sandy siltstones, with faint traces of sedimentary structures (mostly horizontal lamination), and locally abundant plant debris and organic-rich layers (Fig. 5). Graded, horizontally laminated, or structureless sand layers, a few centimetre to decimetre thick, are present at places. Sand layers become progressively thicker and more abundant upwards, forming distinctive sandstone–siltstone alternations. Amalgamated sandstone bodies form the topmost units in the basic depositional cycle. Individual bodies have a tabular shape (some of them are traceable basinwide), gradational base, and consist of horizontal to gently undulating (hummocky cross-stratification—HCS) laminated sand, with discontinuous mud intervals. Symmetrical ripples are common and clay-chips alignments are generally encountered just above amalgamation surfaces.

Mollusc shells are abundant and scattered within the sandy siltstones, where individuals with attached valves and in living position are commonly found. By contrast, poorly preserved mollusc remains are generally concentrated in lags and pavements within sandstone bodies. The mollusc fauna displays also cyclic patterns, showing strict relationships with the above facies characteristics.

The basal, finer-grained portions of cycles are characterized by a fauna generally dominated by *V. nux* and *N. semistriatus* (Bks 20, 28, 35, 36, and 42–45), with less frequent occurrences of *B. brachystoma*, *T. ovata* and *S. commutata* (Bks 25, 32, and 39). The presence of *Neverita josephinia*, *Turbonilla lactea* and *Tornus excalliferus* is also recorded just above cycle boundaries, although in relatively small amounts. The above species decrease upwards within the sandy siltstones, and are progressively replaced by a monospecific/moderate diversity assemblage, with high percentages of *C. gibba* (Bks 22, 31, 34, 37, 38, 40, and 41), locally associated to monospecific assemblages of *T. tricarinata* and *Ditrupa arietina*. Fossil concentration shows a general upward decrease and, in many instances, the upper parts of sandy siltstone bodies have virtually no fossils.

A remarkable change in biofacies is recorded in upper parts of cycles (Bks 23, 24, 27, 29, 30, 33, and 46), where sandy siltstones are progressively replaced by sand-silt alternations and, eventually, by sandstone bodies. Sand-silt alternations are dominated by *Spisula subtruncata*, *Chamelea gallina* and *Euspira nitida*, although in rare instances, a fauna dominated by *Pecten bosniasckii* has been observed. The upward transition to sandstone bodies is generally marked by a high abundance of *G. insubrica*.

3.2.2. Interpretation

The high sandstone/siltstone ratio, combined with identification of diagnostic sedimentary structures and the detailed fossil characterization clearly indicate that M. Adone Formation accumulated in a shallower environment with respect to the underlying Argille Azzurre Formation. The coarsening-upward trend of the 13 depositional cycles, with upward thinning of siltstone interbeds and amalgamation of topmost sand bodies, combined with the cyclic stacking pattern of biofacies suggest episodes of coastal progradation, possibly related to phases of relative sea-level still-stand, alternating with phases of rapid deepening (cycle boundaries).

Maximum palaeodepths (30–60 m), similar to those estimated for the uppermost Argille Azzurre Formation, are recorded in the basal parts of cycles by the occurrence of either *B. brachystoma–T. ovata* or *V. nux–N. semistriatus* biofacies. *V. Nux*, reported from the present-day Italian shelves at relatively high depths (40–200 m, with maximum abundance between 80–150 m), has been observed to characterize shallower sandy substrates (Robba, 1990), with high sedimentation rates (Dominici, 2001), within Pliocene deposits. The presence of relatively shallow-water taxa, such as *N. josephinia, T. lactea* and *T. excalliferus*, is consistent with an inner-shelf (upper circalittoral/lower infralittoral transition) depositional environment, between 30 and 50 m.

Most of sandy siltstone bodies include monospecific assemblages of *C. gibba*. This biofacies, handling large quantities of suspended materials (Yonge, 1946), and showing tolerance for fluctuating salinity condition (14–35 per thousand, see Lewy and Samtleben, 1978), suggests proximity to river mouths and is here interpreted to be representative of a lower prodelta environment. This interpretation is consistent with the abundance of plant debris and the presence of monospecific assemblages of *T. tricarinata* and *D. arietina*, commonly developed under high mud inputs due to river discharge (Bernasconi and Robba, 1993; Dominici, 2001). The upward transition to sandy siltstone bodies virtually devoid of fossils is consistent with an increasing influence by riverine waters, here interpreted to characterize upper prodelta deposits.

The sandstone–siltstone alternations are typical of shoreface–offshore transition environments below normal wave base (Kumar and Sanders, 1976; Howard and Reineck, 1981), and are likely to record transition from prodelta to delta front deposits. This interpretation is consistent with (i) identification of *S. subtruncata–C. gallina* biofacies, which is characteristic of the Fine Well Sorted Sands (SFBC) of Pérès and Picard (1964), at depths up to 25 m (Picard, 1965; Corselli and Scola, 1990 among the others), and (ii) the local presence of *Pecten bosniasckii* (Aguirre et al., 1996 and references therein).

The abundance of HCS and symmetrical wave ripples within the amalgamated sandstone bodies in the uppermost parts of cycles suggests a lower shoreface environment (Harms et al., 1975; Dott and Bourgeois, 1982) , probably related to a lower delta front (see also Ricci Lucchi et al., 1981). This interpretation is consistent with the occurrence of *Glycymeris insubrica*, a typical infralittoral species commonly found in nearly monospecific assemblages, at slightly lower water depths than *S. subtruncata–C. gallina* biofacies, preferably within low-salinity shoreface environments close to river mouths (Vatova, 1949).

4. Discussion and conclusions

The depositional history of PIB, reconstructed at its northern margin by integrated palaeoecologic and sedimentologic studies, is characterized by a general regressive trend, encompassing the entire Pliocene deposits (Argille Azzurre Formation and M. Adone Formation). This sedimentary evolution reflects the progressive filling of the basin during the early-middle Pliocene.

The vertical *suite* of biofacies identified within the Argille Azzurre Formation in the Palazzo dei Rossi section shows a distinctive shallowing-upward tendency, from an upper bathyal (slope-outer shelf) environment, 120–300 m deep, to a circalittoral (inner shelf) environment, with 30–50 m water depth. The upward transition to M. Adone Formation marks a significant palaeogeographic change, reflecting the onset and progradation of wave-influenced delta systems, with preservation of prodelta and delta front deposits (Oomkens, 1970; Hamblin and Walker, 1979). As suggested by previous work (Ricci Lucchi et al., 1981), the boundary between the two formations (broadly corresponding to the boundary between cycles 1 and 2 of Ricci Lucchi et al., 1981) is transitional and an obvious unconformity cannot be detected, neither in the field nor on the basis of detailed palaeoecologic studies.

The distinctive cyclic arrangement of M. Adone Formation, superposed to the overall regressive trend of PIB, consists of a repeated alternation, a few tens of metres thick, of prodelta to delta front deposits, which enable the reconstruction of the patterns of shoreline migration in the study area. The lower boundaries of the 13 cycles identified along the Pieve del Pino section correspond to flooding surfaces, marking abrupt shifts to relatively deeper environments (lower prodelta to inner shelf), whereas the cycle itself records distinct episodes of delta progradation. A general balance among sediment input, subsidence and sea-level changes allowed vertical stacking of very similar facies sequences during deposition of the entire formation.

In terms of sequence stratigraphic interpretation, the 13 high-frequency (fifth-order?) cycles, reflecting the repeated alternation of phases of rapid deepening with phases of gradual shallowing, can be regarded as parasequences in the sense of Van Wagoner et al. (1990) and Kamola and Van Wagoner (1995). Taking into account that: (i) age of M. Adone Formation is constrained within *G. puncticulata* zone, the total duration of which is approximately 630 ka, and (ii) additional parasequences can be present in the poorly exposed uppermost part of PIB, an average duration of about 35–45 ka can be estimated for any individual parasequence. This periodicity is in the range of Milankovitch cyclicity (obliquity cycles).

It cannot be excluded that cyclic changes in shoreline position, similar to those identified within M. Adone Formation, took place in the lower part of PIB, also during deposition of the Argille Azzurre Formation. These cycles, however, cannot be easily detected by either sedimentologic or palaeoecologic studies, owing to low-sensitivity of bathyal to circalittoral environments to small-scale sea-level changes, in terms of grain-size and molluscan biofacies variations.

The detailed palaeoecologic and sedimentologic analysis at the northern margin of PIB carried out in this work enables comparison with the well-known stratigraphic framework reconstructed at the southern margin of basin by Ricci Lucchi et al. (1981). Particularly, facies characteristics of M. Adone Formation, described at length in this paper, are fully consistent with previous work from the southern part of PIB, showing a physical link between these delta front sandstones and the fluvial-littoral deposits cropping out in proximal areas. By contrast, there does not appear to exist possible correlation between the “regressive” trend clearly documented in this paper from the Argille Azzurre Formation and the opposite, overall “transgressive” trend recognized within the supposed coeval cycle-1 deposits at the southern margin of PIB (Ricci Lucchi et al., 1981). This raises some questions about the correctness of correlation between the two successions, as indicated by previous work, and suggests that caution should be taken in establishing basinwide stratigraphic-correlation lines before a detailed chronological framework is available for the entire basin.

Preliminary, new biostratigraphical data record for the first time the presence of *G. margaritae* in the lower part of the Argille Azzurre Formation in PIB, suggesting an attribution of the lower part of the succession to the lower part of the early Pliocene (Zanclean). The youngest age recorded for the PIB fill is assigned to the lower part of the Piacenzian.

Acknowledgements

We are grateful to reviewers S. Milli and E. Robba for their useful suggestions. This study was supported by MURST (40%) 2001 (Co-ordinator: F. Massari).

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